Univerza
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LUKA PAJEK

ENERGIJSKA UČINKOVITOST ENOSTANOVANJSKIH BIOKLIMATSKIH STAVB GLEDE NA PODNEBNE SPREMEMBE

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Doktorska disertacija

ENERGY EFFICIENCY OF SINGLE-FAMILY BIOCLIMATIC BUILDINGS IN RELATION TO CLIMATE CHANGE

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Izvleček

V luči podnebnih sprememb, s katerimi se soočamo, so prizadevanja za poznavanje in obvladovanje njihovega vpliva na energijsko učinkovitost stavb vedno večja, medtem ko se moramo o vplivu globalnega segrevanja na grajeno okolje še veliko naučiti. Navkljub vse večjemu številu raziskav še vedno ni povsem jasno, kakšen je in bo vpliv globalnega segrevanja na bioklimatski potencial ter učinkovitost pasivnih načrtovalskih ukrepov pri enostanovanjskih stavbah. S pomočjo obširnega pregleda literature in simulacijskih študij smo v doktorski disertaciji odgovorili na nekaj neznank, ki se ob tem pojavljajo. Posebno pomemben del raziskave se nanaša na predstavljeno metodo izračuna bioklimatskega potenciala lokacije, pri čemer je bila veljavna metodologija nadgrajena z upoštevanjem podatka o sončnem sevanju. Izsledki raziskav so pomemben prispevek k znanosti, saj so pokazali na potrebo po idejnem preskoku v trenutni praksi bioklimatskega načrtovanja enostanovanjskih stavb. Podatki, pridobljeni s 15.897.600 parametričnimi simulacijami, ki so dostopni v doktorski disertaciji, pomenijo bistvene informacije za pravočasno prilagajanje podnebnim spremembam. Ugotovljeno je bilo, da je glede na skupno rabo energije za ogrevanje in hlajenje energijska učinkovitost enostanovanjskih stavb v prihodnosti odvisna od lokacije, in sicer je v splošnem pričakovati, da bo na toplih lokacijah nižja, na hladnih višja, na zmerno toplih pa bo najprej višja, nato nižja. Na podlagi podatkov je bil predlagan nov pristop k bioklimatskemu načrtovanju stavb, pri čemer s pasivnimi ukrepi zagotovimo energijsko učinkovitost v trenutnem in prihodnjem podnebnem stanju, hkrati pa obravnavamo ranljivost stavbe za pregrevanje v prihodnosti.

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Abstract

In light of the current climate change, efforts to recognise and mitigate its impact on the energy performance of buildings are increasing. However, there is still a lot to learn about the impact of global warming on the built environment. Despite numerous research studies, the impacts of global warming on the bioclimatic potential and the applicability of passive design measures in the case of single-family buildings are not completely clear. The exposed knowledge gaps were filled in the doctoral dissertation by performing an extensive literature review and numerous simulations. An essential part of the research refers to the presented method of calculating the location's bioclimatic potential, where the existing methodology was upgraded by considering the data on solar radiation. Moreover, the research results represent an essential contribution, as they showed the need for a conceptual leap in the current bioclimatic design practice of single-family buildings. The data obtained by 15,897,600 parametric simulations represent essential information for timely adaptation to climate change. It was found that, given the combined energy need for heating and cooling, the energy efficiency of single-family buildings in the future depends on the location. It can be generally expected that energy efficiency will be lower in warm climates, higher in cold and firstly higher and then lower in temperate climates. Based on the data, a new approach to bioclimatic building design was proposed, where passive design measures are applied to ensure energy efficiency in the current and future climate while the future overheating vulnerability is addressed.

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SIMBOLI/SYMBOLS

α	količnik vpojnosti [-]
α_{sol}	sončna vpojnost (absorptivnost) materiala [-]
β	standardizirani regresijski količnik [-]
ε	efektivna emisivnost materiala [-]
η	učinek toplotnih virov [-]
θ_i	faktor presevnosti energije sončnega sevanja [-]
λ	toplotna prevodnost [W/mK]
ρ	količnik odboja [-]
ρ_a	gostota zraka [kg/m^3]
ρ_m	gostota [kg/m^3]
σ	Stefan-Boltzmannova konstanta [J/sm^{2}K^4]
τ	količnik presevnosti [-]
χ	točkovna toplotna prehodnost točkovnega elementa [W/mK]
ψ	linijska toplotna prehodnost linijskega elementa [W/K]
A	površina elementa [m^2]
A_f	projicirana površina okenskega okvirja [m^2]
A_g	površina zasteklitve [m^2]
A_h	izmenjava energije z delom [J]
A_j	najmanjša vrednost kazalnika zmogljivosti v podnebnem scenariju j
A_{ovoj}	površina toplotnega ovoja stavbe [m^2]
$A_{T,i}$	amplituda nihanja notranje temperature [K]
ACH	število urnih izmenjav zraka [1/h]
C_h	izmenjava energije s konvekcijo [J]
C_{CO2}	koncentracija CO_2 v atmosferi [ppm]
$C_{0,CO2}$	koncentracija CO_2 v atmosferi pred začetkom industrijske revolucije [ppm]
Clo/c	vpliv stopnje oblečenosti
C_m	toplotna kapaciteta stavbe [J/K]
c_p	specifična toplota [J/kgK]
d	debelina [m]
DHC	dnevna toplotna kapaciteta konstrukcijskega sklopa [kJ/m^{2}K]
E	moč notranjega toplotnega vira [W]
E_e	sevalni toplotni tok s površine v okolico [W/m^2]
E_h	izguba energije zaradi evaporacije vlage na površini človeškega telesa [J]
f_0	faktor oblike stavbe [m^{-1}]
g	faktor presevnosti energije sončnega sevanja [-]
G	gostota moči sončnega sevanja [W/m^2]
G_{avg}	povprečna dnevna gostota moči sončnega sevanja na vodoravni ravnini [W/m^2]
G_{max}	maksimalna dnevna gostota moči sončnega sevanja na vodoravni ravnini [W/m^2]

h_c	konvekcijski prestopni količnik [W/m^{2}K]
h_{c+s}	skupen prestopni količnik zračne plasti [W/m^{2}K]
h_s	sevalni prestopni količnik [W/m^{2}K]
I	globalno sončno obsevanje [kWh/m^2]
K_h	izmenjava energije s kondukcijo [J]
L	dolžina linijskega elementa [m]
L_s	dolžina medstekelnega distančnika [m]
M_h	metabolna toplota človeškega telesa [J]
n	časovno obdobje
n_k	število točkovnih elementov
NV_C	hlajenje z naravnim prezračevanjem [h^{-1}]
OV	ocena ranljivosti za pregrevanje [-]
P	trajanje periode
PI_{ij}	kazalnik zmogljivosti i-tega modela stavbe v podnebnem scenariju j
q	toplotni tok [W]
Q_{acc}	količina akumulirane toplote [J]
Q_e	evaporacijske toplotne izgube [J]
Q_f	dovedena energija za delovanje sistemov [kWh]
Q_i	toplotni dobitki notranjih toplotnih virov [J]
$\dot{Q}_i$	povprečni toplotni tok notranjih virov v obravnavanem časovnem obdobju [W]
Q_{NC}	letna potrebna energija za hlajenje stavbe na enoto kondicionirane uporabne površine stavbe [kWh/m^2]
Q_{NH}	letna potrebna energija za ogrevanje stavbe na enoto kondicionirane uporabne površine stavbe [kWh/m^2]
Q_r	sevalne toplotne izgube in dobitki [J]
$\dot{q}_{rad}$	sevalni toplotni tok med dvema vzporednima površinama [W]
Q_s	sončni (solarni) toplotni dobitki [J]
Q_{sol}	prejeta sončna toplota [J]
$\dot{Q}_{sol}$	povprečni toplotni tok sončnih dobitkov v obravnavanem časovnem obdobju [W]
$\dot{Q}_{sys}$	povprečen toplotni tok, ki je v obravnavanem časovnem obdobju vnesen v ali vzet iz stavbe z namenom doseči toplotno ravnovesje [W]
Q_t	transmisijske toplotne izgube in dobitki [J]
Q_T	skupna letna potrebna energija za ogrevanje in hlajenje na enoto uporabne kondicionirane površine stavbe (Q_{NH} + Q_{NC}) [kWh/m^2]
$\dot{q}_v$	stopnja prezračevanja [m^3/h]
Q_v	prezračevalne (ventilacijske) toplotne izgube in dobitki [J]
R	toplotna upornost [m^{2}K/W]
R_{ij}	obžalovanje zmogljivosti i-tega modela stavbe v podnebnem scenariju j
$R_{max,i}$	največja vrednost kazalnika zmogljivosti i-tega modela stavbe
R_f	sevalni prispevek [W/m^2]
R_h	izmenjava energije s sevanjem [J]

RES_h	toplotne izgube, ki so posledica dihanja [J]
RH	relativna vlažnost [%]
RH_{max}	maksimalna relativna vlažnost [%]
RH_{min}	minimalna relativna vlažnost [%]
R_s	toplotni upor mejne prestopne zračne plasti [m^2K/W]
R_{se}	toplotni upor mejne prestopne zračne plasti na zunanji strani [m^2K/W]
R_{tot}	toplotna upornost celotnega konstrukcijskega sklopa [m^2K/W]
ΔS_b	toplotna bilanca stavbe [J]
S_c	delež telesa, izpostavljen sevanju [-]
ΔS_h	toplotna bilanca človeškega telesa [J]
S_t	povprečna površina telesa oblečenega človeka [m^2]
$SHGC$	faktor presevnosti energije sončnega sevanja [-]
t	čas opazovanega trenutka
Δt	časovni korak
ΔT	razlika med notranjo in zunanjo temperaturo [K]
T_1	temperatura, izražena na absolutni temperaturni lestvici na prvi površini [K]
T_2	temperatura, izražena na absolutni temperaturni lestvici na drugi površini [K]
T_{avg}	povprečna temperatura suhega termometra [°C]
T_{db}	temperatura suhega termometra [°C]
T_e	temperatura zunanjega zraka [°C]
$T_{e,av}$	povprečna mesečna temperatura zunanjega zraka [°C]
$T_{e,t}$	temperatura zunanjega zraka v trenutku t [°C]
T_i	temperatura notranjega zraka [°C]
$T_{i,avg}$	povprečna dnevna temperatura notranjega zraka [°C]
$T_{i,t}$	temperatura notranjega zraka v trenutku t [°C]
$T_{i,t-1}$	temperatura notranjega zraka v prejšnjem časovnem koraku [°C]
T_{max}	maksimalna temperatura suhega termometra [°C]
T_{min}	minimalna temperatura suhega termometra [°C]
T_{mr}	srednja sevalna temperatura [°C]
T_n	temperatura zraka, okrog katere se giblje človekova cona toplotnega udobja [°C]
T_o	občutena oz. operativna temperatura [°C]
T_{PSH}	temperatura zraka, pri kateri je še možno koriščenje pasivnega sončnega ogrevanja [°C]
T_s	površinska temperatura elementa v okolici [°C]
T_{sa}	temperatura sol-air [°C]
$T_{si,j,t}$	površinska temperatura na notranji strani j-tega elementa v trenutku t [°C]
T_{skin}	temperatura kože [°C]
T_{sub}	nadomestna udobna temperatura zraka [°C]
$TSET$	faktor presevnosti energije sončnega sevanja [-]
U	toplotna prehodnost [W/m^2K]
U_f	toplotna prehodnost okenskega okvirja [W/m^2K]
U_g	toplotna prehodnost zasteklitve [W/m^2K]

U_O	toplotna prehodnost netransparentnega elementa stavbnega ovoja [W/m^{2}K]
U_W	toplotna prehodnost transparentnega elementa stavbnega ovoja [W/m^{2}K]
v	hitrost gibanja zraka [m/s]
V	bruto prostornina stavbe [m^3]
V_net	neto prostornina stavbe [m^3]
V.Clo/c	vpliv gibanja zraka na toplotno izolativnost obleke
V_max	maksimalna ranljivost za pregrevanje zaradi podnebnih sprememb
W_dis	razporeditev oken glede na orientacijo stavbe
WFR	razmerje med površino oken v ovoju in tlorisno uporabno površino stavbe [%]
WWR	razmerje med površino oken in površino zunanjih sten [%]

OKRAJŠAVE/ABBREVIATIONS

AOMSC	atmosfera-ocean model splošne cirkulacije	*ang.*	Atmosphere-Ocean General Circulation Model (AOGCM)
CMIP6	6. faza projekta medsebojne primerjave spojenih modelov	*ang.*	Coupled Model Intercomparison Project Phase 6
CTF	funkcija kondukcijskega prenosa	*ang.*	Conduction Transfer Function
DHC	dnevna toplotna kapaciteta konstrukcijskega sklopa	*ang.*	diurnal heat storage capacity
EMIC	modeli zemeljskega sistema vmesne kompleksnosti	*ang.*	Earth system Models of Intermediate Complexity
EPBD	Direktiva o energetski učinkovitosti stavb	*ang.*	Energy Performance of Buildings Directive
EPC	energetska izkaznica	*ang.*	Energy Performance Certificate
EPW	EnergyPlus podnebna datoteka	*ang.*	EnergyPlus Weather file
ESM	model celotnega Zemljinega sistema	*ang.*	Earth System Model
GIS	geografski informacijski sistem	*ang.*	Geographic Information System
HadCM3	združeni model Hadleyjevega centra, različica 3	*ang.*	Hadley Centre Coupled Model, version 3
HVAC	ogrevanje, prezračevanje in klimatizacija	*ang.*	Heating, Ventilation, and Air Conditioning
IDW	inverzna utežena razdalja	*ang.*	Inverse Distance Weighted
IPCC	Medvladni odbor za podnebne spremembe	*ang.*	Intergovernmental Panel on Climate Change
JRC	Skupno raziskovalno središče	*ang.*	Joint Research Centre
MKE	metoda končnih elementov	*ang.*	Finite Element Method (FEM)
MKR	metoda končnih razlik	*ang.*	Finite Difference Method (FDM)
MLR	multipla linearna regresija	*ang.*	Multiple Linear Regression
MRE	metoda robnih elementov	*ang.*	Boundary Element Method (BEM)
MSC	model splošne cirkulacije	*ang.*	Global Circulation Model (GCM)
PMV	indeks pričakovane presoje toplotnega občutja	*ang.*	Predicted Mean Vote
PURES	Pravilnik o učinkoviti rabi energije v stavbah	*ang.*	Rules on efficient use of energy in buildings with a technical guideline

PV	fotonapotestni ali fotovoltaični	*ang.* Photovoltaics
RCP	značilni poteki koncentracij	*ang.* Representative Concentration Pathways
SHGC	faktor presevnosti energije sončnega sevanja	*ang.* Solar Heat Gain Coefficient
SRES	scenariji izpustov	*ang.* Special Report on Emissions Scenarios
sNES	skoraj nič-energijska stavba	*ang.* nearly Zero-Energy Building (nZEB)
TMY	značilno meteorološko leto	*ang.* Typical Meteorological Year
TRY	testno referenčno leto	*ang.* Test Reference Year
TSET	faktor presevnosti energije sončnega sevanja	*ang.* Total Solar Energy Transmittance
WFR	razmerje med površino oken v ovoju in tlorisno uporabno površino stavbe	*ang.* window to floor ratio
WMO	Svetovna meteorološka organizacija	*ang.* World Meteorological Organization
WWR	razmerje med površino oken in površino zunanjih sten	*ang.* window to wall ratio
ZMSC	združeni model splošne cirkulacije	*ang.* Coupled Global Circulation Model (CGCM)

1 UVOD

Povzetek

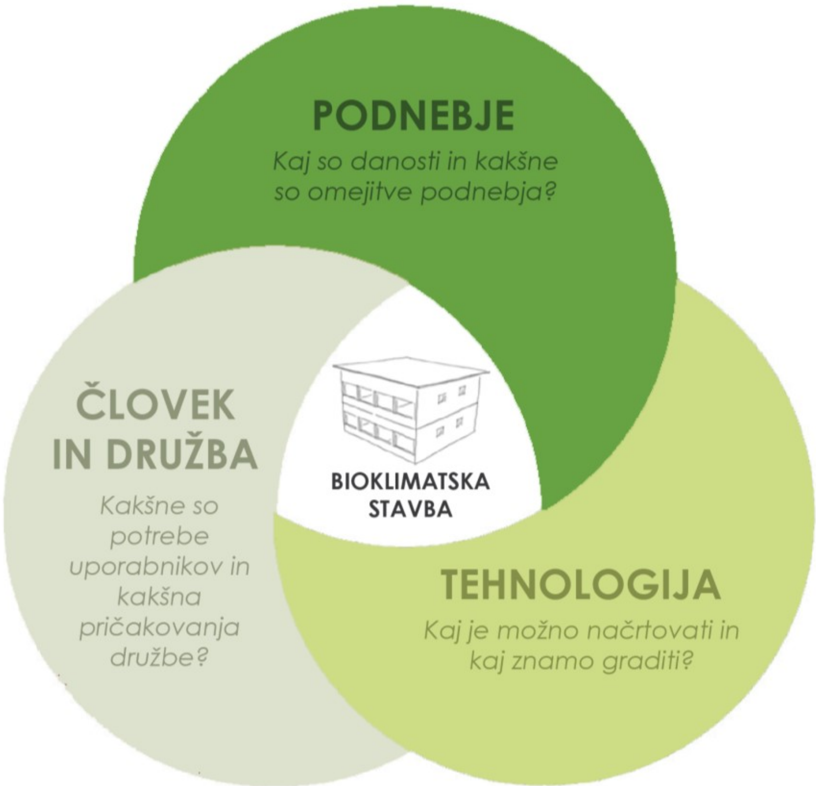
Poglavje uvodoma na kratko predstavlja bioklimatsko načrtovanje stavb in problematiko energijske učinkovitosti enostanovanjskih stavb glede na podnebne spremembe. S pomočjo orisa obravnavanega področja in izzivov, ki jih prinaša, so v nadaljevanju natančneje opredeljena poglavitna znanstvena vprašanja obravnavanem področju, in namen doktorske disertacije. Oblikovani so štirje glavni cilji raziskovanja, nato pa predstavljene tri hipoteze. Zadnje podpoglavje opisuje strukturo doktorske disertacije s kratko vsebino posameznega poglavja.

Abstract

The chapter briefly introduces the bioclimatic design of buildings and the questions about the energy efficiency of single-family buildings, which arise with climate change. Based on the short outline of the considered field and its challenges, the leading research questions and the aim of the doctoral dissertation are defined in more detail. After that, four main objectives of the research are formulated, and then the three hypotheses are presented. The last subchapter describes the structure of the doctoral dissertation with a brief content of each chapter.

1.1 Opis obravnavanega področja

Od nekdaj je ljudem izgradnja domov zagotavljala večjo stopnjo prilagodljivosti in neodvisnosti od podnebja in jim s tem omogočala boljše bivanjske razmere. Zavetišča in hiše so tako prve ljudi varovali pred okoljem, plenilci in vsiljivci [1]. Z gradnjo bivališč ljudje niso bili več prisiljeni v selitve na območja s prijetnejšim vremenom, kadar so se bivanjske razmere zaradi menjave letnih časov in podnebnih sprememb na nekem območju poslabšale. Posledično so bila naseljena številna razmeroma manj gostoljubna okolja. S širitvijo bivališč v različna, prej neposeljena podnebja, so se načrtovalci in graditelji soočili z izzivom, kako izkoristiti ali pa se boriti s podnebnimi značilnostmi neke lokacije. Ljudje so sčasoma izluščili najboljše načrtovalske ideje, znanje o podnebno prilagojenih stavbah pa se je prenašalo iz generacije v generacijo. Naučene priložnosti in omejitve, ki jih za gradnjo stavb pomeni neko podnebje, skupaj s potrebami ljudi oz. uporabnikov in pričakovanji družbe ter tehnološkim znanjem o gradnji, tvorijo t. i. trojnost bioklimatskega načrtovanja stavb (slika 1) [1]. Prav zato je koncept bioklimatskega načrtovanja stavb pogosto povezan z doseganjem harmonije med podnebjem, udobjem in energijsko učinkovitostjo [2]. Jasno je, da bolje kot stavba lahko sledi in se odziva na dinamiko zunanjega okolja, tj. temperature, sončno sevanje in relativno vlažnost, bolj učinkovita je [3].



Slika 1: Trije osnovni sestavni deli bioklimatskega načrtovanja stavb, povzeto po Košir [1].
Figure 1: The three basic constituents of bioclimatic design, adapted from Košir [1].

Bioklimatsko načrtovanje se v arhitekturi in gradbeništvu običajno opisuje kot sposobnost stavbe izkoriščati podnebne razmere in razpoložljive vire na neki lokaciji za izboljšanje učinkovitosti njenega delovanja. Cilj je, da stavba in njeni elementi zagotavljajo udobje uporabnikov, pri tem pa omogočajo učinkovito rabo energije in virov, tako da se kar najbolj prilagodijo podnebnim razmeram na lokaciji [4, 5]. V stroki velja splošno mnenje, da je ljudska (tj. tradicionalna oz. vernakularna) arhitektura popolnoma prilagojena podnebnim značilnostim neke lokacije, saj se je temu podnebju stoletja prilagajala. Zato so pri načrtovanju novih stavb primeri vernakularne arhitekture pogosto vir bioklimatskih strategij in pasivnih načrtovalskih ukrepov [1, 6, 7]. V današnjem času so pri načrtovanju stanovanjskih stavb bioklimatske strategije skoraj vedno dopolnjene z naprednimi tehnologijami in aktivnimi sistemi za ogrevanje, hlajenje, prezračevanje in razsvetljavo, ti pa lahko dinamično zmanjšajo rabo energije in povečajo toplotno udobje uporabnikov [8, 9].

Pri načrtovanju bioklimatskih stavb ima ključno vlogo podnebje. Čeprav na Zemlji lahko najdemo večje dele celin z istim podnebnim tipom, je na nekaterih delih, kot na primer v evropski regiji Alpe-Jadran, na zelo majhnem območju moč najti več različnih podnebnih tipov [10]. Podnebna mnogovrstnost se zato tudi na razmeroma majhnih geografskih območjih izraža v raznoliki bioklimatski arhitekturi [11]. V podnebjih celinske Evrope naj bi stanovanjska stavba, zasnovana v skladu z načeli bioklimatskega načrtovanja, v glavnem izkoriščala pasivne sončne dobitke energije, imela nizke toplotne izgube v hladnejšem delu leta in omogočila dnevno shranjevanje toplote s pomočjo visoke toplotne kapacitete oz. toplotne mase stavbnega ovoja [1]. V zmerno-celinskem in borealnem podnebju je zato toplotni odziv stanovanjskih stavb običajno pogojen s toplotnim ovojem stavbe [12]. Tako je v takšnih podnebjih uporaba pasivnih načrtovalskih ukrepov na ravni ovoja stavbe pri optimizaciji rabe energije za ogrevanje stavb lahko zelo učinkovita.

V zadnjem stoletju so bile ugotovljene opazne podnebne spremembe [13–17], do konca 21. stoletja pa naj bi se globalna temperatura v povprečju zvišala za do 4 °C [18] v primerjavi s predindustrijskim obdobjem. V obdobju lovcev in nabiralcev (paleolitik) so se ljudje ob večjih podnebnih spremembah lahko selili na druga, za bivanje prijetnejša območja. Z uporabo stavb takšno migracijsko vedenje kot strategija podnebnih prilagoditev za večino ljudi ni bilo več privlačno, saj bi človek za seboj pustil rezultat svojega trdega dela – stavbo. To privede do spoznanja, da je v podnebno prilagojene stavbe vgrajeno tveganje za pojav bivalnega neugodja ter slabšega (energijskega) delovanja, ki se lahko pokaže ob večjih podnebnih spremembah. Poročilo o migracijah in podnebnih spremembah [19] opisuje, da naj bi bila, zaradi segrevanja podnebja in posledičnih ekoloških groženj do leta 2050 v selitev prisiljena več kot milijarda ljudi. Ogroženi so zlasti podsaharska Afrika, Južna Azija, Bližnji vzhod in Severna Afrika, ki se zaradi podnebnih sprememb soočajo z največjim številom nevarnosti, kot so pomanjkanje dostopa do hrane in vode ter povečanje števila naravnih nesreč [20]. Po drugi strani naj bi podnebne spremembe razvitim regijam v Evropi in Severni Ameriki predstavljale manjšo ekološko grožnjo [20], kljub temu pa niti v teh regijah ni zagotovila za neobčutljivost na širše posledice podnebnih sprememb, kot je vpliv na urbano okolje in stavbe.

Toplejše podnebje bo neizbežno vplivalo na toplotni odziv stavb, tudi bioklimatskih stavb, prilagojenih trenutnemu ali preteklemu podnebju. Wang in sod. [21] so opozorili, da nastaja vedno večja potreba po razjasnitvi izzivov, ki jih predstavlja globalno segrevanje, z namenom, da bi lahko z uporabo pasivnih načrtovalskih ukrepov omejili morebitno toplotno neudobje, ki bi ga le-to povzročilo. Navedeno lahko ugotovimo s preprostim primerom. V podnebjih Srednje Evrope v stavbah uporabljeni pasivni načrtovalski ukrepi temeljijo predvsem na zmanjševanju potrebe po ogrevanju stavb, z željo, da se v zimskih mesecih doseže toplotno udobje ob čim nižji rabi energije. Zato lahko v takšnih stavbah opazimo večja južno orientirana okna za pasivno sončno ogrevanje, ovoje stavb z nizko toplotno prehodnostjo in kompaktne oblike stavb, kot sta kocka in kvader [22, 23]. Kljub temu, da so takšne stavbe dobro prilagojene podnebju, v katerem se nahajajo, obstaja nevarnost, da bodo predvideni učinki segrevanja ozračja povzročili pregrevanje, zlasti, če je meja med toplotno udobnim in prevročim notranjim okoljem tanka. V tem primeru lahko uporaba velikih južno orientiranih okenskih površin privede do prevelike toplotne obremenitve in do pregrevanja v poletnem času. To je pomembno predvsem pri stavbah na lokacijah, na katerih do sedaj ni bilo nevarnosti za pregrevanje stavb. Zato bi bilo na takšnih lokacijah treba vnovič oceniti bioklimatske strategije, ki se uporabljajo v stavbah. V preteklosti so bile opravljene številne raziskave, usmerjene v oceno učinkov podnebnih sprememb na energijsko učinkovitost stavb. Berardi in Jafarpur [24] sta za primer Toronta v Kanadi ob upoštevanju različnih scenarijev in tipologij stavb pokazala, da lahko do leta 2070 pričakujemo povprečno zmanjšanje potrebne energije za ogrevanje stavb za 18–33 %. Nasprotno je pričakovano povprečno povečanje rabe energije za hlajenje stavb za 15–126 %. Tudi Rodrigues in Fernandes [25] sta napovedala, da se v stanovanjskih stavbah v Sredozemlju do leta 2050 pričakuje povečanje potrebe po hlajenju (za do 137 %) in zmanjšanje potrebe po ogrevanju (za do 63 %), medtem ko naj trenutne optimalne vrednosti toplotne prehodnosti (*U* vrednosti) ne bi povzročale nevarnosti za pregrevanje. Bravo Dias in sod. [26] so preučili vpliv podnebnih sprememb na učinkovitost pasivnih ukrepov v stavbah v 43 najbolj naseljenih mestih v Evropski uniji. Ugotovili so, da bodo s podnebnimi spremembami še posebej prizadete stavbe, ki uporabljajo pasivne načrtovalske ukrepe, katerih učinkovitost je zelo odvisna od podnebja. Na primer v južni Evropi je predvideno, da se bo čas, v katerem je potrebno senčenje, podaljšal za 2,5 meseca, zaradi česar bo senčenje z nadstreški ali drugimi fiksnimi senčili manj učinkovito.

Zaradi pričakovanega spremenjenega vpliva podnebja na toplotni odziv stavb in potrebo po energiji bi morali pri izbiri pasivnih ukrepov za načrtovanje stavb slediti zagotavljanju najvišje možne odpornosti (ang. *resilience*) stavbe. Martin in Sundley [27] definirata odpornost kot skupek več meril, vključno z ranljivostjo (ang. *vulnerability*), upiranjem (ang. *resistance*), robustnostjo (ang. *robustness*) in obnovljivostjo (ang. *recoverability*). Po navedbah Attia in sod. [28] bi morala biti ocena ranljivosti stavbe za pregrevanje v različnih podnebnih scenarijih obvezen del postopka pri načrtovanju energijsko učinkovitih stavb. Cilj takšnega pristopa je najti načrtovalsko rešitev z manj občutljivimi lastnostmi na »šume« iz okolja, kot je sprememba temperature zraka [29]. Tudi v živalskem svetu lahko idejo o odpornih »stavbah« najdemo v drevesnih mravljiščih (ang. *ant garden*), ki očitno mravljam omogočajo, da so odpornejše na podnebne spremembe, kot bi bile zunaj tega sistema [30]. Za oceno odpornosti mest in stavb na podnebne spremembe je bilo opravljenih nekaj raziskav, predvsem ocene robustnosti in ranljivosti (glej reference [31–37]). Na primer Fonseca in sod. [31] so preučevali učinke podnebnih sprememb na rabo energije stavb v ZDA. Ugotovili so, da so zato, da se zagotovijo natančnejše ocene o vplivu podnebnih sprememb na grajeno okolje, potrebne dodatne raziskave. Podobno sta Shen in Lior [32] naredila analizo ranljivosti na vplive podnebnih sprememb za sisteme izrabe obnovljivih virov energije, ki se uporabljajo v ničenergijskih stavbah. Različni avtorji, kot so Moazami in sod. [29], Kotireddy in sod. [33] in podobni, so predstavili predloge pristopov k ocenjevanju in metode za oceno robustnosti stavb na spremembe podnebja, z namenom preprečevanja občutnih razlik v rabi energije. Da bi zmanjšali podnebno ranljivost stavb, sta v tem kontekstu Houghton in Castillo-Salgado [38] priporočila uporabo metod za ocenjevanje in certificiranje energijske učinkovitosti stavb ter namensko usmerjanje k t. i. zelenim tehnologijam gradnje in delovanja stavb.

Pariški sporazum o podnebnih spremembah iz leta 2015 je določil cilje in omejitve, da bi zmanjšali nadaljnje višanje temperatur zraka na globalni ravni. V skladu z evropskimi direktivami sta pri doseganju teh ciljev ključna elementa zmanjšanje vpliva stavb na okolje [39] in izboljšanje njihove energijske učinkovitosti [40, 41]. Vse očitneje je, da zaradi vse večje ozaveščenosti o rabi naravnih virov in varstvu okolja pomen energijske učinkovitosti stavb nenehno narašča. Hkrati raste tudi pomen kakovosti bivanja, ki ima ključno vlogo pri dojemanju »zdravih domov« [42, 43]. Na tej točki je smiselna razprava o konceptu odpornosti in ranljivosti stavb za globalno segrevanje, predvsem o rabi energije v stavbah Evropske unije (EU), natančneje, v okviru Direktive o energetski učinkovitosti stavb v EU (ang. *Energy Performance of Buildings Directive*, EPBD) [40], ki na ravni EU ureja rabo energije v stavbah in spodbuja članice v nizkoenergijsko gradnjo. Za izboljšanje energijske učinkovitosti stavb je Direktiva EPBD kot pravni instrument uvedla tudi certificiranje energijske učinkovitosti stavb (ang. *Energy Performance Certificates*, EPCs), kar je bilo v Sloveniji vpeljano s pomočjo energetskih izkaznic stavb. Tako lahko stavbe glede na energijske kazalnike razvrstimo v energijske razrede A–G. Kljub uvedbi EPC-jev ima v večini držav EU več kot polovica vseh obstoječih stanovanjskih stavb z registriranimi EPC energijski razred D ali nižji [44]. Za Slovenijo to pomeni letno potrebno toploto za ogrevanje stavbe na enoto kondicionirane površine stavbe (Q_{NH}), višjo od 60 kWh/m^2. Vendar pa se po drugi strani povečuje delež na novo zgrajenih skoraj ničenergijskih stavb (sNES), ki so bile prav tako uvedene z Direktivo EPBD in za katere je značilna visoka energijska učinkovitost in vsaj delna energijska neodvisnost. Pri tem je, kot poudarjajo Šijanec Zavrl in sod. [45], zlasti za stanovanjske stavbe največji izziv doseči ustrezno kakovost v načrtovanju in izgradnji stavb. Leta 2019 so članice EU sklenile Evropski zeleni dogovor (ang. *The European Green Deal*) [46], z namenom premagati izzive, ki jih prinašajo podnebne spremembe, in postati prva podnebno nevtralna celina. Cilj zelenega dogovora je preoblikovanje EU v sodobno, z viri gospodarno in konkurenčno gospodarstvo, pri čemer je poudarek na zagotavljanju ničelnih neto emisij toplogrednih plinov do leta 2050 (podnebna nevtralnost), od rabe virov ločene gospodarske rasti in pravičnega ter vključujočega prehoda za vse ljudi in kraje. Evropska komisija je leta 2020 predstavila tudi strategijo za spodbujanje energijskih prenov stavb, z namenom doseganja podnebne nevtralnosti stavb v EU [47], kar je eden od ciljev Evropskega zelenega dogovora. S tem je Evropska komisija poudarila pomen upoštevanja in analize ranljivosti stavb za podnebne spremembe. Zato vse omenjene zahteve in usmeritve na ravni EU spodbujajo pospešen napredek glede energijsko učinkovitih stavb, pri čemer so sNES postale tehnološka resničnost in nuja. Kljub temu z uporabo prej omenjenih predpisov vprašanje o vplivu stavb na celotno rabo energije in na podnebne spremembe ni rešeno. Ključno vlogo pri doseganju trajnostne družbe bi moralo imeti podnebno prilagodljivo načrtovanje stavb, kar bi hkrati z vzdržnejšo in manj ranljivo energijsko učinkovitostjo zagotavljalo tudi višje stopnje udobja. Zato je pomembno, da je večja pozornost usmerjena k povezavam med načrtovalskimi pristopi in dejanskim energijskim odzivom stavb.

Bioklimatsko načrtovanje stavb je pogosto povezano z energijsko učinkovitimi stavbami, zlasti v zmernem celinskem podnebju, kjer v stavbah večinoma prevladuje ogrevanje, hkrati pa imajo stavbe velik potencial za pasivno sončno ogrevanje. V takih podnebnih razmerah so zasnove stavbe običajno osredotočene na energijsko učinkovitost v času ogrevanja, pri tem pa je pogosto spregledano potencialno tveganje za pojav pregrevanja v toplejšem delu leta. Še vedno ni povsem jasno, koliko uveljavljene prakse načrtovanja pomenijo potencialno tveganje za pregrevanje v predvidenih scenarijih prihodnjih podnebnih stanj. Z raziskovalnim delom želimo odgovoriti na vprašanja, ki se ob tem pojavljajo.

1.2 Znanstveno ozadje in namen

V zadnjih treh desetletjih se je gradbeništvo začelo intenzivno ukvarjati s toplotnim odzivom stavb in potrebo po energiji ter z zagotavljanjem višjih standardov udobja v notranjem okolju. Eden tradicionalnih, vendar hkrati tudi naprednejših pristopov, ki omogoča obenem zagotavljanje zgoraj naštetih prvin, je t. i. bioklimatsko načrtovanje stavb. Bioklimatsko načrtovanje je tudi eden izmed ustaljenih pristopov k načrtovanju stavb. Pomeni prilagajanje človeka in njegovega bivalnega okolja danostim lokacije ter podnebju. Takšno sožitje z okoljem je v človekovi naravi že odkar je začel postavljati svoja bivališča. Posledično so se v odvisnosti od različnih podnebij lokalno izoblikovali različni vzorci tradicionalne arhitekture, ki načeloma vsebujejo štiri glavne bioklimatske prilagoditve (strategije) [1]. Med slednje spadajo zaščita pred izgubo toplote (zadrževanje toplote), zajemanje toplote, zaščita pred čezmerno količino le-te (izključevanje toplote) in disipacija toplotnega presežka (odvajanje toplote). Glavni rezultat prilagoditve podnebju naj bi bilo zagotavljanje (toplotnega) udobja, hkrati pa tudi večja samozadostnost oziroma energijska učinkovitost stavbe. Bioklimatika je v gradbeništvu s pojavom industrializacije in poceni energije postala manj pomembna. Njena aktualnost se je zopet izrazila z energetskimi krizami v drugi polovici 20. stoletja. V sodobnem gradbeništvu bioklimatski (imenovani tudi pasivni) ukrepi, kot so npr. nizka toplotna prehodnost ovoja, uporaba fiksnih senčil ipd., na specifični lokaciji pomenijo preverjene pristope načrtovanja, zato se pri načrtovanju novih stavb večkrat uporabljajo. Tukaj se pojavi vprašanje: ali tradicionalni ukrepi bioklimatske arhitekture na neki lokaciji res predstavljajo ustrezne smernice za načrtovanje sodobnih stavb in tudi stavb v prihodnosti? Namreč podnebne spremembe lahko pomembno vplivajo na toplotni odziv stavbe, ta pa je odvisen tudi od izbranih pasivnih strategij.

Ob predpostavki, da danes načrtujemo stavbo na podlagi preteklosti in v prepričanju, da se nič ni in nič ne bo spremenilo, je poglavitno znanstveno vprašanje: ali bi bilo bolje bioklimatske stavbe načrtovati na podlagi napovedi in pričakovanj stanja podnebja ter koliko? Katere podatke bi bilo pri tem treba uporabiti? Ali je moč na podlagi bioklimatskih analiz predlagati ustrezne načrtovalske ukrepe, ki bodo zadostili zahtevam uporabnikov enostanovanjskih stavb in energijski učinkovitosti ter stavbi hkrati omogočili prilagoditev trenutnemu in prihodnjemu stanju podnebja? V okviru navedenega z raziskovanjem želimo preveriti stanje znanosti na tem področju in s pomočjo bioklimatskih analiz oceniti stanje podnebja v različnih obdobjih ter posledični bioklimatski potencial na izbranih lokacijah. Pri čemer bioklimatski potencial predstavlja interpretacijo podnebnih podatkov tako, da so identificirane priložnosti prilagajanja stavbe podnebju s pasivnimi načrtovalskimi ukrepi. Ob upoštevanju tega in na podlagi primerov energijskih modelov stavb želimo ugotoviti pasivne načrtovalske ukrepe, ki bodo najbolj vplivali na energijsko učinkovitost enostanovanjskih stavb v trenutnem stanju podnebja in v prihodnosti. S tem nameravamo omogočiti načrtovanje novih stavb in prilagoditev obstoječih prihodnjemu stanju, kar pomeni ključen konceptualni preskok pri nadaljnjem načrtovanju stavb.

1.3 Cilji raziskovanja

Glavni cilj disertacije je razširiti znano na področju energijske učinkovitosti enostanovanjskih bioklimatskih stavb in se poglobiti v razumevanje učinkov segrevanja ozračja, ki ga prinašajo podnebne spremembe. Specifične cilje raziskovanja lahko povzamemo v naslednjih točkah:

- Opraviti obsežen pregled literature o bioklimatskem načrtovanju stavb ter vplivu podnebnih sprememb na njihovo energijsko učinkovitost.

- Izdelati orodje za bioklimatsko analizo lokacije na podlagi podnebnih značilnosti.

- Glede na nabor tipičnih primerov enostanovanjskih stavb in različnih vhodnih podatkov, kot so lastnosti ovoja in podnebni podatki, preveriti energijsko učinkovitost obravnavanih stavb v sedanjosti ter na podlagi napovedi tudi v prihodnosti.

- Določiti bioklimatske strategije, ki bodo v prihodnosti omogočale učinkovito rabo energije enostanovanjskih stavb na izbranih lokacijah.

1.4 Predstavitev hipotez

Na podlagi pregleda relevantnih in aktualnih raziskav smo oblikovali tri raziskovalne hipoteze, ki so bile glavno vodilo raziskovanja, opravljenega v okviru doktorske disertacije:

- Poleg temperature zraka in relativne vlažnosti je pri bioklimatski analizi lokacije nujno upoštevanje količine prejetega sončnega sevanja, vse tri pa je treba obravnavati istočasno.

- Energijska učinkovitost obstoječih enostanovanjskih bioklimatskih stavb bo v prihodnosti slabša od energijske učinkovitosti istih stavb v sedanjosti, vendar je relativna razlika močno odvisna od prvotno izbranih bioklimatskih načrtovalskih strategij in podnebnih značilnosti lokacije.

- Izbira le bioklimatskih načrtovalskih ukrepov za zajem sončne energije pri načrtovanju enostanovanjskih bioklimatskih stavb v zmernem podnebju ni najučinkovitejši pristop za energijsko učinkovitost stavb v prihodnosti, pač pa vedno bolj pomembni tudi na teh lokacijah postajajo ukrepi za preprečevanje pregrevanja.

1.5 Struktura doktorske disertacije

Doktorsko disertacijo sestavlja sedem osrednjih poglavij. Poleg prvega poglavja, v katerem so predstavljeni tema, namen in cilji raziskovanja, je disertacija sestavljena še iz šestih poglavij.

Drugo poglavje vsebuje teoretična izhodišča. Podrobneje je predstavljen koncept bioklimatskega načrtovanja stavb, predstavljeni so fizikalni procesi v ozračju in lastnosti podnebja, razloženi so dejavniki, ki vplivajo na podnebne spremembe in modeliranje podnebnih sprememb. Nato je razloženo področje o zagotavljanju toplotnega udobja v stavbah, predstavljeni so bioklimatska karta in bioklimatski potencial ter primeri o njihovi uporabi. Podrobneje sta razložena energijska učinkovitost stavb in toplotni odziv stavb. V zadnjem delu pa so predstavljene bioklimatske strategije in pasivni načrtovalski ukrepi, čemur sledi pregled znanstvenega področja energijske učinkovitosti stavb glede na podnebne spremembe, na podlagi česar je opredeljena vrzel znanstvenega področja, ki jo naslavlja pričujoča doktorska disertacija.

V tretjem poglavju je predstavljena izdelava programskega orodja za bioklimatsko analizo in določevanje bioklimatskega potenciala (prispevek na konferenci *ISES Solar World Congress 2017, Abu Dhabi*, Košir in Pajek [48], priloga E) in primer uporabe orodja (prispevek na konferenci *Sustainable Built Environment SBE19: Resilient Built Environment for Sustainable Mediterranean Countries, Milano*, Pajek in sod. [49], priloga F). Jedro poglavja pa predstavlja študija primera bioklimatskega potenciala regije Alpe-Jadran, s katero smo dokazali pomembnost upoštevanja sončnega sevanja pri analizi bioklimatskega potenciala (1. znanstveni članek, Pajek in Košir [10], priloga A).

Četrto poglavje vsebuje povzetek rezultatov raziskave o vplivu podnebnih sprememb na bioklimatski potencial lokacije ter potrebno energijo za ogrevanje in hlajenje dveh realnih primerov stavbe na petih različnih lokacijah v Sloveniji (2. znanstveni članek, Pajek in Košir [50], priloga B).

Peto poglavje je namenjeno obravnavi učinkov podnebnih sprememb na rabo energije enostanovanjskih stavb ter vpliva bioklimatskih strategij in pasivnih načrtovalskih ukrepov na le-to na osmih lokacijah v Evropi. Preučevani sta pomembnost pasivnih ukrepov ter dolgoročna energijska učinkovitost – določevanje ustreznih strategij bioklimatskega načrtovanja stavb (3. znanstveni članek, Pajek in Košir [51], priloga C).

Šesto poglavje vsebuje natančno analizo učinkov podnebnih sprememb na energijsko učinkovitost stavb in ranljivost za pregrevanje za primer Ljubljane. Predstavljeni so napotki za načrtovanje odpornih energijsko učinkovitih bioklimatsko načrtovanih enostanovanjskih stavb (4. znanstveni članek, Pajek in Košir [52], priloga D).

Doktorsko disertacijo končuje sedmo poglavje s sklepnimi ugotovitvami opravljene raziskave, obravnavo postavljenih hipotez in usmeritvami za nadaljnje raziskovalno delo.

2 TEORETIČNA IZHODIŠČA BIOKLIMATSKEGA NAČRTOVANJA STAVB

Povzetek

Poglavje povzema glavna teoretična izhodišča, pomembna za razumevanje vsebine doktorske disertacije, in vsebuje obširen pregled znanstvenih raziskav na obravnavanem področju. Na začetku so povzeti osnovni principi in pristopi k bioklimatskemu načrtovanju stavb, podprti z izsledki, objavljenimi v številnih znanstvenih publikacijah. V nadaljevanju so opisani osnovni principi in procesi podnebja in podnebnih pojavov ter podnebni tipi. Poleg tega so razloženi osnovni mehanizmi, ki so vzrok za podnebne spremembe, predstavljeni so podatki o trenutnem stanju podnebja in načini modeliranja projekcij podnebnih sprememb. Nato so opisani osnovni principi človeškega zaznavanja toplotnega udobja, načini interpretacije podnebnih podatkov za pomoč pri načrtovanju stavb, kot je na primer bioklimatska karta in določevanje bioklimatskega potenciala, poleg pa so predstavljeni primeri uporabe v različnih raziskavah. V drugem delu poglavja so opisani fizikalni procesi, pomembni pri določevanju energijske učinkovitosti stavb. Predstavljeni so osnovni principi izmenjave energije med stavbo in okoljem ter s tem povezan toplotni odziv stavbe. Opredeljena je energijska učinkovitost stavbe in opisane so metode za izračun in simulacije le-te. Natančneje so opisane bioklimatske strategije za načrtovanje stavb in najpogosteje uporabljani pasivni načrtovalski ukrepi. V zadnjem delu poglavja je na podlagi obširnega pregleda raziskav o energijski učinkovitosti stavb glede na podnebne spremembe opisano stanje raziskovalnega področja in opredeljena vrzel v njem, ki jo naslavlja pričujoča doktorska disertacija.

Abstract

The chapter summarizes the theoretical fundamentals significant for understanding the content of the doctoral dissertation and contains an extensive literature review of the considered topics. In the beginning, the basic principles and approaches to the bioclimatic design of buildings are described and supported by the results published in numerous scientific publications. After that, the elementary principles and processes of climate and climate types are described. The latter is followed by the explanation of fundamental mechanisms that cause climate change, supported by recent data on the current state of the climate. Climate modelling and climate change projections are presented as well. Next, the basic principles of human perception of thermal comfort and ways to interpret climate data to support building design are presented. Following that, a bioclimatic chart, bioclimatic potential and applications in various studies are described. In the second part of the chapter, the physical processes that are important in determining the energy efficiency of buildings are described. The basic principles of energy exchange between the building and the environment and the related building thermal response are presented. Besides, building energy efficiency is defined, followed by methods for its calculation and building simulation. Next, bioclimatic building design strategies and the most commonly used passive design measures are clarified. In the last part of the chapter, state of the art concerning the energy efficiency of buildings related to climate change is described, based on an extensive literature review. Furthermore, the knowledge gap is determined, which is later addressed in the doctoral dissertation.

2.1 O bioklimatskem načrtovanju stavb

Bioklimatsko načrtovanje je v inženirski praksi najpogosteje definirano kot izkoriščanje podnebnih (klimatskih) danosti (virov) na neki lokaciji, pri čemer je ovoj stavbe uporabljen tako, da zagotovimo udobje bivanja (zahteve) in omogočimo učinkovito rabo energije [3, 5]. Glede na definicijo bioklimatske stavbe torej le-ta uporabnikom zagotavlja ugodne bivalne pogoje ob premišljeni rabi energije in je hkrati kar najbolj prilagojena podnebnim danostim lokacije. V strokovnih krogih je v splošnem privzeto mnenje, da je tradicionalna (tudi vernakularna) arhitektura popolnoma prilagojena podnebnim značilnostim na neki lokaciji ali v neki regiji, saj naj bi se v stoletjih »evolucijsko« prilagodila danostim lokacije. Zato tradicionalna arhitektura za načrtovalce pogosto predstavlja vir bioklimatskih strategij [6, 7].

Slika 2: Štirje primeri različne bioklimatske arhitekture v različnih podnebjih. Zgoraj, levo: oceansko podnebje (Dungeness, Anglija). Zgoraj, desno: hladno podnebje (Pyhäjärvi, Finska). Spodaj, levo: vlažno tropsko podnebje (Tegallalang, Indonezija). Spodaj, desno: sredozemsko podnebje (Hora, Grčija). Vir fotografij: Unsplash [53].

Figure 2: Four examples of different bioclimatic architecture in diverse climates. Top left: oceanic climate (Dungeness, England). Top right: cold climate (Pyhäjärvi, Finland). Bottom left: humid tropical climate (Tegallalang, Indonesia). Bottom right: Mediterranean climate (Chora, Greece). Source of photographs: Unsplash [53].

Na primer, v hladnih in zmernih podnebjih so v tradicionalni arhitekturi bioklimatske strategije osredotočene predvsem na zagotavljanje toplotnega udobja, ko so zunanje temperature nizke. V takšnih primerih se izbrane bioklimatske strategije odražajo v različnih pasivnih načrtovalskih ukrepih, kot so kompaktna oblika stavbe, ustrezna uporaba toplotne kapacitete oz. toplotne mase, ekvatorialno orientirani transparentni deli stavbnega ovoja z nizko toplotno prehodnostjo, višja sončna vpojnost (absorptivnost) zunanjih površin (temnejše barve) ipd. (slika 2, zgoraj, levo). V ekstremnih podnebjih, kot je na primer ekstremno hladno ali arktično podnebje, je edina učinkovita bioklimatska strategija za ohranjanje toplote v stavbi preprečevanje toplotnih izgub skozi stavbni ovoj, kar je mogoče zagotoviti z nizkimi toplotnimi prehodnostmi ovoja in izbiro kompaktne oblike stavbe (slika 2, zgoraj, desno) [1]. Nasprotno so na primer na območjih s sredozemskim podnebjem vidnejši bioklimatski ukrepi, kot so visoka toplotna masa, senčenje transparentnih elementov, prečno prezračevanje, nižja sončna vpojnost zunanjih površin (svetle barve) ipd. [54] (slika 2, spodaj, desno). V vlažnih tropskih podnebjih so pomembni bioklimatski ukrepi, kot so izbira manj kompaktnih oblik stavb z nižjo toplotno maso, izdatno senčenje, svetlejše barve ovoja in intenzivno naravno prezračevanje (slika 2 spodaj, levo) [1]. Kljub temu, da primeri tradicionalnih bioklimatskih stavb veljajo za dobro podnebno prilagojene, je pri obravnavi bioklimatskih ukrepov in repliciranju strategij iz tradicionalne arhitekture v novodobno treba biti še posebej pozoren, saj nekateri ukrepi iz preteklosti v prihodnosti morda ne bodo dali pričakovanih rezultatov. Szokolay [55] pravi, da je pri zagotavljanju ugodnih razmer notranjega okolja načrtovalčeva naloga, da objektivno in kritično presodi okolijske danosti (npr. lokacijo, podnebje itd.) in jih nato čim bolj izkoristi ter nadzira le s pomočjo pasivnih ukrepov – s stavbo samo. Prav zato je k bioklimatskemu načrtovanju in določitvi najboljših pasivnih ukrepov pri načrtovanju stavbe smiselno pristopiti z analizo podnebnih virov in podatkov. Na podlagi teh informacij lahko kritično ocenimo znane oz. obstoječe bioklimatske strategije in pasivne ukrepe na neki lokaciji.

Bioklimatsko načrtovanje stavb je bilo obravnavano v več znanstvenih delih. Eden izmed načinov, kako na samem začetku načrtovanja ugotoviti, kateri možni bioklimatski ukrepi so najprimernejši, je obravnava podnebja s pomočjo bioklimatske karte, ki jo je prvi leta 1963 predstavil Olgyay [56] ter kasneje v drugačni obliki še Givoni [57]. Bioklimatske karte so v njihovi prvotni obliki uporabljali z namenom ugotoviti, ali lahko na neki lokaciji s pripadajočim podnebjem z bioklimatskimi ukrepi dosežemo človekovo toplotno udobje ali to ni mogoče. Primer uporabe bioklimatske karte je bil prikazan v več znanstvenih delih. Hyde in sod. [58] so izvedli raziskavo s poudarkom na bioklimatski analizi specifične stavbe (La Casa de Luis Barragán), zgrajene 1948 v Mehiki. Avtorji so ugotovili, da je obravnavana stavba odličen primer nizkoenergijske stavbe v svojem času. Vendar kljub temu, da ugotovitve omenjene raziskave poudarjajo pomembnost brezčasne prilagoditve obravnavane stavbe njenim uporabnikom, avtorji ne podajajo specifičnih priporočil. Tudi Lomas in sod. [59] so naredili študijo primera toplotnega udobja v poslovni stavbi v južni Evropi. Za določitev robnih pogojev za pasivno hlajenje so klimatološke podatke analizirali s pomočjo Givonijevih bioklimatskih kart. Slednjo so primerno prilagodili, saj je izvorna bioklimatska karta namenjena stanovanjskim stavbam. Ugotovili so, da je za zadovoljivo analizo podnebja treba zajeti čim več klimatoloških podatkov. Podoben primer bioklimatske obravnave specifične stavbe sta izvedla Pozas in González [60]. Poudarila sta povezavo med tradicionalno arhitekturo in energijsko učinkovitostjo stavb, ki izhaja iz prilagoditve podnebju in lokaciji. Poleg tega sta opozorila na potrebo po ohranjanju bioklimatskih strategij, ki koristijo ohranjanju toplotnega udobja v poletnem času (npr. toplotna masa). V tem pogledu so Hudobivnik in sod. [61] ter Pajek in sod. [62] pokazali, da lahko zanemarjanje povezave med podnebjem ter tipom konstrukcije in njenih lastnosti privede do neželenega toplotnega odziva stavbe, npr. do pregrevanja v poletnem času. Slednje se pogosto dogaja v stavbah z nizko toplotno maso [63]. Podobno so Košir in sod. [64] izrazili pomembnost konfiguracije stavbnega ovoja in razmerja med transparentnim in netransparentnim delom, ki je zelo odvisen od lokacije in pripadajoče količine prejetega sončnega sevanja. Vse zgoraj naštete raziskave so se večinoma ukvarjale s specifičnimi stavbami ali pa so dajale splošne napotke na ravni bioklimatskih strategij in pasivnih ukrepov. V nekaterih preostalih raziskavah pa je bil uporabljen drugačen, obrnjen pristop, pri katerem je bila opravljena bioklimatska analiza širših območij ali regij. Takšna analiza in klasifikacija bioklimatskega potenciala širšega območja sta zelo uporabni pri načrtovanju podnebno odzivnih stavb ter posledičnem zagotavljanju toplotnega udobja in smotrne rabe energije. Takšen pristop je za regionalno podnebno analizo v Nigeriji uporabil Ajibola [65]. V svoji raziskavi je podal splošne ugotovitve v obliki priporočenih bioklimatskih strategij, vendar pri tem izpustil kakršno koli interpretacijo obdelanih podatkov.

Pri načrtovanju sodobnih bioklimatskih stavb lahko v grobem ločimo dva načrtovalska pristopa. Prvi pristop je repliciranje bioklimatskih strategij in ukrepov, ki jih lahko najdemo v tradicionalni arhitekturi [54, 58, 60, 66, 67]. Slednja se je v stoletjih prilagodila podnebnim značilnostim na neki lokaciji. Drugi pristop za izhodišče uporablja analizo podnebja, s katero se na podlagi podnebnih vzorcev določi najobetavnejše načrtovalske bioklimatske strategije. Takšen pristop so v svojih raziskavah uporabili Pajek in Košir [10] na primeru regije Alpe-Jadran, Alonso Monterde in sod. [68] na primeru španske Valencije z okolico ter Yang in sod. [69] na primeru petih klimatskih con na Kitajskem. Navkljub obstoječim takšnim in podobnim raziskavam so Dubois in sod. [70] poudarili, da prenos znanja med znanstvenimi raziskavami in prakso v gradbeništvu ni dovolj učinkovit. Navedeno se odraža v dejstvu, da se v prvi fazi načrtovanja stavb le redko uporabljajo orodja, ki bi podpirala prilagajanje podnebju. Kot posledica se pri definiciji pasivnih ukrepov, primernih za neko lokacijo, kot osnova uporabljajo nove, večinoma še nepreverjene rešitve, ali pa se, kot prej omenjeno, posnemajo ukrepi iz tradicionalne arhitekture. Oba pristopa načrtovalci sodobnih stavb s pridom uporabljajo [71]. S premislekom ugotovimo, da je prav možnost za prilagajanje podnebju tista lastnost stavbe, ki načrtovalce najbolj spodbuja, da vnovič pretehtajo vse možnosti za načrtovanje stavb [5].

Načrtovalsko vprašanje je še bolj opazno zaradi dejstva, da bioklimatski ukrepi, ki jih najdemo v vernakularni arhitekturi, slonijo na preteklem podnebnem stanju. Takšni pristopi niti ne bi bili težavni, če podnebje ne bi bilo dinamična značilnost. Glede na opravljene raziskave [15, 17, 72] se je stanje podnebja v zadnjih desetletjih začelo opazno spreminjati, spremembe pa se bodo v prihodnosti nadaljevale. Le-te so bile opredeljene kot hitre in večjih razsežnosti. Če se bodo podnebne spremembe nadaljevale v tem obsegu, bo njihov vpliv na stavbe v prihodnosti lahko precejšen. Zato sta Pajek in Košir [10] poudarila, da je treba bioklimatski potencial na lokacijah ponovno definirati ali še bolje – napovedati na podlagi projekcij podnebnega stanja v prihodnosti. Takšna vnovična preučitev bioklimatskega potenciala je pomembna, saj nekatere pasivne strategije, ki se uporabljajo v tradicionalni arhitekturi na neki lokaciji, ne pomenijo več optimalnih načrtovalskih strategij, ki bi stavbo podnebno prilagodile oz. jo naredile za odpornejšo na podnebne spremembe. Fezzioui in sod. [73] so pokazali, da podnebne spremembe vplivajo tudi na stavbe, ki niso opredeljene kot bioklimatske.

Zaradi spreminjanja podnebja in vremenskih razmer bomo pri načrtovanju stavb morali narediti konceptualni preskok. Natančneje, obstoječe paradigme načrtovanja stavb bo treba nadomestiti z novimi pristopi, znotraj katerih se bo preučilo stanje trenutnega in prihodnjega podnebja ter se bo le-to upoštevalo pri načrtovanju [10].

2.2 Podnebje in bioklimatska analiza

Ko govorimo o bioklimatskem načrtovanju in podnebno prilagojenih stavbah je odločilno poznavanje podnebnih danosti in procesov, ki vplivajo na podnebna stanja in podnebne spremembe. Bioklimatsko načrtovanje stavb je eden ključnih pristopov k načrtovanju stavb prihodnosti, saj lahko z njim zagotavljamo nižjo rabo energije stavb, kar pomembno prispeva k energijski in podnebni nevtralnosti ter ciljem Evropskega zelenega dogovora. Kot ugotovljeno, je treba, preden se lotimo načrtovanja stavbe po bioklimatskih načelih, opraviti premišljeno analizo podnebja na izbrani lokaciji. V ta namen lahko uporabimo t. i. bioklimatsko analizo lokacije, za kar poznamo več metod in orodij. Najelementarnejšo metodo ocene o bioklimatskih danostih lokacije s pomočjo bioklimatske karte je leta 1963 razvil Viktor Olgyay [56], nekoliko kasneje pa v drugačni obliki tudi Baruch Givoni [74]. Ti dve metodi za analizo uporabljata elementarne podnebne podatke, kot sta temperatura zraka in relativna vlažnost. S pomočjo bioklimatskih kart lahko določimo bioklimatski potencial, ki služi kot izhodišče za načrtovanje podnebno prilagojenih stavb na neki lokaciji.

2.2.1 Podnebje in podnebne spremembe

2.2.1.1 O podnebju

Vedi, ki preučujeta Zemljino ozračje ali atmosfero – meteorologija in klimatologija – sta neločljivo povezani. Meteorologija preučuje vreme, ki je trenutno stanje atmosfere na neki lokaciji. Vreme je večinoma izraženo s pomočjo merljivih atmosferskih podatkov, kot so temperatura, padavine, vlažnost, smer in hitrost vetra ter oblačnost [75]. Ker se meteorologija zanaša na izbrane neposredno izmerjene podatke o atmosferi, je vreme kratkotrajna lastnost atmosfere. Veda o vremenu se ukvarja z opisovanjem trenutnih vremenskih stanj in z napovedovanjem stanj v bližnji prihodnosti, pri čemer si pomaga z razumevanjem pojavov, ki vplivajo na stanje atmosfere. Z vedno natančnejšimi meritvami, globljim razumevanjem pojava in preciznimi modeli atmosfere je v zadnjih letih znanje, povezano z napovedovanjem vremena, občutno napredovalo.

Podnebje je glede na vreme širši pojem, ki preučuje celotnost vremenskih pojavov, značilnih za nek kraj ali neko območje v daljšem časovnem intervalu, na primer z metodo variacijske statistike [76]. Glede na definicijo, ki sta jo podala McGuffie in Handerson-Sellers [77], podnebje predstavlja vse statistične značilnosti podnebnih stanj, dobljene v dogovorjenem časovnem odboju, naj bo to sezona, desetletje ali daljše obdobje, izračunane globalno ali le za izbrano regijo. Rakovec in Vrhovec [78] ter Goosse [79] navajajo, da je za dovolj natančno opredelitev lastnosti podnebja na izbranem območju treba zajeti časovni okvir vsaj 30 let izmerjenih podatkov. Podnebje nekega območja je običajno predstavljeno kot povprečje, variabilnost, ekstremi, odstopanja od povprečij in periodičnost meteoroloških elementov, kot so temperature, padavine, vlažnost, oblačnost, sončno obsevanje ipd. [78]. Kako so ti podatki predstavljeni, je odvisno predvsem od namena uporabe, ki definira časovni (npr. mesečni, dnevni, urni podatki) in prostorski okvir (npr. makro, mezo in mikro raven) ter potrebne okolijske spremenljivke [80]. Prostorski okvir je najbolj zaznaven v kontekstu primerjave mikroklime, v katerem opazimo razlike med dolinami in hribovji, prisojnimi in osojnimi pobočji ter tudi razlike med ruralnimi in urbanimi območji zaradi pojava toplotnega otoka v večjih mestih. Dejavnike, ki vplivajo na podnebje, lahko po Manohinu [76] razdelimo v tri skupine: astronomski, geofizikalni in biološki. Med astronomske dejavnike uvrščamo nagib zemeljske osi (vpadni kot sončnih žarkov in dolžina dneva), ekscentričnost zemeljske orbite, premik točke ekvinokcija in procese na Soncu. V skupino geofizikalnih dejavnikov uvrščamo zemljepisno širino (lega glede na cirkulacijo zraka), položaj v prostoru glede na vodne mase (celinska lega, obvodna lega) in vetrove, nadmorsko višino, oblikovanost in lastnosti zemeljskega površja ter vulkanske pojave. K biološkim dejavnikom spadajo vegetacija in vpliv mest [76]. Sestavo atmosfere, ki prav tako vpliva na podnebje, bi lahko uvrstili tako med geofizikalne kot tudi biološke dejavnike – zaradi vpliva biosfere ter v zadnjem času tudi vpliva ljudi.

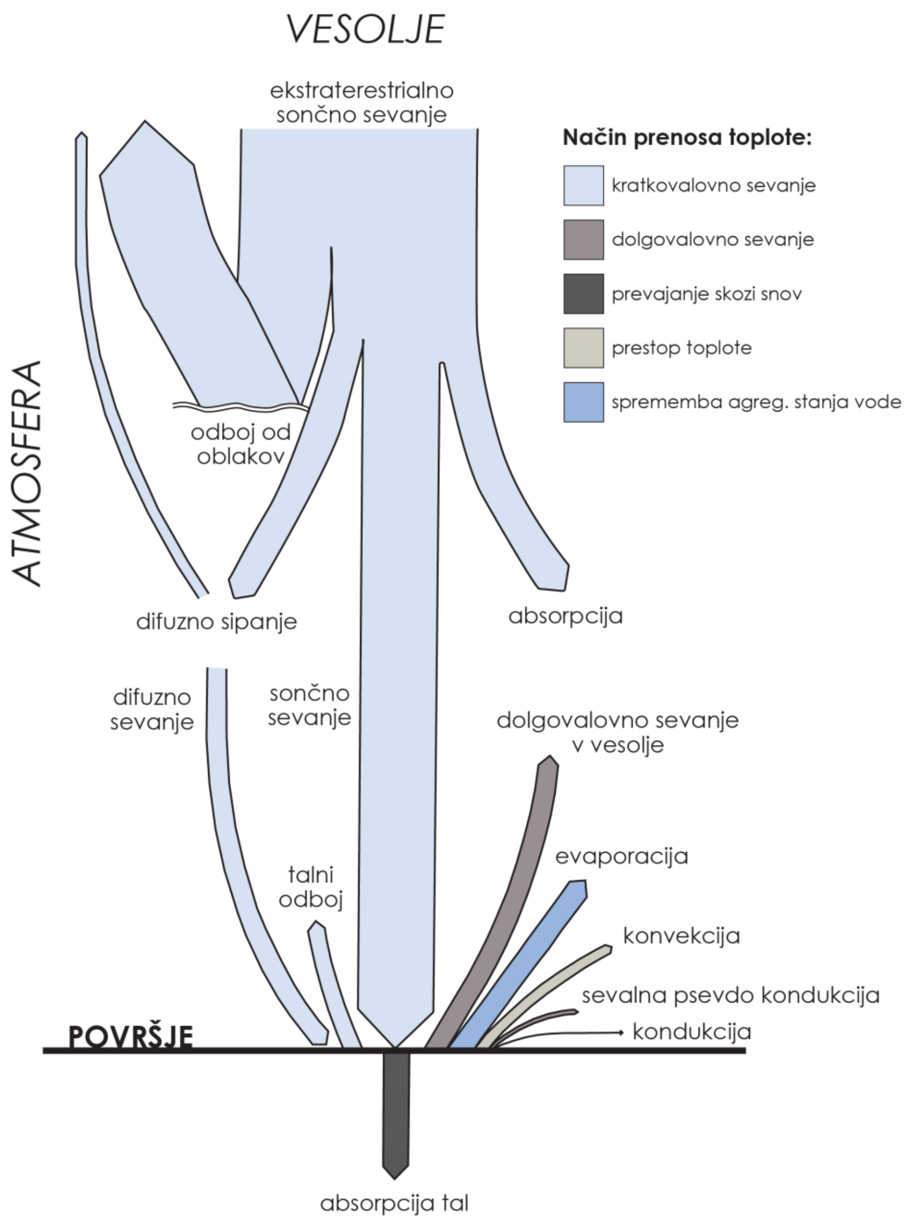
Veda, ki na osnovi meteoroloških podatkov preučuje podnebje, se imenuje klimatologija. Natančneje je klimatologija znanstvena veda, ki celovito obravnava podatke, ideje in teorije vseh elementov Zemlje kot planeta: njeno atmosfero ali ozračje, litosfero ali kopno površino, hidrosfero ali vodo in biosfero ali območje življenja; in s pomočjo vseh teh informacij razlaga dogajanje v atmosferi [75, 80]. Atmosfera ali ozračje je relativno tanka plinska plast, ki obkroža planet Zemlja [81] in ključno vpliva na procese izmenjave energije in na temperaturo površja. Atmosfera s t. i. učinkom tople grede vpliva na energijsko ravnovesje med temperaturo Zemljinega površja, prejeto energijo sončnega sevanja in dolgovalovnim toplotnim sevanjem površja nazaj v Vesolje. Slednje ravnovesje se pogosto izraža tudi s sevalno energijsko bilanco atmosfere (ang. *radiative atmospheric energy balance*) [80]. Litosfera ali kopna površina vključuje Zemljino skorjo in zgornji del plašča [81]. Litosfera vpliva na vremenske procese, saj topografija vpliva na gibanje zračnih in vodnih tokov v atmosferi in hidrosferi. Vpliv litosfere na procese v ozračju pa je moč zaznati tudi pri vulkanskih izbruhih [1]. Pod pojem hidrosfera uvrščamo vodo v vseh njenih nahajališčih, kot so podzemlje, površje in ozračje, in v vseh agregatnih stanjih (trdno, tekoče, plinasto) [81]. Glavni masni in energijski tok hidrosfere predstavlja vodni krog, ki hidrosfero in atmosfero povezuje v neločljivo celoto [1]. Biosfera predstavlja skupek vseh ekosistemov ali z drugimi besedami območje življenja na Zemlji [81] in je posledica primerne kombinacije atmosfere, litosfere in hidrosfere, ki je omogočila življenje na našem planetu. Tudi biosfera na energijske procese v ozračju precej vpliva, kar se izraža z njenim vplivom na albedo površin, skladiščenje in sproščanje ogljika, proizvodnjo in porabo kisika in preostalih plinov ter z vplivom evapotranspiracije na vodni krog [1].

V atmosferi je moč zaznati več fizikalnih procesov. Atmosfera je mešanica plinov, ki Zemljo obdaja zaradi prisotnosti gravitacije. Zaradi nižanja zračnega tlaka z višino in zadrževanja vlage v spodnjih slojih atmosfere (troposfera) je zračna plast ob površju Zemlje veliko gostejša kot tista v višjih slojih. Zaradi temperaturnih razlik v atmosferi pride do konstantnega konvekcijskega (navpično) in advekcijskega (vodoravno) gibanja zračnih mas. Zemeljsko površje segreva zračne mase, kar pripelje do konvekcijskega gibanja zraka v višje plasti atmosfere. V procesu dviganja zraka se le-ta ohlaja, pri čemer pogosto pride do kondenzacije zračne vlage in padavin, nato pa ohlajen zrak zopet potone v nižje dele atmosfere [75]. Ob prisotnosti vetrov je ta pojav lahko še izrazitejši [78]. Večji del atmosfere predstavljata plina dušik (N_2) in kisik (O_2). Dušik predstavlja 78 % atmosfere, kisik 21 %, preostali odstotek pa predstavljajo žlahtni plini, med katerimi je najbolj zastopan argon (Ar), in preostali plini, kot je na primer ogljikov dioksid (CO_2) [75]. Sestava atmosfere vpliva na učinek tople grede, ki ohranja temperaturo Zemlje na za življenje ustrezni ravni. Učinek tople grede se doseže s tem, ko v atmosferi prisotni plini, kot so vodna para, CO_2, metan (CH_4), ozon (O_3) ipd. [78], absorbirajo energijo, ki jo z dolgovalovnim valovanjem seva Zemlja, in jo nato izsevajo nazaj proti Zemljinemu površju. Zemljino površje ima tako vsaj 20 °C višjo temperaturo, kot bi jo imelo sicer, temperaturno nihanje med dnevom in nočjo pa je bistveno manjše [16]. Prispevek posameznega toplogrednega plina na učinek tople grede je odvisen od njegove koncentracije v atmosferi in sposobnosti absorpcije dolgovalovnega infrardečega valovanja. Med njimi sta najpomembnejša vodna para in CO_2 [16]. T. i. toplogredni plin CO_2 je od nastanka Zemlje pomemben člen v kroženju ogljika. Slednji je prisoten v atmosferi kot del plina CO_2, v biosferi kot sestavni del flore in favne ter v oceanih, v katerih so prisotni raztopljeni karbonati. Ogljik se nenehno premešča iz enega nahajališča v drugega [75]. Največja skladišča ogljika so sedimentne kamnine na oceanskih tleh, oceani sami, celotna biosfera in tudi prst. S pomočjo naravnih procesov raztapljanja, vezave in sproščanja ogljika le-ta ves čas kroži med atmosfero, hidrosfero in biosfero, procesi pa trajajo od 100 do tudi več kot milijardo let [75]. Poleg ogljikovega dioksida največji del atmosfere s spremenljivo koncentracijo predstavlja vodna para. Najvišja koncentracija v atmosferi prisotne vodne pare je 4 %, navzgor je omejena s procesi, kot sta nastajanje padavin in tvorjenje oblakov [75]. Vlaga v zraku je močno geografsko odvisna, saj nanjo vplivata pojavnost vode na Zemljinem površju in zadostna količina energije, da sprožita proces izhlapevanja. Poleg tega je zmožnost zraka za kopičenje določene količine vlage odvisna tudi od temperature zraka. Z izhlapevanjem vode s površja Zemlje se površina tal zaradi latentne spremembe toplote ohlaja. Nasprotno pa lahko voda na tleh tudi kondenzira, kar opišemo kot pojav rose, slane ali ivja [78]. Tudi v atmosferi voda nastopa v vseh agregatnih stanjih, pri čemer s procesom utekočinjanja (kondenzacije) in izhlapevanja (evaporacije) prehaja iz enega stanja v drugo [78].

Pomembno vlogo pri vremenskih in podnebnih pojavih ima hidrosfera, v kateri poleg vodnega kroga med atmosfero in hidrosfero potekajo ključni procesi izmenjave in skladiščenja toplote. Tako imajo oceani zaradi velike toplotne kapacitete vode za skladiščenje toplote in konvekcijskih tokov največji vpliv na atmosfero [80]. Slednje ključno vpliva na fizikalne procese in na temperaturo zraka. V oceanih poznamo morske tokove, ki nastanejo zaradi razlike v temperaturi in slanosti vode ter zaradi prisotnosti vetrov. Hladni in topli morski tokovi predstavljajo ponor ali izvir toplote, ki se sprošča v atmosfero in s tem pomembno vpliva na preostale fizikalne procese v atmosferi [79]. Tako imajo na primer kraji ob oceanu podnebje, ki ga močno pogojujeta lega in morebitni bolj ali manj stalen advekcijski dotok energije in vlage zaradi toplih ali mrzlih vod [78]. V nekaterih primerih je zaradi advekcijskega dotoka energije zanemarljiva celo lokalna sevalna bilanca.

Pri podnebnih in vremenskih pojavih imata poleg fizikalnih procesov v atmosferi in hidrosferi ključno vlogo Sonce in osončenost. Energija Sonca doseže Zemljo v obliki sončnega sevanja v različnih valovnih dolžinah. Sončno sevanje ima valovne dolžine 100–3000 nm, sevanje 3000–10000 nm pa opišemo kot dolgovalovno (toplotno) sevanje. Sončno sevanje nadalje delimo na ultravijolično (UV, 100–380 nm), vidno (380–700 nm) in infrardečo (IR, >700 nm) svetlobo [75]. Gostota energijskega toka s strani Sonca je zunaj atmosfere na povprečni oddaljenosti Zemlje od Sonca in pri pravokotnem vpadu enaka 1367 W/m^2 (solarna konstanta) [78]. Zemlja kroži okrog Sonca po elipsi, zato se med letom razdalja do Sonca spreminja, s tem pa gostota obsevanja Zemlje za ± 3,3 % [78]. Na sončno obsevanje, prejeto na Zemljini površini, vplivajo tudi geografska širina, letni časi in čas v dnevu, saj sta zenitni kot in azimut Sonca odvisna od lege na Zemlji, letnega časa in časa v dnevu, slednja pa sta posledica nagiba Zemljine osi in osne rotacije Zemlje. Zato je pomemben podatek geografska lega, ki jo opišemo z geografsko širino in dolžino. Geografska širina Ekvatorja je 0°, geografska širina polov pa 90°. Od geografske širine je odvisno, pod kakšnim kotom sončni žarki dosežejo zemeljsko površje. Nižji kot je vpadni kot sonca, šibkejše je prejeto sončno sevanje na površini, saj pri nižjih vpadnih kotih energijski tok obseva večjo površino. Pojemanje energije sončnega sevanja od vrha atmosfere proti Zemeljskemu površju je odvisno tudi od dolžine poti skozi atmosfero (zenitni kot), odboja na oblakih in gostote absorbirajočega plina. Moč sevanja, ki ga prejme posamezna ploskev na Zemeljskem površju, je odvisna od vpadnega energijskega toka, velikosti ploskve in kota med normalo na ploskev in smerjo energijskega toka [78].

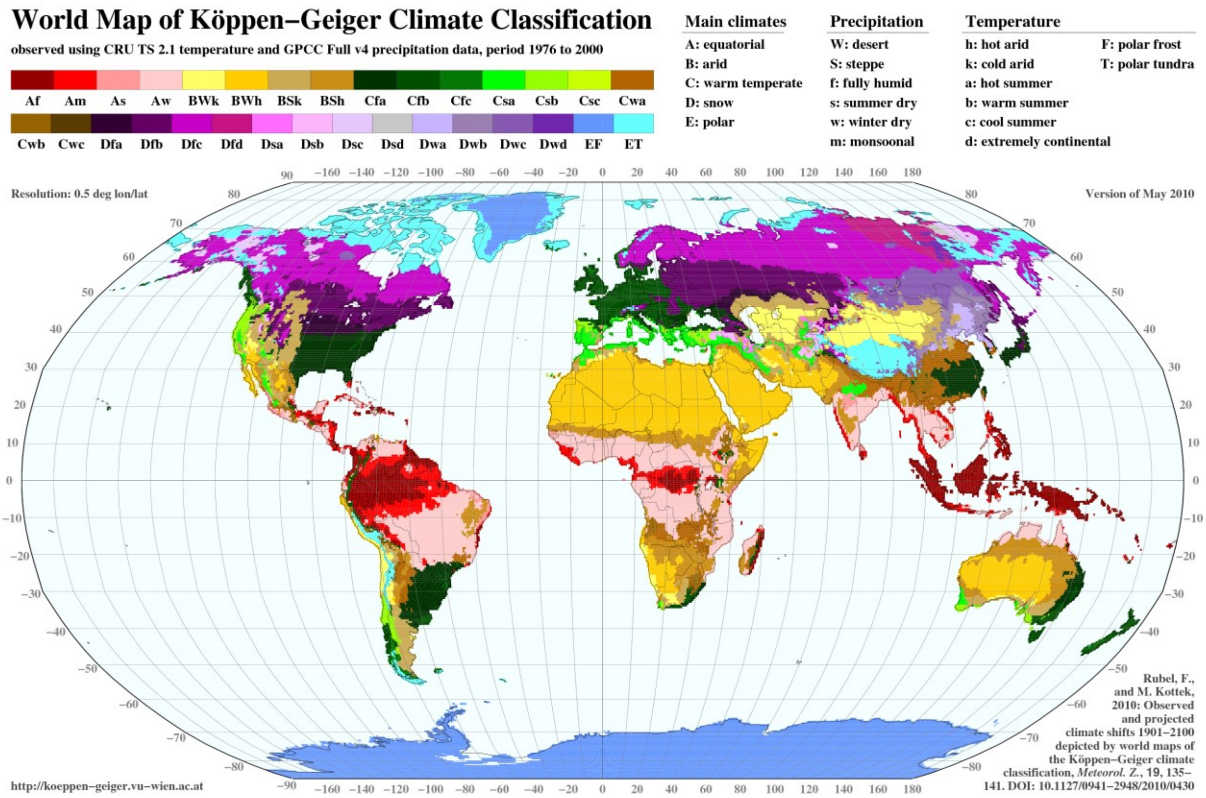
Sončna energija se na površju Zemlje deloma absorbira, deloma odbije (slika 3). Absorbirana energija povzroči segrevanje površja, le-ta pa atmosfero segreva z dolgovalovnim toplotnim sevanjem, konvekcijskim in tudi s kondukcijskim prenosom toplote. V obravnavanem sistemu, ki ga tvorita površje in atmosfera, je glavni ponor toplote dolgovalovno IR sevanje ozračja in tal [78]. S tem se del energije izseva v Vesolje (dolgovalovno sevanje v Vesolje), del pa se prerazporeja med deli atmosfere in zemeljskega površja (sevalna psevdokondukcija). Gostota izsevanega energijskega toka je po Planckovem zakonu in integraciji po vseh valovnih dolžinah odvisna od površinske temperature in emisivnosti. Tako je na primer pri temperaturah na vrhu spodnjega dela atmosfere (troposferi) gostota izsevanega energijskega toka 50 W/m^2, pri temperaturi površine puščavskih pokrajin pa do 500 W/m^2 [78]. Razlike so očitne tudi med površinami z različnim albedom, npr. s snežno odejo pokrita površina izseva manjši delež toplote.



Slika 3: Izmenjava toplote na poletni dan opoldne. Razmerja med širinami puščic predstavljajo okvirna razmerja med količino toplote. Vpliv tople grede ni zajet (Povzeto po Olgyay [56]).
Figure 3: Heat exchange on summer day at noon. The width of arrows corresponds to the transferred heat amounts. The greenhouse effect is not considered (adapted from Olgyay [56]).

Ugotovimo, da podnebje nekega območja oblikujeta predvsem lokalna bilanca energije in bilanca vlažnosti [78]. V splošnem lahko trdimo, da je temperatura zraka odvisna predvsem od prejete in oddane toplote, vlažnost zraka od procesov izhlapevanja in utekočinjenja ter gibanja zračnih mas, na sončno obsevanje pa poleg astronomskih dejavnikov vplivajo še vremenski in reliefni faktorji. Pri bioklimatskem načrtovanju stavb je najpomembnejše poznavanje podnebnih značilnosti, kot so letni in mesečni potek temperatur, relativne vlažnosti in prejetega sončnega sevanja [1,56]. Natančneje nas pri načrtovanju toplotnega odziva stavb zanima temperatura zraka, ki jo opišemo s pomočjo temperature suhega termometra (ang. *dry-bulb temperature*, T_{db}), izmerjeno na višini 1,2–1,8 m nad tlemi, zaščiteno pred vplivom sončnega sevanja in vetra [4]. Podatek običajno predstavimo s povprečnimi (T_{avg}) in ekstremnimi (T_{min}, T_{max}) vrednostmi ter dnevnim temperaturnim nihanjem. Poleg tega je pomemben podatek tudi vlažnost zraka, običajno opisana s pomočjo relativne vlažnosti (*RH*) v odstotkih, pri čemer vrednost 100 % pomeni popolnoma nasičen zrak z vodno paro. Navadno nas zanima predvsem podatek o minimalni (RH_{min}) in maksimalni (RH_{max}) relativni vlažnosti. Nadalje je, predvsem ko obravnavamo toplotno udobje, pomembna informacija o hitrosti gibanja zraka oz. vetra, ki se izmeri na neovirani višini 10 m. Pri vetru je pomemben podatek o hitrosti in smeri. Nazadnje pa načrtovalce stavb zanima tudi podatek o gostoti moči sončnega sevanja (*G*), ki jo izmerimo s piranometrom in podajamo v W/m^2, po času integrirano vrednost – sončno obsevanje (*I*) – pa izražamo z Wh/m^2. Pri tem sta pomembni tako neposredna (direktna) kot difuzna komponenta sončnega sevanja. Te informacije o podnebju dobimo s pomočjo izmerjenih podatkov in s pomočjo statističnih metod, kot so opisna statistika, regresijska analiza, analiza variance, analiza časovnih vrst, multivariantne metode itd. [78]. Za uporabo v izračunih energijske oz. toplotne bilance stavb pogosto uporabljamo t. i. značilno meteorološko leto (ang. *Typical Meteorological Year*, TMY) oz. testno referenčno leto (ang. *Test Reference Year*, TRY). TMY in TRY predstavljata 365-dnevni niz urnih povprečnih vrednosti izbranih meteoroloških spremenljivk, najpogosteje temperaturo in relativno vlažnost zraka dva metra nad tlemi, gostoto toka globalnega sevanja na vodoravno ploskev ter smer in hitrost vetra [82].

Kot opisano, je podnebje kompleksen pojav, odvisen od fizikalnih procesov v ozračju, v oceanih, na kopni površini in v živi naravi, na vse skupaj pa močno vpliva Sonce, ki daje sistemu potrebno energijo [76]. Neštete kombinacije teh fizikalnih procesov imajo združujoč učinek na zemeljsko površje, rastlinstvo, živalstvo in človeka. Po lastnostih teh elementov je moč prepoznati različne tipe podnebij, ali z drugimi besedami abstraktno efektivno vreme, ki bi imelo isti učinek na naravo [76]. Podnebja na Zemlji so zelo raznolika in obsegajo območja od vročih tropov do hladnih arktičnih predelov, vse do sušnih puščav in deževnih gozdov [80]. Ker podnebne podatke beležimo razmeroma kratek čas, večinoma ne več kot zadnjih 100 let, je tudi opredelitev podnebnih tipov razmeroma mlada veda. Leta 1870 je botanik Vladimir Köppen oblikoval definicijo podnebij s pomočjo podatkov o mesečnih temperaturah zraka in količini padavin, ki temelji tudi na podatkih o rastju [75]. Leta 1931 je Warren C. Thornthwaite predstavil še alternativno možnost za klasifikacijo podnebnih tipov. Kasneje, v letih 1961 in 1980, so klimatologi Rudolf Geiger, Glenn Trewartha in Lyle Horn nadgradili Köppnovo klasifikacijo, ki je od takrat najpogosteje uporabljana metoda za klasifikacijo podnebij – Köppen-Geigerjeva klasifikacija [75]. S pomočjo slednje definiramo lastnosti podnebja na treh ravneh. Prva raven predstavlja pet glavnih podnebnih tipov: A – tropsko, B – suho, C – zmerno toplo, D – hladno in E – arktično. V drugi ravni podnebje opišemo glede na prisotnost padavin. Pri podnebnih tipih A, C in D z drugo črko definiramo sezonskost padavin: f – vlažno celo leto, s – podnebje s suhim poletjem in w – podnebje s suho zimo. Pri tropskem podnebnem tipu (A) poznamo še monsunski podnebni tip, ki ga označujemo s črko m. Pri suhih podnebjih (B) na drugi ravni označimo s črko W, če je suho podnebje pravo puščavsko, in s črko S, če je podnebje polpuščavsko (stepsko). Na tretji ravni klasifikacije podnebje še podrobneje opišemo s pomočjo temperatur. Pri arktičnem podnebnem tipu (označen s črko E) poznamo dva podtipa, in sicer s črko T označimo tundro (milejše arktično podnebje), s črko F pa označimo podnebje večnega snega in ledu. Pri preostalih glavnih podnebnih tipih podamo podatek o temperaturah: a – vroča poletja, b – topla poletja, c – mila poletja in d – sveža poletja (ekstremno celinsko podnebje). Pri suhih podnebnih tipih (označenih s črko B) pa na tretji ravni opišemo, ali gre za vroče suho (h) ali hladno suho (k) podnebje [75, 83, 84]. Po Köppen-Geigerjevi klasifikaciji tako skupaj poznamo 29 različnih podnebnih tipov (slika 4).



Slika 4: Karta Köppen-Geigerjevih podnebnih tipov na podlagi opazovanih podatkov med letoma 1976 in 2000 po Rubel in Kottek [17].

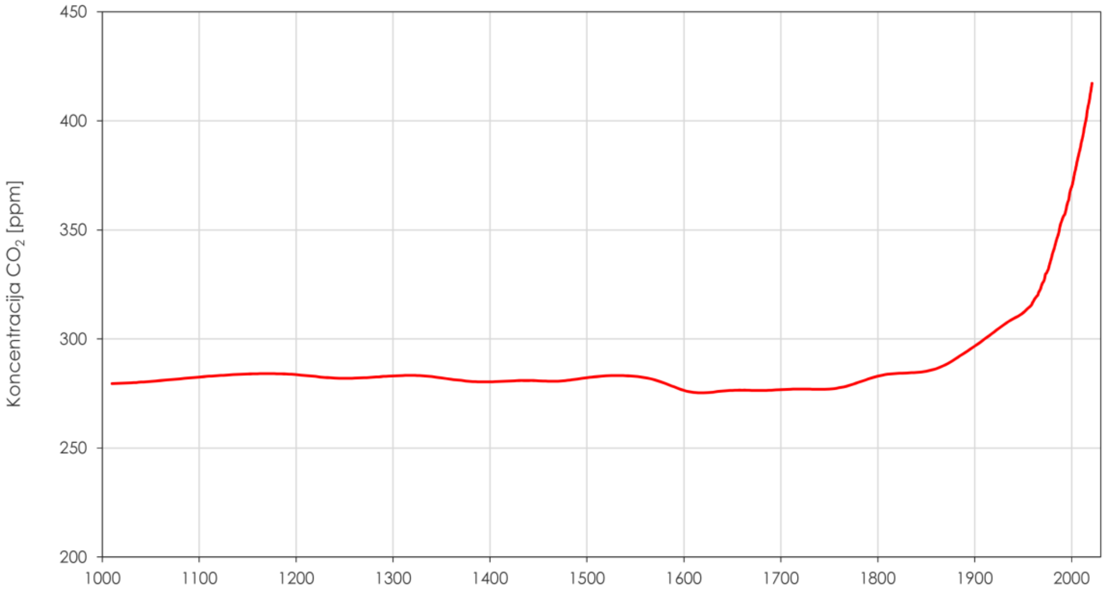
Figure 4: Köppen-Geiger climate type map based on the observed data for the period between 1976 and 2000 by Rubel and Kottek [17].

2.2.1.2 O podnebnih spremembah

Podnebje na Zemlji v preteklosti nikoli ni bilo dlje časa stalno, zaradi različnih dejavnikov se je nenehno spreminjalo in se bo spreminjalo [16, 75, 78]. Danes je s pomočjo merjenih in zapisanih podatkov ter znanja paleoklimatologov in ved, kot so geologija, geofizika, botanika, paleontologija, vulkanologija, kemija itd., znano, da so podnebne spremembe na Zemlji od nekdaj. Kot navajata Rohli in Vega [75] poznamo več oblik spreminjanja podnebja, ki jih v grobem lahko opredelimo kot: naključna variabilnost ali šum, periodična variabilnost, sprememba v variabilnosti (sprememba odklona), trend in stopničasta sprememba. Pogosto so posledica teh variabilnosti podnebja ekstremni vremenski pojavi, kot so intenzivne poplave, pogosti orkanski vetrovi, vročinski valovi ipd. Podnebne spremembe pa so, poleg kratkoročnih in očitnih ekstremnih vremenskih pojavov, vidne tudi v dolgoročnih odstopanjih od povprečnih vrednosti, kot sta npr. sprememba v temperaturi zraka med obdobji ledenih dob in otoplitev ter postopno spuščanje in dviganje morske gladine [75]. Vse omenjene podnebne spremembe lahko opišemo kot naravno prisotne.

Naravno prisotne podnebne spremembe in variabilnost so posledica več geoloških, astronomskih biosferskih in oceanografskih mehanizmov, ki se odražajo v časovnem okvirju od nekaj mesecev do več milijonov let [75]. Pred 280 milijoni let je bilo vse kopno združeno v eno celino Pangea, ki se je kasneje preoblikovala v ločene celine. Spreminjanje lege celin je vplivalo na cirkulacijo vode in prerazporejanje temperature v oceanih, tektonska dejavnost (in s tem nastajanje gorovij) je spreminjala zračne tokove in albedo površja (saj so gorski vrhovi pogosto pokriti s snežno odejo). S tem je prišlo do večjih podnebnih sprememb. Prerazporejanje kopne površine je pomenilo, da se je spreminjalo tudi težišče Zemlje, s tem pa os in hitrost vrtenja Zemlje. Tudi tirnica kroženja Zemlje okrog Sonca, in posledična osončenost, ni bila ves čas enaka [78]. Omenjene astronomske spremembe so opisane s t. i. Milankovićevimi astronomskimi cikli o spreminjanju časa začetka letnih časov, spreminjanju nagiba Zemljine osi in ekscentričnosti njene orbite; vse to pa pomembno vpliva na količino prejetega sončnega sevanja in pojav ledenih dob. Poleg Milankovićevih ciklov in tektonskega delovanja, ki imajo daljšo povratno dobo, pa na podnebne spremembe vplivajo tudi pojavi s krajšo povratno dobo, kot so vulkanska dejavnost, sončni cikli (periodična variabilnost sončnega sevanja) in dolgotrajnejši odkloni temperature na morski gladini (npr. El Niño – južna oscilacija) [75]. Periode za astronomske dejavnike, ki vplivajo na podnebne spremembe, so sicer za življenje enega človeka dolge (20 do 150 tisoč let), glede na zgodovino človeštva pa kratke [78]. Veliko daljši (več sto milijonov let) je razvoj sestave ozračja, zato je le-ta, z izjemo vpliva vulkanskih izbruhov, s stališča človeštva bolj ali manj stalnica. Sicer pa se je tudi Zemljino ozračje od nekdaj spreminjalo. V zgodnji dobi Zemlja ozračja niti ni imela, le-to je nastalo z izhlapevanjem iz tal in z vulkanskimi izbruhi [78]. Vse odtlej sestava plinov v ozračju ni bila konstantna, posledično pa je bila drugačna tudi sevalna bilanca.

Čeprav v geološki zgodovini Zemlje poznamo vrsto podnebnih sprememb, niso vse nastale zaradi mehanizmov naravnega izvora. Ljudje s spreminjanjem rabe tal, krčenjem gozdov ter vplivom na erozijo in dezertifikacijo močno vplivamo na okolje in podnebje. Poleg tega so trije najvplivnejši antropogeni (tj. človeškega izvora) dejavniki, ki povzročajo spremembe podnebja: povečan učinek tople grede, pojav urbanega toplotnega otoka in onesnaženost atmosfere [75]. Vsi ti dejavniki lahko povzročajo globalno segrevanje. Onesnaženost atmosfere z aerosoli pa je lahko vzrok tudi za manjšanje toplogrednega učinka. Aerosoli v zraku lahko višajo ali nižajo učinek tople grede, odvisno od tipa delcev. Na zmanjšanje vpliva najbolj učinkujejo delci, kot so sulfati (npr. SO_2), organski ogljik, mineralni prah in nitrati (npr. NH_3), posredno pa je učinek tople grede zmanjšan tudi zaradi nastajanja oblakov [16]. Pojav urbanega toplotnega otoka je predvsem posledica znižanega učinka evapotranspiracije, višje toplotne kapacitete in proizvedene toplote v okolici večjih mest v primerjavi z ruralnimi območji ter pomembno vpliva na globalno segrevanje. Zrak v mestih je v povprečju 1–5 °C toplejši kot v okoliških nenaseljenih območjih [75]. Učinek tople grede je, kot opisano v poglavju 2.2.1.1, naraven proces, ki je posledica t. i. obratnega toplotnega sevanja atmosfere nazaj proti zemeljskemu površju. Učinek tople grede povzročajo plini v atmosferi, kot so vodna para, ogljikov dioksid (CO_2), metan (CH_4), dušikov oksid (N_2O) in drugi toplogredni plini. Kljub temu, da je vodna para najbolj zastopan toplogredni plin v atmosferi, pa pri podnebnih spremembah nima poglavitne vloge, saj je atmosfera sposobna nenehno uravnavati delež vodne pare. Pri tem človeštvo na vodni krog lahko zelo malo vpliva [75]. Čeprav je v primerjavi z deležem vodne pare v ozračju koncentracija CO_2 izredno nizka (npr. le nekaj več kot 400 ppm – delcev na milijon, ang. *parts per million*), ima le-ta na učinek tople grede izredno velik vpliv. Na prisotnost CO_2 v atmosferi s svojo dejavnostjo močno vplivamo ljudje, veliko bolj kot, denimo, na delež vodne pare. V zadnjem stoletju je sestava ozračja zaznamovana z izredno hitro rastjo količine CO_2 in drugih toplogrednih plinov [16]. Z industrializacijo in pospešeno rabo fosilnih goriv smo ljudje povzročili hitrejše sproščanje ogljikovega dioksida in preostalih toplogrednih plinov v ozračje. Vsebnosti plinov CO_2, CH_4 in N_2O v ozračju so se dvignile do ravni, ki so brez primere v najmanj zadnjih 800.000 letih [16, 85]. Pri tem se je koncentracija delcev CO_2 v ozračju samo v zadnjih dveh stoletjih povečala z 270 na več kot 410 ppm [75, 86]. Slednje je vidno iz časovne odvisnosti koncentracije CO_2 v zadnjih nekaj več kot 1000 letih na sliki 5. V letu 2021 je bila povprečna izmerjena vrednost koncentracije CO_2 v atmosferi že 417 ppm.

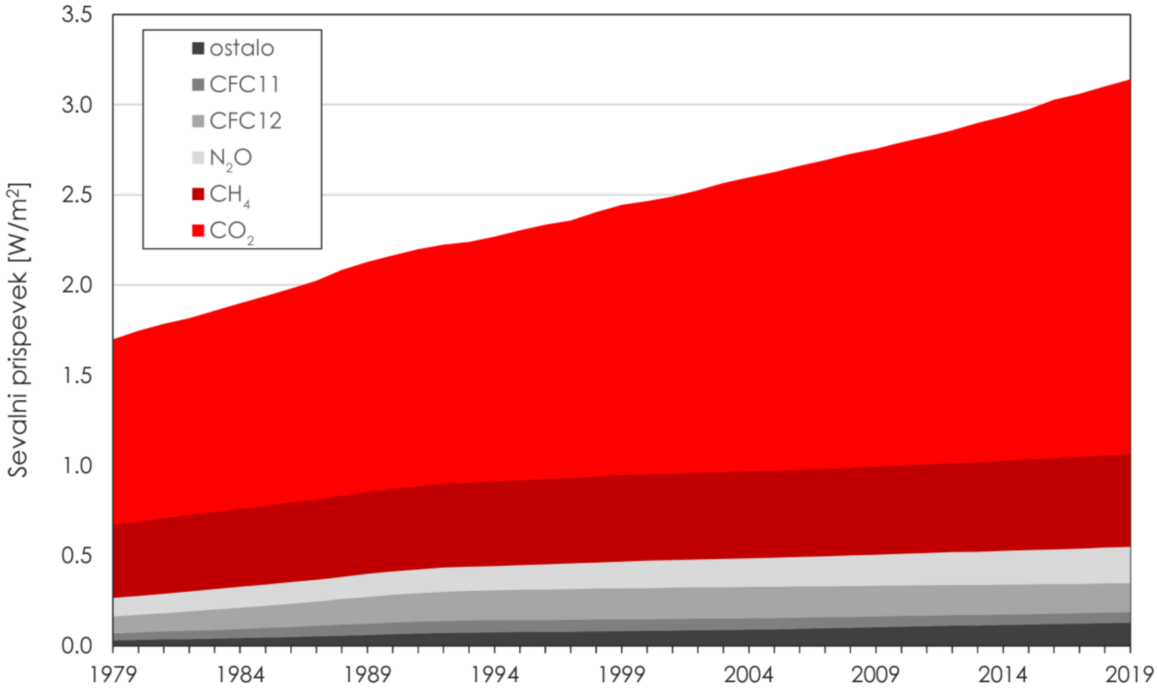


Slika 5: Zgodovinski potek koncentracije ogljikovega dioksida (CO_2) v atmosferi v delcih na milijon (ppm). Vrednosti so pridobljene s pomočjo vzorcev ledu [87] in atmosferskih meritev [88].
Figure 5: Historic global atmospheric concentrations of CO_2 in ppm. Values from ice core samples [87] and atmospheric measurements [88].

Velika rast koncentracije CO_2 v atmosferi je glavni vzrok za povečan učinek tople grede. CO_2 je dober absorber dolgovalovnega toplotnega sevanja in za zemeljsko površje deluje kot odeja, s tem pa temperature na Zemlji dosežejo višje vrednosti, kot bi jih sicer [16]. Z višanjem temperatur se poveča tudi stopnja vlage v zraku, kar še okrepi učinek tople grede in spremembo v energijski bilanci Zemlje. Nasprotno pa povišana vlaga vpliva tudi na pojavnost oblačnosti, kar povečuje odboj sončnega sevanja v atmosferi in prispeva k zmanjšanemu učinku tople grede. Preoblikovanje energijskih tokov ovrednotimo s sevalnim prispevkom (ang. *radiative forcing*). Pozitiven sevalni prispevek vodi k segrevanju in negativen k ohlajanju zemeljskega površja. V zadnjih desetletjih je skupni sevalni prispevek Zemlje pozitiven in je vodil k vnosu energije v podnebni sistem. Skupni sevalni prispevek zaradi človekove dejavnosti je leta 2019 glede na leto 1750 znašal 3,14 W/m^2, od tega kar 2,08 W/m^2 zgolj zaradi prisotnosti plina CO_2 (slika 6). Sevalni prispevek zaradi spremenjene solarne konstante je ocenjen na 0,05 W/m^2 [85]. Torej je največji doprinos k skupnemu sevalnemu prispevku zagotovo povzročila rast koncentracije CO_2 in preostalih toplogrednih plinov v atmosferi. Ugotovimo, da je višanje koncentracije CO_2 najpomembnejši dejavnik človeškega izvora, ki vpliva na globalno segrevanje [16]. Na podlagi enačbe 1, ki jo navaja Houghton [16], lahko s pomočjo koncentracije CO_2 v atmosferi, podane v ppm, ocenimo sevalni prispevek zaradi CO_2:

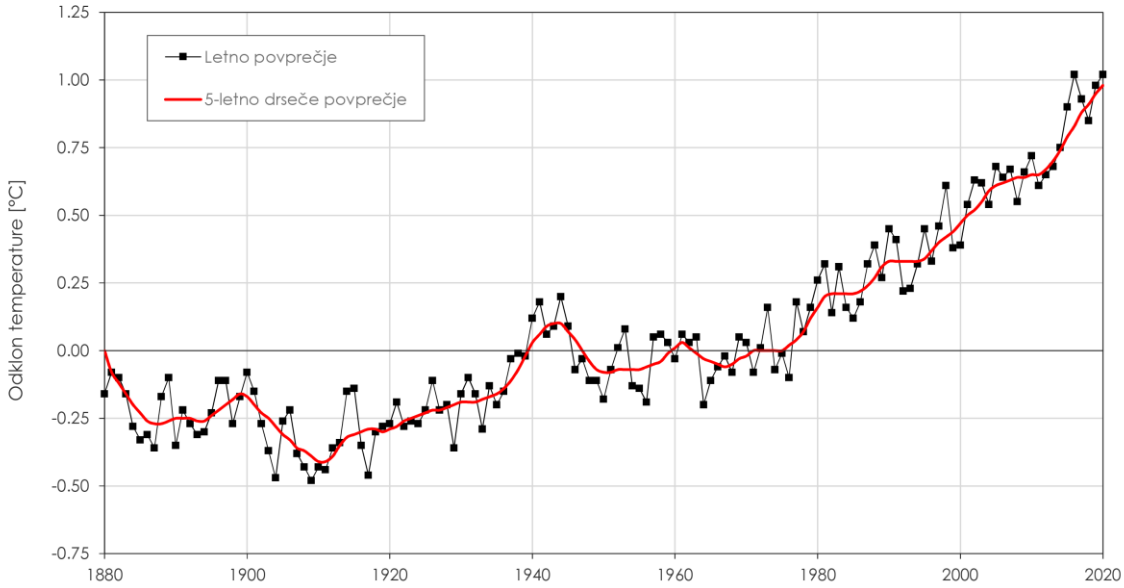
$$R_f = 5{,}3 \cdot \ln\left(C_{CO2}/C_{0,\mathrm{CO2}}\right) \quad (1)$$

R_f predstavlja sevalni prispevek zaradi CO_2 v W/m^2, C_{CO2} koncentracijo CO_2 v atmosferi v ppm in $C_{0,CO2}$ koncentracijo CO_2 v atmosferi pred začetkom industrijske revolucije, enako 280 ppm.



Slika 6: Globalni sevalni prispevek vseh dolgo obstojnih toplogrednih plinov, relativno glede na leto 1750 (podatki pridobljeni pri Laboratorijih za raziskovanje zemeljskih sistemov [89]).
Figure 6: Global radiative forcing of all the long-lived greenhouse gases, relative to the year 1750 (data sourced from Earth System Research Laboratories [89]).

Hitrost spreminjanja in obseg podnebnih sprememb na svetovni ravni sta določena s sevalnim prispevkom, podnebnimi povratnimi zankami in kopičenjem energije v podnebnem sistemu [85]. Ker pozitiven sevalni prispevek vodi k segrevanju zemeljskega površja in atmosfere, je pričakovano naraščanje temperatur. Meritve globalne temperature zraka (slika 7) dokazujejo, da je v zadnjih treh desetletjih povprečna temperatura zraka glede na zadnjih 140 let močno narasla. Verjetno gre za eno toplejših obdobij v zadnjih 1400 letih [75]. Glede na to, da je znana razlika med globalno temperaturo najhladnejšega obdobja ledene dobe in najtoplejšega dela v času med ledenimi dobami le 5 ali 6 °C [16], pomeni dvig globalne temperature za 1 °C opazno podnebno spremembo. Poročilo Svetovne meteorološke organizacije (ang. *World Meteorological Organization*, WMO) [90] navaja, da je bilo zadnjih šest let najtoplejših šest zabeleženih let, leto 2020 pa eno izmed treh najtoplejših. Višanje globalne temperature zraka prinese tudi vrsto sekundarnih pojavov, med katerimi so taljenje ledenega pokrova, taljenje kriosfere na tečajih in znižanje albeda arktičnih predelov, višanje gladine oceanov ipd. Led na Antarktiki se tali s hitrostjo 175–225 Gt na leto, viša se gladina morja, v letu 2020 pa so bili še posebej aktivni orkanski vetrovi [90]. Román-Palacios in Wiens [91] opozarjata, da bo zaradi segrevanja ozračja v 21. stoletju na robu izumrtja vsaj 16–30 % živalskih in rastlinskih vrst.



Slika 7: Globalna povprečna letna sprememba temperature zraka pri tleh preko kopnega in oceanov glede na referenčno povprečno temperaturo zraka v obdobju med 1951 in 1980 (podatki, pridobljeni na straneh NASA, Goddardov inštitut za vesoljske študije [92]).
Figure 7: Global annual mean surface air temperature change relative to the average air temperature in 1951–1980 period (data sourced from NASA Goddard Institute for Space Studies [92]).

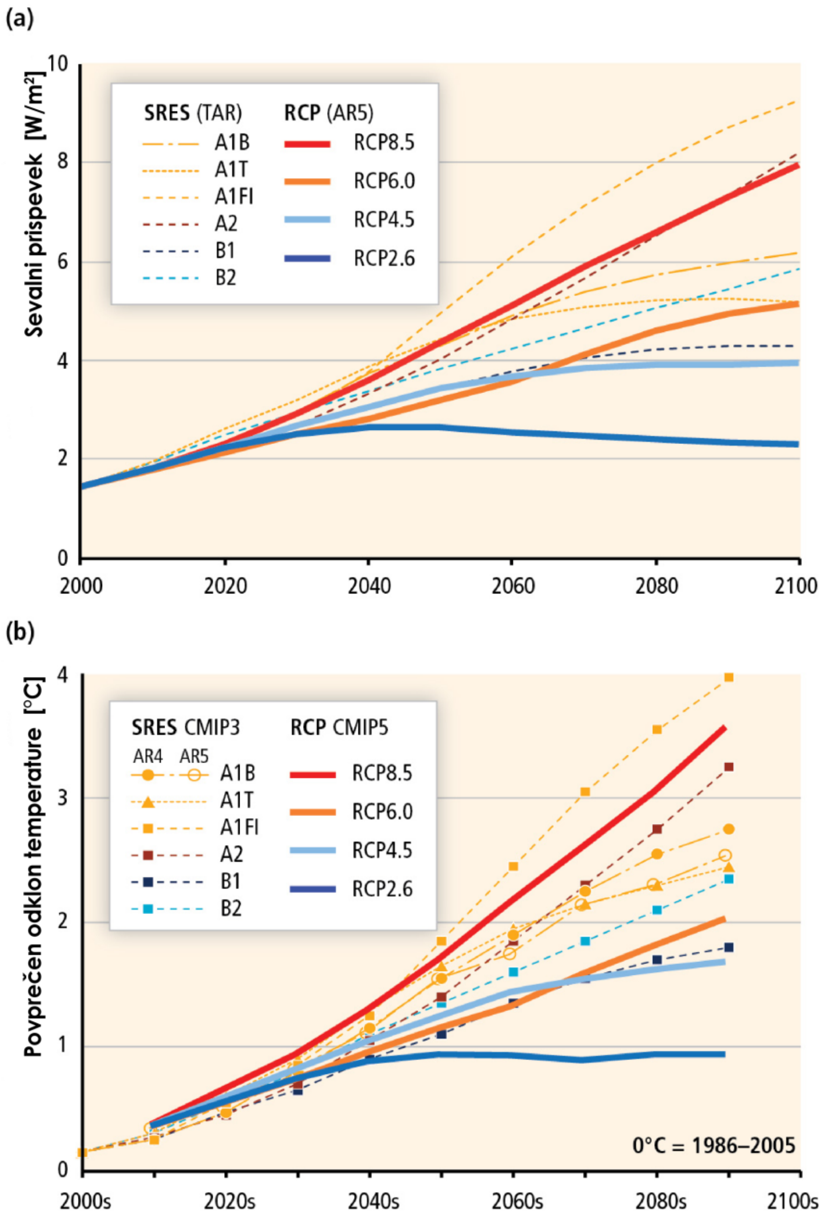
Kakšno bo podnebje v prihodnosti, odločajo predvsem astronomski dejavniki in sestava ozračja. Kot ugotovljeno, zaradi hitre rasti koncentracija CO_2 najbolj vpliva na globalno segrevanje. Da bi lahko ocenili nadaljnje segrevanje ozračja, so potrebne ocene o koncentraciji CO_2 v atmosferi v prihodnosti ter poznavanje vzrokov in vzgibov, ki vodijo do višanja ali nižanja le-teh, predvsem pa, kakšne so pričakovane emisije CO_2, ki jih bo ustvarilo človeštvo. Procesi skladiščenja CO_2 v oceanih in živi naravi so tako dolgotrajni, da bi tudi, če bi v celoti ustavili vse človeške procese, ki povzročajo izpuste CO_2, trajalo več sto let, preden bi se koncentracija tega toplogrednega plina v ozračju spet znižala na predindustrijsko raven [16]. Posledice rasti koncentracije CO_2 v ozračju v prihodnosti niso povsem jasne, bodo pa drugačne za različne predele Zemlje, predvsem na račun scenarijev glede emisij ogljikovega dioksida in drugih toplogrednih plinov [78]. Zato so za preučevanje prihodnih podnebnih stanj potrebni numerični modeli ozračja in podnebja.
Projekcije sprememb v podnebnem sistemu so izračunane z različnimi podnebnimi modeli: poznamo preproste modele, modele zmerne kompleksnosti, celovite podnebne modele do modelov celotnega Zemljinega sistema (ESM, ang. *Earth System Model*) [85]. Prvi primeri modeliranja podnebja za napoved vremena so se pojavili v času med 1. svetovno vojno, nato pa so z razvojem numeričnega modeliranja postajali bolj natančni in obsežni [16]. Danes podnebni modeli lahko vsebujejo podatke z minutno, urno, ali manjšo natančnostjo. Grobi podnebni modeli obsegajo povprečne vrednosti na globalni ali regionalni ravni, dočim natančnejši podnebni modeli opisujejo podnebne podatke s 100-kilometrsko natančnostjo in bolje [1]. Zaradi večjih območij, ki jih obsegajo podnebni modeli, in kompleksnosti le-teh, je natančnost običajno manjša kot pri modelih za napovedovanje vremena. Tako v podnebnih modelih ne moremo zajeti in modelirati informacij, kot so lokalna topografija, nevihte in izoblikovanje oblakov, ki jih je treba natančneje preučiti. Navedeno pomeni nekaj negotovosti, zato podnebni modeli niso vedno veljavni [79]. Za modeliranje odziva podnebja na spremenjeno sestavo

ozračja, torej za projekcijo stanja podnebja v prihodnosti, se uporabljajo t. i. modeli splošne cirkulacije (MSC, ang. *Global Circulation Model, GCM*). Trenutno se najbolj uporabljajo natančnejši modeli, kot je AOGCM (ang. *Atmosphere-Ocean General Circulation Model* oz. model splošne cirkulacije atmosfera-ocean, AOMSC). Pogosto je AOMSC model poimenovan tudi kot združen model splošne cirkulacije (ZMSC, ang. *Coupled Global Circulation Model*, CGCM). To so tridimenzionalni numerični modeli, v katerih so z diferencialnimi enačbami zajeti poglavitni fizikalni, kemijski in biološki procesi v ozračju, oceanih, ledu in na zemeljskem površju ter njihova medsebojna odvisnost [79]. Medvladni odbor za podnebne spremembe (ang. *Intergovernmental Panel on Climate Change*, IPCC) v svojih projekcijah in poročilih uporablja HadCM3 CGCM podnebni model z resolucijo 2,5 geografske širine in 3,75 geografske dolžine z 19 vertikalnimi sloji [93]. V modelih je možno z zelo visoko stopnjo zaupanja poustvariti izmerjene vzorce temperature zraka in trendov za mnogo desetletij, vključno s hitrejšim segrevanjem ozračja in morebitnim ohlajanjem, ki sledi ognjeniškim izbruhom [85]. Družino HadCM3 modelov so zdaj nadomestile družine modelov HadGEM2 in HadGEM3. V primerjavi z novejšimi modeli ima HadCM3 relativno nizko ločljivost, vendar kljub temu v povprečju deluje dobro, njegova prednost pa je predvsem hitrost računanja [94]. Kot odziv na potrebo po hitrih modelih so bili sicer razviti modeli zemeljskega sistema vmesne kompleksnosti (EMIC, ang. *Earth system Models of Intermediate Complexity*), razvita je bila tudi različica HadAM3BH z zelo visoko ločljivostjo 0,62 × 0,4166 [94].

Nadaljnji razvoj antropogenih podnebnih sprememb bo odvisen od več med seboj prepletenih dejavnikov, katerih potek je izredno težko napovedati. Mednje sodijo demografske spremembe in trendi, ekonomski razvoj družb pa tudi vpliv zakonodajnih okvirjev, ki jih postavljamo za blaženje podnebnih sprememb [1, 95, 96]. Ker je prihodnost nepredvidljiva, lahko vpliv človeka na lastnosti ozračja in odziv stanja podnebja ocenimo le ob predpostavkah o razvoju družbe in posledičnih izpustih toplogrednih plinov [97]. Predpostavke lahko opišemo z različnimi scenariji nadaljnjih emisij toplogrednih plinov, kot je CO_2, med katerimi so najpogostejši t. i. socio-ekonomski scenariji. Le-ti so zajeti v poročilih Medvladnega odbora za podnebne spremembe (IPCC), v katerih je opisana široka paleta scenarijev o nadaljnjem razvoju družbe do konca 21. stoletja [98]. Scenariji emisij toplogrednih plinov so v tretjem in četrtem IPCC poročilu [98,99] združeni pod SRES (scenariji izpustov, ang. *Special Report on Emissions Scenarios*), v petem poročilu IPCC [93] pa pod RCP (značilni poteki koncentracij, ang. *Representative Concentration Pathways*) (slika 8). V SRES skupini v grobem poznamo štiri scenarije, poimenovane A1, A2, B1 in B2 [99]. Skupina scenarijev A1 predpostavlja hiter globalen gospodarski razvoj in nadaljnjo hitro rast prebivalstva. V tej skupini so definirane še podskupine, ki z vpeljavo čistejših in učinkovitejših tehnologij zajemajo tudi možnosti za blaženje podnebnih sprememb. V scenariju A1FI je zajeta nadaljnja intenzivna raba fosilnih goriv, scenarij A1T predvideva prehod na obnovljive vire energije, scenarij A1B pa zajema uravnoteženo rabo fosilnih goriv in obnovljivih virov energije. Scenarij A2 predvideva raznolik svet s hitrim naraščanjem prebivalstva (obrat v rasti prebivalstva na sredini 21. stoletja), z zmernim gospodarskim razvojem in brez večje skrbi za okolje. Scenarij B1 predvideva obrat v rasti prebivalstva na sredini 21. stoletja, hitro preusmeritev gospodarskih struktur v oskrbovalno in informacijsko gospodarstvo, manjšo porabo surovin ter vpeljavo čistejših in učinkovitejših tehnologij. Scenarij B2 predvideva enakomerno rast prebivalstva (manj izrazito kot pri A2 in B1), osredotočanje na lokalne rešitve za zmerno gospodarsko rast, na socialno enakost in varovanje okolja. V drugi skupini scenarijev, poimenovani RCP, so bili definirani štirje novi scenariji o rasti koncentracije CO_2, imenovani RCP2.6, RCP4.5, RCP6.0 in RCP8.5 [93], pri čemer številka v imenu predstavlja približen skupen sevalni prispevek leta 2100, glede na leto 1750 kot posledico različnih kombinacij socio-ekonomskih dejavnikov (npr. pri RCP8.5 je predviden sevalni prispevek ob koncu 21. stoletja enak 8,5 W/m^2). Med omenjenimi štirimi scenariji RCP2.6 upošteva ukrepe za blaženje podnebnih sprememb, kar ključno prispeva k nižjemu sevalnemu prispevku. Scenarija RCP4.5 in RCP6.0 sta t. i. stabilizacijska scenarija, v katerih se emisije toplogrednih plinov postopoma stabilizirajo. Scenarij RCP8.5 pa je scenarij z nadaljnjim zelo velikim izpustom toplogrednih plinov. Pri scenarijih RCP6.0 in RCP8.5 vrh sevalnega prispevka do leta 2100 sicer še ni dosežen.

Z uporabo različnih scenarijev glede koncentracije toplogrednih plinov do konca 21. stoletja in od njih odvisnega sevalnega prispevka (slika 8) je moč predvideti nadaljnjo rast globalne temperature zraka. Pri uporabi projekcij sprememb v sevalnem prispevku in temperaturah se je treba zavedati, da scenariji vsebujejo ocene vplivov na koncentracije toplogrednih plinov. Le-te izhajajo iz več virov, nekatere, kot sta ocena o rabi površja in vplivu oblačnosti, pa so precej negotove [16]. Ob upoštevanju scenarijev emisij naj bi se na globalni ravni povprečna temperatura površja in zraka ob površju med letoma 1990 in 2100 dvignila za 1,4 do 5,8 °C [93, 99, 100]. Rubel in Kottek [17], Rubel in sod. [101] in He in sod. [102] so opozorili, da ob tako znatnih projiciranih spremembah temperature zraka lahko pričakujemo večje spremembe pri lastnostih podnebja na posameznih lokacijah. Rubel in Kottek [17] sta poudarila, da bodo največje spremembe glede na Köppen-Geigerjevo tipologijo podnebnih tipov v primeru SRES A1FI, A2, B1 in B2 scenarijev opazne med 30° in 60° geografske širine. V tem primeru bi na severnejših geografskih legah našli toplejše podnebne tipe, kot je zmerno toplo (C) podnebje. Tudi pri RCP podnebnih scenarijih (RCP2.6, RCP4.5 in RCP8.5) so He in sod. [102] opozorili na prostorski premik Köppen-Geigerjevih podnebnih tipov proti polom, pri čemer naj bi se povečala površina s puščavskim (B) podnebjem ter zmanjšala površina s hladnim (D) in arktičnim (ET) podnebjem.

Da bi omilili podnebne spremembe, je bil leta 2016 podpisan Pariški sporazum o podnebnih spremembah [103]. Najambicioznejši cilj Pariškega sporazuma je, da bi odklon globalne temperature ostal pod 1,5 °C. Za dosego tega bi bilo treba globalne emisije toplogrednih plinov do leta 2030 zmanjšati za vsaj 50 %. Analiza trenutnih zavez za zmanjšanje emisij med letoma 2020 in 2030 kaže, da je skoraj 75 % obljub blaženja podnebnih sprememb delno ali popolnoma nezadostnih za to, da bi prispevali k zmanjšanju emisij toplogrednih plinov v ozračje [104]. Hausfather in sod. [105] so primerjali razlike med modeliranimi in izmerjenimi koncentracijami CO_2 ter drugimi parametri, ki vplivajo na podnebje, ter ugotovili, da so bili podnebni modeli, objavljeni v zadnjih petih desetletjih, pri napovedovanju globalnega segrevanja precej natančni. Pri tem so sicer nekateri modeli vplive podnebnih sprememb precenili, drugi pa podcenili. Schwalm in sod. [106] navajajo, da lahko trenutno najbolj »črn« scenarij, RCP8.5, še naprej služi kot koristno orodje za količinsko opredelitev podnebnih tveganj, zlasti v bližnje- in srednjeročnih strateških ciljih. Scenarij RCP8.5, ki je sicer zelo podoben scenariju SRES A2 (glej slika 8), trenutno tesno sledi dejanskim kumulativnim emisijam CO_2 (v okviru 1 %) in se tudi najbolje ujema s trenutnimi političnimi strategijami [106]. Kljub temu Zhu in sod. [107] opozarjajo, da na podlagi CMIP6 (*Coupled Model Intercomparison Project Phase 6*) podnebni modeli ne izkazujejo visoke natančnosti pri zelo visokih koncentracijah CO_2, ki so projicirane proti koncu stoletja, kar se lahko pokaže v previsokih projiciranih temperaturah zraka.



Slika 8: Projekcije (a) sevalnega prispevka in (b) povprečnega odklona temperature površja do konca 21. stoletja na podlagi različnih SRES in RCP scenarijev IPCC (Povzeto po Field et al. [108]). Sevalni prispevek je podan relativno glede na predindustrijsko dobo.

Figure 8: Projected (a) radiative forcing and (b) global mean surface temperature change over the 21st century according to the IPCC's SRES and RCP climate change scenarios (adapted from Field et al. [108]). Radiative forcing is shown relative to pre-industrial values.

2.2.2 Bioklimatska analiza

Bioklimatska analiza je temelj načrtovanja bioklimatskih stavb in sloni na povezavi med podnebjem, toplotnim udobjem uporabnikov in stavbo. Surove podnebne podatke navadno težko neposredno interpretiramo. Z znanjem o človekovem toplotnem zaznavanju okolice, podatki o podnebnih danosti in predvsem z orodji, kot je bioklimatska karta, združimo informacije ter s pomočjo t. i. bioklimatskega potenciala postavimo izhodišča za načrtovanje bioklimatskih stavb.

2.2.2.1 Toplotno udobje

Podnebne danosti niso povsod idealne in ugodne za človeka. Zato je glavno vodilo za bivanje doseganje udobja uporabnikov, predvsem toplotnega, kar je večinoma mogoče doseči z uporabo bivališč in vzdrževanjem udobnih razmer v njih. Človekova energijska bilanca, počutje in zdravje so močno odvisni od neposredne povezave telesa z okoljem. Okolijske elemente, ki vplivajo na človeka, lahko opišemo kot svetlobo, zvok, podnebje, prostor in življenje [56]. Človeško telo se nenehno prilagaja okolju v želji zmanjšati rabo energije v telesu na najnižjo možno raven. Ko je takšno ravnovesje doseženo, lahko stanje definiramo kot cono udobja. Pri načrtovanju stavb se osredotočamo predvsem na toplotno udobje, saj je le-to pri doseganju toplotnega ravnovesja človeškega telesa ključno, hkrati pa neposredno vpliva na energijsko učinkovitost stavb [1]. Dejavnike, ki vplivajo na izmenjavo toplote človeškega telesa z okoljem in posledično na toplotno udobje, lahko združimo v tri skupine, prikazane v preglednici 1. Znano je, da je zaradi velikega vpliva na konvekcijsko izmenjavo toplote najpoglavitnejši dejavnik temperatura zraka [4].

Preglednica 1: Vplivni dejavniki izmenjave toplote človeškega telesa [4].
Table 1: The variables that affect heat exchange of human body [4].

okolijski dejavniki	osebni dejavniki	posredni dejavniki
temperatura zraka	metabolizem (aktivnost)	hrana in pijača
vlažnost zraka	oblečenost	oblika telesa
gibanje zraka	zdravstveno stanje	podkožna maščoba
sevanje (toplotno in sončno)	aklimatizacija	starost in spol

Osnovni princip izmenjave toplote človekovega telesa z okoljem lahko opišemo z enačbo 2 [1, 4, 109].

$$\Delta S_h = M_h \pm A_h \pm R_h \pm C_h \pm K_h - E_h - RES_h \tag{2}$$

ΔS_h predstavlja toplotno bilanco človeškega telesa. Če je vrednost višja od nič, ima človekovo telo presežek toplotne energije, zato se bo bazična temperatura telesa začela dvigovati in obratno, pri negativni toplotni bilanci zniževati. Človeško telo stremi k ničti bilanci, torej k toplotnemu ravnovesju. M_h predstavlja metabolno toploto človeškega telesa, ki se sprošča pri oksidaciji hrane, A_h je izmenjava energije z delom (prehajanje energije med telesi), R_h je izmenjava energije s sevanjem, C_h je izmenjava energije s konvekcijo, K_h s kondukcijo, E_h je izguba energije zaradi evaporacije vlage na površini človeškega telesa, RES_h pa predstavlja toplotne izgube, ki so posledica dihanja.
Nadalje lahko del, ki predstavlja izmenjavo toplote s sevanjem in konvekcijo, opišemo z enačbo 3 [56].

$$R + C = S_t \cdot S_c \cdot \frac{(T_{skin} - T_{db})}{\frac{Clo}{c} + \frac{V.Clo}{c}} \tag{3}$$

Pri tem S_t predstavlja povprečno površino telesa oblečenega človeka, S_c je delež telesa, izpostavljen sevanju, T_{skin} pomeni temperaturo kože, T_{db} je temperatura suhega termometra zraka, *Clo/c* predstavlja vpliv stopnje oblečenosti, *V.Clo/c* pa opisuje vpliv gibanja zraka na toplotno izolativnost obleke.

Izmenjava toplote člověkovega telesa z okolico je primarno odvisna od temperature suhega termometra (T_{db} v °C), srednje sevalne temperature (T_{mr} v °C) in hitrosti gibanja zraka (v v m/s). T_{mr} izračunamo kot uteženo povprečje temperature površin, ki obdajajo uporabnika. Ko predpostavimo stacionarno stanje, lahko T_{mr} izračunamo s pomočjo enačbe 4,

$$T_{mr} = \frac{\sum_{i=1}^{n} T_{s,i} \cdot A_i}{\sum_{i=1}^{n} A_i} \tag{4}$$

pri kateri je $T_{s,i}$ površinska temperatura i-tega elementa v okolici, A_i pa površina i-tega elementa. S pomočjo podatkov o temperaturi suhega termometra, srednji sevalni temperaturi in hitrosti gibanja zraka lahko izračunamo občuteno oz. operativno temperaturo (T_o). T_o je srednja temperatura med T_{db} in T_{mr}, določena z enačbo 5.

$$T_o = \frac{T_{mr} \cdot h_s + T_{db} \cdot h_c}{h_s + h_c} \tag{5}$$

Vrednost h_s predstavlja sevalni prestopni koeficient, h_c pa konvekcijski prestopni koeficient, ki je odvisen od konvekcije oz. od hitrosti gibanja zraka.

Na toplotno bilanco in toplotno zaznavo okolice človeškega telesa poleg opisanega vpliva temperature vpliva tudi vlažnost. Le-ta se izraža predvsem z vplivom na izgubo toplote z evaporacijo. Pri višjih vrednostih relativne vlažnosti je tako sposobnost izhlapevanja vlage s površine človeškega telesa zmanjšana, s tem pa je nižja tudi stopnja izgube toplote. Naprednejše metode izračunavanja člověkovega toplotnega udobja tako vsebujejo več dejavnikov. Najpogostejša metoda izračuna je model PMV (ang. P*redicted Mean Vote*) [109], pri čemer so v izračunu člověkove zaznave toplotnega udobja zajeti vsi dejavniki, tako metabolizem, stopnja aktivnosti in oblečenosti, kot temperatura zraka, srednja sevalna temperatura, relativna vlažnost, in gibanje zraka. Izvzeta je le zmožnost prilagoditve na spremembo temperatur, ki pa jo opisujejo novejši modeli prilagodljivega toplotnega udobja (ang. *adaptive thermal comfort*) [110, 111]. Temperaturno prilagoditev lahko razumemo na podlagi enačbe 6, ki opisuje temperaturo ravnovesja T_n, pridobljeno na podlagi empiričnih raziskav. Pri tem $T_{e,av}$ predstavlja povprečno mesečno zunanjo temperaturo.

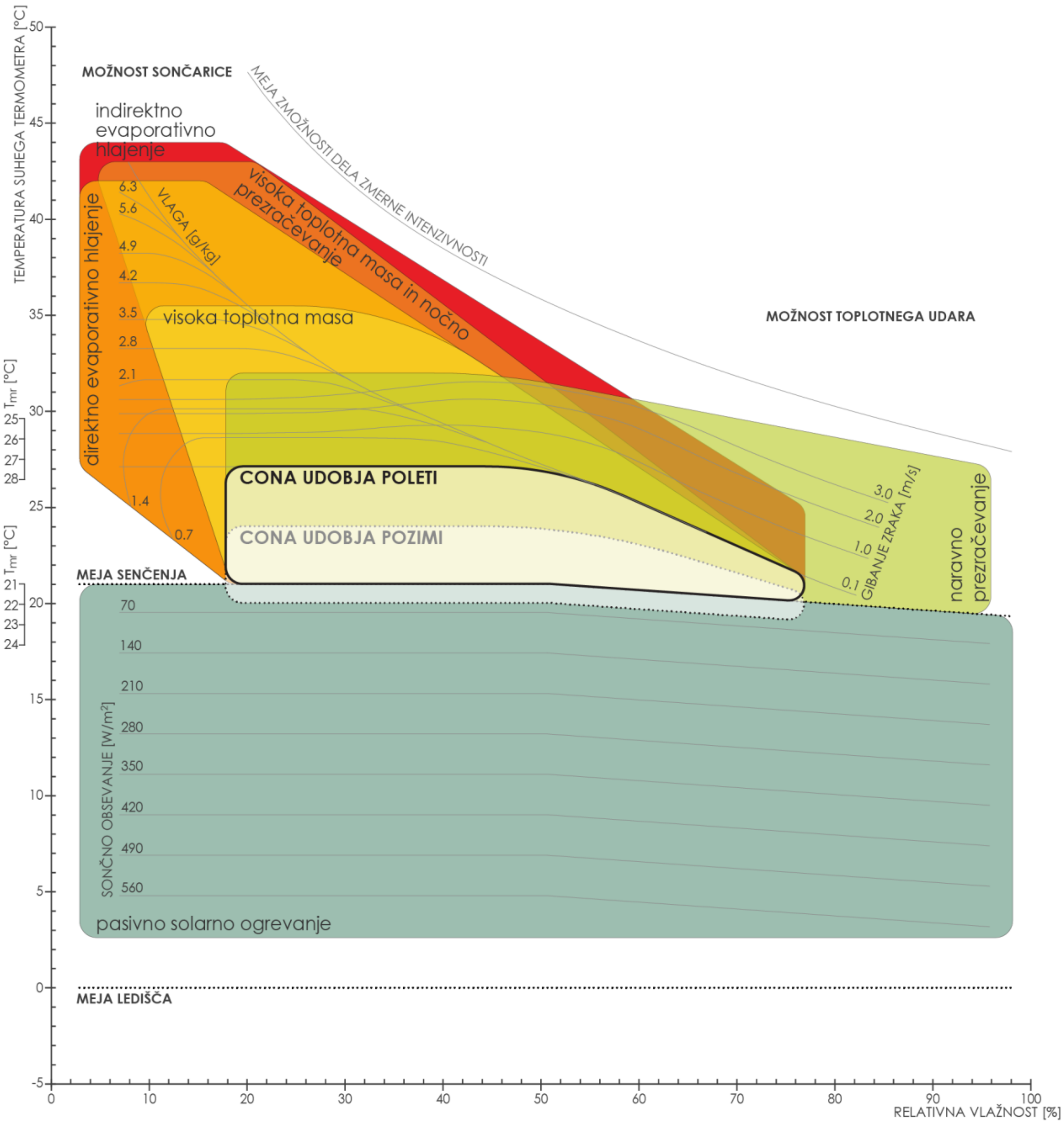
$$T_n = 17{,}8 + 0{,}31 \cdot T_{e,av} \tag{6}$$

T_n predstavlja temperaturo zraka, okrog katere se giblje člověkova t. i. cona toplotnega udobja. Le-ta je z 90-odstotno zanesljivostjo opredeljena kot $T_n \pm 2{,}5$ °C [4]. Navedena enačba je le ena od možnih in ne velja za vsa okolja. Poleg kratkoročne temperaturne prilagoditve je pomembna tudi dolgoročna, pri kateri so pomembne značilnosti podnebja, v katerem živimo, pa tudi kulturološki dejavniki, kot so vplivi družbe in grajenega okolja. Razumevanje človeškega toplotnega udobja ter določitev sprejemljivih mej sta za izvedbo bioklimatske analize ključna podatka, saj tako definiramo cono udobja ter s tem povežemo podnebne danosti in človeško udobje.

2.2.2.2 Bioklimatska karta in bioklimatski potencial

Bioklimatska karta je orodje, ki nam pri načrtovanju podnebno prilagojenih stavb služi kot osnova. Prvi, ki je bioklimatsko karto prilagodil uporabi pri načrtovanju stavb, je bil leta 1963 Olgyay [56]. Njegovo bioklimatsko karto sestavljata dve koordinatni osi, ki predstavljata temperaturo suhega termometra (T_{db}) in relativno vlažnost (*RH*) (slika 9). T_{db} je predstavljena na ordinatni osi, *RH* pa na abscisi. S pomočjo podatka o T_{db} in *RH* lahko za poljuben časovni okvir (urna, dnevna, mesečna natančnost) na bioklimatski karti narišemo točko ali premico, ki predstavlja okolijske razmere obravnavane lokacije v danem intervalu. S tema dvema podatkoma je določena človekova toplotna zaznava, le-ta pa je omejena na cono udobja in preostale kombinacije T_{db} in *RH*, ki so za človeka neudobne. Toplotno udobje na Olgyayevi bioklimatski karti je definirano pri T_{db} med 21 in 27 °C ter *RH* med 20 in 80 %. Pri *RH*, ki so višje od 50 %, je toplotno udobje zaradi znižane stopnje evaporacije navzgor omejeno z nižjimi temperaturami (slika 9). Naveden okvir cone toplotnega udobja velja predvsem za toplejšo polovico leta, v hladnejšem delu leta pa je zaradi toplotne prilagoditve cona udobja omejena na T_{db} med 20 in 24 °C. Olgyay je pri definicij cone udobja upošteval robne pogoje za naslednje dejavnike: stopnja metabolizma človeškega telesa je izbrana enaka 126 W (stoječi položaj v mirovanju), toplotna izolativnost obleke enaka 1 clo ali 0,155 m^2K/W (dolge hlače, kratka majica, srajca z dolgimi rokavi, pulover z dolgimi rokavi), gibanje zraka pa med 0,45 in 0,90 m/s.

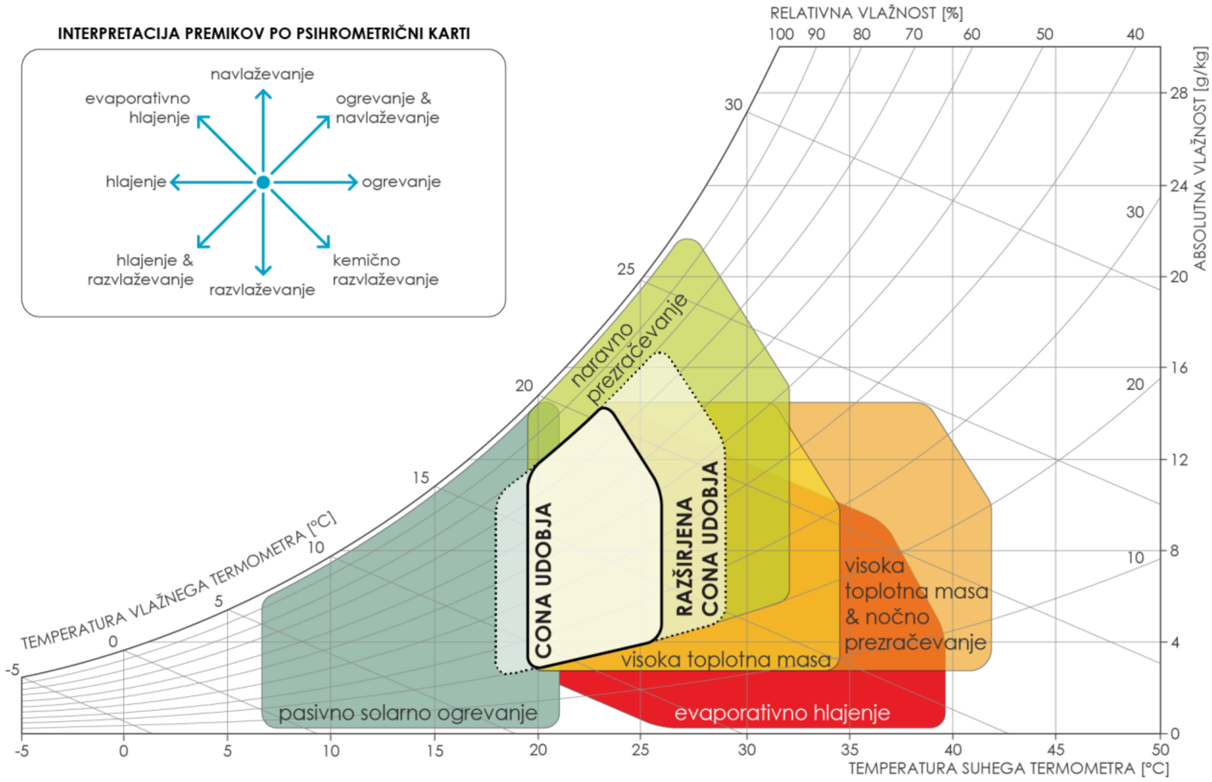
Kasneje sta DeKay in Brown [112] Olgyayevi bioklimatski karti dodala območja, ki predstavljajo različne možnosti doseganja toplotnega udobja s prilagajanjem stavb podnebnim danostim, pri čemer sta uporabila pasivne ukrepe, ki sta jih predstavila Milne in Givoni [1]. V primerih, ko toplotno udobje pri nekaterih kombinacijah T_{db} in *RH* ni doseženo, so na bioklimatski karti predstavljena območja, pri katerih lahko za doseganje toplotnega udobja uporabnikov posežemo po različnih pasivnih (bioklimatskih) ukrepih. To so pasivno sončno ogrevanje, senčenje, naravno prezračevanje, visoka toplotna masa stavbe, nočno prezračevanje ter neposredno in posredno evaporacijsko hlajenje. Znotraj posameznih območij so predstavljene vrednosti različnih parametrov (slika 9), ki jih je treba zagotoviti, da bo toplotno udobje doseženo s pasivnimi ukrepi. Mednje spadajo prejeto sončno sevanje v W/m^2, hitrost gibanja zraka v m/s, srednja sevalna temperatura T_{mr} v °C in dodatna količina vlage v g/kg zraka. Na bioklimatski karti je pri 21 °C označena meja senčenja, ki pomeni, da je pri vseh kombinacijah T_{db} in *RH* nad njo potrebno senčenje oz. zaščita pred sončnim sevanjem. S prilagajanjem navedenih parametrov lahko vplivamo na toplotno udobje uporabnikov, s tem pa lahko na pasiven način, brez večjih vložkov energije v sistem, dosežemo temperaturo ravnovesja človeškega telesa. Tako lahko z uporabo bioklimatskih kart preprosto in nazorno povežemo vplive podnebja na človekovo toplotno udobje ter ugotavljamo možnost prilagajanja grajenega okolja podnebju z uporabo pasivnih ukrepov. Ena od omejitev bioklimatske karte je, da je uporabna pretežno za zmerni tip podnebja pri uporabljenih predpostavkah stopnje aktivnosti in toplotne izolativnosti obleke. Pri drugačnih robnih pogojih je treba njeno interpretacijo smiselno prilagoditi. Po drugi strani pa je velika prednost Olgyayeve bioklimatske karte možnost posredne ocene o vplivu sončnega sevanja na toplotno udobje, kar npr. pri Givonijevi psihrometrični karti neposredno ni mogoče.



Slika 9: Olgyayeva bioklimatska karta, nadgrajena z označenimi priporočenimi pasivnimi ukrepi (povzeto po Košir [1] in Olgyay [56]).

Figure 9: Olgyay's bioclimatic chart with recommended passive design measures (adapted from Košir [1] and Olgyay [56]).

Givoni [113] je sicer uporabo pasivnih načrtovalskih ukrepov predstavil na primeru psihrometrične karte (slika 10). Podobno kot pri Olgyayevi bioklimatski karti so tudi na Givonijevi predstavljeni ukrepi, potrebni za zagotavljanje človekovega toplotnega udobja v danih okolijskih razmerah. Tu sta pomembna predvsem temperatura in vlažnost zraka. Kombinacija navedenega pove, ali je toplotno udobje doseženo ali pa so za to potrebni pasivni oz. aktivni ukrepi.



Slika 10: Psihrometrična karta, nadgrajena z označenimi priporočenimi pasivnimi ukrepi (povzeto po Košir [1] in Givoni [113]).
Figure 10: Psychrometric chart amended by recommended passive design measures (adapted from Košir [1] and Givoni [113]).

S pomočjo interpretacije bioklimatske karte v širšem kontekstu lahko določimo bioklimatski potencial lokacije. Le-ta nam pri načrtovanju stavb lahko pomaga pri izbiri bioklimatskih strategij in pasivnih ukrepov za doseganje ravnovesja med človekovim toplotnim udobjem in podnebjem. Z uporabo bioklimatske karte tako lahko na za načrtovalce razumljivejši način interpretiramo surove podnebne podatke, kot sta T_{db} in RH, jih s tem prevedemo v bioklimatski potencial, s pomočjo le-tega pa izberemo ustrezne pasivne ukrepe. S tem načrtovalci na analitični način pridobijo podatke o primernosti pasivnih ukrepov za načrtovanje stavb v nekem podnebju. Zaradi povezave med bioklimatskimi stavbami in podnebnimi danostmi lokacije je določanje bioklimatskega potenciala bistven korak pri načrtovanju [10, 114]. Bioklimatski potencial lahko opišemo kot čas, ko lahko z uporabo pasivnih ukrepov dosežemo toplotno udobje na ravni stavbe. S pomočjo bioklimatskega potenciala in priporočenih pasivnih ukrepov na neki lokaciji lahko določimo čas, ko stavba v nekih podnebnih razmerah lahko deluje v t. i. prostem teku. Torej stavba za svoje delovanje, tj. doseganje toplotnega udobja uporabnikov, ne potrebuje dodatne energije. Kljub temu se je treba zavedati, da bioklimatski potencial pomeni le grobo oceno primernosti posameznih pasivnih ukrepov za doseganje toplotnega udobja, saj je zasnovan na generičnih predpostavkah o stavbi in njenih uporabnikih. Za natančnejšo oceno je zato nujno potrebna premišljena analiza toplotne bilance posamezne obravnavane stavbe. Prednost uporabe bioklimatskega potenciala je predvsem v tem, da lahko le s pomočjo osnovnih podnebnih podatkov razmeroma preprosto in hitro ocenimo ustreznost uporabe posameznih pasivnih ukrepov pri načrtovanju stavb.

2.2.2.3 Primeri uporabe

Analiza bioklimatskega potenciala lokacije je eden najpomembnejših začetnih korakov pri načrtovanju stavb. Vse, odkar je Olgyay predstavil bioklimatsko karto, se je razmeroma znana metodologija za njeno izdelavo razvijala in dobila več različic, ki so jih predstavili različni avtorji [57, 115–120]. Kljub temu pa je njen osnovni namen, torej določitev bioklimatskega potenciala lokacije z uporabo le osnovnih okolijskih parametrov, kot sta T_{db} in *RH*, ostal bolj ali manj enak, kot ga je predstavil Olgyay. Narejenih je bilo kar nekaj raziskav, pri katerih so bioklimatske analize uporabljali za oceno toplotnega udobja [6, 7, 58–60, 66, 116, 121–125] in/ali analizo potenciala pasivnih ukrepov za ogrevanje in hlajenje stavb [6, 7, 67, 122, 126–128]. Večinoma je bila v ta namen uporabljena Givonijeva psihrometrična karta, medtem ko je bila Olgyayeva bioklimatska karta uporabljena redkeje. Kljub temu se, ne glede na izbrano metodo, lahko oblikujejo podobne ugotovitve, zato rezultati analiz niso bistveno odvisni od tipa uporabljene karte. Več avtorjev je izdelalo nova orodja za bioklimatsko analizo (Rohles in sod. [116], Arens in sod. [117], Al-Azri in sod. [118], Martínez in Freixanet [119]). Martínez in Freixanet [119] sta predstavila celovito orodje za bioklimatsko analizo, imenovano BAT. Omogoča risanje bioklimatskih kart in več drugih grafikonov na podlagi podnebnih podatkov, ki jih pripiše uporabnik. Kljub temu lahko preveč informacij, ki jih ponuja orodje BAT, zmanjša uporabniško prijaznost. Poleg tega je glavna pomanjkljivost orodja BAT ta, da vpliv sončnega sevanja ni neposredno upoštevan pri glavni bioklimatski analizi, temveč je predstavljen v ločenem poglavju. Drug primer široko uporabljenega orodja za bioklimatsko analizo je tudi programsko orodje Climate Consultant, zasnovano na Kalifornijski univerzi v ZDA [120]. Rezultati podnebne analize, ki jo lahko naredimo s pomočjo orodja Climate Consultant, uporabnikom omogočajo vpogled v podnebne posebnosti izbrane lokacije. Orodje uporabnika vodi tudi k ustreznemu načrtovanju stavbe s pomočjo nabora načrtovalskih strategij, potrebnih za doseganje človeškega toplotnega udobja; bodisi s pasivnimi bodisi z aktivnimi ukrepi. Podobno kot pri orodju BAT tudi pri orodju Climate Consultant pri določanju toplotnega udobja vpliv sončnega sevanja ni neposredno upoštevan. Če povzamemo, obstaja več orodij, ki jih je mogoče uporabiti za bioklimatsko analizo, da bi pri načrtovanju stavb izbrali ustrezne pasivne ukrepe. Kljub temu v zgoraj navedenih orodjih v izračunih ni neposredno upoštevan vpliv sončnega sevanja, zato bioklimatski potencial dane lokacije lahko ne odraža povsem realnega stanja. To je še posebej pomembno za lokacije z zmernim ali hladnim podnebjem. Čeprav je sončno sevanje večinoma predstavljeno kot eden od odločilnih dejavnikov, ki vplivajo na bioklimatski potencial, njegov vpliv ni nikoli neposredno zajet v izračune bioklimatskega potenciala. V nekaterih primerih se podatek o sončnem sevanju uporablja le kot nepovezan parameter, s posredno interpretacijo, ločeno od tolmačenja temperature zraka in relativne vlažnosti.

Katafygiotou in Serghides [121] sta v svojih analizah uporabili Olgyayeve bioklimatske karte, s katerimi sta preučevali podnebna območja na Cipru. Ker pri bioklimatski analizi s pomočjo Olgyayeve karte vpliv sončnega sevanja na človekovo udobje ni neposredno zajet, sta v raziskavi le-tega upoštevali posredno, in sicer s tem, ko sta primerjali potrebno in razpoložljivo sončno sevanje. Izkazalo se je, da so bioklimatske analize specifičnih podnebij zelo pomembne in da je upoštevanje sončnega sevanja v bioklimatskih analizah ključno. Desogus in sod. [6] so izvedli primerjalno študijo bioklimatskih ukrepov, uporabljenih v tradicionalni arhitekturi na Sardiniji. Za analizo bioklimatskega potenciala je bila uporabljena Szokolayeva bioklimatska karta, vendar pa analiza ni upoštevala vpliva sončnega sevanja. V zaključku so povzeli, da so rezultati raziskave uporabni pri identifikaciji pasivnih ukrepov na specifični lokaciji, ki imajo potencial v energijsko učinkovitih stavbah. Vendar je treba poudariti, da je neupoštevanje sončnega sevanja pri sami analizi velika pomanjkljivost pričujoče raziskave, saj obstaja večja verjetnost, da pasivni ukrepi za nadzor sončnega sevanja (npr. senčenje, zajem sončne energije itd.) v rezultatih niso dovolj poudarjeni. Več avtorjev je v okviru raziskav na ravni države ali regije izdelalo bioklimatske cone [122, 123, 127] in tudi bioklimatske atlase [125]. Lam in sod. [122] so dodatno preiskovali potencial za pasivno solarno arhitekturo v osemnajstih mestih na Kitajskem. Kakor koli, ko so Lam in sod. [122], Morillón-Gálvez in sod. [125] ter Singh in sod. [127] izdelovali bioklimatske karte za Kitajsko, Mehiko in severovzhodno Indijo, so v analizo zajeli le osnovne podnebne podatke, kot so temperatura zraka, relativna vlažnost, hitrost vetra, pri tem pa niso upoštevali prejete energije sončnega sevanja. Za razliko od preostalih raziskav pa je Mahmoud [123] v bioklimatsko analizo zunanjih urbanih prostorov v Egiptu zajel tudi sončno sevanje. S podobno analizo in uporabo bioklimatske karte so Bodach in sod. [129] pokazali, da je v Nepalu tradicionalna arhitektura zelo dobro prilagojena lokalnemu podnebju, pri čemer bi lahko vernakularne bioklimatske ukrepe in strategije preslikali tudi v sodobno arhitekturo. Kljub temu avtorji niso ponudili nobenih specifičnih rešitev, ki bi jih na ta način lahko preslikali, ampak le predlagajo nadaljnje raziskave na tem področju.

Če povzamemo, ni veliko bioklimatskih analiz, ki bi sistematično in analitično obravnavale problematiko, čeprav število znanstvenih objav narašča. Večinoma se za bioklimatske analize uporabljajo psihrometrične karte, kar ne igra ključne vloge, saj so rezultati zelo podobni tistim, izdelanim z Olgyayevo bioklimatsko karto. Zanimivo je, da je raziskav, ki bi analizirale bioklimatski potencial podnebnih regij, izredno malo. Še bolj presenetljivo je, da je v večini analiz energija sončnega sevanja izvzeta iz neposrednih izračunov bioklimatskih analiz, le-ta je upoštevana zgolj posredno, kot je to storjeno pri raziskavi, ki sta jo naredili Katafygiotou in Serghides [121]. Prav sončno sevanje pa je eden izmed ključnih podnebnih dejavnikov, ki vpliva na načrtovanje in obnašanje stavb v zmernem in hladnem podnebju, zlasti pri analizah z bioklimatsko karto [64, 130]. Poleg naštetega v literaturi ni zaznati raziskave, ki bi se neposredno ukvarjala s povezavo med bioklimatskim potencialom lokacije/regije in energijskim odzivom stavbe. Čeprav je bioklimatsko načrtovanje velikokrat obravnavano kot splošno znanje, Cañas in Martín [71] opozarjata na še vedno prisotno pomanjkanje informacij o povezavi med podnebjem in sodobno arhitekturo.

Postopek analize bioklimatskega potenciala je sicer v zgodnjih fazah načrtovanja pogosto izpuščen in obravnavan kot nepotreben, saj se načrtovalci običajno zanašajo na generične rešitve, priporočene za določen podnebni tip ali regijo. Na primer, pogosto se domneva, da je treba stavbe, zasnovane v geopolitični regiji srednje Evrope [131], optimizirati za ogrevalno sezono, medtem ko pregrevanje ne predstavlja potencialne skrbi za zagotavljanje udobja uporabnikov. Takšno posploševanje načrtovalske skupnosti je nenavadno, saj omenjena regija obsega 1.036.380 km^2, devet držav (tj. Avstrijo, Češko, Nemčijo, Madžarsko, Lihtenštajn, Poljsko, Slovaško, Slovenijo in Švico) in pet različnih Köppen-Geigerjevih podnebni tipov (tj. Cfa, Cfb, Dfb, Dfc in ET) [83]. Poleg tega se zemljepisne širine lokacij v srednji Evropi močno razlikujejo (tj. 45 ° do 55 ° S), kar vpliva na količino prejetega sončnega obsevanja [132], ki je eden vplivnejših podnebnih dejavnikov, ki določajo toplotni odziv stavb. Na podlagi zgornjega opisa je jasno, da podnebnih razmer, ki opredeljujejo delovanje in načrtovanje bioklimatskih stavb, ni mogoče obravnavati kot ločene, razmejene s političnimi ali geografskimi konstrukti, temveč je treba nanje gledati kot na geoprostorski kontinuum, pri katerem se en podnebni tip počasi spreminja v drugega. V zvezi s tem so celo dobro uveljavljene sheme klasifikacije podnebja (npr. Köppen-Geiger, Thornthwaite itd.) delno zavajajoče, ker so različni podnebni tipi zaradi praktičnih razlogov predstavljeni kot diskretne kategorije [83]. Prav tako je treba omeniti, da je takrat, ko podnebne klasifikacije temeljijo na podnebnih parametrih, ki niso neposredno povezani z zasnovo stavb (npr.

temperatura in padavine pri Köppen-Geigerjevi klasifikaciji), njihova uporabnost kot vodilo pri bioklimatskem načrtovanju stavb omejena.

2.3 Energijska učinkovitost stavb

Energija opredeljuje, koliko dela lahko opravi nek sistem oz. koliko dela je shranjenega v njem [133]. Pri spreminjanju oblike energije velja zakon o ohranitvi energije, zato se pri pretvarjanju spreminja le oblika energije, ne pa tudi količina. Ena od oblik energij je tudi notranja energija ali toplota, pri čemer je temperatura sistema merilo količine energije v tem sistemu. Razlika v temperaturi je gonilo prenosa toplote, ki se prenaša s toplotnim tokom [133]. Tako je pri stavbi ves čas prisotna izmenjava toplote z okolico, katere temperatura je mnogokrat različna od človeku udobne. Da bi v stavbah lahko neprestano zagotavljali udobne razmere, tj. toplotno udobje, je pogosto potreben dodatni vložek ali odvzem toplote. Ob primanjkljaju toplote v stavbi z ogrevalnimi sistemi dovajamo toploto in obratno, ob presežku toplote le-to s hlajenjem odvajamo. Količino energije za delovanje stavbe lahko opredelimo na treh ravneh: primarna energija, končna energija in potrebna oz. koristna energija [133]. Razlika med njimi je posledica različnih učinkovitosti uporabljenih sistemov in energijskih pretvorb.

Pojem energijska učinkovitost stavbe pomeni, kako potrošni oz. varčni so stavba in njeni sistemi pri rabi energije za ogrevanje, hlajenje, prezračevanje, razsvetljavo itd. Energijska učinkovitost stavbe nam običajno pove, kakšna je raba energije na kvadratni meter uporabne talne površine stavbe v kWh/m^2 glede na postavljene cilje oz. tipične vrednosti v nekem podnebju. Nižja kot je potrebna energija za delovanje stavbe, bolj energijsko učinkovita je. Vsaka država je odgovorna za zagotovitev varne oskrbe z energijo. Z določanjem ciljev za izboljšanje energijske učinkovitosti stavb države zagotavljajo varnost pri oskrbi z energijo, namen pa je zmanjšati rabo energije in ohraniti kakovost bivanja v stavbah.

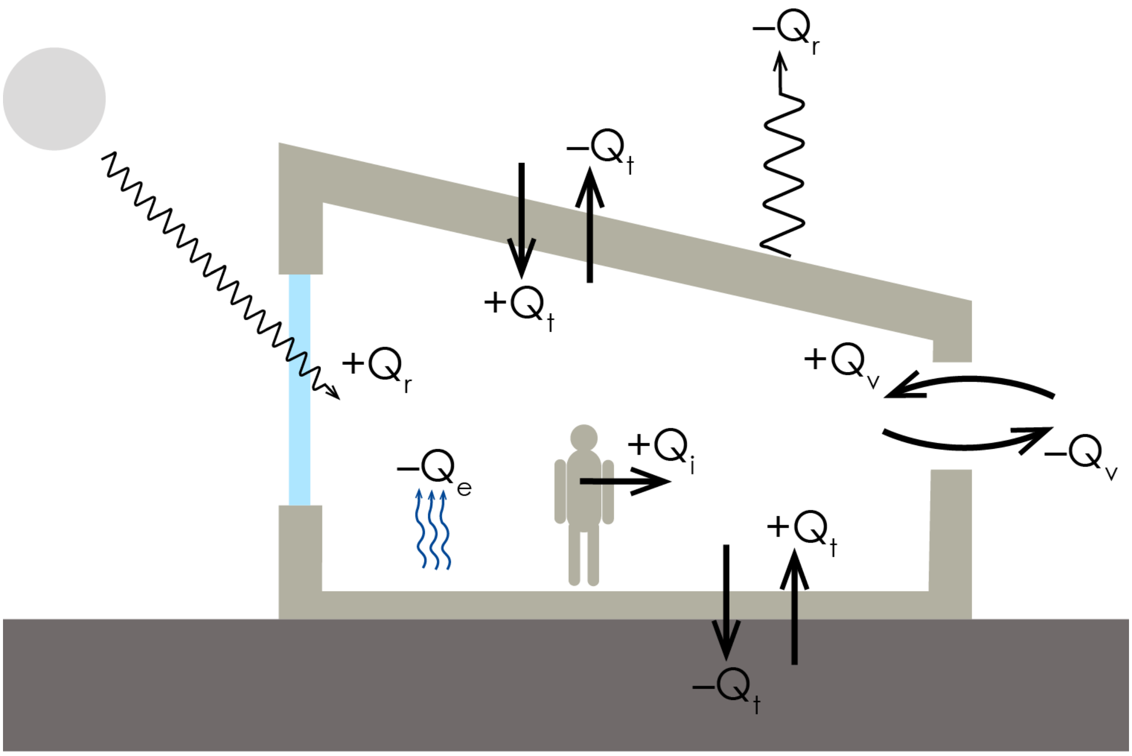
Pri načrtovanju stavb nas najprej zanimata potrebna energija za ogrevanje (Q_{NH}) in potrebna energija za hlajenje (Q_{NC}) stavbe, ki sta odvisni od geometrije stavbe, toplotno-tehničnih lastnosti ovoja, uporabe stavbe itd. V drugi fazi pa je pomembna učinkovitost sistemov stavbnih instalacij, k čemur spadajo sistem ogrevanja, hlajenja, prezračevanja, priprava tople sanitarne vode in razsvetljava. Ko je upoštevana tudi učinkovitost teh sistemov, govorimo o končni energiji oz. dovedeni energiji za delovanje sistemov (Q_f). Za namen raziskovalnega dela je bil obravnavan le del energijske učinkovitosti stavb, ki se nanaša na potrebno energijo za ogrevanje (Q_{NH}) in hlajenje (Q_{NC}) stavb. Le-ta je odvisen od geometrijsko-tehničnih lastnosti stavbe (npr. geometrija, toplotni upor ovoja, toplotnih in optičnih lastnosti oken ipd.) in uporabe stavbe (zasedenost, prezračevanje, senčenje ipd.), ne pa tudi od učinkovitosti sistemov stavbnih instalacij. Energijsko učinkovitost stavbe oz. učinkovitost, s katero se omeji ali prepreči prehod toplote iz stavbe in v stavbo, preverjamo z analizo toplotnega odziva stavb.

2.3.1 Toplotni odziv stavb

Stavbo lahko opišemo kot sistem, ki je v konstantni interakciji z okoljem, s katerim neprestano izmenjuje energijo (npr. toplota), snovi (npr. zrak) in informacije (npr. svetloba) [1]. Toplotni odziv stavbe lahko obravnavamo v stacionarnih pogojih, kjer so zunanji in notranji pogoji konstantni, lahko pa problem obravnavamo natančneje, pri čemer ugotavljamo dinamični (tj. nestacionaren) toplotni odziv stavbe in so notranji in zunanji pogoji časovno odvisni [55]. Pri slednjem se tako pogoji nenehno spreminjajo v letnih, sezonskih, dnevnih ali urnih ciklih. Vsako stavbo lahko podobno kot človeško telo obravnavamo kot toplotni sistem (slika 11), ki ga opišemo z enačbo 7 [55]:

$$\Delta S_b = +Q_i \pm Q_r \pm Q_t \pm Q_v - Q_e \quad (7)$$

Pri tem vrednost ΔS_b predstavlja toplotno bilanco stavbe, torej toplotni presežek ali primanjkljaj stavbe. Toplotno ravnovesje sistema je doseženo, ko je vsota vseh delov enačbe, torej vrednost ΔS_b, enaka nič. Če je vsota večja od nič, se temperatura znotraj stavbe dviga in obratno, če je vsota negativna, se stavba ohlaja. Če je v stavbi vrednost ΔS_b enaka ali blizu nič, je stavba v t. i. prostem teku in za doseganje toplotnega udobja ne potrebujemo dodatnega vložka ali odvzema toplote. V izrazu vrednost Q_i predstavlja toplotne dobitke notranjih virov. To je toplota, ki jo v prostor oddajajo ljudje, naprave in razsvetljava. Q_r ponazarja sevalne toplotne izgube in dobitke, pri čemer imajo poglavitno vlogo sončni dobitki toplote, ki jo skozi transparentne elemente v stavbo vnaša sončno sevanje. S Q_t označujemo transmisijske toplotne dobitke ali izgube, ki so posledica prehajanja toplote skozi ovoj stavbe (netransparentni in transparentni). Vrednost Q_v predstavlja prezračevalne oz. ventilacijske toplotne izgube in dobitke, ki so posledica izmenjave toplote med stavbo in okoljem, ki jo s seboj nosi topel zrak. Q_e predstavlja evaporacijske toplotne izgube, ki nastanejo pri izhlapevanju vode.



Slika 11: Shema toplotnih dobitkov in izgub v stavbi. Q_i – dobitki notranjih virov, Q_r – sevalne izgube in dobitki, Q_t – transmisijske izgube in dobitki, Q_v – prezračevalne izgube in dobitki, Q_e – evaporacijske izgube.
Figure 11: Scheme of heat gains and losses in a building. Q_i – internal heat gain, Q_r – radiative heat loss and gain, Q_t – transmission heat loss and gain, Q_v – ventilation heat loss and gain, Q_e – evaporation loss.

2.3.1.1 Dobitki notranjih virov

Notranji viri, ki jih označimo s Q_i, so vsota vse notranje proizvedene toplote. Le-ta se v stavbni toplotni sistem vnaša kot toplota, ki jo oddajajo ljudje, in je posledica metabolizma človeškega telesa, in tudi kot toplota, ki jo v stavbo oddajajo naprave in razsvetljava. Notranji viri so posledica uporabe stavbe in pri stanovanjskih stavbah običajno niso visoki. Nanje lahko vplivamo le minimalno z načrtovanjem uporabe stavbe in prerazporejanjem naprav po prostorih. Opišemo jih lahko s pomočjo enačbe 8 [55].

$$Q_i = \eta \cdot \sum_{i=1}^{n} (E_i \cdot n_i) \tag{8}$$

Pri tem je E_i moč i-tega notranjega toplotnega vira v W, n_i je časovno obdobje prisotnosti oziroma aktivnosti vira v urah, η pa predstavlja učinek toplotnih virov, ki opredeljuje, koliko se notranji viri toplote pretvorijo v toploto za ogrevanje stavb. Faktor η je odvisen od shranjevanja toplote v stavbi ter razmerja med toplotnimi dobitki in izgubami [133].

2.3.1.2 Sevalne izgube in dobitki

Sevalne toplotne izgube in dobitki (Q_r) so odvisni od sevalnega toplotnega toka na površinah stavbe. Glavni del sevalnih dobitkov predstavljajo sončni (solarni) toplotni dobitki (Q_s), zlasti del, ki v stavbo prehaja skozi transparentne elemente (okna) in notranjost ogreva s pomočjo pasivnega sončnega ogrevanja. Sončni dobitki predstavljajo dobršen del toplotnih dobitkov, nanje pa je moč vplivati z velikostjo transparentnih elementov, lastnostmi zasteklitve, orientacijo transparentnih elementov in senčenjem. Koliko sončne energije se skladišči v stavbnih elementih in koliko se je sprosti iz njih, je odvisno tudi od toplotne mase stavbe. Del sončnega sevanja, ki pade na transparentni element, se preseva (τ), del odbije (ρ), preostanek pa se v steklu vpije oz. absorbira (α). Vsota $\alpha + \tau + \rho$ je vedno enaka 1. Absorbirani del energije povzroči segrevanje stekla, ki nato del toplote izseva navznoter, del pa nazaj proti zunanjosti. S tem navznoter izsevani del energije prispeva k delu sončne energije, ki se skozi steklo preseva. Sončne dobitke toplotne energije lahko opišemo z enačbo 9 [55].

$$Q_s = \eta \cdot \sum_{i=1}^{n} (A_i \cdot I_i \cdot \theta_i) \tag{9}$$

Pri tem je A_i površina i-tega transparentnega elementa v m^2, I_i je globalno sončno obsevanje v ravnini transparentnega elementa v kWh/m^2 oz. MJ/m^2 v izbranem časovnem obdobju, θ_i predstavlja celotni del toplote sončnega sevanja, ki se preseva skozi steklo in izseva od stekla proti notranjosti. Faktor θ_i pogosto označujemo tudi kot g vrednost (*TSET – Total Solar Energy Transmittance*) ali pa s *SHGC* (ang. *Solar Heat Gain Coefficient*) in predstavlja razmerje med celotno presevano toploto sončnega sevanja in prejeto količino sončnega obsevanja v ravnini transparentnega elementa. η predstavlja učinek toplotnih virov, ki opredeljuje, koliko se sončni dobitki toplotne energije pretvorijo v toploto za ogrevanje stavb.

Sončno sevanje, ki obseva netransparentne dele stavbe, vpliva na površinsko temperaturo in posledični kondukcijski toplotni tok skozi stavbni ovoj ter sevalni toplotni tok v okolico. Višanje površinske temperature zaradi sončnega sevanja je odvisno od optičnih lastnosti površine, predvsem od sončne vpojnosti materiala (α_{sol}). Višja kot je α_s, več energije sončnega obsevanja sprejme površina in višja je površinska temperatura. Prejeta toplota na zunanji netransparentni površini se tako lahko opiše z enačbo 10:

$$Q_{sol} = I \cdot A \cdot \alpha_{sol} \tag{10}$$

kjer je Q_{sol} prejeta sončna toplota na površini elementa, I je globalno sončno obsevanje v ravnini elementa v kWh/m^2 oz. MJ/m^2, A površina elementa v m^2 in α_{sol} sončna vpojnost površine.

Vsa segreta telesa oddajajo toploto s pomočjo dolgovalovnega toplotnega sevanja, zato zunanja površina stavbe seva toploto v svojo okolico, kar predstavlja sevalne toplotne izgube. Največ toplote je izsevane v nebo, sevalni tok pa je močnejši v jasnem in suhem vremenu. Sevalni toplotni tok med površino elementa in okolico lahko opišemo z enačbo 11 [55].

$$\dot{q}_{rad} = A \cdot \sigma \cdot \varepsilon \cdot \left({T_1}^4 - {T_2}^4\right) \quad (11)$$

Kjer je A površina elementa v m^2, σ Stefan-Boltzmannova konstanta enaka 5,67 · 10^{-8} W/m^{2}K^4, ε efektivna emisivnost (odvisna od temperature), T_1 absolutna temperatura okolice v K in T_2 absolutna površinska temperatura elementa v K.
Skupni vpliv sončnega sevanja na netransparentne elemente ter vpliv sevalnih in kondukcijskih izgub s površin v okolico lahko opišemo s konceptom nadomestne površinske temperature na zunanji strani, imenovani sol-air temperatura, ki jo izračunamo z enačbo 12 [55].

$$T_{sa} = T_e + (G \cdot \alpha_{sol} - E_e) \cdot R_{se} \quad (12)$$

T_{sa} predstavlja temperaturo sol-air, T_e je temperatura zunanjega zraka, G je gostota moči sončnega sevanja v ravnini elementa v W/m^2, α_{sol} je vpojnost (absorptivnost) elementa (materiala) za sončno sevanje, E_e je sevalni toplotni tok s površine v okolico (npr. 20 W/m^2 pri oblačnem nebu in 90 W/m^2 pri jasnem nebu [55]), R_{se} pa je toplotni upor mejne prestopne zračne plasti na zunanji strani ($R_s = 1/h = 1/(h_c+h_s)$).
S pomočjo T_{sa} je tako možno poenostavljeno obravnavati vpliv sončnega in dolgovalovnega sevanja na kondukcijski toplotni tok skozi netransparentne elemente stavbnega ovoja. Na sevalne izgube lahko vplivamo s spreminjanjem emisivnosti površin.

2.3.1.3 Transmisijske izgube in dobitki

Transmisijske toplotne izgube in dobitki (Q_t) so posledica prehajanja toplote skozi stavbni ovoj (kondukcija); tako skozi transparentne kot netransparentne elemente. Toplota skozi ovoj stavbe prehaja zaradi razlike v temperaturi med notranjostjo in zunanjostjo. Transmisijske toplotne izgube in dobitke (Q_t) lahko opišemo z enačbo 13 [134, 135]:

$$Q_t = \left[\sum_{i=1}^{n}(A_i \cdot U_i) + \sum_{j=1}^{n}(\psi_j \cdot L_j) + \sum_{k=1}^{n}(\chi_k \cdot n_k)\right] \cdot \Delta T \cdot n \quad (13)$$

pri čemer je A_i površina i-tega elementa v m^2, U_i je toplotna prehodnost i-tega površinskega elementa v stavbnem ovoju v W/m^{2}K, ψ_j (v W/mK) in χ_k (v W/K) sta linijski in točkovni toplotni prehodnosti j-tega in k-tega linijskega oz. točkovnega elementa v stavbnem ovoju zaradi toplotnih nepravilnosti (toplotni most), L_j je dolžina j-tega toplotnega mostu v m, n_k število točkovnih toplotnih mostov, ΔT je razlika v temperaturi med notranjostjo in zunanjostjo ($T_i - T_e$) in n je časovno obdobje v urah. Z upoštevanjem, da je $T_e = T_{sa}$ iz enačbe 12, lahko poenostavljeno zaobjamemo tudi vpliv sevalnega prenosa toplote na transmisijske izgube skozi stavbni ovoj.

Toplotna prehodnost konstrukcijskega sklopa U_i je definirana kot toplotni tok q skozi 1 m^2 konstrukcijskega sklopa pri temperaturni razliki 1 K. Kljub temu, da se toplotni tok skozi stavbni ovoj zaradi nekonstantnih robnih pogojev dinamično spreminja, lahko za določevanje toplotnih lastnosti ovoja privzamemo stacionarno stanje [135]. U_i zato lahko v homogenih konstrukcijskih sklopih, pri katerih toplotni tok teče vzporedno z normalo površine, izračunamo z enačbami 14–16 [135].

$$U_i = \frac{1}{R_{tot}} \tag{14}$$

$$R_{tot} = R_{si} + \sum_{i=1}^{n} R_{\lambda,i} + R_{se} \tag{15}$$

$$R_{\lambda,i} = \frac{d_i}{\lambda_i} \tag{16}$$

R_{tot} je toplotna upornost celotnega konstrukcijskega sklopa v m^2K/W. R_{si} in R_{se} sta toplotni upornosti mejnih prestopnih zračnih plasti na notranji in zunanji strani konstrukcijskega sklopa ($R_s = 1/h = 1/(h_c+h_s)$). $R_{\lambda,i}$ je toplotni upor i-te plasti v konstrukcijskem sklopu, d_i debelina posamezne plasti v m in λ_i toplotna prevodnost posamezne plasti v W/mK.

Toplotne prehodnosti transparentnih elementov ovoja oz. oken (U_w) ne moremo izračunati po metodi, predstavljeni z enačbami 14–16, zlasti pri večslojnih zasteklitvah, pri čemer v vmesnih, s plinom polnjenih prostorih, izmenjava toplote poteka predvsem s sevanjem in konvekcijo. U_w definirajo toplotna prehodnost (U_g) in površina (A_g) zasteklitve, toplotna prehodnost (U_f) in površina (A_f) okvirja in linijska toplotna prehodnost (ψ_s) in dolžina (L_s) distančnika. U_w izračunamo z enačbo 17 [134, 135].

$$U_w = \frac{U_g \cdot A_g + U_f \cdot A_f + \psi_s \cdot L_s}{A_g + A_f} \tag{17}$$

Transmisijske izgube so poleg razlike med notranjo in zunanjo temperaturo (ΔT) in toplotne prehodnosti ovoja (U) odvisne tudi od površine posameznih elementov ovoja oz. površine toplotnega ovoja stavbe (A_{ovoj}), le-ta pa od oblike stavbe, ki jo lahko opišemo s faktorjem oblike f_0 (enačba 18).

$$f_0 = \frac{A_{ovoj}}{V} \tag{18}$$

Faktor oblike f_0 predstavlja razmerje med površino ovoja stavbe, ki je v stiku z zunanjostjo (A_{ovoj}), in bruto prostornino stavbe (V).

Ugotovimo, da na transmisijske izgube in dobitke lahko vplivamo s spreminjanjem faktorja oblike, in s tem velikostjo površin v stiku z zunanjostjo, ter s spreminjanjem toplotne prehodnosti stavbnega ovoja. Na transmisijske tokove pa lahko vplivamo tudi s spreminjanjem toplotne mase oz. toplotne kapacitete konstrukcij. Toplotna kapaciteta vpliva na fazni zamik nihanja med zunanjo in notranjo temperaturo zraka ter na temperaturno dušenje konstrukcijskega sklopa. Od toplotne kapacitete stavbe je odvisno skladiščenje oz. akumulacija toplote v stavbi in njenih elementih, le-ta pa vpliva na toplotno udobje in potrebe stavbe po ogrevanju in hlajenju. Za analizo vpliva akumulacije toplote je zato potrebna nestacionarna analiza toplotnega odziva stavbe, ki se običajno analizira v 24-urnem ciklu, znotraj katerega je treba upoštevati nihanje vrednosti zunanjih temperatur zraka in sončnega sevanja [135]. Približek spreminjanja notranje temperature zraka lahko opišemo s periodično funkcijo povprečne dnevne temperature notranjega zraka $\overline{T_i}$ in amplitude nihanja notranje temperature $A_{T,i}$ v enačbi 19 [135]:

$$T_{i,t} = T_{i,avg} + A_{T,i} \cdot \cos\left(\frac{2\pi}{P} \cdot t\right) \tag{19}$$

pri čemer je $T_{i,t}$ temperatura notranjega zraka v trenutku t, $T_{i,avg}$ je povprečna dnevna temperatura notranjega zraka v °C, $A_{T,i}$ je amplituda nihanja temperature notranjega zraka v °C, P je trajanje periode (24 ur) in t je čas opazovanega trenutka v urah.
Količina akumulirane toplote v materialu v prvih dvanajstih urah opazovanja (prejemanje toplote) je enaka količini sproščene toplote v naslednjih dvanajstih urah (ohlajanje konstrukcijskega sklopa) in je odvisna od nihanja (amplitude) notranje temperature zraka $A_{T,i}$ in od fizikalnih lastnosti materialov v obravnavanem konstrukcijskem sklopu [135]. Količino akumulirane toplote Q_{acc} lahko opišemo z enačbo 20 [136, 137].

$$Q_{acc} = \sqrt{\frac{P}{2\pi} \cdot \lambda \cdot \rho_m \cdot c_p \cdot \left(\frac{\cosh\left(2d \cdot \sqrt{\frac{\pi \rho_m c_p}{P\lambda}}\right) - \cos\left(2d \cdot \sqrt{\frac{\pi \rho_m c_p}{P\lambda}}\right)}{\cosh\left(2d \cdot \sqrt{\frac{\pi \rho_m c_p}{P\lambda}}\right) + \cos\left(2d \cdot \sqrt{\frac{\pi \rho_m c_p}{P\lambda}}\right)} \right)} \cdot A_{T,i} \cdot A_i = DHC_i \cdot A_{T,i} \cdot A_i \tag{20}$$

P predstavlja periodo 24 ur v sekundah, λ je toplotna prevodnost snovi v W/mK, ρ_m je gostota snovi v kg/m^3, c_p je specifična toplota snovi v J/kgK, d je debelina sloja v m, $A_{T,i}$ je amplituda nihanja temperature notranjega zraka v K in A_i je površina elementa, v katerem se akumulira toplota. Z DHC_i označimo dnevno toplotno kapaciteto konstrukcijskega sklopa (ang. *diurnal heat storage capacity*) v kJ/m^{2}K.
Vpliv toplotne kapacitete in skladiščenja toplote v delih stavbe je najbolj očiten v okoljih, v katerih zaznamo visoka temperaturna nihanja med dnevom in nočjo. S pomočjo učinka toplotne mase lahko uravnavamo, v katerem delu dneva se sprošča v konstrukciji akumulirana toplota, s čimer lahko opazno vplivamo na toplotno udobje in rabo energije v stavbi.

2.3.1.4 Prezračevalne izgube in dobitki

Prezračevalne oz. ventilacijske izgube in dobitki (Q_v) nastanejo pri konvekcijski izmenjavi zraka med notranjostjo stavbe in okolico. Pozimi tako topel zrak zapusti stavbo, vstopi pa nov, svež in hladen zrak, ki se mora segreti na udobno temperaturo. Poleti je situacija ravno obratna. Stopnja in način prezračevanja stavbe sta posledica njene uporabe in zagotavljanja kakovostnega zraka, pri čemer je treba stavbe, ki so bolj zasedene, tudi intenzivneje prezračevati [1]. V splošnem se pojem prezračevanje nanaša na tri procese v stavbah, ki služijo različnim namenom [55]. Prvi namen je dovajanje svežega zraka in odstranitev vonjav ter odvečnega CO_2. Drugi, prezračevanje se uporablja za odvajanje odvečne toplote, če je, denimo, zunanja temperatura nižja od notranje. In tretji, stavbe prezračujemo, da bi ustvarili gibanje zraka, ki poveča odvajanje toplote s površine človeške kože, s tem pa človekovo telo v vročih dneh lažje uravnava toplotno bilanco. Načeloma poznamo dve vrsti prezračevanja: nadzorovano in nenadzorovano (infiltracijo). Pri nadzorovanem prezračevanju lahko uporabljamo naravno prezračevanje, ki ga dosežemo z odpiranjem oken in preostalih odprtin, zrak med stavbo in okolico pa se izmenja zaradi tlačnih razlik (npr. prečno prezračevanje). Primer nadzorovanega prezračevanja je tudi mehansko prezračevanje, pri katerem notranji zrak s pomočjo prezračevalnega sistema in naprav prisilno izmenjamo z zunanjim. Primer nenadzorovanega prezračevanja je infiltracija zunanjega zraka, do katere pride zaradi netesnosti stavbnega ovoja in tlačnih razlik med notranjostjo in zunanjostjo. Tako so prezračevalne izgube odvisne od dejavnikov, kot so velikost odprtin v stavbnem ovoju, njihove orientacije glede na smer vetra, zrakotesnost stavbnega ovoja, stopnja izmenjave zraka ipd. Opišemo jih lahko z enačbo 21 [55, 134].

$$Q_v = \rho \cdot c_p \cdot \frac{ACH}{3600} \cdot V_{net} \cdot \Delta T \cdot n \tag{21}$$

ρ je gostota zraka v kg/m^3, c_p je specifična toplota zraka v J/kgK, ACH je število izmenjav zraka na uro v h^{-1}, V_{net} je neto prostornina stavbe v m^3, ΔT predstavlja temperaturno razliko med notranjostjo in zunanjostjo ($T_i - T_o$) v K in n je časovno obdobje v urah.

2.3.1.5 Evaporacijske izgube

Evaporacijske izgube so posledica absorpcije latentne toplote pri spremembi agregatnega stanja vode iz tekočega v plinasto (izparevanje). Pri tem se toplota porabi za spremembo faze vode. Evaporacijske izgube lahko predstavljajo dobršen del v toplih in vročih podnebjih, kjer je nizka tudi relativna vlažnost zraka. Za izparevanje 1 kg vode se porabi kar 2257 kJ energije [55]. Evaporacijske izgube so načeloma zelo nizke v hladnejših in vlažnih okoljih, kjer je zrak že močno nasičen z vodno paro. Ker ima evaporacija večinoma zelo majhen vpliv na toplotni odziv stavb, se le-ta pri izračunih in simulacijah pogosto ne upošteva in se njen vpliv zanemari.

2.3.1.6 Simulacije toplotnega odziva stavb

Danes za analizo toplotnega odziva stavb najpogosteje uporabljamo računalniške simulacije, s katerimi opisujemo fizikalne procese v stavbi. Pri tem sta pomembna opis in definicija realnega primera stavbe z energijskim modelom stavbe, pri katerem določimo spremenljivke notranjega in zunanjega okolja ter definiramo robne pogoje in poenostavitve nekaterih procesov. S tem fizični model stavbe opišemo z matematičnim modelom, ki je običajno analitičen, lahko pa obsega tudi nekatere numerične približke. Simulacijska orodja z dinamično metodo navadno toplotni odziv simulirajo z urno ali manjšo natančnostjo, ločeno za vsako toplotno cono v stavbi. Običajno se za simulacije toplotnega odziva stavb uporabljajo podnebne datoteke, v katerih so zapisani celoletni podnebni podatki z urno natančnostjo npr. TMY in TRY. Pri modeliranju se natančno opišejo in simulirajo dinamične interakcije med vsemi stavbnimi elementi, povezanimi s toplotnim udobjem in rabo energije. Metoda simulacije toplotnega odziva stavb z urno natančnostjo temelji na ravnovesju povprečnih toplotnih tokov v urnih intervalih [135]. Tako je moč natančneje opisati vpliv spreminjajočih se robnih pogojev in učinek akumulacije energije v stavbi in njenih elementih. V tem primeru toplotni tok na zunanji in notranji strani stavbnega ovoja ni enak, za izračun pa so potrebni vsi materialni podatki, ne le toplotna prehodnost konstrukcijskega sklopa. Dinamični pogoji vplivajo tudi na temperaturo notranjega zraka, ki se tako iz trenutka v trenutek spreminja oz. se spreminjajo potrebe po toploti za ogrevanje in hladu za hlajenje prostorov. V najpreprostejši obliki lahko toplotni odziv vozlišča (ang. *node*) v stavbi opišemo z enačbo 22, ki definira temperaturo notranjega zraka v naslednjem časovnem koraku [135].

$$\frac{C_m}{\Delta t} \cdot T_{i,t} + \sum_{j=1}^{n} A_j \cdot h_{c+s,j} \cdot \left(T_{i,t} - T_{si,j,t}\right) + \rho_a \cdot c_{p,a} \cdot \dot{q}_v \cdot \left(T_{i,t} - T_{e,t}\right) = \frac{C_m}{\Delta t} \cdot T_{i,t-1} + \dot{Q}_i + \dot{Q}_{sol} + \dot{Q}_{sys} \tag{22}$$

C_m je toplotna kapaciteta stavbe v J/K, Δt je časovni korak v sekundah, $T_{i,t}$ je temperatura notranjega zraka v trenutku t v K, A_j je površina j-tega elementa stavbnega ovoja, $h_{c+s,j}$ je skupen (konvekcijski in sevalni) prestopni količnik mejne zračne plasti j-tega elementa stavbnega ovoja v W/m^{2}K, $T_{si,j,t}$ je površinska temperatura na notranji strani j-tega elementa stavbnega ovoja v trenutku t v °C, ρ_a je gostota zraka v kg/m^3, c_p je specifična toplota zraka v J/kgK, $\dot{q}_v$ je stopnja prezračevanja v m^3/h, $T_{e,t}$ je temperatura zunanjega zraka v trenutku t v °C, $T_{i,t-1}$ je temperatura notranjega zraka v prejšnjem časovnem koraku (v trenutku t–1) v °C, $\dot{Q}_i$ je povprečni toplotni tok notranjih virov v obravnavanem časovnem obdobju v W, $\dot{Q}_{sol}$ je povprečni toplotni tok sončnih dobitkov v obravnavanem časovnem obdobju v W in $\dot{Q}_{sys}$ je povprečen toplotni tok, ki je vnesen v stavbo ali vzet iz stavbe, z namenom doseči toplotno ravnovesje v obravnavanem časovnem obdobju v W.

Če je stavba v prostem teku in ni ogrevana ali hlajena, je $\dot{Q}_{sys}$ enak nič in lahko s pomočjo enačbe 22 izračunamo $T_{i,t}$. Ko je stavba ogrevana ali hlajena, je $T_{i,t}$ definirana s pomočjo nastavljene želene vrednosti (ang. *set-point*) temperature notranjega zraka. Takrat je v primeru ogrevanja $\dot{Q}_{sys} > 0$, v primeru hlajenja pa je $\dot{Q}_{sys} < 0$. S pomočjo enačb 23 in 24 lahko izračunamo potrebno energijo za ogrevanje (Q_{NH}) in hlajenje (Q_{NC}) stavbe.

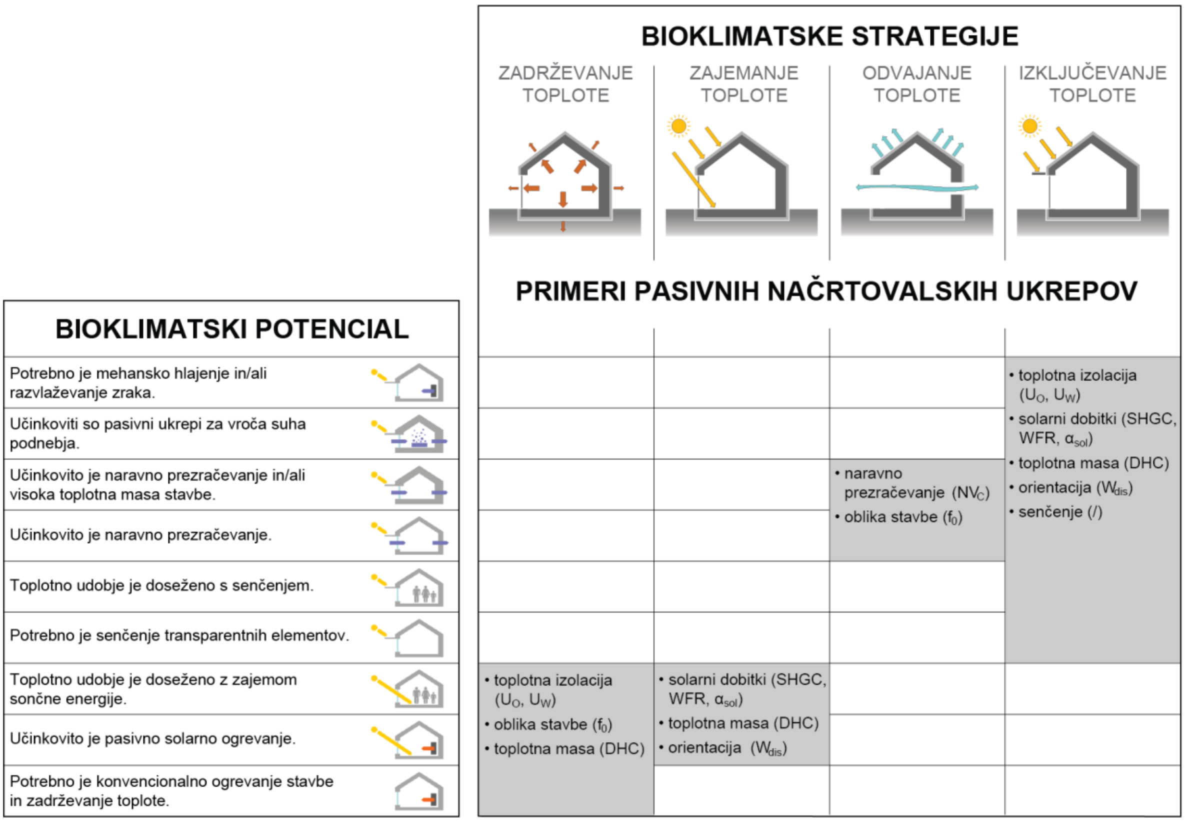
$$Q_{NH} = \dot{Q}_{sys} \cdot \Delta t, \quad \dot{Q}_{sys} > 0 \tag{23}$$

$$Q_{NC} = \dot{Q}_{sys} \cdot \Delta t, \quad \dot{Q}_{sys} < 0 \tag{24}$$

V zadnjih desetletjih so z napredkom računalniških orodij z namenom zmanjšanja zapletenosti osnovnih algoritmov in krajšega časa, potrebnega za izračune, močno napredovale tudi simulacije toplotnega odziva stavb. Glede na metodo izračuna lahko orodja za simulacijo toplotnega odziva stavb razdelimo na tista s poenostavljeno (statično) metodo in tista z natančno (dinamično) metodo. Orodja, ki uporabljajo dinamično metodo izračuna z visoko natančnostjo, za izračun toplotnega odziva in energijskih potreb stavbe navadno uporabljajo metodo končnih razlik (MKR, ang. *finite difference method* – FDM), metodo končnih elementov (MKE, ang. *finite element method* – FEM) ali metodo robnih elementov (MRE, ang. *boundary element method* – BEM). Kot pogosteje uporabljana poznamo orodja, kot so EnergyPlus, TRNSYS, IDA ICE ipd. [1]. Orodje EnergyPlus je zbirka številnih programskih modulov, ki sodelujejo pri izračunu energije, potrebne za ogrevanje in hlajenje stavbe z uporabo različnih sistemov in virov energije [138], pri čemer se najpogosteje uporabljata metodi CTF (ang. *conduction transfer function*) in FDM.

2.3.2 Bioklimatske strategije in pasivni ukrepi

Kot smo spoznali v poglavju 2.2.2.2 lahko s pomočjo bioklimatskega potenciala lokacije določimo, katere bioklimatske strategije in pripadajoči ukrepi nam lahko služijo pri bioklimatskem načrtovanju stavb, da bi v stavbi dosegli toplotno udobje uporabnikov ob čim nižji rabi energije. Poznamo štiri bioklimatske strategije, s katerimi uravnavamo izmenjavo energije med stavbo in okoljem (slika 12) [1].



Slika 12: Bioklimatski potencial, bioklimatske strategije in pasivni načrtovalski ukrepi za načrtovanje stavb ter povezava med njimi (na podlagi Košir [1]).

Figure 12: Bioclimatic potential, bioclimatic strategies and passive design measures for building design and the relation between them (based on Košir [1]).

Pri strategiji zadrževanja toplote želimo zmanjšati toplotne izgube skozi stavbni ovoj in jo uporabljamo takrat, ko stavba zaradi temperaturnih razlik izgublja toploto v okolje. Strategija zadrževanja toplote je še posebej pomembna v hladnih podnebjih. Če želimo v stavbi zadržati toploto, lahko kot pasivni ukrep spreminjamo (slika 12): toplotno izolativnost stavbnega ovoja (npr. U_O – toplotna prehodnost netransparentnih elementov, U_W – toplotna prehodnost transparentnih elementov), obliko stavbe (npr. f_0 – faktor oblike stavbe), toplotno kapaciteto/maso stavbnega ovoja (npr. *DHC*), zrakotesnost stavbnega ovoja ali organizacijo prostorov v stavbi [1].

Pri strategiji zajemanja toplote želimo v stavbo zajeti čim več toplote, s katero ogrejemo prostore. Najpogosteje izkoriščamo sončno energijo oz. sončne dobitke, lahko pa koristimo tudi geotermalno energijo. Uporabljamo jo takrat, ko stavba zaradi temperaturnih razlik izgublja toploto v okolje in se zato ohlaja. Učinkovitost zajema sončne energije je sicer nizka pri ekstremno nizkih zunanjih temperaturah zraka, pri katerih so toplotne izgube v okolje visoke, razpoložljivega sončnega sevanja pa je malo. Če želimo v stavbo vnesti toploto sončnega sevanja, lahko kot pasivni ukrep spreminjamo (slika

12): sončne dobitke, pri čemer imajo glavno vlogo parametri, kot so prepustnost stekla za sončno sevanje (npr. *SHGC*), delež zasteklitve v stavbnem ovoju (npr. razmerje med površino oken v ovoju in tlorisno površino stavbe *WFR*, ang. *window to floor ratio*) in vpojnost (absorptivnost) stavbnega ovoja za sončno sevanje (npr. α_{sol}), toplotno kapaciteto/maso stavbe, (npr. *DHC*) in orientacijo stavbe oz. razporeditve prostorov in površin (npr. W_{dis} – razporeditev oken glede na orientacijo fasade) [1]. Poleg naštetega lahko uporabimo tudi posredni zajem sončne energije, in sicer v obliki zimskega vrta, Trombe-Michelove stene, strešnega bazena, termosifona ipd. [1].

S strategijo odvajanja toplote želimo vso odvečno toploto v stavbi odvesti v okolje in s tem znižati temperaturo v notranjosti stavbe. Uporabljamo jo takrat, ko se stavba segreva, hkrati pa imamo možnost toploto odvesti v ponore energije v okolju. Učinkovitost strategije je odvisna predvsem od podnebnih in okolijskih dejavnikov, pri čemer je le-ta nižja v podnebjih z višjimi temperaturami zraka in neučinkovitimi ponori energije (npr. ob visoki vlažnosti, pogosti oblačnosti ipd.). Kadar želimo iz stavbe odvesti toploto, lahko kot pasivni ukrep spreminjamo (slika 12): stopnjo naravnega prezračevanja (npr. hlajenje z naravnim prezračevanjem NV_C s spreminjanjem parametra *ACH*), obliko stavbe (npr. f_0 – faktor oblike stavbe), sevalne izgube z zunanjih površin stavbe (npr. emisivnost) in evaporacijske izgube [1]. Poleg tega lahko toploto odvajamo iz stavbe tudi z izmenjavo toplote z zemljino, z uporabo vetrnih stolpov, strešnega bazena ipd. [1].

Četrta strategija je izključevanje toplote, s čimer želimo popolnoma izključiti ali zmanjšati toplotne dobitke, ki iz zunanjosti prehajajo v stavbo. Pri tem želimo uravnavati tako transmisijske pritoke toplote, kot tudi prezračevalne in sončne dobitke. Učinkovitost strategije raste z višanjem zunanjih temperatur zraka in intenziteto sončnega sevanja. Če želimo preprečiti vstop toplote v stavbo, lahko kot pasivni ukrep spreminjamo (slika 12): toplotno izolativnost stavbnega ovoja (npr. U_O in U_W), sončne dobitke, pri čemer imajo glavno vlogo senčenje stavbe in parametri, kot so prepustnost stekla za sončno sevanje (npr. *SHGC*), delež zasteklitve v stavbnem ovoju (npr. *WFR*) in vpojnost ovoja za sončno sevanje (npr. α_{sol}), toplotno kapaciteto/maso stavbe (npr. *DHC*), orientacijo stavbe oz. razporeditve prostorov in površin (npr. W_{dis}) ter zrakotesnost stavbe [1].

2.3.3 Pregled znanstvenega področja

V Evropski uniji (EU) ogrevanje in hlajenje v stavbah in industriji pomenita polovico rabe energije. Samo ogrevanje in oskrba s toplo sanitarno vodo v stanovanjskih stavbah skupaj predstavljata 79 % celotne končne rabe energije stanovanjskega sektorja [139]. Trenutno sicer hlajenje stanovanjskih stavb v EU predstavlja manjši delež celotne rabe energije, vendar pa potreba po hlajenju notranjih prostorov v poletnem času narašča [139] in pričakuje se, da se bo v prihodnjih desetletjih zaradi predvidenih podnebnih sprememb še opazno povečala. Zato je EU zvišala število javnih sredstev, ki so na voljo za izboljšanje energijske učinkovitosti [140], poleg tega pa državam članicam EU zagotovila pravno podlago za določanje stroškovno optimalnih minimalnih zahtev glede energijske učinkovitosti novih stavb [40]. Kot rezultat izpolnjevanja ciljev EU se energijska učinkovitost stavb in v stavbe vgrajenih sistemov v EU nenehno izboljšuje [141]. Kljub temu je po mnenju Guo in sod. [142] pri rabi energije v stavbah med različnimi državami opaziti očitne vrzeli pri uspešnosti energijske učinkovitosti, predvsem zaradi socialno-ekonomskih razlik in energetske politike, ki se od države do države razlikujejo. Trendi naraščanja rabe energije in vrzeli v zmogljivosti stavb so v stroki spodbudili iskanje stroškovno optimalnih rešitev za izboljšanje učinkovitosti rabe energije v stavbah. Medtem ko so v poslovnih in industrijskih stavbah priporočljive in pogosto uporabljane visokotehnološke rešitve, so v stanovanjskih stavbah običajno cenovno ugodnejše »nizkotehnološke« in preproste rešitve. Takšne rešitve so za vlagatelje in lastnike glede na višino investicije pogosto sprejemljivejše. Energijsko učinkovitost stavb je mogoče izboljšati s povečanjem učinkovitosti pasivnih (npr. oblika stavbe, ovoj stavbe itd.) ali aktivnih (npr. sistem HVAC, PV sistemi itd.) stavbnih elementov in sistemov. Kot smo spoznali v prejšnjih poglavjih, se pri optimizaciji pasivnih elementov stavbe pogosto uporablja koncept bioklimatskega načrtovanja, s katerim stavbo prilagodimo podnebnim razmeram. Z bioklimatskim načrtovanjem in uporabo pasivnih načrtovalskih ukrepov je v stavbah mogoče doseči višjo raven energijske učinkovitosti in toplotnega udobja [143,144]. Dobra lastnost nekaterih pasivnih načrtovalskih ukrepov, kot sta na primer orientacija stavbe in naravno prezračevanje, je, da za celotni projekt med načrtovanjem in gradnjo pomenijo malo ali nič dodatnih stroškov. Pri drugih pasivnih ukrepih je priporočljiva analiza koristi in obremenitev, s katero ocenimo sprejemljivost posamezne rešitve glede na stroške gradnje oz. vgradnje in kasnejše prihranke energije. Po drugi strani je pomanjkljivost pasivnih načrtovalskih ukrepov v tem, da so nekateri elementi togi in jih je po izgradnji stavbe zelo težko spreminjati. Na primer, kakršne koli spremembe v obliki stavbe, razporeditvi oken ali zasteklitvi zahtevajo obsežne posege v stavbo ali njen ovoj. Zato so takšni posegi vedno zahtevni in navadno dragi. Če stavba ni ustrezno zasnovana in trajnostno prilagojena podnebju in predvideni uporabi, lahko ob podnebnih spremembah pasivni elementi za stavbe pomenijo vgrajeno tveganje. Na splošno lahko pasivne ukrepe razdelimo v štiri glavne bioklimatske strategije: zadrževanje toplote, zajemanje toplote, odvajanje toplote in izključevanje toplote (slika 12). Kot poudarjajo Olgyay [56], Szokolay [55] in Košir [1], mora izbira ustreznih pasivnih ukrepov pri načrtovanju stavb vedno sloneti na podnebnih in lokacijskih značilnostih. Glede prilagajanja podnebju je za energijsko učinkovitost stavb v zadnjem času postala pomembna tudi podnebna odpornost stavb. Na tej točki je zato nujno razumeti, da ob trenutnem trendu globalnega segrevanja številni bioklimatski ukrepi, ki so bili nekoč na neki lokaciji stroškovno optimalna rešitev, v prihodnosti morda ne bodo več optimalni. Kot primer vzemimo situacijo, ko lahko z naraščajočimi temperaturami na nekaterih lokacijah ukrepi za izključevanje toplote (npr. manjša površina zasteklitve, učinkovito senčenje itd.) postanejo pomembnejši kot ukrepi za zajemanje toplote (npr. velike zastekljene površine za pasivno sončno ogrevanje), ki so bili ustreznejši v hladnejšem podnebju v preteklosti. Skrb vzbujajoče napovedane učinke globalnega segrevanja v 21. stoletju bi lahko vsaj delno ublažili z ustreznim in podnebno prilagojenim načrtovanjem, pri čemer je treba upoštevati trend predvidenih podnebnih sprememb.

Da bi bilo bioklimatsko načrtovanje stavb učinkovito, je treba razmisliti o možnosti prilagoditve stavb ne le trenutnemu podnebju, ampak tudi prihodnjim podnebnim stanjem. Skarbit in sod. [145] navajajo, da opazovanje podnebja in podnebni modeli kažejo na to, da bo podnebje v tem stoletju postalo toplejše in bolj suho. Obseg predvidenih podnebnih sprememb je sicer odvisen od scenarija, uporabljenega v modelih podnebnih sprememb. Medvladni odbor za podnebne spremembe (IPCC) je uvedel več scenarijev o globalnem segrevanju, ki zajemajo različna predvidena tehnološka, demografska, gospodarska, družbena in politična dogajanja po vsem svetu, in so predstavljeni v poglavju 2.2.1.2. Trenutno je precej negotovo, kateri scenarij se bo sčasoma odvil, če sploh kateri od predvidenih [146]. Kljub temu pa ob opazovanju predvidenih izidov scenarijev skupin SRES in RCP postane očitno, da do konca 21. stoletja vsi scenariji predvidevajo toplejše podnebje. S pomočjo scenarijev podnebnih sprememb ter podatkov in modelov o trenutnem podnebju lahko z zvezno transformacijo (ang. *morphing*) ustvarimo projicirane podnebne datoteke. S postopkom se ustvari vremenska časovna zaporedja, ki zajemajo povprečne vremenske razmere prihodnjih podnebnih scenarijev, hkrati pa ohranjajo realistične vremenske vzorce iz podatkov, pridobljenih z meteorološkimi opazovanji [147]. Z uporabo te metode se podatki z manjšo ločljivostjo iz modelov podnebnih sprememb s statističnimi metodami prevedejo v informacije natančnih prostorskih in časovnih ločljivosti. Le-ti so potrebni za izvedbo simulacij toplotnega odziva stavbe. S tem pridobimo podnebne datoteke, s katerimi lahko toplotni odziv stavbe simuliramo v projiciranem prihodnjem podnebnem stanju. Nekaj primerov metod zvezne transformacije so predstavili Belcher in sod. [147], Jentsch in sod. [148], Arima in sod. [149], Soga [150] in Jiang in sod. [151]. Tako pri scenarijih RCP (npr. Spinoni in sod. [152]), kot SRES (npr. Berardi in Jafarpur [24]) simulacije rabe energije v stavbah predvidevajo zmanjšanje potrebe po ogrevanju in povečanje potrebe po hlajenju stavb. Tudi v bolj optimističnih podnebnih scenarijih, kot je npr. RCP2.6, ki do konca stoletja v povprečju predvideva povečanje globalne površinske temperature za 1 °C, bo večina mest najverjetneje imela precej drugačno podnebje kot danes [26] ali pa bodo mesta podvržena ekstremnim razmeram, ki jih trenutno ni v nobenem večjem mestu, kot trdijo Bastin in sod. [153].

Jiang in sod. [151] so poudarili, da je uporaba projiciranih podnebnih podatkov o stanju podnebja v prihodnosti ključna za preučevanje vpliva podnebnih sprememb na stavbe. Bistveni pogled na problem so predstavili Zhou in sod. [154], ki so poudarili, da podnebne spremembe geografsko heterogeno vplivajo na potrebo po ogrevanju in hlajenju stavb. Opravljene so bile številne raziskave, ki so ocenjevale energijsko učinkovitost stavb glede na pričakovano prihodnje podnebje. Vse so soglasno ugotovile, da bo posledica segrevanja ozračja povečanje potrebe po hlajenju in zmanjšanje potrebe po ogrevanju stavb [155]. Primer takšne raziskave so na vzorcu stanovanjskih stavb v Argentini predstavili Flores-Larsen in sod. [156]. Pokazali so opazno zmanjšanje potrebe po energiji za ogrevanje in povečanje potrebe po energiji za hlajenje stavb. V tem okviru so bili kot najučinkovitejši pasivni načrtovalski ukrepi za preprečevanje učinkov podnebnih sprememb na stavbe prepoznani senčenje, zmanjšanje neposrednih sončnih dobitkov in naravno prezračevanje. Nadalje so Andrić in sod. [157] pokazali, da naj bi bilo predvideno zmanjšanje potrebe po ogrevanju stavb v toplih podnebjih vidnejše kot v hladnih. Zhai in Helman [96] pa sta navedla, da se bo skupna raba energije v stavbah povečala predvsem zaradi velikega povečanja potrebe po hladilni energiji. Tudi Kishore [158] je navedel podobne ugotovitve v primeru tipične stanovanjske stavbe, ki jo je na podlagi podnebnih sprememb obravnaval v različnih projiciranih podnebnih stanjih v petih glavnih podnebjih Indije. Pokazal je, da lahko v indijskih stanovanjskih stavbah pasivni načrtovalski ukrepi zmanjšajo pričakovano letno hladilno obremenitev za približno 50 do 60 %. Pérez-Andreu in sod. [159] so ugotovili, da v njihovi raziskavi, ki obravnava pasivne in aktivne ukrepe v tipični sredozemski stanovanjski stavbi v različnih scenarijih podnebnih sprememb, ima in bo imelo najbolj zanemarljiv vpliv prezračevanje. Nasprotno pa so ugotovili, da bosta v prihodnosti večja toplotna izolativnost in zrakotesnost stavbnega ovoja pomembneje vplivala na energijsko učinkovitost stavb. Podobno sta Rodrigues in Fernandes [25] izvedla statistično primerjavo naključnih modelov dvonadstropnih družinskih stavb z različnimi toplotnimi prehodnostmi ovoja (*U* vrednostmi) za sedanje in prihodnje predvidene podnebne razmere na šestnajstih lokacijah na območju Sredozemlja. Ugotovila sta, da naj bi bilo v prihodnosti za več lokacij še vedno učinkovito nadaljnje zmanjševanje *U* vrednosti stavbnega ovoja. Potrebe po energiji v prihodnjih podnebnih stanjih so ocenili tudi Ciancio in sod. [160] za primer hipotetične trinadstropne stanovanjske stavbe, postavljene in simulirane v 19 evropskih mestih. Poudarili so, da se običajno potrebna energija za ogrevanje stavb v severnih mestih zmanjšuje, medtem ko naj bi se potrebna energija za hlajenje v južni Evropi povečala. Gercek in Arsan [161] sta za primer Turčije navedla, da so najbolj kritični parametri glede energijske učinkovitosti stanovanjskih stavb povezani s transparentnimi površinami stavbnega ovoja. Podobno so Harkouss in sod. [162] izvedli optimizacijo pasivnih ukrepov za načrtovanje energijsko učinkovitih stanovanjskih stavb v trenutnem podnebju. Pokazali so, da je med parametri, kot so razmerje med površino oken in površino zunanjih sten (ang. *window to wall ratio*, *WWR*), *U* vrednost ovoja in vrsta zasteklitve, najpomembnejša *U* vrednost stavbnega ovoja, ki naj bo v hladnem in zmernem podnebju nizka (npr. $U = 0{,}2$ W/m^{2}K), v vročem podnebju pa je lahko višja (npr. $U = 0{,}6$ W/m^{2}K). Tudi Moazami in sod. [29] so uspešno pokazali robusten pristop k ocenjevanju energijske učinkovitosti stavb v okviru predvidenih podnebnih sprememb. Podoben pristop, pri katerem je bila energijska učinkovitost stavb ocenjena glede na projekcije podnebja v prihodnosti, so predstavili Shen in Lior [32] in Shen [163] v ZDA, Yu in sod. [164] ter Cao in sod. [165] na Kitajskem, Nik [166] v Italiji in na Švedskem, Díaz-López in sod. [167] v Španiji, van Hooff in sod. [168,169] ter Hamdy in sod. [170] na Nizozemskem, Berger in sod. [171] v Avstriji in Yang in sod. [172] za večji del Evrope. Navedene raziskave so obravnavale energijsko učinkovitost različnih vrst stavb (npr. pisarniške, stanovanjske itd.). Toplotni odziv stavb je bil ocenjen glede na sedanje in/ali prihodnje podnebne projekcije. Obravnavani so bili pasivni in/ali aktivni ukrepi za doseganje energijske učinkovitosti stavb. Številne raziskave (kot na primer van Hoof in sod. [169] in Hamdy in sod. [170]) so preučevale potencial uporabe pasivnih ukrepov (npr. senčil) v starejših stavbah. Berger in sod. [171], Cao in sod. [165] in Pierangioli in sod. [173] so poudarili, da bo treba stavbe, ki so pretežno zasnovane za ogrevalno sezono, naknadno opremiti v skladu s predvidenimi dodatnimi potrebami po hlajenju. V tem kontekstu so Li in sod. [174] navedli, da bodo podnebne spremembe imele najpomembnejši vpliv v toplejših podnebjih, kjer prevladuje potreba po hlajenju, in da bo v močno hladnih podnebjih prevladovalo zmanjšanje povpraševanja po ogrevanju nad skromnim povečanjem potrebe po hlajenju v poletnem času. Shen in sod. [175,176] so predlagali optimizacijsko metodo za energijsko prenovo stavbe kampusa v ZDA z upoštevanjem vpliva podnebnih sprememb, za katero je bilo pridobljenih več kot tisoč Pareto front. Uporabljali so spremenljivke, kot so *U* vrednost, vrsta zasteklitve, stopnja naravnega prezračevanja in stopnja infiltracije zraka, učinkovitost ogrevalnih in hladilnih sistemov, uporaba sistemov za koriščenje obnovljivih virov energije itd. Opravljene so bile številne raziskave glede optimizacije rabe energije in obratovanja stavb, vendar pa učinki podnebnih sprememb v raziskavah niso bili upoštevani. Nekaj primerov podobnih raziskav so predstavili še Robic in sod. [177], Chiesa in sod. [178], Gou in sod. [179] in Ciardiello in sod. [180]. V ugotovitvah omenjenih raziskav poudarjajo, da je v optimizacijo energijske učinkovitosti stavbe nujno treba vključiti velik nabor spremenljivk, saj so optimalni parametri odvisni od lokacije. Jordan in sod. [181] so s simulacijami poslovne stavbe v Sloveniji (Ljubljana) pokazali, da je glede na rabo energije za ogrevanje in hlajenje za doseganje toplotnega udobja optimalen *WWR* okrog 36 % celotne fasade. Zmanjšanje tega razmerja se je izrazilo v večji skupni rabi energije za ogrevanje in hlajenje. Maučec in sod. [182] so izdelali občutljivostno analizo parametrov, ki vplivajo na rabo energije lesene stavbe na treh lokacijah: v Ljubljani, Atenah in Helsinkih. Pri tem so parametrično spreminjali vrednosti, kot so oblika stavbe, toplotne lastnosti ovoja, velikost in razporeditev odprtin, način senčenja in notranja želena (ang. *set-point*) temperatura zraka. Ugotovili so, da imajo največji vpliv na potrebno energijo za ogrevanje *U* in *SHGC* vrednost oken ter notranja želena temperatura zraka, na potrebno energijo za hlajenje stavbe pa najbolj vpliva senčenje in *SHGC*. Lešnik in sod. [183] so za primer modularne lesene stavbe v Sloveniji (Maribor) preučevali optimalno razmerje *WWR* za doseganje ustrezne energijske učinkovitosti stavbe in primerne dnevne osvetljenosti. Rezultati so pokazali, da je optimalna vrednost *WWR* med 25 in 30 % za severno, vzhodno in zahodno ter med 20 in 30 % za južno orientirane fasade. Podobna raziskava je bila opravljena tudi za Atene in Sevillo [184].

Nadalje so Moazami in sod. [29] predstavili robusten pristop k ocenjevanju rabe energije v stavbah v okviru predvidenih podnebnih sprememb, z namenom doseganja večje robustnosti stavb za podnebne spremembe. Za referenčno poslovno stavbo so uporabili optimizacijo z več cilji oz. večciljno optimizacijo (ang. *multi-objective*) s spremenljivkami, kot so toplotne lastnosti stavbnega ovoja in infiltracija zraka. Na podlagi izvedene optimizacije so identificirali sklop parametrov, ki predstavlja globalni optimum rabe energije. Podobno so Gou in sod. [179] s pomočjo simulacij toplotnega odziva stavbe izvedli optimizacijo z več cilji, pri čemer so preučevali vpliv pasivnih načrtovalnih ukrepov za novo zgrajeno stolpnico v sedanjih podnebnih razmerah v Šanghaju na Kitajskem (vroča poletja in hladne zime). V analizo so bile zajete spremenljivke, kot je naravno prezračevanje, senčenje, delež toplotne izolacije in pasivno sončno ogrevanje. Izvedli so tudi analizo občutljivosti (linearna regresija), s čimer so zmanjšali število v optimizaciji uporabljenih spremenljivk. Drugi avtorji so predstavili primerljive raziskave, ki se ukvarjajo z optimizacijo z več cilji (glej reference [162, 175, 177, 178, 185–189]).

Podobno lahko za ugotavljanje linearnih razmerij med lastnostmi stavbe in izbranimi merili uspešnosti uporabimo tudi statistično analizo multiple linearne regresije (MLR, ang. *multiple linear regression*). Metoda MLR se pri raziskavah interakcije stavbe z okoljem pogosto uporablja. Različni avtorji so MLR uporabljali za analizo o rabi energije v stavbah (npr. Hygh in sod. [190], Chen in Yang [191]), analizo o dnevni svetlobi (npr. Potočnik in Košir [192]), toplotnega udobja (npr. Singh in sod. [193], Kumar in sod. [194]) itd. Ciulla in D'Amico [195] in D'Amico in sod. [196] so pokazali, da je mogoče modele MLR uporabljati kot alternativno metodo za obravnavo zapletenih problemov, kot sta toplotna bilanca stavb in raba energije v stavbah, s čimer lahko enostavne korelacije prepoznavamo z visoko stopnjo zanesljivosti. Kompleksne nelinearne povezave med stavbnimi elementi in rabo energije je sicer pri uporabi MLR težje opisati. Kljub temu se zaradi enostavne uporabe in interpretacije rezultatov MLR analiza pogosto uporablja za primerjalno analizo rabe energije v stavbah [197]. Poleg tega so Hygh in sod. [190] pokazali, da se v zgodnjih fazah načrtovanja stavb za iskanje vplivnih dejavnikov, ki vplivajo na rabo energije v stavbi, lahko neposredno uporabljajo standardizirani regresijski količniki (tj. β), ki izhajajo iz MLR. Še en primer uporabe občutljivostne analize so predstavili Mechri in sod. [198]. Ugotovili so, kateri parametri najbolj vplivajo na spreminjanje rabe energije večnadstropne poslovne stavbe v petih različnih podnebjih v Italiji. Poudarili so, da je treba nadaljnje raziskave razširiti na bolj zapletene oblike stavb. Vse ugotovitve navedenih raziskav so zelo pomembne pri iskanju stroškovno optimalnih rešitev v sedanjih podnebnih razmerah, vendar pa je vpliv nekaterih pasivnih načrtovalskih ukrepov na dolgoročno rabo energije, na katero vplivajo tudi podnebne spremembe, v enostanovanjskih stavbah še vedno precej neraziskan.

Pregled literature je pokazal, da je nižanje toplotne prehodnosti ovoja stavbe (*U* vrednosti) eden najučinkovitejših in najtrajnejših pasivnih načrtovalskih ukrepov za zmanjšanje rabe energije v stavbah [199, 200]. Zato je precej običajno, da zakonodajalci določijo zgornjo dovoljeno mejo *U* vrednosti toplotnega ovoja stavb. Poleg zmanjševanja toplotnih izgub skozi stavbni ovoj z uporabo nizkih *U* vrednosti pa je mogoče energijsko učinkovitost stavb še povečati z uporabo dodatnih pasivnih načrtovalnih ukrepov [201]. Kljub temu so Andrea in sod. [202] poudarili, da se lastniki stanovanj bioklimatskih strategij in ukrepov zavedajo, a je znanje površinsko in so zato za zagotavljanje zadostne energijske učinkovitosti stanovanjskega sektorja potrebne učinkovite nacionalne strategije. Kljub temu, da študije toplotnega odziva stavb predstavljajo izhodišča in smernice za načrtovanje novih stavb, pa so pogosto podnebno prilagojene stavbe izvzete iz analiz. Prav te stavbe so v nevarnosti, da jih bodo spremembe podnebja najbolj prizadele, saj so prilagojene stanju in podnebnim lastnostim v preteklosti. Zaradi navedenega so, da bi ohranili prilagojenost podnebju, v tem smislu spodbudne energijske prenove oz. prilagoditve obstoječega stavbnega fonda [203–206], tudi kulturne dediščine [207]. Holck Sandberg in sod. [208] poudarjajo, da bi do leta 2050 večini stavb, ki so jih obravnavali v raziskavi, koristila prenova za izboljšanje energijske učinkovitosti, še posebej pa je pomembno, da se v fazi načrtovanja in prenove stavb uporabijo najbolj energijsko učinkoviti ukrepi, ki so v danem trenutku na voljo. Zato je pomembno identificirati pretekle, trenutne in prihodnje trende bioklimatskega načrtovanja stavb ob upoštevanju podnebja ter na podlagi ugotovljenega definirati ustrezen nabor bioklimatskih strategij in pasivnih načrtovalskih ukrepov za načrtovanje stavb danes in v prihodnosti. Kot poudarjajo zgoraj omenjene raziskave, je sicer področje široko raziskano. Vendar so raziskave običajno osredotočene na energijsko prenovo specifičnih poslovnih ali stanovanjskih stavb (npr. Shen et al. [176]), ciljajo v iskanje specifičnih optimalnih rešitev za energijsko učinkovitost (npr. Shen et al. [175]), se izvajajo z omejenim naborom parametrov (npr. Robic et al. [177], Košir et al. [64]), ali pa ne obravnavajo učinkov podnebnih sprememb na toplotni odziv stavb (npr. Ciardiello et al. [180]). Zato dolgoročni prispevek pasivnih načrtovalnih ukrepov k zmanjšanju rabe energije za ogrevanje in hlajenje podnebno prilagojenih enostanovanjskih stavb v različnih evropskih podnebjih ni znan. Skladno s tem obstaja precejšnje pomanjkanje smernic in priporočil glede uporabe ustreznih pasivnih načrtovalskih ukrepov za doseganje ciljev energijske učinkovitosti stavb. Zato je namen raziskovalnega dela predstaviti ključne informacije za načrtovanje podnebno prilagojenih in energijsko učinkovitih stavb, ki bi zagotavljale učinkovito rabo energije v sedanjih in predvidenih podnebnih razmerah v prihodnosti.

»Ta stran je namenoma prazna«

3 DOLOČEVANJE BIOKLIMATSKEGA POTENCIALA IN ŠTUDIJE PRIMERA

Povzetek

V poglavju povzemamo vsebino dveh konferenčnih prispevkov v prilogah E in F (Košir in Pajek [48], *Pajek in sod.* [49]*) in izvirnega znanstvenega članka v prilogi A (Pajek in Košir* [10]*). Glavni cilj poglavja je predstaviti metodo za analizo bioklimatskega potenciala in njeno uporabo prikazati na študijah primera. Najprej je bila analiza bioklimatskega potenciala narejena za 21 izbranih značilnih lokacij v regiji Alpe-Jadran. V ta namen so bile z uporabo osnovnih podnebnih podatkov izdelane bioklimatske karte, v katerih je bilo upoštevano tudi sončno sevanje. V okviru raziskave je bilo razvito orodje BcChart, s katerim lahko izvedemo analizo bioklimatskega potenciala lokacije. Glavna prednost orodja, v nasprotju z drugimi orodji, je, da neposredno upošteva vpliv sončnega sevanja, ki je upoštevano z nadomestno udobno temperaturo. Slednje ima velik vpliv na rezultate bioklimatske analize. Poleg tega je bila narejena primerjava bioklimatskega potenciala z rabo energije za ogrevanje in hlajenje generičnega modela stavbe, ki je bil simuliran na petih izbranih lokacijah. Rezultati so pokazali, da lahko uporaba predstavljene metode učinkovito in zanesljivo pokaže, katere pasivne načrtovalske ukrepe je treba uporabiti pri načrtovanju stavb na neki lokaciji, da bi v stavbah dosegli nižjo rabo energije in večje toplotno udobje. Študija je pokazala, da je predstavljeni pristop mogoče uporabiti tudi pri projiciranih podnebnih podatkih. Nadalje je bil s pomočjo geoprostorskih podatkov in orodij GIS z namenom ugotavljanja primernih bioklimatskih strategij in pasivnih ukrepov bioklimatski potencial izračunan na širšem območju Evrope. Za izbrano mrežo točk so bile izdelane karte bioklimatskih potencialov. Poleg tega je bilo s pomočjo podatkov o gostoti prebivalstva izbranih več lokacij, za katere je bil bioklimatski potencial podrobneje preučevan. Predstavljene karte bioklimatskih potencialov je mogoče uporabiti pri oblikovanju politik za izboljšanje regionalnih razvojnih strategij pri načrtovanju stavb.*

Abstract

The chapter summarises the content of two conference papers in Appendices E and F (Košir and Pajek [48], Pajek et al. [49]) and the original scientific paper in Appendix A (Pajek and Košir [10]). The main goal is to present a bioclimatic potential analysis method and demonstrate its application in several case studies. Firstly, a bioclimatic potential analysis was performed for 21 selected locations in the Alpine-Adriatic region. For this purpose, bioclimatic charts were used with elementary climate data and additionally considered solar radiation. As part of the study, the BcChart tool was developed and used to perform a bioclimatic potential analysis. In contrast to other tools, its main advantage is that it directly includes the effect of solar radiation, which is considered by the substitute comfortable temperature. The latter has a significant impact on the results of the bioclimatic analysis. In addition, a comparison of bioclimatic potential with energy use for heating and cooling of a generic building model was made, which was simulated at five selected locations. The results showed that the use of the presented method could effectively and reliably show which passive planning measures should be used in the design of buildings in a particular location to achieve lower energy use and better thermal comfort in buildings. The study showed that the presented approach could also be used in the case of projected climate data. Furthermore, using the geospatial data and GIS tools, the bioclimatic potential in the broader area of Europe was calculated to identify recommended bioclimatic strategies and passive measures. Maps of bioclimatic potentials were made based on the selected point grid. In addition, several sites were selected based on population density data, for which the bioclimatic potential was studied in greater detail. The bioclimatic potential maps can aid policy formulation and improve regional development strategies in building design.

3.1 Ideja in teoretično ozadje

Gradbeništvo se v zadnjih letih vsestransko osredotoča na energijsko učinkovitost stavb in doseganje višjih standardov bivalnega udobja. Pri tem se načrtovalci pogosto odločajo za bioklimatsko načrtovanje, ki v zadnjem času postaja vse pomembnejše. Posledično se povečuje potreba po razvoju analitičnih orodij, s pomočjo katerih bi lažje in učinkoviteje izvedli proces načrtovanja stavb. Obstaja več orodij, s katerimi lahko izračunamo bioklimatski potencial, vendar pri večini podatki o sončnem sevanju niso neposredno zajeti v izračunih. Prav upoštevanje sončnega sevanja je še posebej pomembno pri lokacijah z zmernim ali hladnim podnebjem. Zato smo v sklopu raziskovanja izdelali in predstavili orodje, ki bolj celostno zajema podnebne podatke, kot so temperatura zraka, relativna vlažnost zraka in sončno sevanje. Orodje, s katerim si pomagamo pri določanju bioklimatskega potenciala lokacije, je bilo predstavljeno v konferenčnem prispevku Košir in Pajek [48] (priloga E). Bistvena ideja pri izdelavi orodja je bila v izračun bioklimatskega potenciala vpeljati upoštevanje podatkov o sončnem sevanju. Slednje je bilo doseženo z uvedbo in izračunom nadomestnih temperatur (T_{sub} in T_{PSH}) v metodologijo, ki se uporablja pri Olgyayevi bioklimatski karti.

Sistematične analize bioklimatskega potenciala, zlasti za širša območja, so razmeroma redke. Večinoma se za tovrstne analize uporabljajo bioklimatske ali pa psihrometrične karte, pri katerih sončno sevanje v izračunih ni zajeto, zato so analize bioklimatskega potenciala lahko pomanjkljive. Po Köppen-Geigerjevi podnebni klasifikaciji je Evropa pod vplivom vsaj desetih podnebnih tipov. Tako lahko tu najdemo različna podnebja, od polarne tundre (ET) in hladnega podnebja (npr. Dfc) v Alpah in severni Evropi, do vročega suhega podnebja v južnih delih Španije (npr. BSk). Zaradi te stopnje podnebne raznolikosti je evropsko ozemlje zanimivo za analizo bioklimatskega potenciala. Za študijo primera smo si najprej izbrali regijo Alpe-Jadran, v kateri lahko najdemo pet različnih podnebnih tipov. Rezultati so predstavljeni v članku Pajek in Košir [10] (priloga A). Ker bioklimatske stavbe pogosto načrtujemo z na podlagi bioklimatske analize izbranimi pasivnimi ukrepi, ima analiza tudi posreden vpliv na toplotni odziv stavbe in energijsko učinkovitost. Zato smo v naslednjem koraku študije izvedli primerjavo pridobljenih bioklimatskih potencialov s simulacijami generičnega modela stavbe. Primerjava z rabo energije za ogrevanje in hlajenje stavbe je bila izvedena za pet izbranih značilnih lokacij. S tem smo rezultate bioklimatske analize posredno povezali s potencialnimi prihranki energije pri bioklimatsko zasnovanih stavbah.

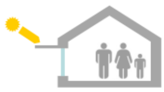
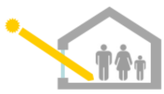
Za konec je bila narejena še študija primera analize bioklimatskega potenciala za celotno Evropo, ki je predstavljena v konferenčnem prispevku Pajek in sod. [49] (priloga F). Glavni cilj te študije je bil izračunati bioklimatski potencial na celotnem območju evropske celine ter predstaviti geoprostorsko porazdelitev bioklimatskih potencialov z uporabo geografskega informacijskega sistema (GIS). Dobljeni rezultati tako s pomočjo uporabe najnovejših geoprostorskih in podnebnih podatkov jasno definirajo potencial za zagotavljanje toplotnega udobja in učinkovite rabe energije z uporabo izključno pasivnih načrtovalskih ukrepov.

3.2 Metodologija raziskave

3.2.1 Programsko orodje BcChart

Raziskovalno delo, prikazano v poglavju 3, temelji na izdelavi metodologije in programskega orodja za bioklimatsko analizo lokacije. Razvoj orodja za bioklimatsko analizo lokacije, ki smo ga poimenovali BcChart, sloni na analizi trenutnega stanja raziskav o bioklimatskem načrtovanju in poglavitnih ciljih, ki smo jih postavili za izhodišče naše raziskave. Orodje je podrobneje predstavljeno v konferenčnem prispevku Košir in Pajek [48] (priloga E), delno pa še v znanstvenem članku Pajek in Košir [10] (priloga A). Izračuni, ki so uporabljeni v izdelanem programskem orodju, temeljijo na teoriji Olgyayjeve bioklimatske karte (glej poglavje 2.2.2.2). Osnovna vhodna podnebna parametra, ki sta potrebna za izdelavo bioklimatske karte in sta uporabljena v metodi programskega orodja, sta temperatura zraka (*T*) in relativna vlažnost (*RH*). Poleg *T* in *RH* smo pri izrisu bioklimatske karte in določevanju bioklimatskega potenciala vpeljali upoštevanje sončnega sevanja z uporabo gostote moči sončnega sevanja (*G*). Slednje smo v metodo vključili s tem, da sta bili uvedeni nadomestna udobna temperatura zraka (T_{sub}) in temperatura zraka, pri kateri je še možno koriščenje pasivnega sončnega ogrevanja (T_{PSH}), izračunani za posamezni mesec. Vhodni podnebni podatki so analizirani na mesečni ravni, pri čemer sta v izračunih uporabljeni najvišja in najnižja povprečna dnevna vrednost. Glavni rezultat programskega orodja BcChart je bioklimatski potencial analizirane lokacije (preglednica 2). Ta je izražen v odstotkih, ko kombinacije temperature, relativne vlažnosti in sončnega sevanja zagotavljajo toplotno udobje (cona udobja) ali pa je za zagotavljanje le-tega potrebna uporaba pasivnih načrtovalskih ukrepov. Bioklimatski potencial je s pomočjo orodja BcChart predstavljen na letni ali mesečni ravni.

Preglednica 2: Oznake bioklimatskega potenciala iz orodja BcChart.
Table 2: Bioclimatic potential segments as calculated by BcChart.

Nova oznaka[a]	Stara oznaka[b]	Barva	Bioklimatski potencial	Pasivni načrtovalski ukrep
Q	/		potrebno je mehansko hlajenje in/ali razvlaževanje zraka	
A	/		učinkoviti so pasivni ukrepi za vroča suha podnebja	
M	/		učinkovito je naravno prezračevanje in/ali visoka toplotna masa	
V	B		učinkovito je naravno prezračevanje	
C_{sh}	A		toplotno udobje je doseženo s senčenjem	
C_{sn}	A'		toplotno udobje je doseženo z zajemom sončne energije	
R	C'		učinkovito je pasivno sončno ogrevanje	
H	D'		potrebno je konvencionalno ogrevanje in zadrževanje toplote	
S_h	S		potrebno je senčenje transparentih elementov ($S_h = Q + A + M + V + C_{sh}$)	

[a] Oznake, uporabljene v orodju BcChart od različice 2.0 dalje.
[b] Oznake, uporabljene v prvih različicah orodja BcChart in članku Pajek in Košir [10].

3.2.2 Študija primera regije Alpe-Jadran

Študija primera, predstavljena v znanstvenem članku Pajek in Košir [10] (priloga A), je bila narejena na ravni regije Alpe-Jadran, ki jo definirajo velike razlike v podnebnih značilnostih v relativno majhnem geografskem prostoru in je v tem kontekstu verjetno ena najbolj podnebno raznolikih regij v Evropi. Regija predstavlja mešanico celinskega (hladne zime z visokimi vrednostmi prejetega sončnega sevanja in daljšimi dnevi, vroča poletja), toplega, sredozemskega (blage zime z visokimi vrednostmi prejetega sončnega sevanja in dolgimi dnevi, vroča poletja) pa tudi hladnega podnebja. Podnebna raznolikost je služila kot podlaga za ovrednotenje metode orodja BcChart. Za podrobno študijo primera smo izbrali lokacije, navedene v preglednici 3.

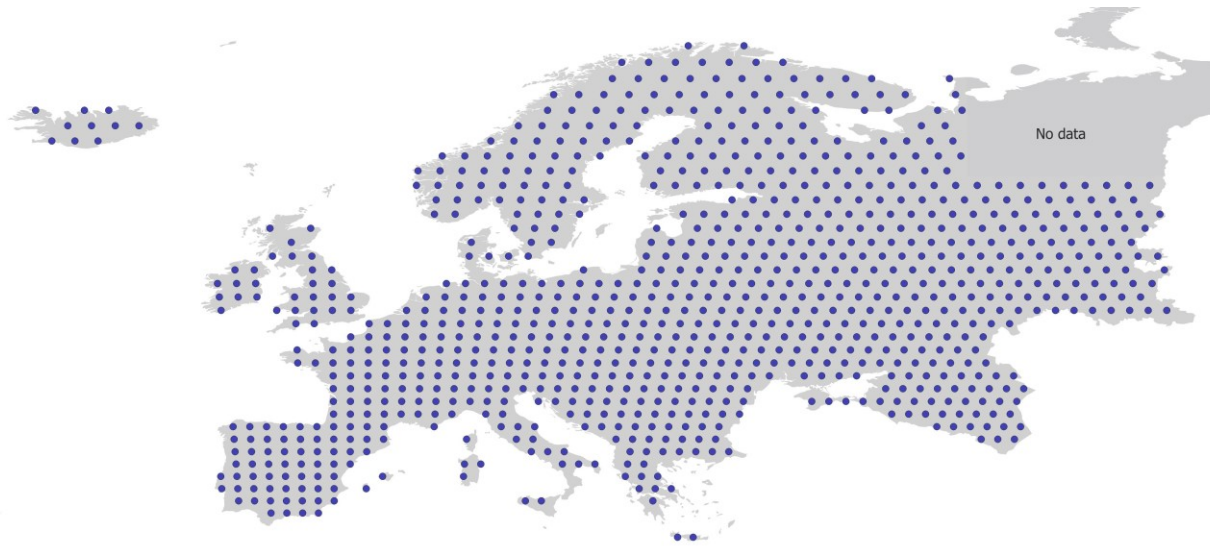
Preglednica 3: Izbrane lokacije v regiji Alpe-Jadran.
Table 3: Selected location in Alpine-Adriatic region.

Država	Oznaka	Lokacija	Koordinate	Nadmorska višina	Tip površja	Köppen-Geigerjeva klasifikacija
Slovenija	1	Maribor	N 46°32' E 15°39'	275 m	nižina/gričevje	Cfb
	2	Ljubljana	N 46°04' E 14°31'	299 m	nižina/gričevje	Cfb
	3	Bizeljsko	N 46°01' E 15°41'	179 m	nižina/gričevje	Cfb
	4	Bilje	N 46°04' E 14°31'	299 m	nižina/gričevje	Cfb
Hrvaška	5	Pazin	N 45°14' E 13°56'	291 m	nižina/gričevje	Cfa
	6	Parg	N 45°36' E 14°38'	863 m	hribovje	Cfb
	7	Rovinj	N 45°05' E 13°38'	20 m	obala	Cfa
	8	Mali Lošinj	N 44°32' E 14°29'	53 m	obala	Cfb
Italija	9	Trbiž	N 46°30' E 13°35'	778 m	hribovje	Dfc
	10	Trst	N 45°40' E 13°45'	29 m	obala	Cfb
	11	Videm-Rivolto	N 45°59' E 13°02'	53 m	nižina	Cfa
	12	Passo Rolle	N 46°18' E 11°47'	2006 m	visokogorje	ET
	13	Benetke	N 45°30' E 12°21'	2 m	obala	Cfa
	14	Verona	N 45°23' E 10°53'	68 m	nižina	Cfa
Avstrija	15	Celovec	N 46°39' E 14°20'	447 m	nižina/gričevje	Dfb
	16	Mallnitz	N 46°59' E 13°11'	1185 m	hribovje	Dfc
	17	Preitenegg	N 46°56' E 14°55'	1055 m	hribovje	Dfb
	18	Altenberg	N 47°15' E 16°02'	429 m	gričevje	Cfb
	19	Bad Aussee	N 47°37' E 13°47'	665 m	hribovje	Cfb
	20	Gradec	N 47°05' E 15°27'	366 m	nižina/gričevje	Dfb
	21	Mariazell	N 47°46' E 15°19'	875 m	hribovje	Dfb

Vsi potrebni podnebni podatki za izvedbo študije primera so bili pridobljeni s pomočjo nacionalnih okolijskih agencij. Za analizo bioklimatskega potenciala z orodjem BcChart smo za vsak mesec pridobili povprečne dnevne najnižje (T_{min}, RH_{min}) in najvišje (T_{max}, RH_{max}) vrednosti temperature suhega zraka in relativne vlažnosti zraka ter povprečno in največjo dnevno gostoto moči sončnega sevanja na vodoravni ravnini (G in G_{max}). Da bi ovrednotili opravljeno analizo bioklimatskega potenciala, smo z orodjema EnergyPlus [138] in OpenStudio [209] izvedli simulacije toplotnega odziva enodružinske stanovanjske stavbe na petih izbranih lokacijah. Simulacije so bile izvedene z 10-minutnim računskim korakom. Uporabljeni so bili idealni grelci (ang. *ideal air loads*), torej smo spremljali potrebno energijo za ogrevanje in hlajenje stavbe, brez vpliva učinkovitosti ogrevalnega in hladilnega sistema. Izbrane lokacije so bile Trst (Cfb), Verona (Cfa), Ljubljana (Cfb), Gradec (Dfb) in Trbiž (Dfc), ki so primerne za predstavitev podnebne variabilnosti v regiji. Definirali smo model enodružinske stavbe, ki ima pravokotni tloris 7 x 10 m, z daljšo stranico usmerjeno proti jugu in vključuje bioklimatske značilnosti, kot so velika, proti jugu usmerjena okna, podolgovat tloris in uporaba senčenja. Skupna neto tlorisna površina stavbe znaša 140 m^2, prostornina pa 392 m^3. Toplotna prehodnost zunanje stene je bila izbrana 0,28 W/m^{2}K, strehe 0,20 W/m^{2}K in tal na terenu 0,30 W/m^{2}K, kar ustreza maksimalnim dovoljenem vrednostim U faktorjev glede na slovenski Pravilnik o učinkoviti rabi energije v stavbah [210]. Nosilna konstrukcija je masivna. Toplotna prehodnost oken je enaka 1,18 W/m^{2}K, *SHGC* stekla pa 0,59. Površina zasteklitve je bila modelirana v treh različnih konfiguracijah: WFR enak 16 % (tj. 22,40 m^2), 20 % (tj. 28,00 m^2) in 24 % (tj. 33,60 m^2), pri čemer smo spreminjali le južne transparentne površine. Simulacije rabe energije so bile izvedene pri uporabi senčenja (SH) in situacije brez senčil (UN). Opazovani so bili rezultati letne potrebne energije za hlajenje (Q_{NC}) in ogrevanje stavbe (Q_{NH}) v kWh/m^2, razmerje med njima in skupna letna potrebna energija ($Q_T = Q_{NC} + Q_{NH}$). Metodologija študije je podrobneje predstavljena v znanstvenem članku Pajek in Košir [10] (priloga A).

3.2.3 Študija primera Evrope

V nadaljevanju je bila narejena študija primera Evrope, predstavljena v konferenčnem prispevku Pajek in sod. [49] (priloga F), v katerem je metodologija tudi podrobneje predstavljena. Za območje celotne celine je bil s pomočjo orodja BcChart izračunan bioklimatski potencial. V ta namen je bilo za pridobitev referenčnih prostorskih koordinat in prikaz izračunanega bioklimatskega potenciala uporabljeno geoprostorsko orodje v odprtokodnem okolju QGIS [211]. S pomočjo le-tega smo definirali vektorsko plast točk na medsebojni razdalji 100 km z enakomerno geoprostorsko porazdelitvijo. Izbranih je bilo 908 točk, v katerih je bil s pomočjo orodja BcChart izračunan bioklimatski potencial (slika 13).



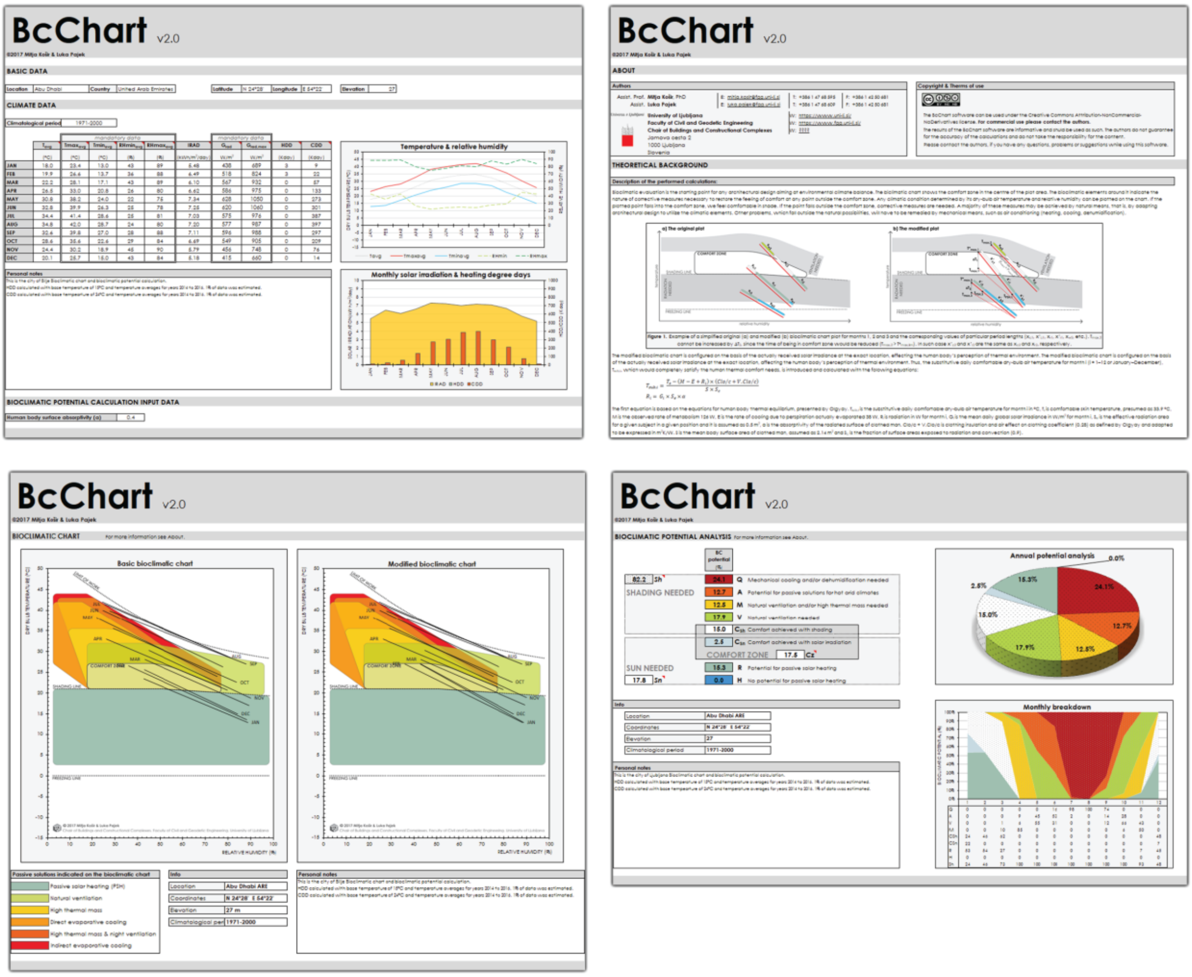
Slika 13: Enotna mreža 908 točk z medsebojno razdaljo 100 km, v katerih je bil izračunan bioklimatski potencial. Opomba: Zaradi uporabljene kartografske projekcije se zdi, da so točke neenakomerno porazdeljene.
Figure 13: A uniform grid of 908 points with 100 km spacing, where bioclimatic potential was calculated. Note: Due to the used cartographic projection, the points appear unevenly distributed.

Izračun bioklimatskega potenciala v izbranih točkah je bil izveden s pomočjo podnebnih podatkov TMY (tipično meteorološko leto) za obdobje 2006–2015. Le-to vsebuje podnebne značilnosti, kot so temperatura zraka, relativna vlažnost zraka in sončno obsevanje, s katerimi smo določili bioklimatski potencial vsake točke. Vrednosti so bile nato interpolirane z algoritmom *Inverse Distance Weighted* (IDW). Nazadnje smo za namen vizualizacije rezultatov interpolirane rastrske površine izbranih parametrov bioklimatskega potenciala zgladili z Gaussovim filtrom. V drugem delu raziskave smo se osredotočili na analizo parametrov bioklimatskega potenciala najgosteje naseljenih lokacij. Izbrali smo lokacije, kjer živi 35 % Evropejcev, površina pa hkrati predstavlja le 6 % celotne površine Evrope.

3.3 Rezultati

3.3.1 Programsko orodje BcChart

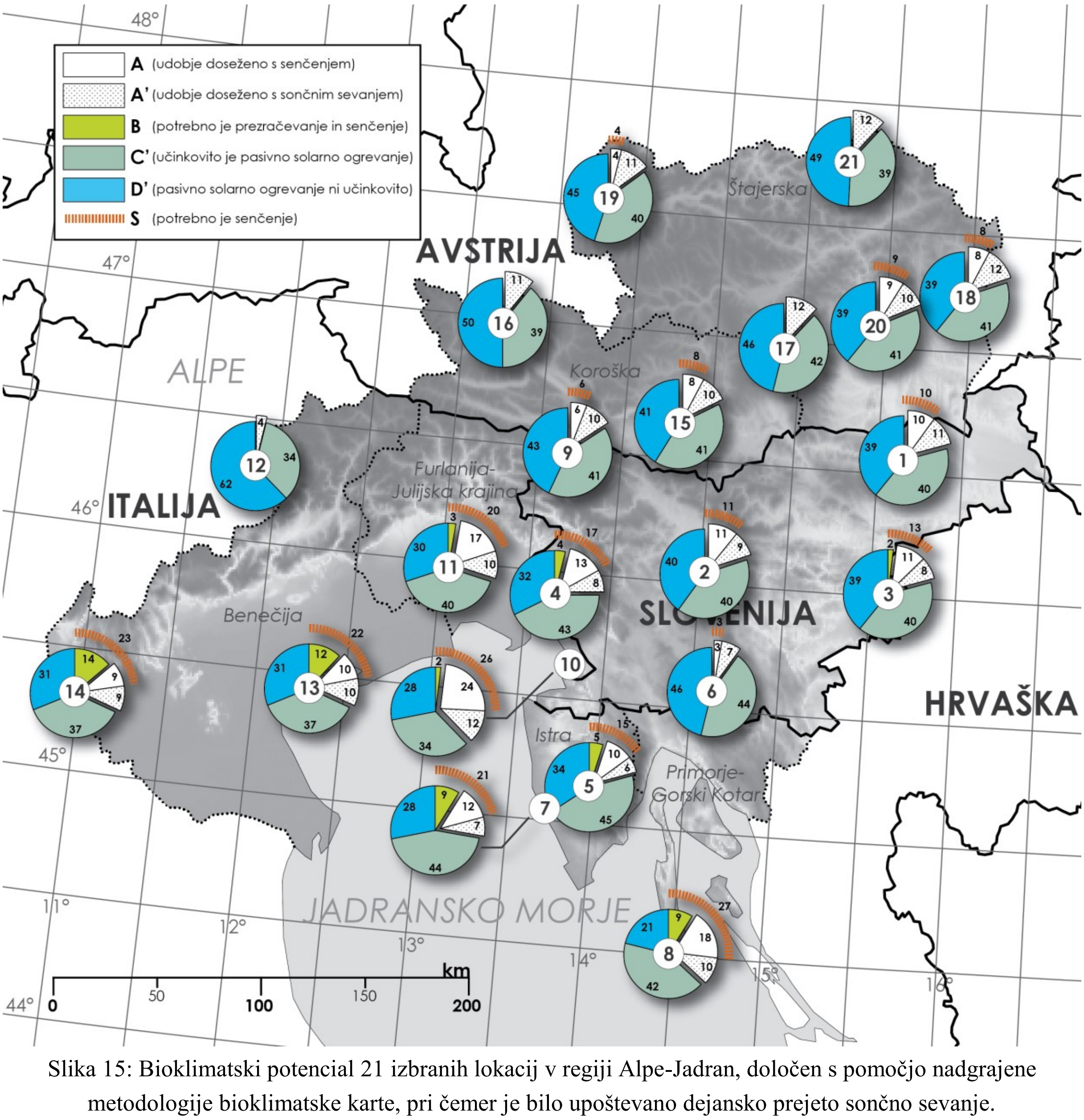
Glaven rezultat raziskovalnega dela, predstavljenega v konferenčnem prispevku Košir in Pajek [48] (priloga E), je prosto dostopno programsko orodje BcChart. Uporabniški vmesnik programskega orodja BcChart je bil izdelan v okolju MS Excel in sestoji iz 4 zaporednih zavihkov (slika 14), ki vodijo uporabnika od vhodnih podatkov do interpretacije rezultatov. Najnovejša različica programskega orodja je prosto dostopna na spletnem naslovu https://kske.fgg.uni-lj.si/raziskovalno-delo/.



Slika 14: Posnetki zaslona uporabniškega vmesnika programskega orodja BcChart v2.0. Zgoraj, levo: vhodni podatki in osnovni grafikoni. Zgoraj, desno: podatki o orodju in avtorjih. Spodaj, levo: osnovna in modificirana bioklimatska karta. Spodaj, desno: analiza letnega in mesečnega bioklimatskega potenciala.
Figure 14: BcChart v2.0 user interface screen shots. Top left – Input data and basic graphs. Top right: information about the tool and the authors. Bottom left: basic and modified bioclimatic chart. Bottom right: analysis of yearly and monthly bioclimatic potential.

3.3.2 Študija primera regije Alpe-Jadran

V okviru študije na primeru regije Alpe-Jadran, v znanstvenem članku Pajek in Košir [10] (priloga A), smo predstavljeno metodologijo določevanja bioklimatskega potenciala uporabili na dejanskem primeru. Bioklimatski potencial je bil najprej izračunan z osnovno bioklimatsko karto, nato pa še s pomočjo dodatnega podatka o sončnem sevanju. Slednje smo opisali kot nadgrajeni bioklimatski potencial na podlagi nadgrajene bioklimatske karte (ang. *modified bioclimatic chart*). Rezultati le-tega so prikazani na sliki 15.



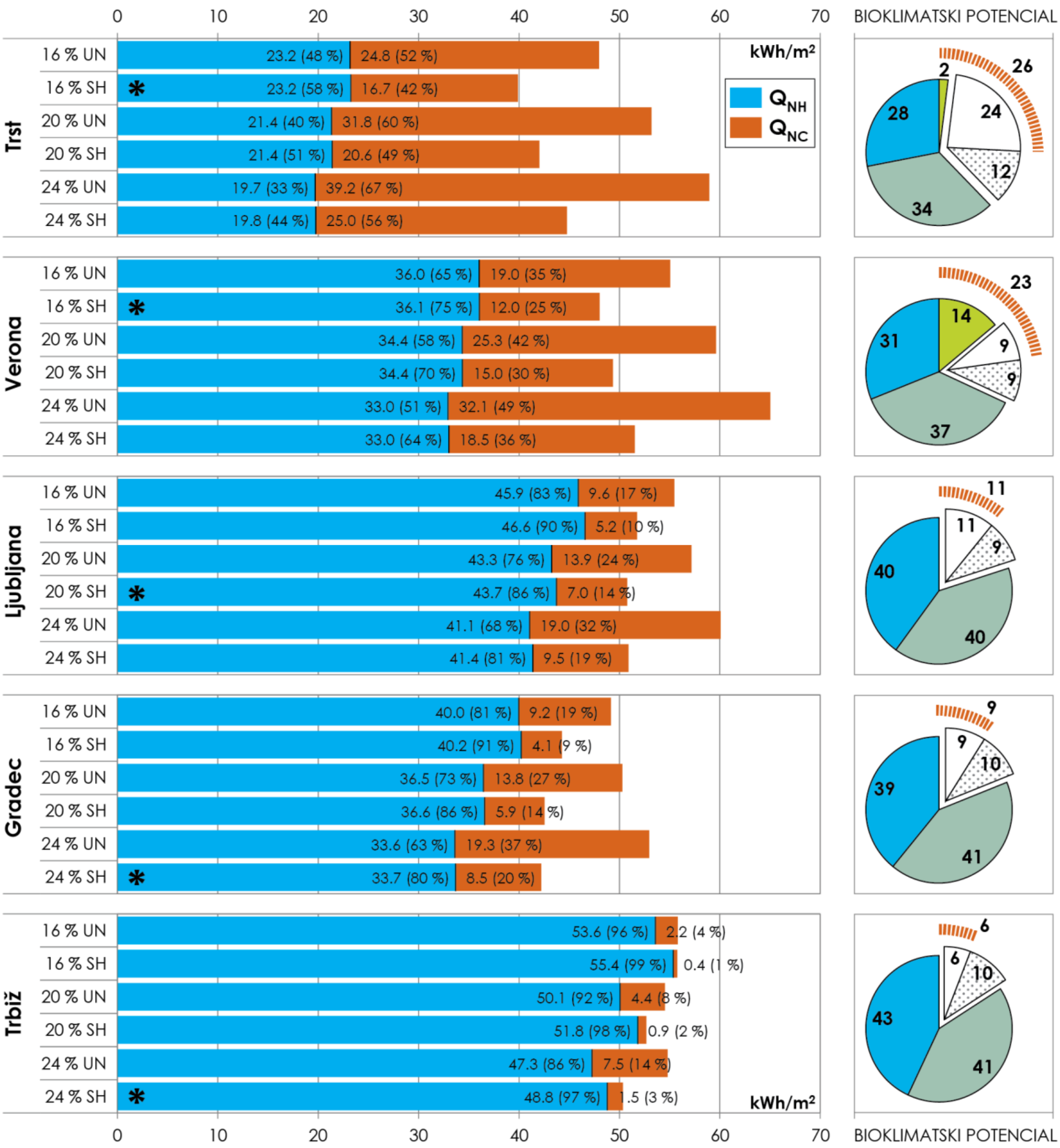
Slika 15: Bioklimatski potencial 21 izbranih lokacij v regiji Alpe-Jadran, določen s pomočjo nadgrajene metodologije bioklimatske karte, pri čemer je bilo upoštevano dejansko prejeto sončno sevanje.
Figure 15: Bioclimatic potential of Alpine-Adriatic region for 21 selected locations using a modified bioclimatic chart as a result of considering actual solar irradiance.

Rezultati so pokazali, da se upoštevanje prejetega sončnega sevanja pri bioklimatskem potencialu odraža z vrednostjo A' (kasneje preimenovan v C_{sn}), vpliva pa tudi na vrednosti C in D, ki postaneta C' (kasneje preimenovan v R) in D' (kasneje preimenovan v H), (za razlago oznak glej sliko 15 in preglednico 2).

Pričakovano smo ugotovili, da se bioklimatski potencial, pridobljen s pomočjo nadgrajenih bioklimatskih kart (slika 15), bistveno razlikuje od potenciala, določenega na podlagi osnovnih bioklimatskih kart, pri katerih sončno sevanje ni upoštevano. Če primerjamo rezultate osnovne in nadgrajene metodologije, so zaradi zelo nizkih zunanjih temperatur v zimskem času vrednosti D' glede na D na vseh lokacijah višje, kar je posledica velike potrebe po sončnem sevanju, ki od novembra do marca na večini lokacij ni na voljo. Poleg tega se zaradi upoštevanja prejete sončne energije v nadgrajeni bioklimatski karti podaljša čas, ko je dosežena cona udobja (A'). Le-to se predvidoma zgodi predvsem v prehodnih mesecih med zimo in poletjem (tj. april, maj, junij, september, oktober), ko je na voljo dovolj sončnega sevanja in so hkrati zunanje temperature zraka dovolj visoke, vendar ne previsoke. Zaradi upoštevanja sončnega sevanja tako na nekaterih lokacijah (npr. visokogorska lokacija Passo Rolle, ET) zaznamo, da je cono udobja mogoče doseči s koriščenjem sončne energije, česar z osnovno metodologijo ni moč ugotoviti. Zaradi razlike v D' in A', ki jo zaznamo pri primerjavi obeh metod, se spremeni tudi vrednost C'. Rezultati bioklimatskega potenciala glede senčenja stavb so v primerjavi med osnovnim in nadgrajenim bioklimatskim potencialom nespremenjeni, saj je v obeh metodah predpostavljeno učinkovito senčenje. Visoke vrednosti S (poimenovane tudi S_h) za določeno lokacijo kažejo, da so za znižanje rabe energije za hlajenje stavb potrebni pasivni ukrepi za preprečevanje pregrevanja. Ugotovili smo, da je na lokacijah z visokimi vrednostmi D' potencial za pasivno sončno ogrevanje (C' oz. R) razmeroma majhen. Na lokacijah, kjer ena vrsta podnebja (npr. sredozemsko podnebje) prehaja v drugo (npr. hladno celinsko ali predalpsko podnebje), pa je treba v obzir vzeti tako ukrepe za preprečevanje toplotnih izgub, kot tudi ukrepe za preprečevanje pregrevanja.

Rezultati bioklimatske analize so pokazali, da se lahko bioklimatski potencial določene lokacije uporabi kot podlaga za načrtovanje stavb. S pomočjo rezultatov je moč izbrati ustrezne bioklimatske strategije in pasivne načrtovalske ukrepe (npr. senčenje), ki jih je treba spoštovati pri načrtovanju bioklimatskih stavb. S predstavljenim pristopom je lažje doseči, da načrtovana stavba učinkovito izkorišča podnebne danosti, kar je podlaga za zmanjšanje rabe energije za hlajenje in ogrevanje. Zato smo v naslednjem koraku analizo bioklimatskega potenciala primerjali z rabo energije enostanovanjske stavbe. Na petih izbranih lokacijah v regiji smo s pomočjo simulacij toplotnega odziva enostavnega modela stavbe opazovali potrebno energijo za hlajenje (Q_{NC}) in ogrevanje (Q_{NH}) v kWh/m^2, razmerje med njima in skupno letno potrebno energijo (Q_T).

Za vsako od petih izbranih lokacij je bilo izračunanih šest različnih modelov stavbe: tri različne konfiguracije glede na *WFR* in dve opciji senčenja južno orientiranih oken, vse skupaj 30 kombinacij. Rezultati simulacij o potrebni energiji so predstavljeni na sliki 16. Na njej so predstavljene tudi vrednosti bioklimatskega potenciala, pridobljene z bioklimatsko analizo, ki služijo posredni primerjavi z rezultati o potrebni energiji. V Trstu in Veroni, ki sta primera toplejšega podnebja, je bil višji Q_T dosežen pri zasteklitvi večje površine, kar je posledica večje rabe energije za hlajenje, tako v primeru s senčili ali brez. Najvišji Q_T je bil dosežen v primerih brez senčenja, pri čemer je najvišja vrednost dosežena v Veroni (65,10 kWh/m^2, pri *WFR* = 24 %). Za Trst in Verono je bila z rezultati rabe energije pokazana korist uporabe senčenja, kar sovpada z visoko vrednostjo S (npr. enaka 26 % v Trstu in 23 % v Veroni), pridobljeno z bioklimatsko analizo. Primeri z višjimi *WFR* imajo nižjo Q_{NH}, pri čemer se Q_{NC} povečuje sorazmerno z večanjem *WFR*. Slednje je povezano z bioklimatskim potencialom, saj nizka vrednost D' (28 % v Trstu in 31 % v Veroni) in visoka vrednost S pomenita, da na lokaciji v primerno zasnovanih stavbah prevladuje hlajenje. V Trbižu, ki je primer hladnejšega podnebja, je situacija ravno obratna, kot v Veroni in Trstu. Tu je značilna nizka vrednost S (6 %) in od vseh petih izbranih lokacij najvišja vrednost D' (43 %). Ta značilnost se odraža v visoki potrebni energiji za ogrevanje, kjer Q_{NH} predstavlja od 86 do 99 % Q_T. Izbira velikih transparentnih površin je koristna v vseh simuliranih primerih, tudi pri nezasenčenih oknih, čeprav se v takšnih primerih prispevek Q_{NC} k Q_T poveča. Na podlagi teh informacij smo potrdili, da Trbiž spada med lokacije, kjer v stavbah prevladuje potreba po ogrevanju.

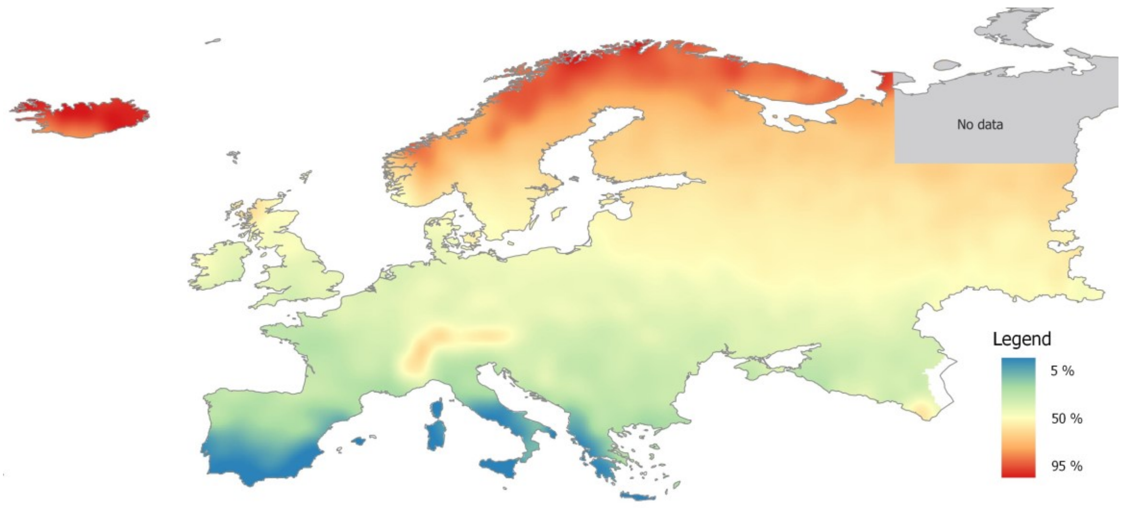


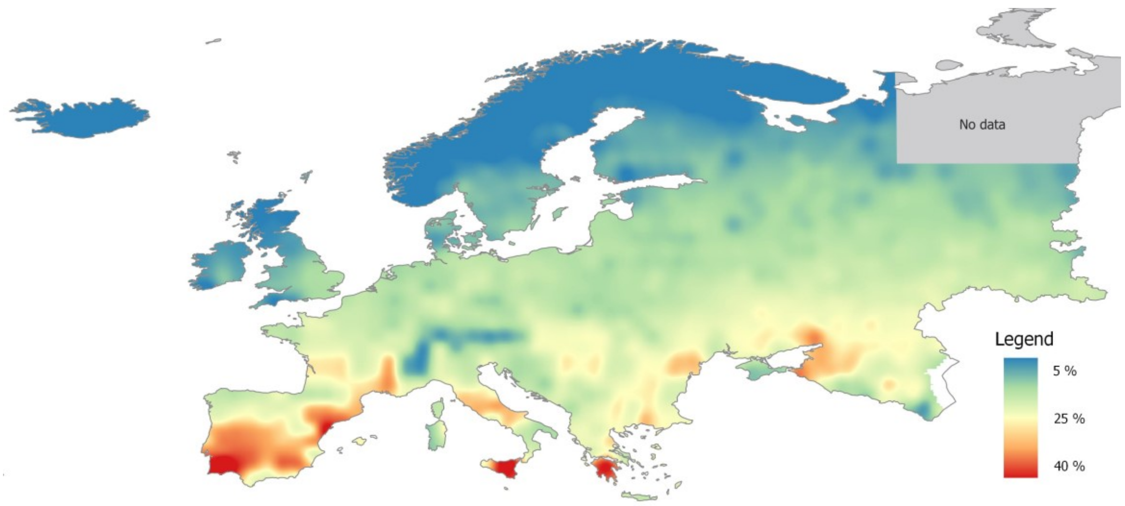
Slika 16: Rezultati simulacij rabe energije in bioklimatskega potenciala na izbranih lokacijah. Predstavljeno je razmerje med Q_{NH} in Q_{NC} pri različnih WFR (16 %, 20 % in 2 %) s (SH) in brez (UN) senčenja. Z zvezdico so označeni primeri z najnižjo Q_T. Legenda pomena bioklimatskega potenciala je predstavljena na sliki 15.
Figure 16: Results of energy simulations and bioclimatic potential at selected locations. The figure presents the ratio between Q_{NH} and Q_{NC} at different WFR (16 %, 20 % and 24 %) with (SH) and without (UN) shading. Cases with the lowest Q_T are marked by an asterisk. The legend for bioclimatic potential is located in Figure 15.

Ljubljana in Gradec sta primera lokacij z zmernim podnebjem, zato izračunani bioklimatski potencial in raba energije stavbe dosežeta vrednosti med obema prej opisanima ekstremoma. Za obe lokaciji sta značilni vrednosti S okoli 10 % in D' okoli 40 %, pri tem pa so v Ljubljani izračunane višje vrednosti, kar pomeni, da je potrebna večja pozornost za preprečevanje pregrevanja; hkrati pa je potencial za pasivno sončno ogrevanje v zimskih mesecih nižji kot v Gradcu. Rezultati simulacij rabe energije so potrdili, da sta lokaciji kombinacija toplejšega in hladnejšega podnebja, zato je v stavbah potrebno ogrevanje in hlajenje. Slednje se odraža v nižji vrednosti Q_T pri večji površini oken, vendar le, če so le-ta poleti učinkovito senčena. V nasprotnem primeru je Q_T odnosno do preostalih primerov višji, ker se Q_{NC} z večanjem površine oken viša hitreje, kot se niža Q_{NH}. Majhna razlika v bioklimatskem potencialu med Ljubljano in Gradcem pove, da je možno doseči optimalen Q_T pri različnih velikostih okenskih površin. Na podlagi simulacij rabe energije je bil za primer Ljubljane najnižji Q_T dosežen pri senčenju oken, velikosti $WFR = 20$ % (50,7 kWh/m^2), v Gradcu pa z uporabo senčenja pri oknih z velikostjo $WFR = 24$ % (42,2 kWh/m^2). Poudariti velja, da so rezultati specifični za izbrani tip in lastnosti simulirane stavbe.

3.3.3 Študija primera Evrope

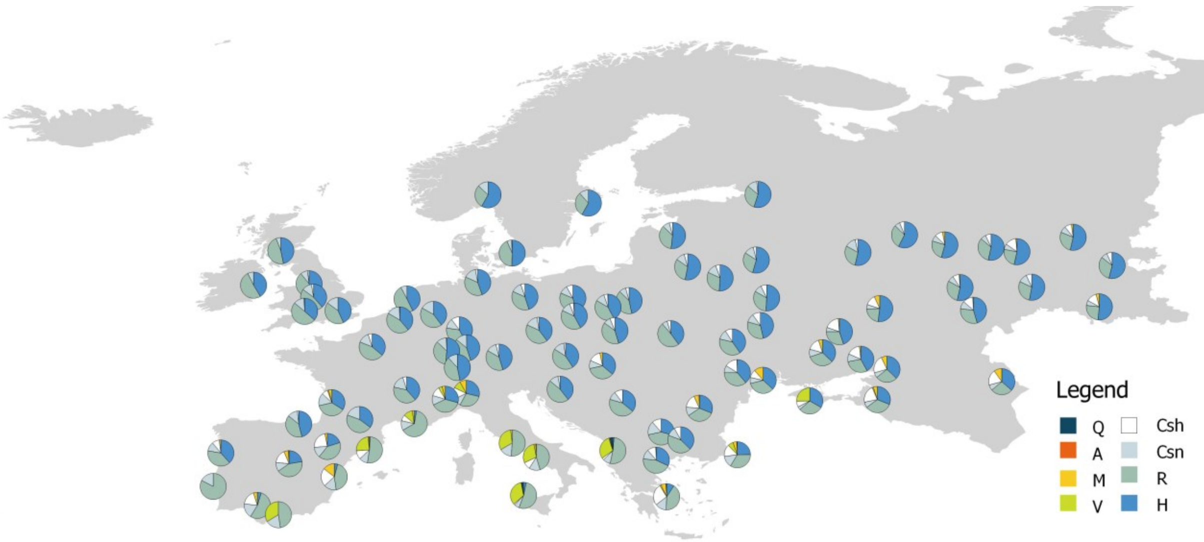
V okviru študije primera celotne Evrope, predstavljene v konferenčnem prispevku Pajek in sod. [49] (priloga F), smo predstavljeno metodologijo določevanja bioklimatskega potenciala uporabili na širšem območju. S tem smo preverili širšo uporabnost in aplikativnost predstavljene metode in orodja ter hkrati pripravili informativne podatke za pomoč pri načrtovanju stavb v različnih delih Evrope. Rezultate bioklimatskega potenciala smo za posamezni parameter prikazali na karti evropske celine. Tako so bile izdelane karte bioklimatskega potenciala, ki vsebujejo informacije o primernosti uporabe različnih pasivnih načrtovalskih ukrepov. Primera bioklimatske karte za vrednosti H in C_z sta predstavljena na sliki 17. Preostali bioklimatski karti za primer vrednosti S_h in AMV sta dostopni v prilogi F.V drugem delu študije smo se osredotočili na analizo bioklimatskega potenciala najgosteje poseljenih območij, za katera so bile izračunane vrednosti Q, A, M, V, C_{sn}, C_{sh}, R in H (glej preglednico 2), ki so na sliki 18 prikazane s pomočjo tortnih diagramov. Vsaka točka predstavlja eno izmed 85 najgosteje poseljenih območij in opredeljuje, na katere pasivne ukrepe morajo biti osredotočeni načrtovalci stavb na posamezni lokaciji.





Slika 17: Zgoraj: bioklimatska karta Evrope za vrednost H. Višja kot je vrednost H, daljši čas je treba uporabljati konvencionalno ogrevanje. Spodaj: bioklimatska karta Evrope za vrednost C_z. Višja kot je vrednost C_z, daljši del leta je moč doseči toplotno udobje in je pomembna regulacija sončnega sevanja.
Figure 17: Top: bioclimatic map of Europe for the H value. The higher the H value, the longer part of the year conventional heating must be used. Bottom: bioclimatic map of Europe for the C_z value. The higher the C_z value, the longer part of the year thermal comfort is achieved and more important is the regulation of solar radiation.

Na podlagi študije najgosteje naseljenih območij smo poiskali pet lokacij z najvišjo vrednostjo C_z (tj. najvišjo stopnjo doseženega udobja izključno z regulacijo vpliva sončnega sevanja). To so Atene v Grčiji (C_z = 40,8 %), Valencia (C_z = 37,8 %), Sevilla (C_z = 36,4 %) in Zaragoza v Španiji (C_z = 36,1 %) ter Istanbul v Turčiji (C_z = 29,1 %). Kazan (Rusija) je najsevernejša obravnavana lokacija z vrednostjo C_z nad 20 %. Pet lokacij z najvišjimi vrednostmi H (tj. potrebno ogrevanje in zadrževanje toplote) so Oslo na Norveškem (H = 58,1 %), Stockholm, na Švedskem (H = 58,1 %), Ivanovo (H = 57,6 %) in Sankt Peterburg v Rusiji (H = 55,0 %) ter Vitebsk v Belorusiji (H = 54,5 %). Bilbao (Španija) je najjužnejša lokacija z vrednostjo H, višjo od 40 %, in sicer 46,1 %. Lizbona (Portugalska) je mesto z največjim potencialom za koriščenje pasivnega sončnega ogrevanja (R = 82,6 %). Tirana v Albaniji pa je lokacija z najvišjo vrednostjo Q = 3,9 %.



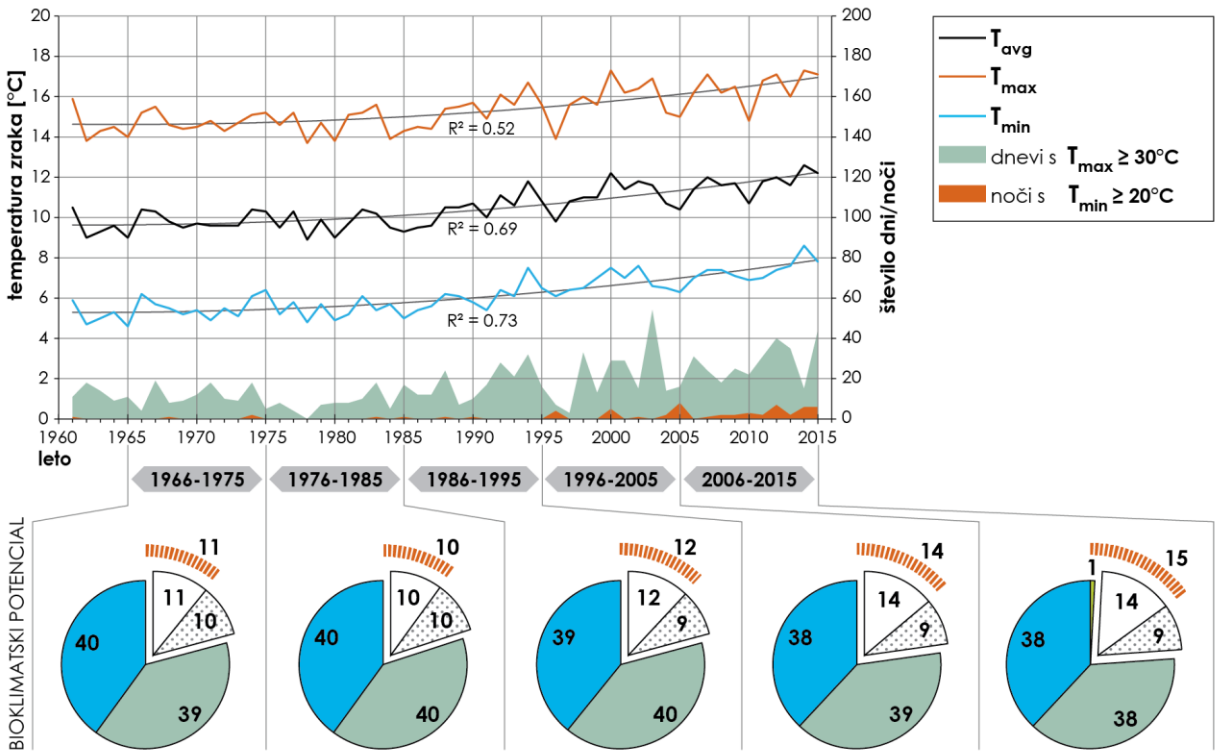
Slika 18: Bioklimatski potencial 85 najgosteje poseljenih lokacij v Evropi. Diagrami predstavljajo delež leta, ko je treba za doseganje toplotnega udobja uporabiti določen pasivni ukrep.
Figure 18: Bioclimatic potential of 85 most densely populated locations in Europe. Pie charts represent the share of year when a distinct passive design measure should be used to achieve thermal comfort.

3.4 Razprava

Ugotovljeno je bilo, da sta predstavljeni pristop in metodologija za določevanje bioklimatskega potenciala, pri čemer so uporabljeni tudi podatki o sončnem sevanju, izjemno pomembna, saj dajeta natančnejše rezultate. S pomočjo natančnih podatkov o bioklimatskem potencialu je mogoče natančneje določiti ustrezne in najučinkovitejše pasivne načrtovalske ukrepe. Glavni razlog za navedeno je, da je pomen strategije zajemanja toplote, torej koriščenja energije sončnega sevanja, največji v prvih treh navedenih podnebjih. Zavedamo se, da je metodologijo orodja BcChart možno še izboljšati. Zanimivo bi bilo v izračunu bioklimatskega potenciala upoštevati vpliv dejanske hitrosti gibanja zraka podobno kot pri sončnem sevanju. Rezultati so pokazali, da sta predstavljena metodologija in orodje BcChart učinkovita v zgodnjih fazah načrtovanja stavbe, ko je potrebna splošna in hitra ocena primernih bioklimatskih strategij in pasivnih načrtovalskih ukrepov na izbrani lokaciji.

Na podlagi študije primera na območju evropske celine smo ugotovili, da se izračunani bioklimatski potencial precej ujema s porazdelitvijo podnebnih tipov. Najti je mogoče podobnosti med vrednostmi H, C_z ter S_h in Köppen-Geigerjevo podnebno klasifikacijo, pri čemer so rezultati bioklimatskega potenciala v toplejših podnebjih bolj primerljivi s podnebnim tipom. Kljub temu je študija pokazala, da lahko na nekaterih lokacijah s hladnim (npr. Dfb) ali zmernim (npr. Cfb) podnebjem, vrednosti S_h in A, M, V bistveno odstopajo od mediane tega podnebnega tipa. Zato lahko na podlagi bioklimatskega potenciala predlagani pasivni ukrepi za načrtovanje stavb odstopajo od splošnega znanja o bioklimatskem načrtovanju stavb. Na primer, rezultati so pokazali, da je senčenje v času hlajenja pomembno na nekaterih delih Evrope s hladnim podnebjem, kjer le-to ni intuitivno. Zato so lahko izdelane karte, ki prikazujejo bioklimatski potencial, uporabno orodje za izbiro pasivnih ukrepov z veliko več podrobnostmi, kot jih pomeni podatek o podnebnem tipu. Predstavljena in uporabljena analiza bioklimatskega potenciala je zelo pomembna, zlasti na območjih, kjer je podnebje raznoliko, kot sta na primer regija Alpe-Jadran in območje Slovenije. Slednja je primer, kjer je kljub izjemno majhnemu geografskemu območju pri načrtovanju bioklimatskih stavb treba uporabiti različne pristope.

Rezultati izvedenih simulacij rabe energije hipotetičnega modela enostanovanjske stavbe na izbranih lokacijah so potrdili točnost predstavljene metode in analize bioklimatskega potenciala. Izkazalo se je, da se predstavljena metoda določanja bioklimatskega potenciala lahko uporabi za ugotavljanje primernosti in učinkovitosti pasivnih načrtovalskih ukrepov v začetnih fazah načrtovanja. Zelo pogosto je sicer, da načrtovalci stavb uporabljajo bolj ali manj enake pasivne ukrepe, ki jih črpajo iz tradicionalne arhitekture, le-ta pa temelji na preteklih značilnostih podnebja. Zato je bilo s študijo dodatno raziskano, kako se je bioklimatski potencial v času v Ljubljani spreminjal. Na podlagi merjenih podatkov smo analizirali temperaturo zraka od leta 1961 do 2015, za vsako desetletje pa ločeno izračunali bioklimatski potencial (slika 19).



Slika 19: Temperatura zunanjega zraka in število značilnih dni/noči v Ljubljani v obdobju od leta 1961 do leta 2015. Bioklimatski potencial je izračunan za navedena 10-letna obdobja.

Figure 19: External air temperature and number of characteristic days/nights in Ljubljana during the period from 1961 until 2015. Bioclimatic potential is calculated for the specified 10-year periods.

Grafikon temperatur zraka (slika 19) prikazuje, da se povprečna letna temperatura zraka (T_{avg}) v Ljubljani viša in se je v zadnjih 50 letih povišala za približno 2 K, hkrati pa narašča število tropskih noči (T_{min} ≥ 20 °C) in zelo vročih dni (T_{max} ≥ 30 °C). V zadnjih petdesetih letih se je spremenil tudi bioklimatski potencial. Delež leta, ko je potrebno senčenje (vrednost S), se je povečal z 11 na 15 %. Vse pomembnejši postajajo pasivni načrtovalski ukrepi za preprečevanje pregrevanja. Ker je glavni cilj bioklimatskega načrtovanja stavbe prilagoditi podnebju, je v analize bioklimatskega potenciala smiselno zajeti učinke podnebnih sprememb. Navedeno potrjuje tudi analiza, predstavljena na sliki 19. Zato je pomembno, da se pri načrtovanju stavb ne uporablja obstoječih načrtovalskih rešitev brez ustrezne predhodne preverbe podnebnih danosti. Pri analizah toplotnega odziva stavb imata zato pomembno vlogo tudi natančnost in obdobje izbranih podnebnih podatkov. Le-ti morda trenutnega stanja podnebja ne opisujejo ustrezno, smiselno pa je uporabiti tudi projicirane podnebne podatke, ki omogočajo, da preverimo, kakšen bo toplotni odziv stavbe v projiciranih podnebnih stanjih. Predstavljeni pristop in orodje za ugotavljanje ustreznosti pasivnih ukrepov na izbrani lokaciji je zato pri načrtovanju stavb in zmanjšanju rabe energije zelo pomembno ter pomeni pomemben, pogosto izpuščen korak pri ugotavljanju podnebne prilagojenosti stavb in načrtovanju energijsko učinkovitih stavb.

3.5 Prispevek k znanosti

Glavni prednosti bioklimatske analize, katere temelj je programsko orodje BcChart, sta njena preprosta uporaba in hitrost. Bistven prispevek k znanosti predstavljenega pristopa je upoštevanje dejanskega sončnega sevanja pri izračunih bioklimatskega potenciala z uvedbo T_{sub} in T_{PSH}. Narejene analize in ocena orodja so pokazale, da sončno sevanje poglavitno vpliva na rezultate analize bioklimatskega potenciala, zlasti v zmernem in hladnem podnebju. Navedeno je izredno pomembno pri uporabi podnebnih podatkov za ugotavljanje pomena bioklimatskih načrtovalskih strategij. Orodje BcChart je zato prosto dostopno strokovni in znanstveni javnosti. Študije primera so pokazale, da je predstavljena metodologija za določanje bioklimatskega potenciala zelo uporabno načrtovalsko orodje in pomeni korak k trajnostno grajenemu okolju, saj s tem načrtovalce v zgodnjih fazah načrtovanja stavb vodi k uporabi primernih bioklimatskih strategij oz. pasivnih načrtovalskih ukrepov. S tovrstnim analitičnim pristopom je moč preveriti ustreznost konvencionalnega pristopa načrtovanja, pri katerem se kot vir pasivnih ukrepov uporablja tradicionalna arhitektura. V ta namen so bile bolj natančno za regijo Alpe-Jadran in s 100-kilometrsko natančnostjo za celotno območje Evrope izdelane karte bioklimatskega potenciala. Kljub temu, da slednjega sicer ni mogoče neposredno povezati z energijsko učinkovitostjo stavb, pa je ta zanesljiv in nedvoumen pokazatelj potencialno učinkovitih pasivnih ukrepov, ki vplivajo na toplotni odziv stavb. S študijo smo prav tako pokazali, da je s predstavljeno metodo možno in pomembno v analize zajeti novejše podnebne podatke in vpliv podnebnih sprememb.

4 BIOKLIMATSKI POTENCIAL IN PODNEBNE SPREMEMBE

Povzetek

V poglavju povzemamo vsebino izvirnega znanstvenega članka, dostopnega v prilogi B (Pajek in Košir [50]*), katerega namen je bil preučiti učinke prisotnih in prihajajočih sprememb bioklimatskega potenciala na energijsko učinkovitost stanovanjskih stavb. Bioklimatski potencial je bil izračunan za pet lokacij v Sloveniji: Portorož, Mursko Soboto, Novo mesto, Ljubljano in Rateče, kjer smo podrobno opazovali rezultate za zadnjih pet desetletij. Rezultati so pokazali, da se je na vseh obravnavanih lokacijah letno ravnovesje med priporočenimi pasivnimi načrtovalskimi ukrepi za ogrevanje in hlajenje sčasoma spreminjalo. Uporaba načrtovalskih ukrepov za preprečevanje pregrevanja postaja vse pomembnejša. Na primer, obdobje leta, ko je za zagotavljanje toplotnega udobja potrebno senčenje, se je podaljšalo za 2–7-odstotnih točk, odvisno od lokacije. V drugem delu raziskave smo izdelali energijska modela in simulirali energijsko učinkovitost dveh primerov realne enodružinske stanovanjske stavbe, ene bioklimatsko in ene ne-bioklimatsko zasnovane, v sedanjih in projiciranih podnebnih stanjih. Analiza energijske učinkovitosti izbranih stavb je pokazala, da se bo v obdobju 2041–2070 v obeh analiziranih stavbah znižala raba energije za ogrevanje in zvišala raba energije za hlajenje ter da bodo trenutno optimalne načrtovalske rešitve v bioklimatskih stavbah postale manj učinkovite. Ugotovitev je zlasti pomembna v zmernem podnebju, kjer se prevladujoče bioklimatske strategije osredotočajo na ogrevalno sezono. Zato je treba primernost pasivnih načrtovalskih ukrepov na nekaterih lokacijah ponovno ovrednotiti. Le tako bo moč zagotoviti energijsko učinkovitost novogradenj in prenovljenih obstoječih stavb, ki bodo uspešno zagotavljale udobne bivalne pogoje tudi v naslednjih desetletjih.*

Abstract

The chapter summarises the content of the original scientific paper available in Appendix B (Pajek and Košir [50]), the purpose of which was to observe the effects of current and upcoming changes in bioclimatic potential on the energy performance of residential buildings. The bioclimatic potential was calculated for five locations in Slovenia: Portorož, Murska Sobota, Novo mesto, Ljubljana and Rateče, and the results were observed in detail for the last five decades. It was shown that the relation between the recommended passive design measures for heating and cooling changed over time at all considered locations. The use of passive measures to prevent overheating is becoming increasingly significant. For example, the period when shading is needed to provide thermal comfort has been extended by 2-7 percentage points, depending on the location. In the second part of the research, we simulated the thermal performance of two existing single-family residential buildings, one bioclimatic and one non-bioclimatic. The simulations were performed in current and projected climatic conditions. The results showed that in 2041–2070, the energy use for heating in both analysed buildings is expected to decrease while the energy use for cooling increases. Therefore, the existing optimal design solutions in bioclimatic buildings may become less efficient in future. The latter is particularly important in temperate climates, where bioclimatic strategies are focused on the heating season. Hence, the applicability of passive design measures in specific locations needs to be re-evaluated. In this way, it will be possible to ensure energy efficiency in new and in retrofitted existing buildings to provide comfortable living conditions in the future.

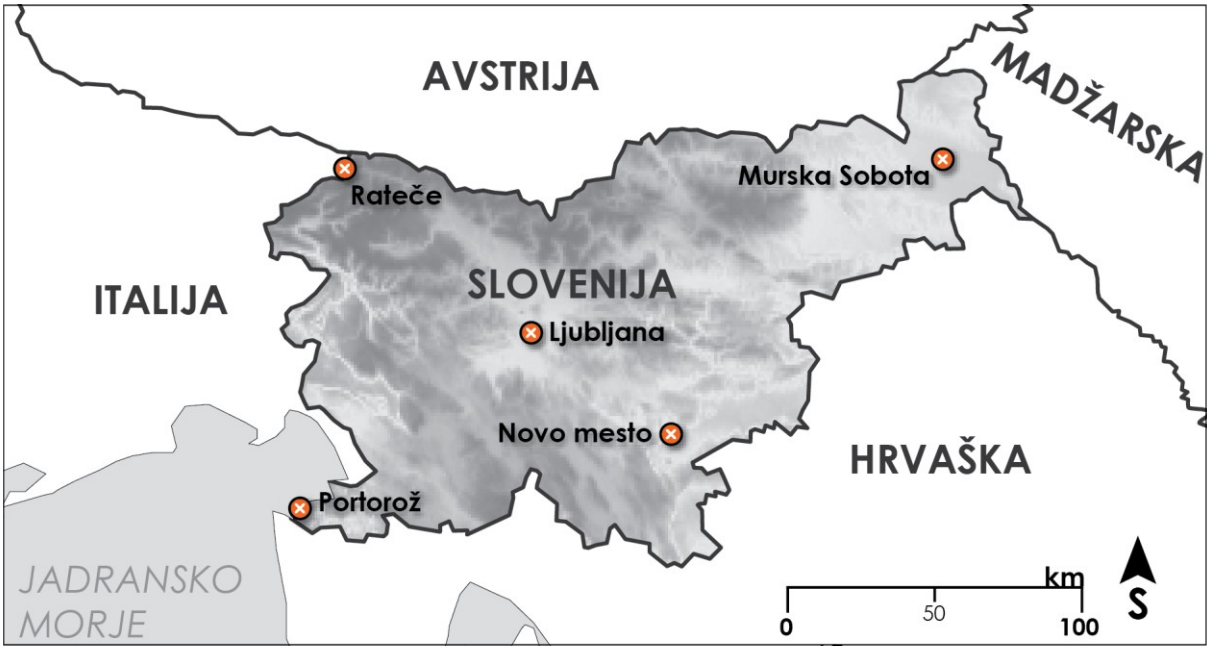
4.1 Ideja in teoretično ozadje

Glede na izzive, kot so podnebne spremembe, s katerimi se v zadnjih desetletjih sooča človeštvo, je pri bioklimatskem načrtovanju stavb potreben idejni preskok. Obstoječe vzorce načrtovanja je treba nadomestiti z novimi pristopi, ki bodo upoštevali stanje trenutnega, se hkrati pripravili na izzive prihodnjega podnebja in omogočili učinkovito prilagajanje podnebnim spremembam. Čeprav so omenjene študije v poglavju 2 široko obravnavale vpliv podnebnih sprememb na sedanje in prihodnje potrebe po energiji v poslovnih, javnih ali stanovanjskih stavbah, še vedno ostaja veliko nejasnosti o bioklimatskem potencialu, bioklimatskih stavbah ter njihovi prilagojenosti in prilagodljivosti spreminjajočemu se podnebju. Obstoječe raziskave večinoma obravnavajo le hipotetične, tipične in navadno nebioklimatske modele stavb in njihovo energijsko učinkovitost v sedanjosti, nekatere pa tudi v prihodnosti. Podnebne spremembe lahko bistveno vplivajo tudi na obstoječi stanovanjski fond, še posebej, če so bile te stavbe prilagojene preteklim podnebnim razmeram. Da bi zagotovili podnebno prilagodljivost celotnega stavbnega fonda, je treba poleg iskanja novih metod in pristopov k bioklimatskemu načrtovanju novih stavb spodbujati tudi obnovo obstoječega stavbnega fonda v skladu s sprotnim znanjem o učinkovitosti bioklimatskih strategij. V ta namen je nujno treba identificirati pretekle, sedanje in prihodnje trende bioklimatskega potenciala na izbrani lokaciji. S tem bi lažje odgovorili na vprašanje, ali bodo obstoječe smernice načrtovanja podnebno prilagojenih stavb v prihajajočih podnebnih razmerah še primerne.

Raziskava, opisana v članku Pajek in Košir [50] (priloga B), temelji na zgoraj predstavljeni ideji. Namen prispevka je bil temeljito ovrednotiti bioklimatski potencial petih izbranih lokacij v Sloveniji za zadnjih pet zaporednih desetletij, da bi s tem zaznali morebitne spremembe v bioklimatskem potencialu, ki so posledica podnebnih sprememb, in nato prepoznali morebitne vzorce vpliva le-teh. Bioklimatski potencial je bil na podlagi pridobljenih izmerjenih podatkov in vzorca o segrevanju ozračja v preteklih desetletjih ocenjen tudi za naslednji dve desetletji. Poleg tega so bile opravljene simulacije rabe energije dveh realnih primerov stavbe, ene bioklimatske in ene nebioklimatske, pri čemer smo na podlagi podnebnih projekcij ocenili njun toplotni odziv v različnih podnebnih scenarijih. Glavna ideja raziskave je bila z izračunom bioklimatskega potenciala na posamezni lokaciji ovrednotiti pomembnost izbranih pasivnih načrtovalskih ukrepov, ki se najpogosteje uporabljajo v zmernem podnebju, in s pomočjo simulacij rabe energije za ogrevanje in hlajenje stavbe še njihov vpliv na energijsko učinkovitost stavb v sedanjosti in prihodnosti. Osredotočili smo se tudi na razliko v toplotnem odzivu bioklimatske in nebioklimatske stavbe. Te ugotovitve pomembno vplivajo na odločitve pri načrtovanju (bioklimatskih) stavb in na razvoj energetske politike.

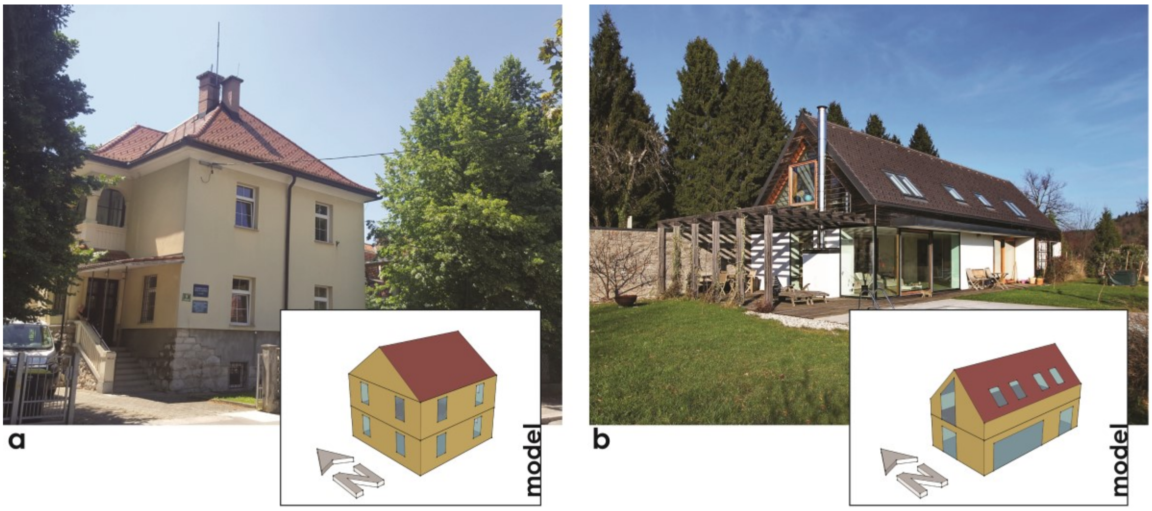
4.2 Metodologija raziskave

Raziskava temelji na bioklimatski analizi izbranih lokacij v Sloveniji v časovnem okviru nekaj desetletij in je nadgrajena s študijo toplotnega odziva (energijske učinkovitosti) dveh primerov realne enodružinske stanovanjske stavbe na eni izmed lokacij. S tem postopkom je mogoče oceniti obseg vpliva podnebnih sprememb na bioklimatski potencial in priporočene pasivne načrtovalske ukrepe, analiza toplotnega odziva dveh primerov stavb pa je omogočila ovrednotenje bioklimatskega načrtovanja s prisotnimi pasivnimi ukrepi glede na podnebne spremembe. V ta namen je bilo izbranih pet lokacij v Sloveniji, ki predstavljajo značilne podnebne razmere v zmernem podnebnem pasu (podnebni tip Cfb). Obravnavane lokacije so predstavljene na sliki 20. Analiza bioklimatskega potenciala izbranih lokacij je bila izdelana na podlagi merjenih podnebnih podatkov med letoma 1961 in 2015. Pridobljeni so bili naslednji podnebni podatki: povprečna (T_{avg}), povprečna najvišja ($T_{max,avg}$) in povprečna najnižja ($T_{min,avg}$) letna temperatura zraka, povprečna najvišja ($T_{max,i}$) in povprečna najnižja ($T_{min,i}$) dnevna temperatura zraka in relativna vlažnost ($RH_{max,i}$ in $RH_{min,i}$) za vsak mesec ter povprečno ($G_{avg,i}$) in povprečno najvišjo ($G_{max,i}$) dnevno gostoto moči sončnega sevanja na vodoravni ravnini za vsak mesec. Vsi podatki so bili pridobljeni iz arhiva avtomatskih vremenskih postaj Agencije Republike Slovenije za okolje [212].



Slika 20: Izbrane lokacije v Sloveniji.
Figure 20: Selected locations in Slovenia.

Na podlagi podnebnih podatkov je bil za izbranih pet lokacij in za vsako obdobje, s pomočjo metode in orodja BcChart, ki smo ga izdelali in je podrobneje predstavljeno v poglavju 3, izračunan bioklimatski potencial. Dobljene rezultate analize bioklimatskega potenciala smo želeli povezati s praktičnimi posledicami za energijsko učinkovitost stanovanjskih stavb, zato smo poiskali in izbrali dve tipični enodružinski stanovanjski stavbi, katerih toplotni odziv bi simulirali na lokaciji z največjimi spremembami bioklimatskega potenciala. Prva stavba (slika 21a) je tipična nebioklimatska stavba (označena kot ne-BK stavba), ki jo pogosto najdemo v slovenskem stavbnem fondu. Druga (slika 21b) je tipična bioklimatska stavba (označena kot BK stavba), ki je pogost primer sodobne energijsko učinkovite stavbe, za katero velja, da je dober primer bioklimatske arhitekture. Obe izbrani stavbi sta bili uporabljeni kot podlaga za izdelavo geometrijskih simulacijskih modelov, s katerimi smo izračunali toplotni odziv (geometrijska modela sta predstavljena na sliki 21). Uporabna tlorisna površina modelov je enaka in znaša 162 m^2. Stavba na sliki 21a, ki ni bioklimatska (ne-BK stavba), ima kvadratni tloris dimenzij 9,0 x 9,0 m, medtem ko ima bioklimatska stavba na sliki 21b (BK stavba) pravokoten tloris dimenzij 6,5 x 12,5 m. Obe stavbi imata dve nadstropji in sta orientirani v smeri sever-jug, pri BK stavbi je daljša fasada obrnjena proti jugu. Pri ne-BK stavbi je razmerje med tlorisno površino in površino oken (*WFR*) enako 15 % (25,2 m^2), pri BK stavbi pa 24,5 % (39,7 m^2). Razporeditev oken v stavbi, ki ni bioklimatsko načrtovana, je skoraj enakomerna s 7,2 m^2 oken, usmerjenih proti jugu, vzhodu in zahodu, ter s 3,6 m^2 oken, usmerjenih proti severu. V primeru BK stavbe so okna razporejena in skoncentrirana na površinah, ki omogočajo koriščenje sončne energije. V tem primeru površina oken, usmerjenih proti jugu, skupaj s strešnimi okni znaša 25,4 m^2, preostalih 14,3 m^2 oken pa je razporejenih na vzhodni in zahodni fasadi.



Slika 21: Primera dveh tipičnih enostanovanjskih stavb s pripadajočima geometrijskima modeloma.
Figure 21: Examples of two typical residential buildings with the corresponding geometric models.

Za vsak geometrijski model smo predpostavili dva različna tipa toplotnega ovoja stavbe. Prvi tip, označen kot »STAR«, je ovoj z lastnostmi tipične stavbe, zgrajene v sedemdesetih letih prejšnjega stoletja. Drugi tip ovoja, označen kot »NOV«, izpolnjuje minimalne zahteve veljavnega slovenskega Pravilnika o učinkoviti rabi energije v stavbah [210] in Tehnične smernice o učinkoviti rabi energije v stavbah [213]. Lastnosti obeh konfiguracij toplotnega ovoja stavbe ter podatki o toplotnih dobitkih notranjih virov (uporabniki, naprave, svetila), prezračevanju ter nastavljenih temperaturah ogrevanja in hlajenja so predstavljeni v preglednici 4. Vpliv senčenja oken, kot enega od najpogosteje uporabljanih pasivnih načrtovalskih ukrepov za preprečevanje pregrevanja, smo zasnovali z uporabo zunanjih premičnih aluminijastih senčil (žaluzij) na vseh oknih. Senčenje imitira obnašanje uporabnikov in je aktivno od 1. maja do 30. septembra, pri čemer ob presežnem sončnem sevanju v ravnini oken (> 120 W/m^2) žaluzije zastrejo celotno površino okna, lamele pa se nagnejo pod kotom 45 °.

Za lokacijo, kjer se je pokazala največja sprememba v bioklimatskem potencialu, so bile narejene simulacije toplotnega odziva oz. energijske učinkovitosti posameznega modela stavbe z uporabo orodja EnergyPlus [138] in vmesnika OpenStudio [209]. Simulacije so bile izvedene z 10-minutnim časovnim korakom, pri čemer so bili uporabljeni t. i. idealni grelci (ang. *ideal air loads*), torej smo spremljali potrebno energijo za ogrevanje in hlajenje stavbe, brez vpliva učinkovitosti ogrevalnega in hladilnega sistema. Urni podnebni podatki so bili pridobljeni s pomočjo spletnega generatorja EPW datotek (*EnergyPlus Weather* format) na podlagi tipičnega meteorološkega leta (TMY), ki ga zagotavlja Skupno raziskovalno središče (ang. *Joint Research Centre*, JRC) pri Evropski komisiji [214]. EPW datoteka t. i. trenutnega stanja je bila izdelana z uporabo izmerjenih podatkov za obdobje med 2006 in 2015. Ista datoteka je bila nato uporabljena za izdelavo projiciranih podnebnih EPW datotek za obdobje 2011–2040 (poimenovano 2020) in obdobje 2041–2070 (poimenovano 2050). Za izdelavo projiciranih datotek smo uporabili prosto dostopno orodje CCWorldWeatherGen [215], ki za izdelavo projiciranih podnebnih datotek uporablja podnebni model HadCM3 (*Hadley Center Coupled Model*, različica 3) in IPCC SRES A2 scenarij podnebnih sprememb (za opis in teoretično ozadje glej poglavji 2.2.1.2 in

2.3.3). Rezultati za obdobje 2006–2015 so bili uporabljeni kot izhodišče in primerjani z izračunano rabo energije za obdobja 2020 in 2050.

Preglednica 4: Značilnosti stavbnega ovoja, prezračevanja, dobitkov notranjih virov in nastavljene temperature.
Table 4: Building envelope characteristics, ventilation, internal heat gains and temperature set-point parameters.

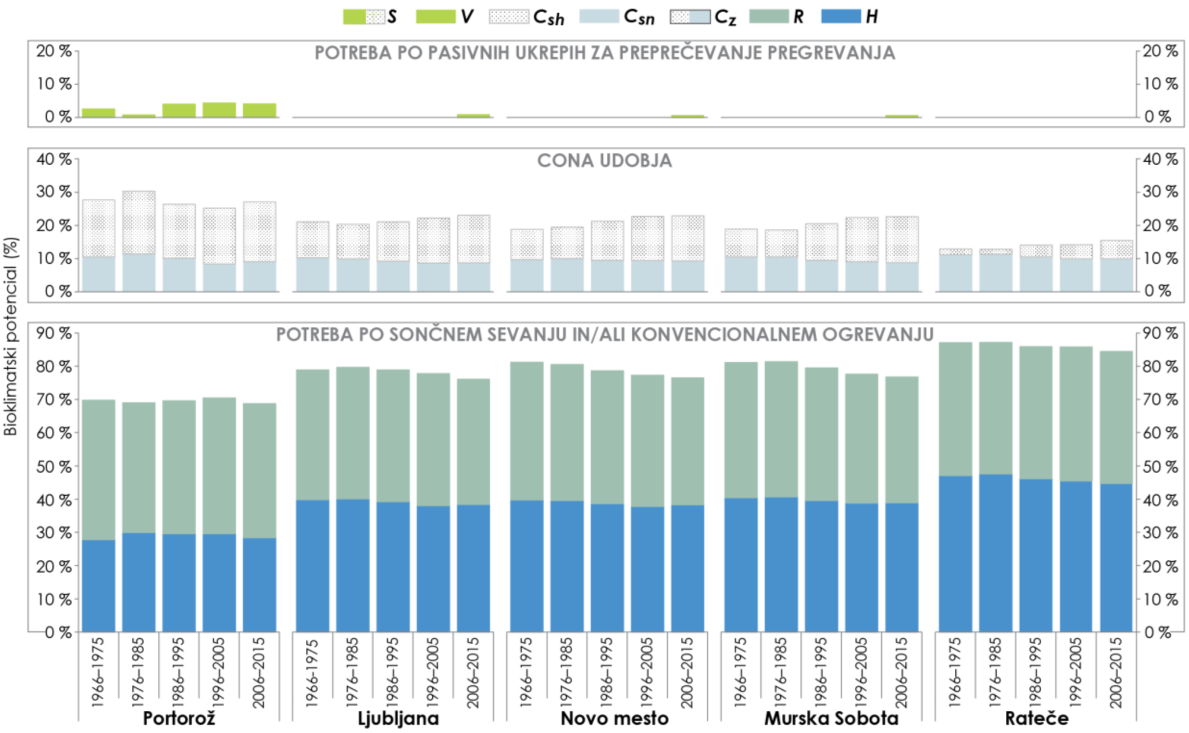
značilnost	parameter	enota	stavbni ovoj	
			STAR	NOV
stavbni ovoj	$U_{\text{zunanja stena}}$	(W/m²K)	0,90	0,28
	U_{streha}	(W/m²K)	0,60	0,20
	U_{tla}	(W/m²K)	0,90	0,30
	U_{okna}	(W/m²K)	2,50	0,70
	g_{okna}	(-)	0,75	0,53
prezračevanje	n	(ACH)	0,50 [a] (0,80, 1. maj do 30. september)	
dobitki notranjih virov	uporabniki	(W)	280 [b]	
	naprave	(W)	972 [c]	
	razsvetljava	(W)	486 [c]	
nastavljena temperatura	$T_{\text{ogrevanje}}$	(°C)	21.0	
	T_{hlajenje}	(°C)	26.0	

[a] ustreza minimalnim zahtevam EN 15251[216].
[b] 70 W/uporabnika [217], 4 uporabniki, urnik glede na ASHRAE standard 90.1-2004. [218].
[c] vrednost in urnik glede na ASHRAE standard 90.1-2004 [218].

V analizi energijske učinkovitosti je bila upoštevana potrebna energija za ogrevanje (Q_{NH}) in hlajenje (Q_{NC}), normirana na m^2 talne površine. Izračunana je bila tudi skupna potrebna energija ($Q_T = Q_{NH} + Q_{NC}$). Energijska učinkovitost vseh simuliranih modelov je bila ocenjena glede na geometrijo stavbe in konfiguracijo stavbnega ovoja, kjer so bili variirani parametri, kot so toplotne značilnosti stavbnega ovoja in optične lastnosti oken (npr. STAR, NOV), ter glede na izbrane bioklimatske strategije oz. pasivne ukrepe (senčenje, orientacija in površina oken, oblika stavbe), ki so bili prisotni v dveh izbranih realnih primerih stavb.

4.3 Rezultati

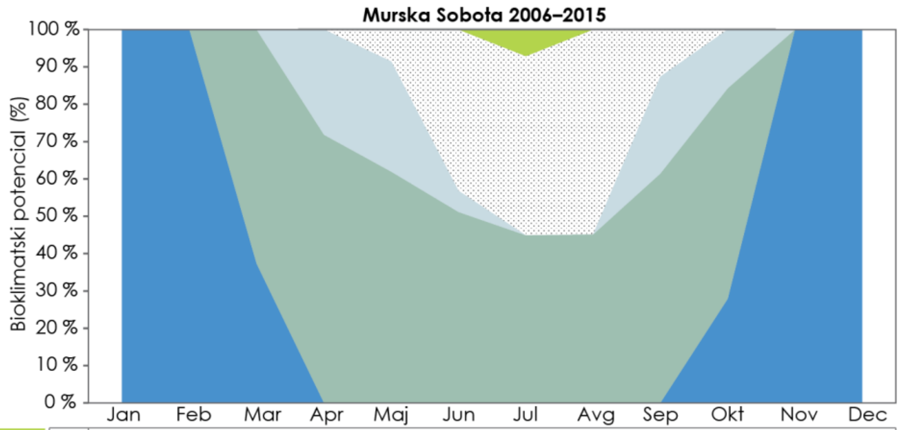
Podrobni rezultati raziskave so predstavljeni v članku Pajek in Košir [50] (priloga B), to poglavje pa povzema le glavne ugotovitve. Bioklimatski potencial smo za vsako lokacijo izračunali ločeno za vsako obravnavano desetletje med 1966 in 2015. Rezultati so predstavljeni na sliki 22. Če izračunan bioklimatski potencial na vseh lokacijah v zadnjem obravnavanem desetletju (2006–2015) primerjamo s tistim v prvem (1966–1975), lahko opazimo, da se na vseh lokacijah s časom daljša obdobje v letu, ko je dosežena cona udobja ($C_z = C_{sh} + C_{sn}$) (glej sliko 22). Poleg tega sta se bistveno spremenila tudi način, kako se doseže cona udobja, in razmerje med C_{sh} in C_{sn}. Sprememba je najbolj očitna v Murski Soboti, kjer se je razmerje C_{sh}/C_{sn} z 0,80 v letih 1966–1975 spremenilo na 1,57 v zadnjem desetletju (2006–2015). To nakazuje, da je bilo v preteklosti toplotno udobje na letni ravni pogosteje doseženo z zajemom sončne energije (npr. neposredni sončni dobitki skozi transparentne elemente) kot s senčenjem oken v toplejši polovici leta. V zadnjem desetletju se je zaradi segrevanja ozračja razmerje spremenilo, cona udobja pa je na letni ravni zato veliko pogosteje dosežena s senčenjem kot pa z zajemom sončnega sevanja. Podobno je bilo ugotovljeno tudi na drugih obravnavanih lokacijah, razen v Portorožu, kjer je bilo senčenje vseskozi prevladujoč ukrep. V Portorožu se je razmerje C_{sh}/C_{sn} povečalo z 1,76 v obdobju 1966–1975 na 2,03 v obdobju 2006–2015. Višanje vrednosti C_{sh} pomeni, da kljub temu, da se je na vseh analiziranih lokacijah podaljšalo obdobje, ko je cono toplotnega udobja moč doseči s pasivnimi ukrepi, je treba vse večjo pozornost namenjati obdobju hlajenja, torej toplejši polovici leta. Poleg tega se zmanjšuje pomen koriščenja sončnih dobitkov za namen pasivnega sončnega ogrevanja (vrednosti C_{sn} in R), povečuje pa se pomen naravnega prezračevanja v topli polovici leta (pojav vrednosti V v Ljubljani, Novem mestu in Murski Soboti). Slednje je običajno povezano s sredozemskim podnebjem (npr. Portorož). Na podlagi letne analize bioklimatskega potenciala zato lahko ugotovimo, da se zadnjih pet desetletij konstantno veča pomen bioklimatskih strategij za preprečevanja pregrevanja (višanje vrednosti C_{sh} in V) ter hkrati manjša pomen pasivnih ukrepov za zadrževanje in zajemanje toplote (nižanje vrednosti C_{sn}, R in H). Ugotovimo lahko, da če stavbe niso zasnovane z ustreznimi pasivnimi ukrepi za preprečevanje pregrevanja, kot je npr. učinkovito senčenje, na vseh obravnavanih lokacijah obstaja nevarnost pregrevanja in posledično toplotno neudobje.



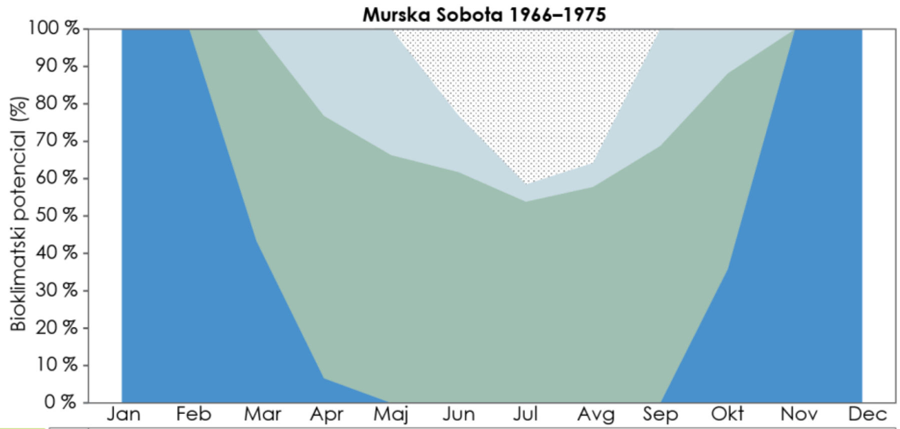
Slika 22: Letni bioklimatski potencial analiziranih lokacij, izračunan za vsako desetletje. V – učinkovito je naravno prezračevanje in/ali visoka toplota masa stavbe s hkratnim senčenjem, C_{sh} – toplotno udobje je doseženo s senčenjem, S (tj. V + C_{sh}) – potrebno je senčenje, C_{sn} – toplotno udobje je doseženo z zajemom sončne energije, C_z (tj. C_{sh} + C_{sn}) – cona udobja, R – učinkovito je pasivno sončno ogrevanje, H – potrebno je konvencionalno ogrevanje stavbe in zadrževanje toplote.

Figure 22: The yearly bioclimatic potential of the analysed locations, calculated separately for each decade. V – shading and high thermal mass and/or natural ventilation needed, C_{sh} – comfort achieved with shading, S (i.e. V + C_{sh}) – shading needed, C_{sn} – comfort achieved by using solar irradiation, C_z (i.e. C_{sh} + C_{sn}) – comfort zone, R – potential for passive solar heating, H – conventional heating and heat retention is needed.

Zaradi ugotovljenih sprememb bioklimatskega potenciala na letni ravni smo le-tega podrobneje raziskali še na mesečni ravni. Najbolj značilno spremembo v bioklimatskem potencialu in priporočenih pasivnih ukrepih v analiziranih petih desetletjih smo zaznali v Murski Soboti, pri čemer je trend sprememb primerljiv s tistim v Novem mestu in Ljubljani. Primerjava bioklimatskega potenciala na mesečni ravni za Mursko Soboto za prvo (1966–1975) in zadnje (2006–2015) obravnavano desetletje je prikazana na sliki 23. Preostali rezultati so dostopni v članku Pajek in Košir [50] (priloga B). Primerjava med obdobjema na sliki 23 je pokazala, da se na letni ravni zaznan padec vrednosti R in H (slika 22) večinoma zgodi v času prehoda med obdobjem ogrevanja in hlajenja, torej v prehodnih mesecih, kot sta npr. april in oktober. Na primer, bioklimatski potencial v Murski Soboti se je zaradi segrevanja ozračja v aprilu spremenil v smeri lažjega zagotavljanja toplotnega udobja, pri čemer se je vrednost H zmanjšala s 6,6 na 0,0 %. Posledično so se povečale vrednosti C_{sn} in R. Poleg tega je mogoče v zadnjih 50 letih v poletnih mesecih (junij, julij in avgust) opaziti znatno povečanje vrednosti S (čas, ko je potrebno senčenje, S = V + C_{sh}). Za Mursko Soboto se je vrednost v juniju skoraj podvojila in se je s 23,1 % (1966–1975) zvišala na 43,2 % (2006–2015).



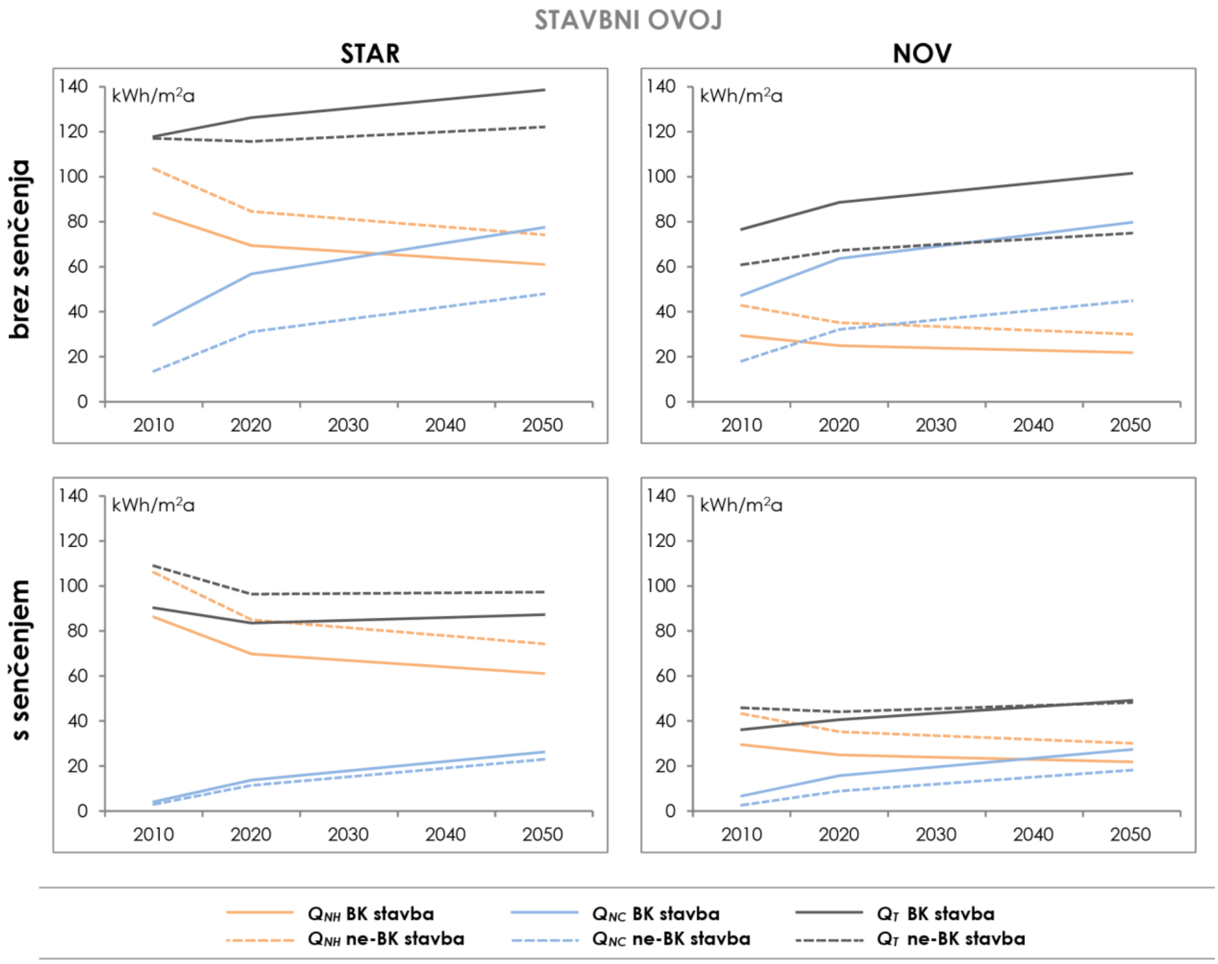
	Jan	Feb	Mar	Apr	Maj	Jun	Jul	Avg	Sep	Okt	Nov	Dec
V	0.0	0.0	0.0	0.0	0.0	0.0	**9.6**	0.0	0.0	0.0	0.0	0.0
C_{sh}	0.0	0.0	0.0	0.0	**8.5**	**43.2**	**46.7**	**54.8**	**12.6**	0.0	0.0	0.0
C_{sn}	0.0	0.0	0.0	**28.3**	**29.5**	**5.7**	0.0	0.0	**26.0**	**15.7**	0.0	0.0
R	0.0	0.0	**62.7**	**71.7**	**62.0**	**51.1**	**43.7**	**45.2**	**61.4**	**56.4**	0.0	0.0
H	**100.0**	**100.0**	**37.3**	0.0	0.0	0.0	0.0	0.0	0.0	**27.9**	**100.0**	**100.0**
S	0.0	0.0	0.0	0.0	**8.5**	**43.2**	**53.6**	**54.8**	**12.6**	0.0	0.0	0.0



	Jan	Feb	Mar	Apr	Maj	Jun	Jul	Avg	Sep	Okt	Nov	Dec
V	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
C_{sh}	0.0	0.0	0.0	0.0	0.0	**23.1**	**41.6**	**35.8**	0.0	0.0	0.0	0.0
C_{sn}	0.0	0.0	0.0	**23.2**	**33.7**	**15.1**	**4.6**	**6.4**	**31.2**	**11.8**	0.0	0.0
R	0.0	0.0	**56.7**	**70.2**	**66.3**	**61.8**	**53.8**	**57.8**	**68.8**	**52.4**	0.0	0.0
H	**100.0**	**100.0**	**43.3**	**6.6**	0.0	0.0	0.0	0.0	0.0	**35.8**	**100.0**	**100.0**
S	0.0	0.0	0.0	0.0	0.0	**23.1**	**41.6**	**35.8**	0.0	0.0	0.0	0.0

Slika 23: Mesečna razčlenitev bioklimatskega potenciala za Mursko Soboto v obdobjih med 1966 in 1975 (spodaj) ter med 2006 in 2015 (zgoraj). Razlaga oznak bioklimatskega potenciala je v opisu slike 22.
Figure 23: Monthly breakdown of the bioclimatic potential for the location of Murska Sobota, during the periods of 1966 to 1975 (bottom) and 2006 to 2015 (top). The description of bioclimatic potential is located in the Figure 22 caption.

Poleg splošnega povečanja vrednosti S, senčenje ni več omejeno le na poletne mesece, ampak se potreba po senčenju v zadnjem času pojavlja tudi v prehodnih mesecih, kot sta maj in oktober, hkrati se zaradi višjih temperatur zraka v toplejših mesecih niža vrednost C_{sn}. Zato je očitno, da sončno sevanje na letni ravni ni več zaželeno oz. potrebno v enaki meri, kot je bilo v preteklosti. Izračunane vrednosti S rastejo tudi v Ratečah, najhladnejši od analiziranih lokacij. Tam se je vrednost potrojila, z 1,8 % v letih 1966–1975 na 5,6 % v zadnjem analiziranem desetletju (2006–2015). Na podlagi zgoraj opisanih rezultatov bioklimatskega potenciala so bile simulacije trenutnega in predvidenega toplotnega odziva izbranih dveh stanovanjskih stavb (prikazanih na sliki 21), narejene s podnebnimi podatki Murske Sobote (podobni učinki podnebnih sprememb so bili ugotovljeni tudi za Ljubljano in Novo mesto). Analiza energijske učinkovitosti na sliki 24 zajema potrebno energijo za ogrevanje (Q_{NH}) in hlajenje (Q_{NC}) na m^2 uporabne tlorisne površine stavbe ter kumulativno energijo, potrebno za kondicioniranje stavbe ($Q_T = Q_{NH} + Q_{NC}$). Energijska učinkovitost obeh tipov analiziranih stavb (BK stavba, ne-BK stavba) je bila ocenjena glede na tip toplotnega ovoja stavbe in optičnih lastnosti oken (tj. STAR oz. NOV) ter uporabo senčenja (s senčenjem, brez senčenja).

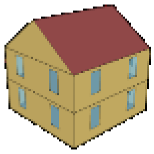
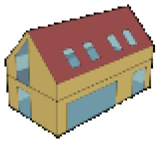
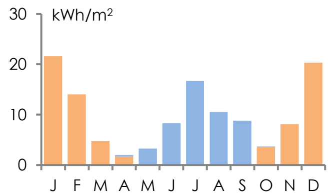
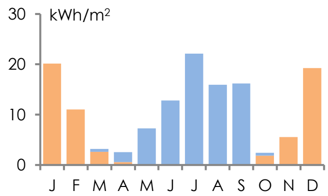
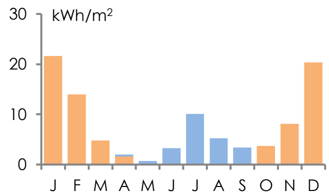
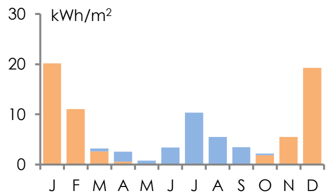
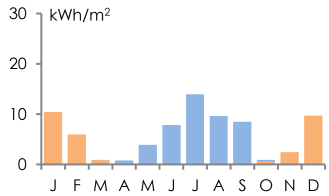
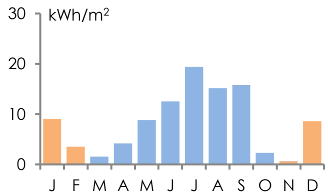
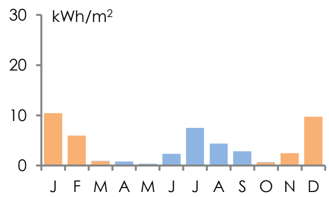
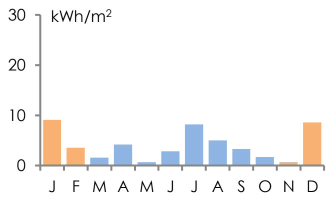


Slika 24: Trendi sedanje in prihodnje predvidene rabe energije analiziranih modelov stavb v Murski Soboti.
Figure 24: Trends of present and future projected energy use of the analysed building models in Murska Sobota.

Rezultati na sliki 24 prikazujejo, da bodo predvidene podnebne in posledične spremembe v bioklimatskem potencialu bistveno vplivale na energijsko učinkovitost obravnavanih modelov stavb v prihodnosti. V prihodnjih desetletjih je mogoče pričakovati opazno zmanjšanje potrebe po energiji za

ogrevanje; tako za bioklimatsko načrtovano (BK) stavbo kot za nebioklimatsko (ne-BK). Pri dobro toplotno izoliranem stavbnem ovoju (tj. NOV) je predvidena vrednost Q_{NH} za BK stavbo glede na trenutno stanje (29,5 kWh/m^2) v obdobju 2020 za 15 % (4,5 kWh/m^2) nižja, v obdobju 2050 pa za 26 % (7,6 kWh/m^2) nižja. Za ne-BK stavbo je predvideno znižanje Q_{NH} še nekoliko večje. Le-to je, glede na trenutno stanje (43,3 kWh/m^2), v obdobju 2020 19 % (8,1 kWh/m^2) nižje in v obdobju 2050 31 % (13,23 kWh/m^2) nižje, kot bi bilo v trenutnih podnebnih razmerah (2006–2015). Podoben trend je mogoče opaziti tudi pri toplotno manj izoliranem tipu ovoja (tj. STAR).
Simulacije rabe energije so potrdile z bioklimatsko analizo zaznano povečanje potrebe po preprečevanju pregrevanja. Primerjava modelov s senčenjem in brez njega (slika 24, preglednica 5) je pokazala, da bo v obeh primerih stavb v obdobju 2050 začela prevladovati potreba po hlajenju. Predvideno je, da se bo v primeru BK stavbe s senčenjem in ustrezno toplotno izoliranim ovojem (tj. NOV) Q_{NC} povečala s 6,7 kWh/m^2 (obdobje 2006–2015) na 27,3 kWh/m^2 v obdobju 2050, kar je povečanje za 308 %. Učinek je še večji v primerih brez senčenja, kjer v BK stavbi močno prevladuje potreba po hlajenju. Pri ne-BK stavbi je vpliv podnebnih sprememb na rabo Q_{NC} zaradi manjše površine oken in njihove razpršenosti po orientacijah bistveno manjši. Q_{NC} za primer BK stavbe s senčenjem in toplotno izoliranim ovojem (NOV) v obdobju 2006—2015 znaša 2,6 kWh/m^2, medtem ko je predvidena vrednost v obdobju 2020 enaka 8,9 kWh/m^2, v obdobju 2050 pa 18,2 kWh/m^2. Vrednost Q_T večinoma izkazuje naraščajoči trend. V primeru stavbe s toplotno izoliranim ovojem (tj. NOV) in zasenčenimi okni, ki je najbolj realistična od kombinacij, je predvidena vrednost Q_T v obdobju 2050 skoraj enaka pri BK (49,2 kWh/m^2) in pri ne-BK stavbi (48,2 kWh/m^2). Slednje dokazuje, da bodo prednosti bioklimatsko načrtovane stavbe (BK), ki je zasnovana tako, da omogoča zajem sončne energije v ogrevalni sezoni, izničene zaradi hkratne povišane rabe energije za hlajenje zaradi segrevanja ozračja. Predstavljeni rezultati so specifični za izbrani tip in lastnosti simulirane stavbe, pri čemer so parametri, kot so oblika stavbe, toplotna kapaciteta, stopnja naravnega prezračevanja ipd., omejeni na izbrane vrednosti.

Preglednica 5: Rezultati simulacij energijske učinkovitosti analiziranih stavb v predvidenih podnebnih razmerah (obdobje 2050) v Murski Soboti.
Table 5: Energy performance simulation results of the analysed buildings, conducted under the predicted future (2050) climatic conditions for the location of Murska Sobota.

obdobje 2050 (2041–2070)				**ne-BK stavba**	**BK stavba**
					
Tip ovoja					
STAR	**brez senčenja**	Q_{NH}	(kWh/m^2)	74,22	61,06
		Q_{NC}	(kWh/m^2)	47,93	77,51
		Q_T	(kWh/m^2)	122,15	138,57
					
	s senčenjem	Q_{NH}	(kWh/m^2)	74,32	61,14
		Q_{NC}	(kWh/m^2)	22,96	26,17
		Q_T	(kWh/m^2)	97,28	87,31
					
NOV	**brez senčenja**	Q_{NH}	(kWh/m^2)	30,04	21,83
		Q_{NC}	(kWh/m^2)	44,92	79,72
		Q_T	(kWh/m^2)	74,96	101,55
					
	s senčenjem	Q_{NH}	(kWh/m^2)	30,06	21,83
		Q_{NC}	(kWh/m^2)	18,17	27,32
		Q_T	(kWh/m^2)	48,23	49,15
					
	Legenda			Q_{NH} (oranžno)	Q_{NC} (modro)

4.4 Razprava

Analiza bioklimatskega potenciala je pokazala naraščajoči trend pomena glede preprečevanja pregrevanja pri načrtovanju novih in obnovi obstoječih stavb. Narašča pomen strategij za preprečevanje pregrevanja stavb, hkrati pa se krajša čas za potrebno pasivno sončno ogrevanje (zajem sončne energije). Opisani trend je v nasprotju s prevladujočimi smernicami pri načrtovanju stavb v zmernem podnebju, kjer stavbe optimiziramo predvsem za pasivni zajem sončne energije. Tudi bioklimatski pasivni ukrepi, ki jih najdemo v tradicionalni arhitekturi, so večinoma prilagojeni bistveno drugačnim podnebnim razmeram, kot so današnje. Rezultati analize energijske učinkovitosti obeh izbranih enostanovanjskih stavb so pokazali trend naraščajočega pomena hlajenja, kar se kaže v večji kumulativni rabi energije analiziranih stavb. Bioklimatsko načrtovane stavbe (npr. BK stavba), zasnovane po bioklimatskih načelih zmernega podnebja, v trenutnih podnebnih razmerah (2006–2015) glede energijske učinkovitosti prekašajo običajne stavbe (npr. ne-BK stavba). Kljub temu lahko pričakujemo, da se bo prednost v naslednjih desetletjih zmanjšala ali izničila, saj segrevanje ozračja vpliva na relativni pomen načrtovalskih strategij, posledično pa se bo optimum z uporabe ukrepov pasivnega sončnega ogrevanja (npr. velike transparentne površine, nizka toplotna prehodnost stavbnega ovoja itd.) preusmeril v uporabo ukrepov za preprečevanje pregrevanja (npr. senčenje oken, manjše transparentne površine, visoke stopnje naravnega prezračevanja itd.). Prilagajanje stanju podnebja v prihodnosti ima zato velik pomen, kar je zlasti pomembno pri izbiri pasivnih načrtovalskih ukrepov v bioklimatskih stavbah; rezultati pa so pokazali, da bo predvideno segrevanje ozračja zelo vplivalo na energijsko učinkovitost stavb. Prvič, z naraščanjem pomena preprečevanja pregrevanja stavb je zaradi višjih temperatur zraka vprašljivo toplotno udobje v obstoječem stavbnem fondu, saj so bile te stavbe zasnovane na podlagi znanja in podatkov o preteklem podnebnem stanju, pri čemer načrtovalci niso poudarjali pomena preprečevanja pregrevanja. Pogosto se zaradi neudobnih razmer v obstoječe stavbe vgrajujejo sistemi mehanskega hlajenja, zaradi česar se kaže vse večja potreba po energiji za hlajenje in s tem niža energijska učinkovitost stavbe. Drugič, rezultati so pokazali, da je pri načrtovanju novih stavb kopiranje preteklih in sedanjih vzorcev bioklimatskega načrtovanja, ki so pretežno osredotočeni na pasivno ogrevanje, tvegano, saj so bile v obravnavanem obdobju naslednjih 50 let s pomočjo bioklimatske analize zaznane bistvene spremembe v bioklimatskem potencialu in priporočenih pasivnih ukrepih. Simulacije energijske učinkovitosti pa so potrdile, da bodo trenutno optimalne rešitve načrtovanja bioklimatskih stavb v obdobju 2050 postale manj učinkovite. Zato je potrebno, da načrtovalci stavb z uporabo trenutnih in predvidenih podnebnih podatkov kritično ocenijo ustreznost pasivnih načrtovalskih ukrepov, ustreznih za doseganje energijske učinkovitosti stavb na neki lokaciji. V vseh analiziranih primerih je bila v prihodnosti predvidena raba energije za ogrevanje nižja, raba energije za hlajenje pa višja kot trenutno. Spremenjeno razmerje med rabo energije za ogrevanje in hlajenje stavb bo pomembno vplivalo tudi na oskrbo z energijo. S povečanim povpraševanjem po energiji za hlajenje bi se opazno povečalo povpraševanje po električni energiji, kar bi povečalo obremenitev sistemov za oskrbo z le-to in povečalo emisije CO_2 zaradi večjega ogljičnega odtisa električne energije.

Na koncu je treba poudariti, da rezultati predstavljene bioklimatske analize pomenijo splošne smernice za analizirana tipa in lokacijo stavbe, saj je bil bioklimatski potencial izračunan za tipično stanovanjsko stavbo na petih urbanih lokacijah. Ena od omejitev uporabljene metodologije za izračun bioklimatskega potenciala je, da pri izračunu ni možno upoštevati vpliva dobitkov notranjih virov. Druga omejitev raziskave je, da lastnosti vetra niso neposredno zajete v analizo bioklimatskega potenciala, temveč je z analizo ugotovljena le potreba po naravnem prezračevanju (vrednost V), kar je mogoče doseči z vetrom, pa tudi s prepihom, prezračevanjem s pomočjo vzgona in z mehanskim prezračevanjem. Omejitev raziskave je tudi iz analize izključena raba energije za umetno razsvetljavo, ki je posledica slabe osvetljenosti z dnevno svetlobo, na kar vplivajo lastnosti in velikost transparentnih elementov ter raba senčil, ki smo jih med drugim variirali v analizi.

4.5 Prispevek k znanosti

Rezultati raziskave veljajo kot pomemben prispevek pri upoštevanju podnebnih analiz in učinka podnebnih sprememb v procesu načrtovanja stavb. Pri tem vse bolj pomembni postajajo pasivni ukrepi za preprečevanje pregrevanja, ki bi jih bilo treba upoštevati pri načrtovanju novih stavb in tudi pri energijskih prenovah. Čeprav je zakonodaja na tem področju večinoma osredotočena na ogrevalno sezono in preprečevanje toplotnih izgub, bodo v prihodnosti podnebno prilagojene stavbe v zmernem podnebju soočene s pregrevanjem. Skladno s tem ugotovitve raziskave kažejo na potrebo po idejnem preskoku v bioklimatskem načrtovanju stavb, da bi lahko držali korak s sedanjimi in prihodnjimi izzivi, ki jih predstavljajo podnebne spremembe. Le-te pomenijo veliko nevarnost za zmanjšanje energijske učinkovitosti in toplotnega udobja v stavbah. Rezultati in ugotovitve so podlaga in usmeritve za nadaljnje raziskovanje na tem področju (poglavje 5), hkrati pa postavljajo temelje za strateške odločitve pri načrtovanju in energijski prenovi stavbnega fonda, pri čemer imajo ključno vlogo pasivni načrtovalski ukrepi.

5 PODNEBNE SPREMEMBE, ENERGIJSKA UČINKOVITOST STAVB IN VPLIV PASIVNIH UKREPOV

Povzetek

Poglavje povzema izvirni znanstveni članek v prilogi C (Pajek in Košir [51]*), katerega glavni cilj je preučiti vpliv podnebnih sprememb na energijsko učinkovitost stavb ter raziskati vpliv pasivnih načrtovalskih ukrepov na rabo energije za ogrevanje in hlajenje enostanovanjskih stavb v izbranih reprezentativnih podnebjih v Evropi. Na primeru enostanovanjske stavbe smo z variacijo parametrov izdelali 496.800 različnih kombinacij pasivnih načrtovalskih ukrepov. Le-te smo opisali z energijskimi modeli, njihov toplotni odziv pa simulirali na osmih lokacijah in v štirih različnih podnebnih stanjih. Parametrična študija je vsebovala parametre, kot so toplotna prehodnost ovoja, površina oken, razporeditev oken, faktor oblike stavbe, toplotna kapaciteta stavbe, vpojnost zunanjih površin za sončno sevanje in hlajenje z naravnim prezračevanjem. Simulacije rabe energije so bile narejene glede na predvidene podnebne spremembe do konca 21. stoletja. Ugotovljeno je bilo, da se bo skupna raba energije stavb v hladnih in večini zmernih podnebij v prihodnosti zmanjšala, v toplih podnebjih pa povečala. S pomočjo rezultatov je bil prikazan vpliv posameznih pasivnih načrtovalskih ukrepov na rabo energije glede na podnebje in podnebne spremembe. Kot najbolj univerzalno uporaben pasivni ukrep za uravnoteženje predvidenega učinka globalnega segrevanja se je izkazala uporaba manjših transparentnih površin. Uporabnost preostalih pasivnih ukrepov se razlikuje glede na tip podnebja in preučevano obdobje. Ugotovljeno je bilo, da bo le s pomočjo pasivnih načrtovalskih ukrepov težko nevtralizirati predvidene učinke podnebnih sprememb na rabo energije, tudi v primeru najučinkovitejše kombinacije. Glede na izsledke je nove stavbe najbolje načrtovati v skladu s srednjeročnimi optimumi. Prikazani trendi rabe energije in vpliva pasivnih načrtovalskih ukrepov predstavljajo temelj za načrtovanje energijsko učinkovitih stavb, odpornih na podnebne spremembe.*

Abstract

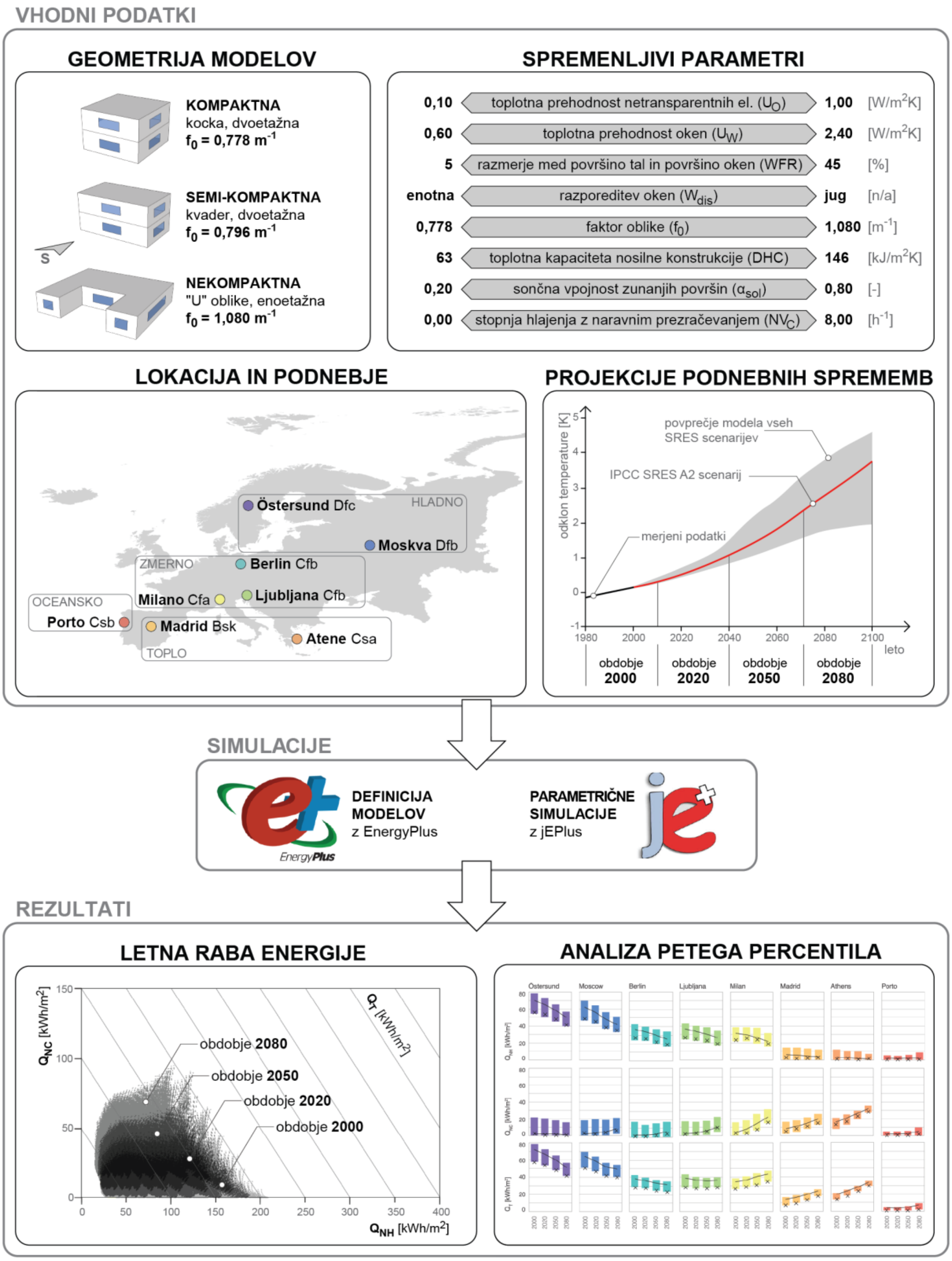
The chapter summarises the original scientific paper in Appendix C (Pajek and Košir [51]). Its main aim is to examine the impact of climate change on buildings' energy efficiency and investigate the impact of passive design measures on energy use for heating and cooling of single-family buildings in representative climates in Europe. Therefore, we modelled 496,800 different combinations of passive design measures by varying the parameters in the example of a single-family building. The thermal response of building models was simulated at eight locations and in four different climate conditions. The parametric study included thermal transmittance of the building envelope, window area, window distribution, building shape, building heat storage capacity, solar absorptivity of external surfaces and natural ventilation cooling. Energy simulations were performed according to projected climate change until the end of the 21st century. It has been found that the overall building energy use in cold and most temperate climates will decrease and increase in warm climates in the future. The results demonstrate the impact of individual passive design measures on energy use in different climate types and climate change scenarios. The use of smaller transparent surfaces was shown as the most generally applicable passive measure to counterbalance the projected effect of global warming. The applicability of the remaining passive measures depends on climate type and period. It has been found that using only passive design would not be enough to neutralize the projected effects of climate change on energy use, even in the case of the most optimal combination. According to the results, it is best to plan new buildings following the mid-term optimums. The presented trends in energy use and the impact of passive design measures represent the basis for designing energy-efficient buildings resistant to climate change.

5.1 Ideja in teoretično ozadje

Številne raziskave o energijski učinkovitosti stavb, vključno z vsebino, predstavljeno v poglavjih 3 in 4, za iskanje in predstavitev optimalnih rešitev uporabljajo študije primerov, ki so narejene na omejenem številu primerov stavb in omejenem številu pasivnih načrtovalskih ukrepov. Študije so običajno osredotočene na energijsko prenovo specifičnih poslovnih ali stanovanjskih stavb in iščejo optimalne načrtovalske rešitve z omejenim nizom spremenljivk, pogosto pa pri tem ne obravnavajo učinka podnebnih sprememb na energijsko učinkovitost stavbe. Področje je relativno slabo raziskano, pri čemer je neraziskan potencialni dolgoročni prispevek pasivnih ukrepov k zmanjšanju rabe energije za ogrevanje in hlajenje bioklimatsko načrtovanih enostanovanjskih stavb v različnih evropskih podnebjih. Zato primanjkuje smernic in priporočil za implementacijo ustreznih pasivnih načrtovalskih ukrepov, s katerimi bi dosegli cilje energijske učinkovitosti stavb. Raziskava, predstavljena v članku Pajek in Košir [51] (priloga C), temelji na ideji predstaviti ključne informacije za načrtovanje podnebno prilagojenih in energijsko učinkovitih stavb, ki bi omogočale učinkovito rabo energije v trenutnih in predvidenih podnebnih stanjih. Cilj raziskave je bila izvedba obsežne parametrične študije, osredotočene na toplotni odziv oz. energijsko učinkovitost enostanovanjskih stavb, ki predstavljajo dobršen delež stanovanjskega fonda v Evropi. Pri optimizaciji rabe energije enostanovanjskih stavb so zaradi precejšne interakcije z okoljem pasivni načrtovalski ukrepi zelo učinkoviti. Poleg tega se enostanovanjske stavbe pogosto uporabljajo več desetletij, ne da bi jih takrat bistveno prenavljali. Zato je bil glavni del raziskave namenjen iskanju najučinkovitejših kombinacij pasivnih načrtovalskih ukrepov glede na predvidene podnebne spremembe do konca 21. stoletja. Zasnovali smo nov, celosten pristop in naredili obširno parametrično študijo v štirih podnebnih stanjih. Učinkovitost pasivnih načrtovalskih ukrepov je bila ocenjena na podlagi od njih odvisne energijske učinkovitosti posamezne kombinacije. Rezultati so kot podlaga za razvoj strategij in smernic glede energijsko učinkovitih stavb.

5.2 Metodologija raziskave

Najprej smo na podlagi izbranih parametrov definirali 496.800 energijskih modelov stavb, pri čemer je vsak primer predstavljal edinstveno kombinacijo pasivnih načrtovalskih ukrepov. Za parametrične spremenljivke smo izbrali tri različne oblike stavbe (f_0), deset vrednosti toplotnih prehodnosti netransparentnega dela stavbnega ovoja (U_O), deset toplotnih prehodnosti transparentnega dela stavbnega ovoja oz. oken (U_W) s pripadajočimi *SHGC* faktorji, devet razmerij med površino tal in površino oken (*WFR*), dve različni razporeditvi okenskih površin (W_{dis}), tri različne toplotne kapacitete nosilne konstrukcije (*DHC*), štiri vrednosti sončne vpojnosti zunanjih površin (α_{sol}) in devet različnih stopenj hlajenja z naravnim prezračevanjem (NV_C). Nato je bil vsak energijski model simuliran s pomočjo podnebne datoteke osmih izbranih lokacij v Evropi, pri čemer smo obravnavali štiri značilna podnebna stanja oz. obdobja: »trenutno« podnebno datoteko in tri podnebne datoteke, pri katerih so upoštevani učinki podnebnih sprememb. Z vsemi kombinacijami je bilo simuliranih 15.897.600 različnih kombinacij energijskih modelov stavb. Za vsak model so bile s pomočjo orodij EnergyPlus [138] in jEPlus [219] izračunane letna potrebna energija za ogrevanje (Q_{NH}), hlajenje (Q_{NC}) in skupna (kumulativna) potrebna energija (Q_T), najboljše kombinacije pa so bile poiskane z analizo 5. percentila glede na Q_T. Simulacije so bile izvedene s 15-minutnim korakom in uporabo t. i. idealnih grelcev (ang. *ideal air loads*). Za simulacije v predvidenih prihodnjih podnebnih stanjih so bili uporabljeni znani podatki za obdobje 2000 (EPW datoteka za obdobje 1981–2010) ter projicirane podnebne datoteke EPW za obdobje 2020 (2011–2040), obdobje 2050 (2041–2070) in obdobje 2080 (2071–2100). Podnebne datoteke za prihodnja podnebna stanja po scenariju SRES A2 smo pripravili po postopku, opisanem v poglavju 4.2. Analizirane lokacije, geometrijski modeli, izbrani parametri in oris uporabljene metodologije so predstavljeni na sliki 25.



Slika 25: Pregled vhodnih podatkov in uporabljene raziskovalne metodologije.
Figure 25: Overview of the applied input data and research methodology.

Podrobnejši podatki o vhodnih parametrih so navedeni v preglednicah 6 in 7. Preostali vhodni podatki ter natančen opis metod in definicije modelov pa so dostopni v članku Pajek in Košir [51] (priloga C).

Preglednica 6: Nespremenljivi/konstantni vhodni parametri energijskih modelov.
Table 6: Constant input parameters for the energy models.

Parameter	Vrednost	Referenca
ogrevalna temperatura	21 °C	EN 16798-1, preglednica B.2 [220]
hladilna temperatura	26 °C	EN 16798-1, preglednica B.2 [220]
regulacija temperature	operativna temperatura	Dovjak in sod.[221]
infiltracija + stopnja naravnega prezračevanja	0,600 (1. april do 31. oktober), 0,375 (1. november do 31. marec)	Hou in sod. [222], Bekö in sod. [223]
moč dobitkov notranjih virov in urnik (naprave)	2,4 W/m^2	EN 16798-1, Annex C [220]
moč dobitkov notranjih virov in urnik (uporabniki)	2,8 W/m^2	EN 16798-1, Annex C [220]
moč dobitkov notranjih virov in urnik (razsvetljava)	3,3 W/m^2	EN 16798-1, Annex C [220]
urnik senčenja	aktivno med 1. aprilom in 31. oktobrom	Tzempelikos in Athienitis [224]
nastavljena vrednost za aktivacijo, vrsta in delovanje senčenja	prejeta intenziteta sončnega sevanja na okenski površini ≥ 130 W/m^2 in zunanja temperatura zraka ≥ 16 °C, zunanje žaluzije, blokiranje sončnih žarkov	EN 15232, razred A [225]
sistem toplotnega ovoja stavbe in toplotna emisivnost zunanjih površin	z zunanje strani toplotno izoliran ovoj, ε = 0,80	Pisello [226]

Preglednica 7: Spremenljivi vhodni parametri energijskih modelov.
Table 7: Variable input parameters for the energy models.

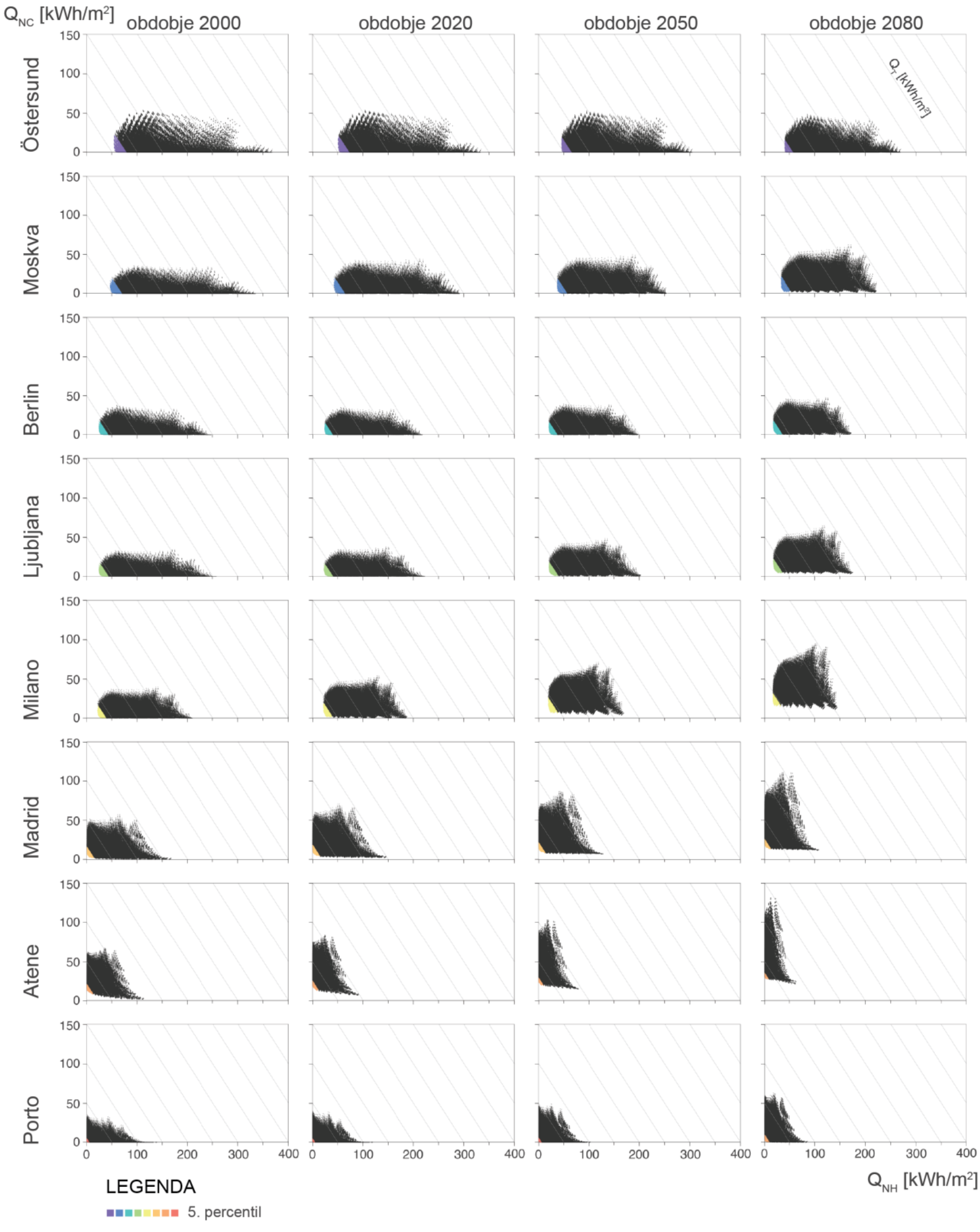
Parameter	Število prirastkov	Razpon parametrov
U_O [W/m^{2}K]	10	0,10, 0,15, 0,20, 0,25, 0,30, 0,40, 0,50, 0,60, 0,80, 1,00
U_W [W/m^{2}K], v oklepajih pripadajoči *SHGC* [-]	10	2,40 (0,75), 2,20 (0,75), 2,00 (0,70), 1,80 (0,70), 1,60 (0,65), 1,40 (0,65), 1,20 (0,60), 1,00 (0,55), 0,80 (0,50), 0,60 (0,45)
WFR [%]	9	5 (»osnovni« primer), 10, 15, 20, 25, 30, 35, 40, 45
W_{dis} [/]	2	enaka površina oken na vseh orientacijah, južno skoncentrirana okna (in le 3,75 % WFR enakomerno porazdeljene površine po preostalih orientacijah)
f_0 [m^{-1}]	3	0,778 (kompaktna, kocka, dvoetažna), 0,796 (semi-kompaktna, kvader, dvoetažna), 1,080 (nekompaktna, "U" oblike, enoetažna)
DHC nosilne konstrukcije [a] [kJ/m^{2}K], v oklepajih: debelina [m], toplotna prevodnost [W/mK], gostota [kg/m^3], specifična toplota [J/kgK]	3	63 (0,06, 0,20, 600, 2090, npr. križno lepljen les), 98 (0,15, 0,50, 1200, 920, npr. opeka), 146 (0,24, 0,80, 2000, 960, npr. beton/kamen)
α_{sol} [-]	4	0,2, 0,4, 0,6, 0,8
NV_C [b] [h^{-1}]	9	0, 1, 2, 3, 4, 5, 6, 7, 8
skupno število modelov [c]	496,800	

[a] *R* = toplotna upornost = konstantna = 0,30 m^{2}K/W
[b] NV_C se uporablja med aprilom in oktobrom, ko so izpolnjeni naslednji pogoji: notranja temperatura zraka >24 °C, temperatura zunanjega zraka med 16 in 30 °C in temperaturna razlika med notranjim in zunanjim zrakom >4 K.
[c] dejansko število vseh kombinacij bi sicer bilo 583.200, vendar kompaktna in nekompaktna oblika stavbe ne omogočata izvedbe *WFR* višjih od 35 % oz. 30 %.

5.3 Rezultati

V nadaljevanju so predstavljene splošne usmeritve o priporočenih pasivnih načrtovalskih ukrepih, potrebnih za doseganje dolgoročne energijske učinkovitosti. Energijska učinkovitost modelov stavb je bila ocenjena glede na letno potrebno energijo za ogrevanje (Q_{NH}) in hlajenje (Q_{NC}) ter skupno energijo, potrebno za kondicioniranje (Q_T) na m^2 uporabne površine stavbe. Na sliki 26 so prikazani diagrami kombinacij Q_{NH} in Q_{NC} za vsak izračunani energijski model stavbe na osmih preučevanih lokacijah ter za vsakega od štirih preučevanih obdobij. Rezultati so pokazali, da na splošno predvidene podnebne spremembe močno vplivajo na Q_{NH} in Q_{NC} na vsaki izmed lokacij, pri čemer opazimo trend postopnega nižanja Q_{NH} in višanja Q_{NC}. Na primer v Atenah je pričakovati, da bodo podnebne spremembe povzročile, da bo v obdobju 2080 v 1,7 % izračunanih primerih Q_{NH} padla na 0 kWh/m^2. V obdobju 2000 takšnih primerov v Atenah ni bilo, so pa imeli nekateri modeli stavb Q_{NH} blizu nič. V Milanu in Ljubljani predvideno povišanje Q_{NC} odraža, da v obdobju 2080 na obeh lokacijah v stanovanjskih stavbah ne bo več mogoče doseči Q_{NC} enak 0 kWh/m^2 le z uporabo analiziranih pasivnih načrtovalskih ukrepov, kot je bilo to možno v obdobju 2000, kjer ima 4 % modelov stavb v Ljubljani Q_{NC} enako nič, medtem ko je v Milanu že v obdobju 2000 le 0,6 % takšnih primerov.

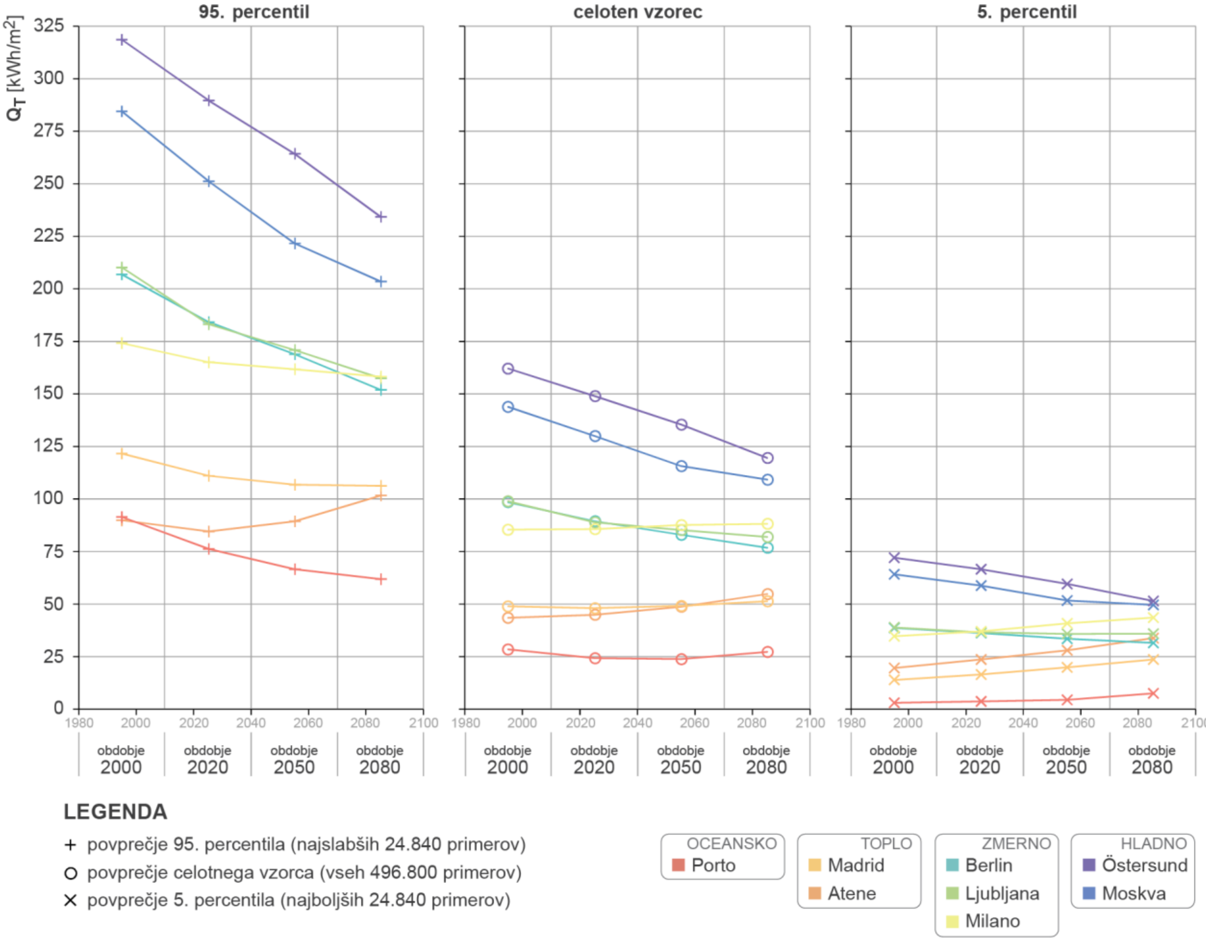
Nadalje smo energijsko učinkovitost obravnavanih modelov stavb preučili s stališča skupne potrebne energije ($Q_T = Q_{NH} + Q_{NC}$). Če opazujemo obnašanje povprečne vrednosti Q_T za celotni vzorec (slika 27), opazimo, da bodo predvidene podnebne spremembe povzročile nižanje skupne rabe energije stavb v hladnem in zmernem podnebju, kot je v Ljubljani in Berlinu, in višanje le-te v lokacijah s toplim podnebjem, kot je v Atenah. Rezultati so pokazali, da bo v Milanu, Madridu in Portu povprečna vrednost Q_T celotnega vzorca ves čas ostala podobna. Čeprav je pričakovati, da se bosta Q_{NH} in Q_{NC} sčasoma spreminjala v vseh obravnavanih primerih (slika 26), so v povprečju primeri v 5. percentilu manj, v 95. percentilu pa na predvideno segrevanje podnebja bolj občutljivi (slika 27). 5. percentil predstavlja modele stavb z najboljšo, 95. percentil pa z najslabšo kombinacijo pasivnih načrtovalskih ukrepov glede na njihovo energijsko učinkovitost in podnebno prilagojenost. Q_T se bo sicer v povprečju zaradi globalnega segrevanja najbolj znižal pri kombinacijah 95. percentila. Slednje velja za vse analizirane lokacije, razen Aten, kjer je situacija obratna in se povprečni Q_T 95. percentila sčasoma občutno poviša. Ta izjema je posledica nadaljnjega segrevanja že toplega podnebja, kar privede v opazno povečanje pregrevanja v tistih stavbah, ki so najmanj prilagojene podnebju (95. percentil). To so tipično manj toplotno izolirane stavbe (imajo visoke vrednosti U_O in U_W), z nizkimi vrednostmi *DHC* in NV_C ter hkrati visokimi *WFR* in α_{sol}, odražajo pa povečano ranljivost za segrevanje podnebja. Podnebne spremembe imajo običajno manjši učinek na povprečni Q_T modelov stavb v 5. percentilu. Trend spreminjanja povprečnih vrednosti Q_T v 5. percentilu na nekaterih lokacijah (Atene, Madrid, Milano, Porto) pa je kljub temu različen od preostalih. Na teh lokacijah je pričakovati, da se bo do konca 21. stoletja povprečna Q_T modelov stavb v 5. percentilu povišala. Vzrok za to je, da ima na Q_T stavb v 5. percentilu prirast Q_{NC} večji vpliv kot zmanjšanje Q_{NH}.



Slika 26: Predvidena raba energije simuliranih primerov na različnih preučevanih lokacijah in v različnih obdobjih. Vsaka pika predstavlja posamezni model s pripadajočo potrebno energijo za ogrevanje (Q_{NH}) in hlajenje (Q_{NC}) na m^2 površine. Za vsako lokacijo in obdobje je bilo izračunanih 496.800 kombinacij, vse skupaj 15.897.600 simuliranih primerov.

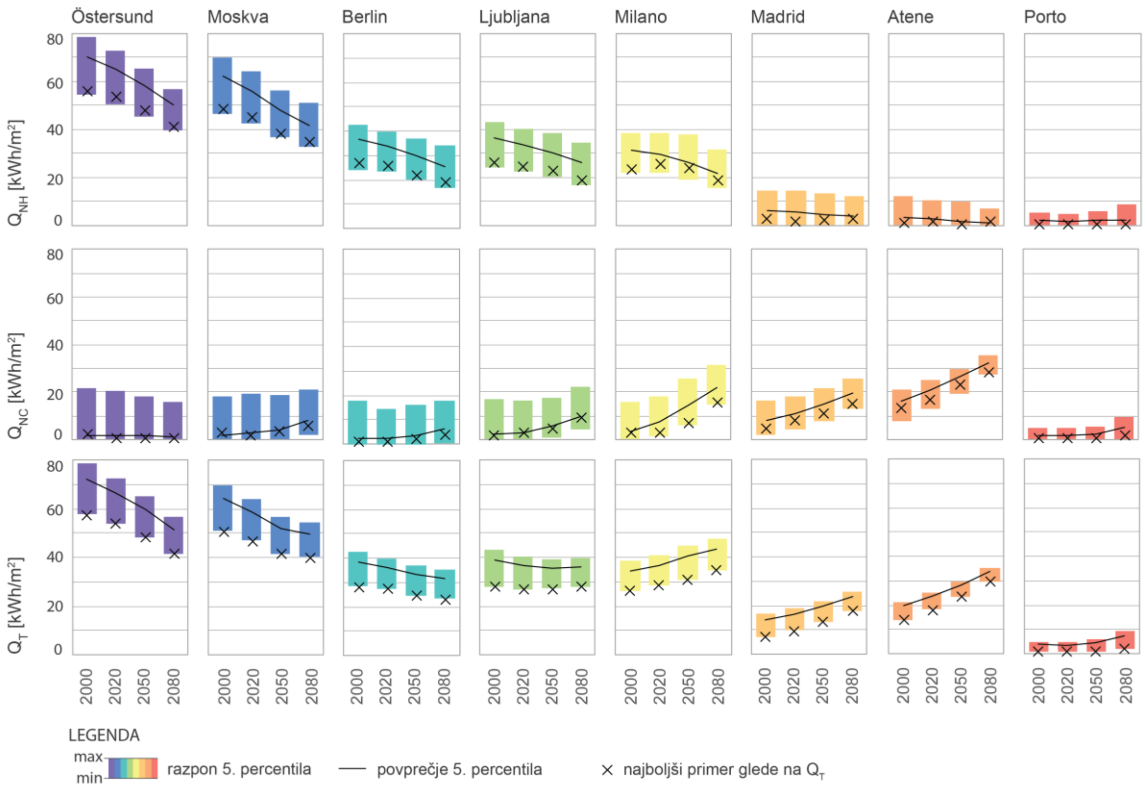
Figure 26: Projected energy performance of simulated cases at various studied locations and periods. Each dot represents an individual model with particular annual energy use for heating (Q_{NH}) and cooling (Q_{NC}) per m2 of the floor area. For each location and period, 496,800 cases were simulated, resulting in total of 15,897,600 cases.

Za nadaljnjo podrobno analizo so bili izbrani modeli 5. percentila, saj le-ti predstavljajo najbolj energijsko učinkovite in podnebju prilagojene primere stavb, s tem pa je omogočen vpogled v načrtovalske ukrepe, ki zagotavljajo doseganje nizke Q_T in optimiziranje Q_{NH} in Q_{NC}. Splošni rezultati so pokazali, da se bo relativni pomen preučevanih pasivnih ukrepov in njihov vpliv na Q_{NH} in Q_{NC} sčasoma spreminjal, saj lahko do leta 2100 glede na obdobje 2000 pričakujemo bistvene spremembe v povprečnih vrednostih Q_T (sliki 26 in 27).



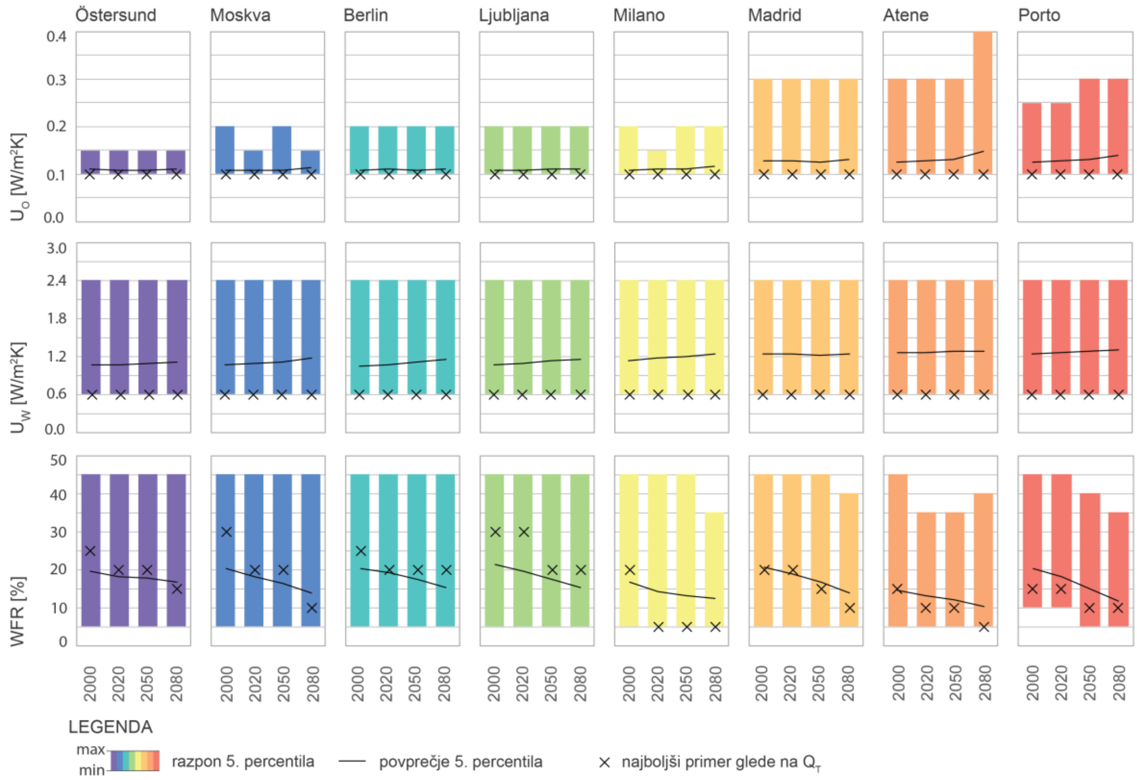
Slika 27: Predvideno letno povprečje Q_T (= Q_{NH} + Q_{NC}) za celotni vzorec (sredina), 95. percentil (levo) in 5. percentil (desno) na različnih lokacijah in v različnih obdobjih.
Figure 27: Annual projected average Q_T (= Q_{NH} + Q_{NC}) for the entire sample (middle), the 95th percentile (left) and the 5th percentile (right) at various studied locations and periods.

Rezultati so pokazali, da je z uporabo ustrezne kombinacije pasivnih načrtovalskih ukrepov možno doseči visoko raven energijske učinkovitosti, zato smo podrobneje preučili odnos med podnebnimi spremembami in Q_{NH}, Q_{NC} in Q_T (slika 4) za modele stavb v 5. percentilu. Slika 28 prikazuje, da so vrednosti Q_{NH} pričakovano najvišje v hladnih podnebjih, kot je v Östersundu in Moskvi, najnižje pa v toplih, kot je v Madridu in Atenah, ter v oceanskem podnebju, kot je v Portu. Po drugi strani je v toplih podnebjih pričakovana večja potreba po Q_{NC}, razpon vrednosti Q_T, Q_{NH} in Q_{NC} pa je manjši. Kot posledica vpliva podnebnih sprememb je na toplejših lokacijah (npr. Atene, Madrid, Porto, Milano) pričakovati, da se bo Q_T do konca stoletja opazno povečala. Obrnjen trend velja za hladnejše lokacije, kot so Ljubljana, Berlin, Moskva in Östersund, kjer naj bi se Q_T postopoma zmanjšal. V Ljubljani je opazen obrat krivulje povprečne Q_T, kjer bi bila najmanjša predvidena skupna raba energije dosežena nekje okrog polovice stoletja. Opazimo lahko, da se bo razlika v povprečni Q_T med hladnimi in toplimi lokacijami s časom znatno zmanjšala, medtem ko se bo razmerje med Q_{NH} in Q_{NC} glede na skupno rabo energije na vseh obravnavanih lokacijah močno spremenilo. Oba opisana trenda predstavljata spremembo vzorcev rabe energije za stavbe po vsej Evropi. Ugotovimo lahko tudi, da je v primerjavi s hladnimi podnebji v zmernih in toplih podnebjih lažje doseči nizko Q_T le z uporabo pasivnih ukrepov, vendar pa lahko v toplem in zmernem podnebju kljub temu pričakujemo, da se bo do obdobja 2080 ne glede na uporabljene pasivne ukrepe Q_T povišala (slika 28).



Slika 28: Dolgoročna energijska učinkovitost najbolj učinkovitih modelov stavb glede na Q_T (peti percentil), predstavljena s pomočjo tipičnih vrednosti Q_{NH}, Q_{NC} in Q_T. Barvni stolpci prikazujejo razpon izračunanih vrednosti rabe energije, črne črte pa njeno povprečno vrednost za stavbne modele v 5. percentilu.
Figure 28: Long-term energy performance of the best performing building models according to Q_T, presented through the 5th percentile's Q_{NH}, Q_{NC} and Q_T. The coloured bars demonstrate the energy use range, while the black lines show the average value for the building models in the 5th percentile.

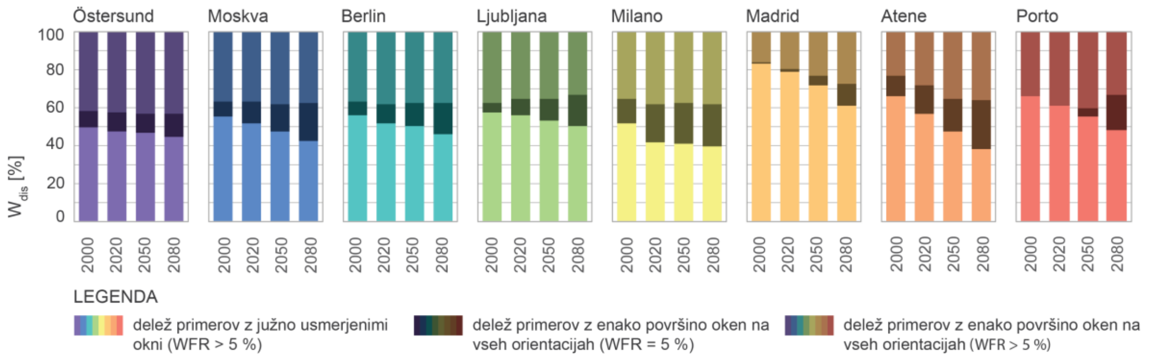
Vpliv specifičnih pasivnih načrtovalskih ukrepov na vsaki lokaciji in za vsako časovno obdobje je bil natančneje kvantitativno preučen s pomočjo opisne statistike 5. percentila (slike 29, 30 in 31). Slika 29 prikazuje, da je v toplih podnebjih, za zagotavljanje Q_T v 5. percentilu, razpon ustreznih vrednosti U_O večji kot v zmernih in hladnih. Na primer na ekstremno hladnih lokacijah, kot je Östersund, je treba za doseganje najnižjih 5 % vrednosti Q_T uporabiti $U_O \leq 0{,}15$ W/m^{2}K. Podobno je treba v Moskvi in zmernih (Berlin, Ljubljana, Milano) podnebjih uporabiti $U_O \leq 0{,}20$ W/m^{2}K, v toplih in oceanskih podnebjih pa $U_O \leq 0{,}30$ W/m^{2}K, pri čemer je povprečna vrednost U_O v 5. percentilu povsod nižja od 0,15 W/m^{2}K, pričakovano najnižja v hladnem ter najvišja v toplem in oceanskem podnebju. Rezultati analize 5. percentila so pokazali, da je ne glede na tip podnebja uporaba nizkih vrednosti U_O ($\leq 0{,}15$ W/m^{2}K) koristna za zagotavljanje visoke energijske učinkovitosti in podnebne prilagojenosti stavb. Pri najboljšem primeru glede na Q_T je vrednost U_O za vse lokacije in vsa obdobja pri 0,10 W/m²K. Povprečna vrednost U_O v 5. percentilu se za vse analizirane lokacije proti koncu stoletja postopoma povečuje in nakazuje trend, da bo v prihodnosti visoka energijska učinkovitost v povprečju dosegljiva z nekoliko višjimi vrednostmi U_O kot danes.



Slika 29: Značilne vrednosti parametrov U_O, U_W in *WFR* v 5. percentilu Q_T. Barvni stolpci prikazujejo razpon vrednosti parametra, črne črte pa njegovo povprečno vrednost za stavbne modele v 5. percentilu.
Figure 29: Characteristic values of U_O, U_W and *WFR* represented in the 5th percentile according to Q_T. The coloured bars demonstrate the parameter range, while the black lines show the average value for the building models in the 5th percentile.

Tudi pri parametru U_W (slika 29) je možno opaziti podoben trend kot pri parametru U_O, vendar pa lahko na vseh lokacijah v vzorcu modelov 5. percentila najdemo tudi relativno visoke vrednosti U_W (do 2,40 W/m²K). Kljub temu je pri uporabi visokih vrednosti U_W (2,40 W/m²K) vedno uporabljen ovoj z nižjimi *WFR* (≤ 10 % v hladnem ali ≤ 20 % v toplem podnebju) in U_O (0,10 W/m²K v hladnem ali ≤ 0,20 W/m²K v toplem podnebju). Pričakovano je povprečna vrednost U_W najnižja v hladnih ter najvišja v toplih in oceanskem podnebju. Povprečna vrednost U_W v 5. percentilu je vedno ≤ 1,30 W/m²K, ne glede na lokacijo in obravnavano obdobje. Pri najboljšem primeru glede na Q_T je vrednost U_W za vse lokacije in vsa obdobja pri 0,60 W/m²K, to je pri najnižji analizirani vrednosti. Podobno kot pri parametru U_O, je pričakovati, da se bodo povprečne vrednosti U_W v 5. percentilu v prihodnosti oz. do obdobja 2000 stalno povečevale ($\Delta U_{W,hladno}$ ≈ 0,04–0,10 W/m²K, $\Delta U_{W,zmerno}$ ≈ 0,09–0,10 W/m²K , $\Delta U_{W,toplo}$ ≈ 0,01–0,04 W/m²K, $\Delta U_{W,oceansko}$ ≈ 0,07 W/m²K).
V primeru parametra *WFR* (slika 29) je analiza pokazala, da je v hladnih in zmernih podnebjih v vseh obdobjih mogoče doseči najnižjih 5 % Q_T z uporabo katere koli od analiziranih vrednosti *WFR* (5–45 %). Nasprotno je vrednost *WFR* v drugi polovici stoletja v toplih podnebjih navzgor omejena na 35 %,

v oceanskem pa na 40 %. Poleg tega je v oceanskem podnebju *WFR* v obdobjih 2000 in 2020 omejen tudi navzdol, in sicer na 10 %. V hladnem podnebju (npr. Östersund) mora biti v primeru modelov z *WFR* enakim 45 % $U_W \leq 0{,}8$ W/m^{2}K in hkrati $U_O \leq 0{,}15$ W/m^{2}K. V zmernem podnebju (npr. Ljubljana) se *WFR* enak 45 % lahko uporablja z $U_W \leq 1{,}0$ W/m^{2}K in $U_O \leq 0{,}15$ W/m^{2}K. V toplih podnebjih (npr. Atene) pri WFR = 45 % U_W ne sme biti višji od 0,6 W/m^{2}K. Katera koli vrednost U_W se lahko v zmernih in toplih podnebjih (npr. Ljubljana, Atene) uporablja pri *WFR* do 20 %, v hladnih podnebjih (npr. Östersund) pa pri *WFR* do 15 %. Vpliv *WFR* na Q_T v 5. percentilu je zaradi predvidenih podnebnih sprememb najbolj spremenjen. Trend do obdobja 2080 kaže, da se bodo povprečne vrednosti *WFR* v 5. percentilu na vseh analiziranih lokacijah opazno znižale. *WFR* je edini preučevani parameter, za katerega se pričakuje konstantno nižanje vrednosti pri najboljšem primeru glede na Q_T na vseh lokacijah in v vseh obdobjih.

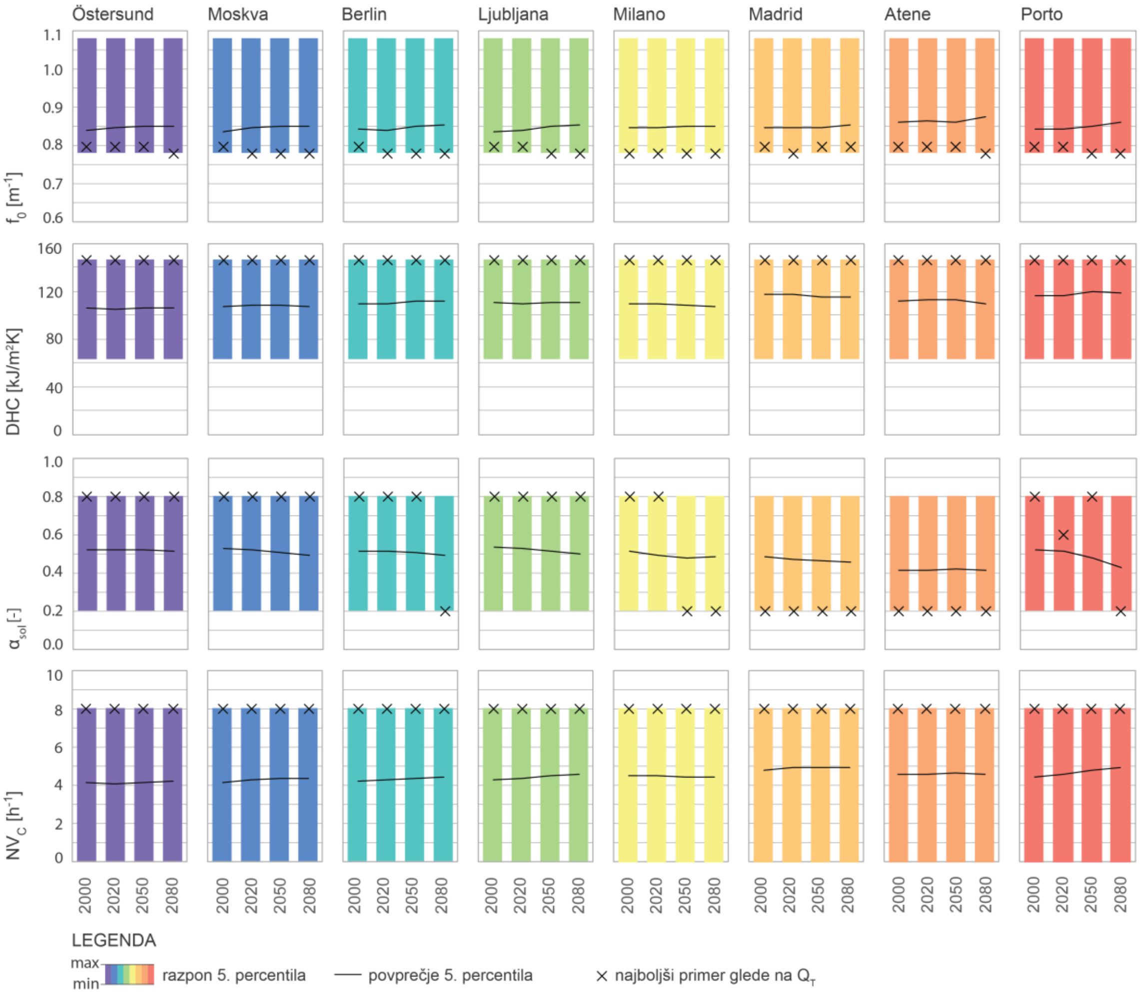


Slika 30: Deleži W_{dis} v 5. percentilu Q_T. Barvni stolpci prikazujejo delež primerov z južno skoncentriranimi okni in *WFR*>5 %, delež primerov z enako površino oken na vseh orientacijah in *WFR* > 5 % ter delež primerov z enako površino oken na vseh orientacijah in *WFR* = 5 % (tj. »osnovni« primeri).

Figure 30: W_{dis} shares represented in the 5th percentile according to Q_T. The coloured bars show the share of cases with south-concentrated windows with WFR > 5 %, equal area of windows at all orientations with WFR> 5 % and equal area of windows at all orientations with WFR = 5 % (i.e. »base« cases).

Slika 30 prikazuje delež stavbnih modelov v 5. percentilu glede na parameter W_{dis}. Delež modelov stavb z južno skoncentriranimi okni in *WFR,* večjim od 5 %, je v toplem in oceanskem podnebju višji kot v hladnem in zmernem. Rezultati so pokazali, da izbira južno koncentriranih oken omogoča uporabo višjih vrednosti U_O v zmernem (npr. Ljubljana) in hladnem podnebju (npr. Moskva), in sicer 0,20 W/m^{2}K, ter v toplem podnebju (npr. Atene), in sicer 0,30 W/m^{2}K. »Osnovni« primeri z enakomerno porazdeljenimi 5 % *WFR* se običajno najbolje obnesejo le v kombinaciji z U_O enako 0,10 W/m^{2}K, kar je posledica povečanega vpliva netransparentnega dela ovoja stavbe na Q_T. Opazovanje deležev W_{dis} odraža, da se ob upoštevanju vpliva podnebnih sprememb v 5. percentilu sčasoma zmanjšuje delež modelov stavb z južno skoncentriranimi okni, povečuje pa se delež »osnovnih« primerov, kar kaže, da zasteklitev na jugu zaradi povečanega pregrevanja s stališča Q_T postaja problematična.

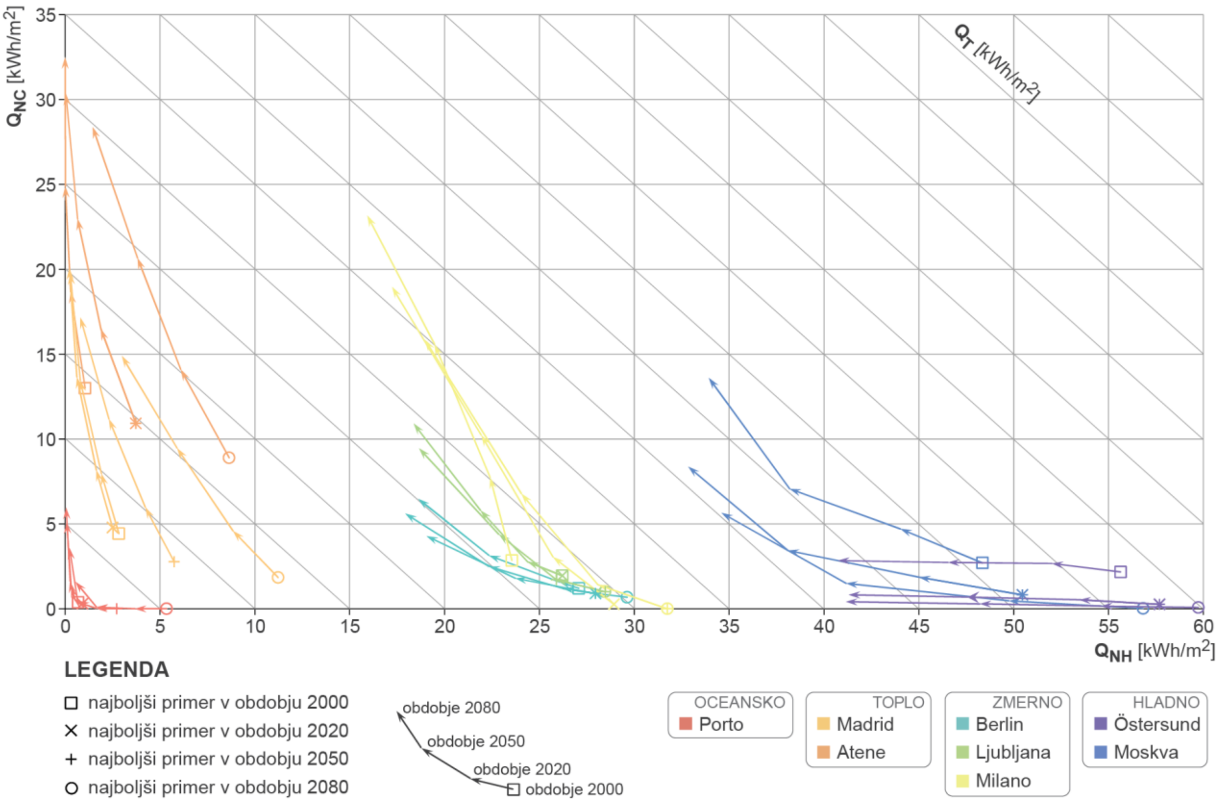
Po pričakovanjih je povprečna vrednost f_0 za stavbe v 5. percentilu glede na Q_T nižja v hladnem podnebju in višja v toplem in oceanskem podnebju (slika 31). Kljub temu je za zagotavljanje nizke Q_T na vseh lokacijah možna uporaba katere koli analizirane oblike stavbe. V hladnih podnebjih uporaba nižje vrednosti U_O (npr. 0,10 W/m^{2}K) omogoča uporabo višje vrednosti f_0 (npr. nekompaktna oblika stavbe). Enako velja za tople lokacije (npr. Atene), kjer lahko ob izbiri nekompaktne oblike stavbe uporabimo vrednost U_O do 0,20 W/m^{2}K. Na vseh obravnavanih lokacijah se povprečne vrednosti f_0 v 5. percentilu do obdobja 2080 ves čas povečujejo. Najboljši primer glede na Q_T je običajno z f_0 enakim 0,796 m^{-1} (semi-kompaktna oblika stavbe), s časom pa se bolj nagiba h kompaktni obliki stavbe (f_0 = 0,778 m^{-1}).



Slika 31: Značilne vrednosti parametrov f_0, *DHC*, α_{sol} in NV_C v 5. percentilu Q_T. Barvni stolpci prikazujejo razpon vrednosti parametra, črne črte pa njegovo povprečno vrednost za stavbne modele v 5. percentilu.
Figure 31: Characteristic values of f_0, *DHC*, α_{sol} and NV_C represented in the 5th percentile according to Q_T. The coloured bars demonstrate the parameter range, while the black lines show the average value for the building models in the 5th percentile.

Povprečni *DHC* (≈ 110 ± 5 kJ/m^{2}K) 5. percentila je med srednje težko in težko nosilno konstrukcijo (slika 31). Glede na parameter *DHC* lahko na vseh lokacijah in v vseh obdobjih za doseganje rabe energije znotraj 5. percentila Q_T uporabimo vse analizirane vrednosti *DHC*. Slednje je predvsem posledica možnosti, da se z nizkimi vrednostmi U_O nevtralizira vpliv nizke vrednosti *DHC* (npr. 63 kJ/m^{2}K). Če je v zmernem (npr. Ljubljana) in hladnem podnebju (Östersund, Moskva) za nosilno konstrukcijo izbrana lahka lesena konstrukcija (npr. *DHC* = 63 kJ/m^{2}K), mora biti $U_O \leq 0{,}15$ W/m^{2}K, če želimo doseči rabo energije znotraj 5. percentila Q_T. Podobno velja za Atene, kjer mora biti pri uporabi lahke lesene konstrukcije $U_O \leq 0{,}20$ W/m^{2}K.
Podobno kot pri drugih parametrih tudi za parameter α_{sol} velja, da je mogoče za doseganje rabe energije znotraj 5. percentila Q_T uporabiti katero koli od analiziranih vrednosti (slika 31). V toplem podnebju (npr. Atene) se lahko v vseh primerih uporablja α_{sol} enak 0,2, višje vrednosti pa so omejene z istočasno

uporabo nižje vrednosti U_O (α_{sol} = 0,8 je mogoče uporabiti le z $U_O \leq 0{,}20$ W/m^{2}K). Nasprotno velja za lokacije z zmernim podnebjem (npr. Ljubljana, Milano), kjer se α_{sol} 0,2 lahko uporablja le v kombinaciji z $U_O \leq 0{,}15$ W/m^{2}K, medtem ko je α_{sol} = 0,8 sprejemljiv v vseh primerih. V prihodnjih podnebnih scenarijih lahko pričakujemo, da se bo povprečna vrednost α_{sol} nižala, pri čemer je slednje manj opazno v hladnem in bolj izrazito v toplem, predvsem pa v oceanskem podnebju.
Rezultati za parameter NV_C v 5. percentilu glede na Q_T (slika 31) so pokazali, da so, kot pričakovano, v toplih podnebjih potrebne višje, v zmernih in hladnejših podnebjih pa nižje povprečne vrednosti NV_C. Sicer pa za doseganje rabe energije znotraj 5. percentila Q_T lahko uporabimo katere koli vrednosti NV_C. Bolj poglobljena analiza rezultatov je pokazala, da se višje stopnje NV_C običajno uporabljajo v primerih, ko je na zunanjih netransparentnih površinah uporabljena višja vrednost α_{sol} (0,6 in 0,8). Poleg tega je bilo, kadar je bil uporabljen NV_C višji od nič (≥ 1 h^{-1}), v 5. percentilu zajetih več modelov stavb z nižjim *DHC*. Proti koncu stoletja se na vseh lokacijah povprečna vrednost NV_C v 5. percentilu postopoma povečuje, kar je logična posledica segrevanja ozračja, vendar je obseg omejen s podnebnimi značilnostmi in razmerjem med Q_{NH} in Q_{NC}, saj NV_C vpliva le na vrednost Q_{NC}.



Slika 32: Dolgoročni potek energijske učinkovitosti posameznega najboljšega primera glede na Q_T.
Figure 32: Long-term development of energy performance of each best case according to Q_T.

V naslednjem koraku smo za vsako od analiziranih obdobij in lokacij poiskali najboljši primer stavbe (tj. absolutni optimum) z absolutno najnižjo Q_T. S tem smo raziskali dolgoročne učinke pričakovanih podnebnih sprememb na rabo energije energijsko najbolj učinkovitih zasnov stavb. Rezultati so predstavljeni na sliki 32, kjer je mogoče za vsako posamezno obdobje in vsako lokacijo primerjati dolgoročni potek rabe energije za absolutno najboljši primer kombinacije pasivnih načrtovalskih ukrepov. Rezultati so pokazali, da je v hladnih podnebjih za obravnavane najboljše oz. optimalne primere pričakovati drastično znižanje skupne rabe energije (Q_T), ne glede na obdobje, za katerega velja najboljši primer kombinacije pasivnih ukrepov. Kljub temu je v Moskvi pričakovati opazno spremembo v razmerju med Q_{NH} in Q_{NC}. V toplih in nekaterih zmernih podnebjih (npr. Atene, Madrid in Milano) je pričakovati, da se bo zaradi segrevanja ozračja in višanja Q_{NC}, Q_T najboljšega primera opazno povečal, stavbe pa bodo porabile bistveno več energije kot v trenutnih razmerah. V nekaterih primerih, kot sta na primer Berlin in Ljubljana, bodo podnebne spremembe drastično vplivale na razmerje med Q_{NH} in Q_{NC}. Na podlagi rezultatov lahko ugotovimo, da je na vseh lokacijah, razen v Milanu, v kontekstu kumulativne Q_T najbolje načrtovati novo stavbo v skladu s srednjeročnim optimumom (to je glede na obdobje 2020 oz. 2050). Milano je edini primer, kjer je bila najboljša kombinacija pasivnih ukrepov dosežena z uporabo najboljšega primera za obdobje 2080.

5.4 Razprava

Namen raziskave je bil oceniti učinkovitost izbranih pasivnih načrtovalskih ukrepov in njihov vpliv na rabo energije enostanovanjskih stavb glede na predvidene podnebne spremembe. Slednje smo ovrednotili s celovito parametrično študijo in poglobljeno analizo najboljših 5 % modelov stavb glede na Q_T (peti percentil). Rezultati so pokazali, da je rabo energije v obravnavanih modelih stavb mogoče učinkovito regulirati s pasivnimi načrtovalskimi ukrepi. Z več različnimi kombinacijami parametrov je bilo moč doseči zadovoljivo energijsko učinkovitost, kar je razvidno z opazovanjem rabe energije v 5. percentilu, na primer Q_T pod 20 kWh/m^2 v toplem in pod 40 kWh/m^2 v zmernem podnebju. Rezultati so pokazali tudi, da bo globalno segrevanje kljub uporabi najboljših kombinacij pasivnih načrtovalskih ukrepov opazno vplivalo na izračunani Q_T. Na splošno je bilo ugotovljeno, da lahko zaradi podnebnih sprememb na vseh lokacijah pričakujemo padec potrebne energije za ogrevanje (Q_{NH}) in rast potrebne energije za hlajenje (Q_{NC}). S pomočjo rezultatov smo predlagali pasivne načrtovalske ukrepe, ki jih je priporočljivo uporabljati pri načrtovanju podnebno prilagojenih nizkoenergijskih stavb. Študija je pokazala, da je za zagotavljanje nižjih vrednosti Q_T v enostanovanjskih stavbah v prihodnosti možna oz. priporočena uporaba višjih vrednosti U_O, U_W, f_0, *DHC* in NV_C ter nižjih vrednosti α_{sol}. Kljub temu pa rezultati ne predstavljajo potrebe po bistveni spremembi trenutnih optimalnih vrednosti. Nasprotno so rezultati pokazali, da bo v prihodnjih desetletjih za zagotavljanje energijske učinkovitosti stavb potrebna uporaba opazno nižjih vrednosti *WFR* od trenutno uporabljanih, vendar z ozirom na zahteve po osvetljevanju prostorov z dnevno svetlobo. Na slednje poglavitno vpliva velikost okenskih odprtin [192, 227], zato lahko z nižjimi *WFR* konkretno poslabšamo svetlobno okolje v stavbi. Ko v stavbah uporabimo nižjo toplotno kapaciteto nosilne konstrukcije (*DHC*) in visoke vrednosti *WFR* ali $\alpha_{sol,}$ sicer lahko le-to nadomestimo tudi z uporabo zelo nizkih vrednosti U_O. Segrevanje ozračja bo, razen v hladnih podnebjih, kot je v Östersundu, bistveno vplivalo tudi na razmerje med rabo energije za hlajenje in ogrevanje. V toplih in zmernih podnebjih je pričakovati, da se bo Q_T povečal, prirastka pa z uporabo preučevanih pasivnih načrtovalskih ukrepov ne bo mogoče učinkovito uravnotežiti. Ti rezultati predstavljajo ključne informacije za načrtovanje bioklimatskih energijsko učinkovitih stavb. Globalno segrevanje bo povzročilo spremenjeno razmerje med Q_{NH} in Q_{NC} in povečanje Q_{NC}. Pričakovati je, da bo slednje bistveno vplivalo na energijsko učinkovitost enostanovanjskih bioklimatskih stavb in njihovo optimizacijo. Višja potreba po Q_{NC} pomeni večjo potrebo po električni energiji za hlajenje, kar je še posebej skrb vzbujajoče. Če bo v poletnem času aktivno hlajenih vedno več stavb, bo to pomenilo bistveno drugačno potrebo po energiji za delovanje stavb, na katero dobavitelji energije morda ne bodo pripravljeni.

5.5 Prispevek k znanosti

Glaven prispevek k znanosti je analiza energijske učinkovitosti enostanovanjskih bioklimatskih stavb v različnih obdobjih glede na izbrani scenarij podnebnih sprememb. Pričakovati je, da bo v analiziranih stavbah globalno segrevanje spremenilo razmerje med rabo energije za ogrevanje in hlajenje, pri čemer bo potreba po ogrevanju manjša in potreba po hlajenju višja kot v trenutnih podnebnih razmerah. Trdimo lahko, da bodo stavbe zaradi globalnega segrevanja sčasoma glede potrebne energije za ogrevanje bolj energijsko učinkovite, glede potrebne energije za hlajenje pa manj energijsko učinkovite. Pričakuje se, da se bo skupna raba energije v toplih podnebjih povečala, v hladnih zmanjšala, medtem ko je v zmernem podnebju dolgoročna vrednost skupne rabe energije odvisna od lokacije. Velik prispevek k znanosti je tudi, da smo s pomočjo študije pokazali, da je v enostanovanjskih stavbah mogoče doseči nizko skupno rabo energije ($Q_T \leq 30$ kWh/m^2 na leto) le z uporabo pasivnih načrtovalskih ukrepov, še zlasti v oceanskem, toplem in zmernem podnebju. Pri tem smo ugotovili, da je pri enostanovanjskih stavbah poleg senčenja najučinkovitejši pasivni načrtovalski ukrep za dolgoročno prilagajanje podnebju na vseh analiziranih lokacijah uporaba nižjih vrednosti *WFR*, v toplem podnebju pa tudi nižje α_{sol}. Izbira kombinacije pasivnih načrtovalskih ukrepov precej vpliva tudi na razmerje med potrebno energijo za ogrevanje in hlajenje. Rezultati raziskave zato predstavljajo pomembno izhodišče pri definiciji dolgoročnih strategij za zagotavljanje energijske učinkovitosti enostanovanjskih stavb v prihodnosti.

6 UČINKI GLOBALNEGA SEGREVANJA NA ENERGIJSKO UČINKOVITOST ENOSTANOVANJSKIH STAVB V SLOVENIJI

Povzetek

Pričakovati je, da bodo podnebne spremembe poudarile tveganje za pregrevanje stavb, prilagojenih določenemu preteklemu podnebnemu stanju. V poglavju povzemamo vsebino izvirnega znanstvenega članka v prilogi D (Pajek in Košir [52]*), katerega cilj je bil najti energijsko učinkovite zasnove stavb, ki so hkrati najbolj odporne na pojav pregrevanja in posledično povečano potrebo po energiji za hlajenje zaradi podnebnih sprememb. V raziskavi smo podrobneje preučili rezultate celovite parametrične študije vpliva pasivnih načrtovalskih ukrepov na rabo energije enostanovanjskih stavb za zmerno podnebje (Ljubljana). Oblikovali smo metodo za oceno ranljivosti stavbe za pregrevanje, ki je bila uporabljena na analiziranih primerih z uporabo podatkov o rabi energije za hlajenje kot kazalnika uspešnosti. Rezultati so pokazali, da je glede na slovenski Pravilnik o metodologiji izdelave energetskih izkaznic najvišji dosegljiv razred energijske učinkovitosti glede na letno potrebno toploto za ogrevanje stavbe, ki ga lahko dosežemo v Ljubljani zgolj s pasivnimi načrtovalskimi ukrepi, razred B1, pri tem pa je pričakovati, da se bo raba energije za ogrevanje sčasoma znižala. Nasprotno je pri enostanovanjskih stavbah pričakovati vse višjo rabo energije za hlajenje. Ugotovljeno je bilo, da je pri modelih stavb z visoko rabo energije za ogrevanje lažje doseči zelo nizko ranljivost za pregrevanje, kljub temu pa pri modelih z nizko rabo energije za ogrevanje ni pričakovati zelo visoke ranljivosti za pregrevanje. V skladu s tem je treba stavbe načrtovati glede na doseganje ustrezne energijske učinkovitosti v sedanjosti in zagotavljanja nizke ranljivosti za pregrevanje v prihodnosti. Raziskava prikazuje nov pristop k bioklimatskemu načrtovanju stavb, pri katerem je v načrtovalski postopek zajeto prilagajanje na globalno segrevanje. Tako so bila podana priporočila za energijsko učinkovito, robustno in trajnostno bioklimatsko zasnovo enostanovanjskih stavb v zmernem podnebju, kot ga imamo v Sloveniji.*

Abstract

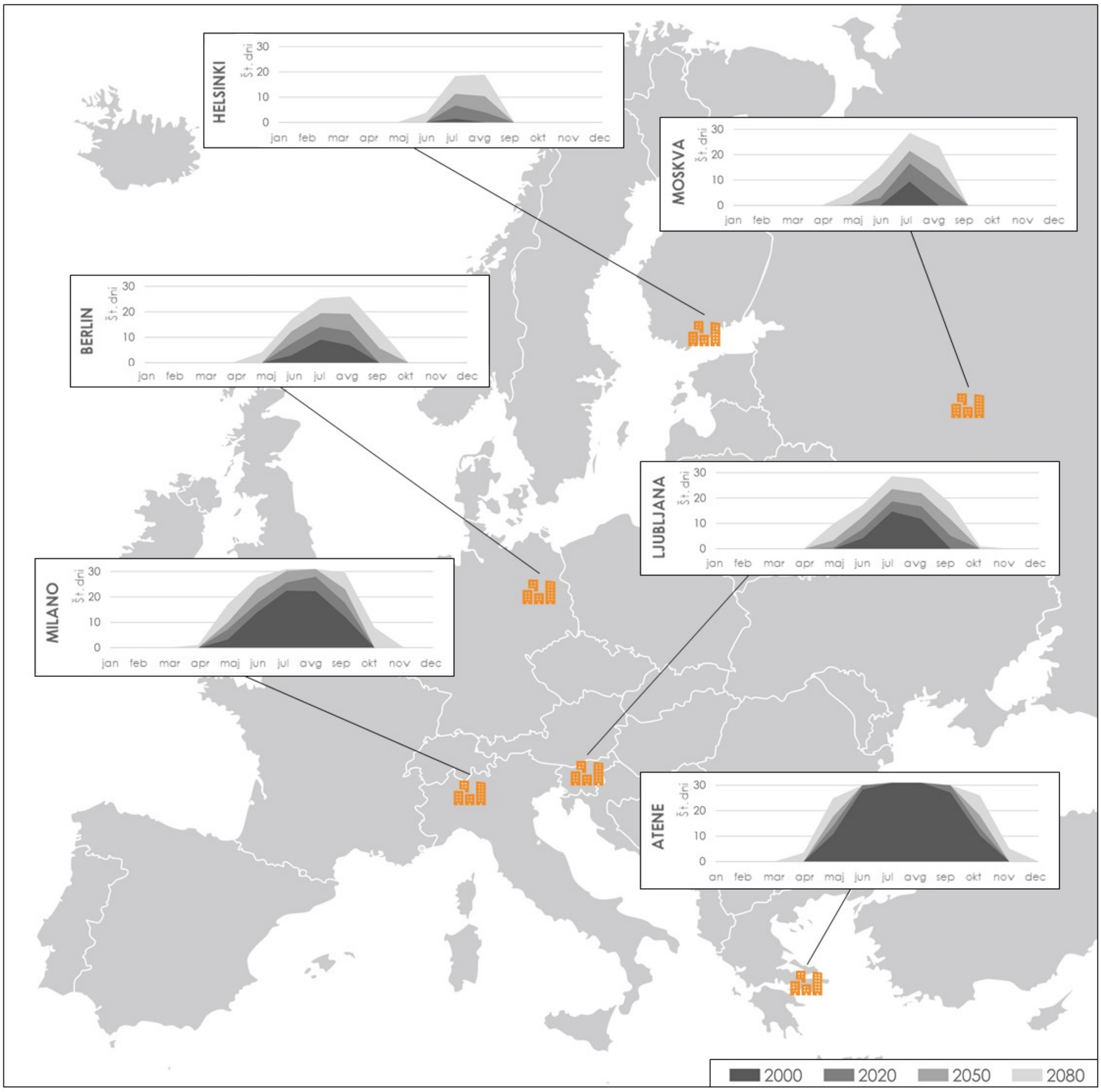
Climate change is expected to highlight the risk of overheating of buildings adapted to a particular past climate. The chapter summarises the content of the original scientific paper in Appendix D (Pajek and Košir [52]), which aimed to find energy-efficient designs of buildings that are most resistant to overheating and increased energy demand for cooling due to climate change. Therefore, we additionally studied the results of a comprehensive parametric study of passive design measures on the energy use of single-family buildings in a temperate climate (Ljubljana). We presented a method for overheating vulnerability assessment using cooling energy use data as a performance indicator applied to the analysed building models. The results showed that concerning heating energy use, the highest attainable energy efficiency class achieved solely by using passive design measures is class B1, according to the Slovenian Rules on the methodology for the production and issuance of energy performance certificates for buildings. Nevertheless, energy use for heating is expected to decrease and energy use for cooling to increase over time. The results demonstrated that it is easier to achieve very low overheating vulnerability of building models with high energy use for heating. However, a very high overheating vulnerability is not expected in models with low energy use for heating. Therefore, buildings need to be designed to achieve acceptable energy efficiency now and ensure low overheating vulnerability in the future. The study shows a new approach to the bioclimatic design of buildings, where climate change adaptation is included in the design process. Besides, recommendations were given for the energy-efficient, robust and sustainable bioclimatic design of single-family buildings in the temperate climate of Slovenia.

6.1 Ideja in teoretično ozadje

Načrtovanje stavb po bioklimatskih načelih je pogosto povezano z zagotavljanjem energijske učinkovitosti, zlasti v zmernem podnebju, kjer v enostanovanjskih stavbah pretežno prevladuje potreba po ogrevanju, hkrati pa podnebje omogoča učinkovito koriščenje sončne energije, torej pasivno sončno ogrevanje. V takšnih podnebnih razmerah so stavbe običajno zasnovane s poudarkom na energijski učinkovitosti glede na potrebno energijo za ogrevanje. Redkeje je pri načrtovanju obravnavano tudi morebitno tveganje za pojav pregrevanja v toplejšem delu leta. Glavna ideja raziskave, predstavljene v članku Pajek in Košir [52] (priloga D), je bila raziskati, koliko različne kombinacije pasivnih načrtovalskih ukrepov pomenijo potencialno tveganje za pregrevanje ob nadaljnjem globalnem segrevanju na primeru Ljubljane, ki predstavlja lokacijo z zmerno toplim srednjeevropskim podnebjem. Jedro raziskave je razvoj koncepta postopka za ocenjevanje ranljivosti stavb za pregrevanje. S tem smo dosegli namen raziskave, ki je bil pri bioklimatsko načrtovanih enostanovanjskih stavbah poiskati možne rešitve za sočasno zagotavljanje visoke energijske učinkovitosti za ogrevanje, hkrati pa ohraniti nizko ranljivost na segrevanje podnebja. Cilj je bil ovrednotiti modele bioklimatskih stavb glede na rabo energije za ogrevanje in hlajenje, za kar smo uporabili rezultate obsežne parametrične študije pasivnih načrtovalskih ukrepov, opisane v poglavju 5. Poleg tega smo za oceno ranljivosti stavbnih modelov za pregrevanje uporabili metodo minimax obžalovanja (ang. *minimax regret method*). S tem je bil predstavljen nov pristop k bioklimatskemu načrtovanju stavb, pri katerem sta prilagajanje in odpornost na globalno segrevanje zajeta v proces načrtovanja.

6.2 Metodologija raziskave

Za opredelitev lokacij s potencialno nevarnostjo za pregrevanje smo uporabili rezultate analize bioklimatskega potenciala šestih lokacij, kjer smo s pomočjo orodja BcChart (opis metode v poglavju 3) preverili število dni, ko je na posamezni lokaciji potrebno senčenje. Slednje je bilo analizirano za trenutno stanje podnebja (1981–2010) in za prihodnje projekcije podnebja v obdobjih 2011–2040 (obdobje 2020), 2041–2070 (obdobje 2050) in 2071–2100 (obdobje 2080). Za prihodnje podnebne razmere so bile uporabljene projekcije podnebnih sprememb SRES, scenarij A2 (glej poglavji 2.2.1.2 in 2.3.3). Podrobnejši opis raziskave je v konferenčnem prispevku Pajek in Košir [228]. Na podlagi analize smo ugotovili, na katerih lokacijah lahko pričakujemo največjo spremembo v številu dni, ko je oz. bo potrebno senčenje. Slika 33 prikazuje distribucijo dni, ko je na vsaki od obravnavanih lokacij potrebno senčenje. V sedanjih podnebnih razmerah so od obravnavanih lokacij Atene mesto z največjo potrebo po senčenju, Helsinki pa mesto z najnižjo. Projicirane podnebne spremembe bodo do konca stoletja postopoma vplivale na podaljšanje obdobja hlajenja, Ljubljana in Milano pa sta lokaciji, kjer se bo potreba po senčenju stavb najbolj povečala. Podrobnejšo analizo, ki je opisana v članku Pajek in Košir [52] (priloga D) in pričujočem poglavju, smo zato opravili na primeru podnebnih podatkov za Ljubljano. V naslednjem koraku smo za nadaljnjo obravnavo uporabili rezultate parametrične študije za Ljubljano, opisane v poglavju 5. Le-te smo uredili v bazo podatkov in jih pripravili za nadaljnjo obdelavo. Podatkovna zbirka je obsegala podatek o Q_{NH} in Q_{NC} za vsako kombinacijo pasivnih načrtovalskih ukrepov, med katerimi smo obravnavali tri različne oblike stavbe (f_0), deset vrednosti toplotnih prehodnosti netransparentnega dela stavbnega ovoja (U_O), deset toplotnih prehodnosti transparentnega dela stavbnega ovoja oz. oken (U_W) s pripadajočimi *SHGC* faktorji, devet razmerij med površino tal in površino oken (*WFR*), dve različni razporeditvi okenskih površin (W_{dis}), tri različne toplotne kapacitete nosilne konstrukcije (*DHC*), štiri vrednosti sončne vpojnosti zunanjih površin (α_{sol}) in devet različnih stopenj hlajenja z naravnim prezračevanjem (NV_C). Za podrobnejšo razlago parametrov, njihovih uporabljenih vrednosti in postopek definicije energijskih modelov glej poglavje 5 ter članek Pajek in Košir [51] (priloga C) ter Pajek in Košir [52] (priloga D).



Slika 33: Mesečna distribucija dni, ko je potrebno senčenje za trenutno in prihodnje stanje podnebja.
Figure 33: Monthly distribution of days when shading is needed for present and future climate state.

Nato smo pri vsakem modelu stavbe letno potrebno energijo za ogrevanje (Q_{NH}) in hlajenje (Q_{NC}) ocenili glede na zahteve Pravilnika o učinkoviti rabi energije v stavbah (PURES) [210], ki na ravni slovenske nacionalne zakonodaje izvaja zahteve EPBD. Zahteve veljajo za vse nove stavbe in vse prenove, pri čemer se posega v vsaj 25 % površine toplotnega ovoja. PURES določa najvišji dovoljeni Q_{NH} na m^2 uporabne tlorisne površine stanovanjske stavbe, določen z enačbo 25 [210].

$$Q_{NH} = 45 + 60 \cdot f_0 - 4{,}4 \cdot T_L \qquad (25)$$

Q_{NH} je letna potrebna energija za ogrevanje stavbe v kWh/m^2, f_0 je faktor oblike stavbe v m^{-1} in T_L je povprečna letna temperatura zunanjega zraka na lokaciji v °C (uporabljeni T_L za Ljubljano (1981–2010) je 10,7 °C). Najvišja dovoljena vrednost Q_{NH} je za obravnavane tri oblike stavbe na podlagi enačbe 25 enaka 44,7 kWh/m^2 (pri f_0 = 0,78 m^{-1}), 45,9 kWh/m^2 (pri f_0 = 0,80 m^{-1}) in 62,7 kWh/m^2 (pri f_0 = 1,08 m^{-1}). Medtem ko je najvišja dovoljena Q_{NH} odvisna od oblike in lokacije stavbe, PURES omejuje Q_{NC} na 50 kWh/m^2, ne glede na obliko in lokacijo. Skladnost Q_{NH} s PURES je bila ocenjena za podnebne podatke, ki predstavljajo obdobje 1981–2010, saj so to podnebni podatki, ki se uporabljajo v trenutnih analizah energijske učinkovitosti stavb. Nadalje smo na podlagi slovenske klasifikacije v razrede energijske učinkovitosti stavbe, podane v Pravilniku o metodologiji izdelave in izdaji energetskih izkaznic stavb [229], stavbne modele razvrstili v razrede energijske učinkovitosti tako glede vrednosti Q_{NH} kot tudi Q_{NC}. Razredi, barvne oznake in razpon rabe energije so predstavljeni v preglednici 8.

Preglednica 8: Razredi energijske učinkovitosti stavbe glede na pravilnik [229].
Table 8: Energy Performance Certificate efficiency classification [229].

Razred	Raba energije [kWh/m^2]	Barva razreda
A1	$Q \leq 10$	
A2	$10 < Q \leq 15$	
B1	$15 < Q \leq 25$	
B2	$25 < Q \leq 35$	
C	$35 < Q \leq 60$	
D	$60 < Q \leq 105$	
E	$105 < Q \leq 150$	
F	$150 < Q \leq 210$	
G	$Q > 210$	

V nadaljevanju je bila ocenjena ranljivost posameznega modela stavbe za pregrevanje. Za izhodišče ocene ranljivosti za pregrevanje je bila uporabljena metoda za analizo robustnosti, ki so jo predstavili Kotireddy in sod. [37] ter sloni na teoriji minimax obžalovanja, ki jo je predstavil Savage [230]. Slednja temelji na hipotezi, da je lahko potem, ko so znani rezultati, ki so posledica določene odločitve, odločevalcu žal za predhodno sprejeto odločitev, saj zdaj pozna izid in si morda želi, da bi v fazi odločanja izbral drugo alternativo. S kriterijem minimax obžalovanja tako želimo zmanjšati (minimizirati) maksimum obžalovanja neke odločitve v preteklosti, s tem identificirati najboljše in najslabše scenarije ter se približati optimalni odločitvi. Z aplikacijo metode minimax obžalovanja smo za določitev največjega obžalovanja v zmogljivosti nekega modela stavbe v izbranem podnebnem obdobju le-tega primerjali z najuspešnejšim stavbnim modelom v istem obdobju. Največje obžalovanje v zmogljivosti nekega modela stavbe znotraj vseh podnebnih obdobij nam poda absolutno mero robustnosti. Tako je najbolj robustna zasnova stavbe tista z najmanjšim obžalovanjem glede na najboljšo možno zmogljivost, ki jo lahko dosežemo z izbranimi kriteriji. Izbrana metoda minimax obžalovanja je opisana z enačbami 26–28.

$$R_{max,i} = max(R_{i1}, R_{i2}, \dots, R_{ij}) \tag{26}$$

$$R_{ij} = PI_{ij} - A_j \tag{27}$$

$$A_j = min(PI_{1j}, PI_{2j}, \dots, PI_{ij}) \quad (28)$$

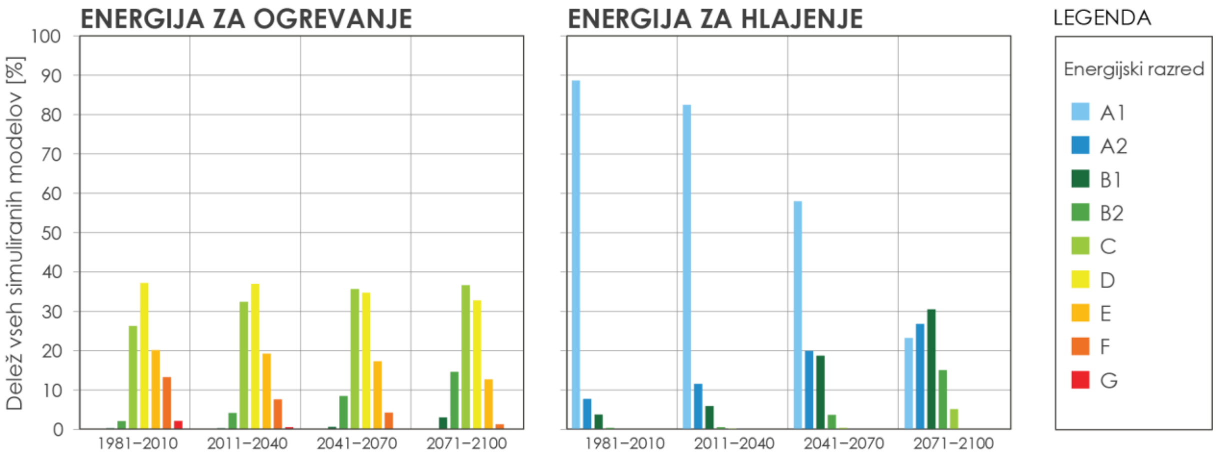
Metoda je bila prilagojena parametrom, uporabljenim v raziskavi. $R_{max,i}$ je največja vrednost kazalnika zmogljivosti i-tega modela stavbe, R_{ij} je obžalovanje zmogljivosti i-tega modela stavbe v podnebnem scenariju j, A_j je najmanjša vrednost kazalnika zmogljivosti v podnebnem scenariju j in PI_{ij} je kazalnik zmogljivosti i-tega modela stavbe v podnebnem scenariju j. Vrednost i = 1–496.800 in j = 1–4, saj je parametrična študija vsebovala 496.800 posameznih modelov stavb, simuliranih v štirih različnih podnebnih scenarijih. Kot kazalnik zmogljivosti (tj. *PI*) je bil za vsak model stavbe v vsakem prihodnjem podnebnem scenariju (2011–2040, 2041–2070 in 2071–2100, za podrobnosti glej poglavje 5) izbran in izračunan prirastek letne potrebne energije za hlajenje (tj. ΔQ_{NC}) v primerjavi s Q_{NC} v obdobju 1981–2010. Nato je bil s pomočjo enačbe 29 identificiran stavbni model z največjo ranljivostjo (in najnižjo robustnostjo) za pregrevanje zaradi podnebnih sprememb.

$$V_{max} = max(R_{max,i}) \quad (29)$$

Pri tem V_{max} pomeni za pregrevanje najranljivejšo kombinacijo pasivnih ukrepov. Nato je bila izdelana ocena ranljivosti za pregrevanje ali vrednost *OV* (ang. *overheating vulnerability score*, *OV score*). Le-to smo izračunali tako, da smo obžalovanje zmogljivosti vsakega modela stavbe (tj. R_{ij}) normirali z obžalovanjem zmogljivosti za pregrevanje najbolj ranljivega modela stavbe. Stavbni model z najnižjo vrednostjo *OV* (enako 0) je opredeljen kot najmanj ranljiv (tj. najbolj robusten), stavbni model z najvišjo vrednostjo *OV* (enako 1) pa je najbolj ranljiv za podnebne spremembe glede pregrevanja.

6.3 Rezultati

Parametrično simulirani modeli stavb so bili ovrednoteni glede skladnosti s PURES, njihova Q_{NH} in Q_{NC} pa glede na razrede energijske učinkovitosti. S tem je bila ocenjena možnost za izpolnjevanje zahtev in zagotavljanje energijske učinkovitosti enostanovanjskih stavb z uporabo izključno analiziranih bioklimatskih oz. pasivnih načrtovalskih ukrepov in brez uporabe aktivnih ukrepov, kot je na primer mehansko prezračevanje z vračanjem toplote. Rezultati so pokazali, da vsi obravnavani modeli stavb z $U_O \leq 0{,}25$ W/m^{2}K izpolnjujejo kriterije PURES glede dovoljene vrednosti Q_{NH}. Kriterij PURES glede Q_{NC} je bil izpolnjen v vseh analiziranih modelih, saj je bil najvišji Q_{NC} simuliranih modelov za obdobje 1981–2010 enak 34,1 kWh/m^2. Na podlagi rezultatov lahko pričakujemo, da bo Q_{NC} analiziranih modelov stavb prvič presegel dovoljeno mejo 50 kWh/m^2 v obdobju 2041–2070. Rezultati, predstavljeni na sliki 34, so pokazali, da z uporabo izbranih pasivnih načrtovalskih ukrepov lahko dosežemo zadovoljivo energijsko učinkovitost. Nobeden od obravnavanih primerov stavb se sicer ni uvrstil v razred energijske učinkovitosti glede na ogrevanje z oznako A1 (Q_{NH} < 10 kWh/m^2) ali A2 (10 < Q_{NH} > 15 kWh/m^2); ne v trenutnem podnebju ne v katerem koli prihodnjem. Stavbni modeli so bili zato glede na Q_{NH} uvrščeni v razrede B1 do G. Pod vplivom predvidenih podnebnih sprememb je pričakovati, da se bo energijska učinkovitost analiziranih stavb glede na ogrevanje sčasoma povečevala, torej se bo povečal delež stavb z višjo energijsko učinkovitostjo glede Q_{NH} (tj. razredi B1, B2 in C). Skladno s tem je pričakovati zmanjšanje deleža energijsko manj učinkovitih modelov (tj. razredov D, E, F in G). V obdobju 1981–2010 je približno 28 % modelov stavb v razredu C ali višje (Q_{NH} < 60 kWh/m^2), medtem ko se bo v obdobju 2071–2100 ta delež skoraj podvojil na 54 %. V obdobju 1981–2010 je le 37 (0,01 %) modelov stavb označenih z razredom energijske učinkovitosti ogrevanja B1 (1 < Q_{NH} > 25 kWh/m^2), to število se v obdobju 2071–2100 poveča na 13.740 primerov (2,77 %). Največjo spremembo deleža modelov stavb v posameznih razredih med obdobji 1981–2010 in 2071–2100 smo zaznali za razred B2 in razred F, predvideno pa je, da od obdobja 2041–2070 med analiziranimi modeli ne bo več stavbe z oznako G energijske učinkovitosti glede na ogrevanje. Če vzamemo za izhodišče obdobje 1981–2010, lahko na podlagi rezultatov pričakujemo, da se bo Q_{NH} do konca stoletja zmanjšal za 24–39 %, s povprečnim zmanjšanjem za 32 %. Ugotovljeno je bilo, da je izbira pasivnih ukrepov za uvrstitev stavbe pod oznako B1 energijske učinkovitosti glede na Q_{NH} v obdobju 1981–2010 relativno omejena, pri razredih B2 in slabših je izbira pasivnih ukrepov svobodnejša. Natančnejši podatki so dostopni v članku Pajek in Košir [52] (priloga D).

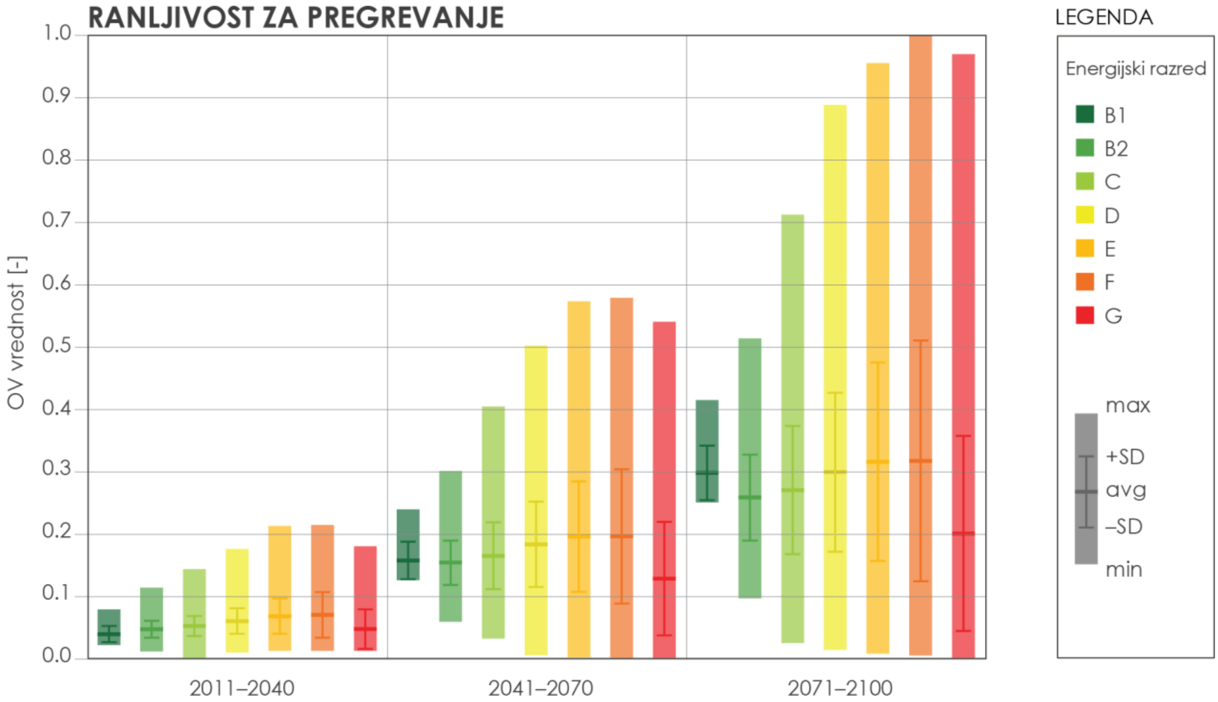


Slika 34: Delež vseh simuliranih modelov stavb glede na energijski razred potrebne energije za ogrevanje in hlajenje za vsako obdobje.

Figure 34: Share of total simulated building models by heating and cooling energy label for each period.

Kar zadeva Q_{NC}, je mogoče s pasivnimi načrtovalskimi ukrepi v zmernem podnebju, kot je v Ljubljani, doseči zadostno energijsko učinkovitost. Za obdobje 1981–2010 lahko večino (89 %) modelov stavb uvrstimo v razred A1 energijske učinkovitosti glede na potrebo po hlajenju, preostalih 11 % pa v razrede A2–B2. Ugotovljeno je bilo, da se bo energijska učinkovitost stavb glede na Q_{NC} sčasoma opazno zmanjšala. Delež energijsko najučinkovitejših modelov stavb (oznaka A1) naj bi se zmanjšal za 66 odstotnih točk med obdobji 1981–2010 in 2071–2100, pri čemer se sorazmerno povečuje delež stavb v razredih A2, B1, B2 in C (slika 34). Od obdobja 2041–2070 so nekateri modeli stavb glede na Q_{NC} uvrščeni že v razred C in D. Do konca 21. stoletja je pričakovati, da se bo Q_{NC}, ne glede na izbrano kombinacijo pasivnih ukrepov, v primerjavi z obdobjem 1981–2010 povečala za vsaj 59 %. Da bi ob segrevanju podnebja lahko tudi v prihodnje ohranili razred A1 energijske učinkovitosti glede na Q_{NC}, svoboda izbire posameznih pasivnih ukrepov sicer ni tako omejena kot pri Q_{NH}. Kljub temu so priporočene nižje vrednosti U_W, *WFR* in α_{sol} od povprečja celotnega vzorca ter višje *DHC* in NV_C od povprečja celotnega vzorca. Natančnejši podatki so dostopni v članku Pajek in Košir [52] (priloga D).

Predstavljeni rezultati kažejo, da je v skladu s predvidenimi podnebnimi spremembami pričakovati nenehno višanje energijske učinkovitosti glede ogrevanja. Zato je bila ranljivost za pregrevanje posameznega modela stavbe na sliki 35 primerjana z razredom energijske učinkovitosti glede na Q_{NH}, doseženim v obdobju 1981–2010 (trenutno podnebje). Rezultati so pokazali, da modeli z različnimi razredi energijske učinkovitosti glede ogrevanja izkazujejo tudi različno vrednost *OV*. Ker predpostavljamo, da bosta sevalni prispevek in globalna temperatura zraka sčasoma ves čas naraščala, pričakujemo, da bo rast tveganja za pojav pregrevanja stavb sledila temu vzorcu. Tako je vrednost *OV* najvišja za stavbe v obdobju 2071–2100 (slika 35).



Slika 35: Ocena ranljivosti za pregrevanje (vrednost *OV*) enostanovanjskih stavb v vsakem prihodnjem podnebnem obdobju. Modeli stavb so razvrščeni po energijskih razredih glede na rabo energije za ogrevanje v obdobju 1981–2010, torej glede na „trenutni" energijski razred.

Figure 35: Overheating vulnerability score (*OV* score) of single-family houses in each future climate period. Building models are classified by heating energy label attained according to the 1981–2010 climate file, namely "current" heating energy label.

Povprečna vrednost *OV* ima v vseh energijskih razredih podoben trend naraščanja. Modeli stavb, ki so razvrščeni v B2 in C razred energijske učinkovitosti glede ogrevanja, v povprečju izkazujejo najmanjšo dovzetnost za povečanje ranljivosti za pregrevanje. Povprečna vrednost *OV* stavb v energijskem razredu B2 se v obdobju 2011–2040 z 0,041 poveča na 0,256 v obdobju 2071–2100. Hkrati se opazno poveča razpon od najnižje do najvišje vrednosti (z 0,093 v 2011–2040 na 0,413 v 2071–2100). Kljub temu, da je najnižja povprečna vrednost *OV* v obdobjih 2041–2070 in 2071–2100 dosežena za stavbe v razredu G, je zanje značilen največji razpon od najnižje do najvišje vrednosti. Razpon najvišja-najnižja vrednost *OV* je najožji pri večini energijsko najučinkovitejših stavb glede na Q_{NH} (razred B1). Torej je pri tovrstnih stavbah ranljivost za pregrevanje lažje nadzorovati, vendar pa ni mogoče doseči najnižjih vrednosti *OV*. Čeprav imajo stavbe v razredu B1 v obdobju 2011–2040 najnižjo povprečno vrednost *OV* (0,034), je dosežena najnižja vrednost (0,025) višja kot pri preostalih razredih. Trend nakazuje, da je za bioklimatske stavbe z visoko energijsko učinkovitostjo glede potrebe po ogrevanju (razred B1) značilno relativno visoko tveganje za pregrevanje. Glavni razlog za to je, da imajo vsi modeli v razredu B1 južno koncentrirane okenske površine (*WFR* višji od 35 %). Kljub temu lahko za stavbe v razredu B1 v primerjavi z razredi B2–G pričakujemo nižjo najvišjo vrednost *OV*.

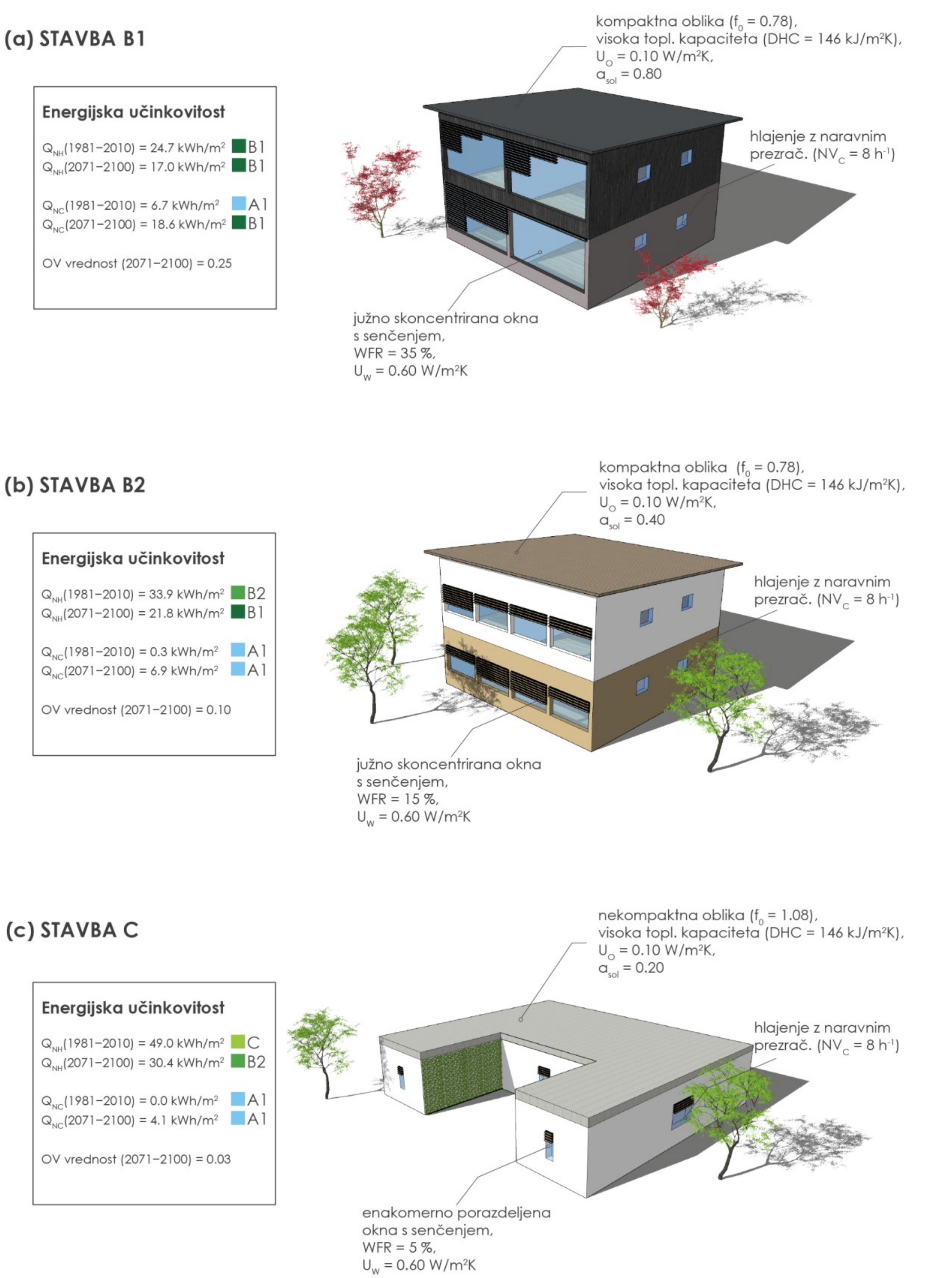
Najnižja ocena ranljivosti za pregrevanje je bila dosežena pri modelu stavbe s slabo toplotno izoliranim ovojem (U_O = 1,0 W/m^{2}K oz. 2 cm toplotne izolacije), z visoko toplotno izolativnimi okni (U_W = 0,6 W/m^{2}K, *SHGC* = 0,45), z majhno površino oken (*WFR* = 5 %), nekompaktno obliko stavbe (f_0 = 1,08), visoko toplotno maso (DHC = 146 kJ/m²K), svetlo obarvanimi zunanjimi površinami (α_{sol} = 0,20) in visoko stopnjo naravne izmenjave zraka za hlajenje (NV_C = 8 h^{-1}). Q_{NC} omenjenega modela stavbe se je povečal z 0,0 kWh/m² v obdobju 1981–2010 na 3,2 kWh/m² v obdobju 2071–2100. Kljub temu je model stavbe z vidika Q_{NH} energijsko neučinkovit (razred G). Za model stavbe z najvišjo vrednostjo *OV* pa so značilni slabo toplotno izoliran ovoj (U_O = 1,0 W/m²K), okna z nizko toplotno izolativnostjo (U_W = 2,2 W/m²K, $SHGC$ = 0,75), po orientacijah enakomerno razporejene izredno velike okenske površine (WFR = 45 %), kompaktna oblika (f_0 = 0,78), visoka toplotna masa (DHC = 146 kJ/m²K), temno obarvane zunanje površine (α_{sol} = 0,80) in brez dodatne naravne izmenjave zraka za hlajenje (NV_C = 0 h^{-1}). Model stavbe glede na Q_{NH} spada v razred F. V preglednici 9 so prikazane tipične vrednosti parametrov po percentilih vrednosti *OV*. Iz rezultatov lahko izluščimo, da so na splošno najmanj nagnjene k pregrevanju stavbe z nadpovprečnimi vrednostmi U_O, W_{dis}, f_0, DHC in NV_C ter podpovprečnimi vrednostmi U_W, WFR in α_{sol}.

Preglednica 9: Značilne vrednosti spremenljivk pasivnih ukrepov za obdobje 2071–2100 glede na vrednost *OV*.
Table 9: Typical values of passive measures variables for the period 2071–2100 according to the *OV* score.

Spremenljivka		Percentili vrednosti *OV* za obdobje 2071–2100						
		p05	Q1	Q2	Q3	Q4	p95	Povprečje celotnega vzorca
U_O [W/m²K]	pov	0,49	0,42	0,41	0,38	0,51	0,74	0,43
	min	0,10	0,10	0,10	0,10	0,10	0,10	0,10
	max	1,00	1,00	1,00	1,00	1,00	1,00	1,00
U_W [W/m²K]	pov	1,30	1,35	1,40	1,51	1,74	1,78	1,50
	min	0,60	0,60	0,60	0,60	0,60	0,60	0,60
	max	2,40	2,40	2,40	2,40	2,40	2,40	2,40
WFR [%]	pov	9,6	13,8	20,8	29,6	34,0	34,2	24,6
	min	5,0	5,0	5,0	5,0	5,0	5,0	5,0
	max	40,0	45,0	45,0	45,0	45,0	45,0	45,0
W_{dis} [-]	pov	0,49	0,52	0,46	0,42	0,38	0,26	0,45
	min	0,00	0,00	0,00	0,00	0,00	0,00	0,00
	max	1,00	1,00	1,00	1,00	1,00	1,00	1,00
f_0 [m^{-1}]	pov	0,94	0,89	0,89	0,87	0,85	0,85	0,88
	min	0,78	0,78	0,78	0,78	0,78	0,78	0,78
	max	1,08	1,08	1,08	1,08	1,08	0,80	1,08
DHC [kJ/m²K]	pov	114	108	106	100	95	85	102
	min	63	63	63	63	63	63	63
	max	146	146	146	146	146	63	146
α_{sol} [-]	pov	0,24	0,35	0,49	0,51	0,64	0,74	0,50
	min	0,20	0,20	0,20	0,20	0,20	0,80	0,20
	max	0,80	0,80	0,80	0,80	0,80	0,80	0,80
NV_C [h^{-1}]	pov	4,7	4,7	4,0	3,9	3,4	3,3	4,0
	min	0,0	0,0	0,0	0,0	0,0	0,0	0,0
	max	8,0	8,0	8,0	8,0	8,0	8,0	8,0

Kljub poznavanju podnebnih modelov in natančnosti scenarijev projekcij podnebnih sprememb še vedno obstaja negotovost glede prihodnjega stanja podnebja. Zato na podlagi rezultatov lahko sklenemo, da je stavbe priporočljivo načrtovati ob upoštevanju doseganja trenutne energijske učinkovitosti glede na potrebo po ogrevanju, hkrati pa si prizadevati za nizko ranljivost stavbe za pregrevanje.

Na sliki 36 so prikazane tri idejne zasnove enostanovanjske bioklimatske stavbe, zasnovane na podlagi rezultatov raziskave toplotnega odziva stavbe v srednjeevropskem zmernem podnebju, kot je v Ljubljani. Prva stavba (slika 36a) dosega energijsko učinkovitost ogrevanja razreda B1 in ima sočasno najnižjo oceno ranljivosti za pregrevanje (vrednost *OV*) med vsemi stavbami v razredu B1. Na sliki 36b je prikazana zasnova stavbe, ki dosega B2 energijsko učinkovitost ogrevanja in najnižjo vrednost *OV* stavb v razredu B2. Zadnja stavba (slika 36c) je za pregrevanje najmanj ranljiva zasnova stavbe v C energijskem razredu glede na Q_{NH}. Izmed treh predstavljenih zasnov ima stavba B1 najnižjo vrednost Q_{NH}, stavba C pa najvišjo glede na podnebje v obdobju 1981–2010. Q_{NC} sledi obratnemu trendu. Pričakovati je, da se bo razlika v Q_{NH} med različnimi primeri do konca stoletja prepolovila, medtem ko naj bi se razlika v Q_{NC} podvojila oz. potrojila. Če obravnavamo skupno energijo, potrebno za kondicioniranje stavbe Q_T (= Q_{NH} + Q_{NC}), postane očitno, da je stavba B1 (Q_T = 31,4 kWh/m^2) najbolj energijsko učinkovita v obdobju 1981–2010, medtem ko je stavba B2 (Q_T = 28,7 kWh/m^2) najbolj učinkovita v obdobju 2071–2100, v katerem stavba B1 izkazuje celo najslabšo energijsko učinkovitost od predstavljenih treh zasnov (Q_T = 35,6 kWh/m^2). Poleg tega je stavba B1 edina, ki v obdobju 2071–2100 potrebuje več Q_T v primerjavi z obdobjem 1981–2010. Zato je, da bi dosegli visoko energijsko učinkovitost glede Q_{NH}, zagotovili nizko ranljivost za pregrevanje in hkrati ustvarili pogoje za ustrezno dnevno osvetlitev, priporočljiva uporaba kombinacije pasivnih načrtovalskih ukrepov, predstavljenih v primeru stavbe B2, ali podobnih.



Slika 36: Tri konceptualne zasnove bioklimatske stavbe za Ljubljano. Primeri predstavljajo na pregrevanje najodpornejšo kombinacijo pasivnih ukrepov za stavbo s tlorisno površino 162 m² v razredu energijske učinkovitosti glede na Q_{NH}: (a) razred B1; (b) razred B2; (c) razred C.

Figure 36: Three conceptual examples of bioclimatic building design for Ljubljana. Examples represent the most overheating resilient combination of passive measures for a building with floor area equal to 162 m² in: (a) B1 heating energy efficiency class; (b) B2 heating energy efficiency class; (c) C heating energy efficiency class.

6.4 Razprava

Pri bioklimatskem načrtovanju stavb se srečamo z različnimi nasprotujočimi se odločitvami, pri katerih je treba upoštevati več ciljev in načrtovalskih meril, kot so udobje uporabnikov, energijska učinkovitost in zagotavljanje dnevne svetlobe. V praksi so kompromisi med temi cilji zelo pogosti, zato je treba tej temi nameniti veliko pozornosti. Kot osrednji del raziskave je bil obravnavan le vidik energijske učinkovitosti stavbe na podlagi potrebne energije za zagotavljanje toplotnega udobja, medtem ko toplotno udobje uporabnikov, kakovost zraka in zagotavljanje dnevne svetlobe niso bili neposredno obravnavani; zato je treba predstavljene rezultate interpretirati v tem kontekstu. V teh okvirih je bil cilj raziskave analizirati energijsko učinkovitost in ranljivost za pregrevanje enostanovanjskih bioklimatskih stavb v zmernem podnebju (Ljubljana). Energijska učinkovitost je bila ovrednotena glede na letno potrebno energijo za ogrevanje (Q_{NH}) in hlajenje (Q_{NC}) na m^2 uporabne tlorisne površine stavbe. Na podlagi slovenske zakonodaje je bil z uporabo izbranih pasivnih načrtovalskih ukrepov glede na Q_{NH} najvišji dosegljivi razred energijske učinkovitosti B1. Proti koncu stoletja se pričakuje veliko toplejše podnebje, ki bo nekoliko izboljšalo energijsko učinkovitost glede na Q_{NH}, saj naj bi se energija, potrebna za ogrevanje, zmanjšala. Glede na rezultate raziskave je za zagotavljanje visoke energijske učinkovitosti in hkrati nizke ranljivosti za pregrevanje priporočljiva uporaba visoko toplotno izoliranih ovojev stavb, predvsem transparentnih elementov (oken). Poleg tega je priporočena uporaba zmerno velikih transparentnih površin, na primer *WFR* v okviru 10–25 %. Transparentne površine so lahko koncentrirane na južni fasadi, pri čemer je priporočeno razmerje med oknom in zunanjo steno (*WWR*) med 20 in 60 %. V skladu s tem se na južni fasadi za delno senčenje lahko uporabijo fiksna senčila – nadstreški. Pri južno usmerjenih oknih je treba za preprečevanje pregrevanja na celotni zastekljeni površini uporabiti zunanja senčila (npr. žaluzije). Poleg tega je za zagotavljanje učinkovitega senčenja treba delovanje senčil nadzorovati z avtomatskim sistemom. Glede oblike stavbe je priporočljiva bolj kompaktna zasnova. Za povečanje toplotne kapacitete stavbe je priporočena uporaba masivnih gradbenih materialov. Čeprav so rezultati raziskave pokazali, da je razred energijske učinkovitosti ogrevanja B1 mogoče doseči le z uporabo temno obarvanih zunanjih površin, je kljub temu priporočljiva uporaba svetlejših barv (npr. α_{sol} = 0,40–0,60), ki omogočajo manjšo ranljivost za pregrevanje. Kot učinkovit ukrep za preprečevanje pregrevanja se lahko uporabijo tudi ozelenjene površine ali površine z nizko sončno vpojnostjo (»hladne« površine). Od pomladi do jeseni je, kadar razmere to zahtevajo in dopuščajo, priporočljivo hlajenje prostorov z naravnim prezračevanjem, običajno ponoči. V ta namen je treba z ustrezno razporeditvijo prostorov in odprtin omogočiti prečno ali vertikalno (vzgonsko) prezračevanje stavbe.

6.5 Prispevek k znanosti

Z raziskavo, predstavljeno v članku Pajek in Košir [52] (priloga D), smo prikazali nov pristop k bioklimatskemu načrtovanju stavb, pri čemer je zagotovljena trenutna in prihodnja energijska učinkovitost, hkrati pa sta obravnavana tudi odpornost za pregrevanje in prilagajanje podnebnim spremembam. Rezultati te raziskave pripomorejo k pojasnjevanju celotnega načrtovanja enostanovanjskih bioklimatskih stavb v zmernem podnebju. Raziskava prikazuje, kako oceniti ranljivost bioklimatskih stavb za pregrevanje v prihodnjih podnebnih stanjih. V Srednji Evropi je pri načrtovanju stavb ranljivost stavb za pregrevanje pomembna, a kljub temu pogosto spregledana, saj se načrtovalci, projektanti in zakonodajalci osredotočajo predvsem na energijsko učinkovitost stavb glede na potrebno energijo za ogrevanje. Ocena ranljivosti za pregrevanje je izredno pomembna, saj je pričakovati, da bodo podnebne spremembe znižale energijsko učinkovitost stavb glede potrebne energije za hlajenje, zlasti tistih stavb, ki so zasnovane za pasiven zajem sončne energije v hladnejšem delu leta. Kot rezultat raziskave so bila podana priporočila za energijsko učinkovito in na segrevanje ozračja odporno zasnovo enostanovanjske bioklimatske stavbe v zmernem podnebju. Takšna priporočila so potrebna, ker v tem podnebju v stanovanjskih stavbah prevladuje ogrevanje, s segrevanjem podnebja pa obstaja nevarnost pregrevanja stavb. Zato rezultati pomenijo pomembne informacije za projektante in oblikovalce strateških ciljev, da prikazan pristop k bioklimatskemu načrtovanju stavb prenesejo v prakso in predpise. Ugotovitve raziskave kažejo na veliko potrebo po opredelitvi jasne poti glede načrtovanja podnebno odpornih in trajnostih stavb, da bi s tem ohranili vire in ublažili nadaljnje podnebne spremembe.

7 ZAKLJUČKI

Povzetek

Z raziskavami, predstavljenimi v doktorski disertaciji, želimo odgovoriti na nekatera vprašanja, ki jih za grajeno okolje prinaša globalno segrevanje, in izpolniti vrzeli v znanju, ki so bile izražene na področju energijske učinkovitosti enostanovanjskih bioklimatskih stavb danes in v prihodnosti. V zaključku doktorske disertacije najprej na kratko povzemamo namen raziskav, v nadaljevanju odgovarjamo na poglavitna raziskovalna vprašanja in hipoteze, nato so ovrednoteni preostali zastavljeni cilji, na koncu opozarjamo na omejitve opravljenih raziskav z izhodišči za nadaljevanje raziskovanja ter prispevek znanosti.

Abstract

With the research presented in the doctoral dissertation, we wanted to answer several questions concerning the effect of global warming on the built environment. Therefore, the research aims at filling the knowledge gaps expressed in the energy efficiency of single-family bioclimatic buildings today and in the future. In the conclusions of the doctoral dissertation, firstly, the purpose of the research is briefly summarised. Then, the main research questions are answered, and hypotheses and goals evaluated. Finally, the research limitations are highlighted, and possible future research opportunities are elaborated. The chapter ends by stating the contribution and novelty of the research.

7.1 Temeljno znanstveno vprašanje in zastavljene hipoteze

Namen doktorske disertacije je bil odgovoriti na vprašanja, ki se pojavljajo zaradi vpliva globalnega segrevanja na energijsko učinkovitost enostanovanjskih bioklimatsko načrtovanih stavb. Na začetku doktorske disertacije (poglavje 2) so zato predstavljeni teoretična izhodišča in rezultati obširnega pregleda literature o obravnavanem znanstvenem področju, s pomočjo katerega je bilo opozorjeno na ključne vrzeli v znanju načrtovanja energijsko učinkovitih enostanovanjskih bioklimatskih stavb. Le-te smo naslovili s pomočjo štirih raziskav, pri katerih smo rezultate pridobili z uporabo različnih analitičnih in simulacijskih orodij. Pri tem smo nadgradili obstoječo metodologijo in izdelali analitično orodje za izvedbo bioklimatske analize lokacije (poglavje 3). Na izbranih lokacijah in širših območjih smo s pomočjo bioklimatskih analiz podnebja ocenili bioklimatski potencial (poglavje 3). Le-ta nam pove, koliko je neko podnebje zahtevno glede zagotavljanja toplotnega udobja v stavbah ter ponuja usmeritve pri izbiri bioklimatskih načrtovalskih strategij. Nato smo za zadnjih pet zaporednih in naslednji dve desetletij ovrednotili bioklimatski potencial petih izbranih lokacij v Sloveniji (poglavje 4), s tem pa prepoznali vzorce vpliva podnebnih sprememb na le-tega. S pomočjo slednjega smo ovrednotili pomembnost pasivnih načrtovalskih ukrepov in njihov vpliv na energijsko učinkovitost stavb v sedanjosti in prihodnosti. Izhajajoč iz dognanj, predstavljenih v poglavjih 3 in 4, smo z uporabo simulacijskega orodja EnergyPlus in simulacij toplotnega odziva stavb ugotovili najbolj vplivne pasivne načrtovalske ukrepe, ki bodo imeli učinek na energijsko učinkovitost enostanovanjskih stavb v trenutnem in prihodnjem stanju podnebja (poglavje 5). Analiza je bila opravljena za več lokacij z različnim podnebjem, pri tem pa smo s pomočjo skupno 15.897.600 simuliranih primerov, opisne statistike in trendov ocenili predviden potek rabe energije simuliranih stavbnih modelov in izluščili optimalne pasivne načrtovalske ukrepe, primerne za posamezno podnebje. Za primer zmerno toplega podnebja Slovenije (Ljubljana) smo raziskavo še razširili, podrobno preučili energijsko učinkovitost enostanovanjskih stavb in učinke segrevanja ozračja na le-to, pri čemer smo s predlagano metodologijo ocenili tudi ranljivost stavb za pregrevanje (poglavje 6).

S pomočjo obširnega pregleda literature in simulacijskih študij smo odgovorili na dve temeljni znanstveni vprašanji in tri hipoteze, zastavljene v dispoziciji doktorske disertacije. Komentarji in spoznanja v zvezi s temeljnimi znanstvenimi vprašanji (<u>*zapisanimi ležeče in podčrtano*</u>) in hipotezami (*zapisanimi ležeče*) so za vsakim navedenim vprašanjem oz. hipotezo.

1. temeljno znanstveno vprašanje

<u>*»Ali bi bilo bolje bioklimatske stavbe načrtovati na podlagi napovedi in pričakovanj stanja podnebja ter koliko? Katere podatke bi bilo pri tem treba uporabiti?«*</u>

Koncept bioklimatske stavbe je povezan z doseganjem harmonije oziroma kompromisom med podnebjem, udobjem uporabnikov in energijsko učinkovitostjo. Pokazali smo, da je bioklimatski potencial lokacije zanesljiv in jasen pokazatelj učinkovitih pasivnih ukrepov, ki vplivajo na toplotni odziv stavb. Z analizami smo pokazali, da predvideno globalno segrevanje prinaša izzive za grajeno okolje, saj vse večji pomen tudi v zmernih in hladnih podnebjih dobivajo pasivni ukrepi za preprečevanje pregrevanja, le-ti pa običajno ne predstavljajo pomembnega elementa v bioklimatskem načrtovanju stavb, ki temelji na stanju preteklega podnebja. Ugotovili smo, podrobneje pri primeru zmerno toplega podnebja, da imata zato izdelava podnebnih analiz in upoštevanje analiz učinka podnebnih sprememb pri načrtovanju stavb velik pomen. Z analizami podnebnih danosti ter simulacijskimi študijami glede rabe energije za ogrevanje in hlajenje stavb smo pokazali, da bi bilo enostanovanjske stavbe smiselno načrtovati ob upoštevanju trenutnih podatkov o stanju podnebja in tudi pričakovanj glede podnebja v prihodnosti, s katerimi lahko učinkovito preučimo vpliv podnebnih sprememb na grajeno okolje in ranljivost enostanovanjskih stavb za pregrevanje. Z razvojem doktorske disertacije smo prišli do ugotovitve, da je pri bioklimatski analizi podnebnih danosti ter določanju bioklimatskega potenciala ključna uporaba podnebnih podatkov, kot so temperatura in relativna vlažnost zraka ter gostota moči sončnega sevanja. Slednja v bioklimatskih analizah do sedaj ni bila neposredno zajeta in je predstavljala večjo slabost pri izračunu bioklimatskega potenciala. Glede analize pričakovanih vplivov globalnega segrevanja na bioklimatski potencial in energijsko učinkovitost stavb lahko trdimo, da je ključno upoštevanje natančnih podnebnih podatkov, kot so na primer zajeti v EPW podnebnih datotekah. Pri tem se podnebne datoteke za analizo vpliva podnebnih sprememb pripravijo s podatki in modeli o trenutnem podnebju, scenariji podnebnih sprememb in postopkom zvezne transformacije (ang. *morphing*); s čimer ustvarimo projicirane podnebne datoteke, ki z zadostno zanesljivostjo predstavljajo podnebne podatke v sicer relativno negotovi prihodnosti.

Iz prvega znanstvenega vprašanja izhajata dve hipotezi:

»Poleg temperature zraka in relativne vlažnosti je pri bioklimatski analizi lokacije nujno upoštevanje količine prejetega sončnega sevanja, vse tri pa je treba obravnavati istočasno.«

Rezultati raziskav, predstavljenih v poglavju 3, so pokazali, da lahko prvo hipotezo potrdimo. Z analizami bioklimatskega potenciala smo pokazali pomembnost upoštevanja količine prejetega sončnega sevanja pri izdelavi bioklimatskih analiz. Le-te smo izdelali s programskim orodjem BcChart, ki je bilo razvito v okviru doktorske disertacije in omogoča izračun bioklimatskega potenciala s pomočjo temperature (T_e) in relativne vlažnosti (RH) zunanjega zraka ter gostote moči prejetega sončnega sevanja (G) na izbrani lokaciji. Dejansko prejeto sončno sevanje pri izračunih bioklimatskega potenciala je bilo upoštevano z uvedbo nadomestne udobne temperature zraka (T_{sub}) in temperature zraka, pri kateri je še možno koriščenje pasivnega sončnega ogrevanja (T_{PSH}). Nato je bila izdelana primerjalna analiza bioklimatskega potenciala z in brez upoštevanja sončnega sevanja, pri čemer smo za isto lokacijo le-tega izračunali po obeh metodah. Opravljene analize so pokazale, da upoštevanje sončnega sevanja pri izračunu bioklimatskega potenciala bistveno vpliva na rezultate in podaja ključno informacijo o tem, kdaj je treba stavbe senčiti in kdaj lahko koristimo sončno energijo za pasivno ogrevanje stavbe. Zato lahko sklenemo, da poleg upoštevanja osnovnih podnebnih karakteristik, kot sta T_e in RH, podatek o sončnem sevanju (G) poglavitno vpliva na rezultate analize bioklimatskega potenciala, zlasti v zmernem in hladnem podnebju.

»Energijska učinkovitost obstoječih enostanovanjskih bioklimatskih stavb bo v prihodnosti slabša od energijske učinkovitosti istih stavb v sedanjosti, vendar je relativna razlika močno odvisna od prvotno izbranih bioklimatskih načrtovalskih strategij in podnebnih značilnosti lokacije.«

S simulacijskimi analizami, katerih rezultati so prikazani v poglavjih 4, 5 in 6, smo pokazali metodološki pristop k oceni energijske učinkovitosti stavb v prihodnjih podnebnih stanjih. Pri tem smo se naslonili na projekcije podnebnih sprememb, ki so bile razvite v okviru Medvladnega odbora za podnebne spremembe (IPCC), in s pomočjo scenarija SRES A2 simulirali toplotni odziv enostanovanjskih stavb v treh prihodnjih obdobjih. S pomočjo rezultatov, predstavljenih v poglavju 4, smo pokazali, da ko govorimo o obravnavanih primerih obstoječih enostanovanjskih stavb v Sloveniji, lahko v prihodnosti pričakujemo slabšo energijsko učinkovitost (oz. višjo rabo energije) glede skupne letne potrebne energije (Q_T). Pri tem je do konca stoletja pričakovati enakomerno rast potrebne energije za hlajenje (Q_{NC}) in padec potrebne energije za ogrevanje (Q_{NH}) stavbe. Podoben trend smo zaznali tako za bioklimatsko načrtovano kot za običajno načrtovano enostanovanjsko stavbo, pri čemer je obseg vpliva globalnega segrevanja odvisen od lastnosti toplotnega ovoja in uporabe senčenja. Ker na podlagi tako majhnega vzorca ni mogoče trditi, ali gre za splošen trend vpliva podnebnih sprememb na energijsko učinkovitost enostanovanjskih stavb, smo v poglavjih 5 in 6 izdelali obsežno, poglobljeno parametrično študijo, v kateri smo na osmih različnih evropskih lokacijah z različnim podnebjem preučili vpliv več bioklimatskih strategij (496.800 različnih kombinacij pasivnih načrtovalskih ukrepov) na energijsko učinkovitost stavbe v smislu Q_T, Q_{NC} in Q_{NH}. Na podlagi rezultatov lahko trdimo, da na vseh lokacijah v prihodnosti pričakujemo boljšo energijsko učinkovitost glede Q_{NH} (nižja Q_{NH}) in slabšo energijsko učinkovitost glede Q_{NC} (višja Q_{NC}). Pri tem lahko poudarimo ugotovitev, ki kaže na trend rasti Q_T na toplih lokacijah (npr. Atene), trend padanja Q_T hladnih lokacij (npr. Östersund, Moskva) ter trend rahlega prevoja vrednosti Q_T na zmerno toplih lokacijah (npr. Ljubljana), kjer po nekem obdobju rahlega padanja vrednosti Q_T le-ta spet začne naraščati. V splošnem to pomeni, da je energijska učinkovitost enostanovanjskih stavb v prihodnosti odvisna od lokacije. Na primeru Ljubljane lahko na podlagi rezultatov pričakujemo, da se bo Q_{NH} do konca 21. stoletja v povprečju zmanjšala za 32 % in Q_{NC} povečala za vsaj 59 % v primerjavi z obdobjem 1981–2010. Skupna energijska učinkovitost bo v prihodnosti pri enostanovanjskih stavbah v Ljubljani lahko višja, podobna ali nižja kot v trenutnem podnebnem stanju. Ali bo le-ta višja, podobna ali nižja pa je odvisno od na začetku izbranih bioklimatskih strategij oz. pasivnih načrtovalskih ukrepov. Pri tem je lahko glede na Q_T določena kombinacija pasivnih načrtovalskih ukrepov v trenutnih podnebnih razmerah bolj energijsko učinkovita od druge, v kasnejših, toplejših obdobjih pa se njena energijska učinkovitost poslabša ali obratno. Na podlagi rezultatov, predstavljenih v doktorski disertaciji, tako lahko trdimo, da je relativna razlika v energijski učinkovitosti enostanovanjskih stavb glede na trenutno podnebje močno odvisna od prvotno izbranih bioklimatskih načrtovalskih strategij in podnebnih značilnosti lokacije. Vendar ne moremo trditi, da bo energijska učinkovitost obstoječih enostanovanjskih bioklimatskih stavb v prihodnosti slabša od energijske učinkovitosti enakih stavb v sedanjosti. Hipotezo lahko torej ovržemo, saj le-ta velja le v določenih primerih.

2. temeljno znanstveno vprašanje

»Ali je moč na podlagi bioklimatskih analiz predlagati ustrezne načrtovalske ukrepe, ki bodo zadostili zahtevam uporabnikov enostanovanjskih stavb, energijski učinkovitosti ter hkrati stavbi omogočili prilagoditev trenutnemu in prihodnjemu stanju podnebja?«

Kakor je moč sklepati iz odgovora na 1. znanstveno vprašanje, bioklimatska analiza predstavlja učinkovit pristop k izbiri primernih pasivnih načrtovalskih strategij, ko v samo analizo zajamemo dovolj širok nabor potrebnih vhodnih podatkov. V odgovoru na 2. hipotezo smo poudarili, da je energijska učinkovitost enostanovanjskih stavb v prihodnosti odvisna od prvotno izbranih pasivnih načrtovalskih ukrepov strategij in podnebnih značilnosti lokacije. Zato lahko trdimo, da s premišljeno izbiro pasivnih načrtovalskih ukrepov, ustreznih za neko lokacijo oz. podnebje, lahko zadostimo potrebam uporabnikov enostanovanjskih stavb in zahtevam po energijski učinkovitosti, hkrati pa omogočimo prilagoditev trenutnemu in prihodnjemu stanju podnebja.

Iz 2. znanstvenega vprašanja sledi hipoteza:

»Izbira le bioklimatskih načrtovalskih ukrepov za zajem sončne energije pri načrtovanju enostanovanjskih bioklimatskih stavb v zmernem podnebju ni najučinkovitejši pristop za energijsko učinkovitost stavb v prihodnosti, pač pa vedno večji pomen tudi na teh lokacijah dobivajo ukrepi za preprečevanje pregrevanja.«

V poglavjih 4, 5 in 6 smo s pomočjo različnih parametričnih študij pokazali vpliv podnebnih sprememb na bioklimatski potencial in energijsko učinkovitost stavb. Poglavje 4 razkriva, da vpliv globalnega segrevanja v zmerno toplem podnebju, kot je v Sloveniji, ključno vpliva na čas v letu, ko je potrebno senčenje oz. nasprotno, ko je potrebno koriščenje sončne energije (pasivno sončno ogrevanje). Na vseh petih obravnavanih slovenskih lokacijah se je v zadnjih desetletjih podaljšalo obdobje, ko je toplotno udobje v stavbi moč doseči zgolj s pasivnimi načrtovalskimi ukrepi. Pri tem se daljša obdobje, ko je za dosego toplotnega udobja potrebno senčenje (viša se vrednost C_{sh}), hkrati pa se krajša obdobje, ko je za namen pasivnega sončnega ogrevanja potrebno koriščenje sončnih dobitkov (vrednosti C_{sn} in R). Rezultati so pokazali, da sončno sevanje na letni ravni ni več zaželeno v enaki količini, kot je bilo v preteklosti. Na podlagi rezultatov analize bioklimatskega potenciala lahko trdimo, da se na obravnavanih lokacijah zadnjih pet desetletij konstantno veča pomen bioklimatskih strategij za preprečevanje pregrevanja (višanje vrednosti C_{sh} in V) in hkrati manjša pomen pasivnih ukrepov za zadrževanje in zajemanje toplote (nižanje vrednosti C_{sn}, R in H). To pomeni, če stavbe niso zasnovane z ustreznimi pasivnimi načrtovalskimi ukrepi za izključevanje toplote oz. preprečevanje pregrevanja (npr. senčenje), na vseh obravnavanih lokacijah obstaja nevarnost pregrevanja. Tudi rezultati analize energijske učinkovitosti izbranih dveh tipov enostanovanjskih stavb v Sloveniji so pokazali trend naraščajoče potrebe po hlajenju stavb in slabši energijski učinkovitosti stavbe glede hlajenja v prihodnosti. V nadaljevanju smo zato naredili obširno parametrično študijo (poglavje 5), rezultate pa poglobljeno obravnavali in predstavili v poglavju 6. Rezultati parametrične študije 496.800 različnih kombinacij pasivnih načrtovalskih ukrepov za zmerno podnebje (Ljubljana) so pokazali, da lahko tudi v prihodnosti za enostanovanjsko stavbo, načrtovano po bioklimatskih načelih, samo z uporabo pasivnih načrtovalskih ukrepov dosežemo razred B1 energijske učinkovitosti glede Q_{NH} in razred A1 glede Q_{NC}. V naslednjem koraku nas je zanimala ranljivost stavbe za pregrevanje, s čimer smo izluščili kombinacije pasivnih načrtovalskih ukrepov, ki so odpornejše na pregrevanje v prihodnosti. Najnižja ocena ranljivosti za pregrevanje je bila dosežena pri modelu stavbe z okni z nizko toplotno prehodnostjo (U_W = 0,6 W/m^{2}K) in nizkim faktorjem presevnosti energije sončnega sevanja (*SHGC* = 0,45) ter z majhno površino oken (*WFR* = 5 %). Bolj ranljivi pa so bili modeli stavb z višjimi vrednostmi. Bioklimatski načrtovalski ukrepi za zajem sončne energije (pasivno sončno ogrevanje) upoštevajo ravno nasprotne ukrepe (višji *SHGC* in *WFR*), za katere na podlagi rezultatov lahko sklepamo, da bodo v prihodnje čedalje manj pomembni. V daljšem obdobju se je tako za optimalno zasnovo glede energijske učinkovitosti stavbe za Q_T v zmernem podnebju izkazala zasnova s splošno nižjim *WFR* (≈ 15 %) in *SHGC* (≈ 0,45). Iz navedenih ugotovitev lahko povzamemo, da je bila na podlagi opravljenih raziskav za doktorsko disertacijo hipoteza v celoti potrjena.

7.2 Preostali zastavljeni cilji

Poleg znanstvenih vprašanj in hipotez smo si zastavili še štiri preostale cilje, ki smo jih med raziskovanjem za doktorsko disertacijo uspešno izpolnili.

»Opraviti obsežen pregled literature o bioklimatskem načrtovanju stavb ter vplivu podnebnih sprememb na njihovo energijsko učinkovitost.«

Da smo lahko spoznali ključne vrzeli v znanju pri načrtovanju energijsko učinkovitih enostanovanjskih bioklimatskih stavb, smo v poglavju 2 predstavili teoretična izhodišča in opisali izsledke obširnega pregleda literature o obravnavanem znanstvenem področju.

»Izdelati orodje za bioklimatsko analizo lokacije na podlagi podnebnih karakteristik.«

V fazi preliminarnih raziskav bioklimatskega potenciala smo izdelali orodje BcChart (poglavje 3), s katerim z uporabo podnebnih karakteristik, kot so temperatura zunanjega zraka (T_e), relativna vlažnost zunanjega zraka (*RH*) in gostota moči sončnega sevanja (*G*), določimo bioklimatski potencial lokacije. Glavne prednosti orodja BcChart so preprosta uporaba, hitrost analize in odprti dostop (dostopno na spletnem naslovu https://kske.fgg.uni-lj.si/raziskovalno-delo/). Orodje BcChart uporabljajo na več univerzah po svetu, med drugim na Curtin University Perth (Avstralija), University of Guadalajara (Mehika), Metropolitan Autonomous University Mexico City (Mehika), Federal University of Santa Catarina (Brazilija), Tianjin University (Kitajska) in National Institute of Technology Hamirpur (Indija). Uporabljeno je bilo tudi v nekaj raziskavah drugih avtorjev.

»Na podlagi nabora tipičnih primerov enostanovanjskih stavb in različnih vhodnih podatkov, kot so lastnosti ovoja in podnebni podatki, preveriti energijsko učinkovitost obravnavanih stavb v sedanjosti ter na podlagi napovedi tudi v prihodnosti.«

Kakor že omenjeno v odgovoru na 2. in 3. hipotezo, smo zaradi ovrednotenja hipotez opravili obširno parametrično študijo, s pomočjo katere smo parametrično simulirali rabo energije tipičnih enostanovanjskih stavb na osmih različnih lokacijah v Evropi, skupno 15.897.600 simulacij. Pri tem smo parametrično variirali tri različne oblike stavbe (f_0), deset vrednosti toplotnih prehodnosti netransparentnega dela stavbnega ovoja (U_O), deset toplotnih prehodnosti transparentnega dela stavbnega ovoja oz. oken (U_W) s pripadajočimi *SHGC* faktorji, devet razmerij med površino tal in površino oken (*WFR*), dve različni razporeditvi okenskih površin (W_{dis}), tri različne toplotne kapacitete nosilne konstrukcije (*DHC*), štiri vrednosti sončne vpojnosti zunanjih površin (α_{sol}) in devet različnih stopenj hlajenja z naravnim prezračevanjem (NV_C). Rabo energije tako parametrično definiranih modelov stavb smo simulirali za trenutno stanje podnebja (1981–2010) in za prihodnje projekcije podnebja v obdobjih 2011–2040 (obdobje 2020), 2041–2070 (obdobje 2050) in 2071–2100 (obdobje 2080). Rezultati so predstavljeni v poglavjih 4, 5 in 6.

»Določiti bioklimatske strategije, ki bodo v prihodnosti omogočale učinkovito rabo energije enostanovanjskih stavb na izbranih lokacijah.«

Izbira kombinacije pasivnih načrtovalskih ukrepov precej vpliva na potrebno energijo za ogrevanje (Q_{NH}) in hlajenje (Q_{NC}) ter razmerje med njima. V poglavjih 4, 5 in 6 smo s pomočjo parametričnih študij in širokega nabora vhodnih podatkov določili pasivne načrtovalske ukrepe, ki omogočajo učinkovito rabo energije v trenutnem podnebnem stanju ter tudi v prihodnosti. Rezultati so pokazali, da je v enostanovanjskih stavbah mogoče doseči nizko skupno rabo energije le z uporabo pasivnih načrtovalskih ukrepov, še zlasti v oceanskem, toplem in zmernem podnebju. S pomočjo opisne statistike smo pokazali, da je pri enostanovanjskih stavbah poleg senčenja najučinkovitejši pasivni načrtovalski ukrep v trenutnem in prihodnjem predvidenem podnebnem stanju na vseh analiziranih lokacijah uporaba nižjih vrednosti *WFR*, v toplem podnebju pa tudi nižje α_{sol}. Podrobnejši podatki so predstavljeni v poglavjih 4, 5 in 6. Kot rezultat raziskave so bila za Ljubljano podana natančnejša priporočila za energijsko učinkovito in na segrevanje ozračja odporno zasnovo enostanovanjske bioklimatske stavbe.

7.3 Omejitve in izhodišča za nadaljnje raziskovanje

Med raziskovanjem in analizo rezultatov smo ugotovili in poudarili nekaj omejitev naših raziskav, ki so bile bodisi posledica določenih predpostavk, robnih pogojev in natančnosti vhodnih podatkov ali pa značilnosti obravnavanega znanstvenega področja. V poglavju zato nanje opozarjamo. Kljub temu omejitve ne vplivajo na končne rezultate tako, da bi zmanjševale njihovo relevantnost, temveč predvsem poudarjajo in odpirajo nove vrzeli v raziskovalnem področju in s tem predstavljajo izhodišča za nadaljnje raziskovanje.

1. Ob razvijanju in uporabi izdelanega predstavljenega orodja BcChart bi radi opozorili na glavne omejitve, ki jih je pri uporabi tega orodja treba upoštevati. Poudariti je treba predvsem omejitve Olgyayeve bioklimatske karte [56], uporabljene za osnovo orodja BcChart, ki je neposredno uporabna samo za uporabnike stavb, ki nosijo običajna oblačila, ki opravljajo sedeče ali lahko fizično delo, na nadmorski višini do 300 m. Vpliv sončnega sevanja je bil izračunan za predpostavljeno efektivno površino človeškega telesa v velikosti 0,5 m^2. Omejitev metodologije izračuna bioklimatskega potenciala z orodjem BcChart je, da pri izračunu ni možno upoštevati notranjih toplotnih dobitkov. Še ena omejitev orodja BcChart je, da mej območja cone toplotnega udobja (med 21 in 27 °C) ni mogoče spreminjati, kar bi omogočalo prilagajanje različnim pogojem in integracijo modela adaptivnega toplotnega udobja. Priložnost za nadaljnje delo vidimo tudi v uporabi urnih oz. dnevnih podnebnih podatkov o temperaturi, vlagi in sončnem sevanju, uporabljenih pri analizi bioklimatskega potenciala z orodjem BcChart. S tem bi se natančnost orodja še nekoliko povečala.
2. Poudariti je treba, da lahko rezultati predstavljenih bioklimatskih analiz z orodjem BcChart, predstavljajo le splošne smernice za določen tip in lokacijo stavbe. Bioklimatski potencial je bil izračunan za stanovanjske stavbe v urbanem okolju. Zato so rezultati bioklimatskega potenciala neposredno uporabni samo za takšne in podobne stavbe ter lokacije. Pri analizi so bili uporabljeni podnebni podatki, kot so temperatura zraka, relativna vlažnost in sončno sevanje. Omejitev torej izhaja iz širine nabora podnebnih podatkov, saj bi bilo možno v analize zajeti tudi podatek o hitrosti vetra, kar v doktorski disertaciji ni bilo analizirano. Hitrost vetra (oz. gibanja zraka) tako ni neposredno zajeta v analizo bioklimatskega potenciala, temveč je le poudarjena potreba po le-ti (vrednosti V – potreba po naravnem prezračevanju). Slednje je mogoče doseči tudi s prečnim ali vertikalnim prezračevanjem s pomočjo tlačnih razlik ali pa

tudi z mehanskim prezračevanjem, zato ocenjujemo, da podatek o hitrosti vetra na rezultate analiz nima poglavitnega vpliva.

3. Glede definicije simulacijskih energijskih modelov stavb in opravljenih parametričnih študij je nujno poudariti naslednje omejitve. Rezultati parametričnih študij so bili pridobljeni na podlagi definiranih energijskih modelov stavb. Zato je pri posploševanju predstavljenih rezultatov primarna omejitev raziskave, da sta bila tlorisna površina ter pripadajoča prostornina in oblika analiziranih stavbnih modelov načrtovana na podlagi statističnega povprečja podobnih stavb v EU. Jasno se zavedamo, da tak vzorec predstavlja povprečne enodružinske samostoječe stanovanjske stavbe v EU, vendar ima pri uporabi rezultatov za nekatere države ali specifične stavbe nekaj omejitev. Zato je treba za stavbe, ki imajo veliko manjše ali veliko večje tlorisne površine ali so v kakršnem koli smislu geometrijsko precej drugačne od uporabljenih modelov, ugotovitve študije uporabljati s previdnostjo. Nadalje, učinek analiziranih pasivnih načrtovalskih ukrepov je verjetno v realnosti večji, saj smo v raziskavi obravnavali vpliv pasivnih načrtovalskih ukrepov na potrebno energijo za ogrevanje in hlajenje stavb, ne pa njihovega neposrednega vpliva na človekovo toplotno udobje. Tako je v raziskavi vpliv pasivnih ukrepov v obdobju t. i. prostega teka stavbe, ko le-ta ni ne ogrevana ne hlajena, zajet le z učinkom na rabo energije. V tem kontekstu se je treba zavedati tudi, da se uporabniki energijsko neučinkovitih stavb pogosto zadovoljijo s slabšim toplotnim udobjem, da bi s tem zmanjšali stroške za rabo energije [231], česar v simulacijah nismo upoštevali. Poleg že omenjenih omejitev moramo razumeti, da so bile parametrične študije narejene z uporabo izbranega nabora pasivnih načrtovalskih ukrepov, medtem ko je bilo nekaj parametrov izključenih iz študije. Pasivni načrtovalski ukrepi, ki jih v parametrični študiji nismo upoštevali, so orientacija stavbe, zrakotesnost, stopnja konstantnega naravnega prezračevanja, evaporacijsko hlajenje, uporaba zimskega vrta (steklenjaka), spremembe v obnašanju uporabnikov (npr. spreminjanje delovanja senčenja) itd. Rezultati raziskave so omejeni tudi z obsegom analiziranih vrednosti parametrov pasivnih načrtovalskih ukrepov. Na primer, v nekaterih specifičnih primerih bi bilo morda smiselno analizirati višje ali nižje vrednosti, od izbranih, npr. $\alpha_{sol} > 0,80$. Poleg tega vidimo velik potencial za nadaljnje raziskovanje v ločeni analizi vpliva parametrov U_W in *SHGC*, kar bi omogočilo boljši vpogled v vpliv tipa zasteklitve na energijsko učinkovitost stavbe in sočasni vpliv na dnevno osvetljevanje. Na slednje lahko opozorimo kot na eno večjih omejitev metodologije, uporabljene v doktorski disertaciji, saj je kombinirani vpliv stavbnega ovoja na energijsko učinkovitost, toplotno udobje in zagotavljanje dnevne svetlobe izredno pomemben [183]. Omejitev raziskave je tudi to, da je bila izključena analiza potreb po energiji za umetno razsvetljavo, zato učinek uporabljenega tipa in načina senčenja na rabo energije za razsvetljavo ni bil ocenjen. Nazadnje bi radi poudarili tudi dejstvo in vrzel, ki odpira priložnosti za nadaljnje raziskovanje, in sicer, da v raziskave nismo zajeli sistemov HVAC, katerih delovanje in učinkovitost vplivata na dovedeno energijo, s tem pa na končno energijsko učinkovitost stavbe.
4. Na področju podnebnih datotek omejitve izhajajo iz modeliranja podnebja in natančnosti vhodnih podatkov. Vsaka obravnavana lokacija je bila opredeljena s podnebno EPW datoteko, ki temelji na dolgoročno merjenih podatkih z obstoječih in relevantnih vremenskih postaj. Slednji navadno ne zajemajo posebnosti, kot so vpliv urbane morfologije na hitrost in smer vetra, senčenje s strani okoliških objektov in vegetacije ter učinek urbanega toplotnega otoka. Vpliv slednjega je zaznaven tudi na širšem območju Ljubljane [232]. Druga omejitev raziskave vpliva podnebnih sprememb na bioklimatski potencial in energijsko učinkovitost stavb se

nanaša na projicirane podnebne podatke. Uporabljene EPW datoteke vsebujejo podatke iz baze IWEC, ki imajo nekoliko drugačen časovni okvir kot podnebni modeli HadCM3, ki so bili uporabljeni za izdelavo projiciranih podnebnih datotek na podlagi učinkov podnebnih sprememb. Zato je pričakovati, da bodo podnebni podatki, pridobljeni na podlagi EPW datotek, nekoliko precenili učinek podnebnih sprememb, kot navajajo Jentsch in sod. [148] in Moazami in sod. [233]. Kljub temu so podnebni podatki dovolj natančni za oceno predvidenega vpliva globalnega segrevanja na energijsko učinkovitost stavb. Nazadnje bi opozorili še na omejitev uporabe SRES scenarijev podnebnih sprememb, ki so jih kasneje nadomestili novejši scenariji RCP. Scenarij SRES A2 (tretje in četrto poročilo IPCC), ki je bil uporabljen v doktorski disertaciji, je sicer glede sevalnega prispevka in spremembe globalne temperature primerljiv s scenarijem podnebnih sprememb RCP8.5 (peto poročilo IPCC). Zavedati se je treba, da je to le eden od možnih scenarijev, kateremu pa trenutno stanje podnebja in družbe najbolj sledi.

7.4 Prispevek k znanosti

Moderna družba se sooča z enakimi frustracijami kot prvi ljudje – s priložnostmi in ovirami pri gradnji domov, ki zagotavljajo varnost in podnebno neodvisnost. Kot so pokazale raziskave, se prizadevanja na tem področju nadaljujejo, medtem ko se moramo še veliko naučiti o globalnem segrevanju in njegovih posledicah za delovanje grajenega okolja in energijsko učinkovitost stavb, zlasti ob omejeni količini naravnih virov. Izsledki raziskav, predstavljenih v doktorski disertaciji, na tem področju so pomemben doprinos k znanosti, saj so med prvimi, ki obravnavajo bioklimatski potencial in energijsko učinkovitost enostanovanjskih stavb glede na podnebne spremembe. Posebno pomemben del raziskave se nanaša na predstavljeno metodo določevanja bioklimatskega potenciala lokacije, kjer je bila obstoječa metodologija nadgrajena z upoštevanjem podatka o sončnem sevanju, kar se je izkazalo za poglavitno nadgradnjo. Navedeno je izredno pomembno pri izbiri bioklimatskih načrtovalskih strategij z uporabo podnebnih podatkov in prepoznavanju sprememb v bioklimatskem potencialu, ki so posledica globalnega segrevanja. Rezultati doktorske disertacije pomenijo relevantno in pomembno bazo podatkov o energijski učinkovitosti enostanovanjskih stavb, ki smo jo dobili s 15.897.600 parametričnimi simulacijami – na vsaki lokaciji in v vsakem podnebnem scenariju po 496.800 različnih kombinacij pasivnih načrtovalskih ukrepov. Ugotovitve raziskave na podlagi simulacij so pokazale na potrebo po idejnem preskoku v trenutni praksi bioklimatskega (podnebno prilagojenega) načrtovanja stavb. S spoznanji o novih potrebah pri načrtovanju podnebno prilagojenih stavb, kot posledico globalnega segrevanja, znanstveni in strokovni javnosti posredujemo pomembne informacije in omogočamo pravočasno prilagajanje podnebnim spremembam. Le-te bodo v bližnji prihodnosti pomenile veliko tveganje za zmanjšanje energijske učinkovitosti in toplotnega udobja v enostanovanjskih stavbah. Raziskava je med prvimi, ki je obravnavala vpliv in pomen pasivnih načrtovalskih ukrepov v kontekstu podnebnih sprememb in s tem postavlja temelje za strateške odločitve pri načrtovanju in prenovah enostanovanjskih stavb z namenom doseči ustrezno energijsko učinkovitost. Bistven prispevek k znanosti je tudi predlog novega pristopa k bioklimatskemu načrtovanju stavb, v sklopu katerega med načrtovanjem s pasivnimi ukrepi zagotovimo energijsko učinkovitost v trenutnem in prihodnjem podnebnem stanju, hkrati pa obravnavamo tudi ranljivost stavbe za pregrevanje v prihodnjem, toplejšem podnebju.

»Ta stran je namenoma prazna«

8 POVZETEK

Bioklimatsko načrtovanje stavb odgovarja na priložnosti in omejitve, ki jih predstavljajo podnebje, potrebe uporabnikov, pričakovanja družbe in tehnološko znanje o gradnji stavb [1]. Tako načrtovane stavbe zato pogosto povezujemo z udobnim notranjim okoljem ter z visoko energijsko učinkovitostjo [2]. V zgodovini gradnje so se s pomočjo bioklimatskega oz. podnebno prilagojenega načrtovanja stavb izoblikovali optimalni načrtovalski vzorci, primerni za gradnjo stavb v nekem podnebju. Le-te običajno opisujemo s pasivnimi načrtovalskimi ukrepi, kot so oblika stavbe, delež odprtin v ovoju stavbe, toplotna izolativnost ovoja, senčenje ipd. Specifični pasivni načrtovalski ukrepi so tako preverjene rešitve, pogosto uporabljane pri načrtovanju stavb v nekem podnebju. Na primer, v tradicionalni arhitekturi zmerno toplih podnebij so najobičajnejši pasivni načrtovalski ukrepi kompaktna oblika stavbe, primerna uporaba toplotne kapacitete oz. toplotne mase, ekvatorialno orientirana okna, stavbni ovoj z nizko toplotno prehodnostjo, višja sončna vpojnost zunanjih površin (temnejše barve) ipd. Ti ukrepi so bili stoletja skrbno preučevani in uporabljani kot najučinkovitejši pri doseganju ravnovesja med stavbo in podnebjem. Danes je za pomoč pri izbiri optimalnih pasivnih načrtovalskih ukrepov smiselno opraviti bioklimatsko analizo podnebja. Pri tem lahko uporabimo metodo ocene bioklimatskih danosti lokacije s pomočjo bioklimatske karte [56] ali psihrometrične karte [74], s katerima z uporabo osnovnih podnebnih podatkov določimo bioklimatski potencial, ki služi kot izhodišče za načrtovanje podnebno prilagojenih stavb na neki lokaciji. Slednje je celo bolj smiselno od repliciranja uveljavljenih načrtovalskih vzorcev, saj podnebje v preteklosti nikoli ni bilo dlje časa stalno in se je zaradi različnih dejavnikov nenehno spreminjalo [16, 75]. V zadnjem stoletju smo priča izredno hitri rasti količine CO_2 in drugih toplogrednih plinov v ozračju [16], kar je glavni vzrok za povečan učinek tople grede, ki povzroča globalno segrevanje. Poročilo Svetovne meteorološke organizacije [90] navaja, da je bilo zaradi globalnega segrevanja zadnjih šest let najtoplejših šest zabeleženih let, do konca 21. stoletja pa naj bi se povprečna globalna temperatura zvišala za do 4 °C [18] v primerjavi s predindustrijskim obdobjem. Učinek podnebnih sprememb in rast temperature zraka lahko opišemo s podnebnimi modeli ter z uporabo različnih scenarijev koncentracije toplogrednih plinov in od njih odvisnega sevalnega prispevka. Z uporabo le-teh lahko predvidevamo, kakšno podnebje nas čaka v prihodnosti. Ker bioklimatsko načrtovanje stavb temelji na ravnovesju med stavbo in podnebjem in ker je večina uveljavljenih pasivnih načrtovalskih ukrepov posledica načrtovalskih izkušenj na podlagi preteklih stanj podnebja, je globalno segrevanje ključni izziv za bioklimatske stavbe. V doktorski disertaciji se zato sprašujemo, ali uveljavljeni pasivni načrtovalski ukrepi na neki lokaciji še pomenijo ustrezne smernice za načrtovanje sodobnih stavb in tudi stavb v prihodnosti. V zmerno toplem in hladnem podnebju so zasnove stavbe pogosto osredotočene na energijsko učinkovitost v času ogrevanja, s tem pa je mnogokrat spregledana nevarnost za pregrevanje v toplejšem delu leta. Tako z raziskovalnim delom želimo odgovoriti na vprašanja, ki se pojavljajo pri bioklimatskem načrtovanju enostanovanjskih stavb glede na podnebne spremembe.

Doktorska disertacija v prvem delu predstavlja teoretična ozadja in rezultate obširnega pregleda literature, v naslednjih poglavjih pa zaporedno vsebinsko povzema štiri znanstvene članke, ki so osrednji del doktorske naloge z rezultati raziskave.

Drugo poglavje povzema glavna teoretična izhodišča, pomembna za razumevanje vsebine doktorske disertacije, in vsebuje obširen pregled znanstvenih raziskav o obravnavanem področju. Le-ta je namenjen identifikaciji aktualnih raziskovalnih tematik, ključnih preteklih raziskav o obravnavanem področju in opredelitvi vrzeli v le-tem, ki jo naslavlja pričujoča doktorska disertacija. Pregled literature je pokazal, da je področje široko raziskano, vendar so raziskave običajno osredotočene na energijsko prenovo specifičnih stavb, ciljajo v iskanje specifičnih optimalnih rešitev, se izvajajo z omejenim naborom parametrov ali pa ne obravnavajo učinkov podnebnih sprememb na toplotni odziv stavb. Dolgoročni vpliv pasivnih načrtovalskih ukrepov na zmanjšanje rabe energije za ogrevanje in hlajenje bioklimatskih enostanovanjskih stavb v različnih evropskih podnebjih, zato ni podrobno raziskan. Zato je bil namen raziskovalnega dela predstaviti ključne informacije za načrtovanje podnebno prilagojenih in energijsko učinkovitih stavb, ki bi zagotavljale učinkovito rabo energije v sedanjih ter predvidenih podnebnih razmerah v prihodnosti.

V tretjem poglavju je opisana metoda za analizo bioklimatskega potenciala, njena uporaba pa je prikazana v študiji primera regije Alpe-Jadran. Za 21 izbranih lokacij v regiji je bila narejena analiza bioklimatskega potenciala s pomočjo bioklimatskih kart. V okviru študije je bilo razvito prosto dostopno programsko orodje BcChart, s pomočjo katerega lahko na podlagi osnovnih podnebnih podatkov, kot so temperatura in relativna vlažnost zunanjega zraka ter gostota moči sončnega sevanja, naredimo analizo bioklimatskega potenciala lokacije. Glavna prednost predstavljenega orodja je, da neposredno zajema vpliv sončnega sevanja, ki je upoštevano z nadomestno udobno temperaturo in temperaturo, pri kateri je še možno koriščenje pasivnega sončnega ogrevanja. Izkazalo se je, da slednje precej vpliva na rezultate bioklimatske analize. V sklopu raziskav je bila narejena primerjava bioklimatskega potenciala z rabo energije za ogrevanje in hlajenje modela stavbe, simuliranega na petih izbranih lokacijah. Z raziskavo smo pokazali, da lahko uporaba predstavljene metode učinkovito in precej zanesljivo pokaže koristnost pasivnih načrtovalskih ukrepov. Nadalje je bila metoda uporabljena še v eni študiji primera, pri čemer so bile analize narejene z izračunom bioklimatskega potenciala na širšem območju Evrope, na podlagi tega pa izdelane karte bioklimatskih potencialov, ki se lahko uporabijo v začetnih fazah oblikovanja regionalnih razvojnih strategij pri načrtovanju stavb. Analize so pokazale, da upoštevanje sončnega sevanja pri izračunu bioklimatskega potenciala bistveno vpliva na rezultate in podaja ključno informacijo o tem, kdaj je treba stavbe senčiti in kdaj lahko koristimo sončno energijo za pasivno ogrevanje stavbe. Pokazali smo tudi, da je s predstavljeno metodo v analize mogoče zajeti novejše podnebne podatke in tudi vpliv podnebnih sprememb.

Namen četrtega poglavja je bil preučiti učinke prisotnih in predvidenih sprememb v bioklimatskem potencialu lokacije na energijsko učinkovitost enostanovanjskih stavb. V okviru raziskave je bil na podlagi razvite metodologije bioklimatski potencial izračunan za pet lokacij v Sloveniji: Portorož, Mursko Soboto, Novo mesto, Ljubljano in Rateče. Na izbranih lokacijah smo za zadnjih pet desetletij preučili vpliv podnebnih sprememb na bioklimatski potencial. Rezultati so pokazali, da se na vseh obravnavanih lokacijah čez čas spreminja potreba po pasivnih načrtovalskih ukrepih. Pri tem so vse pomembnejši pasivni načrtovalski ukrepi za preprečevanje pregrevanja. V drugem delu raziskave smo simulirali energijsko učinkovitost v sedanjih in projiciranih podnebnih stanjih za dva primera enodružinske stanovanjske stavbe: bioklimatsko in nebioklimatsko zasnovane. Za obe obravnavani stavbi je analiza energijske učinkovitosti pokazala, da se bo v obdobju 2041–2070 znižala potrebna energija za ogrevanje in zvišala za hlajenje ter da bodo trenutno optimalne načrtovalske rešitve (na primer pasivno sončno ogrevanje) v bioklimatskih stavbah postale manj učinkovite. Zato je treba primernost pasivnih načrtovalskih ukrepov na nekaterih lokacijah ponovno ovrednotiti. Skladno s tem ugotovitve raziskave kažejo na potrebo po idejnem preskoku v bioklimatskem načrtovanju stavb, da bi s tem lahko držali korak s sedanjimi in prihodnjimi izzivi, ki jih prinašajo podnebne spremembe.

V petem poglavju smo preučevali vpliv podnebnih sprememb na energijsko učinkovitost enostanovanjskih stavb v izbranih podnebjih v Evropi. S pomočjo 496.800 različnih kombinacij pasivnih načrtovalskih ukrepov smo preučili vpliv le-teh na rabo energije za ogrevanje in hlajenje. Toplotni odziv tako definiranih modelov stavb smo simulirali na osmih lokacijah in v štirih različnih podnebnih stanjih. Parametrična študija je vsebovala različne vrednosti parametrov, kot so toplotna prehodnost netransparentnega in transparentnega dela stavbnega ovoja, površina oken, razporeditev oken, faktor oblike stavbe, toplotna kapaciteta stavbe, vpojnost zunanjih površin za sončno sevanje in hlajenje z naravnim prezračevanjem. Toplotni odziv modelov stavb smo simulirali z uporabo trenutne podnebne datoteke in treh podnebnih datotek z zajetimi predvidenimi podnebnimi spremembami do konca 21. stoletja. Pričakovati je, da bo v analiziranih stavbah globalno segrevanje vplivalo na razmerje med rabo energije za ogrevanje in hlajenje, pri čemer bo potreba po ogrevanju manjša in potreba po hlajenju višja, kot v trenutnih podnebnih razmerah. V smislu segrevanja ozračja se je za najbolj splošno uporaben ukrep izkazala uporaba manjših transparentnih površin, izbira kombinacije pasivnih načrtovalskih ukrepov pa precej vpliva tudi na razmerje med potrebno energijo za ogrevanje in hlajenje. Rezultati raziskave so bistveno izhodišče pri definiciji dolgoročnih strategij za zagotavljanje energijske učinkovitosti enostanovanjskih stavb danes in v prihodnosti.

Vsebina šestega poglavja podrobneje preučuje rezultate parametrične študije vpliva pasivnih načrtovalskih ukrepov v zmerno toplem podnebju Ljubljane. Rezultati so pokazali, da je zgolj s pasivnimi načrtovalskimi ukrepi najvišji dosegljivi razred energijske učinkovitosti glede na letno potrebno toploto za ogrevanje stavbe po Pravilniku o metodologiji izdelave energetskih izkaznic v Ljubljani, razred B1. Tudi v Ljubljani je v prihodnosti predvideno znižanje rabe energije za ogrevanje in višanje rabe energije za hlajenje enostanovanjskih stavb. Pomemben del raziskave predstavlja oblikovanje metode za oceno ranljivosti stavbe za pregrevanje. Ugotovljeno je bilo, da pri stavbah z nizko rabo energije za ogrevanje ni pričakovati zelo visoke ranljivosti za pregrevanje, kljub temu pa so nekateri pasivni načrtovalski ukrepi ključni za nizko ranljivost. Ocena ranljivosti za pregrevanje je pri načrtovanju stavb zato zelo pomembna, saj je pričakovati, da bodo podnebne spremembe znižale energijsko učinkovitost stavb glede potrebne energije za hlajenje, zlasti tistih stavb, ki so zasnovane za pasiven zajem sončne energije v hladnejšem delu leta. V zmerno toplem podnebju je pri načrtovanju stavb ranljivost stavb za pregrevanje pomembna, toda kljub temu pogosto spregledana, saj se načrtovalci in zakonodajalci osredotočajo predvsem na energijsko učinkovitost stavb glede na potrebno energijo za ogrevanje. V skladu s tem je treba stavbe načrtovati glede na doseganje ustrezne energijske učinkovitosti v sedanjosti in zagotavljanje nizke ranljivosti za pregrevanje v prihodnosti. Raziskava predstavlja nov pristop k bioklimatskemu načrtovanju stavb, pri katerem je v fazo načrtovanja zajeto prilagajanje na globalno segrevanje.

Izsledki raziskav, predstavljeni v doktorski disertaciji, so pomemben prispevek k znanosti, saj so med prvimi, ki obravnavajo bioklimatski potencial in energijsko učinkovitost enostanovanjskih stavb glede na podnebne spremembe. Posebno pomemben del raziskave je nadgradnja metode za določanje bioklimatskega potenciala lokacije z uporabo podatka o gostoti moči sončnega sevanja, kar je najpomembnejše pri izbiri bioklimatskih načrtovalskih strategij in pri zaznavi učinka globalnega segrevanja na le-te. Rezultati raziskovanja pomenijo relevantno bazo podatkov energijske učinkovitosti enostanovanjskih stavb, ki smo jo dobili s 15.897.600 parametričnimi simulacijami različnih kombinacij pasivnih načrtovalskih ukrepov na različnih lokacijah in v različnih podnebnih stanjih. Ugotovitve raziskave so pokazale na potrebo po idejnem preskoku v trenutni praksi podnebno prilagojenega načrtovanja stavb kot posledico globalnega segrevanja. Rezultati raziskav so pomembne informacije za pravočasno prilagajanje podnebnim spremembam. Bistven prispevek k znanosti je zato tudi predlog novega pristopa k bioklimatskemu načrtovanju stavb, v sklopu katerega med načrtovanjem s pasivnimi ukrepi zagotovimo energijsko učinkovitost v trenutnem in prihodnjem podnebnem stanju, hkrati pa obravnavamo ranljivost stavbe za pregrevanje v prihodnjem podnebju.

9 SUMMARY

Bioclimatic design of buildings responds to the opportunities and limitations posed by climate, occupant needs, society expectations and construction technology [1]. Therefore, bioclimatically designed buildings are often associated with a comfortable indoor environment and high energy efficiency [2]. Throughout the history of building homes, bioclimatic (climate-adapted) design of buildings provided knowledge on optimal design solutions suitable for buildings in a specific climate. These are usually described by passive design measures, such as building shape, the share of window openings in the building envelope, level of thermal insulation, shading, and similar. Therefore, specific passive design measures represent proven solutions, often used in the design of buildings in a given climate. For example, in the traditional architecture of temperate climates, the most common passive design measures are the compact building shape, the appropriate use of thermal mass, equatorially oriented windows, building envelope with low thermal transmittance, a high solar absorptivity of external surfaces (darker colours), etc. These measures have been carefully studied over the centuries and are believed to be the most effective in achieving an equilibrium between buildings and climate. Nowadays, it is recommended to conduct a bioclimatic climate analysis to help select optimal passive design measures. For that reason, a bioclimatic chart [56] or a psychrometric chart [74] may be used. Both charts use elementary climate data to determine the bioclimatic potential, which serves as a starting point for designing climate-adapted buildings in a particular location. The latter makes more sense than replicating established design patterns, as the climate has never been constant and has changed regularly due to various factors [16, 75]. The last century has exhibited an extremely rapid increase in the emissions of CO_2 and other greenhouse gases to the atmosphere [16]. The stated is the main reason for the increased greenhouse effect that causes global warming. The World Meteorological Organization report [90] states that due to global warming, the last six years were the warmest six years ever recorded, while the average global temperature is expected to rise up to 4 °C [18] by the end of the 21st century. The effect of climate change is described using various climate models and different climate change scenarios driving the concentration of greenhouse gases and the radiative forcing. Thus, it is possible to project future climate. Because the bioclimatic design of buildings is based on finding a balance between building and climate, and since established passive design measures result from experience based on past climate states, global warming poses a key challenge for bioclimatic buildings. Therefore, the focal scientific question of the doctoral dissertation was if the established passive design measures at a specific location still represent an appropriate approach for the design of modern buildings and buildings in the future. In temperate and cold climates, building designers often focus on energy efficiency for heating while overlooking the overheating risk in the warmer part of the year. Thus, the study aimed to answer the questions that arise with global warming in the bioclimatic design of single-family buildings.

The first part of the doctoral dissertation presents the theoretical background and results of an extensive literature review. The following four chapters summarise the content of four scientific papers, which are the fundamental part of the research, and in which the main results are presented.

The second chapter summarises the main theoretical fundamentals important for understanding the content of the doctoral dissertation and contains an extensive literature review. The latter aims to identify essential research topics to define the knowledge gap, later addressed by the doctoral dissertation. The literature review showed that the topic is widely researched. However, studies usually focus on energy renovation of specific buildings, aim to find optimal solutions for a specific building, are implemented with a limited set of parameters or do not address the effects of climate change on building thermal response. Therefore, the long-term impact of passive design measures on energy use for heating and cooling of bioclimatic single-family buildings in different European climates has not been studied in detail. The purpose of the study was to present critical information for the design of climate-adapted and energy-efficient buildings that would ensure energy efficiency in the current and projected climate conditions.

The third chapter presents a method for analysing bioclimatic potential, and its application is demonstrated in a case study of the Alpine-Adriatic region. For 21 selected locations in the region, bioclimatic potential analysis was performed using bioclimatic charts. As part of the study, the freely available software tool BcChart was developed to determine bioclimatic potential using the elementary climatic data such as external air temperature, relative humidity and solar radiation. The main advantage of the presented tool is that it directly includes the influence of solar radiation, which is considered by the substitutive comfortable temperature and the temperature at which the utilisation of passive solar heating is still feasible. The latter has been shown to have a significant impact on the results of the bioclimatic analysis. As part of the research, a comparison of bioclimatic potential with energy use for heating and cooling of a building model simulated at five selected locations was performed. Research has shown that the use of the presented method can effectively and reliably demonstrate the applicability of passive design measures. Furthermore, the BcChart method was used in another case study, where analyses were made by calculating bioclimatic potential over a wider area of Europe. The resulting maps can be used in the initial stages of developing regional building design strategies. Analyses have shown that considering solar radiation in calculating bioclimatic potential significantly affects the results and provides critical information on when buildings need to be shaded and when solar energy for passive heating of the building should be used. The study showed that it is possible to include recent climate data and the impact of climate change in the analyses.

In the fourth chapter, the effects of present and projected changes in the bioclimatic potential of the site on the energy efficiency of single-family buildings were analysed. Based on the developed methodology, the bioclimatic potential was calculated for five locations in Slovenia: Portorož, Murska Sobota, Novo mesto, Ljubljana and Rateče. The impact of climate change on the bioclimatic potential for the past five decades was studied in the selected locations. The results showed that the balance between passive design measures needed to lower heating or cooling energy use of the building changes over time in all the considered locations, while passive design measures to prevent overheating are becoming increasingly important. The second part of the study presents a simulated thermal performance in current and projected climatic conditions for two examples of an existing single-family residential building, one bioclimatic and one non-bioclimatic. For both buildings in question, the energy efficiency analysis showed that in the period 2041-2070, the energy required for heating would decrease, and the energy need for cooling would increase. Besides, presently optimal design solutions (such as passive solar heating) in bioclimatic buildings would become less efficient in the future. Therefore, the suitability of passive design measures in specific locations needs to be re-evaluated. Accordingly, the study findings point to the need for a conceptual leap in the bioclimatic design of buildings to keep pace with current and future challenges posed by climate change.

In the fifth chapter, the impact of climate change on the energy efficiency of single-family buildings in selected climates in Europe was examined. With the help of 496,800 different combinations of passive design measures, we studied their impact on energy use for heating and cooling. The thermal response of parametrically defined building models was simulated at eight locations and four different climatic conditions. The parametric study included various parameters such as thermal transmittance of the opaque and transparent part of the building envelope, window area, window layout, building shape factor, building heat storage capacity, solar absorptivity of external surfaces and natural ventilation cooling. The thermal response of building models was simulated using the current climate file and three projected climate change files, describing the climate until the end of the 21st century. The results showed that global warming would affect the ratio between energy use for heating and cooling in the analysed buildings while heating energy needs are expected to decrease, and the cooling energy needs increase compared to the current climatic conditions. In terms of global warming, the use of smaller transparent surfaces has proven to be the most universally applicable measure. Besides, the choice of passive design measures also noticeably affects the ratio between the energy use for heating and cooling. The study results represent an essential starting point for defining long-term strategies for ensuring the energy efficiency of single-family buildings today and in the future.

In the sixth chapter, the results of a parametric study of passive design measures are examined in detail for the temperate climate of Ljubljana. The results showed that while applying only passive design measures in Ljubljana, the highest realizable energy efficiency class is B1, concerning the annual heat required for heating according to the Slovenian Rules on the methodology for the production and issuance of energy performance certificates for buildings. It is expected that the heating energy use will decrease in single-family buildings, and cooling energy use will increase in the future. Furthermore, an essential part of the study is the method to assess building overheating vulnerability. It has been found that buildings with low energy use for heating are not expected to have a very high overheating vulnerability. At the same time, specific passive design measures are critical for achieving it. Therefore, assessing overheating vulnerability is very important in building design, as climate change is expected to reduce the energy efficiency of buildings in terms of cooling energy demand, especially in those buildings primarily designed for passive solar heating. In temperate climates, the overheating vulnerability evaluation of buildings is crucial. However, it is often overlooked, as designers and policymakers focus mainly on the energy efficiency of buildings concerning the energy needs for heating. Accordingly, buildings need to be designed to achieve appropriate energy efficiency at present while ensuring low overheating vulnerability in the future. The study shows a new approach to the bioclimatic design of buildings, where adaptation to global warming is included in the design process.

The research results presented in the doctoral dissertation represent a critical scientific contribution, as they are among the first to address the bioclimatic potential and energy efficiency of single-family buildings in light of climate change. A significant part of the research is upgrading the method to calculate the bioclimatic potential of location using additional data on solar radiation. The latter has considerable importance in choosing bioclimatic design strategies and the investigation of the global warming effects. The research results represent a relevant database of single-family buildings' energy use, obtained by parametrically simulating a total of 15,897,600 combinations of passive design measures, locations and climatic conditions. Due to global warming, the research findings exposed a need for a conceptual leap in the current practice of climate-adapted building design. Therefore, the results provide essential information for timely adaptation to climate change. Hence, a crucial contribution is the proposal of a new approach to the bioclimatic design of buildings by using passive design measures to ensure energy efficiency in the current and future climate while also addressing the overheating vulnerability of the building.

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11 PRILOGE

Ozn.	**Znanstveni članek**	**Revija**	**Dostop**	**Izdajatelj soglasja/Licenca odprtega dostopa**
A	Can building energy performance be predicted by a bioclimatic potential analysis? Case study of the Alpine-Adriatic region	Energy and Buildings	https://doi.org/10.1016/j.enbuild.2017.01.035	Elsevier
B	Implications of present and upcoming changes in bioclimatic potential for energy performance of residential buildings	Building and Environment	https://doi.org/10.1016/j.buildenv.2017.10.040	Elsevier
C	Strategy for achieving long-term energy efficiency of European single-family buildings through passive climate adaptation	Applied Energy	https://doi.org/10.1016/j.apenergy.2021.117116	Elsevier
D	Exploring Climate-Change Impacts on Energy Efficiency and Overheating Vulnerability of Bioclimatic Residential Buildings under Central European Climate	Sustainability	https://doi.org/10.3390/su13126791	CC BY 4.0
Ozn.	**Konferenčni prispevek**	**Zbornik**	**Dostop**	**Izdajatelj soglasja/Licenca odprtega dostopa**
E	BcChart v2.0 – a tool for bioclimatic potential evaluation	ISES Conference Proceedings	https://doi.org/10.18086/swc.2017.21.04	International Solar Energy Society
F	Bioclimatic potential of European locations: GIS supported study of proposed passive building design strategies	IOP Conference Series: Earth and Environmental Science	https://doi.org/10.1088/1755-1315/296/1/012008	CC BY 3.0

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PRILOGA A

Can building energy performance be predicted by a bioclimatic potential analysis? Case study of the Alpine-Adriatic region

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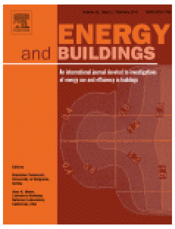

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Can building energy performance be predicted by a bioclimatic potential analysis? Case study of the Alpine-Adriatic region

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A B S T R A C T

In recent years, the construction industry has been comprehensively focusing on energy performance of buildings and on achieving higher standards of living comfort. One of the most sophisticated ways to attain both at the same time is (re)achieving building's climate balance by using bioclimatic design. Therefore, the main goal of this paper was to present a bioclimatic potential prognosis and to show its application on an example of the Alpine-Adriatic region. The bioclimatic potential prognosis was made for 21 characteristic locations. For this purpose, bioclimatic chart plots were made using elementary weather data and additionally, the actually received solar irradiance was precisely considered at every location. The latter was shown to have a large influence on the analysis results. Furthermore, an evaluation of performed bioclimatic potential prognosis was made with simulations of a generic building model using Energy Plus. The generic building model was tested in five selected locations and the heating and cooling demand results were compared with the bioclimatic potential analysis. The results showed that the application of the presented method can indicate which passive solutions should be applied in building design at a specific location in order to facilitate smaller energy usage and consequential higher indoor comfort. In addition, the presented approach can be used in order to incorporate the latest or predicted climate data into bioclimatic potential analysis. The latter has a significant influence on the design of buildings of the future.

1. Introduction

Bioclimatic building design is an engineering practice most commonly defined as using climatic "resources" of a particular location with the help of building envelope elements to ensure living comfort, while energy sources are efficiently utilized [1,2]. In general, it is considered that traditional vernacular architecture is "perfectly" adapted to climatic characteristics of a given location and/or region and, therefore, represents to the designers a source of bioclimatic design strategies [3,4]. For instance, traditional architecture of cold and temperate climates is largely determined by the application of bioclimatic design elements that increase indoor thermal comfort when outdoor air temperatures are low. The reflected bioclimatic approaches applied to vernacular architecture are, thus, easily recognised (e.g. compact buildings, high thermal mass, equatorially-oriented windows, box windows, etc.). Nonetheless, uncritical replication of design strategies from the vernacular architecture in contemporary buildings might not unequivocally result in better performing buildings, because solutions of the past might not be the best for the present and the future. According to Szokolay [5], the designer's task is to objectively and critically examine the given environmental conditions (site, climate, etc.) to establish the satisfactory conditions and to try to control these variables by passive means (building itself) as far as achievable. Therefore, it is recommended to start the bioclimatic design with a regional "climate resources" analysis, which uses basic climatic data to determine best suited passive solutions. One way to initially predict the suitable and/or possible bioclimatic measures is to analyse climate with a bioclimatic chart presented and developed by Olgyay [6], or in a different form by Givoni [7]. Bioclimatic charts in their basic form adequately serve to investigate whether at a specific location with a specific climate, human thermal comfort can be achieved or not. Since its introduction the relatively well-known methodology for creating the bioclimatic charts has been continuously developed and its variations have been presented by several authors [7–13]. Nevertheless, its primary purpose, to determine potential bioclimatic strategies using only

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environmental temperature and relative humidity, has remained roughly the same as shown by Olgyay [6].

Although the bioclimatic chart was introduced decades ago and it was a well-known tool, it was, unexpectedly, rarely used. However, the use of bioclimatic analysis approach in general has significantly increased in the last years. Several studies have been made, where a bioclimatic analysis was used to assess thermal comfort [3,4,9,14–22] and/or passive cooling and heating potential of a location [3,4,16,23–26]. In most of the cases psychrometric charts or Givoni's charts were used, while Olgyay's were seldom utilized. Nonetheless, the obtained results are the same and independent of the type of chart used. Hence, similar conclusions can be drawn. Hyde et al. [14] performed a study with a focus on bioclimatic analysis of a building (i.e. La Casa de Luis Barragán) built in 1948 in Mexico City. The authors resolve that the considered building is a potentially strong passive/low-energy building for its time in history. Although the study conclusions reference the importance of timeless adaption of building to user requirements, it does not address it's wider applicable value in the form of recommendations to others. In a similar way, Lomas et al. [17] performed a case study analysis of thermal comfort conditions in an office building in Southern Europe. They used Givoni's bioclimatic charts to produce climatic boundaries for passive cooling system design on the basis of climate data. Since the original bioclimatic chart is generally intended for residential buildings, the bioclimatic chart was adapted to analysed building type. It was concluded that studies of wider climatic conditions range are recommended. Another example of a specific building analysis with bioclimatic charts was conducted by Pozas and González [22]. They emphasized the link between the vernacular architecture and energy efficiency due to its adaptation to climate and location. Moreover, preserving of bioclimatic strategies that benefit summer conditions in the occasion of building renovations was emphasized (e.g. thermal mass). In this perspective, Hudobivnik et al. [27] showed that in particular climate ignoring the building's construction type can result in significantly different building thermal behaviour. In a similar way, Košir et al. [28] presented the importance of building envelope configuration (e.g. window to wall ratio), which is highly dependent on analysed location and corresponding received solar irradiation. Furthermore, design approaches with different cooling and shading strategies, heat storage concepts and passive solar systems were introduced by Pohl [29] and Goulding et al. [30]. To summarise, a number of different bioclimatic strategies can be applied to building in order to achieve comfortable conditions. In addition, such applications can simultaneously result in lower energy consumption.

However, all the above stated analyses either dealt with a specific building case at a micro location or some general design guidance was proposed. Differently, other studies approached the problem in a top bottom manner and made bioclimatic analysis of wider locations or regions. Such classification supports basic design decisions and is very useful to assure responsive building design and the corresponding adequate thermal comfort and energy conservation. For example, Givoni's charts were used by Ajibola [31] for regional climate analysis in Nigeria. He delivered emblematic conclusions about the recommended bioclimatic approaches; however profound, no interpretation of the analysed data was made. In contrast, Katafygiotou and Serghides [15] used Olgyay's bioclimatic charts to analyse climate zones in Cyprus. In the conducted study the influence of solar radiation was taken into consideration as well, by comparing the required and the available solar energy. The results showed that a particular bioclimatic analysis for each climatic region is necessary and that the influence of solar radiation on the conclusions of bioclimatic analysis can be substantial. A comparable study of bioclimatic features implemented in vernacular architecture of the island of Sardinia was performed by Desogus et al. [3]. They performed a bioclimatic analysis following the procedure outlined by Szokolay using psychrometric charts, but omitting the influence of the solar radiation. The authors conclude that the results of the study can be used to identify which passive solutions are best suited for a specific region and can thus be implemented in energy efficient building design. It has to be stressed that the exclusion of the influence of solar radiation represents a drawback of the study, as bioclimatic strategies designed for solar control (e.g. shading, passive solar heating, etc.) might therefore be underrepresented in the results. Several other authors developed bioclimatic zones [16,18,25] or even bioclimatic atlases [21] for their countries as a result of bioclimatic location analyses. Lam et al. [16] additionally investigated the passive solar design potential in 18 cities in China, which ranged from 7% to 50% of the colder half of the year. However, when making the bioclimatic charts, only basic characteristics (e.g. air temperature, relative humidity, air velocity, etc.) were considered by Lam et al. [16], Morillón-Gálvez et al. [21] for Mexico and Singh et al. [25] for north-east India, while the actual solar irradiation was not taken into account. Nonetheless, solar irradiation was considered in the study conducted by Mahmoud [18] for the bioclimatic design of outdoor built environments in Egypt. Furthermore, on the basis of bioclimatic charts, Bodach et al. [32] showed that in Nepal vernacular architecture is very well adapted to the local climate conditions, while its patterns should be adapted to modern comfort requirements. Nevertheless, the authors do not provide any specific solutions for the application of traditional bioclimatic strategies in modern buildings, but rather conclude that further research in this field is needed. Although bioclimatic design is regarded as common knowledge, the still existing lack of information about the relation between climate and popular architecture was emphasized by Cañas and Martín [33].

To summarise, systematic and analytically conducted bioclimatic analyses are relatively rare, although the number of publications is on the rise. While psychrometric charts are more commonly used than bioclimatic charts, this is of minor importance as both charts basically produce similar results. What is more interesting is that systematically conducted investigations of climatological regions as regards their bioclimatic potential are relatively scarce. It is even more surprising that the influence of solar radiation is rarely factored into the conducted analysis. This is of great importance as solar radiation is the single most important climatological parameter influencing the design of buildings, especially so in temperate and hot climates. Additionally, the investigation of direct association between energy performance and bioclimatic conditions of a region has almost never been investigated in the literature.

With the above information taken into consideration, the main goal of the presented study was to perform a bioclimatic potential prognosis in a selected region and show its implications for the design of new energy efficient buildings. In order to perform such evaluation, elementary weather data were obtained to plot Olgyay's bioclimatic charts [6] of the selected locations. Because the focus of the paper was not on the evaluation of the thermal comfort but on the determination of, e.g., the passive solar design potential of different locations, the Olgyay's method is by far the simplest and the fastest, due to its use of only dry-bulb air temperature and relative air humidity [34]. On the other hand, if the focus of the study was exclusively on the thermal comfort analyses, different approaches to the evaluation of indoor environment would be encouraged [35,36]. This was shown by Jamaludin et al. [37] with the analysis of two buildings in Malaysia, where bioclimatic design strategies had a significant beneficial impact on the satisfaction level of the residents. In the next step the generated bioclimatic charts were modified in order to account for the influence of solar radiation. This is a crucial step that has a substantial impact on the results of the performed bioclimatic analysis and has so far been rarely implemented in previously conducted studies. The analysis was performed for the Alpine-Adriatic European region (see Section 2), which is characterised by large variation of climate characteristics, probably the most diversified in Europe. The latter is very important for method evaluation because a wide variety of possible climate types is being considered. Furthermore, an evaluation of bioclimatic potential prognosis results was carried out with simulations of a generic building model using Energy Plus [38]. Five selected characteristic locations were tested and the heating and cooling demand results were compared with the findings of bioclimatic potential analysis. Therefore, the results of the bioclimatic analysis were directly linked to the potential energy savings of bioclimatically designed new buildings.

2. Alpine-Adriatic region

Alpine-Adriatic region is a unique European region, where Slavic, Germanic and Roman cultures have been intertwining for centuries in a relatively small geographic area. Alpine-Adriatic region consists of the entire country of Slovenia (20273 km^2 [39]), Italian countries of Veneto (18364 km^2 [39]) and Friuli-Venezia Giulia (7847 km^2 [39]), Austrian countries of Styria (16387 km^2 [39]) and Carinthia (9533 km^2 [39]) as well as Croatian countries of Istria (3160 km^2 [39]) and Primorje-Gorski Kotar (3588 km^2 [39]) (Fig. 1). In the context of geomorphological characteristics, the Alpine-Adriatic region is characterised by large diversity. At approximately only 460 km length and 380 km width (79152 km^2), the elevations vary between 0 m and 3342 m (Marmolada) above the sea, resulting in contrasting climates inside a relatively small area. According to Goulding et al. [30], this region is at the same time at the boundary as well as a mixture of Continental (cold winters with high solar radiation and longer days, hot summers), Southern and Mediterranean climatic zones (mild winters with high solar radiation and long days, hot summers).

Generally, the Adriatic coast, Istria and the southern parts of Veneto and Friuli-Venezia Giulia are characterised by the Mediterranean climate (Köppen-Geiger climate type Cfa). Eastern parts of the region, such as Pannonian plain, are strongly characterised by continental or temperate climate. In-between, the mixture of both (Köppen-Geiger climate type Cfb) is present, which is, in particular, mostly characteristic of Slovenia and parts of southern Styria (Fig. 1). Additionally, the Alpine climate type (i.e. Köppen-Geiger climate type Dfb and Dfc) is present in the northern parts of Veneto and Friuli-Venezia Giulia regions, in most parts of Carinthia and Styria and even in some parts of North-West Slovenia. The highest parts of the Alps are characterised by polar climate (Köppen-Geiger climate type ET). Apparently, in this relatively small region, the "collision" and mixture of various topographies, climates and cultures is present. Although the region extends between four different countries, the synthesis of various nations is reflected in a relatively similar vernacular architecture, regardless of the state borders. Consequently, regions such as Alpine-Adriatic region are intermediary levels between countries and people and are, therefore, extremely important.

3. Materials and methods

3.1. Selection of representative locations

For the purpose of this paper, 21 distinct locations in the Alpine-Adriatic region (Fig. 1) were selected. All the 21 locations and information about them including coordinates, elevation, terrain type and Köppen-Geiger classification are presented in Table 1.

3.2. Climate data

All the required climate data for the locations presented in Fig. 1 and Table 1 were obtained with the assistance of national environmental agencies of the considered countries. The climate data for Slovenia were provided by the Slovenian Environment Agency [41], for the Italian sub regions of Veneto and Friuli-Venezia Giulia the data were provided by the Italian Air Force Weather Service [42], the Central Institution for Meteorology and Geodynamics Austria [43] ensured the data for Styria and Carinthia sub regions and the Meteorological and Hydrological Institute of Croatia [44] provided the data for Istria and Primorje-Gorski Kotar regions. Average daily minimum (T_{min}, RH_{min}) and maximum (T_{max}, RH_{max}) values of air dry-bulb temperature and relative humidity for each month and location were collected from regional automatic weather stations. All the data were gathered for the climatological period 1971–2000. Furthermore, with the help of Photovoltaic Geographical Information System [45], mean and maximal daily global solar irradiance on horizontal plane (G_i and $G_{max,i}$) were calculated for each individual month for every analysed location. The data for Köppen-Geiger classification of the locations were obtained [46]. However, these data are provided with a precision of 0.5° and could thus be insufficiently detailed, especially in transitional regions between two climate types (e.g. the zone between the latitudes N 45°30′ and N 46° and longitudes E 13°30′ and E14° in Fig. 1).

3.3. Data analysis using bioclimatic charts

The analysis of bioclimatic conditions in the selected Alpine-Adriatic region was performed based on Olgyay's bioclimatic chart [6] and with the help of BcChart software [47]. The software was developed for the purpose of this research and was evaluated through the educational process at the University of Ljubljana. With the help of BcChart software all the gathered climate data were further analysed. The use of the bioclimatic chart is directly applicable only to inhabitants of the temperate zone. It is assumed that human comfort is calculated for a person wearing customary indoor clothing (1 Clo), engaged in sedentary or light muscular work (M = 126 W) and the air movement is presumed to be 0.45–0.90 m/s.

All the RH_{min}, T_{max} and RH_{max}, T_{min} combinations were plotted on the bioclimatic charts for all the 21 selected locations (e.g. the red lines in Fig. 2a). Further on, the mean and maximal daily solar irradiation was taken into consideration, resulting in modifications of bioclimatic chart plots (Fig. 2b).

The modified bioclimatic chart (Fig. 2b) was configured on the basis of the actually received solar irradiance at the exact location, affecting the human body's perception of thermal environment. Thus, the substitutive daily comfortable dry-bulb air temperature for month i (i = 1–12 or January–December), $T_{sub,i}$, which would completely satisfy the human thermal comfort needs, was introduced and calculated with Eqs. (1) and (2). Eq. (1) is based on the equations for human body thermal equilibrium, presented by Olgyay [6].

$$T_{sub,i} = \frac{T_s - (M - E + R_i) \times \left(Clo/c + V.Clo/c\right)}{S \times S_c} \quad (1)$$

$$R_i = G_i \times S_e \times \alpha \quad (2)$$

$T_{sub,i}$ is the substitutive daily comfortable dry-bulb air temperature for month i in °C, T_s is comfortable skin temperature, presumed as 33.9 °C, M is the observed rate of metabolism 126 W, E is the rate of cooling due to perspiration actually evaporated 38 W, R_i is radiation in W for month i, G_i is the mean daily global solar irradiance in W/m^2 for month i, S_e is the effective radiation area for a given subject in a given position and it is assumed as 0.5 m^2, α

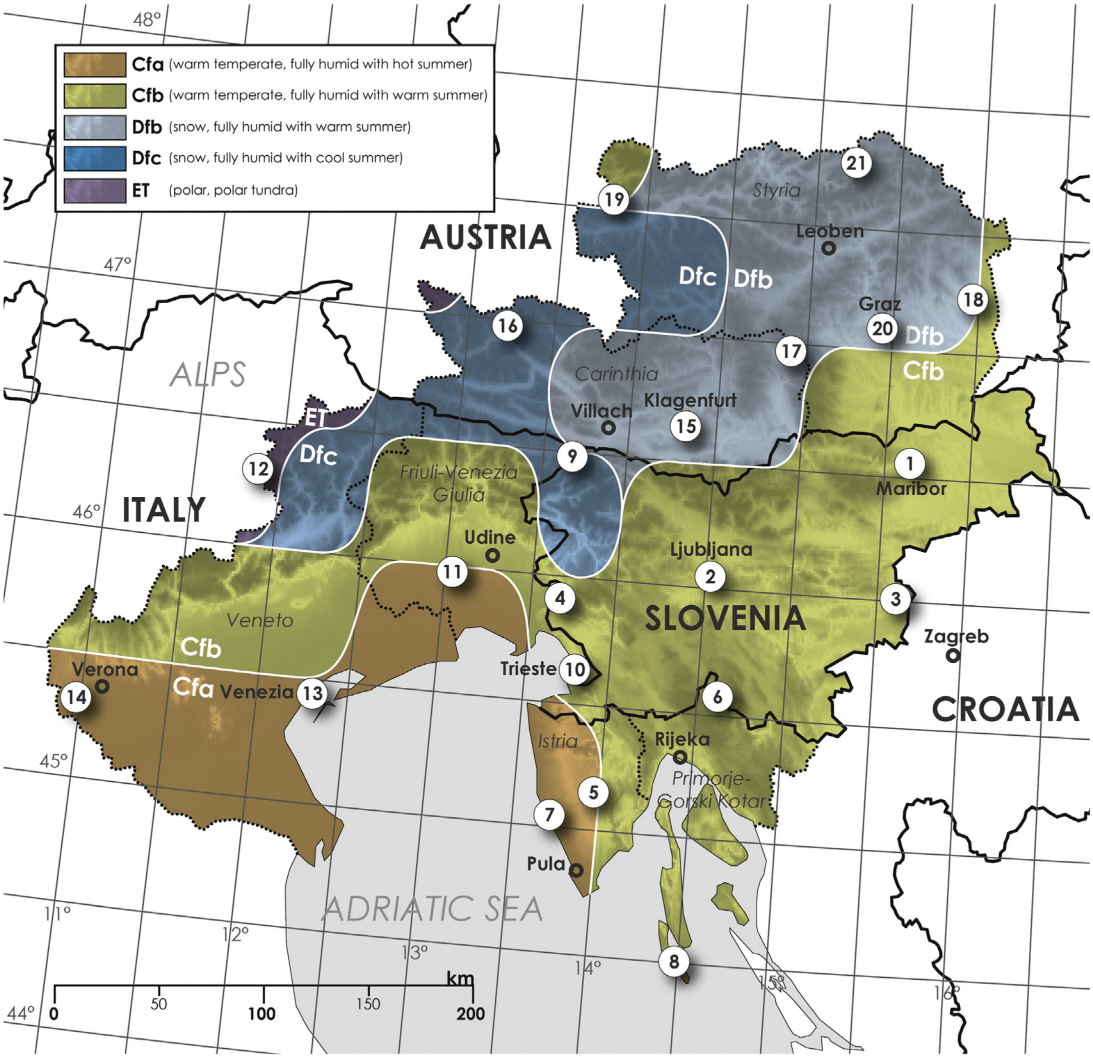

Fig. 1. Alpine-Adriatic region map. The numbered locations (1–21) are described in Table 1.

Table 1
Selected representative locations.

Country	Label	Location	Coordinates	Elevation	Terrain type	Köppen-Geiger classification*
SLOVENIA	1	Maribor	N 46°32′ E 15°39′	275 m	plain/hills	Cfb
	2	Ljubljana	N 46°04′ E 14°31′	299 m	plain/hills	Cfb
	3	Bizeljsko	N 46°01′ E 15°41′	179 m	plain/hills	Cfb
	4	Bilje	N 46°04′ E 14°31′	299 m	plain/hills	Cfb
CROATIA	5	Pazin	N 45°14′ E 13°56′	291 m	plain/hills	Cfa
	6	Parg	N 45°36′ E 14°38′	863 m	highlands	Cfb
	7	Rovinj	N 45°05′ E 13°38′	20 m	coastline	Cfa
	8	Mali Lošinj	N 44°32′ E 14°29′	53 m	coastline	Cfb
ITALY	9	Tarvisio	N 46°30′ E 13°35′	778 m	highlands	Dfc
	10	Trieste	N 45°40′ E 13°45′	29 m	coastline	Cfb
	11	Udine-Rivolto	N 45°59′ E 13°02′	53 m	plain	Cfa
	12	Passo Rolle	N 46°18′ E 11°47′	2006 m	mountains	ET
	13	Venezia	N 45°30′ E 12°21′	2 m	coastline	Cfa
	14	Verona	N 45°23′ E 10°53′	68 m	plain	Cfa
AUSTRIA	15	Klagenfurt	N 46°39′ E 14°20′	447 m	plain/hills	Dfb
	16	Mallnitz	N 46°59′ E 13°11′	1185 m	highlands	Dfc
	17	Preitenegg	N 46°56′ E 14°55′	1055 m	highlands	Dfb
	18	Altenberg	N 47°15′ E 16°02′	429 m	hills	Cfb
	19	Bad Aussee	N 47°37′ E 13°47′	665 m	highlands	Cfb
	20	Graz	N 47°05′ E 15°27′	366 m	plain/hills	Dfb
	21	Mariazell	N 47°46′ E 15°19′	875 m	highlands	Dfb

* The Köppen-Geiger climate classification classes according to Kottek et al. [40]: Cfa – warm temperate, fully humid with hot summer; Cfb – warm temperate, fully humid with warm summer; Dfb – snow, fully humid with warm summer; Dfc – snow, fully humid with cool summer; ET – polar, polar tundra.

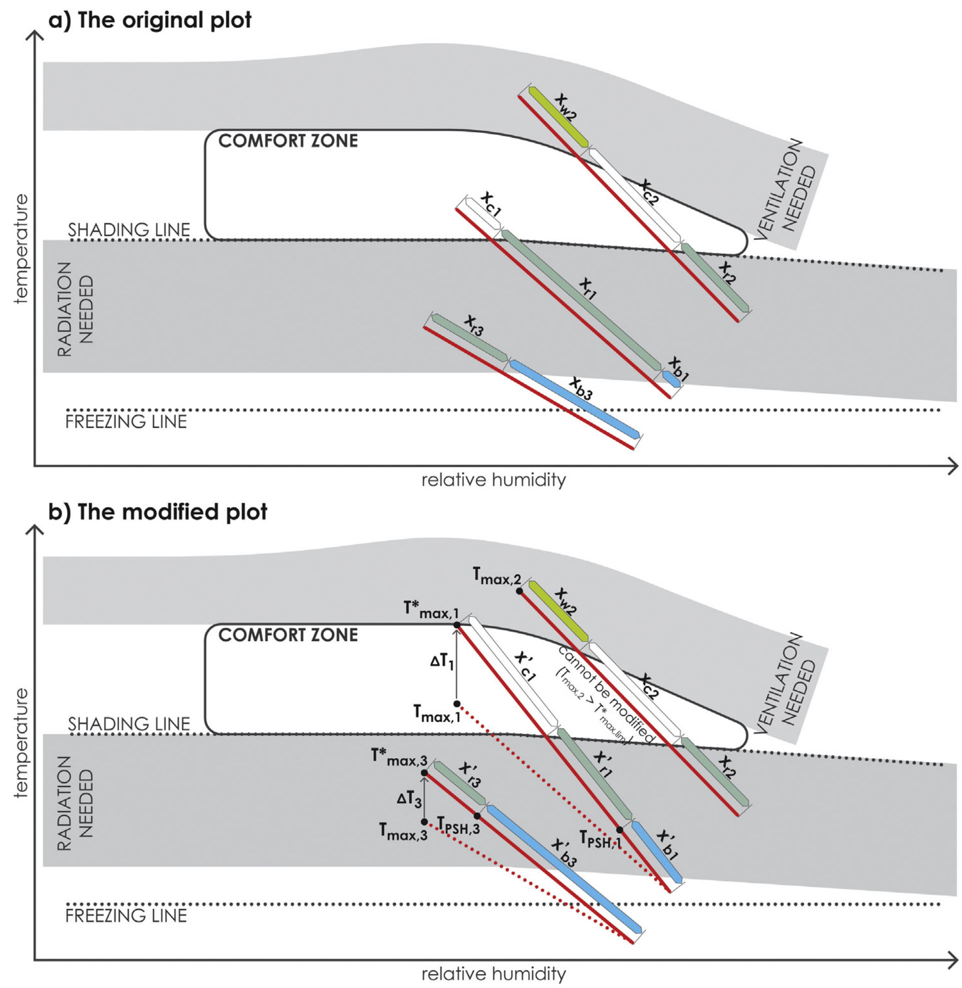

Fig. 2. Illustrative example of the original (a) and the modified (b) bioclimatic chart plot for months 1, 2 and 3 and the corresponding values of particular period lengths (x_{c1}, x'_{c1}, x_{r1}, x'_{r1}, x_{w2}, etc.). $T_{max,2}$ cannot be increased by ΔT_2, since the time of being in comfort zone would be reduced ($T_{max,2} > T^*_{max,lim}$). In such case x'_{c2} and x'_{r2} are the same as x_{c2} and x_{r2}, respectively.

is the absorptivity of the radiated surface of clothed man (= 0.4). Clo/c + V.Clo/c is clothing insulation and air effect on clothing coefficient (= 0.28) as defined by Olgyay [6] and adapted to be expressed in m^2K/W. S is the mean body surface area of clothed man, assumed as 2.14 m^2 and S_c is the fraction of surface areas exposed to radiation and convection (= 0.9).

Next, the decrement of comfortable dry-bulb temperature ΔT_i was calculated as a difference between the lowest temperature of comfort zone 21 °C and the calculated $T_{sub,i}$ (Eq. (3)). Decrement ΔT_i was then added to the maximum value of dry-bulb air temperature $T_{max,i}$ for every distinctive month to simulate the shift of comfort zone towards $T_{sub,i}$ (Eq. (4)) and the new maximum dry-bulb air temperature was denominated as $T^*_{max,i}$. The result of the latter is also a deformation of line length, presented in Fig. 2. However, the upper limit for $T^*_{max,i}$, denominated as $T^*_{max,lim}$ is defined by the upper limit of the comfort zone, as described with Eq. (5). Values below 18% and above 77% of relative humidity are out of the comfort zone. In such cases, the $T_{max,i}$ value was not modified.

$$\Delta T_i = 21^\circ C - T_{sub,i} \tag{3}$$

$$T^*_{max,i} = T_{max,i} + \Delta T_i \tag{4}$$

$$T^*_{max,lim} = \begin{cases} 27^\circ C, 18\% < RH < 45\% \\ 22\sim 27^\circ C, 45\% < RH < 77\% \end{cases} \tag{5}$$

Nevertheless, the modifications of bioclimatic charts were made only in the cases, where additional influence of solar irradiation would not cause overheating and consequentially raise the needed time for shading or ventilation (i.e. T^*_{max} would be above the comfort zone, e.g., months 1 and 2 in Fig. 2b). For the same reason, after the modification, the value of x_{wi} remains the same in all the cases, i.e., a month with a need for ventilation cannot be modified. The plotted combinations of T_{min} and RH_{max} (right end point of the red lines in Fig. 2) remained unchanged as the minimal temperatures usually occur in the morning, before the sunrise. Thus, the solar energy has no effect on it. Although the shift of the comfort zone towards $T_{sub,i}$ could be made directly, the presented approach is more precise, since the solar irradiance has effect only on the temperatures during the day. Consequentially, the relative effect of solar irradiance in the used method is lower, as if the actual shift of the comfort zone was performed, which is more realistic.

Furthermore, one of the goals of the study was to evaluate the time, when the available solar irradiance potential at a specific location is insufficient. In particular, conventional heating is necessary all the time to assure thermal comfort. Therefore, on the basis of maximal daily global solar irradiance on the horizontal plane for each month ($G_{max,i}$), the corresponding dry-bulb air temperature at which the passive solar heating (PSH) is still possible $T_{PSH,i}$ was calculated. All the values on the bioclimatic chart below that temperature represent the time, when PSH cannot be used as an efficient passive strategy, since there is not enough solar energy available at a given analysed location. For this purpose Eqs. (1) and (2) were used, although instead of the mean daily global solar irradiance (G_i), the maximal values were used ($G_{max,i}$) (Eqs. (6) and (7)).

$$T_{PSH,i} = \frac{T_s - \left(M - E + R_{max,i}\right) \times \left(Clo/c + V.Clo/c\right)}{S \times S_c} \quad (6)$$

$$R_{max,i} = G_{max,i} \times S_e \times \alpha \quad (7)$$

To evaluate the time of each month, when the plotted combinations of temperature, relative humidity and solar irradiance are either in comfort zone or out of it (with or without possible passive solutions), the following segments were defined:

- A – comfort zone (achieved with shading),
- A' – comfort zone extension (achieved with solar irradiation),
- B – ventilation and shading needed,
- C and C' – potential for PSH,
- D and D'– no potential for PSH,
- S – shading needed.

Then, for each location the average period of year in every distinct segment (A, A', B, C, C', D, D', S) was calculated and its share expressed in % was presented on pie charts. The calculation was performed on the basis of Eqs. (8)–(17).

$$A = \sum \frac{x_{ci}}{a_i} \times \frac{100}{12} \quad (8)$$

$$A' = \sum \frac{x'_{ci}}{a'_i} \times \frac{100}{12} - A \quad (9)$$

$$B = \sum \frac{x_{wi}}{a_i} \times \frac{100}{12} \quad (10)$$

$$C = \sum \frac{x_{ri}}{a_i} \times \frac{100}{12} \quad (11)$$

$$C' = \sum \frac{x'_{ri}}{a'_i} \times \frac{100}{12} \quad (12)$$

$$D = \sum \frac{x_{bi}}{a_i} \times \frac{100}{12} = 100\% - (A + B + C) \quad (13)$$

$$D' = \sum \frac{x'_{bi}}{a'_i} \times \frac{100}{12} = 100\% - (A + A' + B + C') \quad (14)$$

$$a_i = x_{ci} + x_{wi} + x_{ri} + x_{bi} \quad (15)$$

$$a'_i = x'_{ci} + x_{wi} + x'_{ri} + x'_{bi} \quad (16)$$

$$S = A + B \quad (17)$$

Where i = 1–12 or January–December. Parameters a_i, a'_i, x_{ci}, x'_{ci}, x_{wi}, x_{ri}, x'_{ri}, x_{bi} and x'_{bi} used in Eqs. (8)–(16) are graphically presented in Fig. 2. a_i is the total period of the month (i.e. the sum of x_{ci}, x_{wi}, x_{ri} and x_{bi}), a'_i is the total period of the month considering solar irradiance (different than a_i because $T_{max,i}$ is increased by ΔT_i and the length of x_{ci}, x_{ri} and x_{bi} change (Fig. 2)), x_{ci} is the period of month inside the comfort zone when shading is needed, x'_{ci} is the period of month inside the comfort zone considering solar irradiance, x_{wi} is the period of month when ventilation in combination with shading is needed (x_{wi} remains the same after the modification in all the cases, i.e. month with a need of ventilation cannot be modified), x_{ri} or x'_{ri} is the period of month when the utilization of solar irradiance is efficient, x_{bi} is the period of month when solar irradiance is certainly insufficient, x'_{bi} is the period of month when solar irradiance is certainly insufficient considering actual solar irradiance.

4. Results

According to the methodology presented in Section 3, bioclimatic charts for all the selected 21 locations were plotted. For each location, two sets of bioclimatic charts were created (Fig. 3). The first one (the original plot in Fig. 3a) is plotted using only basic meteorological data (i.e. air temperature and relative humidity). The second one is a modified original plot (Fig. 3b), using additional data of actually received solar irradiance. Fig. 3 presents examples of the original and the modified bioclimatic chart for the location of Mali Lošinj (8) created using BcChart software.

Supplementary results are presented in three progressive levels. Firstly, the results of bioclimatic potential using original bioclimatic charts are presented in Subsection 4.1. Secondly, the determination of bioclimatic potential with the modified charts is demonstrated in Subsection 4.2. And finally, in subsection 4.3 the evaluation of results achieved by the modified charts is presented.

4.1. Bioclimatic analysis with the original charts

The bioclimatic potential was calculated with the results obtained from the original bioclimatic chart plots (Fig. 4). On the basis of the bioclimatic potential results it can be determined how much time of the year particular passive building design measures are efficient and the period when they are not.

The bioclimatic potential analysis, performed on the basis of the original bioclimatic chart plots (Fig. 4), shows that three distinctive types of climatic locations can be identified in the Alpine-Adriatic region. These types are more or less characterised by three typical bioclimatic patterns: warm area, cold area and transitional area. The locations, which belong to the warm area are characterised by high A and S values and by low or equal to zero D values. Additionally, these locations are usually also characterised by the relatively high B values. The latter is a consequence of high air temperatures and quite high relative humidity, e.g., Venice (13) or Verona (14). Although the B value represents the time when shading with ventilation is needed, at some locations discomfort could also be neutralised with the combination of shading and high thermal mass of buildings. In fact, this bioclimatic strategy is more common in the Alpine-Adriatic region than the use of intensive ventilation. For locations in the second, cold area, the A and S values are typically identified as equal to zero or significantly low, while the D value is generally higher than 30%. All the mentioned facts indicate that very low air temperatures occur at these locations, even during the summer. These locations are mostly located at higher elevations (i.e. approximately 875 m above the sea level or higher). In-between the two mentioned areas, the transitional area can be defined. It represents the intermediate area between the warm, Mediterranean and the cold mountainous, Alpine parts of the region. This transitional area is characterised by relatively high A and S values (approximately 10%), while the B value is significantly lower than or equal to zero. In addition, it is typical for these locations that the D value is lower than 30%. The elevation of the analysed locations in transitional area ranges from 179 m to 863 m above the sea level.

However, these results are probably under- or overestimated, since the C and D values were calculated with a fixed upper threshold of solar irradiance (630 W/m^2). This is not realistic since the amount of actually received solar irradiance is highly dependent on season and locational specifics (e.g. sky coverage, temperature inversion, fog, etc.). Thus, the calculations with original bioclimatic charts lack the influence of actually received solar irradiance, which is one of the key climatic impacts in building design. The issue of incorporating the influence of actually received solar irradiance on

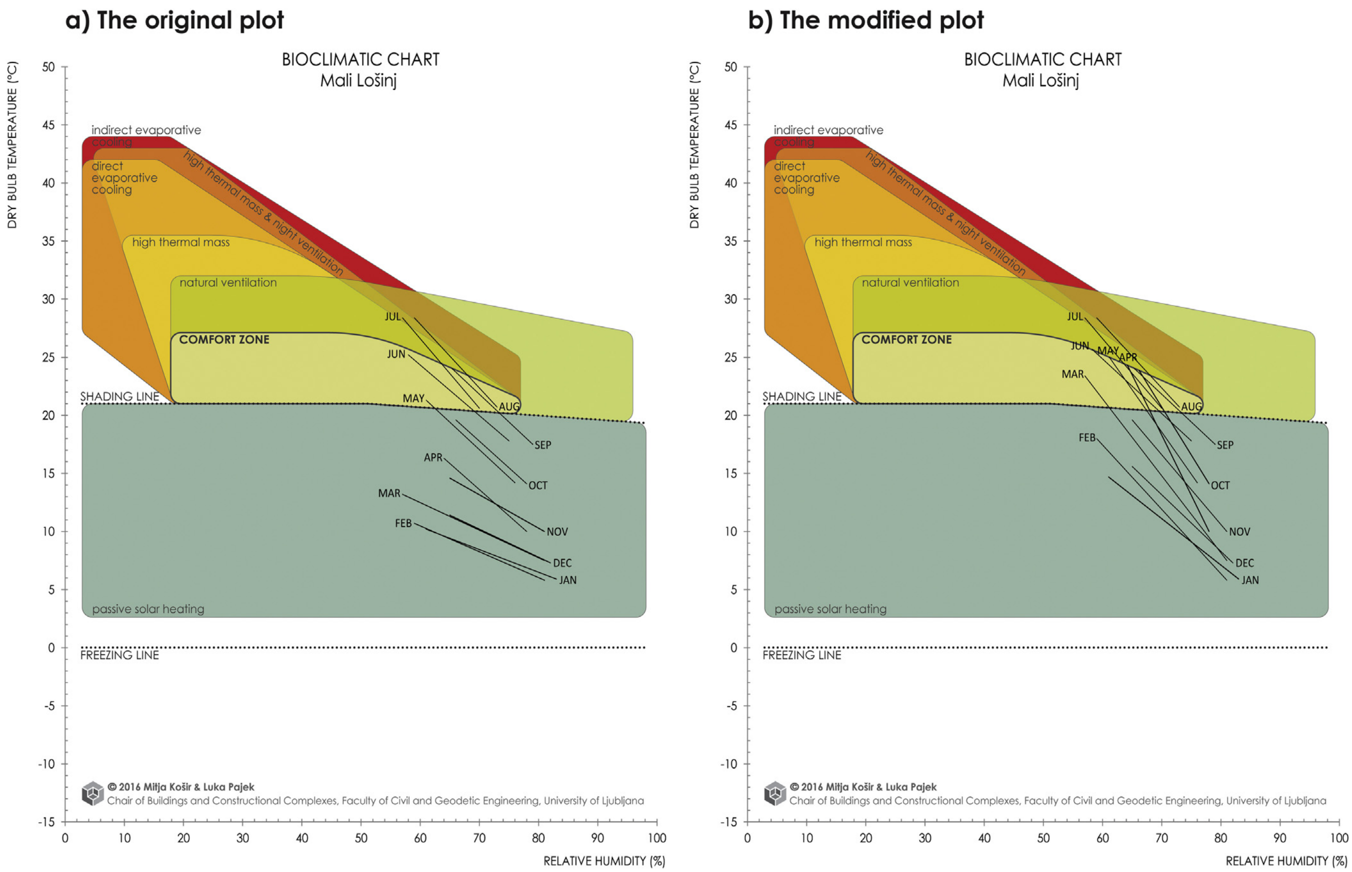

Fig. 3. Example of the original (a) and the modified (b) bioclimatic chart for the location of Mali Lošinj (8), created by the BcChart software.

the bioclimatic potential was further analysed with the modified bioclimatic charts (Fig. 3b) in Section 4.2.

4.2. Bioclimatic analysis with the modified charts

As explained in Section 4.1, the consideration of solar irradiance is vital, when the bioclimatic potential is calculated. Therefore, this section includes the results of bioclimatic potential prognosis with the modified bioclimatic charts. The consideration of actually received solar irradiation is reflected in the newly introduced A' value and affects the values of C and D, which become C' and D', respectively. In some cases the results for bioclimatic potential obtained by modified charts with the inclusion of solar radiation influence presented in Fig. 5 are significantly different from those in Fig. 4. The picture presented in Fig. 5 represents a more realistic estimation of bioclimatic potentials, as, in contrast to the results in Fig. 4, where the results are based only on the temperature and relative humidity, the analysis is also based on the influence of solar radiation.

In comparison to the D values in Fig. 4, the modified D' values of all the locations (Fig. 5) are increased as a result of very low outdoor temperatures during winter time, which corresponds to high need for solar radiation from November till March. However, the required solar energy is unavailable in the majority of locations. For instance, even in the case of location 8 (Mali Lošinj), the maximal available solar irradiance during December (213 W/m^2) and January (230 W/m^2) is inadequate. The required solar irradiance to completely satisfy human comfort needs at location 8 in December and January would, thus, be 440 W/m^2 and 490 W/m^2, respectively. At other locations the described situation is even worse. Furthermore, the comfort zone extends (i.e. addition of A') at every location as a result of solar energy utilization. This predictably occurs mostly in transitional months between winter and summer (i.e. April, May, June, September, October), when enough solar irradiation is available, while outdoor air temperatures are high enough to utilize it, but not too high as they are in July and August when shading is needed in most cases. Due to the latter, comfort zone is achieved at all those locations, where it was not achieved before (Fig. 4), e.g. Passo Rolle as the most extreme of the 21 selected locations. As a result of the difference in D' and A', the C' value is also modified. The C' value corresponds to the period, when the potential for PSH is high. However, the available solar radiation is not substantial enough to achieve comfort zone by passive means alone. Therefore, the combination of passive and active (i.e. conventional) heating measures is necessary. As regards the overheating of buildings, there are no changes between the original and the modified analysis (i.e. the B and S values remain the same). Such condition is assumed to occur when the outdoor temperatures are higher than 21 °C, and therefore shading is needed in order to keep the indoor conditions in the comfort zone. If the external air temperatures rise above 27 °C, additional passive measures like natural ventilation and/or high thermal mass of the building are necessary in order to keep the indoor thermal conditions at the desirable level without mechanical cooling. The acquired results of the executed bioclimatic analysis presume high efficiency of the used shading, i.e. blocking most of the received solar radiation.

The bioclimatic analysis results (Table 2), sorted according to the S value, almost coincide with the arrangement, if the results were sorted by the D' value from the highest to the lowest. Therefore, the correlation between S and D' is evident, while locations with higher S values also have lower D' values and vice versa. However, several locations do not follow this correlation, for example, loca-

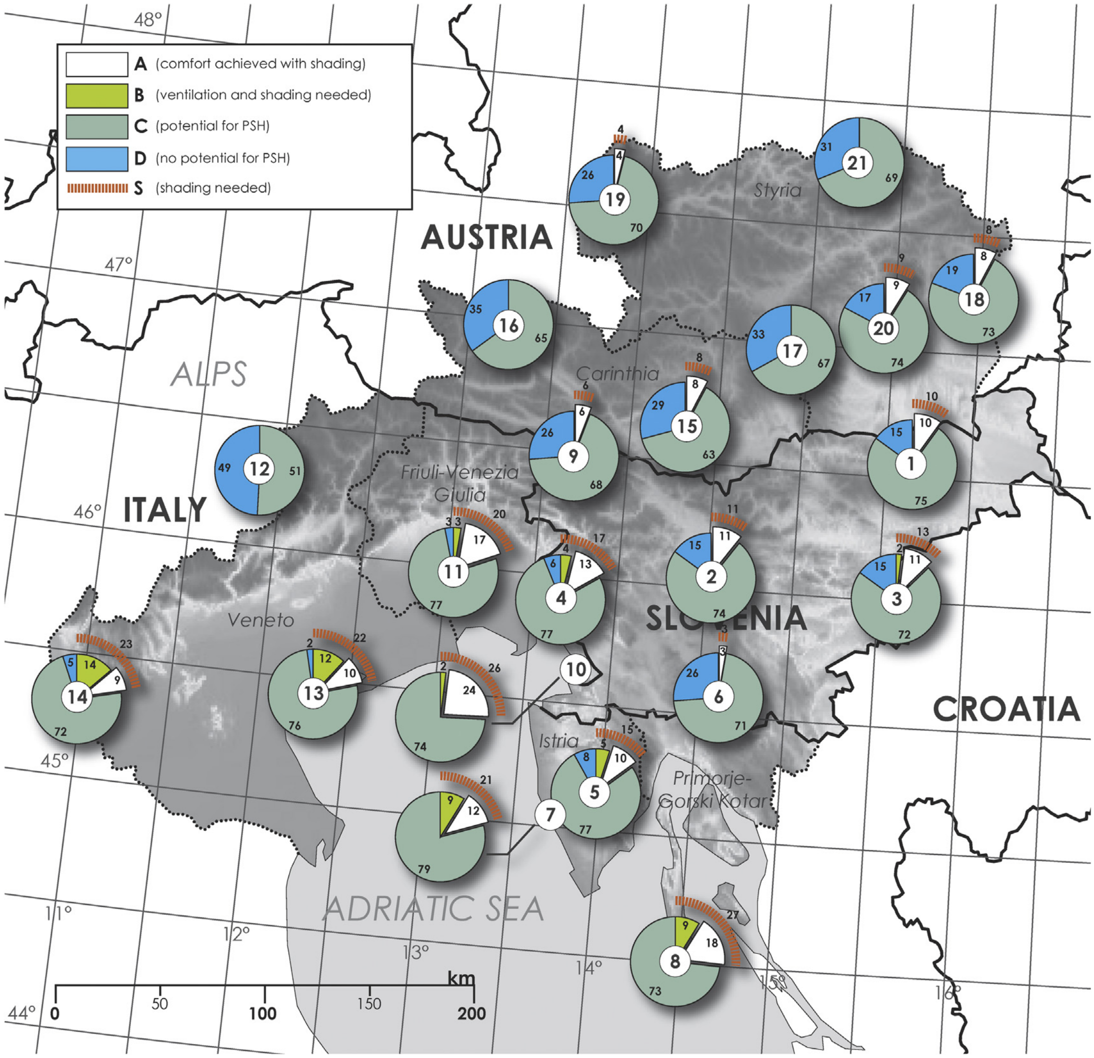

Fig. 4. Bioclimatic potential of Alpine-Adriatic region for 21 locations (Table 1), considering only T_a and RH combinations.

Table 2
Results of bioclimatic potential analysis, sorted by the S value from the lowest to the highest.

Label	Location	Share of year in distinct segment* [%]							Köppen-Geiger
		A	A'	A+A'	B	C'	D'	S	
12	Passo Rolle	0.0	3.6	3.6	0.0	34.0	62.4	0.0	ET
16	Mallnitz	0.0	11.1	11.1	0.0	38.6	50.3	0.0	Dfc
17	Preitenegg	0.0	11.6	11.6	0.0	41.8	46.5	0.0	Dfb
21	Mariazell	0.3	12.0	12.3	0.0	38.9	48.8	0.3	Dfb
6	Parg	2.6	6.9	9.5	0.0	44.5	46.0	2.6	Cfb
19	Bad Aussee	4.2	10.7	14.9	0.0	40.0	45.0	4.2	Cfb
9	Tarvisio	5.6	9.8	15.4	0.0	40.7	44.0	5.6	Dfc
18	Altenberg	8.0	12.1	20.1	0.0	40.6	39.2	8.0	Cfb
15	Klagenfurt	8.1	9.8	17.9	0.0	41.4	40.7	8.1	Dfb
20	Graz	9.2	9.9	19.1	0.0	41.6	39.2	9.2	Dfb
1	Maribor	10.3	10.8	21.1	0.0	40.2	38.7	10.3	Cfb
2	Ljubljana	11.3	9.3	20.6	0.0	39.7	39.6	11.3	Cfb
3	Bizeljsko	10.9	7.6	18.5	1.9	40.8	38.8	12.8	Cfb
5	Pazin	9.7	6.3	16.0	4.5	45.9	33.6	14.2	Cfa
4	Bilje	13.1	7.8	20.9	3.6	43.3	32.2	16.7	Cfb
11	Udine-Rivolto	16.7	10.2	26.9	3.3	39.4	30.4	20.0	Cfa
7	Rovinj	11.7	7.0	18.7	8.6	45.1	27.5	20.3	Cfa
13	Venezia	9.7	10.5	20.2	11.8	37.1	30.9	21.5	Cfa
14	Verona	9.3	8.6	17.9	13.9	37.5	30.7	23.2	Cfa
10	Trieste	23.6	12.1	35.7	2.4	33.7	28.2	26.0	Cfb
8	Mali Lošinj	18.4	9.7	28.1	9.3	41.6	21.0	27.7	Cfb

*A – comfort achieved with shading; A' – comfort achieved with solar irradiation; B – ventilation and shading needed; C' – potential for PSH; D'– no potential for PSH; S – shading needed.

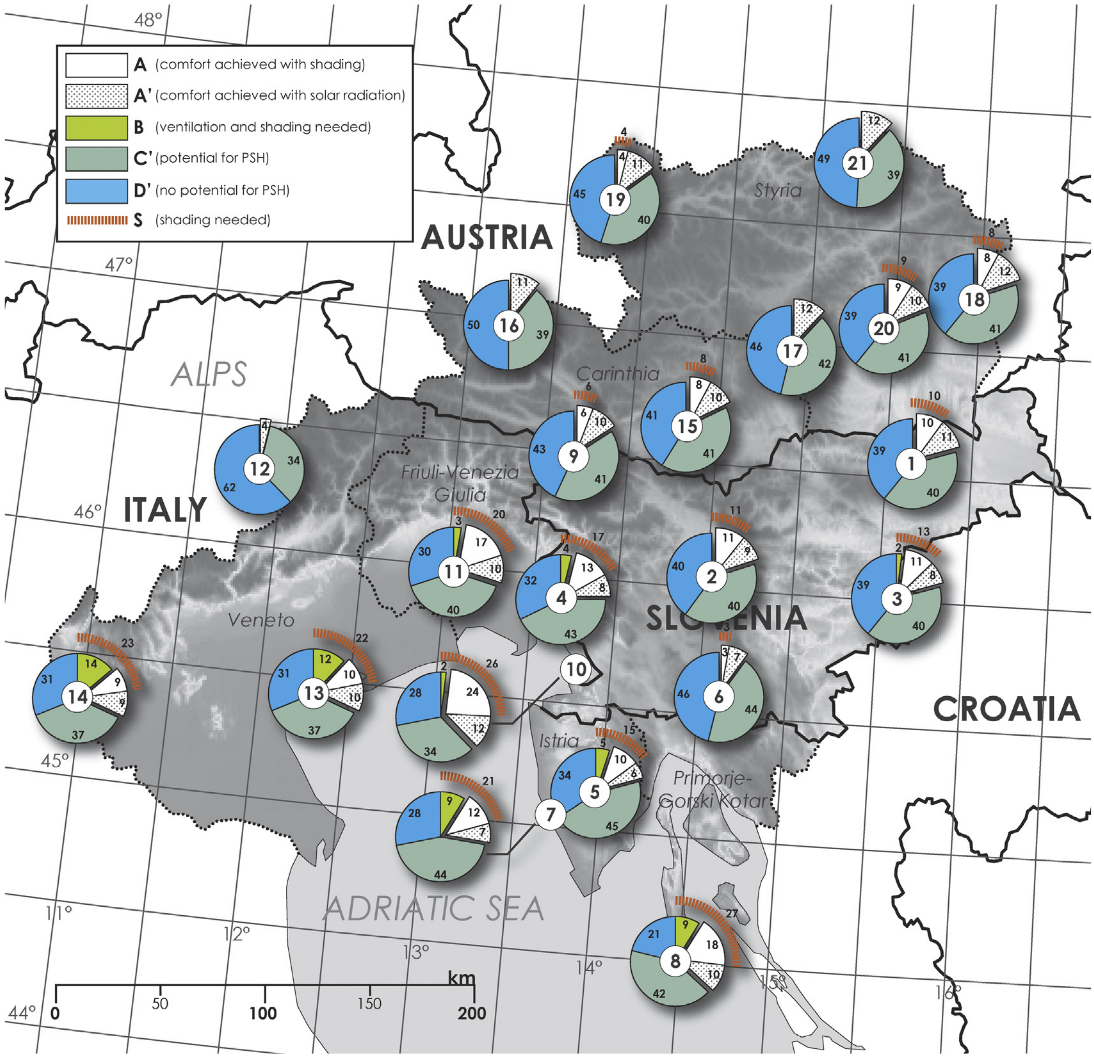

Fig. 5. Bioclimatic potential of Alpine-Adriatic region for 21 locations (Tables 1 and 2) after modification of T_a and RH combinations as a result of considering actual solar irradiance.

tions 10, 13 and 14 (i.e. Trieste, Venezia and Verona), which have similar S values. Nonetheless, 13 and 14 have higher B values as a consequence of very high relative humidity and not necessarily higher temperatures. The latter is a result of comfort zone layout on the bioclimatic chart, as comfort zone is narrower at higher relative humidity (see Fig. 2). As a consequence, different A or B values and the same S values can be identified at two different locations with the same outdoor temperatures, but different relative humidity. High S values indicate that overheating prevention measures are necessary. Otherwise this condition can potentially result in high energy demand for building cooling. On the other hand, at locations with high D' values, the potential for PSH is relatively small. Furthermore, the consideration of PSH efficiency is highly appreciated at such locations (e.g. Passo Rolle), where the focus should nonetheless be primarily on heat loss prevention. In addition, at these locations the overheating prevention measures are not needed. However, at several locations (9, 16, 17 and 21) the application of PSH measures is appropriate, while the need for overheating prevention is small or unnecessary. At the locations in the transitional areas (1, 2, 3, 4, 15, 18 and 20), where one climate type (e.g. Mediterranean climate) transits to another (e.g. cold continental or sub Alpine climate), generally both measures, heat loss and overheating prevention, should be considered. Typically, for such locations the A and A' values are almost equal, the S values are lower than in the case of warm areas and the B values are very low or equal to zero. All the above described results are based on a relative comparison, rather than absolute values.

4.3. Evaluation of bioclimatic potential prognosis using energy simulations

Results presented in the previous sections indicate that the conducted analysis of bioclimatic potentials at a given location can be used as a design guideline. The obtained results are indicative of basic design features (e.g. importance of shading) that should be incorporated into a building in order to make the indoor environment as comfortable as possible. Consequentially, such approach to building design should result in lower energy consumption for cooling and heating, as the planned building better utilizes the environmental potential of the climate. In order to test this presumption and at the same time evaluate the executed bioclimatic potential analysis, energy simulations of a simple building in five selected locations were conducted using EnergyPlus [38] and Open Studio [48] plugin for SketchUp [49]. The selected locations were: Trieste (10), Verona (14), Ljubljana (2), Graz (20) and Tarvisio (9). These locations were chosen in order to represent the variability of climatic conditions identified through the bioclimatic potential analysis in the Alpine-Adriatic region. Additionally, for these loca-

Table 3
Orientation and area of windows in respect to the cardinal axes and ratios of glazing to net floor area.

Ratio of glazing to net floor area	Window area [m^2]				
	South	East	West	North	Total area
16%	14.00	2.80	2.80	2.80	22.40
20%	19.60	2.80	2.80	2.80	28.00
24%	25.20	2.80	2.80	2.80	33.60

tions the weather data for energy simulations were available on the EnergyPlus webpage [50].

4.3.1. Building model description

In order to conduct the evaluation of bioclimatic potential analysis, a simple single family building incorporating basic bioclimatic features (i.e. large windows oriented south, elongated floorplan, shading during summer) was modelled in Open Studio plugin. The modelled building has a rectangular floor plan of 7 by 10 m (ratio of 1: 1.4) with longer side oriented towards south. Such configuration was shown by Košir et al. [28] to be favourable in regards to energy performance of a building, as larger windows can be incorporated into the southern façade. The building has two identical floors with the floor to floor height of 2.8 m. The total net floor area of the building is 140 m^2, while its volume is 392 m^3. The opaque part of the building envelope was presumed to be well insulated, with U value of 0.28 W/(m^{2}K) for the façade wall, 0.20 W/(m^{2}K) for the roof and 0.30 W/(m^{2}K) for the slab on the ground. The load-bearing construction is composed of massive materials (i.e. hollow brick and reinforced concrete slabs) with externally applied thermal insulation. The transparent parts (i.e. windows) of the façade envelope have a U value of 1.18 W/(m^{2}K) and a g factor of 0.59. The glazing area was modelled in three different configurations of 16% (22.40 m^2), 20% (28.00 m^2) and 24% (33.60 m^2) of the total net floor area of the building. The distribution of windows in relation to cardinal axes is presented in Table 3, where it can be seen that only the southern oriented glazing was increased whereas windows on other facades remained relatively small [51] and constant for all the three configurations. For each of the three glazing area configurations, shaded (SH) and unshaded (UN) simulations were executed. In case of shading, external venetian blinds were used on the south oriented windows from 1st of May till 30th of September; other orientations were unshaded in all the simulations.

The building was simulated as a single thermal zone with 4 occupants and an average heat flow of 70 W [52] per person. For the occupancy of the building, a default schedule for midrise apartment buildings from ASHRAE Standard 90.1 [53] was used. The same is true for the lighting and electrical equipment loads, with 6 W/m^2 for the lighting and 3 W/m^2 for the electrical equipment. The heating set-point was defined at 21 °C, while the cooling set-point was set at 26 °C. The ventilation of the building was presumed to be natural with 0.8 ACH between 1st of May and 30th of September, whereas for the rest of the year the ventilation rate was 0.5 ACH, which corresponds to minimal recommended ventilation rate by EN 15251 standard [54]. The increased rate of natural ventilation corresponds to the use of the shading on the southern oriented windows and represents increased ventilation rates normally used by the occupants during the summer. All the calculations were conducted using ideal air loads, meaning that the influence of HVAC systems was idealized.

4.3.2. Energy performance and comparison

The observed simulated results for each simulated case were the energy consumption for cooling (Q_C) and heating (Q_H) in kWh/m^2, the ratio between the two as well as the total cumulative yearly energy consumption (Q_T). For each of the five selected locations five different building models were calculated. Each model was named according to the ratio of glazing to floor area (16%, 20% or 24%) and whether the south oriented windows were shaded or not (SH or UN). The total number of calculated cases was 30. The results of energy simulations are presented in Fig. 6 along with the corresponding pie charts representing the calculated bioclimatic potential for each of the five selected locations.

By observing the simulation results for the locations of Trieste and Verona, a trend becomes obvious, with the increased area of glazing the Q_T increasing due to higher consumption of cooling energy. This is true for the unshaded as well as shaded cases of the modelled buildings, although the impact of cooling is much higher in unshaded cases, where in the instance of Verona for the building case 24% UN the highest cumulative energy consumption (65.10 kWh/m^2) of all of the cases is reached. For both locations the importance of shading is confirmed with the energy simulations, which correspond to a high value of S (i.e. 26% for Trieste and 23% for Verona) in the bioclimatic potential analysis. The same goes for the window area, as by increasing the area of glazing the Q_H decreases, while the Q_C increases in a proportionally larger fraction and, therefore, has a negative effect on the Q_T. The described trend can be linked to the D' as well as S value in the bioclimatic potential analysis, because low D' (i.e. 28% for Trieste and 31% for Verona) with simultaneously large S means that appropriately designed buildings in such locations are predominantly cooling driven (Fig. 6). In contrast to the locations of Verona and Trieste, the opposite situation can be identified at Tarvisio. This location is characterised by low S value (i.e. 6%) and the largest D' (i.e. 43%) value of all the five selected locations. This is reflected in large heating energy consumption, where Q_H represents between 86 and 99% of the Q_T (Fig. 6). Increasing of the area of glazing is beneficial in all of the simulated cases, even if the windows are left unshaded, although the contribution of Q_C in the Q_T increases (e.g. Q_C represents 14% of Q_T in case 24% UN). The last two locations of Ljubljana and Graz fall between the two described extremes, which is reflected in their bioclimatic potential analysis results (Figs. 5 and 6 and Table 2). Both locations are characterised by the S values around 10% and D' around 40%, although Ljubljana has grater S and D' values, which indicate higher summer temperatures and at the same time lower potential for PSH during winter. In general, the results of energy simulations confirm that the two locations are in fact a combination of heating and cooling dominated climates. This is illustrated by the reduction of the Q_T when window area is enlarged, but only if the windows are shaded. In the opposite case the Q_T increases because the portion of the Q_C rises faster than the Q_H decreases (Fig. 6). The ratio between Q_C and Q_H (i.e. 19%) in the case of the unshaded largest windows is comparable to the shaded case (24% SH) in Verona (i.e. 18.5%), but is still smaller than in Trieste (i.e. 25%). From the results presented in Fig. 6 it can also be observed that a small difference in the S and D' values between Ljubljana and Graz leads to the conclusion that the smallest Q_T is reached at different window areas. For Ljubljana this is achieved in the case 20% SH with 50.7 kWh/m^2 of cumulative yearly energy consumption, while for Graz it is at 24% SH with 42.2 kWh/m^2. The results of the executed energy simulations for the selected locations confirmed the accuracy of bioclimatic potential analysis (Section 4.2). In general, the executed evaluation on a simple building model demonstrated that the values of S and D' as well as the related values of A, A' and C' can be used to determine if a building at a specific location should include passive solutions, either to control overheating, enable PSH or both, as in the case of Graz and Ljubljana.

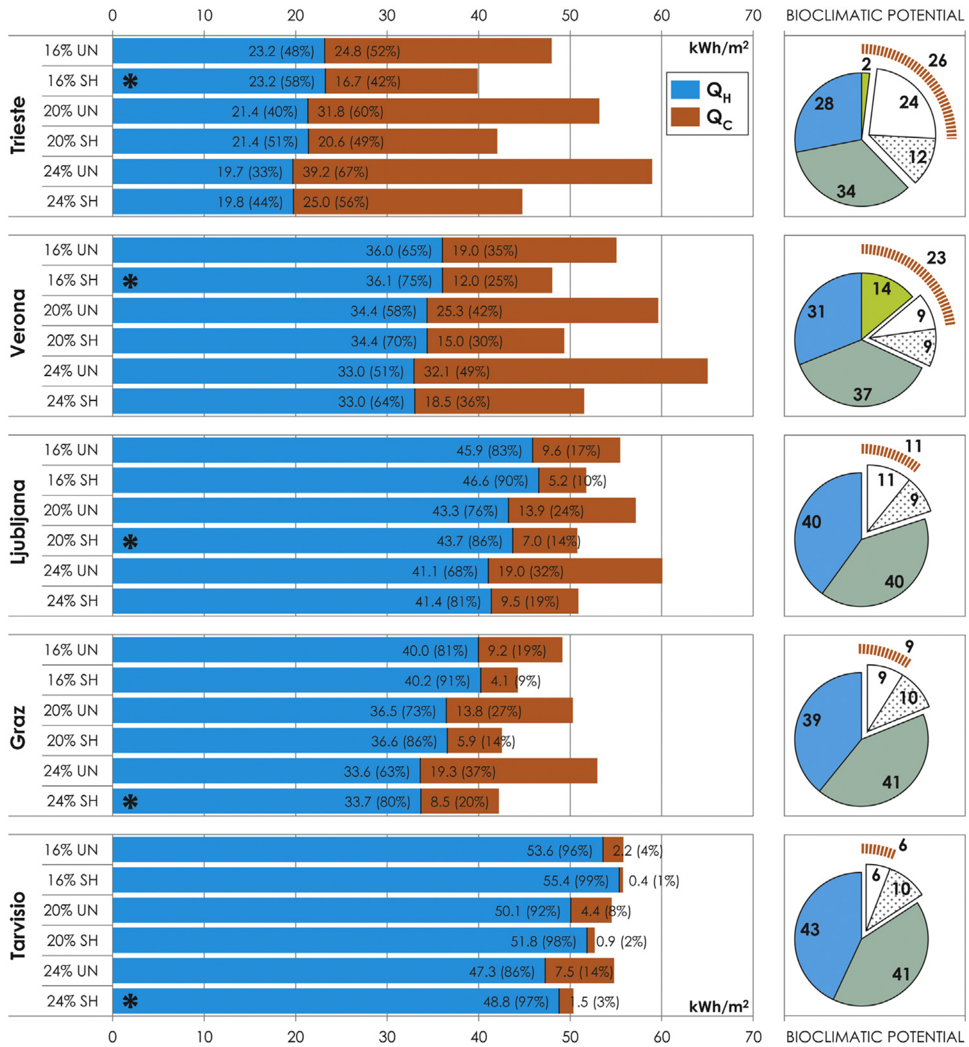

Fig. 6. Results of energy simulations in five selected locations with corresponding bioclimatic potential pie charts. The bar charts present the ratio between heating (Q_H) and cooling (Q_C) energy consumption for different window areas (16%, 20% and 24% of floor space area) with (SH) and without (UN) shading. Cases with the lowest cumulative energy consumption (Q_T) for a given location are marked by an asterisk.

5. Discussion

The presented bioclimatic potential analysis is of great importance, especially at locations like Alpine-Adriatic region, characterised by its great climatic diversity. The latter is evident at mezzo locational level as well – country of Slovenia itself. Slovenia is an example, where completely different building design approaches must be used inside extremely small geographical area (i.e. all of the three different approaches, described in Section 4.3). Unfortunately, in many cases designers select more or less the same bioclimatic building design solutions for all locations. In principle, adapting design patterns of vernacular architecture is encouraged and in many instances regarded by designers as the best possible bioclimatic approach [3,55]. However, it is unclear whether such replication of traditional solutions results in better bioclimatic performance of contemporary buildings. Therefore, it was further investigated how the bioclimatic potential of a certain location changes through time in relation to the changes in climatic conditions. In particular, air temperature in Ljubljana (Slovenia) was studied from 1961 till 2015 and corresponding bioclimatic potential was calculated for each decade (i.e. 1966–1975, 1976–1985, 1986–1995, 1996–2005 and 2006–2015).

Temperature diagram in Fig. 7 shows that average yearly environmental air temperature (T_{avg}) in Ljubljana is slowly increasing through time. T_{avg} has increased approximately 2 K in the last 50 years, and the number of hot nights and very hot days has escalated as well. The trend is expected to continue and even to intensify during the next two decades as a consequence of climate changes [56]. In particular, projections for the Alpine-Adriatic region by Rubel et al. [57] predict even severer climate changes. The changes in climatic conditions are expected to have profound impact on energy performance of existing as well as new buildings, as it was shown by Berger et al. [58] on the example of office buildings in Vienna, Austria. Comparable conclusions were also made by Filippín et al. [59] with retrospective analysis of the energy consumption of dwellings in Argentina, and by Yildiz [60] with bioclimatic thermal comfort predictions for the three largest cities in Turkey. Thus, unselective adaption of traditional bioclimatic approaches should be called into question. The same goes for innovations [61]. Observing bioclimatic potential in different decades in Fig. 7, it can be seen that the portion of the year when shading is needed (S value) in Ljubljana has increased from 11 to 15% in the last 50 years. Thus, bioclimatic approaches for overheating prevention are becoming more important than they were in the past. Consequentially, we can speculate that bioclimatic adaptations of vernacular architecture that have adjusted to the climatic conditions of the past centuries might not be appropriate for the challenges of the future. Because the idea of bioclimatic building design is to adapt to climate, it is

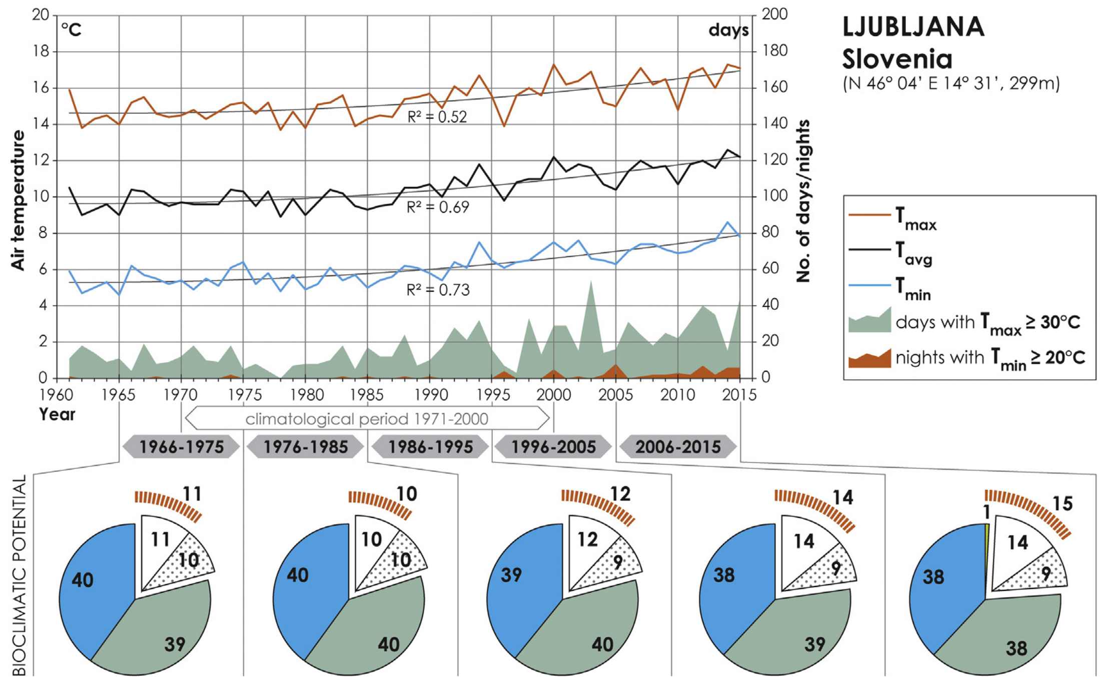

Fig. 7. Environmental air temperature and number of characteristic days in Ljubljana (Slovenia) during the period from 1961 until 2015. Pie charts with bioclimatic potential are calculated for the specified 10-year periods.

of great importance to take into consideration potential climatic changes and not just replicate existing design solutions. Therefore, modifications of design strategies should not be neglected, since they can significantly contribute to building energy performance. In this perspective, Tzikopoulos et al. [62] already highlighted that many passive technologies utilized in contemporary buildings do not affect energy efficiency of bioclimatic buildings across Europe. Therefore, use of appropriate and updated climate data in conjunction to bioclimatic potential analyses is vital. Moreover, the same applies to energy performance analyses, where usually statistical weather data sets are used, which might not adequately describe current state of the climate.

When designing bioclimatic buildings, consideration of local climate specifics and the influence of climate change is necessary. Therefore, the presented approach is a useful tool to identify, which passive building design strategies are dominant at a specific location and should be applied in building design in order to facilitate smaller energy usage and the resulting higher indoor comfort. For example, in the case of location 10 (Trieste), the principal focus should be on the overheating prevention and the corresponding smaller area of windows, applied shading, etc., as shown by Soussi et al. [63], adapted ventilation type and regime as shown by Roslan et al. [64] and Hudobivnik et al. [27], high thermal mass [27], or a mixture of all of the above. In contrast to Trieste, at location 20 (Graz), the primary focus should be on the colder part of the year and the utilization of solar energy (PSH measures [63,65]). These findings do not contradict the established bioclimatic patterns found in vernacular architecture of the region. Nonetheless, in the light of climate change these patterns should be evaluated using objective tools like the presented bioclimatic potential analysis.

Although the presented method is relatively accurate, it has limitations. With hourly instead of daily climate data taken into consideration, the calculation would definitely be more accurate, although not necessarily much different. Thus, using the presented method with basic weather data (e.g. monthly averages) represents a straightforward approach to assessing bioclimatic potential of a specific location. In addition to air temperature and relative humidity, the precise consideration of actually received solar irradiance was shown to have a large influence on the results of the analysis and is, thus, of great importance. Moreover, the presented bioclimatic potential results show a fairly good coincidence with the Köppen-Geiger climatic classification types (Fig. 1 and Fig. 5 and Table 2). However, due to low resolution of the Köppen-Geiger classification data [46] used to classify locations selected in the paper, higher level of attention is needed at transitional areas (e.g., locations 5, 6, 8, 9, 10, 19 and 20). This was demonstrated in the paper through the bioclimatic potential analysis of transitional locations, where the boundary between cooling and heating dominated climates cannot be explicitly defined. With some specific combinations of the D' and S values, a location can be dominated by the both. At other areas, where climate variability is not that high (e.g. Central Europe north of Alps), direct connection between bioclimatic potential and the Köppen-Geiger classification types could be made. This would enable building designers to use the Köppen-Geiger climate type of a location as a starting point to determine the most suitable passive solar architecture features of a building without the need for detailed bioclimatic analysis. This would be extremely useful, as predicted climate shifts expressed through Köppen-Geiger climate types, like those presented by Rubel and Kottek [66] and Rubel et al. [57], could be used to determine building bioclimatic approaches, using also predicted and not only measured data. Nevertheless, this presumption needs further testing on a greater sample of test locations within the same climate type and over a larger geographical area.

6. Conclusions

The presented methodology of bioclimatic building design potential prognosis represents a very useful design tool and a step towards sustainable built environment. The method is extremely quick and simple to use, nonetheless sufficiently accurate. With its help, the designers are guided towards the use of bioclimatic building design features during the early stages of design. The conventional approach where designers use vernacular architecture as a source of bioclimatic inspiration can therefore be verified using analytical approach and appropriate modifications can be made. Although the results of the bioclimatic potential analysis cannot be directly translated into possible building energy consumption reduction, they represent a reliable and unambiguous indicator of energy performance by identifying the most promising passive design features. Thereby, both energy efficiency and user comfort can be addressed. In the end it has to be highlighted that with the presented approach probable changes in the future climate can be accounted for, when designing a building.

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PRILOGA B

Implications of present and upcoming changes in bioclimatic potential for energy performance of residential buildings

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Implications of present and upcoming changes in bioclimatic potential for energy performance of residential buildings

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ABSTRACT

Bioclimatic potential analysis is one of the starting points for bioclimatic building design. However, as climate changes are being brought into the spotlight, bioclimatic potential is being put into question as well, because traditionally used passive strategies at a specific location may no longer represent properly balanced approach. Therefore, the purpose of this paper was to systematically evaluate bioclimatic potential of the selected five locations. At these locations, bioclimatic potential was observed separately for each of the last five decades. In the second part, present and future energy performance of one bioclimatic and one non-bioclimatic real residential building was simulated. The results show that yearly balance between heating and cooling passive strategies changed through time in all the locations. For example, the use of overheating prevention strategies is becoming more significant than it used to be in the past. Specifically, the period of year when shading is needed to achieve thermal comfort increased by 2–7% points, depending on location. Energy performance analysis of the selected buildings showed that by 2050 both analysed buildings will become cooling dominated and that by 2050 the current design solutions in bioclimatic buildings will become irrelevant or at least extremely inefficient. In general, in temperate climate zone the prevailing bioclimatic strategies integrated in architecture focus on heating season. Therefore, bioclimatic strategies in a particular location must be re-evaluated in order to design new and retrofit existing energy efficient contemporary buildings with comfortable indoor thermal conditions.

1. Introduction

The 2015 Paris agreement on climate change set goals and limits in order to reduce further increment of global air temperatures. According to European Directives, lowering of environmental impact of buildings [1] and improving their energy efficiency [2,3] are key elements in achieving those objectives. Evidence is mounting that in the light of increasing awareness about the use of natural resources and the protection of the environment, the importance of energy performance of buildings is continuously growing. Simultaneously, the indoor thermal comfort is also gaining on importance as it plays a crucial role in the perception of “healthy homes” [4]. Therefore, the aforementioned requirements introduced by EU Directives [2,3] encourage accelerated progress in the field of energy efficient buildings, whereby near-zero energy buildings (nZEB) have become a technological reality as well as necessity. However, with the application of previously mentioned regulations the impact of buildings on energy use and climate change is not a resolved issue, as crucial role towards achieving sustainable society should be played by climatically adaptable building design, also resulting in higher level of indoor comfort. Hence, greater attention is paid to the correlation between a selected design approach and the corresponding performance outputs.

All the above mentioned aspects can be entirely or at least to some degree addressed by bioclimatic building design. A building can be declared as bioclimatic when it efficiently uses climatic resources of its location, primarily with the help of building envelope elements [5]. In order to design buildings in a way that they adapt to climate as much as possible, a balance between the chosen heating and cooling passive strategies must be obtained. Accordingly, if the design goal is a thoughtful choice of appropriate bioclimatic strategies, it is necessary to evaluate the climate characteristics at a specific location. One way of assessing location's bioclimatic potential is through the use of bioclimatic chart. This approach was originally pioneered by Olgyay [6] in 1963. With bioclimatic chart, elementary climate data, such as dry-bulb air temperature and relative humidity, can be used to determine the most promising passive design strategies at a specific location. Nevertheless, it has to be stressed that the conventional approach of bioclimatic analysis through bioclimatic charts does not directly incorporate the influence of solar radiation. Thus, the interpretation of results can be insufficient and misleading, because the impact of solar radiation on

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the selection of passive strategies can be substantial.

Several studies have been conducted (see Refs. [7–15]), which involved the calculation of bioclimatic conditions or bioclimatic potential at the selected locations. The referenced studies underlined the importance of such building design and consequential adaptation to the local climate. In order to design a contemporary bioclimatic building, two different approaches can be selected. The first one is replication of bioclimatic patters found in local vernacular architecture (e.g. see Refs. [16–19]), adapted to the climatic characteristics through centuries. On the other hand, the second approach utilizes climate analysis in order to independently determine the most promising design strategies on the basis of dominant climatic patterns. Such approach was shown by Pajek and Košir [14] on the example of the European Alpine-Adriatic region, by Alonso Monterde et al. [20] for the Valencian region in Spain or by Yang et al. [21] for five major climatic zones in China. Notwithstanding the existing studies, Dubois et al. [22] highlighted that knowledge transfer between research and practice in building engineering is insufficient. The latter reflects in the fact that, in general, professionals at an early stage of the design process rarely adopt tools to support the design for climate adaptation. Accordingly, either novel, broadly unverified solutions are practiced or examples from vernacular architecture are replicated as a baseline for the choice of the most appropriate passive strategies at a specific location. Both approaches are frequently used by contemporary designers [23]. Specifically, climate adaption is considered by designers as one of several design-related concerns [21]. Thus, building's ability to adapt to climate has a potential to encourage designers to critically reconsider this subject [24]. The design issue is further deepened as strategies used in vernacular architecture are based on the past climatic conditions. Such approach would not represent a problem if climate characteristics were in fact not a dynamic process. In this respect, Tejero-González et al. [25] highlighted that careful use of available climate data must be done, because it only represents probable occurrence of conditions. Moreover, in the last decades the climate has been in the state of accelerating change and will continue to change, according to several conducted studies [26–28]. The changes in the climate are designated as fast and of large scale. Specifically, the mountainous regions were shown by Miró et al. [28] to be most affected by increased temperatures due to potential climate change, while the least affected were lowlands and inland valleys. Potential consequences of such changes for urban areas could reflect in higher flood risks, intensified urban heat islands, lower indoor comfort and occupant productivity as well as increased heat related health risks [29]. Opposing the stated negative effects, higher temperatures can also decrease energy use for heating and increase the options for outdoor activities and tourism [29]. If the predicted effects of climate change unfold, its potential implications for current and future buildings may be immense. Therefore, Pajek and Košir [14] highlighted that bioclimatic potential at some locations should be reevaluated or even further – predicted by future weather projections. This is of paramount importance, because some passive design strategies, traditionally implemented in local vernacular architecture, might no longer represent the best suited approach to climatically adapted building design. Similarly, the problem is also present in "non-bioclimatic" contemporary buildings, as it was shown by Fezzioui et al. [30]. Their simulation of modern house under desert climate conditions revealed that because the building is not adapted to local climate, except for the air-conditioning, there is in summer no other solution that can ensure indoor thermal comfort. However, it must be emphasised that not only the technical characteristics of buildings should be addressed, but also how the occupants perceive the indoor thermal environment [31]. To sum up, it can be argued that climate is changing and that this will have an impact on indoor thermal conditions in buildings.

According to the challenges of the future, such as climate change, a conceptual leap in (bioclimatic) building design will be necessary. Particularly, current building design paradigms should be replaced by new approaches, which will consider the state of the current and future climate [14,32]. Such approach was already presented by Huang and Gurney [33], Shen and Lior [34] and Shen [35] in the US, Yu et al. [36] and Cao et al. [37] in China, Nik [38] in Italy and Sweden, van Hooff et al. [39,40] and Hamdy et al. [41] in the Netherlands, Berger et al. [42] in Austria, Pierangioli et al. [43] in Italy and Andrić et al. [44] for various climate zones. The referenced studies dealt with the energy performance of different types of buildings (e.g. office, residential, etc.), which were evaluated according to the present and/or future climate projections. Passive and/or active building strategies were considered. Several of the studies (see Refs. [40,41]) also demonstrated the potential of implementing passive measures (e.g. shading devices) in older buildings. Berger et al. [42], Cao et al. [37] and Pierangioli et al. [43] emphasised that buildings dominantly designed for the heating season will have to be retrofitted in accordance with the modern challenge of added cooling demands. In this context, Li et al. [45] underlined that climate change will have the most significant impact in warmer climates dominated by cooling demand and that in severely cold climates a reduction in heating demand would prevail over the modest increase in summer cooling. Although all the referenced studies dealt with the impact of climate change on present and future energy demand of either commercial, public or residential buildings, there is still lack of understanding of bioclimatic architecture and its adaption to the future climate. No recent study that we are aware of addresses this issue.

As has been noted, the conducted studies mostly consider only hypothetical typical (non-bioclimatic) building models and their future energy performance, despite the fact that also the existing building stock can be crucially affected by climate change, especially if these buildings were adapted to past climate conditions. Beside the bioclimatic approach to the design of new buildings, the renovation of the existing building stock in accordance with bioclimatic strategies will have to be encouraged as well, in order to address climate adaptability of the entire building stock. Hence, identification of past, current and future trends in bioclimatic potential of a location is needed. In other words, the question is whether the present "climate-balanced" buildings will still be appropriate for the climatic conditions of tomorrow. Therefore, the purpose of this paper is to thoroughly evaluate bioclimatic potential of five different locations in Slovenia, Europe. Moreover, bioclimatic potential was evaluated for the last five consecutive decades, in order to identify potential changes and any identifiable pattern. Additionally, bioclimatic potential was predicted for the next two decades. Although the reviewed literature showed that predicted energy performance of buildings is gaining on importance and is widely studied, it is not completely clear how bioclimatically designed buildings will respond to the climate change. Therefore, present and future energy performance of one bioclimatic and one non-bioclimatic real residential building was simulated. In particular, the main contribution of the paper to science and building practice is that the selected bioclimatic strategies, which are most commonly used in the temperate climate, and their effect on energy efficiency of buildings were evaluated for the present and the future. This has a significant impact on current and future decisions in building design and energy policy development.

2. Methods

2.1. Selected locations

For the purpose of this paper five locations in the Central European country of Slovenia were chosen in order to represent characteristic climate conditions that occur in Slovenia (Fig. 1) located in temperate climate zone of Central Europe:

- Portorož – 45°30′N 13°34′E, altitude: 31 m
- Murska Sobota – 46°39′N 16°09′E, altitude: 189 m
- Novo mesto – 45°47′N 15°10′E, altitude: 202 m
- Ljubljana – 46°03′N 14°30′E, altitude: 295 m

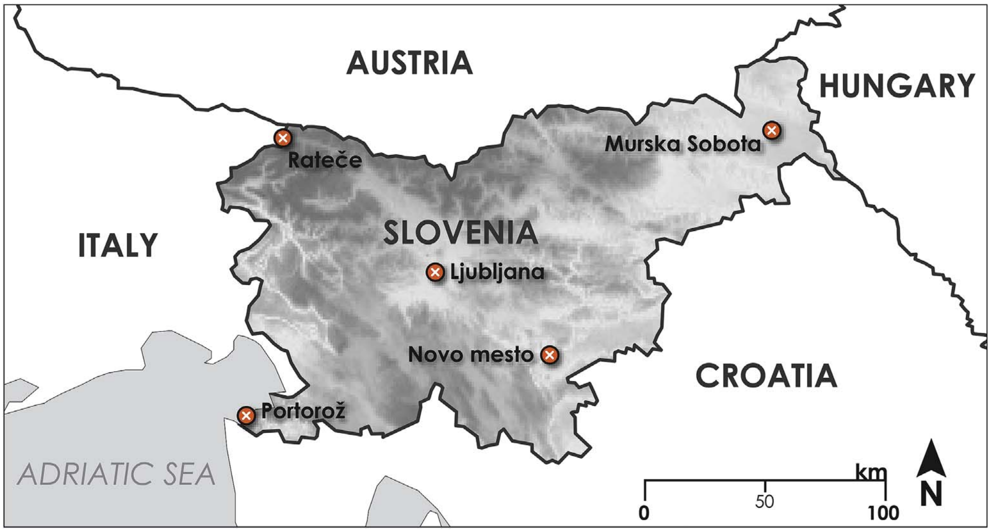


Fig. 1. Selected locations.

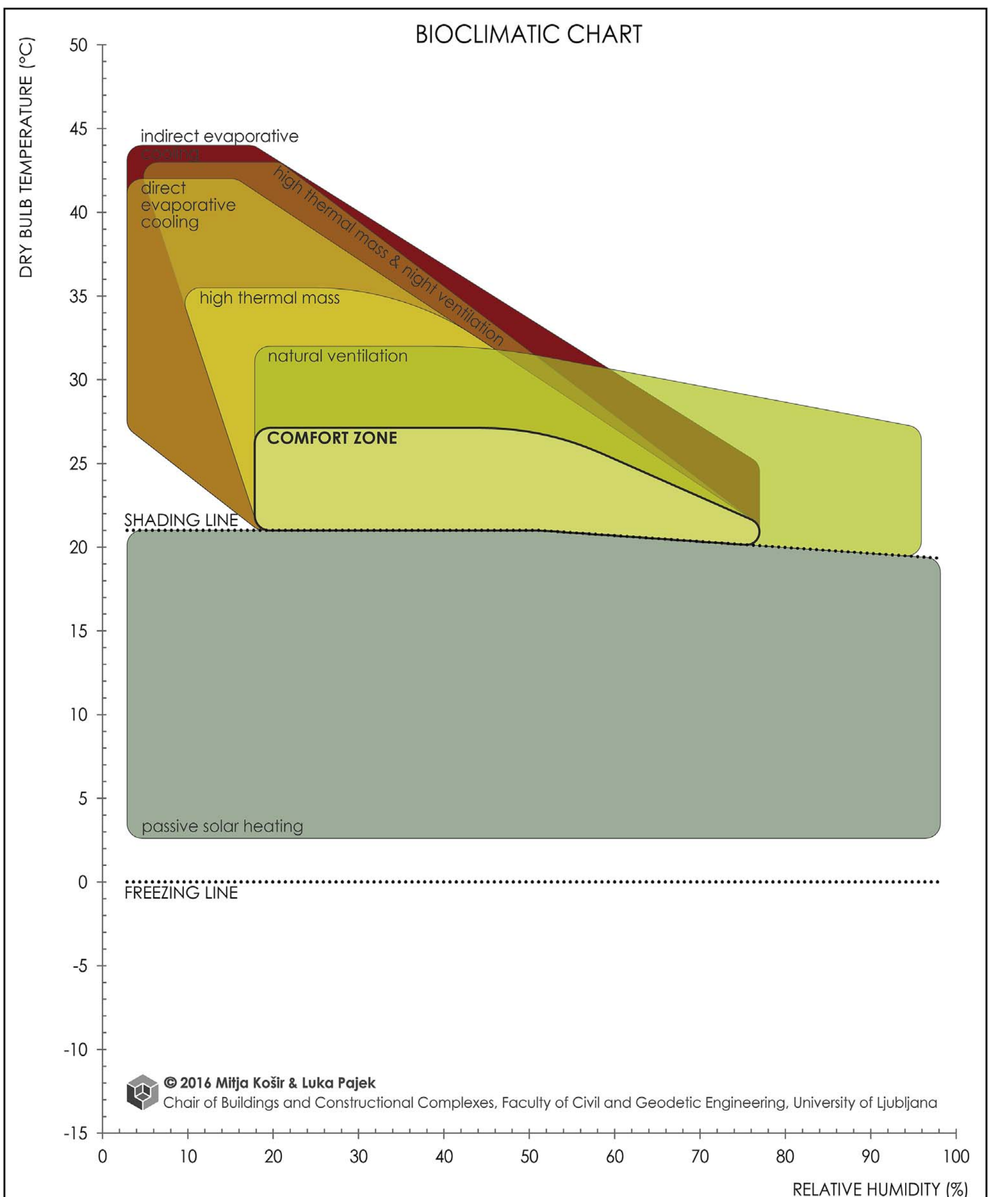


Fig. 2. Bioclimatic chart used in the analysis conducted with BcChart v1.0 tool.

Table 1
Bioclimatic potential as calculated by BcChart with suggestions of bioclimatic design strategies to be used to utilize the potential.

Label	Bioclimatic potential		Bioclimatic design strategy [16,52]
V	high thermal mass and/or natural ventilation and shading needed	S shading needed ($S = V + C_{sh}$)	• external shading • intensive ventilation (i.e. night purge) • high thermal mass of buildings • phase change materials in lightweight buildings
C_{sh}	comfort achieved with shading		• external shading
C_z	comfort achieved ($C_z = C_{sn} + C_{sh}$)		
C_{sn}	comfort achieved with solar irradiation	S_n solar irradiation needed ($S_n = C_{sn} + R + H$)	• equatorially oriented openings (i.e. direct solar gains)
R	potential for passive solar heating		• equatorially oriented openings (i.e. direct solar gains) • sunspace, Trombe-Michel wall, etc.(i.e. indirect solar gains) • partial conventional heating necessary
H	no potential for passive solar heating		• conventional heating necessary

- Rateče – 46°29′N 13°42′E, altitude: 864 m

Although all of the selected locations could be characterised by Köppen-Geiger climate classification type Cfb (temperate, without dry season, warm summer), Slovenia's climate is regarded as highly diversified; hence large variability within the same climate type is common [14]. For example, the analysed location of Portorož has a sub Mediterranean climate (Cfa according to Köppen-Geiger classification) due to its position next to the Adriatic Sea. Similarly, Rateče has colder climate than other locations due to its Alpine location; therefore, it represents a transition from Cfb to Dfb climate types.

2.2. Data analysis

2.2.1. Preparation of meteorological data

In order to analyse the bioclimatic potential of the selected locations, historical weather data were obtained for every year between 1961 and 2015. In particular, the acquired weather data were as follows: average (T_{avg}), average maximum ($T_{max,avg}$) and average minimum ($T_{min,avg}$) yearly air temperature, average maximum ($T_{max,i}$) and average minimum ($T_{min,i}$) daily air temperature and relative humidity ($RH_{max,i}$ and $RH_{min,i}$) for every month, and average ($G_{avg,i}$) and average maximum ($G_{max,i}$) daily global solar irradiance on horizontal plane for every month. All the acquired data were obtained from the archives of automatic weather stations, which were all located in urbanised locations. All of the climate data were provided by Slovenian Environment Agency [46].

For the energy performance simulations the necessary hourly weather data were acquired from the online TMY Generator provided by the Joint Research Centre at the European Commission [47] for the selected representative location (i.e. Murska Sobota). The weather file was generated using measured data for the 2006 to 2015 decade. This file was later used to generate predicted weather files for 2020 and 2050 using HadCM3 (i.e. Hadley Centre Coupled Model, version 3) modelled climate change predictions provided by the Intergovernmental Panel on Climate Change [48]. Weather files with future climatological characteristics were obtained using the CCWorldWeatherGen tool [49] developed by Jentsch et al. [50] at the University of Southampton.

2.2.2. The underlying theory of bioclimatic potential calculations

The bioclimatic potential of locations was calculated for a typical residential building. In order to determine the bioclimatic potential for each location, the BcChart 1.0 tool was used [51]. With the BcChart tool, elementary climate data (T_{avg}, $T_{max,avg}$, $T_{min,avg}$, $T_{max,i}$, $T_{min,i}$, $RH_{max,i}$, $RH_{min,i}$, $G_{avg,i}$, $G_{max,i}$) were analysed and bioclimatic charts were plotted (Fig. 2). Furthermore, location's bioclimatic potential was calculated. The software is based on the theory of Olgyay's bioclimatic chart [6] and upgraded with the calculation of daily substitutive temperature (T_{sub}) through which the influence of actually received solar irradiation is incorporated into calculation. T_{sub} represents a reciprocal air temperature under the influx of solar irradiation. This results in a newly introduced C_{sn} value, which represents the time when human comfort is achieved with the utilization of available and received solar energy. Comfort zone (C_z), as defined by Olgyay, is placed between 21 and 27 °C and 18 and 77% relative humidity (Fig. 2). At higher values of relative humidity (> 50%) and higher temperatures (> 21 °C) the comfort zone is narrower. The temperature at the bottom of the comfort zone (i.e. 21 °C) coincides with the shading line. All temperature and relative humidity combinations that fall above this line will result in a need for shading (S), and those bellow it in the need for solar irradiance (R or H). Similar is true at the upper limit of the comfort zone, where the combinations above it (V) will result in the need for shading and other passive cooling strategies as well (e.g. intensive natural ventilation, high thermal mass, etc.). Correspondingly, comfort can be directly achieved either by shading (C_{sh}), use of solar energy (C_{sn}) or indirectly by passive or active measures (Table 1). It is assumed that human comfort is calculated for a person wearing customary indoor clothing (1 Clo), engaged in sedentary or light muscular work (M = 126 W) and the air movement is presumed to be 0.45–0.90 m/s. The exact methodology, based on which the bioclimatic potential of a location is determined by BcChart software, is presented in greater detail in the paper by Pajek and Košir [14].

As a result of the BcChart analysis, the time expressed in %, calculated either on yearly or monthly level, when the plotted combinations of temperature, relative humidity and solar irradiance fall either in or out of the comfort zone (C_z), is defined. For example, bioclimatic potential, expressed in %, defines the percentage of a particular month, when certain bioclimatic strategy is favourable (e.g. 10% of days in May shading should be used) in order to achieve the desired thermal comfort entirely with passive measures. Periods that determine the principal passive strategies are calculated and denominated as presented in Table 1.

2.3. Selected buildings and energy performance simulations

In order to directly connect the obtained results of bioclimatic potential analysis with practical implications, two existing typical residential buildings were selected. The first building (Fig. 3a) is a typical non-bioclimatic building (labelled as non-BC building) frequently found in Slovenian building stock. The second one (Fig. 3b) is a typical bioclimatic building (labelled as BC building), which is an example of commonly found contemporary energy efficient building, believed to be a good example of bioclimatic architecture. The two selected buildings

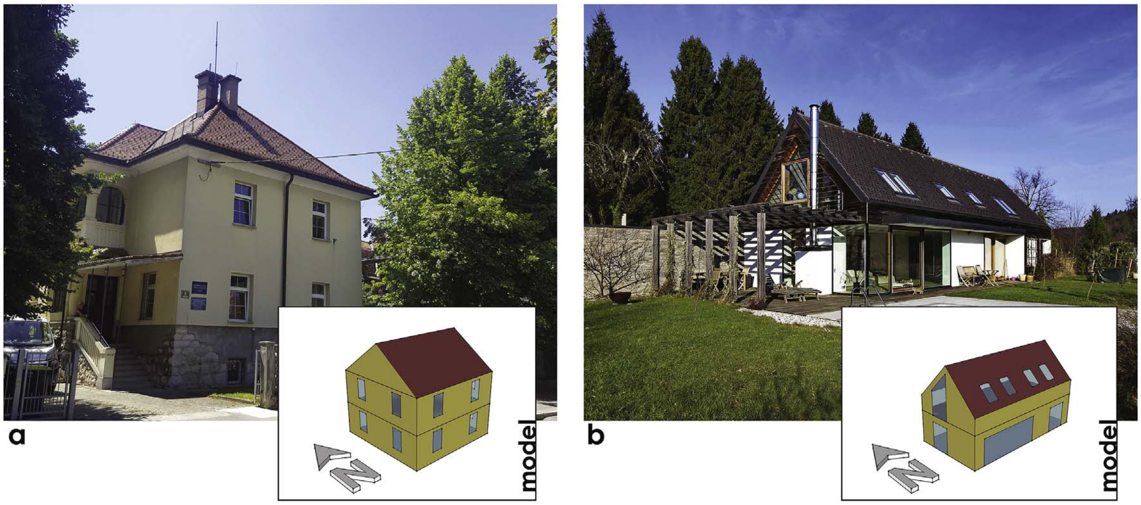


Fig. 3. Examples of two typical residential buildings with the corresponding OpenStudio geometric models (Fig. 3b photo by VELUX Group).

were used as examples for the definition of appropriate simulation models (Fig. 3). The floor area of both models is 162 m^2. The non-BC building has a square floor plan (i.e. 9 by 9 m), while the BC building has a rectangular shape with dimensions of 6.5 by 12.5 m. Both buildings have two floors and are oriented according to the cardinal axes, in case of BC building the longer façade faces south. The ratio between the floor area and the surface of windows is 15% (i.e. 25.2 m^2) for the non-BC building and 24.5% (i.e. 39.7 m^2) for the BC building. The distribution of windows in the case of non-BC building is almost uniform with 7.2 m^2 of windows per south, east and west oriented façades, while there are 3.6 m^2 of north oriented windows. In case of the BC building the distribution of windows is geared towards solar energy harvesting. Therefore, the south oriented windows including skylights amount to 25.4 m^2, while the remaining 14.3 m^2 of windows are distributed between the east and the west façades.

In the energy performance analysis two types of building envelopes were simulated. The first one represents a typical building constructed during the 1970s (labelled as OLD) and the other one reflects the minimum requirements of current Slovenian Technical guidelines about efficient use of energy in buildings [53] (labelled as NEW). The properties of both building envelope configurations as well as data on internal heat gains, lighting loads, ventilation and heating and cooling temperature set-points are presented in Table 2. In order to check the influence of window shading, as one of the most commonly practiced bioclimatic design strategies for overheating prevention, on the energy performance of the analysed buildings, the external aluminium venetian blinds were used on all windows. Shading is active from 1st of May till 30th of September. Blinds are extended and the blades are tilted at an angle of 45°, if the received solar irradiation on the window exceeds 120 W/m^2. Otherwise windows are unobstructed. Energy performance simulations were performed using EnergyPlus [54] and OpenStudio SketchUp plugin [55,56].

2.4. Limitations of the applied methodology

Firstly, it has to be stressed that the results of the presented bioclimatic analysis can only represent general guidelines for a particular analysed building type and location. The bioclimatic potential was calculated for a typical residential building in an urbanised environment. Therefore, the results are directly applicable only to similar buildings. One limitation of the methodology is that the internal heat gains cannot be taken into account when calculating bioclimatic potential. Another limitation, however of a lesser concern, is also that the behaviour of wind flow over time was not analysed. Nevertheless, the wind flow is not directly included into the bioclimatic potential analysis but is only exposed as needed or not (*V* values – natural ventilation needed), which can also be achieved by draft, stack ventilation or even mechanical ventilation. Due to insufficient historical data about solar radiation, all the conducted bioclimatic analyses were made on the basis of daily global solar irradiance on horizontal plane ($G_{avg,i}$, $G_{max,i}$) for the year 2015. It can be speculated that this simplification overestimates the influence of solar radiation during the earlier decades, when we can presume that lower ambient temperatures also coincided with lower solar irradiance. This means that using 2015 data for solar irradiance during these periods would have a far greater influence than the actual irradiance had. Another limitation is that the building energy need for artificial lighting was excluded from the analysis. Thus, the possible effect of potentially applied shading on the increase in electricity demand for lighting cannot be estimated. For this reason, the application of shading devices should be extremely deliberate, because they can significantly affect daylighting in buildings [60,61].

Table 2
Building envelope characteristics, ventilation, internal heat gains and temperature set-point parameters.

			Envelope type	
			OLD	NEW
Envelope characteristics	U_{wall}	(W/m^2K)	0.90	0.28
	U_{roof}	(W/m^2K)	0.60	0.20
	U_{floor}	(W/m^2K)	0.90	0.30
	U_{window}	(W/m^2K)	2.50	0.70
	g_{window}	(−)	0.75	0.53
Ventilation	*n*	(ACH)	0.50[a] (0.80, May to September)	
Internal heat gains	*occupants*	(W)	280[b]	
	el. equip.	(W)	972[c]	
	lights	(W)	486[c]	
Temperature set-point	$T_{heating}$	(°C)	21.0	
	$T_{cooling}$	(°C)	26.0	

[a] Corresponding to minimum requirements defined in EN 15251 [57].
[b] 70 W/occupant [58], 4 occupants, schedule according to ASHRAE Standard 90.1–2004 [59].
[c] Value and schedule according to ASHRAE Standard 90.1–2004 [59].

3. Results and discussion

The results of the study are presented in two steps. Firstly, the bioclimatic analysis and bioclimatic potential calculation at all the

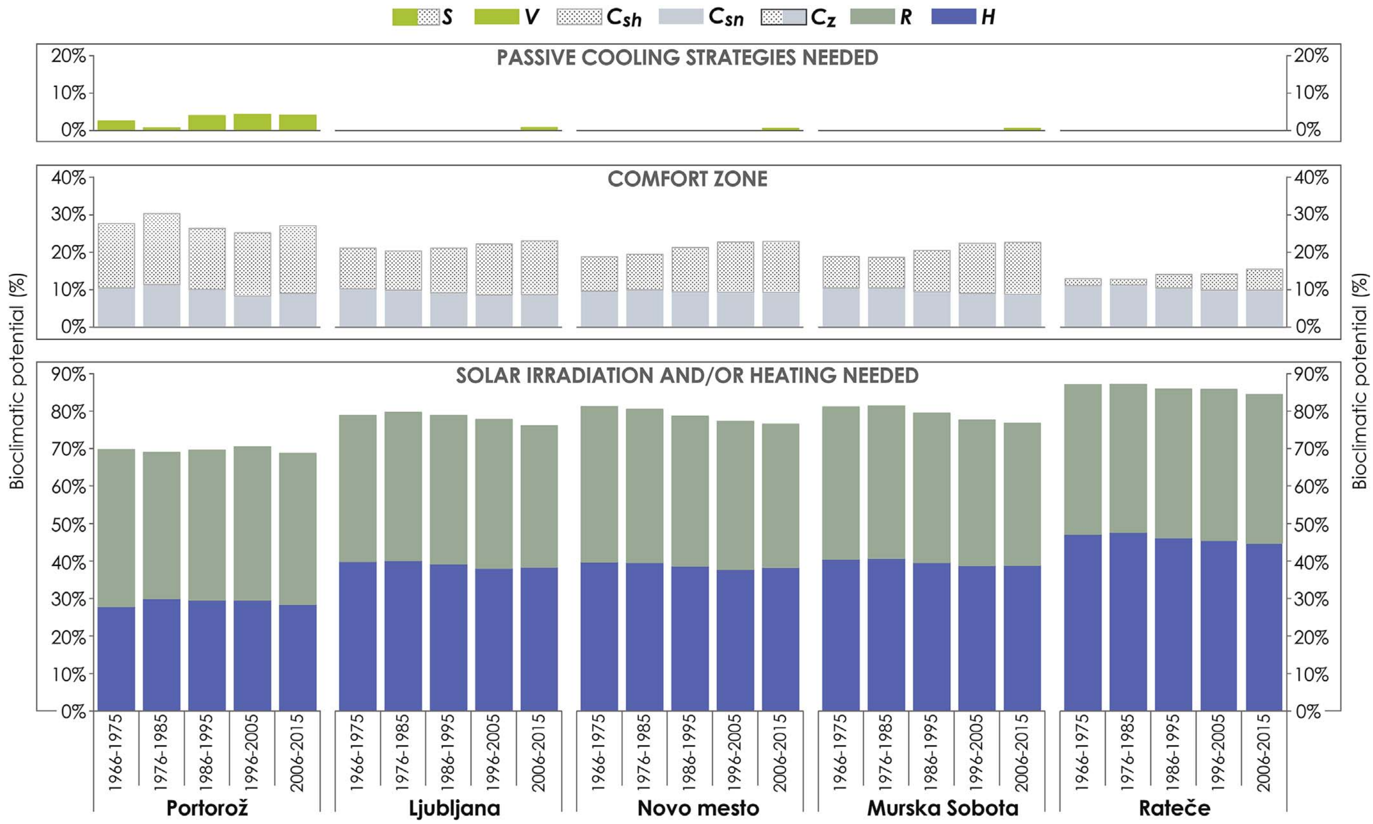


Fig. 4. Yearly bioclimatic potential of the analysed locations calculated separately for each decade. *V* – high thermal mass and/or natural ventilation and shading needed, C_{sh} – comfort achieved with shading, *S* (i.e. $V + C_{sh}$) – shading needed, C_{sn} – comfort achieved with solar irradiation, C_z (i.e. $C_{sh} + C_{sn}$) – comfort zone *R* – potential for passive solar heating, *H* – no potential for passive solar heating.

selected locations were carried out and the results are presented in subsection 3.1. Secondly, present and predicted future energy performance of the selected two real residential buildings was simulated and the results are presented in subsection 3.2.

3.1. Bioclimatic evaluation

Bioclimatic potential was calculated for the selected five locations. It determines the time share of the year (or month) in % when particular passive building design measures are efficient at facilitating building occupant comfort. Accordingly, the most promising passive design strategies and their corresponding yearly ratio were calculated using the BcChart software. Although Fig. 4 represents yearly data, the calculations of bioclimatic potential were conducted using monthly climatological data (i.e. monthly daily averages). Therefore, the yearly bioclimatic potential is a summation of monthly values represented as a share with respect to the whole year. Similarly, when calculating the bioclimatic potential in each of the analysed decades, monthly daily averages were used, calculated discretely for each of the consecutive decades. Bioclimatic potential at each location was observed separately for each decade of the last fifty years (1966 till 2015). The results are presented in Fig. 4.

If bioclimatic potential at all the locations in the last decade (2006–2015) is compared to the first analysed decade, namely 1966–1975, it can be noticed that comfort zone ($C_z = C_{sh} + C_{sn}$) is expanding (see Fig. 4). However, the way how this is achieved, specifically the ratio between C_{sh} (i.e. comfort achieved with shading) and C_{sn} (i.e. comfort achieved with solar irradiation), significantly altered (Table 3). In particular, in Murska Sobota, the C_{sh}/C_{sn} ratio changed from 0.80 in 1966–1975 to 1.57 in the last decade (2006–2015). This means that in the past, occupant comfort on yearly level was predominantly achieved with the utilization of solar energy (e.g. direct

Table 3
Values of *S* (i.e. $V + C_{sh}$) – shading needed, C_{sh} – comfort achieved with shading, C_{sn} – comfort achieved with solar irradiation and the ratio between C_{sh}/C_{sn} for each of the last five decades.

		Portorož	Ljubljana	Novo mesto	Murska Sobota	Rateče
1966–1975	*S* (%)	20.2	10.8	9.1	8.4	1.8
	C_{sh} (%)	17.6	10.8	9.1	8.4	1.8
	C_{sn} (%)	10.0	10.3	9.7	10.5	11.1
	C_{sh}/C_{sn}	1.76	1.05	0.94	0.80	0.16
1976–1985	*S* (%)	19.7	10.4	9.5	8.1	1.5
	C_{sh} (%)	19.0	10.4	9.5	8.1	1.5
	C_{sn} (%)	11.4	9.9	10.0	10.5	11.3
	C_{sh}/C_{sn}	1.67	1.05	0.95	0.77	0.13
1986–1995	*S* (%)	20.3	11.9	11.8	11.0	3.6
	C_{sh} (%)	16.3	11.9	11.8	11.0	3.6
	C_{sn} (%)	10.1	9.2	9.5	9.5	10.5
	C_{sh}/C_{sn}	1.61	1.29	1.24	1.16	0.34
1996–2005	*S* (%)	21.1	13.6	13.3	13.3	4.3
	C_{sh} (%)	16.8	13.6	13.3	13.3	4.3
	C_{sn} (%)	8.4	8.6	9.4	9.1	9.9
	C_{sh}/C_{sn}	2.00	1.58	1.41	1.46	0.43
2006–2015	*S* (%)	22.7	15.3	14.2	14.6	5.8
	C_{sh} (%)	18.5	14.4	13.6	13.8	5.8
	C_{sn} (%)	9.1	8.7	9.3	8.8	10.0
	C_{sh}/C_{sn}	2.03	1.66	1.46	1.57	0.58

solar gains), and far less by shading during hotter parts of the year. However, in the last decade the situation switched, as comfort zone on the yearly level is far more likely achieved by shading (i.e. solar protection) than by the utilization of solar radiation (Table 3 and Fig. 4). Specifically, the alteration of the trend occurs as a consequence of the increase in the C_{sh} value and simultaneous decrease in the C_{sn} value, which is the result of increase in ambient temperatures (the largest in Novo mesto with $\Delta T_{avg} = 2.8$ K and the lowest in Rateče with $\Delta T_{avg} = 1.8$ K). Similar development was also identified at all other locations, with the exception of Portorož, characterized by sub Mediterranean climatic characteristics, where shading has been the predominant strategy for achieving comfort all along. Specifically, the C_{sh}/C_{sn} ratio for the location of Portorož grew from 1.76 for the 1966–1975 period to 2.03 for the 2006–2015 period. The identified increment of the C_{sh} value emphasises the fact that although the bioclimatic potential at all the analysed locations has been shifting towards the extension of the comfort zone, greater attention is needed during the cooling season, as shading of transparent building elements is apparently becoming a priority issue. However, the importance of providing sufficient solar gains for passive solar heating, reflected through the C_{sn} as well as R values, is decreasing. Furthermore, in the last decade the appearance of the V value (i.e. high thermal mass and/or natural ventilation and shading needed) was also identified at several locations (i.e. Ljubljana, Novo mesto, Murska Sobota), which can be observed in Fig. 4. This is a characteristic typically linked with the Mediterranean climate [14] (e.g. Portorož). Moreover, highly urbanised locations, such as Ljubljana, are additionally exposed to overheating due to the phenomenon of urban heat island, which is in the case of Ljubljana further intensified by its geographical location at the bottom of a basin.

The consequence of comfort zone extension and the appearance of the V value in the last decades is the reduction of the R (i.e. potential for passive solar heating) and H (i.e. no potential for passive solar heating) values (Fig. 4). To summarise, bioclimatic potential analysis conducted using the available climatic data for the selected locations shows a steady transition towards overheating prevention strategies (C_{sh} and V) and a decrease in the importance of bioclimatic strategies designed for the utilization of solar gains (C_{sn} and R). Therefore, if existing buildings are not designed with appropriate passive elements for overheating prevention (i.e. effective shading), the actual achieved comfort (C_z would be equal or close to C_{sn}) at all the locations would in fact be decreased during the analysed fifty years (Table 3).

3.1.1. Detailed monthly bioclimatic potential analysis

Due to the identified shift in the calculated bioclimatic potential on a yearly level, the situation was further investigated on a monthly level in order to get a closer look at the phenomenon at work. The most characteristic change of the relationships between bioclimatic potential components and the corresponding passive strategies over the analysed five decades was recognised in Murska Sobota (see Fig. 4 and Table 3). The trend at similar locations (i.e. Novo mesto and Ljubljana) is comparable. Therefore, monthly breakdown of bioclimatic potential of Murska Sobota for the first analysed decade (1966–1975, see Fig. 5, bottom) and the last one (2006–2015, see Fig. 5, top) is presented. Because Rateče and Portorož represent locations with different climatic characteristics (Dfb and Cfa, respectively, according to Köppen-Geiger climate classification), their monthly breakdowns of bioclimatic potential for the first and the last analysed decade are also presented and can be observed in Figs. 6 and 7.

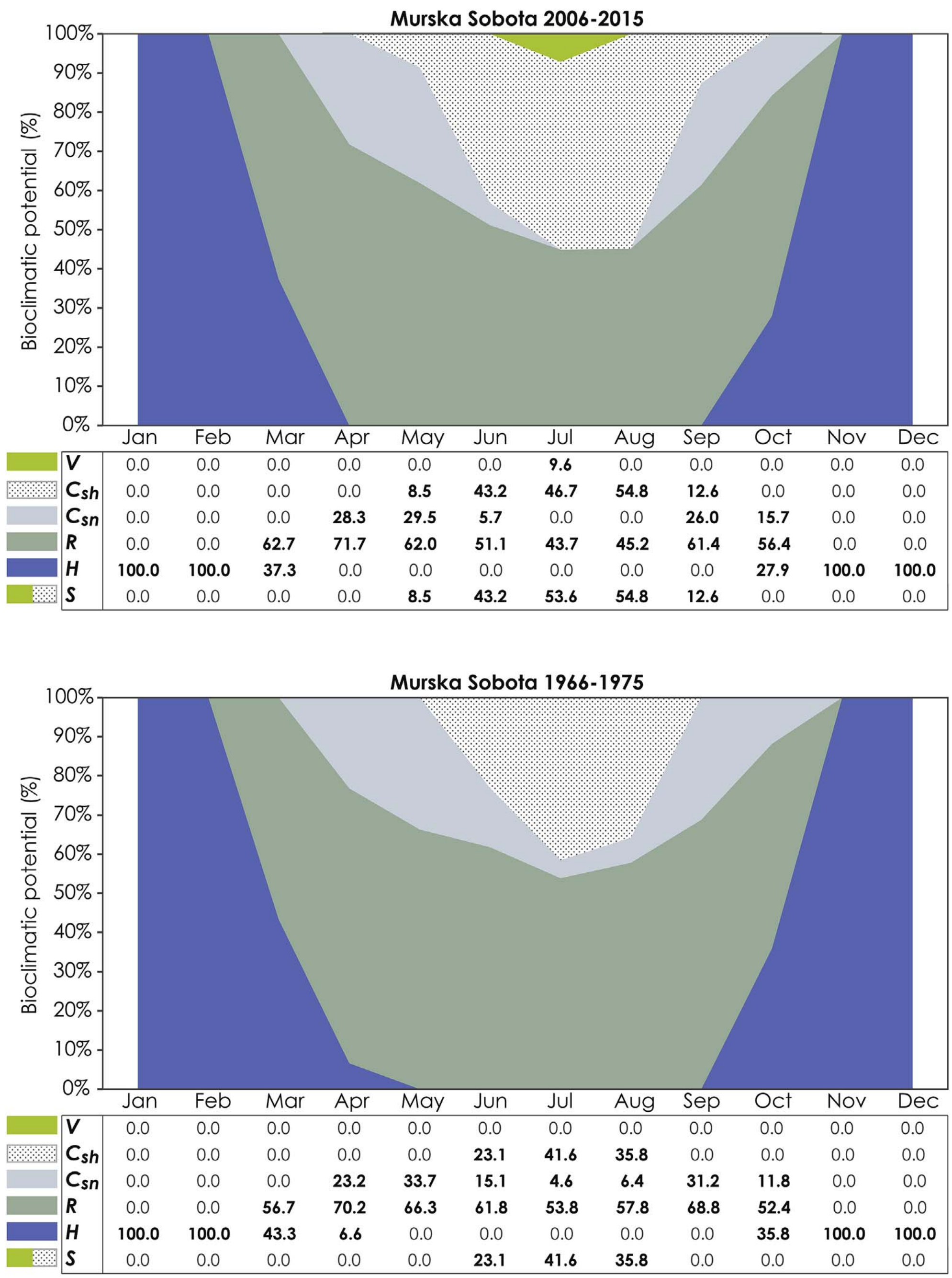
Observing Fig. 5, the aforementioned decrease in the R and H values on the yearly level (Fig. 4) is mostly limited to the time of year when transition between heating and cooling occurs. The latter can be, for example, recognised in transitional months, such as April or October (Fig. 5). In particular, bioclimatic potential of Murska Sobota in April shifted towards more comfortable conditions with a decrease of the H value from 6.6 to 0.0% (Fig. 5). Consequently, the C_{sn} and R values increased. If the bioclimatic potential, presented in Fig. 5, is observed during the summer months of June, July and August, a substantial increase of the S value (i.e. shading needed, $S = V + C_{sh}$) in the last 50 years can be identified. For instance, for Murska Sobota the S value in June almost doubled, rising from 23.1% (1966–1975) to 43.2% (2006–2015). In addition to the increase of the S value, the importance of shading is no longer limited exclusively to the summer months, as its occurrence is spreading into May and October (Fig. 5). Surprisingly, the C_{sn} value during hotter months is decreasing, most likely due to higher air temperatures. Thus, the influx of additional solar radiation is not desired in the same extent as it was in the past. Moreover, in comparison to the previous decades, the last decade the incidence of the H value in is increasingly becoming limited only to the months from November to February. A result of the described trend is the growing importance of overheating prevention in the design of new and renovation of existing buildings.

Similar trends can also be observed in Fig. 6, where monthly breakdown of bioclimatic potential for Rateče with colder climate (Dfb according to Köppen-Giger climate classification) is presented. Again, a significant increase of the S value in June, July and August can be recognised. Specifically, in the last five decades in July and August the S value increased by 17–18% points, while previously (1966–1975) shading was limited only to the months of July ($S = 14.4\%$) and August ($S = 6.9\%$). However, viewed as a whole, comfort zone in Rateče expanded and unlike in Murska Sobota, it still is mostly attributed to the utilization of solar energy and not shading, although the C_{sh}/C_{sn} ratio is on the rise. In particular, the C_{sh}/C_{sn} ratio increased from 0.16 in the first analysed decade to 0.58 for the 2006–2015 period (Table 3). Fig. 6 also clearly shows that in Rateče the H values did not record any significant change. For instance, the difference is most obvious in April, where the H value dropped by 9% points.

Lastly, the monthly breakdown of bioclimatic potential for Portorož with sub Mediterranean climate is presented in Fig. 7. At this location, the most apparent difference that occurred in the last five decades is the increase of the V value. The increase is most obvious in July, where the period of month with high thermal mass and/or natural ventilation and shading needed rose by 14% points. Similar to other locations, the S value in spring and summer months increased, with the highest increment in May, i.e. from 5.5% in 1966–1975 to 19.9% in 2006–2015 (Fig. 7). Accordingly, to achieve comfort in hotter months (i.e. June till August), solar irradiation is no longer desired (i.e. $C_{sn} = 0\%$). Nevertheless, the R value is still present, which means that in Portorož either shading is needed, or comfort can be partially achieved with the utilization of solar energy, which may not be available at the time (i.e. in the morning or during the night).

3.1.2. Comments on the results of bioclimatic potential analysis

The conducted bioclimatic potential analysis highlighted that the time of year when climatic conditions fall within the comfort zone (C_z) is expanding. However, it has to be stressed that the increase in comfort zone appears due to the increase in the C_{sh} (i.e. comfort achieved with shading) value, while at the same time the value of C_{sn} (i.e. comfort achieved with solar irradiation) is in fact being reduced. For example, in the case of Murska Sobota the C_z value increased by 3.7% points, while C_{sn} reduced by 1.7% points and C_{sh} increased by 5.4% points during the last 50 years. The only exception to the described trend is the location of Portorož, where the C_z value slightly decreased by 0.9% points, mainly due to the 1.6% point increase in the V value (i.e. need for intensive ventilation and/or high thermal mass), which also testifies to the increase in ambient air temperatures over the analysed time period. The calculated values of S (i.e. shading needed) are on the rise even in Rateče, the coldest of the analysed locations. There, the S value tripled, from 1.8% in 1966–1975 to 5.6% for the last decade (2006–2015). Similar results are also evident for other locations. Thus, the importance of passive strategies for the reduction of overheating increases with a concurrent reduction in the importance of solar heating of buildings. The latter was also illustrated with the analysis of global



Murska Sobota 2006-2015

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
V	0.0	0.0	0.0	0.0	0.0	0.0	**9.6**	0.0	0.0	0.0	0.0	0.0
C_{sh}	0.0	0.0	0.0	0.0	**8.5**	**43.2**	**46.7**	**54.8**	**12.6**	0.0	0.0	0.0
C_{sn}	0.0	0.0	0.0	**28.3**	**29.5**	**5.7**	0.0	0.0	**26.0**	**15.7**	0.0	0.0
R	0.0	0.0	**62.7**	**71.7**	**62.0**	**51.1**	**43.7**	**45.2**	**61.4**	**56.4**	0.0	0.0
H	**100.0**	**100.0**	**37.3**	0.0	0.0	0.0	0.0	0.0	0.0	**27.9**	**100.0**	**100.0**
S	0.0	0.0	0.0	0.0	**8.5**	**43.2**	**53.6**	**54.8**	**12.6**	0.0	0.0	0.0

Murska Sobota 1966-1975

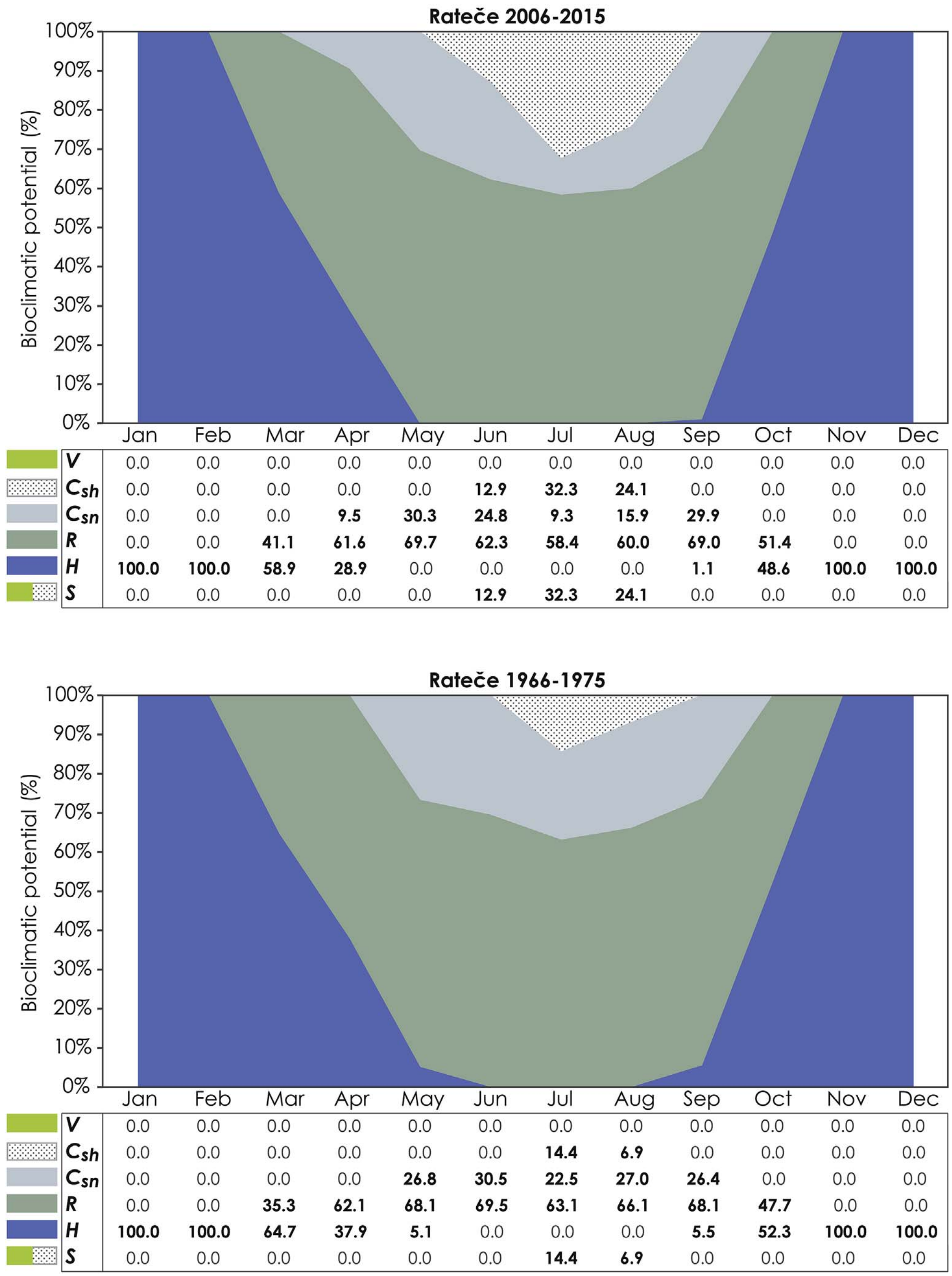
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
V	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
C_{sh}	0.0	0.0	0.0	0.0	0.0	**23.1**	**41.6**	**35.8**	0.0	0.0	0.0	0.0
C_{sn}	0.0	0.0	0.0	**23.2**	**33.7**	**15.1**	**4.6**	**6.4**	**31.2**	**11.8**	0.0	0.0
R	0.0	0.0	**56.7**	**70.2**	**66.3**	**61.8**	**53.8**	**57.8**	**68.8**	**52.4**	0.0	0.0
H	**100.0**	**100.0**	**43.3**	**6.6**	0.0	0.0	0.0	0.0	0.0	**35.8**	**100.0**	**100.0**
S	0.0	0.0	0.0	0.0	0.0	**23.1**	**41.6**	**35.8**	0.0	0.0	0.0	0.0

Fig. 5. Monthly breakdown of the bioclimatic potential for the location of Murska Sobota, during the periods of 1966–1975 (bottom) and 2006 to 2015 (top). V – high thermal mass and/or natural ventilation and shading needed, C_{sh} – comfort achieved with shading, C_{sn} – comfort achieved with solar irradiation, R – potential for passive solar heating, H – no potential for passive solar heating, $S = V + C_{sh}$ – shading needed.

climate trends by Li et al. [62]. Furthermore, Ascione [52] emphasised the increasing importance of passive cooling technologies for mitigating global warming-induced overheating of buildings. The described trend is in contradiction to the prevailing view on building design – that buildings located in Central European locations with temperate climate, such as continental part of Slovenia, should be optimized solely for passive solar utilization. The same goes for the bioclimatic solutions found in vernacular architecture, as these were adapted to considerably different climatic conditions than those that are dominant today.

Moreover, if the above described trends are used for future predictions applying linear extrapolation for the upcoming two decades (2016–2025 and 2026–2035), the increased importance of overheating protection measures becomes even more evident (Table 4). In this way, the forecasted yearly period of S is increased most in Murska Sobota, where its value is predicted to rise up to 19.4% (2026–2035), which represents a 4.8% point increase in comparison to the years between 2006 and 2015. In comparison to the first analysed decade, with such trend the period of year when shading is needed will increase by 11% points. Similar results are true for the comparable locations of Novo mesto ($S = 17.7\%$) and Ljubljana ($S = 18.5\%$), while smaller increase is projected for Portorož ($S = 24.4\%$) and Rateče ($S = 8.6\%$).

These predictions of shifts in bioclimatic potential indicate that the most affected are and will be buildings situated at locations with temperate climate. In case of Slovenia these locations coincide with the most urbanised parts of the country, which means that a large portion of the existing building stock will be affected. As a consequence, an increase of cooling and a decrease of heating energy demand can be expected. Similar conclusions were drawn by Huang and Hwang [63], who demonstrated on a case of residential buildings in Taiwan that substantial increase in cooling energy use will occur due to the effect of global warming. However, it is unclear if the potential increment of cooling load will be nullified by the reduction in heating demand. The



Rateče 2006-2015

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
V	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
C_{sh}	0.0	0.0	0.0	0.0	0.0	**12.9**	**32.3**	**24.1**	0.0	0.0	0.0	0.0
C_{sn}	0.0	0.0	0.0	**9.5**	**30.3**	**24.8**	**9.3**	**15.9**	**29.9**	0.0	0.0	0.0
R	0.0	0.0	**41.1**	**61.6**	**69.7**	**62.3**	**58.4**	**60.0**	**69.0**	**51.4**	0.0	0.0
H	**100.0**	**100.0**	**58.9**	**28.9**	0.0	0.0	0.0	0.0	**1.1**	**48.6**	**100.0**	**100.0**
S	0.0	0.0	0.0	0.0	0.0	**12.9**	**32.3**	**24.1**	0.0	0.0	0.0	0.0

Rateče 1966-1975

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
V	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
C_{sh}	0.0	0.0	0.0	0.0	0.0	0.0	**14.4**	**6.9**	0.0	0.0	0.0	0.0
C_{sn}	0.0	0.0	0.0	0.0	**26.8**	**30.5**	**22.5**	**27.0**	**26.4**	0.0	0.0	0.0
R	0.0	0.0	**35.3**	**62.1**	**68.1**	**69.5**	**63.1**	**66.1**	**68.1**	**47.7**	0.0	0.0
H	**100.0**	**100.0**	**64.7**	**37.9**	**5.1**	0.0	0.0	0.0	**5.5**	**52.3**	**100.0**	**100.0**
S	0.0	0.0	0.0	0.0	0.0	0.0	**14.4**	**6.9**	0.0	0.0	0.0	0.0

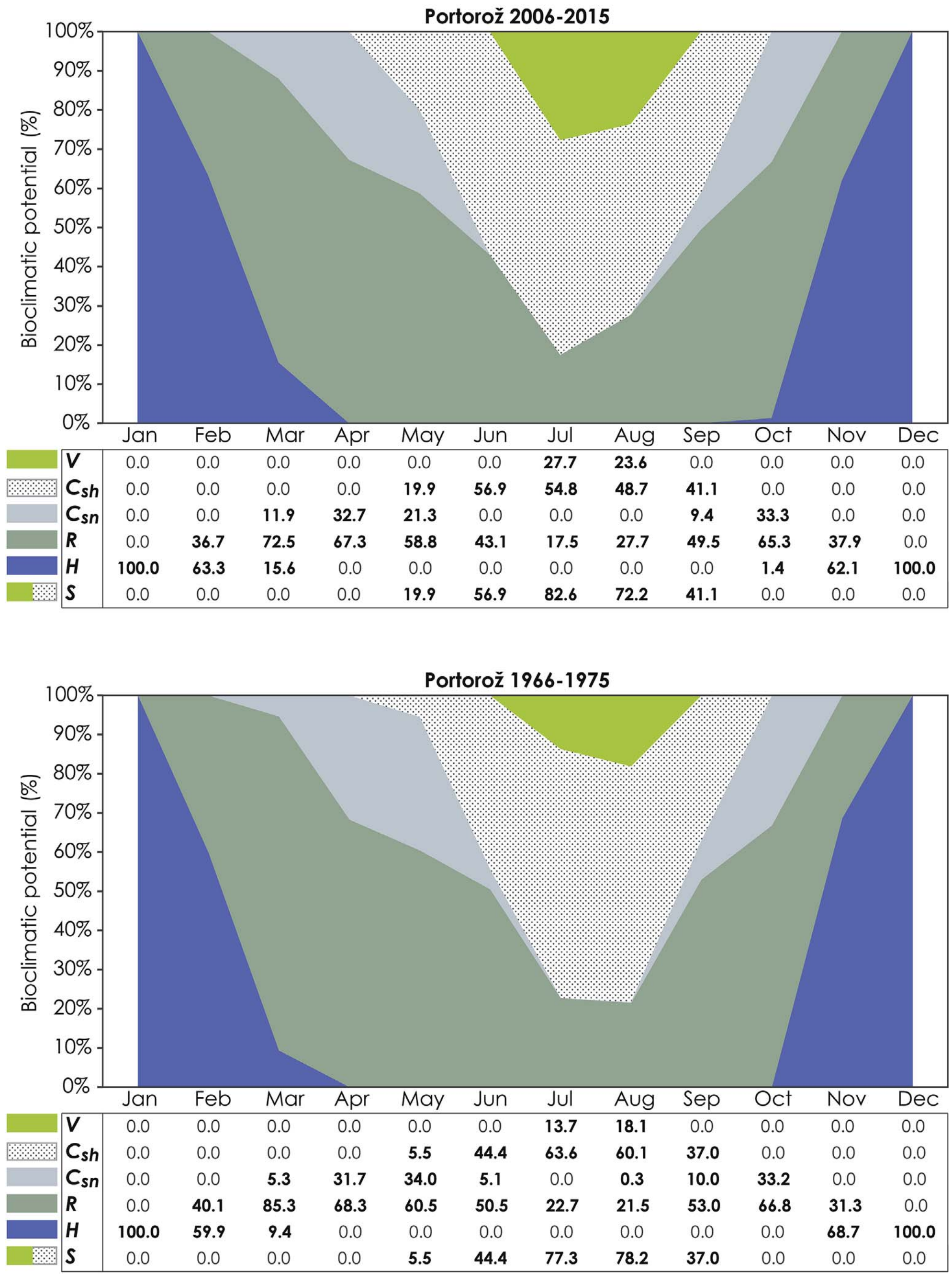
Fig. 6. Monthly breakdown of the bioclimatic potential for the location of Rateče, during the periods of 1966–1975 (bottom) and 2006 to 2015 (top). V – high thermal mass and/or natural ventilation and shading needed, C_{sh} – comfort achieved with shading, C_{sn} – comfort achieved with solar irradiation, R – potential for passive solar heating, H – no potential for passive solar heating, $S = V + C_{sh}$ – shading needed.

latter is more likely to occur in colder climates (e.g. type D of Köppen-Geiger classification), as it was shown by Li et al. [62]. In order to clarify the exposed questions, present and future energy performances of one bioclimatic and one non-bioclimatic building were simulated and are presented in section 3.2.

3.2. Energy performance evaluation

The results of bioclimatic potential analysis showed that the most substantial change can be expected for the location of Murska Sobota (Tables 3 and 4). Therefore, the current and the predicted future energy performances of the selected two residential buildings (Fig. 3) were simulated at that location. Moreover, the location of Murska Sobota also exhibits similar climatic characteristics and changes in bioclimatic potential as the locations of Ljubljana and Novo mesto. The calculations were performed using EnergyPlus and input parameters described in section 2.3. The results for the 2006–2015 decade were used as a baseline and compared with the predicted future energy consumption for the years 2020 and 2050. The energy performance analysis considered the energy use for heating (Q_{NH}) and cooling (Q_{NC}) normalised per m^2 of floor area. Additionally, the cumulative ($Q_{NT} = Q_{NH} + Q_{NC}$) energy use was recorded. Energy performance of both analysed buildings was evaluated with respect to the influence of building envelope thermal characteristics and window optical characteristics (i.e. OLD, NEW envelope type), as well as the selected bioclimatic strategies (i.e. shading, window orientation and area, compactness of building form) present in the modelled buildings.

Results presented in Fig. 8 and Tables 5–7 show that the identified change in the climatic conditions and corresponding bioclimatic potential of the location will have a substantial impact on the future energy performance of the selected buildings. Predictably, in the coming decades a significant reduction in heating energy demand can be



Portorož 2006-2015

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
V	0.0	0.0	0.0	0.0	0.0	0.0	**27.7**	**23.6**	0.0	0.0	0.0	0.0
C_{sh}	0.0	0.0	0.0	0.0	**19.9**	**56.9**	**54.8**	**48.7**	**41.1**	0.0	0.0	0.0
C_{sn}	0.0	0.0	**11.9**	**32.7**	**21.3**	0.0	0.0	0.0	**9.4**	**33.3**	0.0	0.0
R	0.0	**36.7**	**72.5**	**67.3**	**58.8**	**43.1**	**17.5**	**27.7**	**49.5**	**65.3**	**37.9**	0.0
H	**100.0**	**63.3**	**15.6**	0.0	0.0	0.0	0.0	0.0	0.0	**1.4**	**62.1**	**100.0**
S	0.0	0.0	0.0	0.0	**19.9**	**56.9**	**82.6**	**72.2**	**41.1**	0.0	0.0	0.0

Portorož 1966-1975

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
V	0.0	0.0	0.0	0.0	0.0	0.0	**13.7**	**18.1**	0.0	0.0	0.0	0.0
C_{sh}	0.0	0.0	0.0	0.0	**5.5**	**44.4**	**63.6**	**60.1**	**37.0**	0.0	0.0	0.0
C_{sn}	0.0	0.0	**5.3**	**31.7**	**34.0**	**5.1**	0.0	**0.3**	**10.0**	**33.2**	0.0	0.0
R	0.0	**40.1**	**85.3**	**68.3**	**60.5**	**50.5**	**22.7**	**21.5**	**53.0**	**66.8**	**31.3**	0.0
H	**100.0**	**59.9**	**9.4**	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**68.7**	**100.0**
S	0.0	0.0	0.0	0.0	**5.5**	**44.4**	**77.3**	**78.2**	**37.0**	0.0	0.0	0.0

Fig. 7. Monthly breakdown of the bioclimatic potential for the location of Portorož, during the periods of 1966–1975 (bottom) and 2006 to 2015 (top). V – high thermal mass and/or natural ventilation and shading needed, C_{sh} – comfort achieved with shading, C_{sn} – comfort achieved with solar irradiation, R – potential for passive solar heating, H – no potential for passive solar heating, $S = V + C_{sh}$ – shading needed.

Table 4
Predicted future values of S (i.e. $V + C_{sh}$) – shading needed, C_{sh} – comfort achieved with shading, C_{sn} – comfort achieved with solar irradiation and the ratio between C_{sh}/C_{sn} for 2016–2025 and 2026–2035.

		Portorož	Ljubljana	Novo mesto	Murska Sobota	Rateče
2016–2025	S (%)	23.4	16.9	16.1	17.2	7.2
	C_{sh} (%)	17.6	14.3	14.0	14.1	5.6
	C_{sn} (%)	8.8	8.4	9.3	8.7	9.8
	C_{sh}/C_{sn}	1.99	1.69	1.51	1.62	0.57
2026–2035	S (%)	24.4	18.5	17.7	19.4	8.6
	C_{sh} (%)	17.5	15.3	15.3	15.7	6.6
	C_{sn} (%)	8.4	8.0	9.2	8.2	9.5
	C_{sh}/C_{sn}	2.10	1.92	1.67	1.91	0.70

expected for the BC building as well as for the non-BC building (Fig. 8). In the case of building envelope labelled as NEW (i.e. thermally insulated in accordance with current Slovenian legislation), the Q_{NH} for the BC building is projected to decrease by 15% (4.52 kWh/m^{2}a) and 26% (7.64 kWh/m^{2}a) by 2020 and 2050, respectively, in comparison to the current state (29.47 kWh/m^{2}a). In the case of the non-BC building the reduction is slightly larger with 19% (8.08 kWh/m^{2}a) in 2020 and 31% (13.23 kWh/m^{2}a) in 2050, while the current energy use for heating is 43.29 kWh/m^{2}a. Similar trend can also be noted for the thermal characteristics of the OLD envelope (Fig. 8). Due to the predicted increase in the need for overheating prevention, a substantial increase in cooling energy use can also be expected. This is confirmed by energy simulations, where the comparison of shaded and unshaded building models (Fig. 8) shows that by 2050 both buildings will become cooling dominated. For example, the Q_{NC} for the shaded BC building with NEW envelope type is projected to rise from 6.70 kWh/m^{2}a

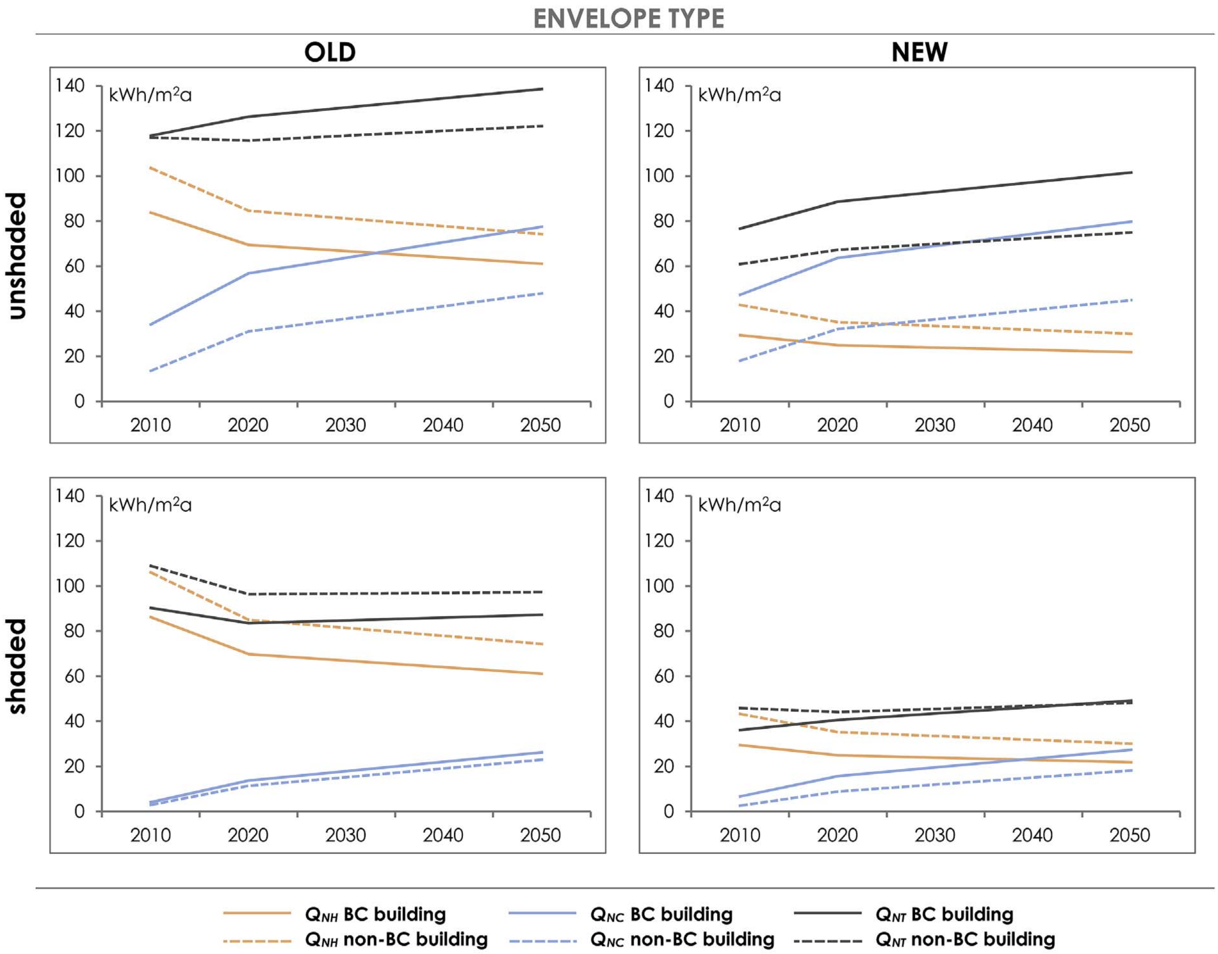


Fig. 8. Trends of present and future predicted energy consumption of the analysed BC and non-BC buildings.

(2006–2015 period) to 27.32 kWh/m^{2}a in 2050, which is a 308% increase. The impact is even greater in the case of unshaded buildings, where the BC building is currently already declared as a cooling dominated (Table 5). For the non-BC building the impact of climatic change on cooling energy use is significantly smaller due to the smaller area of windows and their orientation. The Q_{NC} for the shaded non-BC building with NEW envelope currently amounts to 2.58 kWh/m^{2}a, while the predicted value for 2020 is 8.89 kWh/m^{2}a and 18.17 kWh/m^{2}a for the year 2050.

Inspecting the value of Q_{NT} in Fig. 8, a trend emerges, whereas the cumulative energy use for all cases increases. In the example of buildings with NEW envelope and shaded windows (i.e. the most realistic configuration) the value of Q_{NT} in 2050 is in fact almost the same for the BC (49.15 kWh/m^{2}a) as for the non-BC building (48.23 kWh/m^{2}a). The latter demonstrates that the advantages of the BC building that was designed in order to enable better usage of solar gains during heating season will be nullified by the changes in climatic conditions and increase in cooling energy use. The only exceptions to the trend of increasing Q_{NT} are the shaded BC and non-BC buildings with OLD envelope, where the cumulative energy in 2050 (87.31 kWh/m^{2}a for the BC building and 97.28 kWh/m^{2}a for the non-BC building) is smaller than at present (90.33 kWh/m^{2}a for the BC building and 108.94 kWh/m^{2}a for the non-BC building). This is a consequence of the relatively small increase in the Q_{NC} as a result of shading and higher thermal transmittance of the building envelope, while at the same time the Q_{NH} is substantially reduced due to the increase in winter time ambient temperatures (Fig. 8).

3.2.1. *Comments on the results of energy performance evaluation*

The results of energy performance analysis of the two selected single family buildings exposed the trend of increased importance of cooling at the selected location of Murska Sobota in the upcoming decades. The increase in the cooling energy use will also result in the increase of the cumulative energy use of the analysed buildings. These findings correspond to the predictions of the bioclimatic potential evaluation presented in section 3.1. Similar conclusions were also drawn by Pierangioli et al. [43] on a case study conducted in central Italy for residential (single and multi-unit dwellings) as well as commercial office buildings. A comparable study conducted for the climate of the Netherlands by van Hooff et al. [40] also showed that due to climate change the number of overheating hours inside residential buildings will increase and consequentially the cooling energy use as well. Both referenced studies investigated the effect of different passive design measures (e.g. shading, increased ventilation, increased albedo of external building envelope, etc.) to counteract the impact of climate change on building energy performance. However, these measures were investigated on a typical building and not on buildings with bioclimatic features, which was the focus of the presented energy performance study. As it was described in the previous section, bioclimatic buildings (e.g. BC building) designed for temperate Central European climate presently outperform conventional buildings (Fig. 8 and Table 5). Nevertheless, this advantage will be reduced or completely eliminated in the forthcoming decades, as the relative importance of different design strategies will shift from passive heating (e.g. large windows, low thermal transmittance of building envelope, etc.) to prevention of overheating (e.g. shading of windows, smaller windows, increased

Table 5
Energy performance of the analysed buildings conducted under the present (2006–2015) climatic conditions for the location of Murska Sobota.

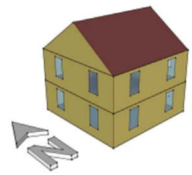
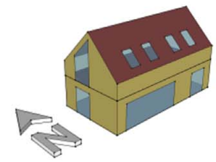
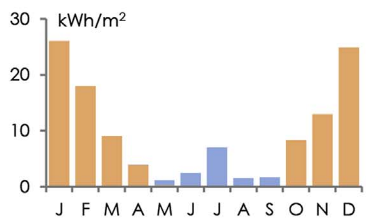
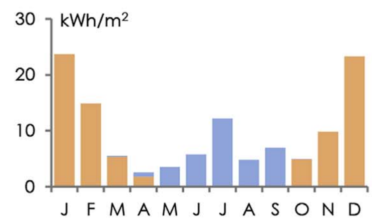
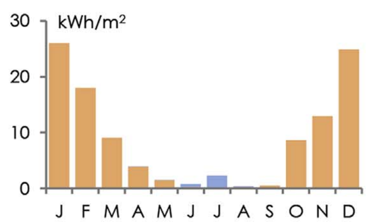
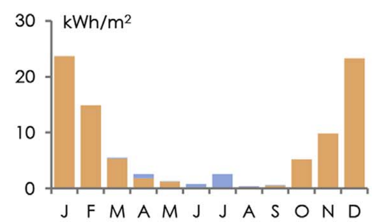
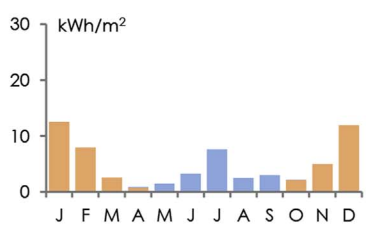
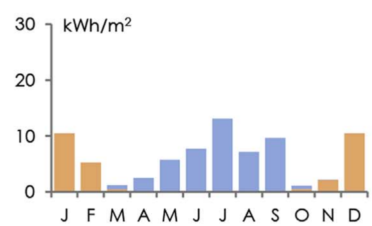
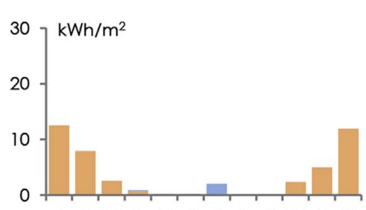
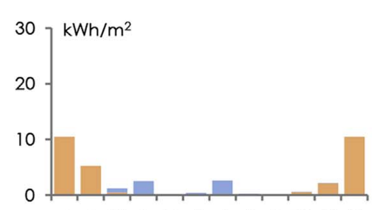
2006 – 2015 period				**non-BC building**	**BC building**
					
Envelope type					
OLD	**unshaded**	Q_{NH}	(kWh/m²a)	103.49	83.74
		Q_{NC}	(kWh/m²a)	13.55	34.17
		Q_{NT}	(kWh/m²a)	117.04	117.91
					
	shaded	Q_{NH}	(kWh/m²a)	106.03	86.21
		Q_{NC}	(kWh/m²a)	2.91	4.12
		Q_{NT}	(kWh/m²a)	108.94	90.33
					
NEW	**unshaded**	Q_{NH}	(kWh/m²a)	42.78	29.35
		Q_{NC}	(kWh/m²a)	18.10	47.27
		Q_{NT}	(kWh/m²a)	60.88	76.62
					
	shaded	Q_{NH}	(kWh/m²a)	43.29	29.47
		Q_{NC}	(kWh/m²a)	2.58	6.70
		Q_{NT}	(kWh/m²a)	45.88	36.16
					
		Legend		Q_{NH}	Q_{NC}

Table 6
Energy performance of the analysed buildings conducted under the predicted future (2020) climatic conditions for the location of Murska Sobota.

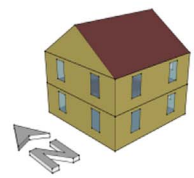
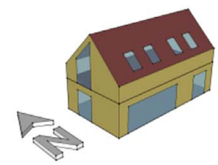
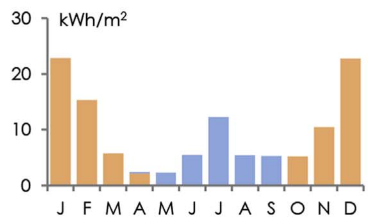
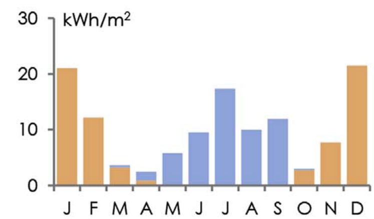
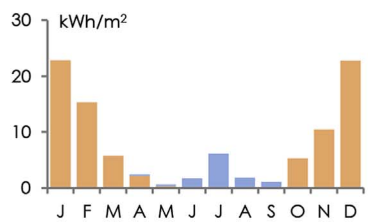
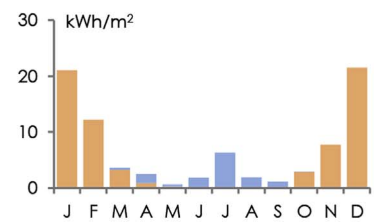
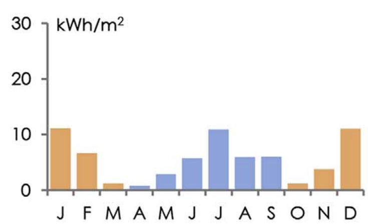
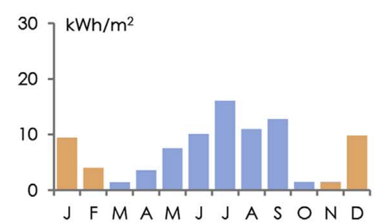
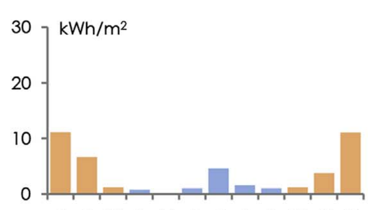
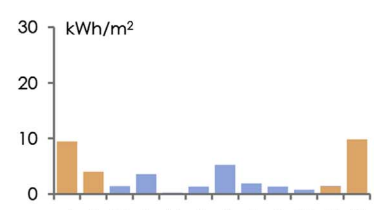
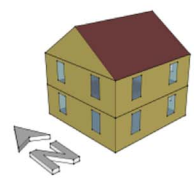
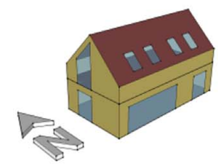
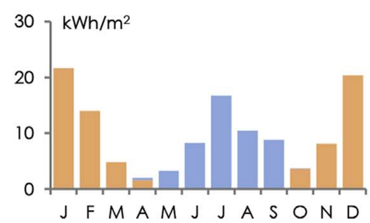
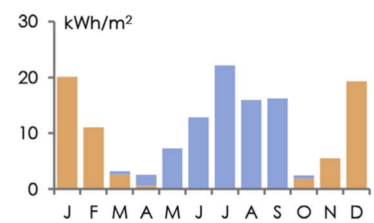
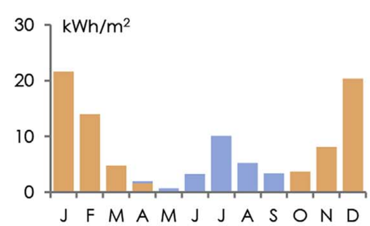
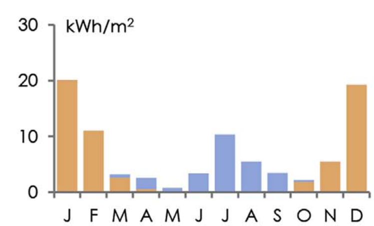
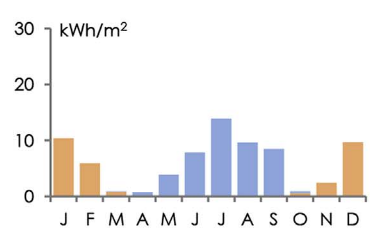
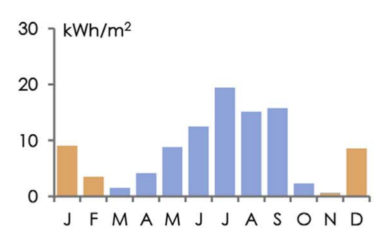
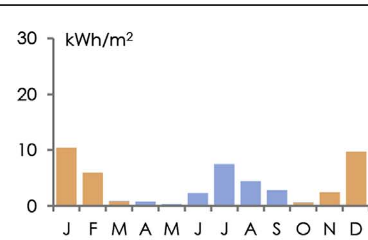
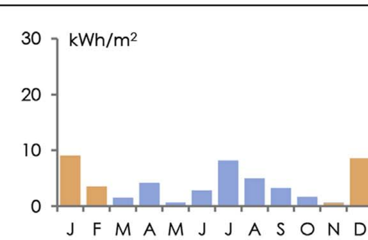
2020 prediction				**non-BC building**	**BC building**
Envelope type					
OLD	**unshaded**	Q_{NH}	(kWh/m²a)	84.63	69.47
		Q_{NC}	(kWh/m²a)	31.10	56.85
		Q_{NT}	(kWh/m²a)	115.73	126.32
					
	shaded	Q_{NH}	(kWh/m²a)	85.04	69.81
		Q_{NC}	(kWh/m²a)	11.37	13.71
		Q_{NT}	(kWh/m²a)	96.41	83.52
					
NEW	**unshaded**	Q_{NH}	(kWh/m²a)	35.14	24.95
		Q_{NC}	(kWh/m²a)	32.14	63.68
		Q_{NT}	(kWh/m²a)	67.28	88.62
					
	shaded	Q_{NH}	(kWh/m²a)	35.21	24.95
		Q_{NC}	(kWh/m²a)	8.89	15.68
		Q_{NT}	(kWh/m²a)	44.09	40.63
					
	Legend			Q_{NH}	Q_{NC}

Table 7
Energy performance of the analysed buildings conducted under the predicted future (2050) climatic conditions for the location of Murska Sobota.

2050 prediction				non-BC building	BC building
					
Envelope type					
OLD	**unshaded**	Q_{NH}	(kWh/m²a)	74.22	61.06
		Q_{NC}	(kWh/m²a)	47.93	77.51
		Q_{NT}	(kWh/m²a)	122.15	138.57
					
	shaded	Q_{NH}	(kWh/m²a)	74.32	61.14
		Q_{NC}	(kWh/m²a)	22.96	26.17
		Q_{NT}	(kWh/m²a)	97.28	87.31
					
NEW	**unshaded**	Q_{NH}	(kWh/m²a)	30.04	21.83
		Q_{NC}	(kWh/m²a)	44.92	79.72
		Q_{NT}	(kWh/m²a)	74.96	101.55
					
	shaded	Q_{NH}	(kWh/m²a)	30.06	21.83
		Q_{NC}	(kWh/m²a)	18.17	27.32
		Q_{NT}	(kWh/m²a)	48.23	49.15
					
		Legend		Q_{NH}	Q_{NC}

natural ventilation, etc.). These conclusions indicate that in order to take advantage of local climatic conditions, the current design paradigm should adapt to the predicted future trends. The stated is especially important when selecting the bioclimatic design strategies to be implemented in the design of bioclimatic buildings. The selected strategies should be thoroughly evaluated, not only with respect to the current or past climate, but also to the future state.

To summarise, the main implications of the conducted analysis in the context of building design are twofold. Firstly, with increased and rising importance of building overheating prevention (e.g. shading, intensive natural ventilation), thermal conditions in the existing building stock are called into question, since these buildings were designed decades ago. Because designers did not put emphasis on the overheating protection due to different climatic conditions, it can be argued that in such buildings thermal discomfort is on the rise [64] due to higher air temperatures. Consequentially, retrofit installation of mechanical cooling can become an issue in view of ever greater importance of building energy performance [64,65]. Secondly, the results show that any replication of current bioclimatic solutions, which are predominantly focused on passive heating, into contemporary buildings without critical evaluation is a risky undertaking. Even in the short time span of the analysed 50 years, substantial differences in bioclimatic potential and corresponding dominant passive solutions were identified. Additionally, the executed simulations for the predicted future energy performance of buildings confirm that current solutions in bioclimatic building design will become irrelevant or at least extremely inefficient by 2050. Therefore, it is necessary for the designers to critically reassess the presumptions of crucial bioclimatic elements at a specific location using current as well as predicted climatic data and to base their design solutions on such data. In this respect, even the most basic presumption of energy efficient building design should be reassessed. For instance, the notion of reducing building envelope thermal transmittance might become less important in the future when heating energy consumption will become smaller. In this respect, the proposition of Andrić et al. [44] that by 2050 building envelopes will have extremely low U values (e.g. $U = 0.08$ W/m^{2}K) might not present an optimal solution, at least not for the locations in the temperate climate. Therefore, the belief that thermal insulation should be ranked at the top of the most effective investments for energy savings in buildings [66] should be re-evaluated in the light of future climate change.

Furthermore, the changed ratio between heating and cooling energy use of buildings will also have a substantial influence on the supply energy mix of such buildings. With the increased cooling energy demand, the use of electricity would grow substantially. This would increase the load on the electrical power supply systems worldwide and increase CO_2 emissions because of the much higher carbon footprint of electricity [31,45]. In the final analysis, this is of special importance in case of the use of NEW envelope and shaded windows, where in 2050 the total energy consumption of BC and non-BC buildings will practically be the same. However, the BC building will have a noticeably higher cooling energy use and thus also a greater electricity consumption. It can be concluded that an overall environmental impact of such building will be larger than the impact of the non-BC building.

4. Conclusions

The results presented in the paper show the importance of climate analysis in the contemporary bioclimatic building design. The latter must be consistently adapted in order to facilitate appropriate functioning, not only for the current conditions but also for the future. Moreover, the existing buildings, the reaction of which to climate change is usually suppressed, should be renovated in accordance with the findings of this study. Thus, overheating prevention measures should be practiced in energy renovation actions as well. Although the legislation in this field is mostly focused on heating season and heat-loss prevention (e.g. prescribed maximum thermal transmittance), architects, engineers and other stakeholders in the building industry must be aware that in the future climate-adapted buildings in temperate climatic zones will have to confront overheating. In this context, the results showed that the shading season is expanding even towards the transitional months, such as April and October. These findings are of particular interest to construction industry, because bioclimatic buildings in temperate climate zone are predominantly designed on the basis of heating season and will not adapt to the future trends without deliberate interventions. Accordingly, the findings of this study suggest a need for a conceptual leap in bioclimatic building design in order to keep designers in step with the current and future challenges posed by climate change. This is especially important as higher level of thermal discomfort can occur in the future due to overheating of buildings.

Policy addressing building design and building energy renovations should be supplemented to encourage the incorporation of passive design strategies into buildings. Primarily, current focus on heating energy consumption reduction in buildings should be critically evaluated and supplemented in accordance to the predicted future trends. Only with such approach, bioclimatically designed buildings will become resilient buildings and the design solutions of today will also be sustainable in the future.

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Strategy for achieving long-term energy efficiency of European single-family buildings through passive climate adaptation

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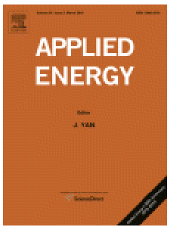

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Strategy for achieving long-term energy efficiency of European single-family buildings through passive climate adaptation

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HIGHLIGHTS

- Low energy use of single-family buildings can be assured solely by passive design.
- Passive adaptation only partly counterbalances climate change effects on energy use.
- Total energy use will decrease in cold and temperate and increase in warm climates.
- The most effective long-term climate adaptation measure is applying smaller windows.
- New buildings should be designed according to mid-term optima (2020/2050 period).

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ABSTRACT

The presented study aims to clarify the implications of passive design measures on heating and cooling energy use of single-family residential buildings under European representative climates. In order to address this matter, different values of thermal transmittance (opaque and transparent), window to floor ratio, window distribution, shape factor, diurnal heat storage capacity, external opaque surface solar absorptivity and natural ventilation cooling rates were combined in 496,800 building energy models, which were simulated at eight locations. Because buildings are in use for many decades, the energy use simulations were made considering the projected climate change up to the end of the 21st century. The results delivered a set of the most effective passive design measures for achieving low energy use in buildings regarding climate type and period. A lower window to floor ratio was identified as the most universally applicable design measure to counterbalance the projected effect of a warming climate. In contrast, other measures vary according to climate type and studied period. Furthermore, it was concluded that it is difficult to neutralise the projected climate change effects on buildings' energy use, even when applying the best performing combination of passive design measures. However, reasonably low energy use can still be assured solely by passive building design, especially in oceanic, warm, and some temperate climate locations. Therefore, the identified trends in energy use and passive design measures represent the foundation for strategies and guidelines aimed at future-proof energy-efficient buildings.

1. Introduction

The resilience of buildings, especially in the context of climate adaptation, has lately become a significant issue in the field of building energy efficiency. Energy performance of buildings can be improved by increasing the efficiency of passive (e.g. building shape, building

Abbreviations: HVAC, Heating, Ventilation and Air Conditioning; PV, photovoltaic; IPCC, Intergovernmental Panel on Climate Change; WWR, window to wall ratio (%); SRES, Special Report on Emissions Scenarios; RCP, Representative Concentration Pathways; SHGC, solar heat gain coefficient (-); f_0, shape factor (m^{-1}); WFR, window to floor ratio (%); W_{dis}, window distribution; U_W, window thermal transmittance (W/m^2K); U_O, opaque envelope thermal transmittance (W/m^2K); DHC, diurnal heat storage capacity (kJ/m^2K); α_{sol}, external surface solar absorptivity (-); NV_C, summer natural ventilation cooling rate (h^{-1} or ACH); Q_{NH}, annual energy use for heating per floor area (kWh/m^2); Q_{NC}, annual energy use for cooling per floor area (kWh/m^2); Q_T, annual total energy use per floor area ($Q_{NH} + Q_{NC}$) (kWh/m^2); ASHRAE, American Society of Heating, Refrigerating and Air-Conditioning Engineers; EPW, EnergyPlus weather file; IWEC, International Weather for Energy Calculation.

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envelope design, etc.) or active (e.g. HVAC system, PV systems, etc.) building elements and systems. According to Olgyay [1], Almusaed [2] and Košir [3], the bioclimatic design concept is often used to optimise a building's passive elements in order to adapt it to the relevant climate conditions. Through bioclimatic design and the use of passive building design measures, a higher level of building energy efficiency and indoor thermal comfort can be achieved [4,5]. An attractive feature of some passive building measures, such as building orientation or natural ventilation, is that they generate little or no additional costs for the building project during the design and construction. However, for other passive measures, cost-effectiveness analysis should be executed in order to validate their implementation regarding application costs and energy savings. For this reason, the bioclimatic approach is an essential aspect of cost-optimal energy-efficient solutions.

On the other hand, passive building elements are rigid and difficult to modify after the building has been constructed. For example, changes to the building shape, window distribution or glazing area require substantial interventions in the building or its envelope. Therefore, they are challenging to implement and usually costly. Consequentially, passive building elements represent a substantial lock-in risk for buildings if they are not appropriately designed and evaluated in terms of climate and the intended building use.

In general, passive measures can be divided into four main strategy groups: heat retention, heat admission, heat exclusion and heat dissipation [3]. The selection of appropriate passive design strategies should always depend on climate and location characteristics, as emphasised by Szokolay [6], Košir [3] and Pajek and Košir [7]. At this point, it is essential to understand that with the current trend of global warming, many of the bioclimatic measures that used to be a cost-optimal solution at a specific location might no longer be considered as such. To illustrate, with increasing atmospheric temperatures, at some locations, heat exclusion measures (e.g. smaller glazing area, efficient shading, etc.) can become more important than heat admission measures (e.g. large glazing area for passive solar heating) that were better suited for a colder climate of the past. The worrying projected effects of global warming for the 21st century could be compensated, at least to some extent, by appropriate and informed climate-adapted building design, considering the trend of projected climate change.

1.1. Theoretical framework

In order for bioclimatic building design to be effective, climate adaptation towards future climatic conditions must be considered. Skarbit et al. [8] state that the observations and climate models demonstrate that the climate will become warmer and dryer during the current century. However, the extent of the projected change depends on the climate change scenario used in the models. Several scenarios have been introduced by the Intergovernmental Panel on Climate Change (IPCC) [9], covering various global projected technological, demographic, economic, social and political developments. These scenarios can be grouped into SRES (Special Report on Emissions Scenarios) scenarios introduced in the Third [10] and Fourth [11] IPCC's Assessment Reports and the RCP (Representative Concentration Pathways) scenarios from the Fifth [12] IPCC's Assessment Report. At the moment, it is quite uncertain which scenario will eventually unfold, if any [13]. However, observing the projected outcomes of the SRES and RCP groups of scenarios, it becomes evident that until the end of the 21st century, all the scenarios lead to a warmer future climate.

For this reason, weather file "morphing" methods have been developed to produce design weather data for use in building thermal response simulations that account for future climate change. Several examples of these methods, but not all, were presented by Jentsch et al. [14], Arima et al. [15], Belcher et al. [16], Soga [17] and Jiang et al. [18]. Morphing combines the observed weather data with climate change models [16]. For both RCP (e.g. Spinoni et al. [19]) and SRES (e.g. Berardi and Jafarpur [20]) scenarios, building energy simulations project a decrease in heating demand and increase in cooling demand of buildings. Even under optimistic climate scenarios (e.g. RCP2.6 – projecting a mean global surface temperature increase of 1 °C by the end of the century), the majority of cities will most likely experience a considerably different climate than today [21] or even extreme conditions that are not currently found in any existing major city, as stated by Bastin et al. [22].

Therefore, using projected future weather data is vital for studying climate change impact on buildings, as highlighted by Jiang et al. [18]. An essential view of the problem was presented by Zhou et al. [23], who highlighted that climate change has a geographically heterogeneous impact on the heating and cooling of buildings. Nevertheless, numerous studies have been conducted evaluating building energy performance against the projected future climate, and a consensus has been reached on the increase in cooling and a decrease in heating demand [24]. An example of such a study was presented by Flores-Larsen et al. [25] in Argentina for residential buildings. They showed a considerable decrease in energy need for heating and an increase in energy need for cooling of buildings. In this context, shading, reducing direct solar gains, and natural ventilation were presented as the most effective design measures to counteract the climate change effects. Furthermore, Andrić et al. [26] showed that heating decrease in warm climates was more significant than in cold climates, and Zhai and Helman [27] stated that the total energy use of buildings would increase, predominantly due to the large increase in cooling energy demand. Kishore [28] also drew similar conclusions to the above-stated ones on a case of a typical residential building evaluated under climate change projections for the 21st century under five main climate types of India. It was demonstrated that passive design strategies could reduce the projected annual cooling load by approximately 50–60% for India's residential buildings.

Concerning the passive and active measures applied to a typical Mediterranean residential building under various climate change scenarios, Pérez-Andreu et al. [29] stated that ventilation has the most negligible impact among several design parameters. In contrast, increased thermal insulation and airtightness will have a more significant effect on future energy performance. Similarly, Rodrigues and Fernandes [30] executed a statistical comparison of random two-storey family building geometries with diverse U values for current and future projected climates in sixteen Mediterranean locations. Importantly, they found that in the future further reduction in U values would continue to be a beneficial design measure for several locations. Future energy needs were also estimated by Ciancio et al. [31] for a hypothetical three-storey residential building placed in 19 European cities. They highlighted that heating energy tends to decrease in northern cities while cooling energy use is expected to increase in southern Europe. Gercek and Arsan [32] stated for the case of Turkey that the most critical parameters concerning the energy performance of residential buildings are related to the transparent surfaces of building envelope. In like manner, Harkouss et al. [33] showed that for the current climate, the optimisation of passive design measures, namely window to wall ratio (WWR), U value and glazing type, for generic residential building results in using high levels of thermal insulation under cold and temperate climates (e.g. U = 0.2 W/m^2 K) and lower levels under hot climates (e.g. U = 0.6 W/m^2 K).

In line with the findings mentioned above, Moazami et al. [34] successfully introduced a robust approach to energy performance evaluation under projected climate change. Similarly, Shen et al. [35,36] proposed an optimisation method for building retrofit planning of a campus building in the US under climate change, for which more than a thousand Pareto fronts were obtained using variables as U value, glazing type, natural ventilation and air infiltration level, heating and cooling system efficiency, renewable energy systems implementation, etc. Although climate change effects were not taken into account, numerous studies in the field of building energy use and operation optimisation, presented by Robic et al. [37], Chiesa et al. [38], Gou et al. [39] and Ciardiello et al. [40], have produced encouraging results. In conclusion, the referenced studies emphasise that it is vital to include a large set of variables to optimise a building's energy performance as the identified critical parameters were certainly location-dependent.

1.2. Knowledge gap identification and study objective

As noted in the literature review, a building envelope's thermal resistance is known to be one of the most efficient and most resilient passive building approaches to reducing energy use in buildings [41,42]. Therefore, it is also quite common for the policymakers to set U values' upper limit for a building envelope and its components. At the same time, the energy efficiency of buildings can be further enhanced by applying additional passive design measures [43], which do not represent such a substantial financial investment as the implementation of a very thick thermal insulation (example of a study aiming at optimum insulation thickness was shown by Raimundo et al. [44]). Besides, Andrea et al. [45] exposed that homeowners are only aware of bioclimatic principles and that effective planning is needed to improve the residential sector's energy efficiency. As exposed by the above-referenced studies, the issue is widely researched. However, studies are typically focused on thermal retrofitting of specific commercial or residential buildings (e.g. Shen et al. [36]), aiming at the optimal specific solution (e.g. Shen et al. [35],), are performed with a limited set of variables (e.g. Robic et al. [37], Košir et al. [46]) or do not concern the climate change effects (e.g. Ciardiello et al. [40]). Therefore, a potential long-term contribution of passive design measures to reducing total energy use for heating and cooling of single-family residential buildings under various European climates is unknown. Accordingly, there is a considerable lack of guidelines and recommendations for implementing appropriate passive design measures concerning the building energy efficiency targets. Overall, the following study aims to present crucial information for the design of climate-adapted and energy-efficient buildings that strive for efficient energy use under current and projected climate conditions. A novel holistic approach was devised, applying a comprehensive parametric study in four climatically different intervals. The effectiveness of passive design measures was evaluated based on the resulting building energy performance. Additionally, the identified energy use trends and the corresponding impact of specific design decisions represent a basis for developing future-proof policy strategies and guidelines in the field of energy-efficient buildings.

2. Methods

The above-exposed knowledge gap was addressed by performing a comprehensive parametric study. The study was focused on the energy performance of single-family detached residential buildings because this building type represents a substantial share of the European residential building stock [47]. Furthermore, such buildings are also particularly suitable for a parametric study because passive design measures might be highly efficient in optimising their energy use due to high interaction with the climate since its thermal response is envelope dominated [48]. Moreover, residential buildings are typically in use for many decades without being substantially remodelled. Therefore, an integral part of the executed study was searching for the best performing sets of passive design measures concerning the projected climate change until the end of the 21st century.

Firstly, 496,800 building models were parametrically defined to achieve the paper's purpose, with each case representing a unique combination of passive building design measures defining characteristics of an individual building. As parametric variables, we chose three different building model geometries, ten values of opaque envelope thermal transmittance, ten values of window thermal transmittance with corresponding SHGCs, nine values of the window to floor ratio, two different window distributions, three different diurnal heat storage capacities, four values of external surface solar absorptivity and nine different summer natural ventilation cooling rates. A total number of 496,800 combinations was reached by combining these values in distinctive building models. However, an actual number of combinations would be 583,200 but in some building shapes very large south-concentrated window areas cannot be applied due to limited facade area. Then, each model was simulated under the climate of the eight selected locations in Europe given four distinctive periods: an original "present" climate file and three additional climate files considering climate change projections. Overall, this resulted in a total of 15,897,600 simulated cases. The annual energy use for heating and cooling was calculated for each model, and best performing models were identified through a 5th percentile analysis. An overview of the applied research methodology is presented in Fig. 1. A detailed description of the methods used can be found in the following subsections.

2.1. Energy models and definition of input data

For the performed analysis, a single-family residential building was selected as a basis for the devised energy models. According to the EU statistical data, the average floor area of a dwelling in the EU 28 is 42.56 m^2 per person [49]. In EU member states, a typical number of people per household is between 2 and 3, with an average of 2.3 people in 2019 [50]. Considering the EN 16798-1 standard [51], 43 m^2 of floor area per person, three persons per household, and a 25% addition to floor area due to technical and communication spaces resulted in 162 m^2 net floor area per modelled building. Therefore, the geometric characteristics of the model represent an average single-family detached residential building in the EU. The floor-to-floor height was set at 3 m so that the corresponding volume of the modelled buildings was 486 m^3.

Next, all building-related inputs were thoroughly defined to represent a distinctive design and operation of European buildings. Due to practical reasons for limiting the number of total possible combinations in the population and reducing the amount of modelled buildings to a manageable number, several building-related input parameters were set constant for all the models. Most of them are related to building use and operation and are presented in Table 1.

For the parametric study, the following variable input parameters were selected: opaque envelope thermal transmittance (U_O), window thermal transmittance (U_W) and the corresponding solar heat gain coefficient (SHGC), window to floor ratio (WFR), window distribution (W_{dis}), building shape expressed through shape factor (f_0), diurnal heat storage capacity (DHC), external surface solar absorptivity (α_{sol}) and summer natural ventilation cooling rate (NV_C) (see Table 2). The U_O parameter was simultaneously altered in each external building envelope element (slab-on-grade, external wall, roof). Unlike in the walls and roof, the DHC of ground floor slab-on-grade construction was not parametrised. There, a concrete slab (i.e. DHC = 146 kJ/m^2 K) was used in all of the cases. The paper aims at achieving universal comparability among the building models. Therefore, WFR was adopted as a variable parameter instead of WWR because the analysed building models with the same WFR also have the same total window area. However, models with the same WWR would not necessarily have the same total window area since also building shape was chosen as a variable parameter of the analysis. Furthermore, the aim of using parameter W_{dis} was to evaluate the impact of the focus either on passive solar heating (i.e. south concentrated windows) or ignoring it (i.e. equal area of windows at all orientations) and not the effect of glazing orientation. Information regarding individual parameter ranges, variable increments and the number of the resulting simulated cases is provided in Table 2; see also Fig. 1.

It should be noted that the chosen parameter ranges (Table 2) represent technologically feasible building solutions to the most extensive possible degree. However, the resulting specific cases might sometimes not be practical due to economic and/or buildability reasons. For example, U_O of 0.10 W/m^2 K will result in extremely thick thermal insulation, challenging to execute and questionable from the point of view of return on investment. Moreover, the selected studied passive measures represent the most universally applicable measures. They are

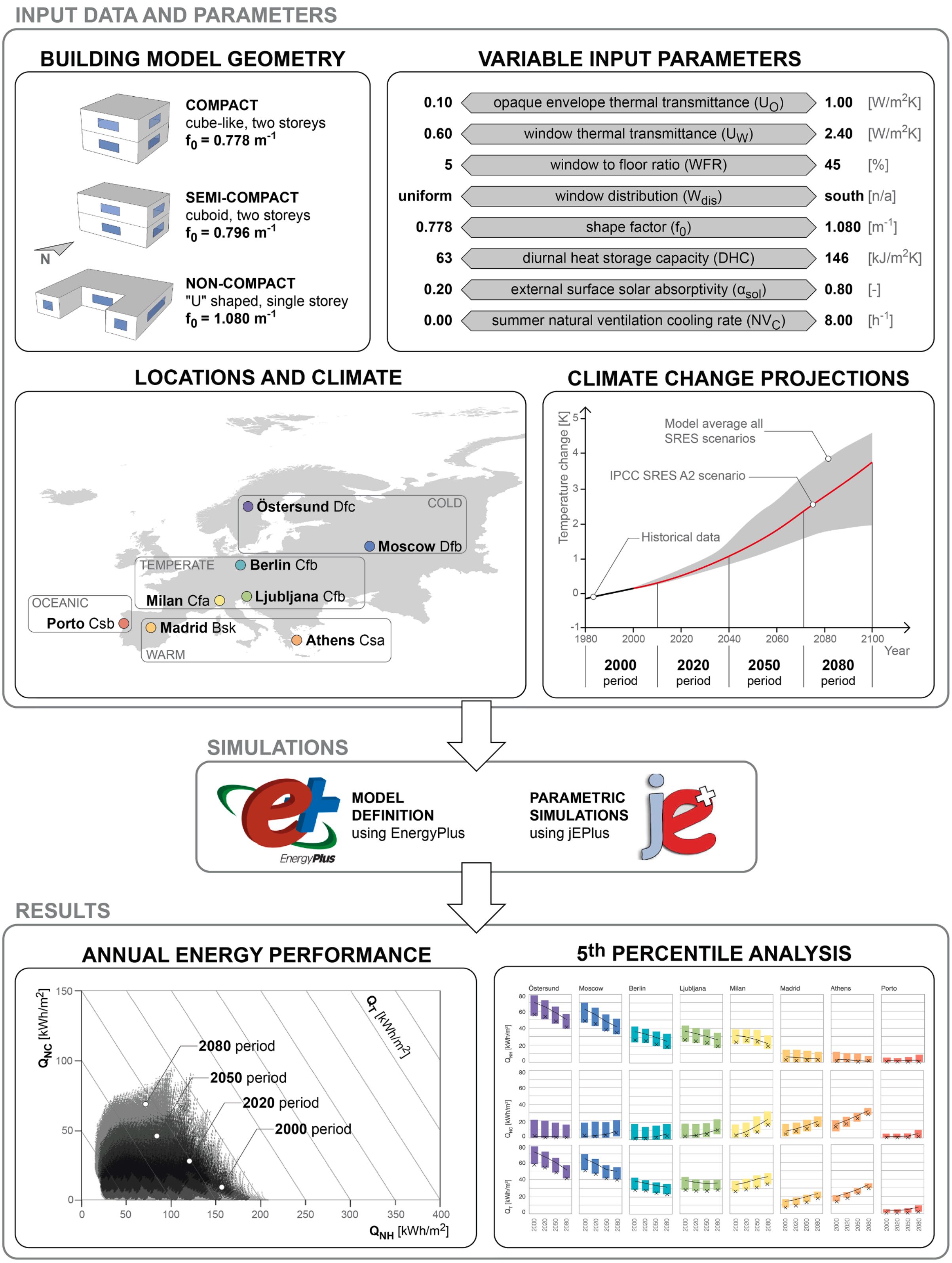

Fig. 1. Overview of the applied research methodology.

used by building designers in contemporary energy-efficient buildings in Europe, either explicitly or implicitly. There are indeed other passive measures (e.g. evaporative cooling) that might be worthy of investigation in the context of building energy performance concerning the projected climate change. However, we opted to limit ourselves to those design measures that are already established in the design community while at the same time showing real potential for enhancing building performance under all studied climates.

Table 1
Constant input parameters for the energy models.

Parameter	Value	Note
Heating set-point	21 °C	EN 16798-1, Table B.2 [51]
Cooling set-point	26 °C	EN 16798-1, Table B.2 [51]
Indoor temperature control	operative temperature	Based on Dovjak et al. [52]
Infiltration + natural ventilation rate	0.600 (1st April to 31st October),0.375 (1st November to 31st March)	Based on Hou et al. [53], Bekö et al. [54]
Internal heat gain rate and schedule (appliances)	2.4 W/m^2	EN 16798-1, Annex C [51]
Internal heat gain rate and schedule (occupants)	2.8 W/m^2	EN 16798-1, Annex C [51]
Internal heat gain rate and schedule (lighting)	3.3 W/m^2	EN 16798-1, Annex C [51]
Shading schedule	active from 1st April till 31st October	Based on Tzempelikos and Athienitis [55]
Shading set-point, type, and operation	incident solar radiation on window ≥ 130 W/m^2 and external temperature ≥ 16 °C, external blinds, always block beam solar	EN 15232, class A [56]
Building envelope system and external surface thermal emissivity	the externally insulated building envelope, 0.80	Based on Pisselo [57]

Table 2
Variable input parameters for the energy models.

Parameter	No. of variable increments	Parameter range
U_O [W/m^{2}K]	10	0.10, 0.15, 0.20, 0.25, 0.30, 0.40, 0.50, 0.60, 0.80, 1.00
U_W [W/m^{2}K], in brackets: corresponding SHGC [-]	10	2.40 (0.75), 2.20 (0.75), 2.00 (0.70), 1.80 (0.70), 1.60 (0.65), 1.40 (0.65), 1.20 (0.60), 1.00 (0.55), 0.80 (0.50), 0.60 (0.45)
WFR [%]	9	5 ("base" case), 10, 15, 20, 25, 30, 35, 40, 45
W_{dis} [n/a]	2	equal area of windows at all orientations, south-concentrated windows (3.75% of WFR equally distributed among other orientations)
f_0 [m^{-1}]	3	0.778 (compact, cube-like, two storeys), 0.796 (semi-compact, cuboid, two storeys), 1.080 (non-compact, "U" shaped, single storey)
DHC of loadbearing construction[a] [kJ/m^{2}K], in brackets: thickness [m], thermal conductivity [W/mK], density [kg/m^3], specific heat [J/kgK]	3	63 (0.06, 0.20, 600, 2090, e.g. cross laminated timber), 98 (0.15, 0.50, 1200, 920, e.g. brick), 146 (0.24, 0.80, 2000, 960, e.g. concrete/stone)
α_{sol} [-]	4	0.2, 0.4, 0.6, 0.8
NV_C[b] [h^{-1}]	9	0, 1, 2, 3, 4, 5, 6, 7, 8
total number of models[c]	496,800	

[a] R = constant = 0.30 m^{2}K/W.
[b] NV_C is applied between April and October when the following conditions are met: internal air temperature >24 °C, external air temperature is between 16 and 30 °C, and temperature difference between internal and external air is <4 K.
[c] an actual number of combinations would be 583,200 if a compact and non-compact building shape allowed larger WFRs than 35% or 30%, respectively.

The building shape factor (f_0) represents the ratio between the building envelope area and the building volume. It was calculated using equation (1).

$$f_0 = \frac{A_{envelope}}{V_{building}} \quad (1)$$

$A_{envelope}$ is the building envelope area (i.e. the area in contact with the external environment), and $V_{building}$ is the building volume.

DHC of loadbearing construction was calculated according to equation (2) [58].

$$DHC = \sqrt{\frac{P\lambda\rho c}{2\pi}\left(\frac{\cosh\left(2t\sqrt{\frac{\pi\rho c}{P\lambda}}\right) - \cos\left(2t\sqrt{\frac{\pi\rho c}{P\lambda}}\right)}{\cosh\left(2t\sqrt{\frac{\pi\rho c}{P\lambda}}\right) + \cos\left(2t\sqrt{\frac{\pi\rho c}{P\lambda}}\right)}\right)} \quad (2)$$

P is the period of 24 h in seconds, λ is material's thermal conductivity in W/m K, ρ is material's density in kg/m^3, c is material's specific heat in J/kg K, and t is the layer thickness in m.

In terms of building geometry, three distinct shapes (see Fig. 1) with equal volumes and floor areas were modelled following the above-described statistical information about average EU dwellings. The first one is a cube-like, compact building ($f_0 = 0.778$ m^{-1}) with a square floor plan (9 × 9 m), two floors and 6 m of total height. The second one is a cuboid-shaped building ($f_0 = 0.796$ m^{-1}) with a rectangular floor plan (12 × 6.75 m), two floors and 6 m of total height. The last one is a non-compact building ($f_0 = 1.080$ m^{-1}) with a semi-enclosed atrium (i.e. "U" shaped) and a single storey with 3 m of total height. Numerical models were implemented in EnergyPlus [59], which is recognised as accurate building energy simulation software with sophisticated features [43]. Each of the models was divided into thermal zones. In particular, each floor was split into four thermal zones according to each cardinal axis. The contact of the slab-on-grade with the ground was simplified by using a constant ground temperature of 18 °C applied directly below the slab-on-grade of the building model.

The defined EnergyPlus models were then entered into the jEPlus [60] software for parametric analysis. Simulations were executed using four time steps per hour and under the presumption that occupant thermal comfort was achieved at all times by the set-point operative temperature for cooling and heating (Table 1). Effectively, this means that the simulated models are in a "free-run" operation when the indoor operative temperature is between 21 and 26 °C. As a result of the energy analysis, the annual energy use for heating (Q_{NH}) and cooling (Q_{NC}) per m^2 of floor area was calculated. Several results were evaluated against Q_T, which is the sum of Q_{NH} and Q_{NC}. However, Q_{NH} and Q_{NC} must be understood only as a part of the overall building energy performance because energy-relevant aspects, such as the efficiency of the heating or cooling system, hot water supply and artificial lighting, are not considered. The specific equations behind the calculations of Q_{NH} and Q_{NC} in EnergyPlus can be found in Engineering Reference [61].

Table 3
Selected locations with corresponding geographical coordinates and altitude, Köppen-Geiger climate classification according to the historical (i.e. recorded) and future projected climate characteristics and ASHRAE climate zone.

Location	Country	Latitude	Longitude	Altitude	Köppen-Geiger (K-G) climate type	K-G climate (2051–2075, IPCC SRES A2 scenario) [65]	ASHRAE climate zone [66]
Östersund	Sweden	63.18	14.50	370 m	Dfc	Dfb	7
Moscow	Russia	55.75	37.63	156 m	Dfb	Dfb	6A
Berlin	Germany	52.47	13.40	49 m	Cfb	Cfb	5C
Ljubljana	Slovenia	46.22	14.48	385 m	Cfb	Cfb	5A
Milan	Italy	45.43	9.28	103 m	Cfa	Cfa	4A
Madrid	Spain	40.45	−3.55	582 m	Bsk	Bsk	3C
Athens	Greece	37.90	23.73	15 m	Csa	Csa	3A
Porto	Portugal	41.23	−8.68	73 m	Csb	Csa	3C

2.2. Selected locations and climate data

The building energy performance calculations were executed for eight locations across Europe, as presented in Table 3 and Fig. 1. Locations were selected in accordance with our previous findings from bioclimatic potential analyses, presented in Pajek et al. [62] and Košir et al. [63] and thus represent various climate types existing in continental Europe. The necessary weather files (i.e. EPWs) were sourced from the official EnergyPlus web page [64] and represent distinct climate types according to the recorded historical weather data.

The climate data in the obtained EPWs are sourced from the International Weather for Energy Calculation (IWEC) database and represent weather data measured between 1982 and 1999. In the paper, this historical climate data period was labelled as “2000″. In order to simulate building performance under projected future climate conditions, historical data for the period of 2000 were used to generate projected EPW weather files for the periods ”2020″ (2011–2040), “2050″ (2041–2070) and ”2080″ (2071–2100). The generation of the projected climate characteristics was executed using the morphing technique in the CCWorldWeatherGen tool [67] introduced by Jentsch et al. [14] from the University of Southampton. As a basis for the executed morphing, the IPCC’s SRES A2 projected climate change emission scenario was used. The SRES A2 scenario describes a heterogeneous world with nations focused on self-reliance and local identity, with continuous population growth and increasing GHG emissions (i.e. a regional and economy-focused world), resulting in projected warming above 3 °C by the end of the current century (Fig. 1) [68]. The SRES A2 climate change scenario has a similar radiative forcing trajectory to a more recent IPCC’s RCP8.5 scenario with both reaching about 8 W/m^2 by 2100, while mean surface temperature change in SRES A2 scenario is projected about 0.3 K lower than in RCP8.5 [12]. In addition, the projected global mean surface temperature increase for the SRES A2 scenario in 2050 is approximately 1.5 °C, which is midway between the projected temperature change of the RCP8.5 and RCP6.0.

3. Results

The following subsections present the simulated building models’ energy performance in current and the projected climate scenarios. Section 3.2 provides general guidance on recommended passive measures for long-term energy efficiency. The presented results are evaluated according to the annual energy use for heating (Q_{NH}) and cooling (Q_{NC}) per m^2 of building floor area as well as Q_T, which is the sum of Q_{NH} and Q_{NC}.

3.1. Impact of projected climate change on building energy use

Fig. 2 presents scatter plots of the Q_{NH} and Q_{NC} combinations for every calculated building energy model at eight studied locations for each of the four investigated periods. As expected, the results show that, in general, Q_{NH} and Q_{NC} are strongly affected by the projected climate change at each location. Observing Fig. 2 also reveals a general trend of the projected decrease in Q_{NH} and increase in Q_{NC} over time. In particular, in Athens, Q_{NH} is projected to drop to 0 kWh/m^2 in 1.7% of the calculated cases until 2080. In 2000 there were no such cases, although some building models had Q_{NH} close to zero. In Milan and Ljubljana, a projected increase in Q_{NC} demonstrates that in 2080 at both locations, it will no longer be possible to achieve 0 kWh/m^2 of Q_{NC} in residential buildings solely by using the studied passive design measures. In particular, at present (i.e. the 2000 period), there are 4% of building models in Ljubljana that have Q_{NC} equal to zero, while in Milan in 2000, there are already only 0.6% of such cases.

If the average value of Q_T (=Q_{NH} + Q_{NC}) for the entire sample is observed in Fig. 3, it can be deduced that the projected climate change will have a positive effect on the overall energy use of buildings under cold and also temperate climates, such as Ljubljana and Berlin, and a negative effect in Athens. In Milan, Madrid and Porto, Q_T’s average value for the entire sample will remain relatively similar throughout the century. Although Q_{NH} and Q_{NC} change over time in all the studied cases, which can be detected through the shift in the point clouds in Fig. 2, generally speaking, the cases in the 5th and the 95th percentiles (i.e. the best and the worst-performing 24,840 building models) are respectively less or more affected by the projected warming climate (Fig. 3).

The 5th percentile represents building models with the best combination of passive design measures regarding their energy efficiency and climate adaptability. In contrast, the highest Q_T cases, namely the 95th percentile, will be more affected by the warming climate (Fig. 3). Therefore, a different conclusion can be drawn for each of the percentiles. For the 95th percentile, which consists of building models with the worst combination of passive measures, global warming will, on average, result in the highest decrease of Q_T by the end of the century. The stated is valid for all the analysed locations, except Athens, where the Q_T increase is the highest in the 95th percentile models. The latter exception is the consequence of the already warm climate getting even warmer, resulting in an above-average increase in overheating in the least climate-adapted building models. These are typically less thermally insulated buildings (i.e. high U_O and U_W values) having low DHC and NV_C, and at the same time high WFR and α_{sol}. This specific combination of parameters results in high vulnerability to a warming climate.

On the other hand, the average Q_T of building models in the 5th percentile is typically less affected by climate change. However, the trend of change in Q_T average values for the 5th percentile during the 21st century at some locations (i.e. Athens, Madrid, Milan, Porto) contradicts the one observed for the entire sample. For the exposed locations, building models in the 5th percentile will exhibit an increase in average Q_T during the 21st century, which means that the increase of Q_{NC} has a more significant effect on Q_T than the decrease of Q_{NH} has at these locations for the buildings of the 5th percentile.

Although climate change is projected to decrease most dramatically the Q_T of building models in the 95th percentile, this change will be far smaller than the effect of making buildings more climate-adapted and thus more energy efficient. Designing a new 5th percentile building or energy retrofitting an existing building of the 95th percentile to get an

Fig. 2. Annual projected energy performance of simulated cases at various studied locations and periods. Each dot represents an individual model with particular annual energy use for heating (Q_{NH}) and cooling (Q_{NC}) per m^2 of the floor area. For each location and period, 496,800 model cases were calculated, resulting in 15,897,600 simulated cases.

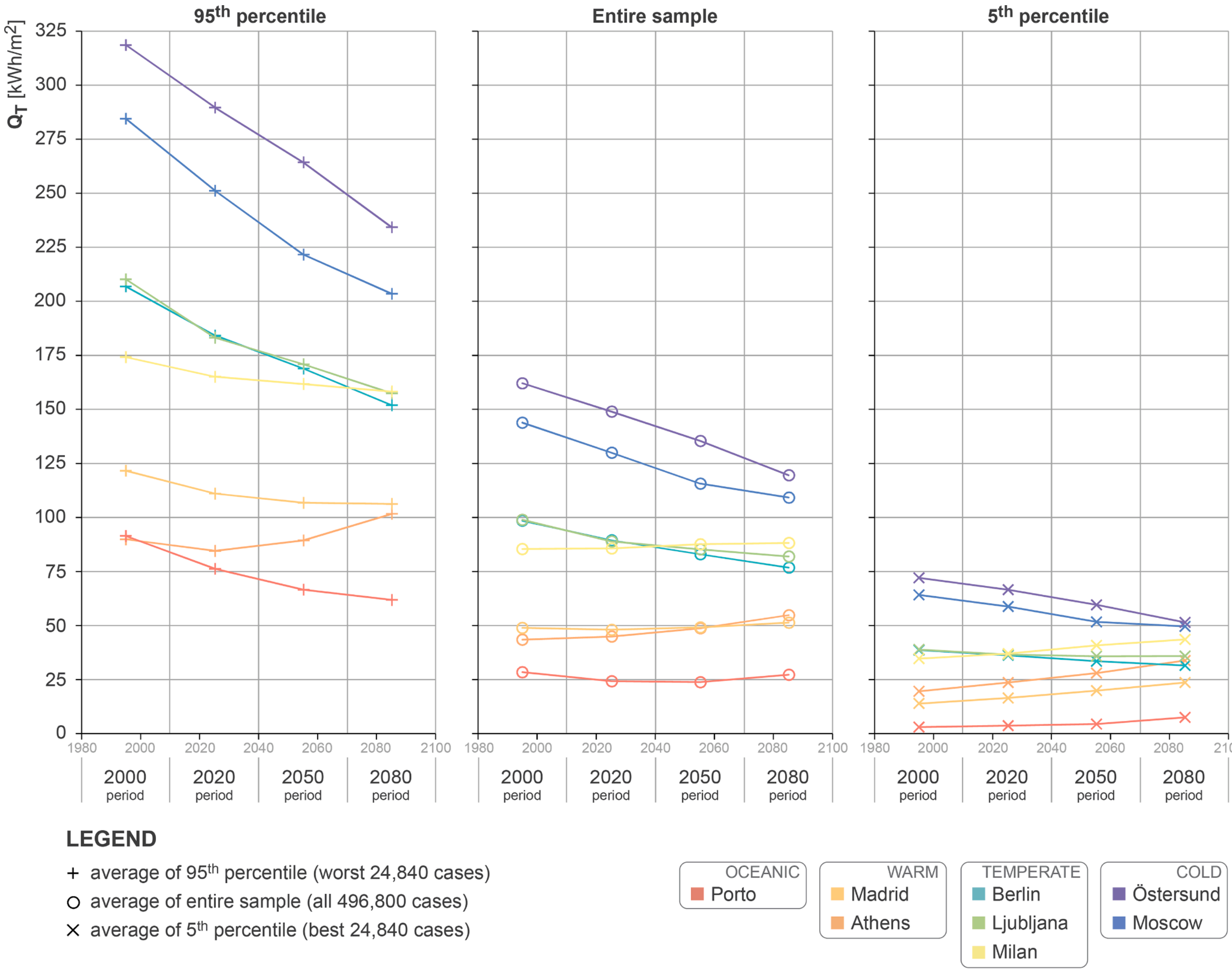

Fig. 3. Annual projected average Q_T ($=Q_{NH} + Q_{NC}$) for the entire sample (middle), the 95th percentile (left) and the 5th percentile (right) at various studied locations and periods.

average building or even a 5th percentile building will have a far greater effect on reducing Q_T than the projected climate change effects. For this reason, the 5th percentile models (colour-coded in Fig. 2) were chosen for detailed analysis because they represent the most energy-efficient and the most climate-adapted examples and provide insight into the design measures required to achieve low Q_T by simultaneously optimising both Q_{NH} and Q_{NC}. According to Q_T, it is crucial to note that the 5th percentile is characterised by promisingly low energy use for cooling and heating buildings. However, it also becomes evident that the relative importance of individual studied passive design measures and their resulting impact on Q_{NH} and Q_{NC} will change over time since the resulting Q_T is significantly different until 2080 compared to the historical period of 2000.

As identified above, a high level of buildings' energy efficiency can be achieved by applying the appropriate combination of the studied passive design measures. Therefore, the relationship between a projected climate change and characteristic values of Q_{NH}, Q_{NC} and Q_T (Fig. 4) for the 5th percentile was observed in greater detail. Fig. 4 shows that Q_{NH} is highest in cold climates, such as Östersund and Moscow, and the lowest in warm climates, such as Madrid and Athens, and oceanic climates such as Porto. On the other hand, warm climates have the highest demand for Q_{NC}. Speaking in absolute terms, according to the reached Q_T in 2000, the energy use of the 5th percentile buildings is confidently below 80, 70, 45, 45, 40, 20, 25 and 5 kWh/m^2 in Östersund, Moscow, Berlin, Ljubljana, Milan, Madrid, Athens and Porto, respectively. Simultaneously, the min–max range of Q_T, Q_{NH} and Q_{NC} is narrower in warm locations (coloured bars in Fig. 4). In terms of climate change impact, in locations with warmer conditions (i.e. Athens, Madrid, Porto, Milan), Q_T is projected to substantially increase until the end of the century, almost doubling the average Q_T of the 5th percentile in the instance of Madrid and Athens. A reverse trend applies to the colder locations of Ljubljana, Berlin, Moscow and Östersund, where Q_T is projected to decrease, albeit to a smaller degree (e.g. average Q_T for Östersund will be reduced approximately by 30% by 2080 in comparison to 2000). Although this trend may apply to all the mentioned locations, a turning point in the average Q_T curve can be detected in Ljubljana, where a minimum projected total energy use would be reached sometime between 2020 and 2050 ($Q_{T,2000} = 28.2$ kWh/m^2, $Q_{T,2020} = 27.2$ kWh/m^2, $Q_{T,2050} = 27.3$ kWh/m^2, $Q_{T,2080} = 28.1$ kWh/m^2). In general terms, this means that the Q_T of the 5th percentile at the end of the century will still be highest in cold climates and lowest in warm and oceanic climates. However, the gap in the average Q_T between the cold and warm locations will decrease substantially, while the ratio between Q_{NH} and Q_{NC} will also change significantly for all locations (Fig. 4). Both described trends signal a profound change in the building energy use patterns across Europe.

This phenomenon indicates that it is easier to achieve low Q_T in temperate and warm locations solely by using passive measures than in colder climates. However, in warm and some temperate climates, by 2080, the situation is projected to change towards higher Q_T regardless

Fig. 4. Long-term energy performance of the best performing building models (according to Q_T) presented through the 5th percentile's Q_{NH}, Q_{NC} and Q_T. The coloured bars demonstrate the energy use range, while the black lines show the average value for the building models in the 5th percentile.

of the used passive measures (see Fig. 4).

3.2. *Impact of individual passive design measure on energy use*

To gain insight into the impact of passive design measures at each location and for every future time slice, a quantitative analysis was performed for the 5th percentile using descriptive statistics. The results can be seen in Figs. 5–7.

3.2.1. *Opaque envelope thermal transmittance (U_O)*

Fig. 5 shows that the range of applicable U_O values in the 5th percentile is wider in warm climates than in temperate and cold climates. Therefore, to achieve the lowest 5% of Q_T, in extremely cold locations, such as Östersund, U_O of 0.15 W/m^2 K or lower should be used. In contrast, in another cold (Moscow) and temperate (Berlin, Ljubljana, Milan) climates, U_O of 0.20 W/m^2 K or lower is necessary. For warm climates, the same analysis shows that in order for a building to be in the 5th percentile, according to Q_T, its U_O should not exceed 0.30 W/m^2 K. However, even under warm (i.e. Madrid and Athens) and oceanic (i.e. Porto) climates, the average U_O of the models in the 5th percentile is lower than 0.15 W/m^2 K, with a noticeable increase towards the end of the 21st century (Fig. 5). The average U_O value is lowest in cold locations and highest in warm and oceanic climates. Nevertheless, the 5th percentile analysis results demonstrated that low U_O values (<0.15 W/m^2 K) are beneficial for the energy performance of the climate-adapted buildings regardless of the climate type. The only difference is that slightly higher U_O values can be used under warmer climates, giving designers in such climate types more freedom of choice in developing their designs. According to Q_T, the U_O value of the best case is for all the locations and all periods at 0.10 W/m^2 K, namely at its lowest analysed value. The average U_O value in the 5th percentile gradually increases towards the end of the century for all the analysed locations. The stated signals a trend indicating that in the future high energy efficiency, i.e. low Q_T, will be achievable on average with slightly higher U_O values than today.

3.2.2. *Window thermal transmittance (U_W)*

A similar observation can be made for the thermal transmittance of windows (U_W), where unexpectedly, even relatively high U_W values of up to 2.40 W/m^2 K can be found in the 5th percentile building models for all locations (Fig. 5). However, in the building models of the 5th percentile, high U_W (i.e. 2.40 W/m^2 K) is always combined with lower WFRs (below 10% in cold or below 20% in a warm climate) and minimal U_O values (i.e. 0.10 W/m^2 K in a cold or 0.20 W/m^2 K and lower in a warm climate). Similarly, as for the U_O, the average U_W value is lowest for cold locations and highest in warm and oceanic climates. Nevertheless, the average U_W is always below 1.30 W/m^2 K, regardless of location and period. The change in the average U_W values of the 5th percentile concerning the projected climate change is similar to that of the U_O. It means that the average U_W values are projected to steadily increase throughout the century with an increment of 0.01 to 0.10 W/m^2 K (i.e. $\Delta U_{W,cold} \approx 0.04$–0.10 W/m^2 K, $\Delta U_{W,temperate} \approx 0.09$–0.10 W/m^2 K, $\Delta U_{W,warm} \approx 0.01$–0.04 W/m^2 K, $\Delta U_{W,oceanic} \approx 0.07$ W/m^2 K) when comparing the 2000 and 2080 periods. The best case's U_W value is for all the locations and all periods at 0.60 W/m^2 K, namely at its lowest analysed value.

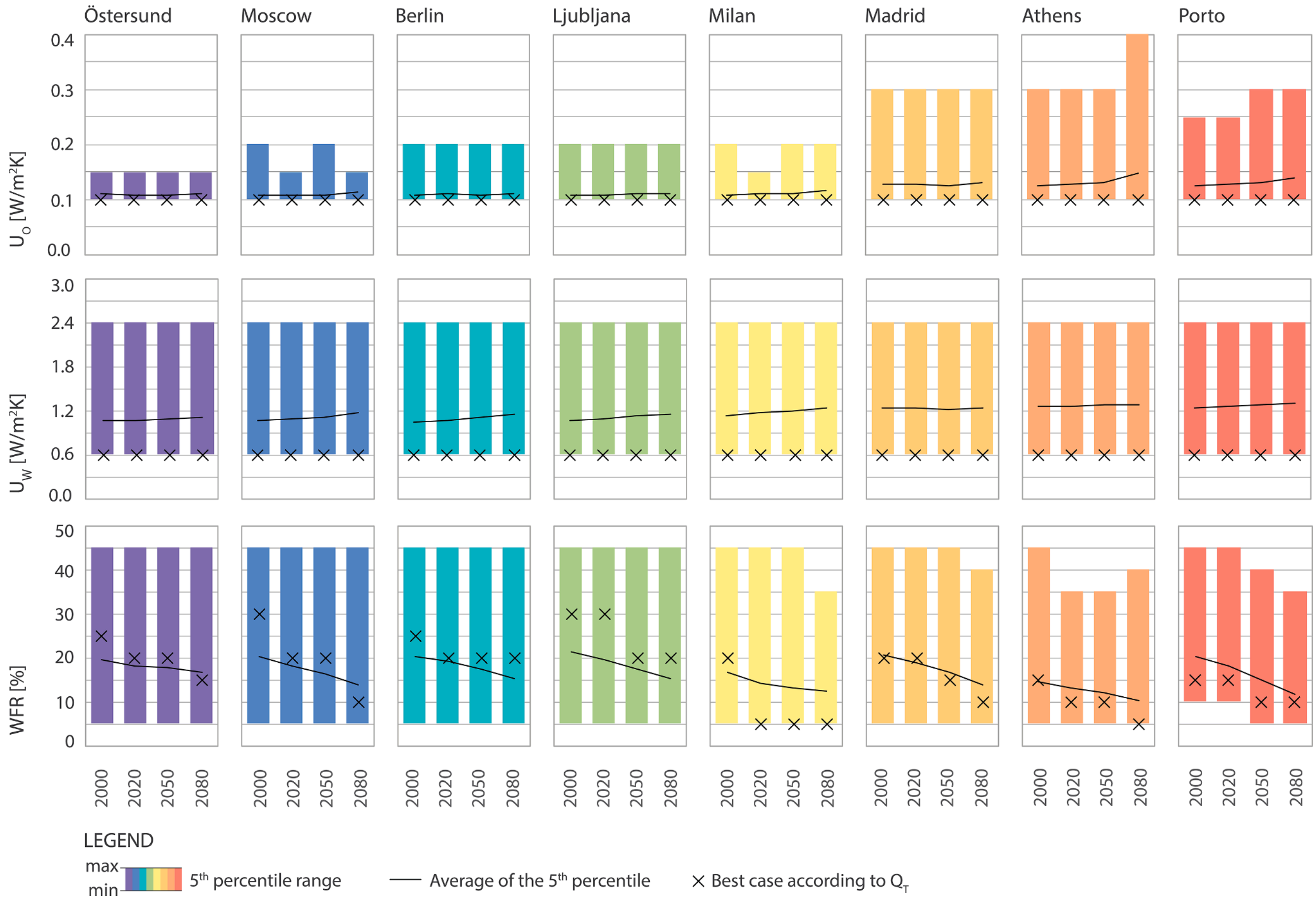

Fig. 5. Characteristic values of U_O, U_W and WFR represented in the 5th percentile according to Q_T. The coloured bars demonstrate the parameter range, while the black lines show the average value for the building models in the 5th percentile.

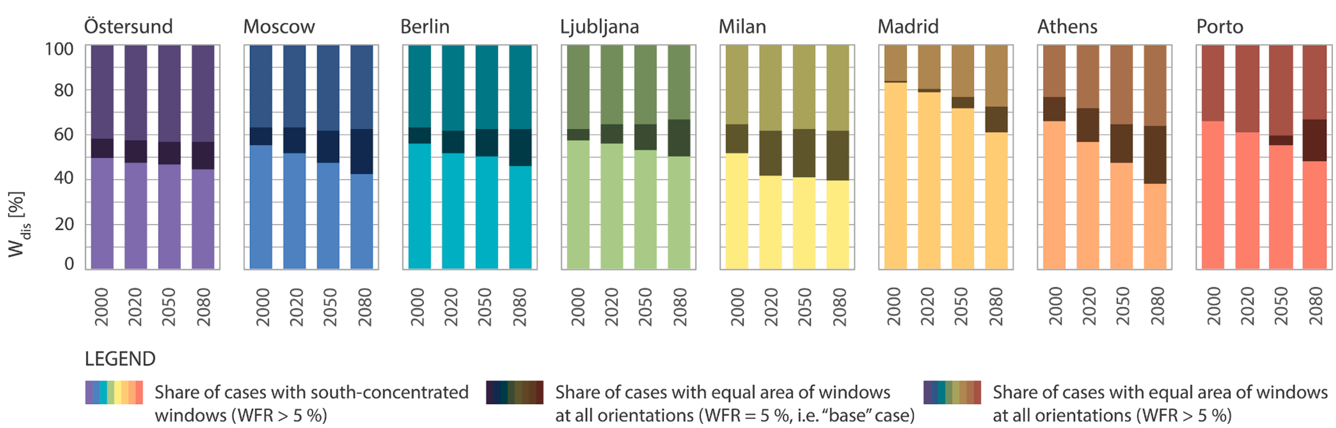

Fig. 6. W_{dis} shares represented in the 5th percentile according to Q_T. The coloured bars show the share of cases with south-concentrated windows of WFR > 5%, equal area of windows at all orientations of WFR > 5% and equal area of windows at all orientations of WFR = 5% (i.e. "base" cases) for the building models in the 5th percentile.

3.2.3. Window to floor ratio (WFR)

For cold and temperate locations, the analysis showed that it would be possible to achieve the 5th percentile Q_T by using any of the analysed WFRs, namely 5–45%, during all periods. In contrast, in warm and oceanic climates, the WFR maximum value in the second half of the century is limited to 35 or 40%. Furthermore, in the oceanic climate (i.e. Porto), the WFR for 2000 and 2020 is also limited to minimum values (Fig. 5). Be that as it may, for building models with a WFR of 45%, in cold locations (e.g. Östersund), U_W needs to be 0.8 W/m^2 K or lower and combined with U_O equal to 0.15 W/m^2 K or less. In temperate climates (e.g. Ljubljana), the maximum WFRs are achievable with U_W of 1.0 W/m^2 K or less and U_O below 0.15 W/m^2 K, while in a warm climate (e.g. Athens), U_W should not be higher than 0.6 W/m^2 K. In the latter case of locations with a warm climate, such high WFR resulted in only two cases out of the whole sample of the 5th percentile. Indeed, one should be aware that such a choice may result in a predominately cooling dominated building. However, any U_W can be used for WFRs up to 20% in temperate and warm locations (e.g. Ljubljana, Athens) and up to 15% in

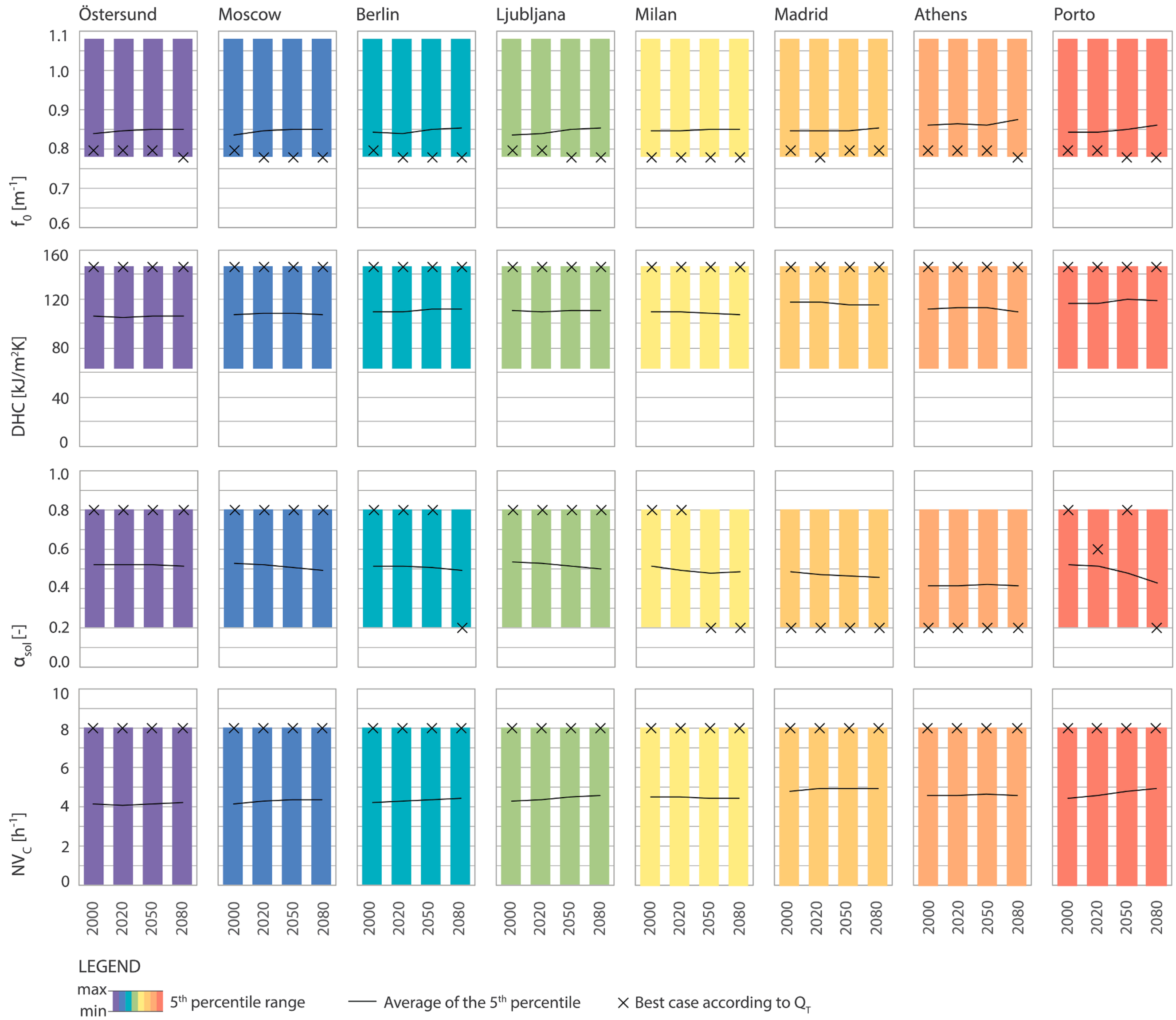

Fig. 7. Characteristic values of f_0, DHC, α_{sol} and NV_c represented in the 5th percentile of Q_T. The coloured bars demonstrate the parameter range, while the black lines show the average value for the building models in the 5th percentile.

cold locations (e.g. Östersund). The influence of WFR on the resulting Q_T of the 5th percentile is probably most affected by the projected climate change, which can be seen by observing WFR ranges and average values in Fig. 5. To demonstrate, observing the 5th percentile WFR average value trend until 2080 shows that they will substantially decrease at all the analysed locations, with the most significant decrease of 8.6 percentage points in Porto and the slightest change of 2.8 percentage points for Östersund. In Porto, the "average optimal" WFR is projected to shift from 20.3% to 11.7%, a decrease of 8.6 percentage points. Simultaneously, even in Östersund, where the decrease in WFR is the smallest, the "average optimal" WFR is projected to shift from 19.5% to 16.7%, a change of 2.9 percentage points. WFR is the only studied parameter that displays a constant projected decrease in its value for the best case at all locations and all periods (Fig. 5).

3.2.4. *Distribution of windows (W_{dis})*

The share of building models with south-concentrated widows and WFR above 5% regarding the total number of building models of the 5th percentile can be seen in Fig. 6. This share is higher for warm and oceanic locations than for cold and temperate locations. Choosing south-concentrated windows allows using higher than average U_O values under temperate (e.g. Ljubljana) and cold climates (e.g. Moscow), namely 0.20 W/m^2 K, as well as in warm climates (e.g. Athens), namely 0.30 W/m^2 K. "Base" cases with an equally distributed 5% WFR usually perform best only when combined with U_O of 0.10 W/m^2 K due to an increased influence of the thermal characteristics of the opaque building envelope on the resulting final Q_T. Observing the W_{dis} shares shows that for a building to be included in the 5th percentile of Q_T, the share of south-concentrated cases decreases over time due to the projected climate change. In particular, at many locations, the number of cases with south-concentrated windows drops below 50% by the 2080 time period. Simultaneously, the share of "base" cases is on the rise for all the locations, indicating that south-concentrated glazing is becoming a burden due to the increased overheating.

3.2.5. *Shape factor (f_0)*

Data presented in Fig. 7 show that, as it could be expected, the average value of f_0 for buildings in the 5th percentile according to Q_T is lower in cold climates and higher in warm and oceanic climates. Nevertheless, at all the locations, any of the analysed building shapes can be used and still result in a low enough Q_T to be included in the 5th percentile. In cold locations, lower U_O application (e.g. 0.10 W/m^2 K) allows for higher f_0 (e.g. a semi-enclosed atrium). The same is true for warm locations (e.g. Athens), but there the value of U_O can be up to 0.20 W/m^2 K when choosing a non-compact building shape. For all locations, the average f_0 values increase until the 2080 time period. However, in terms of Q_T, the best case usually has an f_0 equal to 0.796 (i.e. a semi-compact building shape), with a slight tendency to shift towards a compact building shape (i.e. $f_0 = 0.778$) with the progression of time.

3.2.6. Diurnal heat storage capacity (DHC)

Considering the DHC (Fig. 7), it can be said that although the average DHC ($\approx 110 \pm 5$ kJ/m^2 K) of the 5th percentile is somewhere between a medium (e.g. brick) and a heavy (e.g. concrete or stone) weight construction, all the analysed DHCs can be used to reach the 5th percentile Q_T energy use at all the locations and during all periods. The latter is primarily the result of the ability to offset the undesirable impact of low DHC (i.e. 63 kJ/m^2 K) on the resulting Q_T by using low values of U_O. However, to achieve the 5th percentile of Q_T in temperate (e.g. Ljubljana) and cold (Östersund, Moscow) climates, U_O must be 0.15 W/m^2 K or lower if choosing a lightweight timber construction (i.e. DHC = 63 kJ/m^2 K). Similarly, U_O must be equal to or below 0.20 W/m^2 K in Athens when using lightweight timber construction.

3.2.7. External surface solar absorptivity (α_{sol})

In Fig. 7, the characteristic values of α_{sol} can be seen, where similar as for other parameters, any of the analysed values (i.e. 0.2, 0.4, 0.6 and 0.8) can be used to achieve the 5th percentile of Q_T. Nonetheless, in the case of warm climates (e.g. Athens), α_{sol} equal to 0.2 can be used in all the cases, while higher values are limited by applying lower U_O, namely α_{sol} of 0.8, can only be used with U_O equal to or lower than 0.20 W/m^2 K. The opposite is true for temperate climate locations (e.g. Ljubljana, Milan), where α_{sol} equal to 0.2 can only be used with U_O equal to or lower than 0.15 W/m^2 K, while $\alpha_{sol} = 0.8$ is acceptable in all the cases inside the 5th percentile. Observing the α_{sol} values in future climate projections shows that the average value is steadily decreasing. The projected decrease in the average α_{sol} is less noticeable in cold and more pronounced in warm but above all in oceanic climates.

3.2.8. Summer natural ventilation cooling rate (NV_C)

Lastly, observing the NV_C parameter results in the 5th percentile (Fig. 7) shows that, as expected, higher average NV_C values are found for warm and lower in temperate and cold locations. Using any NV_C value can result in the Q_T of a building model that falls inside the 5th percentile. However, a more in-depth analysis of the results showed that higher NV_C rates are generally used in cases where external opaque surfaces are characterised by higher α_{sol} (i.e. 0.6 and 0.8) in all the locations. Additionally, more models with a lower DHC were included in the 5th percentile when a non-zero NV_C was simultaneously used (i.e. $\geq$ 1 h^{-1}). For all the locations, the average NV_C value of the 5th percentile is gradually rising towards the end of the century, which is a logical consequence of a warming climate trend. In brief, any non-zero NV_C value will effectively decrease Q_T, but the extent is limited by climate characteristics and the ratio between cooling and heating energy use since NV_C only affects the Q_{NC} values.

4. Discussion

The study aimed to evaluate the effectiveness of the selected passive building design measures and their ability to influence building energy use concerning projected climate change. This evaluation was achieved through a comprehensive parametric study, with a further in-depth analysis of the best performing 5% of building models (i.e. the 5th percentile). In our opinion, this approach to finding optimum building configuration is better than the construction of Pareto fronts as it gives a higher number of potential candidates with still acceptable low energy use. Unlike optimisation, the most significant asset of the selected approach is that not just the global or local minimums are found, but also numerous neighbouring solutions are detected, still resulting in a low-energy building. Therefore, a vast pool of candidates is acquired without affecting the precision of the results. However, such an approach has some drawbacks: significantly longer calculation times and a need for a mindful insight by the assessor.

4.1. The effect of passive design measures on building energy efficiency under climate change

The results demonstrate that building energy use can be effectively regulated by passive design measures, while several parameter combinations resulted in an impressive or at least satisfactory energy efficiency level. The latter is expressed by the energy use results for the 5th percentile according to Q_T, where at numerous locations, a relatively low energy use rate was achieved by passive measures only, for example, Q_T below 20 kWh/m^2 in warm and below 40 kWh/m^2 in temperate climates. However, the results show that even if the most favourable combination of the proposed passive design measures is used at any of the analysed locations, the impact of climate change on buildings' thermal performance will be difficult to neutralise. In other words, the calculated Q_T of a building will inevitably be affected by the warming climate, resulting in either higher or lower energy use in comparison to the historical climate (i.e. 2000 period) and a substantially different ratio between cooling and heating energy demand. That is an important outcome in the context of building resilience. Nonetheless, while the stated might not be considered a problem in cold locations, where Q_T is in general projected to decrease with an only slight increase in Q_{NC}, it represents a significant issue for buildings under temperate, oceanic and warm climates. For these locations, Q_T is, in general, projected to increase, and the increment cannot be effectively counterbalanced by modifying the parameters of the studied passive design measures. In this perspective, Attia and Gobin [69] warned that even thermal adaptation strategies, such as clothing level and human thermal comfort adaptation, cannot suppress the effect of global warming. Therefore, the results provide crucial information for designing energy-efficient buildings that strive for climate adaptation and provide a general outlook for policymakers.

Moreover, the results section brings several values of the studied passive design measures, which are recommended to be practised when designing low energy buildings in each evaluated climate type. Besides, for some parameters, potential counterbalances are defined. For example, low DHC can be compensated by using very low U_O. Similar compensation can be made when applying high WFRs or high α_{sol} of the opaque building envelope. The study shows that in order to optimise (i.e. reduce) Q_T of future buildings, slightly higher U_O, U_W, f_0, DHC and NV_C and a slightly lower α_{sol} should be used. Be that as it may, there is no need for any substantial change in the current optimal value of these parameters to achieve the lowest of Q_T also in the future. On the other hand, in future, considerably lower WFRs, than those in contemporary energy-efficient buildings should be used. However, considering WFR, the results should be interpreted to acknowledge its impact on daylighting and view as well as the corresponding occupant preferences.

4.2. Long-term climate adaptation of the best case models

For each period, the best building model (i.e. an absolute optimum) with the lowest Q_T for that period was identified. Given the effects of projected climate change on buildings' energy use and energy efficiency, there has been a broad debate in the literature about how buildings can be optimised to achieve long-term climate adaptation. This issue was further investigated in the study of the effects of passive design measures on climate adaptation. The results are presented in Fig. 8, where the long-term development of energy performance for an absolute best case among building models can be observed for each particular period and each location.

Fig. 8 shows that cold locations (i.e. Östersund and Moscow) could

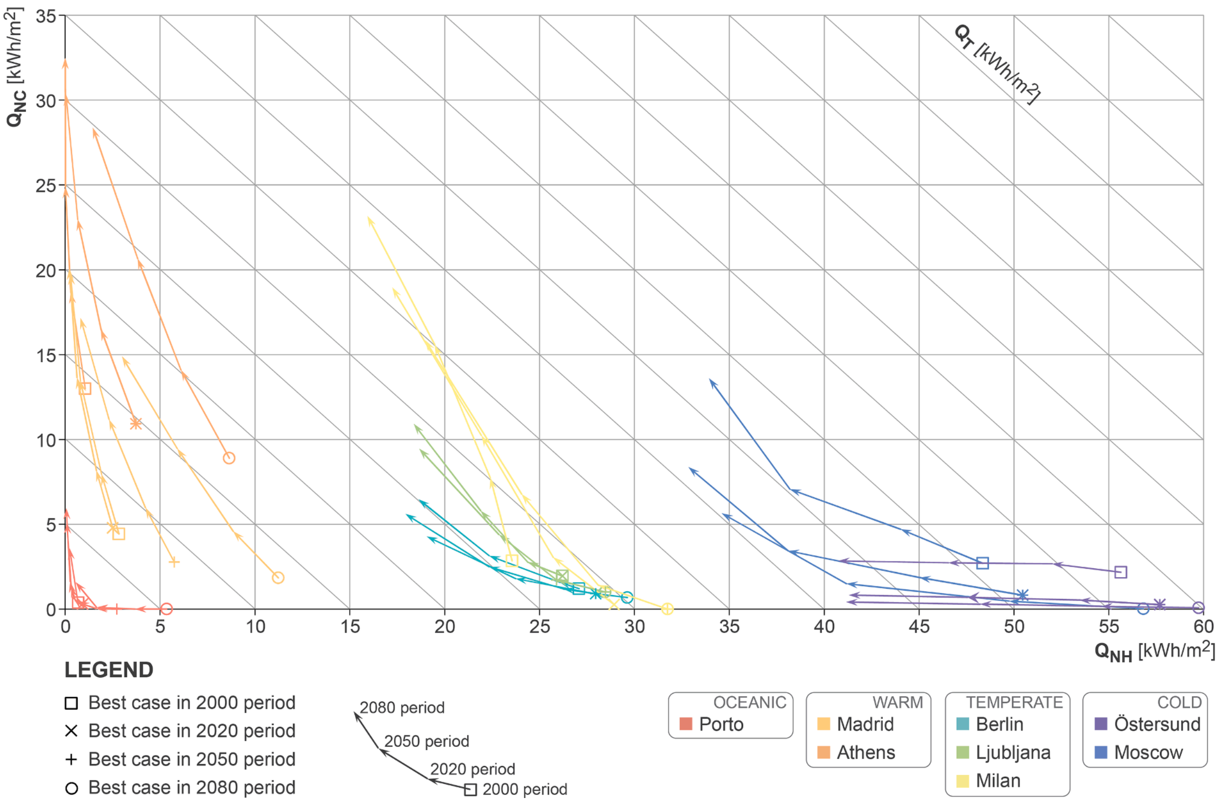

Fig. 8. Long-term development of energy performance of each best case according to Q_T.

benefit from the warming climate since Q_T is projected to drastically decrease regardless of the period to which a building is optimised. If a residential building was built in Östersund in 2020 according to the optimum defined by the climate data for the 2000 period, after 50 years, it would cumulatively use 425.6 MWh of energy with a ratio between heating and cooling energy use (Q_{NH}/Q_{NC}) of 18. If opting for the 2020/2050 period optimum, cumulative energy use would be 418.3 MWh ($Q_{NH}/Q_{NC} = 80$) and 422.1 MWh ($Q_{NH}/Q_{NC} = 214$) if going for the 2080 period optimum.

On the other hand, Q_T of the best case in warm and some temperate locations (i.e. Athens, Madrid and Milan) is projected to significantly increase, so that buildings at such locations will use considerably more energy than in the current situation. If we look at the example of a residential building built in 2020 in Athens, after 50 years, the building will consume 185.5 MWh of energy ($Q_{NH}/Q_{NC} = 0.006$) if opting for the 2000 period optimum, 177.3 MWh ($Q_{NH}/Q_{NC} = 0.057$) if deciding on the 2020/2050 period optimum and 187.7 MWh ($Q_{NH}/Q_{NC} = 0.265$) if going for the 2080 period optimum.

In some cases, such as Berlin and Ljubljana, Q_T does not appear to be significantly affected or dependent on the optimisation period. However, the Q_{NH}/Q_{NC} ratios in these locations will be affected. The same example of a residential building as above, built in Ljubljana in 2020, would use after 50 years 226.9 MWh of energy ($Q_{NH}/Q_{NC} = 5.0$) if opting for the 2000/2020 period optimum and 226.4 MWh ($Q_{NH}/Q_{NC} = 7.3$) if choosing the 2050/2080 period optimum. In general, it is clear that in all the locations, except Milan, in the context of cumulative Q_T, it is best to design a new building according to the mid-term optimum (i.e. the 2020/2050 period). Milan is the only case where the best set of parameters is achieved using the best case for the 2080 period.

It is important to note that even if the above-described energy use indicates that for some locations, the design of a building according to climate change projections does not have a significant impact on the resulting cumulative Q_T, the energy use and heating to cooling energy use ratios are shown for the absolute best cases only. It means that such building models represent one of the best climate-resilient building designs possible. At this point, it also has to be stressed that choosing the long-term optimum building design is not as easy as just choosing a set of passive design measures that would lead to the lowest Q_T but is somewhat more complicated. Since the warming climate will result in lower Q_{NH}/Q_{NC} ratios and higher Q_{NC} use, the building energy performance optimisation must be a thorough process. Higher Q_{NC} results in progressively higher electricity consumption for cooling, which is particularly worrisome [70] due to increased peak demand. If more and more buildings become actively cooled during summer or even in spring and autumn, it will lead to a significantly different energy demand for building operation – the energy demand for which energy suppliers may not be prepared.

4.3. Study limitations

The results of the study must be interpreted within the framework of applicable limitations. The primary limitation to the generalisation of the presented results is that the floor area and the corresponding volume and shape of the analysed building models were devised according to the statistical average of the EU. We are clearly aware that such a sample represents residential buildings in the EU but has limitations in applying the derived results to specific countries or building. Therefore, the study's findings should be used with caution when used as guidelines for the performance of buildings that have much smaller or much larger floor areas or are, in any case, geometrically considerably different. Second, several input parameters for energy models were set constant, limiting our study primarily to passive building envelope elements and natural ventilation. Shading of the transparent elements was set constant since it was recognised by our previous findings (see refs. [7,71]) as one of the crucial actions to control overheating at present and in future. Of course, we are aware that shading performance's parametrisation may provide alternative insights into the problem. Besides, occupant interaction with the built environment was also set constant, essentially limiting the impact of thermal comfort and occupant behaviour on the building's energy performance and vice versa. Third, considering the weather data, the simulated building model's location is defined by the weather station where the weather time series is recorded. The latter ignores aspects such as urban morphology induced wind speed and direction, shading by the surrounding urban context and the effects of the urban heat island [13]. Another limitation of the study concerns the weather data because it considers the IWEC database weather, which has a different timeframe than HadCM3. Therefore the EPW data are expected to slightly overestimate the effect of climate change, as stated by Jentsch et al. [14] and Moazami et al. [72]. However, the weather data are still accurate enough to estimate the projected impact of climate change on building energy use.

5. Conclusions

This paper investigates the long-term energy performance of single-family detached residential buildings by means of a comprehensive parametric study. Numerous sets of passive design measures were simulated and found effective in achieving high building energy performance. The main findings and conclusions of the conducted analysis are as follows:

- In the analysed single-family residential buildings, the projected warming climate will result in lower heating and higher cooling energy use. However, the total energy use (Q_T) is projected to increase in warm climates and decrease in cold climates, while in temperate climates, the evolution of Q_T depends on the location.
- Low total energy use (i.e. $Q_T \leq 30$ kWh/m^2 per year) of single-family residential buildings can be assured to a large extent solely by passive building design measures, particularly in oceanic, warm and temperate climates.
- In all the considered climates, it will be difficult to completely neutralise climate change effect on building energy use for heating and cooling by employing the studied passive building design measures. This issue is especially alarming in warm climates, where total energy use is projected to increase compared to the historical period substantially.
- The most effective passive design measure for long-term climate adaptation of residential buildings is in all the analysed locations applying lower WFR, which in warm climates needs to be supplemented by lower α_{sol}. Due to global warming, the overall importance of low U_O and U_W values will decrease to a certain extent, as illustrated by a slight increase in the average U values of building models in the 5th percentile. However, selecting a combination of passive design measures depends largely on whether one aims for a heating or a cooling dominated building, which leads to different seasonal energy demands.
- The energy efficiency of residential buildings may be further improved by active building measures (e.g. heat recovery ventilation, etc.). Nonetheless, it is inevitable that in a warm oceanic climate, such as Porto's, it would be possible to design a nearly zero-energy building solely by using appropriate passive design.
- Although the results represent crucial information on the effectiveness and eligibility of passive building measures for achieving low energy use and climate change adaptation, additional research in this field is recommended in order to aid policymakers to develop appropriate strategies and guidelines in terms of future energy performance of buildings and their impact on the overall energy supply network.

CRediT authorship contribution statement

Luka Pajek: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing - original draft, Visualization. **Mitja Košir:** Conceptualization, Methodology, Validation, Investigation, Resources, Writing - review & editing, Visualization, Supervision.

Declaration of Competing Interest

The author declare that there is no conflict of interest.

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PRILOGA D

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Exploring Climate-Change Impacts on Energy Efficiency and Overheating Vulnerability of Bioclimatic Residential Buildings under Central European Climate

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Abstract: Climate change is expected to expose the locked-in overheating risk concerning bioclimatic buildings adapted to a specific past climate state. The study aims to find energy-efficient building designs which are most resilient to overheating and increased cooling energy demands that will result from ongoing climate change. Therefore, a comprehensive parametric study of various passive building design measures was implemented, simulating the energy use of each combination for a temperate climate of Ljubljana, Slovenia. The approach to overheating vulnerability assessment was devised and applied using the increase in cooling energy demand as a performance indicator. The results showed that a B1 heating energy efficiency class according to the Slovenian Energy Performance Certificate classification was the highest attainable using the selected passive design parameters, while the energy demand for heating is projected to decrease over time. In contrast, the energy use for cooling is in general projected to increase. Furthermore, it was found that, in building models with higher heating energy use, low overheating vulnerability is easier to achieve. However, in models with high heating energy efficiency, very high overheating vulnerability is not expected. Accordingly, buildings should be designed for current heating energy efficiency and low vulnerability to future overheating. The paper shows a novel approach to bioclimatic building design with global warming adaptation integrated into the design process. It delivers recommendations for the energy-efficient, robust bioclimatic design of residential buildings in the Central European context, which are intended to guide designers and policymakers towards a resilient and sustainable built environment.

Keywords: climate change; bioclimatic design; passive design; energy efficiency; overheating; building resilience; robustness

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1. Introduction

Since Neolithic times, the building of homes has provided people with a higher degree of flexibility and independence in terms of climate and consequential habitability. Shelters and houses offered their occupants protection from the environment, predators and intruders [1]. Moreover, people were no longer forced to migrate towards flourishing regions with pleasant weather as the seasons passed and the climate changed. Thus, many relatively inhospitable environments were settled. Alongside the habitation of diverse climates, the struggle of builders to either utilise or fight the climatic characteristics of a location had begun. Only the best performing building design ideas were passed on, and thus, the knowledge on climate-adapted buildings was passed on intrinsically from generation to generation. Climate opportunities, together with the occupants' and society's needs and expectations, and the technological know-how about building, form the so-called triquetra of bioclimatic building design [1]. Therefore, the concept of bioclimatic building design is often associated with the harmonisation of climate, comfort, and energy efficiency [2]. The closer the building can follow and respond to the external dynamics, such as temperature, solar radiation and relative humidity, the more efficient it is [3].

Bioclimatic design is an engineering practice usually described through the building's ability to utilise climatic conditions and resources in a particular location to advance its performance. Hence, the goal is that a building and its elements should facilitate occupant's comfort through an energy- and resource-efficient approach by adapting to the location's climatic conditions to the highest reasonable degree [4,5]. In professional circles, the general opinion is that vernacular (i.e., traditional) architecture is perfectly adapted to the climatic characteristics of a specific location, as it is presumed that it has "evolutionarily" adapted to the given climate over the centuries. Therefore, vernacular architecture is often a source of bioclimatic strategies and corresponding passive design measures incorporated into new buildings [1,6,7]. Nowadays, in building design, bioclimatic strategies are regularly accompanied by sophisticated and expensive active systems that can dynamically reduce energy use and increase thermal comfort [8,9].

As indicated above, climate plays a crucial role in bioclimatic building design. While there are large parts of continents with the same climate type, in some parts of the Earth, such as the Alpine-Adriatic region in Europe, many climate types are found in a relatively small area [10]. According to Köppen–Geiger climate classification [11], the prevailing climates in Central Europe are warm temperate (i.e., C) and boreal (i.e., D), fully humid (i.e., f) climates with warm (i.e., b) or cool (i.e., c) summers. Such climate diversity results in specific bioclimatic architecture [12]. In these climates, a residential building designed according to the bioclimatic design paradigm should mainly facilitate passive solar gains, reduce thermal losses during the colder part of the year, and allow heat storage through high thermal mass of the envelope [1]. Furthermore, the thermal response of residential buildings under temperate and boreal climates is typically envelope dominated [13]. Therefore, implementing bioclimatic (i.e., passive) measures on the level of the building envelope might be highly efficient in optimising building heating energy use.

During the last century, evident changes in climate have been noted [14–18], and by the end of the twenty-first century, global temperature is projected to rise by up to 4 °C [19]. In the times of hunter-gatherer societies, people had the option of migrating to other, more pleasant regions in the event of significant climatic changes. Once buildings were added to the equation, migratory behaviour was no longer an attractive option as a climate adaptation strategy because one would leave behind the result of one's hard work—a building. Hence, climate-adapted buildings carry a possible built-in risk concerning climate change. However, according to the Migration and Climate Change Report [20], over 1 billion people are expected to face displacement by 2050 due to climate warming and related ecological threats. In particular, sub-Saharan Africa, South Asia, the Middle East, and North Africa face the most significant number of threats, such as lack of access to food and water and increased natural disasters occurrence [21]. On the other hand, developed regions in Europe and North America are expected to face fewer ecological threats [21]. Nevertheless, not giving them the immunity to broader implications of climate change, such as the impact on urbanised environments and buildings.

A warmer climate will inevitably affect the thermal performance of buildings, even bioclimatic buildings adapted to the current or past climate. Wang et al. [22] warned that there is an increasing need to clarify the challenges posed by climate warming to limit potential thermal discomfort by applying passive building measures. In climates present in Central Europe, the bioclimatic design measures integrated into buildings are based primarily on heating need to achieve comfort during the winter months. Namely, south-oriented windows for passive solar heating, building envelopes with low thermal conductivity and compact building shapes are commonly used in building design [23]. Nevertheless, the projected effects of a warming climate will lead to a risk of overheating for such buildings, especially if the line between a thermally comfortable and a hot environment is thin. Therefore, bioclimatic strategies used in buildings in such locations must be re-evaluated, as emphasised by Pajek and Košir [24]. Numerous studies have been conducted in order to assess the effects of climate change on building energy performance. Berardi and Jafarpur [25] in Toronto, Canada, showed an average decrease of 18–33% for heating and an average increase of 15–126% for cooling energy use by 2070, depending on climate file and building typology. Furthermore, Rodrigues and Fernandes [26] stated that, in residential buildings, a general increase in cooling demand (up to 137%) and a smaller reduction in heating demand (up to 63%) is expected until 2050 in Mediterranean locations, while the current ideal U-values will mainly not cause overheating. Bravo Dias et al. [27] explored climate change implications on passive building design efficiency in 43 most populated cities in the European Union. They concluded that buildings using passive design measures, whose performance is highly climate-dependent, will be particularly affected. For example, in Southern Europe, the shading season will increase by 2.5 months, making shading by overhangs or other fixed elements less effective.

Therefore, the selection of passive design measures should be based on the ability to achieve the highest possible resilience of a building. Martin and Sundley [28] define resilience as a process that involves several criteria, including vulnerability, resistance, robustness, and recoverability. According to Attia et al. [29], overheating vulnerability assessment considering future climate scenarios should be part of the building design process. Such an approach aims to achieve a design solution with less sensitive performance to "noise" in the form of change of the environmental boundary conditions [30]. Even in the animal world, the idea of resilient "building" can be found in ant gardens, which apparently allow the species to be more resilient to climate change than they would be outside of this system [31]. However, to assess the resilience of cities and buildings to climate change, studies of robustness and vulnerability evaluation have been made (see refs. [32–38]). For instance, Fonseca et al. [32] studied the effects of climate change on the energy use of buildings in the United States. They concluded that additional research is needed to provide more robust estimates of the impact of climate change on the building sector. Similarly, Shen and Lior [33] performed a vulnerability analysis on climate change impacts of present renewable energy systems used in net-zero energy buildings. Different authors, namely Moazami et al. [30], Kotireddy et al. [35], and others, presented workflows and methods for building performance robustness assessment to prevent significant variations in energy use. Given these points, Houghton and Castillo-Salgado [39] recommended using green building programs and certifications to help reduce the vulnerability of buildings to climate change.

Finally, the concept of building resilience concerning building energy use should be discussed, particularly in the context of the EU Energy performance of buildings directive (EPBD) [40]. To help enhance the energy performance of buildings, the EPBD also introduced building energy performance certification (EPC). However, in most countries, more than half of all existing residential buildings with registered EPCs have energy class D or lower [41]. On the other hand, the share of newly constructed nearly Zero-Energy Buildings (nZEB), also introduced through EPBD and characterised by high energy efficiency, is increasing. Furthermore, in 2020, the EU Commission presented its strategy to boost the energy renovation for climate neutrality of buildings in the EU [42]. For this reason, the vulnerability of buildings to climate change must be considered.

Bioclimatic principles are often associated with energy-efficient buildings, especially in temperate climates where buildings are primarily heating-dominated but have considerable potential for passive solar heating. Under such climatic conditions, buildings are usually designed to address the heating energy efficiency while overlooking the potential overheating risk during the warmer part of the year. Therefore, passive design measures, such as large equatorially oriented windows, compact building shapes, and highly thermally insulated envelopes, are commonly applied [43]. Nevertheless, it is unclear to what extent such design practices pose a potential lock-in overheating risk under projected climate scenarios. The paper aims at investigating potential solutions to simultaneously achieve high energy efficiency for the heating of bioclimatically designed buildings while at the same time maintaining low vulnerability to a warming climate. The study was conducted for Ljubljana, Slovenia, as a representative of a location with a temperate Central European climate. Energy models of bioclimatic buildings were evaluated against heating and cooling energy use, applying a comprehensive parametric analysis of passive design measures. The study's main objective was to demonstrate a novel approach to the bioclimatic design of buildings, where the adaptation and resistance to a warming climate are integrated into the design process. Hence, the paper presents recommendations for the adoption of resilient bioclimatic building design into practice and legislation.

2. Materials and Methods

The study's methodology was developed to enable the reaching of the above-stated objective of the paper. Thus, in principle, the applied methods can be split into four basic steps:

1. Sourcing historical climate data for the location of Ljubljana and preparing future climate data according to climate change projections using the morphing technique (Section 2.1).
2. Building energy model definition with corresponding variable parameters for the conducted parametric analysis (Section 2.2).
3. Definition of the methodology for energy performance evaluation based on the current Slovenian legislation (Section 2.3).
4. Definition of the methodology applied for overheating vulnerability analysis (Section 2.4).

2.1. Location and Climate

The study was performed for a Central European climate. As a representative of such climate, the location of Ljubljana (N 46.22, E 14.48, 385 m above sea level) in Slovenia was selected. This location is characterised by a warm temperate, fully humid climate with warm summers (Cfb according to Köppen–Geiger climate classification). The EPW climate file needed for building energy analysis was sourced from the International Weather for Energy Calculation (IWEC) database representing weather data measured between 1982 and 1999. In the paper, this climate data period was labelled as 1981–2010. Furthermore, the EPW of Ljubljana was used to generate projected EPW climate files for the periods 2011–2040, 2041–2070, and 2071–2100. The projected EPW files were generated using the morphing technique (i.e., time series adjustment method) according to the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emissions Scenarios (SRES) A2 climate change scenario [44] and CCWorldWeatherGen tool [45]. The applied morphing technique uses historical climate data based on representative meteorological measurements in conjunction with projected global climate change patterns derived through numerical computer modelling to generate a new set of future projected climate. The use of recorded climate data as a starting point for future projected climate results in temporal continuity and spatial downscaling. The latter might be an issue for building energy simulations if only projections from global climate models are used.

2.2. Parametric Analysis

An extensive parametric analysis was carried out in order to study a vast pool of differently designed residential buildings. A single-family house with 162 m^2 of net floor area and a volume of 486 m^3 was chosen as the groundwork for the analysed energy models. Several building-related input parameters were fixed as constant for all the models considering the EN 16798-1 standard [46], meaningfully limiting the number of total possible combinations. Accordingly, the heating and cooling set-points were set to 21 °C and 26 °C, respectively, while the indoor temperature was controlled via the operative temperature. The summation of infiltration and natural ventilation was set to 0.60 h^{-1} (April till October) and to 0.375 h^{-1} (November till March). Internal heat gains and occupancy schedules were set according to EN 16798-1, Annex C [46]. Our previous analyses [47] have shown that external window shading is a crucial element of high energy performing bioclimatic buildings and was therefore not parametrised. It was set to block direct solar beams from April till October when incident solar radiation on the window was higher than 130 W/m^2 and external air temperature higher than 16 °C. The external thermal emissivity of all opaque building elements was set to 0.80.

The following variable input parameters were selected: opaque envelope thermal transmittance (U_O), window thermal transmittance (U_W) and the paired solar heat gain coefficient (SHGC), window to floor ratio (WFR), window distribution (W_{dis}), building shape expressed through shape factor (f_0), diurnal heat storage capacity (DHC) of load-bearing construction, external surface solar absorptivity (α_{sol}), and summer natural ventilation cooling rate (NV_C) (see Table 1).

Table 1. Variable input parameters.

Parameter	Parameter Range
U_O [W/m^{2}K]	0.10–1.00
U_W [W/m^{2}K] (paired SHGC [-])	0.60 (0.45)–2.40 (0.75)
WFR [%]	5.0–45.0
W_{dis} [-]	0.00, 1.00 [a]
f_0 [m^{-1}]	0.78 (compact), 0.80 (semi-compact), 1.08 (non-compact)
DHC [kJ/m^{2}K] [b]	63 (cross laminated timber), 98 (brick), 146 (concrete/stone)
α_{sol} [-]	0.20–0.80
NV_C [h^{-1}] [c]	0.0–8.0
total number of models	496,800

[a] 0.00 = equal area of windows at all orientations, 1.00 = south-concentrated windows (3.75% of WFR is distributed among all other orientations); [b] DHC is determined according to the principles presented by Bergman et al. [48]; [c] NV_C is applied between April and October when the following conditions are met: internal air temperature is > 24 °C, external air temperature is between 16 and 30 °C, and temperature difference between internal and external air is ≤4 K.

Given the above-presented constant and variable building parameters, building energy models were formed in EnergyPlus [49]. Each model was divided into four thermal zones according to each cardinal axis. The jEPlus [50] software was used to conduct the parametric analysis. The annual building energy use for heating (Q_{NH}) and cooling (Q_{NC}) per square meter of floor area was calculated to evaluate the performance of each building model. Both Q_{NH} and Q_{NC} values represent the necessary thermal energy that needs to be delivered (or extracted in the case of cooling) to the thermodynamic system of a building in order to reach the specified internal thermal conditions. Therefore, these values do not reflect the effects of heating and cooling systems or specific fuels that would be used for running them. For a detailed explanation of the definition of building models, see the paper by Pajek and Košir [51], where the same methodology was used.

2.3. Energy Performance Evaluation

The annual energy use for heating (Q_{NH}) and cooling (Q_{NC}) of each building model was evaluated in relation to the Slovenian Rules on the efficient use of energy in buildings [52], which implements the EPBD requirements at the national level. These rules apply to all new buildings and all buildings being renovated or retrofitted, where at least 25% of the thermal envelope surface is retrofitted. The rules provide the highest allowed Q_{NH} of a residential building per square meter of conditioned floor area, given by Equation (1):

$$Q_{NH} \leq 45 + 60 \times f_0 - 4.4 \times T_L \quad (1)$$

where Q_{NH} is annual building energy use for heating in kWh/m^2, f_0 is the ratio between the area of the thermal envelope of the building and the net heated volume of the building in m^{-1} (i.e., building shape factor), and T_L is the average annual outdoor air temperature at the location in °C. T_L for Ljubljana (1981–2010) is 10.7 °C [53].

Although the maximum allowed energy for heating depends on the building shape and location, the Rules on the efficient use of energy in buildings [52] limit the Q_{NC} per square meter of the cooled area to 50 kWh/m^2, regardless of building shape and location. Table 2 shows the energy use limits, given the three different building shapes used in the study. The compliance of the building energy use with these rules was evaluated for the climate data, representing the period 1981–2010, since these are the climate data used in current energy efficiency analyses in practice.

Table 2. Building energy use upper limit according to the Slovenian Rules on the efficient use of energy in buildings by building shape [52] for the location of Ljubljana, Slovenia.

f_0	Q_{NH} Limit	Q_{NC} Limit
0.78 (compact)	$\leq$44.7 kWh/m^2	$\leq$50.0 kWh/m^2
0.80 (semi-compact)	$\leq$45.9 kWh/m^2	
1.08 (non-compact)	$\leq$62.7 kWh/m^2	

Furthermore, building models were classified into energy efficiency classes. They were given labels based on the Slovenian EPC classification (Rules on the methodology of production and issuance of energy performance certificates for buildings [54]). According to Slovenian rules, the EPC labels are based only on Q_{NH} value. However, in the conducted study, each model was also labelled according to the Q_{NC} value using the same methodology and criteria as for the Q_{NH}. The EPC labels, colour markings, and corresponding building energy use ranges are presented in Table 3.

Table 3. Energy Performance Certificate efficiency classification [54].

Label	Energy Use [kWh/m^2]	Label Colour
A1	$Q \leq 10$	
A2	$10 < Q \leq 15$	
B1	$15 < Q \leq 25$	
B2	$25 < Q \leq 35$	
C	$35 < Q \leq 60$	
D	$60 < Q \leq 105$	
E	$105 < Q \leq 150$	
F	$150 < Q \leq 210$	
G	$Q > 210$	

2.4. Overheating Vulnerability Analysis

The vulnerability of building models to overheating was assessed by conducting a robustness analysis presented by Kotireddy et al. [34] using a minimax regret method. In this method, the performance regret for each climate scenario is the difference in performance between a building design and the best performing design in a given scenario. The maximum performance regret of a design across all scenarios is the measure of its robustness. Thus, the most robust design is the design with the lowest maximum performance regret. The minimax regret method can be explained through Equations (2)–(4).

$$R_{max,i} = \max(R_{i1}, R_{i2}, \ldots, R_{ij}) \tag{2}$$

$$R_{ij} = PI_{ij} - A_j \tag{3}$$

$$A_j = \min(PI_{1j}, PI_{2j}, \ldots, PI_{ij}) \tag{4}$$

where $R_{max,i}$ is the maximum performance regret of the i-th building model, R_{ij} is the performance regret of the i-th building model in climate scenario j, A_j is the minimum value of the performance indicator in climate scenario j, and PI_{ij} is the performance indicator of the i-th building model in climate scenario j. Here, i = 1–496,800 and j = 1–4 since the performed parametric analysis resulted in 496,800 individual building models simulated through four different climate scenarios. As a performance indicator (i.e., PI), the increase in energy use for cooling (i.e., ΔQ_{NC}) vis-à-vis the Q_{NC} in the 1981–2010 climate was selected and was calculated for each building model in each future climate scenario, namely 2011–2040, 2041–2070, and 2071–2100 climate (see Section 2.1. Location and climate). Then, the building model with the highest climate change vulnerability, and thus the lowest robustness, was identified through Equation (5):

$$V_{max} = \max(R_{max,i}) \tag{5}$$

where V_{max} is the most vulnerable design.

Furthermore, the overheating vulnerability score (OV score) was calculated by normalising the performance regret of each building model with the performance regret of the most vulnerable building model. The building model with the lowest OV score (i.e., equal to 0) is the least vulnerable (i.e., the most robust), and the building model with the highest OV score (i.e., equal to 1) is the most vulnerable to climate change in terms of overheating vulnerability.

3. Results

3.1. Energy Efficiency

The parametrically simulated building energy models were evaluated concerning the compliance with the Slovenian Rules on the efficient use of energy in buildings. This was done to assess the possibility of meeting the requirements of these rules using exclusively the analysed bioclimatic (i.e., passive) design measures without using any active measures, such as mechanical heat recovery ventilation. The conformity with the rules was evaluated for the 1981–2010 period since these are the climate data used in current energy efficiency compliance assessments in Slovenia. The results showed that 15.7% of simulated building models were compliant with the maximum permissible heating energy use (i.e., Q_{NH}) criteria (see Table 2). The median Q_{NH} of the energy-rule-compliant building models was 42.7 kWh/m^2, and the absolute best-performing model had a Q_{NH} equal to 24.1 kWh/m^2. However, the Q_{NH} threshold is related to f_0 of a particular building (see Table 2), which resulted in the fact that compliance with the Q_{NH} criteria was easier achieved in the case of a less compact building design. Namely, the criteria were met in 22.5%, 13.5%, and 11.8% of building models with a non-compact (i.e., f_0 = 1.08), a semi-compact (i.e., f_0 = 0.80), and a compact (i.e., f_0 = 0.78) shape, respectively. At this point, caution should be exercised in generalizing the above-stated results. The described phenomenon is a consequence of the methodology used to determine the threshold Q_{NH} (see Equation (1)) given in the Slovenian Rules on the efficient use of energy in buildings and not of better energy response of such building shape. In general, all the models meeting or surpassing the criteria of Q_{NH} have an equal or lower value of U_O than 0.25 W/m^{2}K. The other parameters are normally distributed. The cooling energy use (Q_{NC}) criterion (see Table 2) was achieved in all the analysed models since the highest Q_{NC} of simulated models for the 1981–2010 period was 34.1 kWh/m^2. The Q_{NC} of the analysed building models is projected to exceed the limit of 50 kWh/m^2 for the first time in the 2041–2070 period.

Furthermore, in order to gain a better insight into energy efficiency, the simulated building models in each of the analysed climate periods were classified according to the Slovenian Rules on the methodology of production and issuance of energy performance certificates for buildings (Figure 1). In general, the results in Figure 1 show that using the selected passive design measures results in building models with relatively satisfactory energy efficiency. Although none of the analysed building models was classified into heating energy efficiency classes A1 (i.e., Q_{NH} < 10 kWh/m^2) and A2 (i.e., 10 < Q_{NH} > 15 kWh/m^2), either under the current or the future climate file, all the other classes (i.e., B1 through G) are represented (Figure 1). Under the influence of the projected climate change, the heating energy efficiency of the analysed buildings is projected to increase over time. The share of building models with higher heating energy efficiency (i.e., classes B1, B2 and C) is increasing. Accordingly, the share of less energy-efficient models is decreasing (i.e., classes D, E, F and G). This means that during the 1981–2010 period, roughly 28% of building models were in class C or higher (Q_{NH} < 60 kWh/m^2), while for the 2071–2100 period, this share almost doubled to 54%, an increase of 26 percentage points (p.p.). Furthermore, in the 1981–2010 period, only 37 (i.e., 0.01%) building models can be classified under heating energy efficiency label B1 (i.e., 15 < Q_{NH} > 25 kWh/m^2), while this number increases to 13,740 (i.e., 2.77%) cases in the 2071–2100 period. In general, the most extensive changes in the shares of building models in individual heating energy efficiency classes between the 1981–2010 and 2071–2100 periods can be observed for class B2 and class F, an increase of 13 p.p. in the former and a decrease of 12 p.p. in the latter. Moreover, concerning the analysed building model population, it is projected that there will be no more models with a G heating energy efficiency label in the 2041–2070 period and beyond (Figure 1).

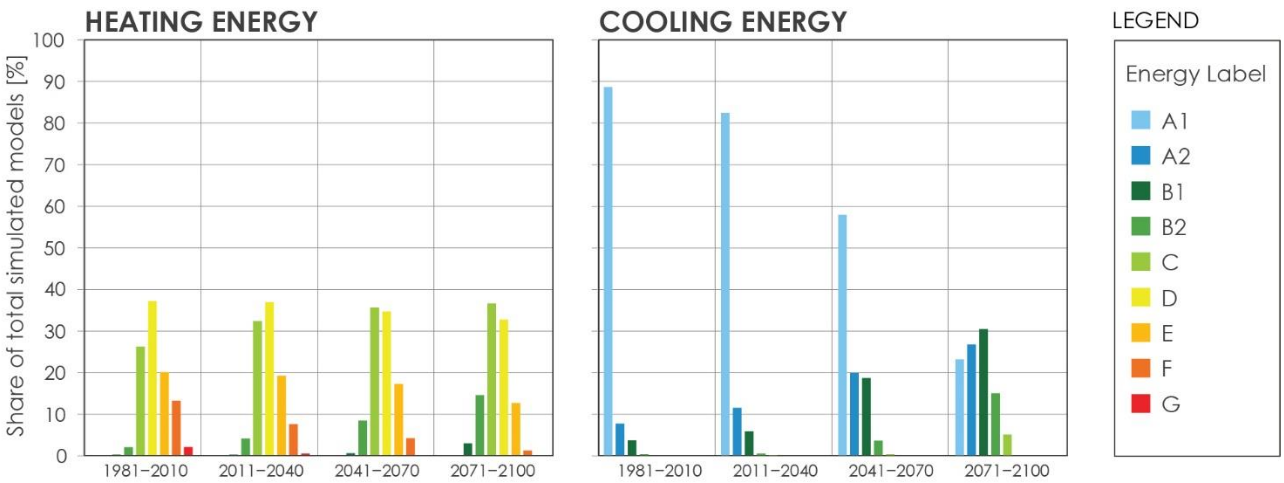

Figure 1. Share of total simulated models by heating and cooling energy label for each period.

Taking the 1981–2010 period as a starting point, the Q_{NH} is expected to decrease by 24–39% until the end of the century, with an average decrease of 32%. Table 4 presents the limits (i.e., variance) of building model parameters necessary for achieving a specific heating energy efficiency label. It can be considered that in order to classify one of the analysed building models under the B1 heating energy efficiency label during the 1981–2010 climate, one may choose from a relatively limited pool of choices (i.e., min-max range of a specific parameter). The latter applies to the range of all investigated variable parameters (see Table 4, B1). The other heating energy classes offer more "freedom of choice" concerning the variance of analysed passive design measures.

Furthermore, concerning the cooling energy use of the analysed building models, good cooling energy efficiency can be achieved using passive design measures under the Ljubljana climate. For the 1981–2010 period, the majority (i.e., 89%) of building models can be classified into the A1 cooling energy-efficient label, while the remaining 11% fall at least in class B2 (i.e., 25 < Q_{NC} > 35 kWh/m^2). However, the cooling energy efficiency of the analysed buildings is projected to decrease significantly over time. The share of the most energy-efficient building models (i.e., label A1) is projected to decrease by 66 p.p. between 1981–2010 and 2071–2100 periods with the A2, B1, B2 and C cooling energy efficiency labels increasing proportionally (Figure 1). After the 2041–2070 period, building models classified under labels C (5% in 2071–2100 period) and D (0.01% in 2071–2100 period) appear, which were not present before. Therefore, by the end of the 21st century, the Q_{NC} of each building model is expected to increase by at least 59%, compared to the 1981–2010 period. For some instances, the Q_{NC} increased from zero in 1981–2010 to up to 10 kWh/m^2 by the end of the 21st century. Table 5 presents the limits (i.e., variance) of building model parameters necessary for achieving a specific cooling energy efficiency label under the 2071–2100 climate file. In order to maintain the A1 cooling energy efficiency label in the future, the "freedom of choice" (i.e., min-max range) for the values of the varied parameters is not as limited as for heating energy use. Nevertheless, lower than the entire sample average U_W, WFR, and α_{sol}, and higher than average DHC and NV_C should be used.

Table 4. Typical building parameter values by heating energy label using the 1981–2010 climate file (i.e., "current" label).

Variable Parameter		Heating Energy Label in the 1981–2010 Period (i.e., "Current" Label)							
		B1	**B2**	**C**	**D**	**E**	**F**	**G**	**Entire Sample Average**
U_O [W/m^{2}K]	mean	0.10	0.10	0.16	0.34	0.63	0.90	0.99	0.43
	min	0.10	0.10	0.10	0.10	0.30	0.50	0.80	0.10
	max	0.10	0.15	0.40	0.80	1.00	1.00	1.00	1.00
U_W [W/m^{2}K]	mean	0.60	0.86	1.40	1.56	1.54	1.57	1.60	1.50
	min	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60
	max	0.60	1.80	2.40	2.40	2.40	2.40	2.40	2.40
WFR [%]	mean	41.2	29.4	24.5	25.2	24.6	22.8	19.7	24.6
	min	35.0	10.0	5.0	5.0	5.0	5.0	5.0	5.0
	max	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0
W_{dis} [-]	mean	1.00	0.75	0.48	0.42	0.43	0.45	0.39	0.45
	min	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	max	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
f_0 [m^{-1}]	mean	0.79	0.81	0.85	0.87	0.88	0.90	1.07	0.88
	min	0.78	0.78	0.78	0.78	0.78	0.78	0.80	0.78
	max	0.80	1.08	1.08	1.08	1.08	1.08	1.08	1.08
DHC [kJ/m^{2}K]	mean	146	109	104	102	102	101	100	102
	min	146	63	63	63	63	63	63	63
	max	146	146	146	146	146	146	146	146
α_{sol} [-]	mean	0.75	0.55	0.52	0.51	0.50	0.46	0.34	0.50
	min	0.60	0.20	0.20	0.20	0.20	0.20	0.20	0.20
	max	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80

Table 5. Typical building parameter values by cooling energy label using the 2071–2100 climate file.

Variable Parameter		Cooling Energy Label in the 2071–2100 Period (i.e., Projected Label)						
		A1	**A2**	**B1**	**B2**	**C**	**D**	**Entire Sample Average**
U_O [W/m^{2}K]	mean	0.44	0.42	0.41	0.44	0.57	0.99	0.43
	min	0.10	0.10	0.10	0.10	0.10	0.80	0.10
	max	1.00	1.00	1.00	1.00	1.00	1.00	1.00
U_W [W/m^{2}K]	mean	1.36	1.43	1.51	1.69	1.86	2.27	1.50
	min	0.60	0.60	0.60	0.60	0.60	1.80	0.60
	max	2.40	2.40	2.40	2.40	2.40	2.40	2.40
WFR [%]	mean	13.2	20.4	29.5	35.0	38.2	44.6	24.6
	min	5.0	5.0	5.0	5.0	5.0	40.0	5.0
	max	45.0	45.0	45.0	45.0	45.0	45.0	45.0
W_{dis} [-]	mean	0.49	0.46	0.37	0.46	0.52	0.92	0.45
	min	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	max	1.00	1.00	1.00	1.00	1.00	1.00	1.00
f_0 [m^{-1}]	mean	0.90	0.89	0.88	0.84	0.83	0.79	0.88
	min	0.78	0.78	0.78	0.78	0.78	0.78	0.78
	max	1.08	1.08	1.08	1.08	1.08	0.80	1.08
DHC [kJ/m^{2}K]	mean	110	106	102	93	79	63	102
	min	63	63	63	63	63	63	63
	max	146	146	146	146	146	63	146
α_{sol} [-]	mean	0.35	0.49	0.54	0.61	0.69	0.80	0.50
	min	0.20	0.20	0.20	0.20	0.20	0.80	0.20
	max	0.80	0.80	0.80	0.80	0.80	0.80	0.80
NV_C [h^{-1}]	mean	4.6	4.0	3.9	3.6	3.1	2.8	4.0
	min	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	max	8.0	8.0	8.0	8.0	8.0	8.0	8.0

3.2. Climate-Change Vulnerability

The above-presented results indicate that heating energy efficiency is projected to improve over time under the projected climate change scenario. Therefore, the overheating vulnerability analysis for each building model was made according to the heating energy efficiency label attainted under the 1981–2010 climate, as explained in Section 2.3. Figure 2 shows that models with different heating energy efficiency labels also have different overheating vulnerability score (OV score). However, since radiative forcing and global average temperatures are projected to increase over time due to climate change, the overheating risk of buildings is expected to follow that pattern. Consequently, the OV score is highest for buildings evaluated under the 2071–2100 climate (Figure 2).

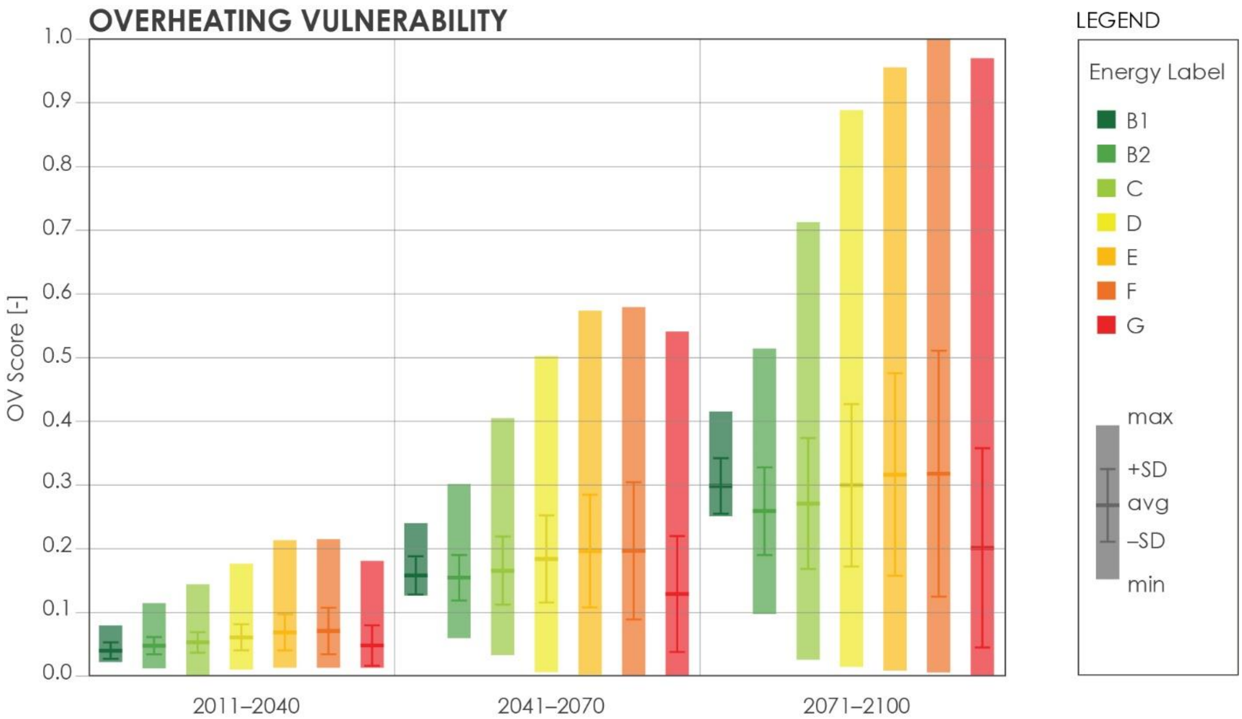

Figure 2. Overheating vulnerability score (OV score) of single-family houses in each future climate period. Building models are classified by heating energy label attained according to the 1981–2010 climate file, namely "current" heating energy label.

The average OV score is projected to increase similarly for all the energy labels. Building models classified under the B2 and C heating energy efficiency labels display on average the lowest susceptibility to increasing overheating vulnerability over the studied period. In particular, the average OV score of the B2 label buildings increases by 0.213 from 0.041 in 2011–2040 to 0.256 in 2071–2100. Simultaneously, the min-max range increases substantially from 0.093 in 2011–2040 to 0.413 in 2071–2100. Although the lower average OV score in 2041–2070 and 271–2100 periods are reached for the G labelled buildings, these buildings are also characterised by one of the highest min-max ranges (i.e., 0.971 in 2071–2100). Consequentially, this indicates that they have on average a low overheating risk, although individual building configurations can be very susceptible to it. The OV score min-max range is the narrowest in most heating energy-efficient buildings (i.e., B1 label), meaning that the overheating vulnerability is easier to control for highly heating energy-efficient buildings. Nevertheless, it should be stressed that buildings with the highest heating energy efficiency are generally not characterised by the lowest OV scores. Although in the 2011–2040 period, the B1 label buildings actually have the lowest average OV score (i.e., 0.034), the reached minimum score (i.e., 0.025) is higher than in the case of all other heating energy efficiency labels. The described situation is projected to escalate in the second part of the 21st century when the OV score of the B1 label buildings increases substantially (Figure 2). So much so that in the 2041–2070 period, the B2 and G labelled buildings have a lower average OV score, while in the 2071–2100 period, the B2, C, and G labelled buildings have lower average scores. This indicates that highly heating energy-efficient bioclimatic buildings (i.e., B1 label) are also characterised by substantial locked-in overheating risk. The main reason is that these models have south-concentrated large window areas (i.e., WFR higher than 35%, see Table 4). On the other hand, the maximum OV score of the B1 labelled buildings is the lowest in all periods (Figure 2). Therefore, when using passive design measures for high heating energy efficiency, an overall lower maximum OV score can be expected than in other designs (i.e., B2 to G labelled buildings).

The overall lowest overheating vulnerability score was achieved by a building model having poor thermal insulation (U_O = 1.0 W/m^{2}K, namely 2 cm of thermal insulation), highly thermally insulated windows (U_W = 0.6 W/m^{2}K, SHGC = 0.45), minimal window areas (WFR = 5%), a non-compact shape (f_0 = 1.08), high thermal mass (DHC = 146 kJ/m^{2}K), light-coloured external surfaces (α_{sol} = 0.20) and high rates of natural ventilation cooling (NV_C = 8 h^{-1}). Its Q_{NC} is projected to increase from 0.0 kWh/m^2 in the 1981–2010 period to 3.2 kWh/m^2 in 2071–2100. However, the building model is highly energy inefficient from the aspect of heating energy use (i.e., G heating energy efficiency label). On the other hand, the most overheating vulnerable building model is characterised by poor thermal insulation (U_O = 1.0 W/m^{2}K), low thermally insulated windows (U_W = 2.2 W/m^{2}K, SHGC = 0.75), equally distributed extremely large window area (WFR = 45%), a compact shape (f_0 = 0.78), high thermal mass (DHC = 146 kJ/m^{2}K), dark-coloured external surfaces (α_{sol} = 0.80) and without natural ventilation cooling (NV_C = 0 h^{-1}). Its heating energy efficiency is classified under the F label, while its Q_{NC} is projected to increase by 37.7 kWh/m^2, from 12.7 kWh/m^2 in the 1981–2010 period to 50.4 kWh/m^2 in 2071–2100, an increase of 297%. Table 6 shows typical values of building parameters by OV score percentiles. It can be concluded that, in general, the least prone to overheating (i.e., p05 in Table 6) were building models with above-average U_O, W_{dis}, f_0, DHC, and NV_C, and below-average U_W, WFR, and α_{sol}.

Table 6. Typical building parameter values by long-term (2071–2100) overheating vulnerability score (OV score) percentiles.

Variable Parameter		Long-Term (2071–2100) OV Score Percentiles						
		p05	**Q1**	**Q2**	**Q3**	**Q4**	**p95**	**Entire Sample Average**
U_O [W/m^{2}K]	mean	0.49	0.42	0.41	0.38	0.51	0.74	0.43
	min	0.10	0.10	0.10	0.10	0.10	0.10	0.10
	max	1.00	1.00	1.00	1.00	1.00	1.00	1.00
U_W [W/m^{2}K]	mean	1.30	1.35	1.40	1.51	1.74	1.78	1.50
	min	0.60	0.60	0.60	0.60	0.60	0.60	0.60
	max	2.40	2.40	2.40	2.40	2.40	2.40	2.40
WFR [%]	mean	9.6	13.8	20.8	29.6	34.0	34.2	24.6
	min	5.0	5.0	5.0	5.0	5.0	5.0	5.0
	max	40.0	45.0	45.0	45.0	45.0	45.0	45.0
W_{dis} [-]	mean	0.49	0.52	0.46	0.42	0.38	0.26	0.45
	min	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	max	1.00	1.00	1.00	1.00	1.00	1.00	1.00
f_0 [m^{-1}]	mean	0.94	0.89	0.89	0.87	0.85	0.85	0.88
	min	0.78	0.78	0.78	0.78	0.78	0.78	0.78
	max	1.08	1.08	1.08	1.08	1.08	0.80	1.08
DHC [kJ/m^{2}K]	mean	114	108	106	100	95	85	102
	min	63	63	63	63	63	63	63
	max	146	146	146	146	146	63	146
α_{sol} [-]	mean	0.24	0.35	0.49	0.51	0.64	0.74	0.50
	min	0.20	0.20	0.20	0.20	0.20	0.80	0.20
	max	0.80	0.80	0.80	0.80	0.80	0.80	0.80
NV_C [h^{-1}]	mean	4.7	4.7	4.0	3.9	3.4	3.3	4.0
	min	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	max	8.0	8.0	8.0	8.0	8.0	8.0	8.0

4. Discussion

In the bioclimatic design of buildings, the decision-making conditions are diverse, with several design objectives and criteria to be considered, particularly occupant comfort, energy efficiency, and daylighting [55–57]. In practice, trade-offs between these goals are very common, which need to be addressed appropriately. Only the energy efficiency aspect for providing thermal comfort was undertaken as a central part of this study, while occupant thermal comfort, indoor air quality and daylighting were not directly addressed. Therefore, the presented results should be interpreted in the exposed context. Similarly, the results should be understood in the framework of the applied passive design parameters and their value ranges. At the same time, several other design measures, such as evaporative cooling, fixed shading, sunspace, ground heat exchanger cooling, etc., were excluded from the analysis. Their exclusion from the analysis was based on the fact that they are either not common in the design practice (e.g., ground heat exchanger cooling) or ineffective (e.g., evaporative cooling) in the studied climatic context. Under these circumstances, the paper aimed to analyse the energy efficiency and overheating vulnerability of bioclimatic single-family houses in the Central European climate of Slovenia, Ljubljana. The energy efficiency was evaluated according to the annual energy use for heating (Q_{NH}) and cooling (Q_{NC}) per m^2 of building floor area. According to the Slovenian building energy efficiency rules, a B1 heating energy efficiency class was the highest achievable using the selected passive design parameters under the currently applicable climate file (i.e., 1981–2010 period) and the projected future climate scenarios. Nevertheless, a much warmer future climate is projected to improve the heating energy efficiency of such buildings because the energy needed for heating is projected to decrease.

Furthermore, it was highlighted that given the uncertainties of future climate, it is advisable to design buildings for current heating energy efficiency while aiming for low vulnerability to future overheating. Accordingly, Figure 3 displays three conceptual examples of a bioclimatic building designed for the analysed Central European temperate climate of Ljubljana. These three concepts were proposed after the interpretation of the study results. The first building (Figure 3a) corresponds to the B1 label heating energy efficiency with simultaneously the lowest overheating vulnerability score (OV score) of the buildings in the B1 energy label. Next, Figure 3b shows the building design, which meets the B2 label heating energy efficiency with the lowest OV score of the buildings in the B2 energy label. The last building (Figure 3c) is the least overheating vulnerable building design of the buildings that fall into the C label according to the heating energy efficiency. The Q_{NH} value of each exposed building example intensifies from 24.7 kWh/m^2 (building B1) to 49.0 kWh/m^2 (building C) according to the 1981–2010 climate. At the same time, the Q_{NC} follows the reverse trend. Namely, according to the 2071–2100 climate, the Q_{NC} is highest for building B1 (18.6 kWh/m^2) and lowest for building C (4.1 kWh/m^2).

Although the best performing concept concerning the heating energy efficiency is the B1 building design (Figure 3a), it has several drawbacks regarding bioclimatic design. According to Potočnik and Košir [58], window size and glazing transmissivity are the dominant parameters to achieve adequate visual and non-visual indoor comfort. Therefore, vast south-concentrated window areas present a significant daylighting related drawback since they would be mainly shaded during summer. In contrast, during the rest of the year, glare might occur while utilising solar gains. On the other hand, building C, shown in Figure 3c, has minimal windows, resulting in potentially inadequate daylighting. It is also less heating energy-efficient than the other two presented design alternatives. Moreover, while using the WFR of 35% (Figure 3a), a natural summer ventilation rate (i.e., NV_C) above 4 h^{-1} is recommended to achieve lower overheating vulnerability, which is, in reality, very hard and rarely achievable in residential buildings [59]. Although high-intensity natural ventilation is also preferred in the case of building B2 (Figure 3b), it is not as crucial. The reason is that building B2 has a smaller WFR, and thus solar heat gains and indoor surface temperatures are more governable. In all the best performing three cases, the lowest analysed U_O and U_W were used.

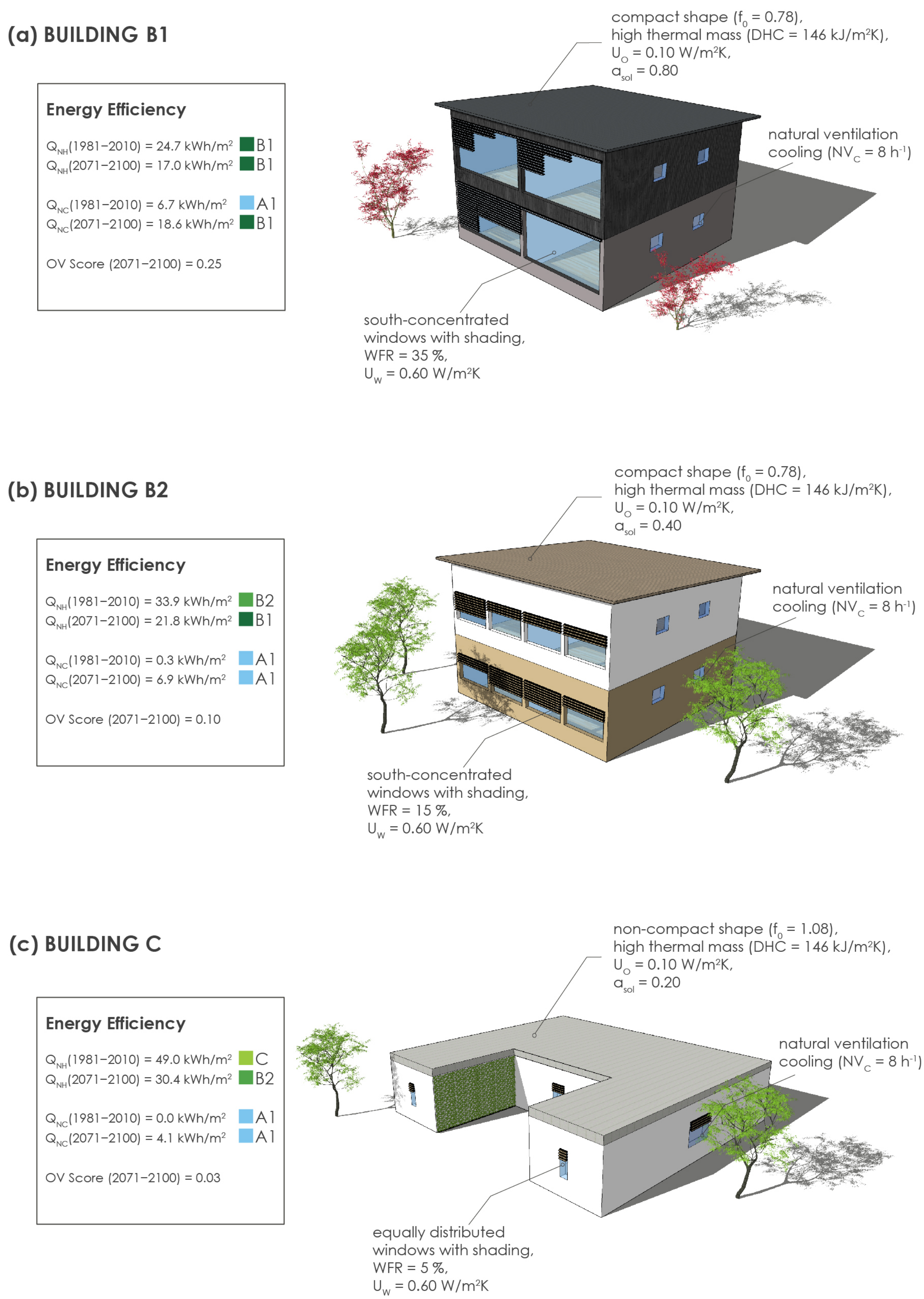

Figure 3. Three conceptual examples of bioclimatic building design for the analysed location. Examples represent a building of the most overheating resilient combination of passive measures for a building in: (**a**) B1 heating energy efficiency class; (**b**) B2 heating energy efficiency class; (**c**) C heating energy efficiency class. Each building has a useful floor area equal to 162 m^2.

Another fact worth noting is that the difference in Q_{NH} between different examples in Figure 3 is projected to halve by the end of the century, while the difference in Q_{NC} is projected to double or triple. Assume both heating and cooling energy use (i.e., Q_{NH} + Q_{NC}) of the three buildings are taken together. In this case, it becomes evident that building B1 (Q_{NH} + Q_{NC} = 31.4 kWh/m^2) is the best performing in the 1981–2010 period, while building B2 (Q_{NH} + Q_{NC} = 28.7 kWh/m^2) is the best performing and building B1 is the worst performing (Q_{NH} + Q_{NC} = 35.6 kWh/m^2) in the 2071–2100 period. Furthermore, of the three, building B1 is the only one with higher cumulative heating and cooling energy use in the 2071–2100 period compared to the 1981–2010 period. Therefore, to achieve adequate heating energy efficiency, assure low overheating vulnerability, and at the same time create conditions for adequate daylighting, the combination of passive design measures presented in the case of building B2 (Figure 3b) or similar should be used. Of course, the highlighted findings are limited to the building geometries and envelope configurations considered. Therefore, substantially differently configured buildings may be designed while being aware of their effects on energy use.

Accordingly, it is recommended to use highly thermally insulated building envelopes, especially windows. Furthermore, not too large window areas should be adopted, e.g., WFRs in the range of 10–25%. The windows can be concentrated on the south façade (e.g., window to wall ratio (WWR) between 20 and 60%) for autumn–spring solar harvesting. South concentrated windows also prevent unwanted solar gains in the forenoon and the afternoon during summer. Accordingly, fixed overhangs on the south façade can be used for partial shading. However, in the case of south-concentrated windows, external shading (e.g., blinds) of the entire glazed surface for overheating prevention should be applied. Furthermore, shading operation should be automatically controlled since the overheating risk would be higher if shading devices were manually controlled by occupants [60]. Concerning the building shape, a more compact design is recommended. It is also suggested to use massive construction materials to increase the thermal capacity of the building. Otherwise, the thermal mass should be added in other forms, such as capacitive furniture [61] or phase change materials [62]. Although the B1 heating energy efficiency class can only be achieved using dark coloured external surfaces, it is recommended to use lighter colours (e.g., α_{sol} = 0.40–0.60) that reduce overheating vulnerability. Alternatively, vegetated surfaces (see Figure 3c) [63] or "cool" surface finishes [64] may be used to act as an effective overheating prevention measure. It is advisable to cool spaces using natural ventilation in summer when conditions allow, typically during the night. To this end, cross ventilation or stack ventilation of the building should be made possible by the appropriate arrangement of rooms and openings.

In addition to the presented and proposed passive design measures, additional either active or passive measures could be applied to reduce the energy use of a building. In particular, heating energy efficiency can be further improved by applying the heat recovery mechanical ventilation, improving the airtightness of the envelope, optimising occupant behaviour and similar. Besides, renewable energy sources, such as solar energy through PV or BIPV systems or solar collectors, are advisable [65]. In either case, an emphasis should be placed on long-term overheating vulnerability and not just current heating and cooling energy efficiency. In this way, high resilience and sustainability of the built environment may be achieved, primarily by raising the awareness of designers and policymakers.

5. Conclusions

Our civilisation faces the same frustration as the first humans—a struggle to build homes that provide safety and climate independence. As the presented research has demonstrated, the effort continues, while we still have a lot to learn about global warming and its implications for the (energy) performance of the built environment, especially with a limited amount of natural resources. The study successfully demonstrated a novel approach to the bioclimatic design of buildings by attaining current and future energy efficiency while also addressing climate adaptation and overheating resistance. The results of this paper clarify the overall picture concerning the design of bioclimatic residential buildings in the Central European climate. The main conclusions and novelty of the paper can be summarised as:

- The paper demonstrates how to assess overheating vulnerability of bioclimatic buildings. In Central Europe, overheating vulnerability is a significant but often overlooked concern in building design, as designers and policymakers focus primarily on heating energy efficiency. However, overheating vulnerability assessment is required since climate change is projected to negatively affect the cooling energy need of buildings, especially those designed for passive solar energy harvesting during the colder part of the year.
- Recommendations for the energy-efficient resilient bioclimatic building design in Central European temperate climate are given. Such recommendations are needed because residential buildings under this climate are heating-dominated, and with a warming climate comes the risk of overheating. Nevertheless, adapting buildings to current heating energy efficiency requirements while aiming for low vulnerability to future overheating can be achieved with reasonable trade-offs presented in the paper.
- Lastly, the results provide designers and policymakers with information to adopt a resilient bioclimatic building design approach into practice and regulations. A clear path towards the resilience and sustainability of buildings should be defined according to the study findings to preserve resources and mitigate climate change.

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PRILOGA E

BcChart v2.0 – a tool for bioclimatic potential evaluation

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BcChart v2.0 – a tool for bioclimatic potential evaluation

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Abstract

As bioclimatic design is becoming increasingly important in contemporary buildings, various analytical tools must be developed and introduced to the designers in order to guide them through the design process. Therefore, the BcChart v2.0 software was developed. It executes bioclimatic potential analysis of a location based on the theory of Olgyay's bioclimatic chart. The main advantage of the introduced tool, in contrast to other bioclimatic analysis tools, is that it directly considers the influence of solar radiation, which is factored through substitutive daily comfortable dry-bulb air temperature. The paper presents the theoretical background of the tool. Additionally, the capabilities and functionality of the software are demonstrated through bioclimatic analysis of two different locations with contrasting climates (i.e. Ljubljana, Slovenia and Abu Dhabi, UAE). The conclusions highlight the importance of considering solar radiation when performing bioclimatic analysis of a location in order to thoughtfully design bioclimatic buildings.

Keywords: bioclimatic analysis, climate analysis, bioclimatic potential, bioclimatic chart, solar radiation, sustainable building

1. Introduction

Bioclimatic building design is one of the key approaches to the design of buildings of the future. A building can be declared bioclimatic when it efficiently uses climatic resources of its location (Krainer, 2008). An aforementioned adapted building simultaneously provides comfortable indoor environment and efficiently uses energy sources, primarily with the help of building envelope elements. Although the use of bioclimatic design in architecture and construction industry was introduced decades ago by Victor Olgyay (1963), it was in some way overlooked by the designers and researchers. However, in recent years, research in the field of bioclimatic design is on the rise, as living comfort, energy use and climate change have been brought into the spotlight. Thus, several studies have been made encouraging the bioclimatic approach to building design. The most recent research by Pajek and Košir (2017), by Khambadkone and Jain (2017), or the one by Manzano-Agugliaro et al. (2015) highlighted the importance of bioclimatic analysis of a specific location in order to define the most efficient bioclimatic design strategies to be integrated into buildings.

Several tools can be used to bioclimatically asses a location. In this respect, the most elementary bioclimatic chart was developed by Olgyay (1963) or in a different form by Givoni (1969). Furthermore, new tools for bioclimatic analysis have been made by several other authors (Rohles et al., 1975; Arens et al., 1980; Al-Azri et al., 2013; Martínez and Freixanet, 2014; University of California, 2017). Martínez and Freixanet (2014) presented a comprehensive bioclimatic analysis tool, named BAT. It enables plotting of bioclimatic charts and several other graphs on the basis of climate data imputed by the user. Nonetheless, too many items of information given by BAT can disorient the user, thus lowering the user-friendliness of this tool. Furthermore, the main deficiency of the BAT tool is that the impact of solar radiation is not directly incorporated into the main bioclimatic analysis but is rather presented in a separate section. Another example of a broadly used bioclimatic analysis tool is also Climate Consultant software designed at the University of California, USA (University of California, 2017). The results of climate analysis performed by the Climate Consultant tool give its users an insight into climate specifics of a certain location. The tool also guides the user towards appropriate building design through a set of design strategies necessary to achieve human comfort with either passive or active solutions. However, similar as the BAT tool, Climate Consultant does not directly consider solar radiation in the determination of comfort conditions.

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To summarise, there exist several tools that can be used for a bioclimatic analysis in order to define possible passive building design measures. However, the above referenced tools do not sufficiently consolidate the influence of solar radiation into the calculations and consequential bioclimatic potential of a given location. This is of special interest in the case of locations with temperate and cold climatic characteristics. Although solar radiation is mostly presented as one of the decisive factors influencing bioclimatic potential, its influence is never directly incorporated into bioclimatic potential calculations. It is rather used comparatively as a separate quantity detached from the external air temperature and relative humidity. Such comparison between the two is relevant, but it is also likely prone to human errors. Bioclimatic location analysis is one of the most important initial steps when designing buildings. Thus, a tool used for the analysis must be on one hand very precise and user-friendly on the other. Nonetheless, it is crucial that bioclimatic analysis tool is freely available to the interested audience, as this will widen the number of designers applying bioclimatic solutions to their projects. All mentioned above is taken into account with BcChart v2.0 – a bioclimatic potential analysis tool, developed by the authors and presented in this paper.

2. Description of applied methodology

2.1 BcChart software and bioclimatic charts

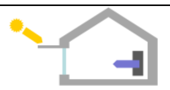
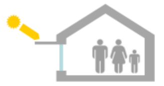
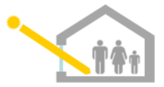
The BcChart v2.0 software was developed at the University of Ljubljana, Slovenia, and has been validated and evaluated through the educational process at the Faculty of Civil and Geodetic Engineering. It can be used for the calculations of bioclimatic potential based on the theory of Olgyay's bioclimatic chart (Olgyay, 1963). Bioclimatic charts are initiated with human comfort, which is calculated for an average person. The basic input climate parameters are average minimum and maximum daily air temperature (*T*) and relative humidity (*RH*). However, in addition to the basic bioclimatic chart input data, the mean and maximum daily solar irradiation is also factored in, resulting in modifications of Olgyay's bioclimatic chart plots. Nonetheless, it has to be noted that the modifications of bioclimatic charts are made only when additional influence of solar irradiation does not cause overheating. In other words, it is presumed that whenever the solar irradiation could cause overheating, effective shading will be used (i.e. when ambient temperatures on the bioclimatic chart are above shading line). Thus, the substitutive daily comfortable dry-bulb air temperature for month *i*, $T_{sub,i}$ is introduced (Equation 1). The derivation of the calculations made with BcChart v2.0 is Equation 1, based on the equation for human body thermal equilibrium, presented by Olgyay (1963). Equation 2 is introduced to describe the influence of actually received solar irradiation.

$$T_{sub,i} = \frac{T_S - (M_m - E + R_i) \times (Clo/c + V.Clo/c)}{S \times S_c} \qquad \text{(eq. 1)}$$

$$R_i = G_i \times S_e \times \alpha \qquad \text{(eq. 2)}$$

Where R_i is radiation in W for month *i*, G_i is the mean daily global solar irradiance in W/m^2 for month *i*, S_e is the effective radiation area for a given subject in a given position and it is assumed as 0.5 m^2, and α = 0.4 is the absorptivity of the radiated surface of a clothed man. T_s is comfortable skin temperature, presumed as 33.9°C, M_m is the observed rate of metabolism 126 W, *E* is the rate of cooling due to perspiration actually evaporated 38 W, *Clo/c* + *V.Clo/c* is clothing insulation and air effect on clothing coefficient (= 0.28) as defined by Olgyay (1963) and adapted to be expressed in m^{2}K/W. *S* is the mean body surface area of clothed man, assumed as 2.14 m^2 and S_c is the fraction of surface areas exposed to radiation and convection (= 0.9). Furthermore, the dry-bulb air temperature at which the passive solar heating (PSH) is still possible ($T_{PSH,i}$) was calculated using maximal daily global horizontal solar irradiance for each month ($G_{max,i}$). The plotted parts on bioclimatic chart, which are below this temperature, represent the part of each month, when passive solar heating cannot be used as an efficient passive strategy, because there is not enough solar energy available at a given location. Therefore, instead of the mean daily global solar irradiance (G_i) in Equations 1 and 2, the maximal values of solar radiation were used ($G_{max,i}$). T_{sub} and T_{PSH} were used only when modified bioclimatic charts were plotted, i.e. the solar radiation was directly incorporated into calculations. The main output of the BcChart v2.0 software is bioclimatic potential of the analysed location. It represents the time, expressed in % and presented either on yearly or monthly level, when the plotted combinations of temperature, relative humidity and solar irradiance fall either in or out of the comfort zone.

Tab. 1. Bioclimatic potential segments as calculated by BcChart.

Label	Colour	Bioclimatic potential	Suggested bioclimatic strategy
Q		mechanical cooling and/or dehumidification needed	
A		potential for passive solutions for hot arid climates	
V		natural ventilation needed	
M		natural ventilation and/or high thermal mass needed	
C_{sh}		comfort achieved with shading	
C_{sn}		comfort achieved with solar irradiation	
R		potential for passive solar heating	
H		no potential for passive solar heating	
S_h		shading needed ($S_h = Q + A + M + V + C_{sh}$)	

The described segments in Table 1 were calculated for every distinct month according to the length of the line plotted by using combinations of monthly average input climate data (Equation 3–14).

$$Q = \sum \frac{x_{q_j}}{l_j} \times \frac{100}{12} \quad \text{(eq. 3)}$$

$$A = \sum \frac{x_{a_j}}{l_j} \times \frac{100}{12} \quad \text{(eq. 4)}$$

$$V = \sum \frac{x_{v_j}}{l_j} \times \frac{100}{12} \quad \text{(eq. 5)}$$

$$M = \sum \frac{x_{m_j}}{l_j} \times \frac{100}{12} \quad \text{(eq. 6)}$$

$$C_{sh} = \sum \frac{x_{c_j}}{l_j} \times \frac{100}{12} \quad \text{(eq. 7)}$$

$$C_{sn} = \sum \frac{x'_{c_j}}{l'_j} \times \frac{100}{12} - C_{sh} \quad \text{(eq. 8)}$$

$$R = \sum \frac{x_{r_j}}{l_j} \times \frac{100}{12} \quad \text{(eq. 9)}$$

$$R' = \sum \frac{x'_{r_j}}{l'_j} \times \frac{100}{12} \quad \text{(eq. 10)}$$

$$H = \sum \frac{x_{h_j}}{l_j} \times \frac{100}{12} \quad \text{(eq. 11)}$$

$$H' = \sum \frac{x'_{h_j}}{l'_j} \times \frac{100}{12} \quad \text{(eq. 12)}$$

$$l_j = \sum x_{ij} \quad \text{(eq. 13)}$$

$$l'_j = \sum x'_{ij} \quad \text{(eq. 14)}$$

Where j = 1–12 or January–December and $i = q, a, m, v, c, c', r, r', h$ or h'. l_j is the total period of the month (i.e. the sum of x_{qj}, x_{aj}, x_{mj}, x_{vj}, x_{cj}, x_{rj} and x_{hj}). l'_j is the total period of the month considering solar irradiance, which is different from l_j because of the consideration of solar radiation, thus the lengths of x_{ci}, x_{ri} and x_{hi} change. x_{ci} is the period of month (i.e. the length of the plotted line) inside the comfort zone when shading is needed, x'_{ci} is the period of month inside the comfort zone utilizing solar irradiance, x_{vi} is the period of month when ventilation in combination with shading is needed, etc. Definition of each calculated segment and the corresponding suggested bioclimatic strategy are explained in Table 1.

In the cases where the plotted lines fall inside the comfort zone, the achieving of comfort is defined as achieved by shading (C_{sh}) or by the use of solar energy (C_{sn}) (Table 1). Further on, the segments presented in Table 1 may also be combined into three main categories: shading needed ($S_h = Q + A + M + V + C_{sh}$), sun needed ($S_n = C_{sn} + R + H$) and comfort zone ($C_z = C_{sh} + C_{sn}$).

2.2 Limitations

The use of the bioclimatic chart used in the BcChart software is directly applicable only to inhabitants wearing customary indoor clothing, engaged in sedentary or light muscular work, at elevations not in excess of 300 m above sea level. The impact of sun radiation is calculated on the basis of Olgyay (1963), assuming the effective area of human body of 0.5 m^2. Internal heat gains cannot be considered when calculating bioclimatic potential, which can be determined as a limitation of the methodology. Another limitation of the BcChart software is that the borders of comfort zone, which is roughly between 21 and 27°C, cannot be manually modified in order to adapt it to different human comfort conditions.

3. BcChart v2.0 – user interface and functionality

The interface of the BcChart v2.0 software was created in MS Excel environment. It consists of 4 consecutive spreadsheets (see Fig. 1 and Fig. 2) guiding the user from input data to the result interpretation:

- Input data (climatological data and basic information about for the analysed location).
- Bioclimatic chart (plot of basic bioclimatic chart w/o the influence of solar radiation and modified bioclimatic chart w/ solar radiation).
- Bioclimatic potential analysis (interpretation of analysed data through yearly and monthly bioclimatic potential of the location).
- About (theoretical background explanation, copyright and terms of use and author contacts).

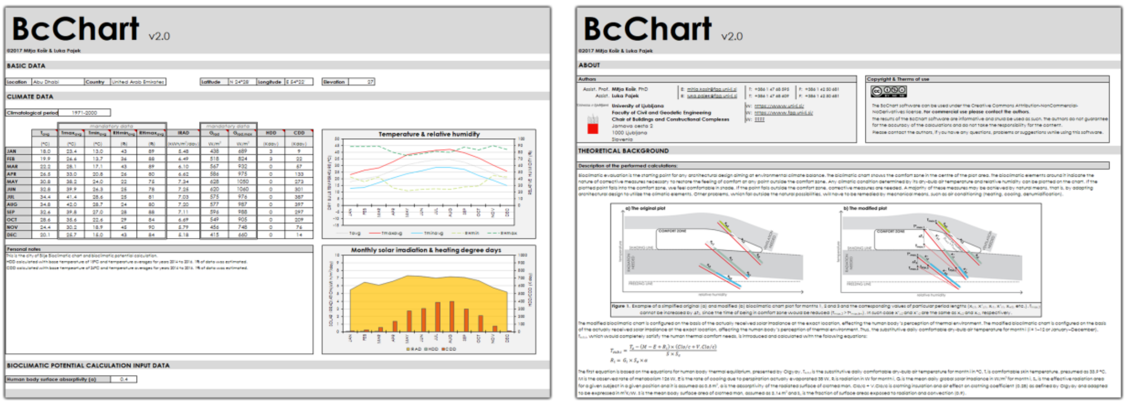


Fig. 1: BcChart v2.0 user interface screen shots: left – Input data (monthly average climatological data), right – About (explanation of calculation background).

In the first spreadsheet named Input data (Fig. 1, left), the user must input the location information data and key climate data used for the calculation of bioclimatic potential. The mandatory data are: average daily maximum ($Tmax_{avg}$) and minimum ($Tmin_{avg}$) dry bulb temperature (°C), average daily maximum ($RHmax_{avg}$) and minimum ($RHmin_{avg}$) relative humidity (%), average (G_{rad}) and maximum ($G_{rad,max}$) global daily irradiance (W/m^2) on the horizontal plane. In addition to the mandatory data necessary for the bioclimatic potential calculation, supplementary climatic characteristics can be entered as well. These are the following: average daily (T_{avg}) dry bulb temperature (°C), average sum of global irradiation ($IRAD$) on the horizontal plane (kWh/m^2) and heating

(*HDD*) and cooling (*CDD*) degree-days (Kday). However, these additional climate data do not influence the bioclimatic potential calculation and are only used in order to enable better interpretation of the bioclimatic analysis. Supplementary data are presented together with the mandatory data through diagrams (Fig. 1, left).

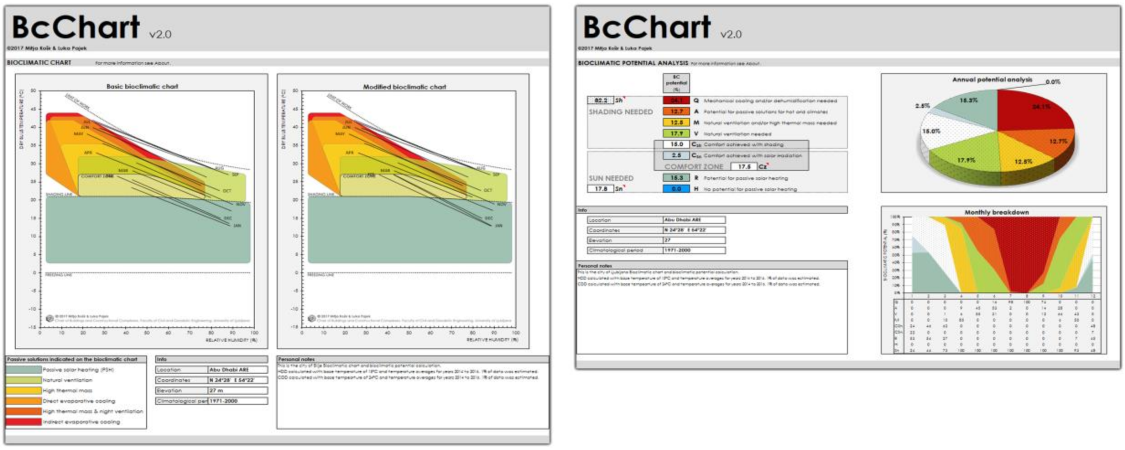


Fig. 2: BcChart v2.0 user interface screen shots: left – Bioclimatic chart (basic and modified bioclimatic chats), right – Bioclimatic potential analysis (yearly cumulative and monthly values of bioclimatic potential).

In the second spreadsheet (i.e. Bioclimatic chart) the basic and modified bioclimatic charts are plotted (Fig. 2, left). In the third spreadsheet (i.e. Bioclimatic potential analysis) the results of the bioclimatic interpretation are given (Fig. 2, right), while the fourth spreadsheet (i.e. About) gives information about the authors, copyright and basic information about used calculation methodology (Fig. 1, right). The results of the bioclimatic analysis can be interpreted directly through the evaluation of bioclimatic chart (Fig. 2, left) and the corresponding passive strategies marked on them, or by the results of yearly and monthly bioclimatic potential calculation (Fig. 2, right), which assist the user in the interpretation of the charts. It must be stressed that the calculated bioclimatic potential with its corresponding evaluation of the most important bioclimatic strategies for the analysed location is only a generic recommendation. Therefore, is up to the user of the software to appropriately apply the proposed solutions to a specific project.

4. Example of performed analysis and discussion

Functionality of the BcChart v2.0 software is presented through the evaluation and determination of bioclimatic potential at two selected characteristic locations. These were chosen in order to demonstrate how the bioclimatic potential analysis is performed with the BcChart v2.0 software. The chosen locations were the following:

- **Ljubljana, Slovenia, Europe** (46.22° N, 14.48°E); Köppen-Geiger climate classification: Cfb (temperate, without dry season, warm summer). In Ljubljana, the minimum average daily dry bulb temperature of –4.9°C occurs in January and the maximum of 26.4°C in July. The lowest average daily minimum *RH* of 43% occurs in July, while the maximum of 98% occurs in October. The lowest average daily global horizontal solar radiation of 17 Wh/m^2 occurs in December and the highest of 687 Wh/m^2 in July.
- **Abu Dhabi, UAE, Middle East** (24.43° N, 54.65°E); Köppen-Geiger climate classification: BWh (arid, desert, hot). In Abu Dhabi, the minimum average daily dry bulb temperature of 13.0°C occurs in January and the maximum of 42.0°C in August. The lowest average daily minimum *RH* of 22% occurs in May, while the maximum of 90% occurs in November. The lowest average daily global horizontal solar radiation of 140 Wh/m^2 occurs in December and the highest of 1020 Wh/m^2 in May.

Firstly, the results of the basic bioclimatic chart analysis (i.e. without considering the influence of solar radiation) are compared with those obtained by Climate Consultant software v6.0 (University of California, 2017) in the section 4.1. Secondly, the results without and with the influence of solar radiation (i.e. basic vs modified bioclimatic chart) are presented in section 4.2. Comparison of the basic and modified bioclimatic potential results will demonstrate the importance and impact of solar radiation on the prevalence of the determined bioclimatic design strategies.

4.1 BcChart vs Climate Consultant

In order to be able to compare the results obtained from both analyses (i.e. BcChart v2.0 and Climate Consultant v6.0), the boundary conditions were equalled as much as possible. Accordingly, the same input climatological data were used, namely the EPW weather data files for Ljubljana and Abu Dhabi (EnergyPlus, 2017). The calculation and the plot of psychrometric chart within Climate Consultant was made according to the ASHRAE Handbook of Fundamentals Comfort Model (up through 2005). Boundaries of comfort zone in the Climate Consultant were set in order to reflect those used by BcChart, i.e. comfort low temperature at 50% *RH* was set to 21°C and comfort high at 50% *RH* was set to 27°C. Minimal dry-bulb temperature when need for shading begins was set to 21°C.

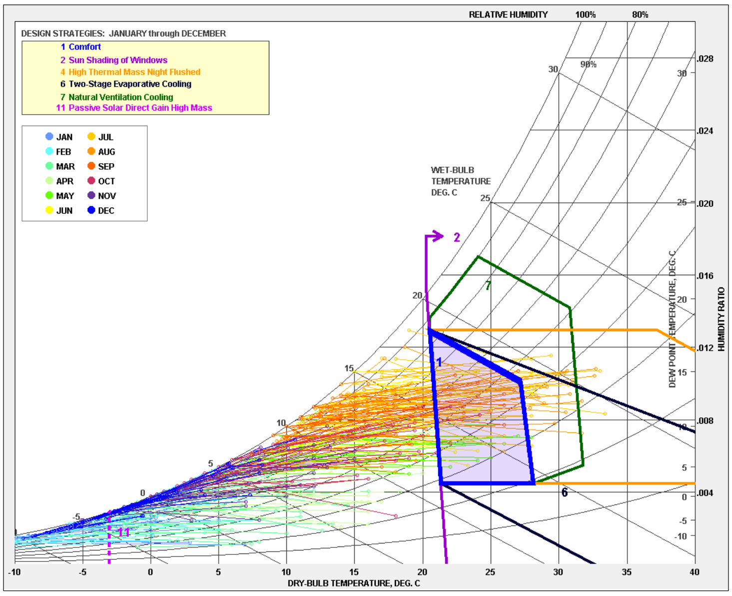


Fig. 3: Bioclimatic analysis for the location of Ljubljana created using Climate Consultant v6.0. Climate data are plotted as daily minimums and maximums in respect to the selected design strategies.

It has to be noted that the results obtained with Climate Consultant are calculated on the basis of hourly climate data, whereas the results obtained with BcChart are calculated using monthly daily averages. Recommended or effective passive measures, displayed on each of the two charts (bioclimatic chart in BcChart and psychrometric chart in Climate Consultant) are comparable but not equivalent. Therefore, a complete equivalency cannot be expected between the results of both tools. Correspondingly, in comparison to BcChart a broader set of passive and active measures is presented and proposed within Climate Consultant. Nevertheless, the results can be to some degree interpreted in such a way to enable the assessment of results between the two applications. For example, value R (for the explanation see Table 1) in BcChart can be compared to design strategy number 11 (i.e. passive solar direct gain, high mass) in Climate Consultant. Similarly, value C_z in BcChart is comparable to design strategy number 1 (i.e. comfort), value V to design strategy number 7 (i.e. natural ventilation), value M to design strategy number 4 (i.e. high thermal mass night flushed) and value A in BcChart to Climate Consultant design strategy number 6 (i.e. two-stage evaporative cooling). Other values found in BcChart (H, Q, C_{sn}, C_{sh}) cannot be directly paired with corresponding strategies proposed by Climate Consultant. All the described passive strategies can be observed and graphically compared in Figures 3 and 4, where the results for Ljubljana calculated with Climate Consultant and BcChart, respectively, are presented.

Because of the different methodology used in each of the selected software and the corresponding results, which cannot be directly compared, the results obtained by BcChart were compared by the Climate Consultant results only through the following three parameters: S_n – sun needed, C_z – comfort zone, S_h – shading needed. These results are presented in Table 2. Value S_n obtained by BcChart can be compared to design strategy number 11 (i.e. passive solar direct gain high mass) in Climate Consultant. Similarly, value S_h can be compared to a sum of design strategies number 1, 13, 14 and 15 in Climate Consultant (i.e. comfort, humidification only, dehumidification only and cooling, add dehumidification if needed). C_z is comparable to design strategy number 1 (i.e. comfort). In order to graphically compare the results, the psychrometric chart from Climate Consultant (Fig. 3) and bioclimatic chart from BcChart (Fig. 4) were plotted for the city of Ljubljana. It can be noted from the results presented in Table 2 that the total sum of all three analysed parameters (S_n, C_z and S_h) is larger than 100%; the reason is that when comfort is achieved, also shading is needed (i.e. the lower boundary of comfort zone overlaps with the shading line – see Fig. 2 and 3). Although the described suggested passive strategies obtained by each of the considered tools are not completely equivalent, a correlation between the results is evident (Tab. 2, Fig. 3 and 4).

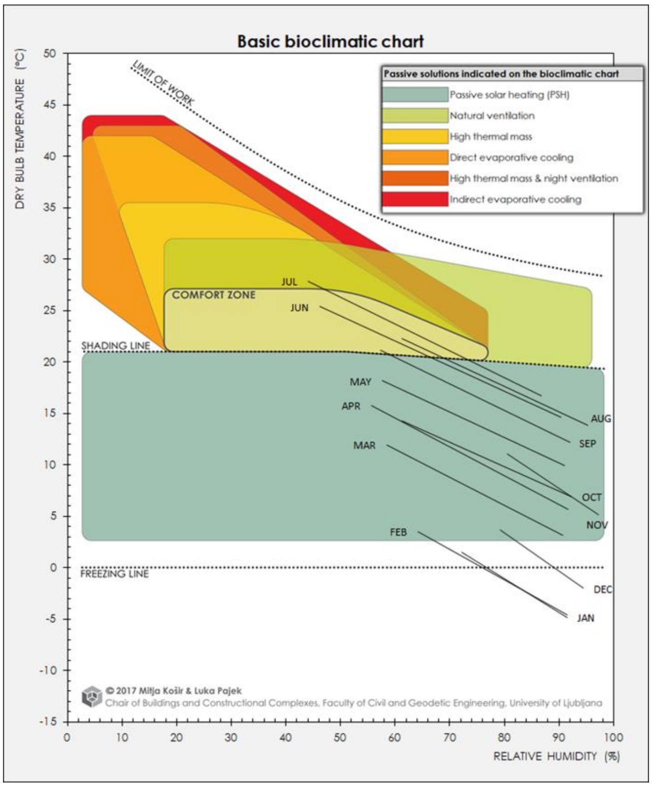


Fig. 4: Basic bioclimatic analysis for the location of Ljubljana created using BcChart v2.0. Climate data is plotted as monthly daily average minimum and maximum in respect to the selected passive solutions.

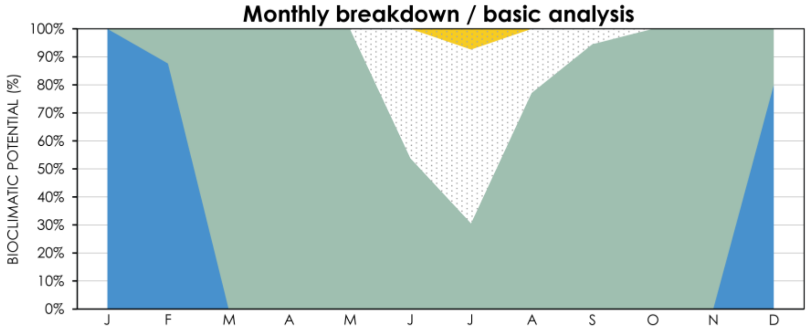
Observing Table 2 it can be concluded that the values of S_n, C_z and S_h, obtained by either BcChart or Climate Consultant are closer together in the case of Ljubljana. The latter was expected since the methodology, which runs in the background of the BcChart software, is more appropriate for the analysis of locations with temperate climate, rather than for locations with hot-arid, hot-humid or polar climate. The differences between the results obtained by BcChart and Climate Consultant in the case of the two selected locations range from 1.3 percentage points (pp) in the case of S_h and 3.9 pp for value C_z, both in Ljubljana (Tab. 2). The observed differences are most probably the consequence of differently processed climate data – Climate Consultant uses hourly, while BcChart uses monthly climate data. Additionally, dissimilarities in the results could also stem from different boundaries of passive (bioclimatic) strategies in both tools (i.e. the "areas of specific passive strategies" in the charts are not equivalent). Nonetheless, the obtained results in both applications can be considered as equivalent. Especially, if a substantial difference in the inputted climatic data is taken into account.

Tab. 2. The selected comparable parameters obtained by bioclimatic analysis using BcChart and Climate Consultant and their absolute differences.

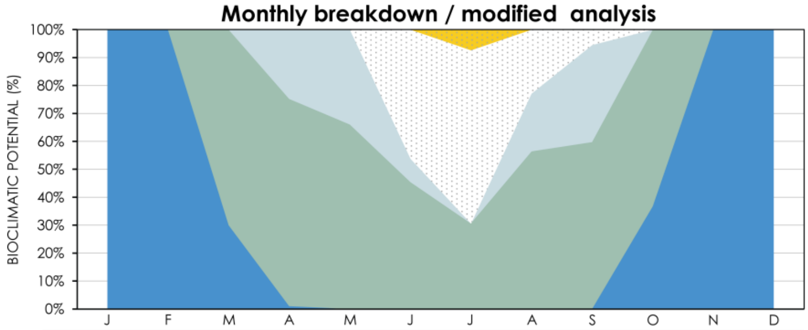
	Abu Dhabi			**Ljubljana**		
	S_n	C_z	S_h	S_n	C_z	S_h
BcChart	17.8%	15.0%	82.2%	87.9%	11.5%	12.1%
Climate Consultant	21.2%	11.3%	78.8%	89.2%	7.6%	10.8%
|Δ|	3.4 pp	3.7 pp	3.4 pp	1.3 pp	3.9 pp	1.3 pp

4.2 Consideration of solar radiation and its effect on BcChart results

In order to assess the influence of the considered solar radiation influence on the BcChart tool results, this section studies monthly breakdown of bioclimatic potential with basic (i.e. original method – no direct consideration of solar radiation) and modified analysis (i.e. actually received solar radiation is included into the calculation) for both locations (i.e. Ljubljana and Abu Dhabi). Figures 5 and 6 represent basic and modified bioclimatic potential for Ljubljana and Abu Dhabi, respectively.



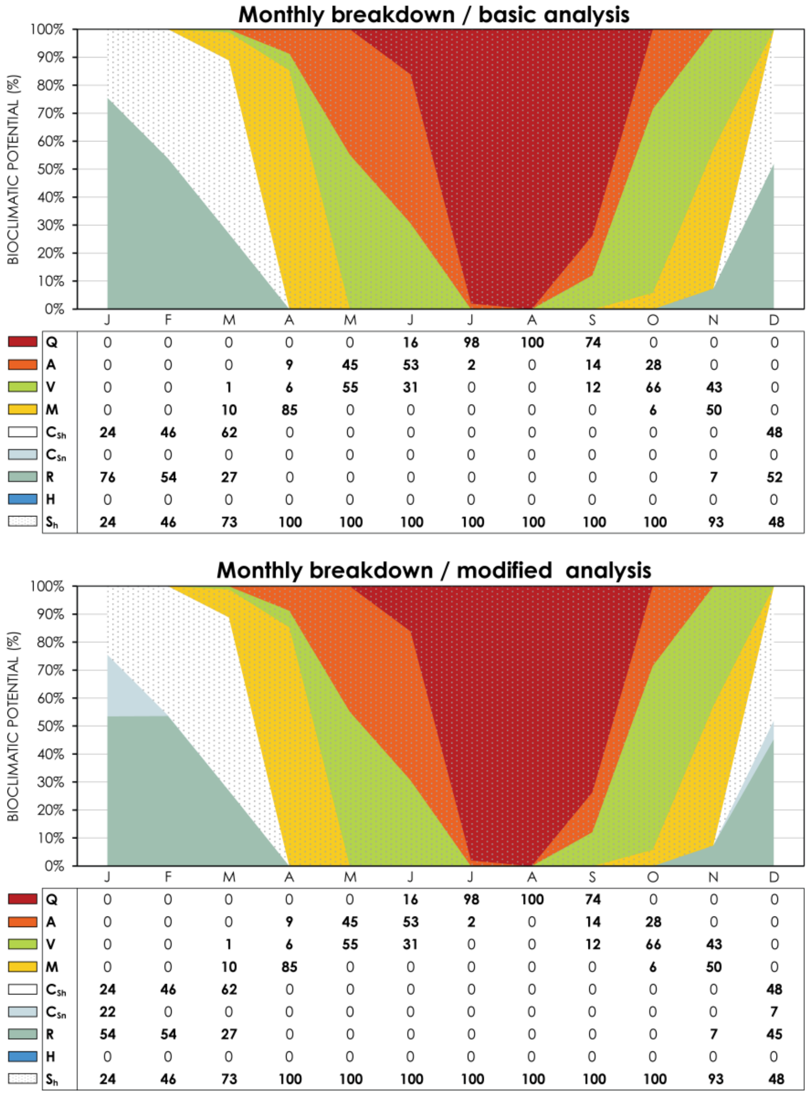
	J	F	M	A	M	J	J	A	S	O	N	D
Q	0	0	0	0	0	0	0	0	0	0	0	0
A	0	0	0	0	0	0	0	0	0	0	0	0
V	0	0	0	0	0	0	0	0	0	0	0	0
M	0	0	0	0	0	0	**7**	0	0	0	0	0
C_{sh}	0	0	0	0	0	**46**	**62**	**23**	**5**	0	0	0
C_{sn}	0	0	0	0	0	0	0	0	0	0	0	0
R	0	**12**	**100**	**100**	**100**	**54**	**31**	**77**	**95**	**100**	**100**	**20**
H	**100**	**88**	0	0	0	0	0	0	0	0	0	**80**
S_h	0	0	0	0	0	**46**	**69**	**23**	**5**	0	0	0



	J	F	M	A	M	J	J	A	S	O	N	D
Q	0	0	0	0	0	0	0	0	0	0	0	0
A	0	0	0	0	0	0	0	0	0	0	0	0
V	0	0	0	0	0	0	0	0	0	0	0	0
M	0	0	0	0	0	0	**7**	0	0	0	0	0
C_{sh}	0	0	0	0	0	**46**	**62**	**23**	**5**	0	0	0
C_{sn}	0	0	0	**25**	**34**	**8**	0	**21**	**35**	0	0	0
R	0	0	**70**	**74**	**66**	**46**	**31**	**56**	**60**	**63**	0	0
H	**100**	**100**	**30**	**1**	0	0	0	0	0	**37**	**100**	**100**
S_h	0	0	0	0	0	**46**	**69**	**23**	**5**	0	0	0

Fig. 5: Monthly breakdown of bioclimatic potential for Ljubljana using basic (top) or modified (bottom) method.

Observing Fig. 5 it can be seen that in Ljubljana, a location with temperate climate, solar radiation has a substantial effect on values C_{sn}, R and H. For example, in February value R changes from 12 to 0% and value H from 88 to 100%, while in April value R drops from 100 to 74%, value H increases from 0 to 1% and value C_{sn} increases to 25% as a consequence of solar energy utilization. The described phenomenon is expected, because values C_{sn} and R represent passive (bioclimatic) strategies, which utilize solar energy (Tab. 1), while value H is reciprocally connected with them. As expected, the modified analysis gives the same results as basic for hot (i.e. summer) months, where shading is needed and the excessive solar radiation is unwanted most of the time (i.e. shading is necessary). If bioclimatic potential in Ljubljana is observed on yearly level, the differences, which occur due to the solar energy consideration, are noteworthy. On yearly level value R decreases from 65.9 to 39.1% and value H increases from 22 to 38.6%, while the overall comfort zone increases by 10.2 pp from 11.5% (basic analysis) to 21.7% (modified analysis) due to the appearance of value C_{sn}. The latter means that in approximately 10% of the year, thermal comfort in Ljubljana can be achieved by utilizing solar energy.



Basic analysis:

	J	F	M	A	M	J	J	A	S	O	N	D
Q	0	0	0	0	0	16	98	100	74	0	0	0
A	0	0	0	9	45	53	2	0	14	28	0	0
V	0	0	1	6	55	31	0	0	12	66	43	0
M	0	0	10	85	0	0	0	0	0	6	50	0
C_{sh}	24	46	62	0	0	0	0	0	0	0	0	48
C_{sn}	0	0	0	0	0	0	0	0	0	0	0	0
R	76	54	27	0	0	0	0	0	0	0	7	52
H	0	0	0	0	0	0	0	0	0	0	0	0
S_h	24	46	73	100	100	100	100	100	100	100	93	48

Modified analysis:

	J	F	M	A	M	J	J	A	S	O	N	D
Q	0	0	0	0	0	16	98	100	74	0	0	0
A	0	0	0	9	45	53	2	0	14	28	0	0
V	0	0	1	6	55	31	0	0	12	66	43	0
M	0	0	10	85	0	0	0	0	0	6	50	0
C_{sh}	24	46	62	0	0	0	0	0	0	0	0	48
C_{sn}	22	0	0	0	0	0	0	0	0	0	0	7
R	54	54	27	0	0	0	0	0	0	0	7	45
H	0	0	0	0	0	0	0	0	0	0	0	0
S_h	24	46	73	100	100	100	100	100	100	100	93	48

Fig. 6: Monthly breakdown of bioclimatic potential for Abu Dhabi using basic (top) or modified (bottom) method.

Observation of bioclimatic analysis for the location of Abu Dhabi with hot-arid climate in Fig. 6 gives completely different conclusions than in the case of Ljubljana. In Abu Dhabi the consideration of solar radiation has only minor effect on values C_{sn}, R and H. For example, the differences between basic and modified analysis appear only in January and December (Fig. 6), where value R changes from 76 to 54% and 52 to 45%, respectively. Consequentially, value C_{sn} appears only during these two months and amounts to 22 and 7% for January and December, respectively. The influence of solar radiation on bioclimatic potential calculation with BcChart in Abu Dhabi is of minor importance because, as mentioned before, solar radiation affects only values C_{sn}, R and H, which are in Abu Dhabi represented to a lesser extent. If these three values are compared on yearly level, value R decreases by 2.5 pp with a correspondingly equivalent increase of C_{sn}. Value H remains at 0%, as there is always enough solar energy and/or the ambient temperatures are high enough to heat up the living environment to comfortable temperatures.

4.3 Discussion

It is crucial to remember that the presented approach of solar energy inclusion into the bioclimatic analysis is extremely important, because such approach gives more precise results of locations' bioclimatic potential. Thus, the appropriate and most efficient bioclimatic strategies can be more accurately identified. However, the approach used by BcChart is far more useful in temperate, Mediterranean and cold climatic zones and less for the polar and hot-dry and hot-humid climatic zones, which was demonstrated in previous section. The main reason for this is that the relative importance of bioclimatic strategy for solar radiation harvesting is the greatest in the stated climates. Another key note is that this theory used by BcChart applies only, when the actually received solar radiation is considered with a concurrent attention given to shading of transparent part of building envelope.

Further improvements of the BcChart tool are possible. It would be interesting to include in bioclimatic potential calculation the influence of actual wind speed at the analysed location, the same as it was done for solar radiation. However, it is questionable if such improvement would be reasonable, because air movement in buildings is a far more complex issue than solar energy utilization. In particular, air movement is harder to control and predict, due to various influential parameters, such as degree of urbanization, building aerodynamics, stack effect, etc. Additionally, with too many variables the tool would lose its simplicity and the results their universality. For such complex evaluations more sophisticated whole building simulation tools would be far better alternatives. Nonetheless, when quick and basic evaluations of applicable bioclimatic strategies in a specific location are needed, the BcChart tool represents the right choice in the early phases of building design.

5. Conclusions

As has been noted, the main advantage of the bioclimatic analysis using the BcChart v2.0 software is that it is simple and quick. The originality of the presented approach to bioclimatic potential analysis is expressed through the consideration of the actually received solar radiation with the introduction of T_{sub}. For instance, the performed analyses showed that solar radiation essentially influences the results of bioclimatic potential analysis, especially in temperate and cold climates, which was also highlighted by Pajek and Košir (2017). The analysis of the two selected locations determined the importance and usefulness of the approach incorporated in the BcChart v2.0. The indicated is certainly relevant when using climate data for the determination of relative importance of different bioclimatic design strategies.

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Bioclimatic potential of European locations: GIS supported study of proposed passive building design strategies

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Bioclimatic potential of European locations: GIS supported study of proposed passive building design strategies

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Abstract. According to the Köppen-Geiger climate classification, Europe is under the influence of at least ten different climate types. Thus, various climates can be found, from the polar tundra and cold climate in the Alps and northern European regions, to hot-arid climate in southern parts of Spain. This level of climate diversity makes the European territory interesting for the analysis from the bioclimatic building design perspective. Therefore, the purpose of the research was to assess the bioclimatic potential of selected European locations. The calculation of bioclimatic potential was done by acquiring the typical meteorological year (TMY) data comprised of climate characteristics, such as air temperature, air relative humidity and received solar irradiance, which was later processed by BcChart tool. In order to make bioclimatic potential maps of Europe, the points with uniform point sampling were generated. Furthermore, several additional locations of great interest were selected based on population density. The bioclimatic potential was used to define the prevailing passive building design strategies and measures at the analysed locations. At the same time, the in-depth analysis was conducted using the geospatial data and GIS tools, where the bioclimatic potential results at the selected locations were additionally analysed in relation to Köppen-Geiger climate types. The resulting bioclimatic potential maps can be used as a relevant onset for the policy makers in order to improve regional development strategies for building design.

1. Introduction

For building performance, the climate of a specific location represents both a limitation as well as a potential for increased indoor occupant comfort and wellbeing. Consequentially, climatic conditions also determine to a substantial degree the energy efficiency of buildings, which is particularly prominent in the case of envelope dominated buildings [1][2]. Therefore, taking into account the opportunities and limitations of a particular climate at an early (i.e. conceptual) stage of building design can contribute to the overall higher efficiency of the building. The described process is commonly referred to as bioclimatic or climate adapted design, where the climatic conditions are the basis for the design of passive building envelope elements that enable environmental modulation between the exterior and interior without relying on the provision of energy through active systems (e.g. heating and/or cooling systems) [3][4]. In its essence, the bioclimatic building design strives to increase the portion of a year when a building is in free-run operation, which means that indoor comfortable conditions are provided exclusively by the external environmental conditions modulated via the building envelope.

Because of the above-mentioned reliance of bioclimatic buildings on the climatic conditions of a location for their performance, the determination of bioclimatic potential (i.e. duration of time when indoor comfort can be facilitated by passive building design strategies) at a specific location is an essential step of the design process [5][6]. Calculation of bioclimatic potential can be achieved using bioclimatic charts [6][8] relating selected climatic variables, usually dry bulb temperature and relative humidity, to the indoor occupant comfort demands (i.e. comfort zone). Simultaneously, the bioclimatic charts can also be used to determine the potential effect of the selected passive strategies for the increase of the achieved duration when a building under specified climatic conditions can be in free-run operation. However, the process of determining the resulting bioclimatic potential through climate analysis is usually omitted at early design stages, as it is often viewed as unnecessary by designers, who rely on generic solutions presumed for a specific climate type or region. For example, it is commonly supposed that buildings designed in the geopolitical region of Central Europe [9] should be optimised for a heating season, while overheating does not represent a potential concern for the provision of indoor occupant comfort [10]. Such generalisation by the professional design community is unusual, as the mentioned region is comprised of 1,036,380 km^2, nine countries (i.e. Austria, Czech Republic, Germany, Hungary, Lichtenstein, Poland, Slovakia, Slovenia and Switzerland) [9] and five different Köppen-Geiger climate types (i.e. Cfa – temperate humid with hot summer, Cfb – temperate humid with warm summer, Dfb – cold humid with warm summer, Dfc – cold humid with cool summer and ET – polar tundra) [11]. Furthermore, the latitudes of locations in the Central European region vary substantially (i.e. 45° N to 55° N), affecting the amount of received solar irradiance [12], which is one of the most influential climate factors determining the thermal response of buildings [5]. Based on the above example it becomes evident that climate conditions, defining the performance and design of bioclimatic buildings, cannot be treated as discrete values demarcated by political or geographical constructs, but should be viewed as a geospatial continuum with one climate type slowly morphing into another. In this respect, even the well-established climate classification schemes (e.g. Köppen-Geiger, Thornthwaite, etc.) devised by climatologist are to some degree misleading, because different climate types are presented as discrete categories due to practical reasons of exposing distinct climatic characteristics and general patterns [11][13][14]. It should also be mentioned that as these climatological classifications are based on climate parameters not directly relatable to the design of buildings (e.g. temperature and precipitation in the instance of Köppen-Geiger classification [11][14]), their applicability in the bioclimatic building design process is limited.

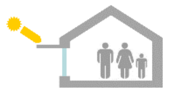
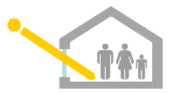
Determination of bioclimatic potentials over selected regions and/or countries has been the subject of numerous previous studies [5][6][15][16][17][18][19]. However, these were predominantly focused on the analysis of bioclimatic potentials at specific locations. This means that variance of geospatial distribution of bioclimatic potentials was reduced to conditions representing a specific geographic location, limiting the spatial resolution of the conducted analysis to a series of points. Moreover, because these studies have been executed either for specific countries (e.g. China [15], Mexico [16], Cyprus [18]) or smaller regions covering parts of a country or countries (e.g. north-east India [19], Alpine-Adriatic region [5]), their scope is limited to a specific state or region. Therefore, the main objective of the present study is to interpret climatic conditions of the European continent through the lens of bioclimatic potentials calculated by BcChart tool developed by Košir and Pajek [20] and to present their geospatial distribution using a geographic information system (GIS) and its data processing tools. The obtained results using recent geospatial and climatic data will give a clear indication of the potential for providing indoor occupant comfort using solely passive bioclimatic strategies. Furthermore, an additional investigation was conducted for selected most densely populated European locations indicating specific bioclimatic potentials at areas of greatest interest to designers, policy makers and other interested stakeholders. Overall, the results of the presented analysis can be used as design guidelines for selecting appropriate passive bioclimatic strategies, as well as a basis for the formation of building codes that would promote the use of passive building envelope integrated technologies.

2. Methods

2.1. Determination of bioclimatic potential

The bioclimatic potential of the selected locations was determined by BcChart tool [20][21]. The tool is based on Olgyay's theory of bioclimatic charts, which can be a starting point for the bioclimatic design of buildings. To use bioclimatic charts as such, two locational climate characteristics are needed – temperature (T) and relative humidity (RH) of air. Although these two attributes are far from being enough to accurately calculate the building thermal or energy performance, they can be used for a quick and general overview of the effective passive building design measures, making the bioclimatic chart useful in the early stages of building design. However, Pajek and Košir [5] stressed that solar radiation is nevertheless so important that its impact cannot be ignored even in the first stages of building design. Therefore, the BcChart tool is adapted to take into account global solar irradiance (*G*) data as well as the air temperature and relative humidity. For the purpose of this study, BcChart v2.1 was used [20]. The entire required climate data (i.e. *T*, *RH*, *G*) were attained from the Photovoltaic Geographical Information System (PVGIS 5) [12]. In particular, the typical meteorological year (TMY) data for the period between 2006 and 2015 were used. The idea of the BcChart tool is to draw a bioclimatic chart for a selected location and then determine on its basis the bioclimatic potential of that location. The yielded bioclimatic potential represents a fraction of year, when the combinations of temperature, relative humidity and solar irradiance fall in or out of the thermal comfort zone. Additionally, the combinations define if specific passive building design solutions can be used to achieve thermal comfort or if active measures (e.g. mechanical cooling, conventional heating) are needed [21]. The comfort zone is defined roughly between 21 and 27 °C (lower at higher *RH* values). Definitions of each bioclimatic potential corresponding to certain passive measure suggested by BcChart are explained in Table 1.

Table 1. Bioclimatic potential measures as calculated by BcChart adapted from Košir and Pajek [21].

Label	Colour	Bioclimatic potential	Suggested bioclimatic measures
Q		mechanical cooling and/or dehumidification needed	
A		potential for passive solutions for hot arid climates	
M		natural ventilation and/or high thermal mass needed	
V		natural ventilation needed	
Csh		comfort achieved by shading	
Csn		comfort achieved by utilizing solar irradiation	
R		potential for passive solar heating	
H		conventional heating needed, focus on heat retention	
Sh		shading needed (Sh = Q + A + M + V + Csh)	

In the cases where the conditions fall inside the comfort zone, comfort can be achieved either by shading (Csh) or by using solar energy (Csn) (Table 1). Further on, the segments presented in Table 1 may also be combined into three main categories: comfort zone (Cz = Csh + Csn), shading needed (Sh = Q + A + M + V + Csh) and sun needed (Sn = Csn + R + H). If values A, M and V are combined into AMV, they represent a share of year, when passive measures for heat exclusion and heat dissipation are recommended (e.g. shading, high thermal mass, etc.).

2.2. Geospatial analysis

The BcChart tool is designed to calculate the bioclimatic potential of a selected location. The selection of the location can yield various insights into the spatial characteristics of the calculated data. In this study, the geospatial, i.e. GIS tools in the open source environment QGIS [22] were used to provide referenced spatial coordinates of locations for bioclimatic potential calculation and for the visualisation of calculated parameters.

Firstly, the values of bioclimatic potential for the whole territory of the European continent were analysed. We decided to analyse the spatial aspect of bioclimatic potential in the selected area. Thus, a spatial interpolation based on the known values of bioclimatic potential was used. In order to perform interpolation, point sampling covering the majority of the study was generated. Using GIS tools in QGIS, we derived a vector layer of points having uniform geospatial distribution with a 100 km grid. This uniform grid of points was calculated for the rectangular extent of Europe and then clipped by the actual shape of the continent, which in the end resulted in 908 points for the calculation of bioclimatic potential values (Figure 1).

Figure 1. Uniform grid of 908 points with 100 km spacing, where bioclimatic potential was calculated. Note: Due to the used cartographic projection, the points appear unevenly distributed.

Next, the BcChart tool was used to calculate bioclimatic potential parameters for all 908 points. After obtaining the parameters (e.g. H, R, Cz, etc.; see section 2.1), we performed the interpolation of the selected parameters to obtain interpolated surfaces over the entire continent. The interpolation was implemented using Inverse Distance Weighted (IDW) algorithm in GIS software QGIS, in which the sampled points are weighted according to the distance from a point at an unknown location. We decided to provide interpolated surfaces only for the selected bioclimatic potential parameters, namely H, Cz, Sh, and a summed value of A, M and V (see section 2.1, Table 1). In the end, each interpolated surface was clipped to the extent of vector geospatial layer of Europe with the area of approx. 10 million km^2, which was acquired from the ArcGIS webpage [23]. Finally, for the visualisation of results, the interpolated raster surfaces of the selected bioclimatic potential parameters were smoothed using Gaussian filter in order to obtain continuous presentations of results.

In the second part of the research, the spatial aspect of the study is focused on the analysis of the bioclimatic potential parameters with respect to the population density and spatial distribution of various climate types considering the extent of the European continent. As the population density layer, we used the open and freely available Global Human Settlement Layer (GHSL), provided by EU Science hub [24]. It is a raster layer with 1 km resolution containing the number of people living in each 1 km^2 raster cell. The third used spatial layer containing climate type polygons was sourced from World maps of Köppen-Geiger climate classification (Figure 2) with the resolution of 5 arc minutes for the period 1986-2010 [25].

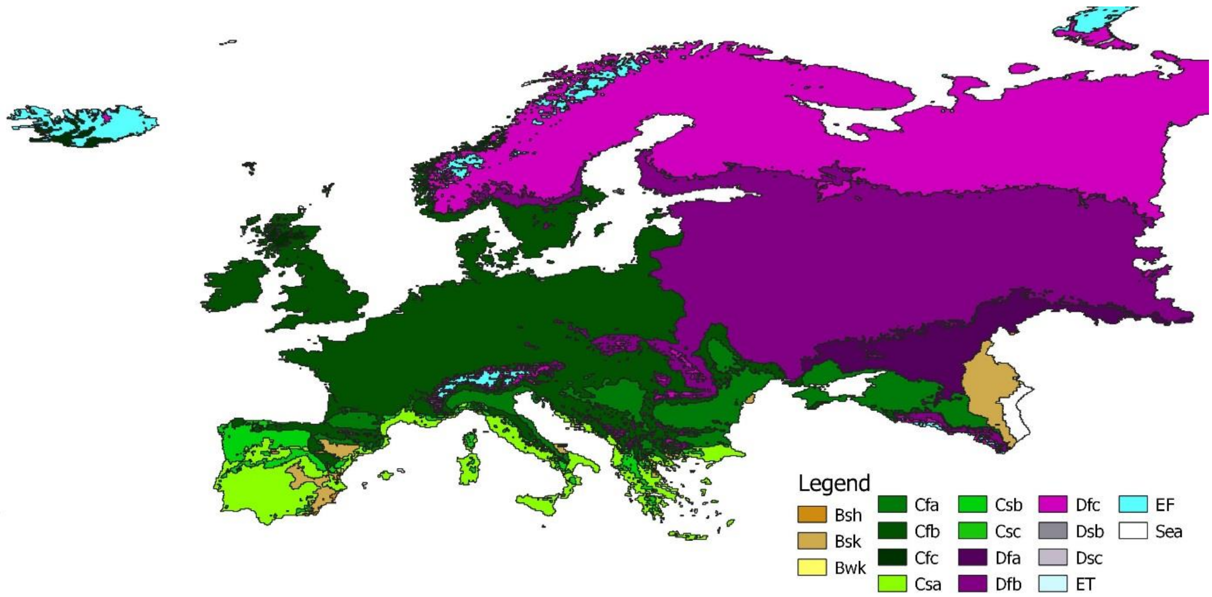


Figure 2: Climate types of Europe as defined by Köppen-Geiger [25]. BWk = cold arid desert, BSh = hot arid steppe, BSk = cold arid steppe, Cfa = temperate humid with hot summer, Cfb = temperate humid with warm summer; Cfc = temperate humid with cool summer, Csa = temperate with dry hot summer (Mediterranean), Csb = temperate with dry warm summer (Mediterranean), Csc = temperate with dry cool summer (Mediterranean), Dfa = cold humid with hot summer, Dfb = cold humid with warm summer, Dfc = cold humid with cool summer, Dsb = cold with dry warm summer, Dsc = cold with dry cool summer, ET = polar tundra, EF = polar frost.

The main aim of the location selection was to extract locations of the most densely populated areas in Europe. The simplest method is to use locations of the raster cells with the highest values. The results are locations concentrated in a few very densely populated areas in Europe. Our method uses the population density raster layer as the initial dataset. It consists of several steps that were implemented using GIS software QGIS:

1. Raster reclassification;
2. Applying the majority filter;
3. Vectorisation;
4. Calculating centroids;
5. Iterative removal of neighbour points;
6. Extracting climate properties of each point.

The input raster layer was firstly reclassified to a binary raster with cell values of 0 or 1. Setting different thresholds for reclassification allows for manual optimisation of the number of selected points. We selected the threshold to be 4000 people per cell. The result was a relatively “noisy” binary raster, with values set to 1 where population density exceeds the value of 4000. The next operation is the application of the majority filter to exclude the small groups of cells with value 1 that do not represent significantly large densely populated areas. The modification of the radius for the majority filter is another option to modify and optimise the selection of the points. The radius of four cells was selected. Each group of the cells with value 1 should then be selected as one location. The optimal GIS solution for this task is to automatically convert these groups of raster cells to polygons with the vectorisation tool. Once we have polygons, the centroids can be determined per each polygon, representing the location of each group of cells. In the end, we used the spatial overlay operation using the selected points and climate type layer. For each point, the climate properties were extracted, depending on the corresponding climate type polygon.

To evaluate the selection of the locations, two ratios were calculated. For the first one, we calculated 50 km buffer polygons around the selected points and calculated the sum of these areas, removing the parts that stretch into the sea. The selected points with 50 km buffer occupy approx. 6 % of the total area of the European continent. The second ratio is focused on comparing the population on the same buffered areas, compared to the total European population calculated by summing all the raster values. The result shows that approx. 35 % of the total population in Europe live in buffered areas. This means that we selected locations where 35 % of Europeans live in the circle with 50 km radius, representing only 6 % of the total area of Europe. After the points of interest had been obtained, which correspond to the most densely populated areas in Europe, we used BcChart to calculate the bioclimatic potential for these points.

3. Results

3.1. Bioclimatic potential of Europe

With respect to evenly distributed sample points with calculated values of bioclimatic potential, the interpolation operations for selected parameters using IDW algorithm was performed. Firstly, we calculated the surface for parameter H, which describes the share of year when conventional heating and heat retention bioclimatic strategy are necessary. The results can be seen in Figure 3. Higher H values describe locations where there is no potential for passive solar heating, so the indoor comfort must be achieved by conventional heating and heat retention.

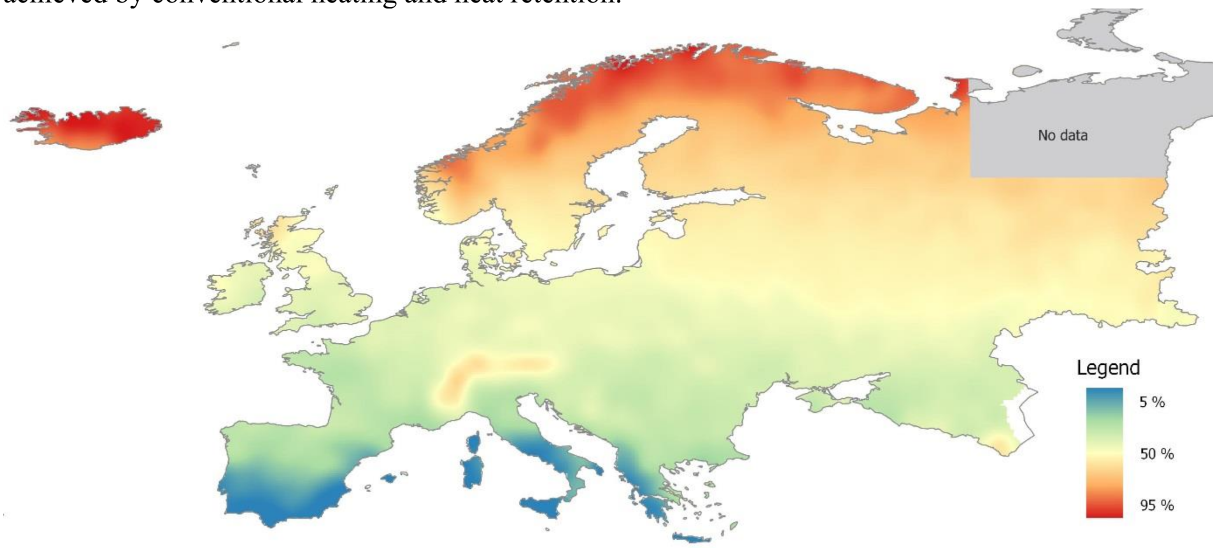


Figure 3: Values of parameter H. The higher is the H value, the longer part of the year conventional heating must be used.

Secondly, the interpolated surface for bioclimatic potential parameter Cz was calculated, which represents the achieved thermal comfort by shading and/or by utilizing solar irradiation. The interpolated values for Europe are shown in Figure 4. Higher Cz values represent locations, where a higher level of comfort can be achieved solely by controlling the impact of solar radiation on a building.

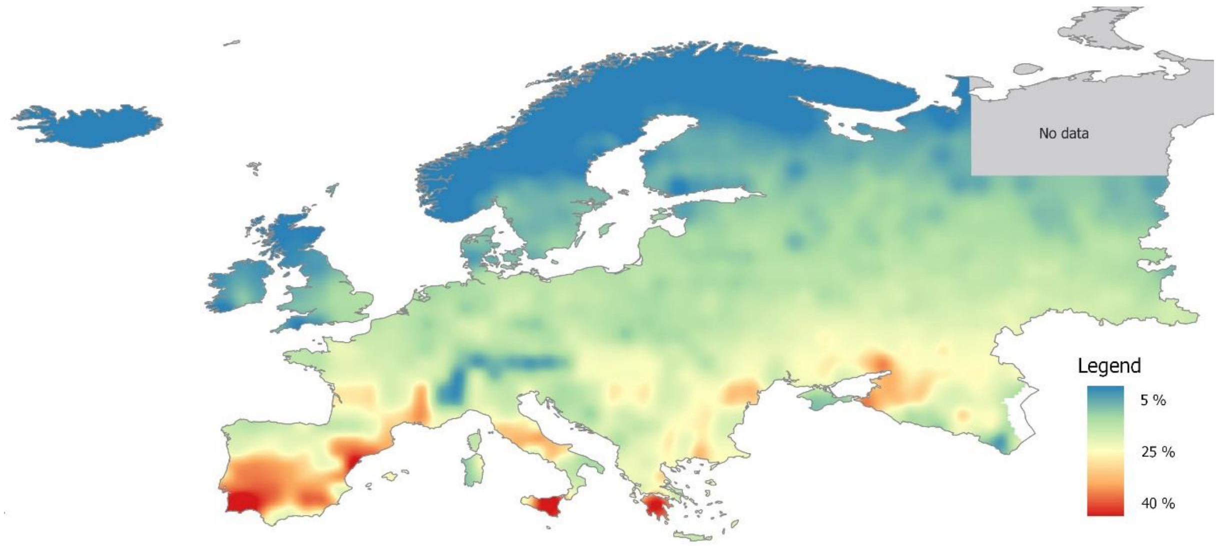


Figure 4: Values of parameter Cz. The higher the Cz value, the more important is the regulation of solar radiation in order to achieve comfort.

The third parameter selected for the interpolation was parameter Sh, which represents the share of year when shading should be applied in order to achieve comfortable conditions. The interpolated values of Sh can be seen in Figure 5, which shows the duration of a year when effective shading of transparent building envelope elements has to be applied in order to facilitate indoor comfort and prevent overheating.

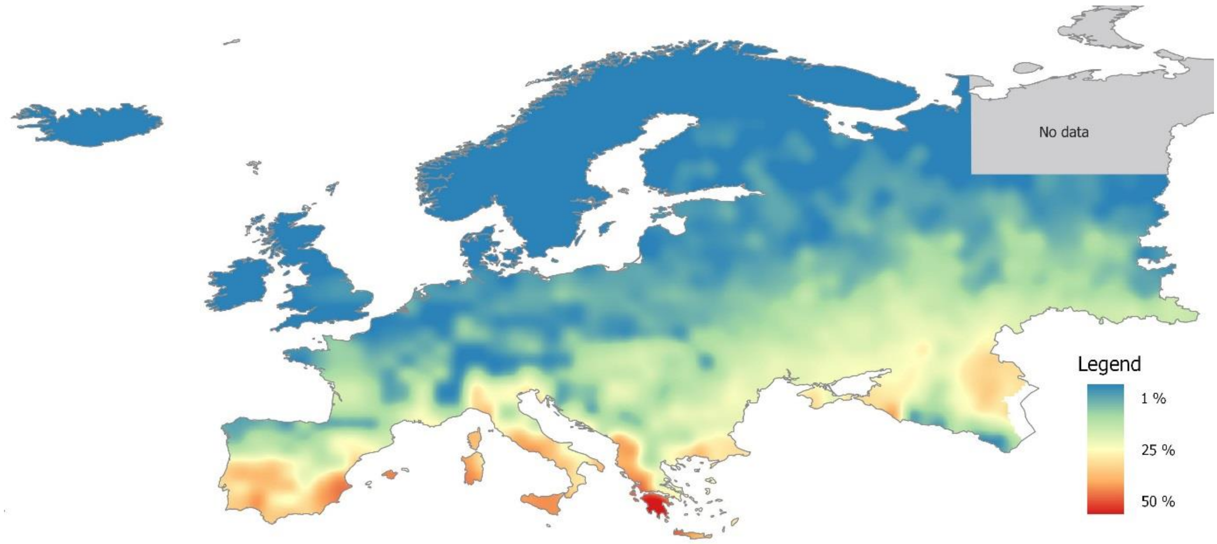


Figure 5: Values of parameter Sh, which represents the share of year when shading should be applied.

In the end, we calculated the composite values of three bioclimatic potential parameters, namely A, M and V. The summed values of the selected parameters, which were interpolated across Europe, represent the potential for using passive building design measures for hot-arid and hot-humid climates, such as high thermal mass, night-time ventilation, etc. The interpolated values are shown in Figure 6. and demarcate the areas of the European continent where in addition to effective shading (Figure 5) also other design measures are necessary to passively control overheating of buildings.

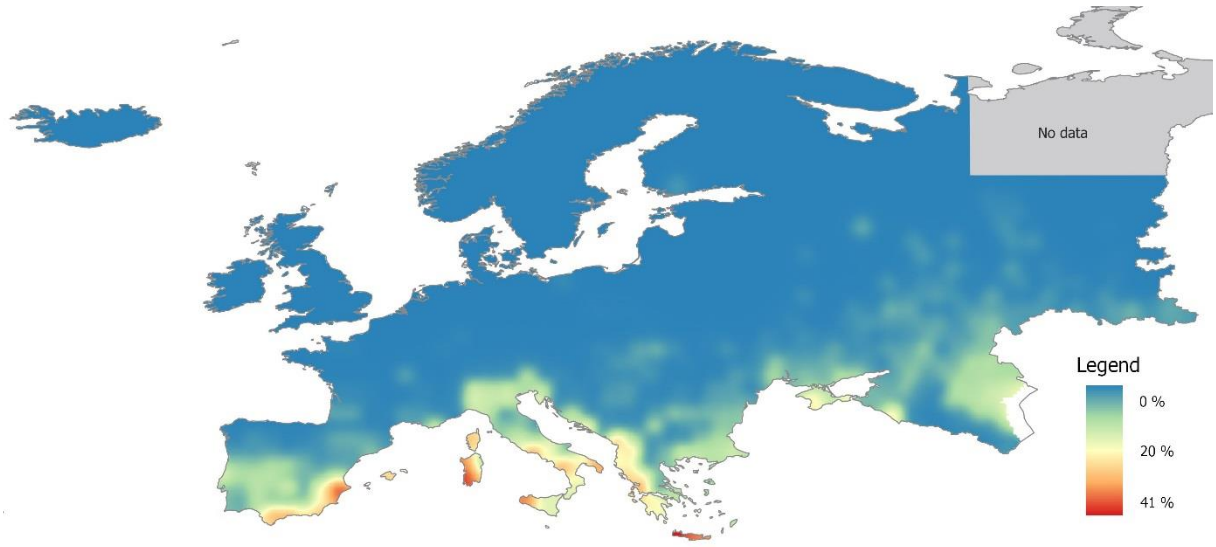


Figure 6: Values of composite parameter AMV show the amount of year when various building design measures for hot climates should be applied in order to achieve comfort.

3.2. Bioclimatic potential of the most populated areas

The second part of the study focuses on the analysis of bioclimatic potential at the most densely populated areas of Europe. Bioclimatic potential values of Q, A, M, V, Csn, Csh, R, and H were calculated and later visualised using pie charts, which can be seen in Figure 7. Each of the pie charts is positioned at one of the 85 most densely populated areas, cumulatively representing 35 % of the European population. Individual pie chart slices illustrate the portion of the entire year when a particular passive building design measure should be used in order to achieve or maintain thermal comfort in a building. In its essence, each individual pie chart clearly defines what should be the focus of building designed at a specific location.

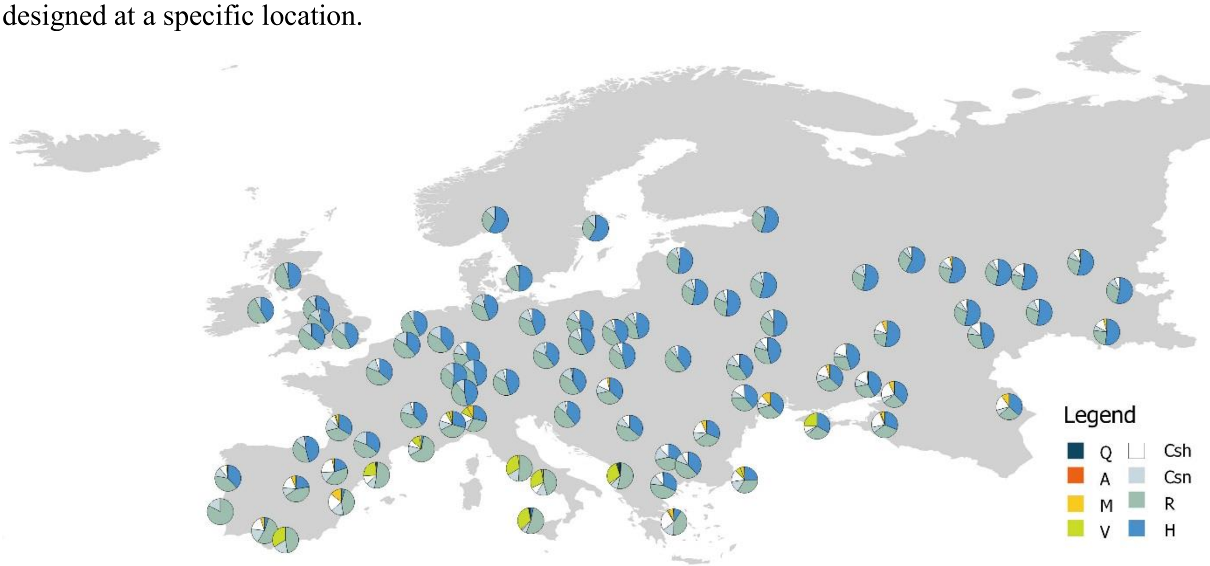


Figure 7: Bioclimatic potential calculated with BcChart tool at 85 most densely populated locations in Europe. Pie charts represent the share of year when a distinct passive building design measure should be used in order to achieve comfort. For the explanation of the legend see section 2.1.

Table 2. Bioclimatic potential of the four Köppen-Geiger climate types in which the majority of the most densely populated areas are located.

Zone		Europe	Cfa	Cfb	Csa	Dfb
Land area [km^2]		9921500 [a]	677277 (7 %)	2452347 (25 %)	591849 (6 %)	2769289 (28 %)
No. of most densely populated locations		85	12 (14 %)	32 (38 %)	12 (14 %)	21 (25 %)
H	Mean	37.6	34.5	42.9	6.5	51.3
	SD	15.8	3.6	5.6	10.2	4.9
	Range	0.0–58.1	28.7–39.4	29.1–58.1	0.0–31.9	39.9–58.1
R	Mean	39.0	36.9	41.2	51.7	30.9
	SD	9.4	6.3	4.8	11.7	5.2
	Range	22.5–82.6	27.0–46.6	30.4–51.2	34.0–82.6	22.5–48.8
Cz	Mean	18.8	21.6	15.7	22.0	17.0
	SD	6.8	5.4	5.1	9.1	3.3
	Range	5.9–40.8	11.2–23.8	5.9–28.3	7.8–40.8	11.2–23.8
Sh	Mean	12.3	18.7	3.9	28.2	8.5
	SD	11.7	10.8	4.3	11.8	5.3
	Range	0.0–41.0	0.0–32.5	0.0–18.4	0.0–41.0	0.0–20.1
AMV	Mean	4.5	7.0	0.3	19.0	0.8
	SD	8.7	7.7	1.1	13.2	1.6
	Range	0.0–34.0	0.0–25.2	0.0–5.5	0.0–34.0	0.0–6.8

[a] The land area of Europe as a continent is determined according to the selected input data. In fact, the land area of Europe is a bit larger.

Among the analysed 85 locations, the "best 5" locations with the highest Cz value (i.e. the highest level of achieved comfort solely by controlling the impact of solar radiation) are: Athens, Greece (Cz = 40.8 %), Valencia, Spain (Cz = 37.8 %), Seville, Spain (Cz = 36.4 %), Zaragoza, Spain (Cz = 36.1 %) and Istanbul, Turkey (Cz = 29.1 %). Kazan (Russia) is the northernmost location (i.e. latitude of 55.8°) with a Cz value above 20 %, namely 20.7 % to be exact. At the same time, the five locations with the highest H values (i.e. conventional heating needed, focus on heat retention), are: Oslo, Norway (H = 58.1 %), Stockholm, Sweden (H = 58.1 %), Ivanovo, Russia (H = 57.6 %), Sankt Petersburg, Russia (H = 55.0 %), Vitebsk, Belarus (H = 54.5 %). Bilbao (Spain) is the southernmost location (i.e. latitude of 43.3°) that has an H value higher than 40 %, namely 46.1 %. Lisbon (Portugal) is the city, which has the highest potential for the utilisation of passive solar heating (R = 82.6 %). The "runner-up" is Marseille, having the R value of 64.1 %. Tirana in Albania is the location with the highest value of Q = 3.9 %. This means that at this location, 3.9 % of the year the climate is so hot and humid that thermal comfort in buildings cannot be achieved by passive means; therefore, mechanical cooling and/or dehumidification is needed.

In Table 2 some typical values of bioclimatic potential are presented for the entire sample of the most populated areas (85 locations). Furthermore, the results for four climate types, where the majority of the most populated locations are situated, are clustered and presented separately.

4. Discussion

Observing Figures 3 to 6 it can be seen that in general the mapped bioclimatic potential parameters are proportional to the specific geographic latitude. This is evident from the fact that locations at higher latitudes (e.g. Scandinavian Peninsula) have higher values of H, while the locations with lower latitudes (e.g. Mediterranean coast) have lower H values (Figure 3). In a similar way, in almost all of the parts of Europe, except in the southernmost regions and near the Caspian Sea (Figure 6), the AMV parameter is relatively small or equal to zero. However, interesting results have been noted for the AMV value in the eastern part of the continent, where even locations at relatively high latitudes have non-zero values. Observing Figures 3 and 4 it becomes evident that the Cz parameter is to some degree inversely proportional to the H values. The relation of the bioclimatic potential parameters to the elevation can be easily observed through a significant change of all the values in the area of the Alps. It can be concluded that, as expected, in most of the cases the resulting bioclimatic potential overlaps to a large extent the climate type distribution over Europe. In particular, as described above, similarities can be drawn between bioclimatic parameters H, Cz, Sh and AMV and the Köppen-Geiger (K-G) climate classification. Observing Figures 2 and 3 we can conclude that there is an evident relation between the H value and the K-G climate types. To be precise, cold climates (i.e. D) are all characterised by an H value above 50 %. Similar relation can also be found for other parameters, as presented in Figure 8. However, the observed parameters of bioclimatic potential are scattered most in the Cfb climate type (i.e. temperate climate with warm summers), especially the H value (Figure 8a), the Sh value (Figure 8c) and the AMV value (Figure 8d). The stated could be a consequence of using the Köppen-Geiger climate classification map with not high enough resolution, so that some locations with Dfb and Cfa climates might be labelled as Cfb climate. Another possible cause of the large distribution of results (Figure 8) may also be that bioclimatic potential calculation with BcChart was made with TMY data for the period between 2006 and 2015, unlike the utilized Köppen-Geiger classification, where climate data from 1986 to 2010 were used.

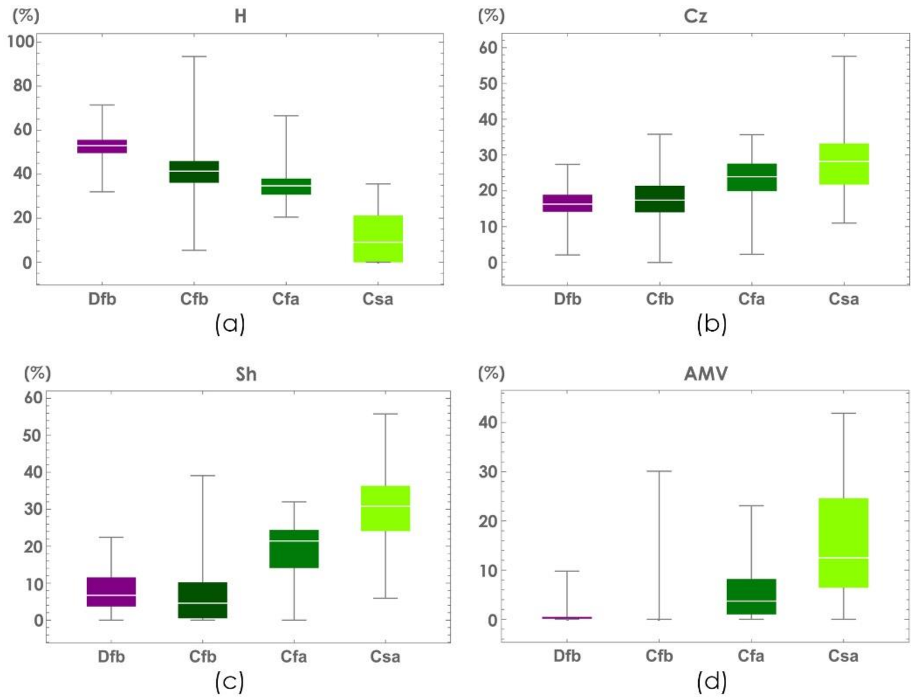


Figure 8: Box plot of the selected four parameters of bioclimatic potential, i.e. H (a), Cz (b), Sh (c) and AMV (d), presented for the four most represented climate types in Europe, namely Dfb, Cfb, Cfa and Csa. White line depicts the median value, coloured area represents the extent of the 2nd and the 3rd quartiles.

Nevertheless, it could be claimed that bioclimatic potential parameters are quite typical for each of the four most represented climate types (Figure 8). The stated was expected because both methods – the K-G climate classification as well as bioclimatic potential calculation method – use air temperature as one of the input parameters. However, in the instance of the K-G classification the amount of precipitation is taken into account besides the air temperature, while in the case of bioclimatic potential, additional parameters used in the calculation are relative humidity and incident global solar irradiance. This results in relatively large variance of the observed bioclimatic parameters for the Cfb climate (Figure 8), where the solar irradiance can have the largest impact on the calculated results. Contrary, the hotter the climate, the more the K-G climate type of a location is comparable to its bioclimatic potential, because in this case the impact of solar radiation on the calculated bioclimatic potential is smaller (e.g.

received solar irradiation marginally influences the achieved values of Cz and H). The same goes for the extremely cold climates.

In the end, the findings of the conducted study have significant importance for (bioclimatic) building design, as they show that certain design presumptions do not stand in line with observed bioclimatic potentials of a particular climate. For example, it was demonstrated that even at specific locations, which are believed to be cold (i.e. Dfb) or have a temperate climate (i.e. Cfb), the Sh and AMV values can significantly deviate from the median value (Figure 8c,d). In this context, the proposed passive building design measures based on the calculated bioclimatic potentials (i.e. Sh and AMV) deviate from the general presumptions of bioclimatic building design. For instance, parts of Eastern Europe (e.g. Ukraine) have very high H values (i.e. extensive conventional heating is needed, see Figure 3), while at the same time they have for their high latitude an unexpectedly high Sh value (i.e. a lot of shading is needed during summer, see Figure 5). The latter parameter significantly affects the resulting Cz value (i.e. achieved comfort, see Figure 4). The opposite situation was identified in the southern part of Great Britain, where the bioclimatic potential analysis exposed that this region is characterised by low H values (i.e. conventional heating of moderate intensity is needed) and pleasant duration of Cz. Considering the combination of the two values it may be expected that also the Sh value (i.e. shading needed) should be high, which, however, was not the case. Therefore, it can be learnt that in this region bioclimatic design strategies and interventions are not strongly emphasized in either way – neither cooling nor heating.

5. Conclusion

The presented bioclimatic analysis of the European continent can represent an efficient starting point for building designers. Particularly, the results of this paper represent a relevant starting point for policy makers in order to improve regional development and building design strategies and regulations. Furthermore, the bioclimatic potential maps may support designers with suggested bioclimatic strategies and measures at a specific location in far greater detail than is attainable from general distribution of climate types or by using rules of a thumb. As an illustration, the results showed that even in some parts of Europe, where it is not intuitive to shade the transparent parts of a building envelope, it should, nevertheless, be applied in order to avoid overheating during summer. Our future work will be focused on preparing a more elaborate and user-friendly bioclimatic potential atlas of Europe.

Acknowledgments

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