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Vključevanje rezultatov ocene tveganja zaradi izrednih vremenskih dogodkov v prostorsko načrtovanje elektroenergetske infrastrukture

V članku so obravnavani praktični ukrepi za vključevanje rezultatov ocene tveganja zaradi izrednih vremenskih dogodkov v postopek prostorskega načrtovanja. Na primerih ocene tveganja zaradi žleda za prenosno in distribucijsko elektroenergetsko omrežje ter za vetrne elektrarne je predstavljen postopek, ki vnaša rezultate ocene tveganja v analizo ustreznosti prostora. Najprej je izdelana ocena tveganja za prenosno in distribucijsko omrežje zaradi žleda. Rezultati ocene tveganja so uporabljeni kot podlaga za presojo predlaganih različic tras visokonapetostnega daljnovoda in kot vhodni podatek za analizo ustreznosti prostora za umestitev vetrnih elektrarn. Različici za umestitev vetrnih elektrarn z upoštevanjem tveganja in brez tega smo primerjali z gospodarskega vidika in ugotovili, da lahko škode zaradi izrednih vremenskih dogodkov pomembno vplivajo na gospodarsko upravičenost načrta. Ugotavljamo, da lahko rezultate ocene tveganja na dva načina vključimo v načrtovanje elektroenergetske infrastrukture, in sicer s posodobitvijo inženirskih standardov in izogibanjem območjem, na katerih bi lahko nastale največje škode na infrastrukturi zaradi izrednih vremenskih dogodkov. Ocena tveganja je pomembna informacija, ki lahko vpliva na odločitve v zvezi z rabo prostora in tehničnimi ukrepi za povečanje odpornosti infrastrukture.

Ključne besede: prostorsko načrtovanje, ocena tveganja, izredni vremenski dogodki, energetska infrastruktura, ranljivost

1 Uvod

Postopne podnebne spremembe z dvigom povprečnih temperatur in spremenjenim vzorcem padavin bodo vplivale na proizvodnjo ter potrebe in obseg rabe električne energije, najverjetneje pa tudi na njeno ceno, dostopnost in distribucijo (Feeley idr., 2008; Wilbanks idr., 2008; Kopytko in Perkins, 2011; Rübbelke in Vögele, 2011; McColl idr., 2012; Schaeffer idr., 2012). Izredni vremenski dogodki (v nadaljevanju: IVD), kot so močen veter, močen dež ali sneg, žled, toča itd. ali različne kombinacije teh dogodkov, lahko povzročijo škodo na hidro- in termoelektrarnah, jedrskih in vetrnih elektrarnah, sončnih panelih, daljnovodih in transformatorskih postajah (Auld idr., 2006; McColl idr., 2012; Schaeffer idr., 2012; Mednarodna agencija za jedrsko energijo, ang. *International Atomic Energy Agency,* v nadaljevanju: IAEA, 2013; Patt idr., 2013, in Sieber, 2013). Medvladni forum za podnebne spremembe (ang. *Intergovernmental Panel on Climate Change,* v nadaljevanju: IPCC, 2012, 2013) ugotavlja, da se je intenzivnost IVD v zadnjem obdobju povečala, hkrati pa se je povečala tudi pogostnost IVD podobnih intenzivnosti (krajšanje povratnih dob), kar je mogoče pričakovati tudi v prihodnosti. Energetska infrastruktura ima dolgo življenjsko dobo, zato bodo imele odločitve o njenih lokacijah in izvedbi, ki jih sprejemamo v sedanjosti, dolgoročne posledice. V postopku načrtovanja bo zato treba upoštevati tudi postopne spremembe podnebja in IVD. V ta namen je treba preučiti mogoče varstvene in prilagoditvene ukrepe (Auld idr., 2006; Wilbanks idr., 2008; Rübbelke in Vögele, 2011; Schaeffer idr., 2012, in IAEA, 2013). Gradnja energetske infrastrukture, ki bo odporna proti postopnim podnebnim spremembam in IVD, je eden ključnih ukrepov prilagajanja energetskega sektorja podnebnim spremembam (Auld idr., 2006; Cortekar in Groth, 2015, ter Panteli in Mancarella, 2015), kar se poudarja tudi v mednarodnih in nacionalnih dokumentih – na primer Okvirna konvencija Združenih narodov o podnebnih spremembah (ang. *United Nations Framework Convention on Climate Change,* 2014), Strategija EU za prilagajanje podnebnim spremembam (Evropska komisija, 2013) in ameriški osnutek načrta prilagajanja podnebnim spremembam (ang. *Climate change adaptation plan: Public review draft*; ameriška agencija za varstvo okolja, ang. *United States Environmental Protection Agency*, v nadaljevanju: EPA, 2012a). V Sloveniji je bila v osnutku predloga nacionalnega energetskega programa (glej Institut Jožef Stefan, 2011) v ciljih za zanesljivost oskrbe navedena »zanesljivost energetskih storitev v izrednih razmerah, kot so naravne katastrofe«. Osnutek predloga nacionalnega energetskega programa iz leta 2011 ni bil sprejet niti se ni začel izvajati. Proces odločanja je po javni obravnavi in čezmejni presoji zamrl, tako da je dokument ostal na ravni osnutka predloga. Splošni programski dokument na področju energetike je še vedno *Resolucija o Nacionalnem energetskem programu* iz leta 2004 (Ur. l. RS, št. 57/2004). Nadomestil jo bo *Energetski koncept Slovenije*, ki je v pripravi. Predlog usmeritev za pripravo Energetskega koncepta (Ministrstvo Republike Slovenije za infrastrukturo, 2015) med tremi temeljnimi cilji trajnostne energetike navaja zanesljivost oskrbe z energijo, ki bi jo dosegli z dobro razvitimi in zanesljivimi omrežji ter z razpršitvijo virov. Odpornost infrastrukture na IVD ni izrecno omenjena.

Obstajata dva pristopa za preprečevanje škod na energetski infrastrukturi: tehnične (mehanske) izboljšave posameznih delov, kar zagotavlja večjo robustnost oziroma odpornost na fizični stres, ter preudarno umeščanje na lokacije, na katerih je ranljivost infrastrukture zaradi postopnih podnebnih sprememb in IVD manjša (Auld idr., 2006, in IAEA, 2013). Operativno se drugi pristop naslanja na prostorsko načrtovanje. Načrtovanje rabe prostora, ki upošteva tveganja zaradi različnih dejavnikov, je stroškovno učinkovitejše kot strukturni ukrepi za zmanjševanje teh tveganj (Sudmeier-Rieux idr., 2015). Raziskave, ki se nanašajo na integriranje ocene tveganja v prostorsko načrtovanje (na primer Applied multi risk mapping of natural hazards for impact assessment, ARMONIA, Lancaster University, 2007; Sutanta idr., 2010; Storch in Downes, 2013, in Prawiranegara, 2014), se osredotočajo predvsem na oblikovanje sistema za podporo odločanju, ne pa na razvoj metod za razporeditev objektov. S člankom želimo zapolniti to vrzel in prikazati, na kakšen način je mogoče obstoječe pristope oziroma prakse načrtovanja rabe prostora dopolniti, da bodo vključevali tudi upoštevanje ocene tveganja zaradi postopnih podnebnih sprememb in IVD.

Raziskovalno ozadje in povezana hipoteza sta, da je z vključitvijo ocene tveganja v prostorsko načrtovanje mogoče vplivati na zmanjšanje škod zaradi IVD na energetski infrastrukturi. V članku najprej predstavimo pomen prostorskega načrtovanja za zmanjševanje tveganj zaradi postopnih podnebnih sprememb in IVD in dosedanjo uporabo ocene tveganja v prostorskem načrtovanju. Nato ti področji povežemo tako, da oblikujemo metodo za njuno integriranje. Sledi uporaba predlagane metode na študiji primera – tveganja za elektroenergetsko infrastrukturo v Sloveniji zaradi žleda. V študiji primera uporabimo oceno tveganja zaradi žleda pri presoji predlaganih različic načrtovanega visokonapetostnega daljnovoda, nato pa poiščemo najustreznejše lokacije za umestitev vetrnih elektrarn ob upoštevanju ocene tveganja. Sledi analiza stroškov in koristi za vetrne elektrarne, pri kateri primerjamo tri razvojne možnosti – tisto, ki tveganja zaradi žleda upošteva tako, da na območjih z največjimi tveganji ni vetrnih elektrarn; tisto, ki na območjih največjih tveganj vključuje tehnične ukrepe za preprečevanje/zmanjševanje morebitnih škod, in tisto, ki tveganj ne upošteva. Predstavitvi rezultatov sledi razprava o uporabnosti predlaganega pristopa ter njegovih prednostih in šibkih straneh, v sklepu pa so navedene smernice za nadaljnje raziskave.

2 Teoretično ozadje

2.1 Vloga prostorskega načrtovanja pri prilagajanju na postopne podnebne spremembe in izredne vremenske dogodke

Prostorsko načrtovanje je bilo kot osnova za prilagajanje na podnebne spremembe prepoznano v znanstveni literaturi (Biesbroek idr., 2009; Wilson in Piper, 2010, ter Hurlimann in March, 2012; Rastandeh, 2015) in več strateških dokumentih, kot so Zelena in Bela knjiga Evropske komisije (Evropska komisija, 2007, 2009) in Teritorialna agenda Evropske unije (Evropska komisija, 2011). Tudi na ravni Slovenije se prostorsko načrtovanje obravnava kot prioriteta pri prilagajanju, saj je pomemben preventivni instrument za prilagajanje podnebnim spremembam prek procesov integralnega načrtovanja in urbanega razvoja (Služba Vlade Republike Slovenije za podnebne spremembe, 2011, ter Kajfež-Bogataj idr., 2012). V zvezi z učinkovitostjo prostorskega načrtovanja pri prilagajanju na podnebne spremembe je bilo več študij izvedenih na mednarodni ravni (na primer International Commission for the Protection of the Alps, 2010; Pütz idr., 2011, in Linkaits, 2013), kot tudi na nacionalni (na primer Rivera in Wamsler, 2014; Flannery idr., 2015, ter Kumar in Geneletti, 2015), regionalni (na primer Rannow idr., 2010, ter De Bruin idr., 2013) in lokalni (na primer Wilson, 2006; Andersson-Sköld idr., 2015, ter Dubois idr., 2015). V Sloveniji so orodja prostorskega načrtovanja kot ukrepe prilagajanja na podnebne spremembe analizirali Mojca Golobič idr. (2012). Avtorji omenjenih študij navajajo, da je prostorsko načrtovanje dejavnost, ki ima zmožnost, da lahko pomaga družbi in gospodarstvu pri prilagoditvi na spremembe rabe tal, pri preprečevanju naravnih nesreč in integriranju različnih področij v načrtovanje (Rannow idr., 2010; Pütz idr., 2011; Greiving in Fleischhauer, 2012; Serrao-Neumann idr., 2015). Poudarjajo, da nekateri instrumenti prostorskega načrtovanja že vključujejo ukrepe prilagajanja na podnebne spremembe, vendar pa ti ne zadostujejo za prenos prilagajanja v prakso ali pa v njej niso primerno uporabljeni (Wilson, 2006; Rannow idr., 2010; Golobič idr., 2012, ter Pütz idr., 2011). Prepričani so, da se je treba od strateške ravni premakniti k bolj konsistentni implementaciji prilagajanja s pomočjo prostorskega načrtovanja na izvedbeni (praktični) ravni. Sven Rannow idr. (2010) ugotavljajo, da so ocenjevanje in upoštevanje pogostnosti in intenzivnosti izrednih dogodkov šibka točka prostorskega načrtovanja, zato bi se to pri upoštevanju IVD moralo opreti na ugotovitve drugih disciplin. Tudi zakonodaja s področja prostorskega načrtovanja obravnava podnebne spremembe večinoma implicitno – v okviru zaščite oziroma obnove naravnega okolja, zaščite naselij pred naravnimi nesrečami ter ekološko in gospodarsko ustreznega prostorskega razvoja (Služba Vlade Republike Slovenije za podnebne spremembe, 2011).

2.2 Ocena tveganja in njeno vključevanje v prostorsko načrtovanje

V zadnjih dveh desetletjih je bilo izdelanih veliko študij na temo naravnih in antropogenih tveganj ter njihovih kombinacij. Velik del teh raziskav so podprle mednarodne institucije – na primer Nato (Briggs idr., 2002), Evropska unija (raziskovalni projekti *Accidental risk assessment methodology for industries* – ARAMIS, 2002–2005; *Sharing experience on risk management (health, safety and environment) to design future industrial systems* – SHAPE-RISK, 2004–2007; ARMONIA, 2004–2007; *Early recognition, monitoring and integrated management of emerging, new technology related risks* – iNTeg-Risk, 2008–2013; *Technology opportunities and strategies towards climate-friendly transport* – TOSCA, 2010–2013; *Coordination of European research on industrial safety towards smart and sustainable growth* – SAFERA, 2012–2015), Urad Organizacije združenih narodov za zmanjšanje tveganja nesreč (ang. *United Nations Office for Disaster Risk Reduction,* v nadaljevanju: UNISDR) in Mednarodna agencija za jedrsko energijo (*CRP Techno-economic evaluation of options for adapting nuclear and other energy infrastructure to long-term climate change and extreme weather*, 2013–2015). Tudi znanstvena literatura, ki se nanaša na ocenjevanje tveganja, je zelo obsežna in v njej so obravnavana tveganja zaradi različnih izrednih dogodkov, na primer erozije (Alder idr., 2015), poplav (Camarasa-Belmonte in Soriano-García, 2012; Zhou idr., 2012; Canters idr., 2014; Prawiranegara, 2014; Foudi idr., 2015), gozdnih požarov (Thompson idr., 2015) itd. Pri tem je glavni poudarek na razvoju različnih metod za zmanjševanje posledic izrednih dogodkov. Melanie Gall idr. (2015) so preučili raziskave tveganj v zadnjih petnajstih letih, ki so povezovale različne znanstvene discipline, metode in udeležence. Trdijo, da je razhajanje med raziskovanjem in implementacijo v praksi zelo veliko. Čeprav je v večini omenjenih znanstvenih člankov o tveganjih poudarjeno, da razvite metode za ocenjevanje tveganja, ki jih predstavljajo, lahko služijo kot podpora pri odločanju in jih je mogoče vključiti v prostorsko načrtovanje (na primer Camarasa-Belmonte in Soriano-García, 2012; Alder idr., 2015; Foudi idr., 2015; Thompson idr., 2015), se s to integracijo v glavnem ne ukvarjajo podrobneje. Večina tistih študij, ki obravnavajo vključevanje ocene tveganja v prostorsko načrtovanje (Lancaster University, 2007; Sutanta idr., 2010; Storch in Downes, 2013; Prawiranegara, 2014), se osredotoča predvsem na oblikovanje sistema za podporo pri odločanju na podlagi kart agregiranih nevarnosti ali tveganj, ne pa na razvoj konkretnih metod za iskanje lokacij za določene dejavnosti/rabe/objekte. Marisa Berry in Todd BenDor (2015) sta v analizo ustreznosti prostora za razvoj dejavnosti sicer vključila napovedi glede dviga morske gladine in poplavljanja zaradi neviht, vendar pa gre pri tem predvsem za umikanje dejavnosti proč od obale in nižje ležečih delov – njuna študija ne upošteva niti verjetnosti pojavljanja dogodkov niti posledic teh. Stefan Greiving idr. (2006) menijo, da ocene tveganja iz različnih znanstvenih ali strokovnih disciplin niso ustrezne za uporabo v prostorskem načrtovanju – potreben je prenos informacij o tveganjih v jezik prostorskega načrtovanja. S tem sta se na primeru tveganj zaradi industrijskih nesreč ukvarjala Davor in Branko Kontić (2008). Pristop, ki ga predstavljamo v prispevku, nadgrajuje njuno metodo za vključevanje tveganj zaradi industrijskih nesreč v postopek prostorskega načrtovanja tako, da se osredotoča na obravnavo tveganj zaradi naravnih izrednih dogodkov. Predvidevamo, da bi z vključitvijo postopnih podnebnih sprememb in IVD v prostorsko modeliranje omogočili umeščanje energetskih objektov v prostor tako, da bi se optimizirala njihova učinkovitost in preprečila/zmanjšala morebitna škoda. V članku je prikazan pristop za izbiro ustreznih lokacij za energetsko infrastrukturo, ki smo ga razvili in testirali na primeru ocene tveganja za energetsko infrastrukturo zaradi žleda v Sloveniji.

3 Metoda

Metoda za vključitev rezultatov ocene tveganja v prostorsko načrtovanje temelji na pristopu, ki sta ga na primeru tveganj zaradi industrijskih nesreč razvila Davor in Branko Kontić (glej Kontić in Kontić, 2008). S pomočjo načrtovanja rabe prostora, ki upošteva verjetnost/pogostnost pojavljanja izrednih dogodkov in tudi intenzivnost/obseg posledic, sta poskušala preprečiti oziroma zmanjšati posledice industrijskih nesreč v bližini organizacij, ki so po Direktivi Sveta 96/82/ES z dne 9. decembra 1996 o obvladovanju nevarnosti večjih nesreč, v katere so vključene nevarne snovi (Direktiva SEVESO II; Ur. l. Evropske unije, št. 10/1997), uvrščene v kategorijo večjega tveganja za okolje. Ta pristop smo nadgradili za obravnavo tveganj zaradi izrednih dogodkov, ki so posledica naravnih procesov, s poudarkom na tveganju zaradi IVD. Izrazi, uporabljeni v prispevku, imajo v različnih kontekstih/strokah različen pomen. Izrazi tveganje, nevarnost in ranljivost imajo v okviru ocenjevanja tveganj te pomene:

- tveganje (ang. *risk*) – pogostnost pojavljanja (izražena s pogostnostjo ali verjetnostjo) določenih posledic kot rezultat izpostavljenosti stresorju (nevarnosti; EPA, 2012b; UNISDR, 2014);
- nevarnost (ang. *hazard*) – pojav, snov ali dejavnost, ki lahko povzroči negativne posledice (izguba življenja, poškodba ali drugi vplivi na zdravje, škoda na objektih, izguba storitev, ki omogočajo preživljanje, družbena in gospodarska motnja, škoda v okolju) v sistemu, ki je tej nevarnosti izpostavljen (UNISDR, 2014);
- ranljivost sistema (ang. *vulnerability*) – značilnosti sistema ali okoliščine, zaradi katerih je ta sistem v primeru izpostavljenosti nevarnosti dovzeten za škodo (posledice; Cardona, 2003, in UNISDR, 2014); ugotavljanje ranljivosti je namenjeno zmanjševanju tveganja z uvajanjem tehničnih ukrepov ali prilagajanju obstoječih rab.

Medvladni forum za podnebne spremembe (IPCC, 2007) pojmuje ranljivost za podnebne spremembe nekoliko drugače. Ta naj bi bila odvisna od treh dejavnikov: 1. funkcije značaja, velikosti in obsega sprememb, ki jim je sistem izpostavljen (izpostavljenosti), 2. občutljivosti sistema in 3. njegove sposobnosti prilagajanja. Vsak od teh dejavnikov je ocenjen na osnovi meril in kazalnikov, ki so lahko opisani s pomočjo kvalitativnih ali kvantitativnih podatkov. Ranljivost okolja/prostora je izraz iz prostorskega načrtovanja in se uporablja za vnaprejšnjo identifikacijo potencialno negativnih okoljskih vplivov predvidenih dejavnosti. V članku se uporabljata termina ranljivost sistema, kot je opredeljena v ocenjevanju tveganj, in ranljivost okolja/prostora po definiciji iz prostorskega načrtovanja.

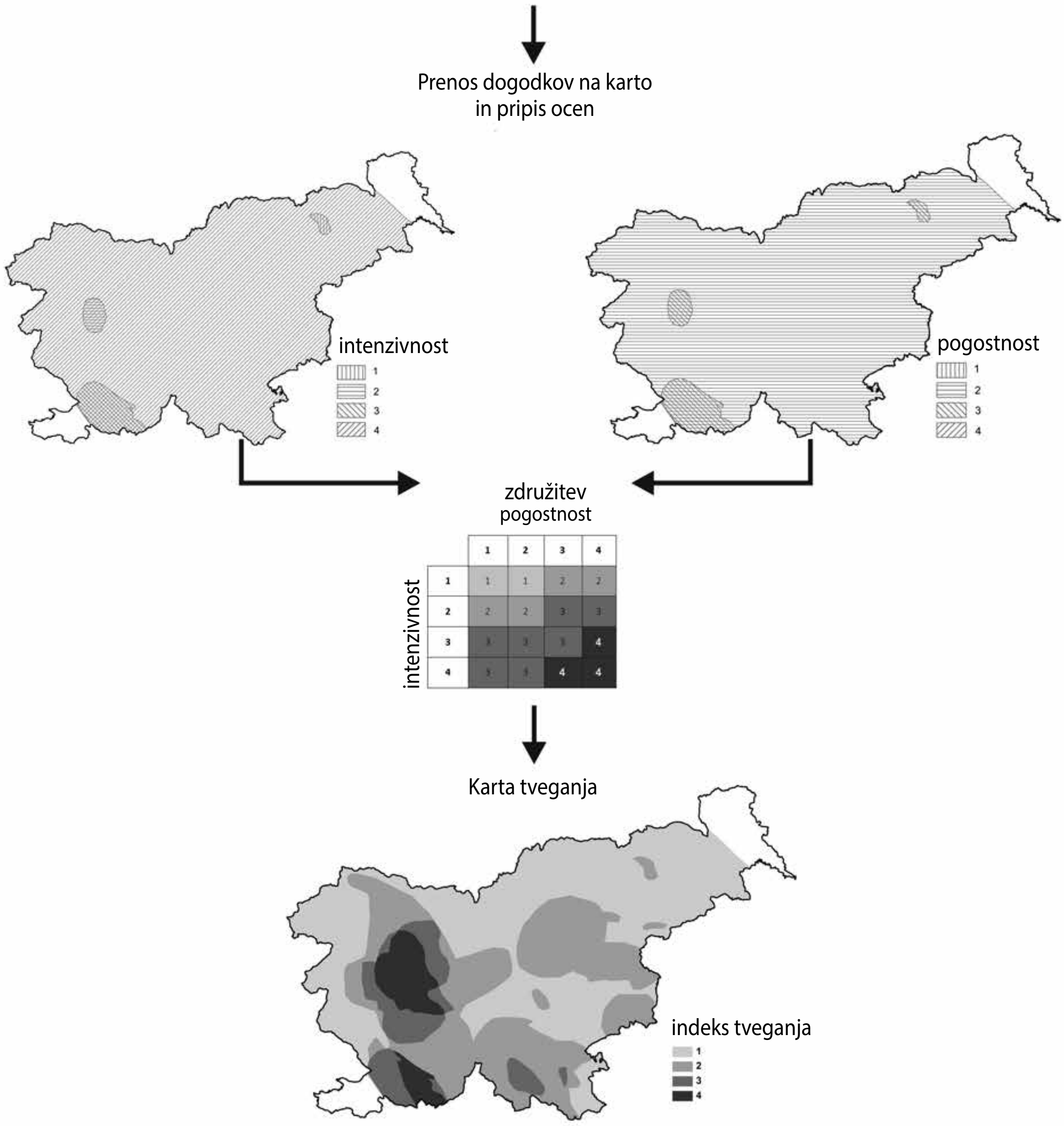
3.1 Metoda za ocenjevanje tveganj za energetsko infrastrukturo zaradi izrednih vremenskih dogodkov

Metodo za ocenjevanje tveganja za energetsko infrastrukturo zaradi IVD smo testirali na primeru tveganj zaradi žleda za energetsko infrastrukturo. Metodo sestavljajo štirje koraki:

1. Določitev prostorskega obsega in intenzivnosti IVD na podlagi podatkov o pojavljanju IVD v preteklosti
   Raven intenzivnosti različnih tipov IVD (na primer temperatura, dodatna obremenitev zaradi žleda, vetra, snega, poplav itd.) se prenese na karte v okolju GIS (glej sliko 1), kjer je vsaki celici pripisana ocena na lestvici od 1 (nizka obremenitev energetske infrastrukture) do 4 (visoka obremenitev energetske infrastrukture). Velikost celice je odvisna od obsega obravnavanega območja in podrobnosti obravnave. V prikazani analizi, izdelani na ravni celotne Slovenije, je imela celica velikost 100 m. Podatki so bili pridobljeni iz arhivov o preteklih IVD. Pri kartiranju lokacij IVD smo se oprli na lokacijske podatke o poškodovanih daljnovodih in podatke o pasovih nadmorskih višin, v katerih je nastala škoda. Pri razvrščanju dogodkov v razrede glede na intenzivnost je bila upoštevana finančna škoda, ki jo je povzročil posamezni dogodek. Pragove teh razredov smo določili na podlagi sredstev, ki jih prenosno podjetje in distribucijska podjetja namenjajo za vzdrževanje infrastrukture.

Podatki o dogodkih

datum	lokacija	škoda (€)	razred intenzivnosti	razred pogostnosti	indeks tveganja
19. 11. 1972	Tezno	528 tisoč	2	3	2
5. 11. 1980	Brkini	33,5 milijona	3	3	3
13.–14. 11. 1985	Idrijsko, Cerkljansko	120 tisoč	2	3	2
30. 1.–8. 2. 2014	vsa Slovenija brez Primorske in Prekmurja	214 milijonov	4	1	3

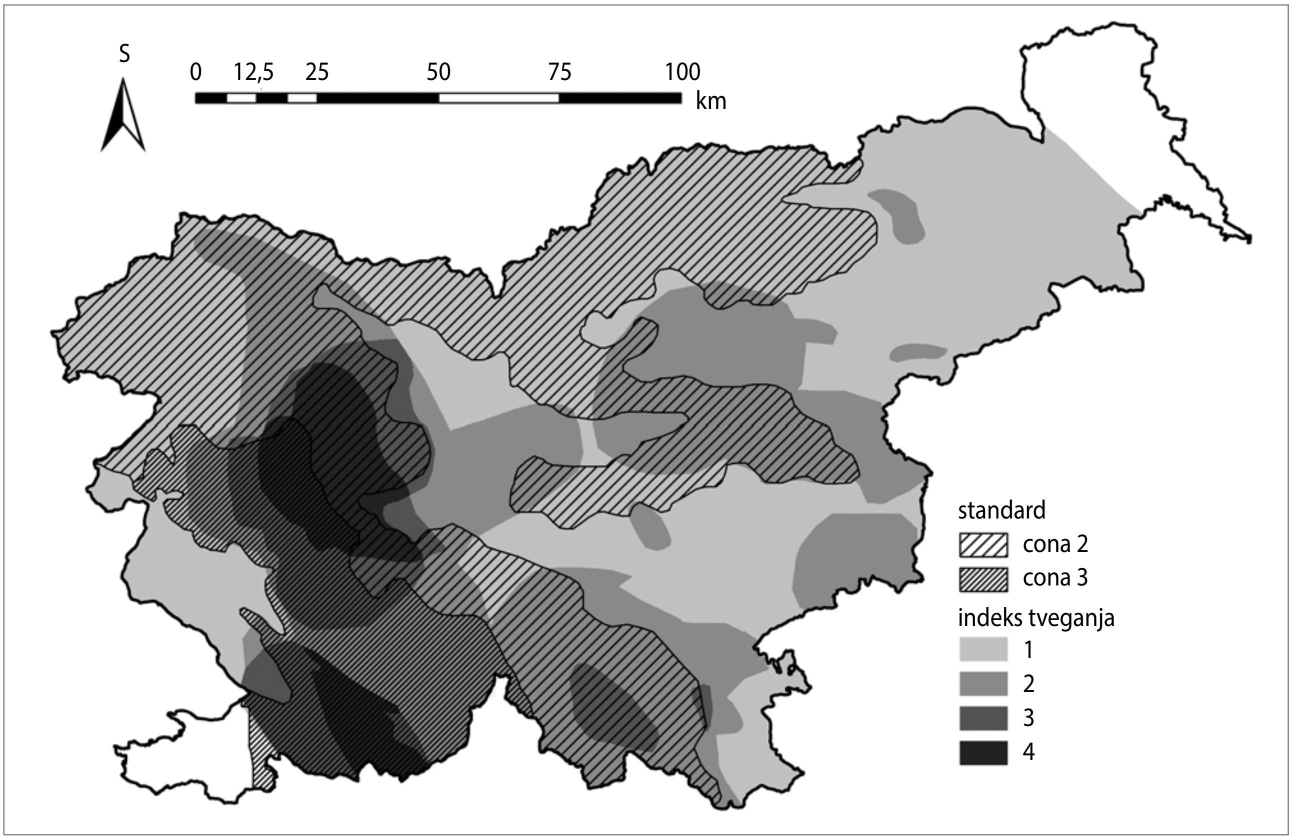


Slika 1: Postopek ocene tveganja (ilustracija: Maruša Matko)

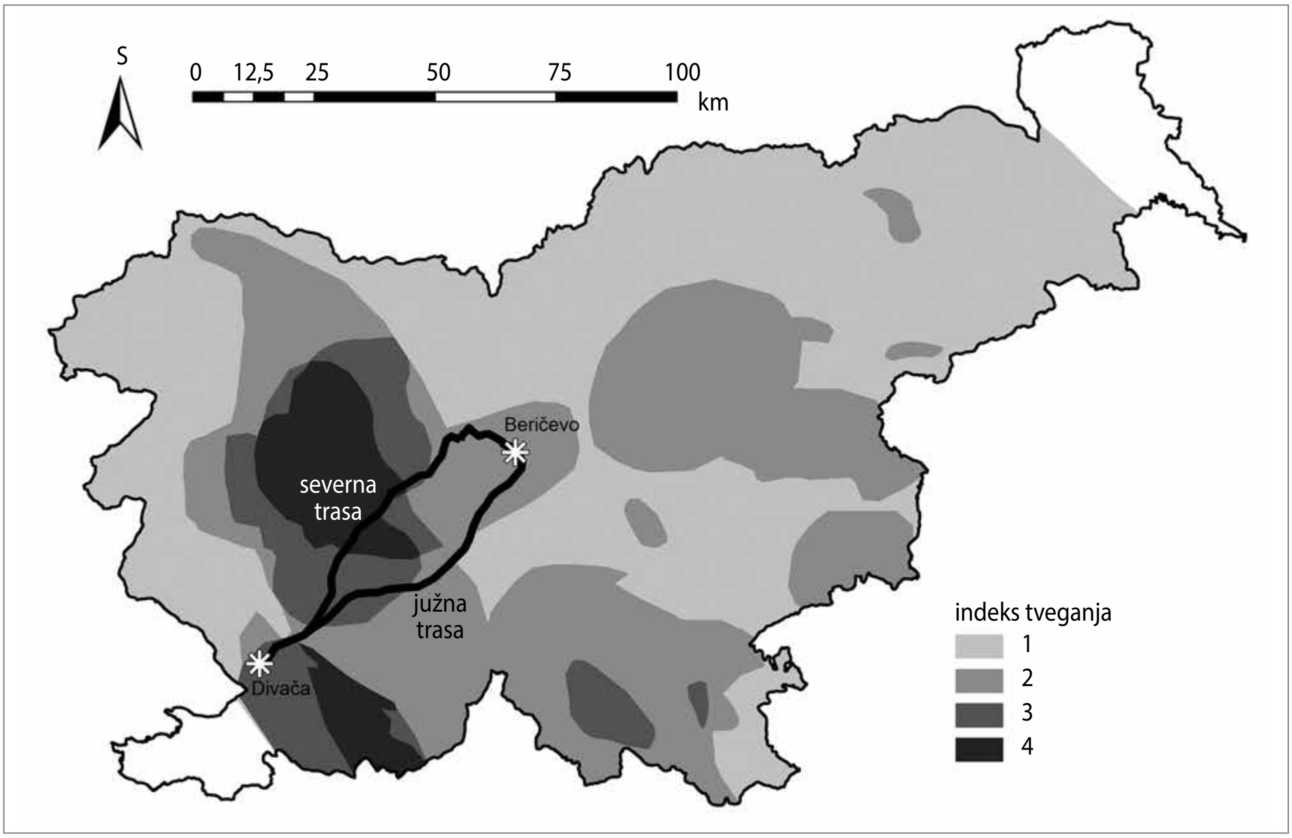
2. Ocena ranljivosti energetske infrastrukture oziroma območja, na katerem je infrastruktura, na določen tip IVD
   Namen tega koraka je ugotavljanje, ali je energetska infrastruktura na izbranem območju zmožna prenesti določeno intenzivnost IVD. IVD lahko neposredno poškodujejo energetsko infrastrukturo, poleg tega pa lahko isti IVD pripomore k temu, da se tudi v okolici pojavijo škode, ki še dodatno prispevajo k poškodbam infrastrukture (na primer lomljenje dreves, erozija). Oboje je vzrok za skupno ranljivost. Ranljivost oziroma odpornost infrastrukture je mogoče neposredno ugotavljati iz statičnih oziroma mehanskih značilnosti objektov (ob upoštevanju inženirskih standardov), ranljivost okolja pa je kompleksnejša in jo je težje opredeliti, saj nanjo vpliva več dejavnikov. V primeru žleda smo se oprli na podatke o poškodovani lesni biomasi v gozdovih zaradi posameznih dogodkov. Ranljivost je izražena kot razmerje med pričakovano stopnjo škode in maksimalno mogočo škodo na lestvici od 1 do 4. Rezultati so predstavljeni na karti GIS (slika 1).
3. Določitev verjetnosti/pogostnosti pojavljanja IVD na določenem območju, na katerem je energetska infrastruktura ali pa bo tja umeščena v prihodnosti
   Na podlagi arhivskih podatkov o IVD je izračunana pogostnost ali verjetnost pojavljanja različnih tipov IVD. Rezultati so preneseni na karto.
4. Združitev zgoraj navedenih korakov za določitev fizičnih in drugih (gospodarskih, zdravstvenih) posledic ter določitve indeksa tveganja za določeno območje in energetsko infrastrukturo
   Indeks tveganja združuje intenzivnost IVD in ranljivost izbrane energetske infrastrukture na določeno stopnjo intenzivnosti IVD, pogostnost ali verjetnost pojavljanja IVD in posledice – družbena škoda zaradi poškodovane infrastrukture. Te kombinacije so podobne standardnim matrikam tveganja, ki se uporabljajo za združevanje pogostnosti/verjetnosti dogodkov s posledicami teh dogodkov.

Praktična izvedba ocene tveganja za izbrane štiri žledne dogodke in povzročeno škodo je ponazorjena na sliki 1. Najprej so bili zbrani podatki o pojavih žleda, njihovih lokacijah in škodah, ki so jih povzročili. Vsak dogodek je bil nato narisan na karto v okolju GIS (glej sliko 1) in na podlagi nastale škode (ki je odvisna od intenzivnosti dogodka in od ranljivosti sistema) uvrščen v razred intenzivnosti. Poleg tega je bil vsak dogodek uvrščen tudi v razred pogostnosti pojavljanja. Na sliki 1 je za prikaz intenzivnosti in pogostnosti izbranih dogodkov zaradi večje nazornosti prikaza uporabljena šrafura, zaradi katere je razvidno, kako se dogodki v prostoru sledijo drug drugemu, kar vpliva na končni rezultat. Zaradi večje berljivosti so na kartah intenzivnosti in pogostnosti prikazani le izbrani štirje dogodki, za podatke o vseh dogodkih glej članek Maruše Matko idr. (2015). Z združitvijo razredov intenzivnosti in pogostnosti je bil vsakemu dogodku pripisan indeks tveganja, nato pa so bili indeksi tveganj vseh dogodkov združeni v končni rezultat – karto tveganja. Karta tveganja na sliki 1 združuje vse obravnavane žledne dogodke.

Ocena tveganja za prenosno in distribucijsko omrežje zaradi žleda temelji na podatkih o preteklih škodah na elektroenergetski infrastrukturi in škodah v gozdovih. Na podlagi arhivskih podatkov o žledenju Agencije Republike Slovenije za okolje med letoma 1961 in 2014 in poročil o nastalih škodah zaradi žleda (Šifrer, 1977; Radinja, 1983; Kern in Zadnik, 1987; Papler, 1996; Bogataj, 1997; Jakša, 1997; Jakše, 1997; Kastelec, 1997; Lapajne, 1997; Nadižar in Papler, 1997; Šipec,1997; Trontelj, 1997a; Trontelj, 1997b; Zadnik, 1997; Špehar, 1998; Rebula, 2001; Rebula, 2002; Zadnik, 2006; Habjan in Bahun, 2009; Habjan, 2010; Sinjur idr., 2010; Bahun, 2014; Bahun idr., 2014; Belak in Maruša, 2014; Belak idr., 2014; Jakomin, 2014; Zavod za gozdove Slovenije, 2014, in Elektro Slovenija, 2015) so bili zbrani podatki o osnovnih značilnostih posameznega dogodka (območje, na katerem je prišlo do dogodka, škoda v gozdovih – po površini in poškodovani lesni biomasi) ter škodah na prenosnem in distribucijskem omrežju (dolžina poškodovanih daljnovodov in število poškodovanih stebrov ter s tem finančna škoda, število odjemalcev brez električne energije). Finančna škoda na elektroenergetski infrastrukturi je bila iz podatkov o fizični škodi preračunana na podlagi šifranta F – povprečna cena po skupinah del v elektroenergetskem omrežju (Uprava Republike Slovenije za zaščito in reševanje, 2014), ki je bil uporabljen pri izračunu škode zaradi žlednega dogodka v letu 2014. Za preračun finančne škode v gozdovih smo uporabili povprečno odkupno ceno lesa v zadnjem desetletju, ki znaša približno 50 evrov/m^3 (Statistični urad Republike Slovenije, 2015). Škoda v gozdovih in škoda v energetiki sta bili obravnavani ločeno – za vsako področje je bila najprej izdelana ocena tveganja in pripravljena karta, nato pa so bili rezultati združeni. Glede na povzročeno fizično škodo na elektroenergetski infrastrukturi in v gozdovih ter s tem glede na finančno škodo so bili dogodki razvrščeni v razrede od 1 do 4 (1 – najmanjša škoda, 4 – največja škoda). Za vsak dogodek je bila izračunana pogostnost pojavljanja v obravnavanem obdobju (1961–2015). Tudi po pogostnosti so bili dogodki razvrščeni v razrede od 1 (zelo redko) do 4 (pogosto). Intenzivnost žleda in pogostnost pojavljanja sta bili združeni z matriko. Tako je bil vsak dogodek uvrščen v razred indeksa tveganja (1 – najmanjše tveganje, 4 – največje tveganje). Dogodki, razvrščeni glede na indeks tveganja, so bili narisani na karti – končni rezultat je bila karta tveganja, ki jo prikazuje slika 2.



Slika 2: Karta tveganja za elektroenergetsko infrastrukturo zaradi žleda, prekrita s standardom SIST EN 50341-3-21 za gradnjo visokonapetostnih nadzemnih vodov (ilustracija: Maruša Matko).



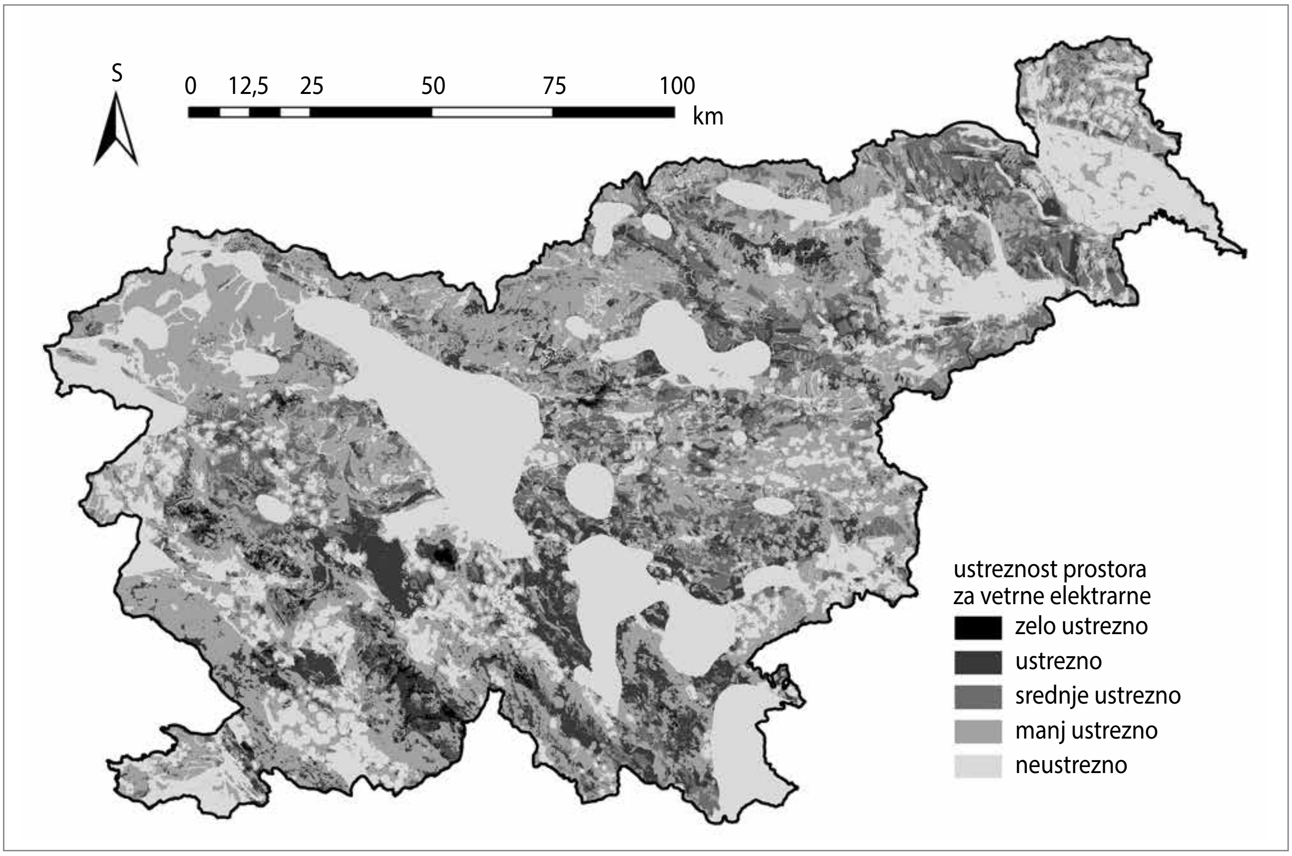
Slika 3: Karta tveganja za elektroenergetsko infrastrukturo zaradi žleda in predlagani različici tras daljnovoda 400 kV Beričevo–Divača (ilustracija: Maruša Matko)

3.2 Metoda vključevanja rezultatov ocene tveganja v analizo ustreznosti prostora za določeno dejavnost

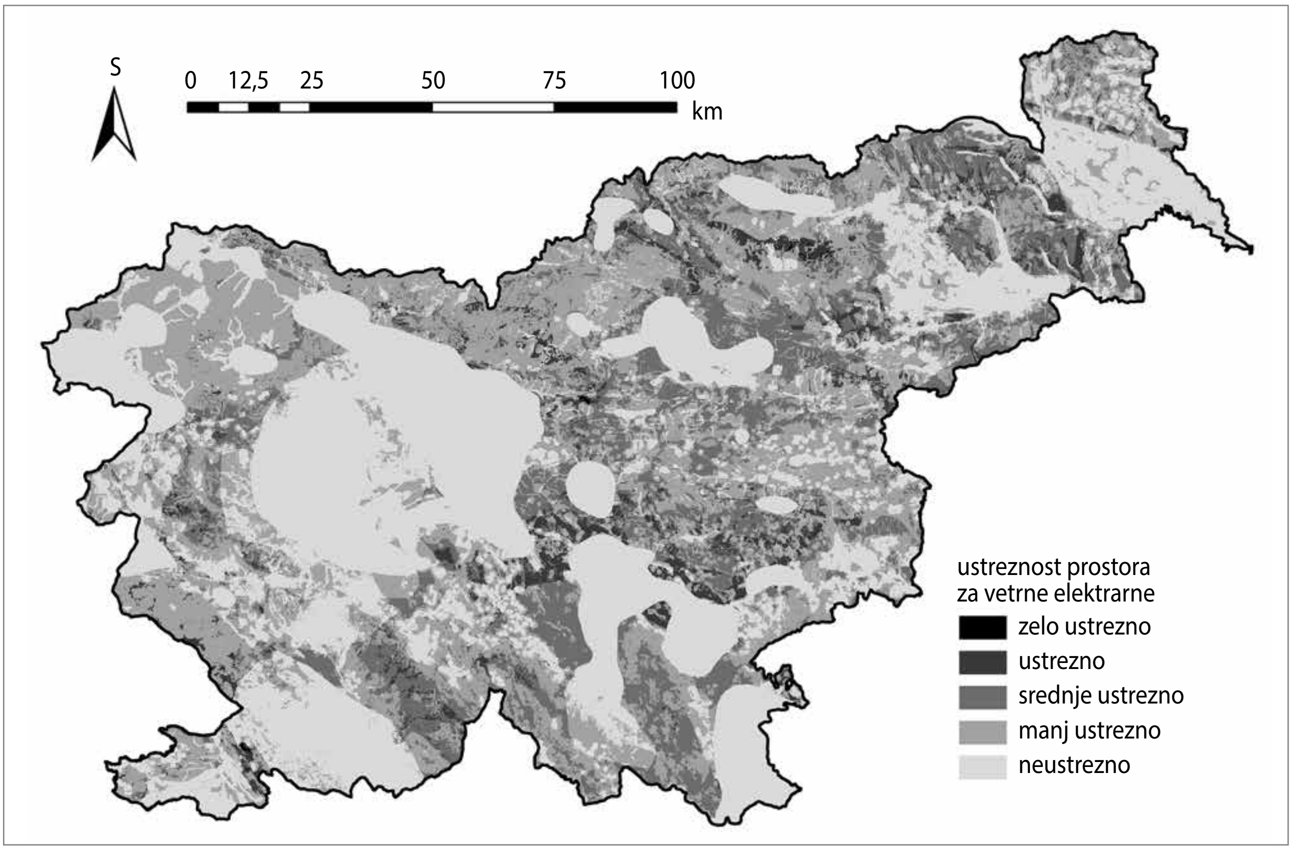
Za območje Slovenije je bila najprej izdelana analiza ustreznosti prostora za umestitev vetrnih elektrarn. V Sloveniji je analiza ustreznosti prostora za določeno dejavnost v prostorskem načrtovanju uveljavljena od začetka devetdesetih let dvajsetega stoletja. Sestoji iz dveh delov: analize privlačnosti prostora za obravnavano dejavnost in analize ranljivosti okolja zaradi te dejavnosti. Analiza privlačnosti prostora za dejavnost ocenjuje značilnosti prostora v kontekstu tehnične in gospodarske izvedljivosti oziroma privlačnosti za izvedbo načrtovanega razvojnega projekta. Analiza ranljivosti okolja hkrati ugotavlja, kako ranljivo je isto območje zaradi te dejavnosti, in služi kot orodje za zgodnje opozarjanje na vplive, ki jih bo dani razvojni projekt imel na okolje, če bo izveden. Rezultati analize privlačnosti in analize ranljivosti so z optimizacijo združeni v model ustreznosti. Celoten postopek je izveden v okolju GIS. Metoda in postopek analize ustreznosti v članku nista podrobno opisana, ker sta sledila standardnim pristopom (Marušič, 1993; Marušič idr., 1993; Koblar idr., 1997; Marušič idr., 2004). Merila, upoštevana pri analizi privlačnosti prostora za vetrne elektrarne, so: vetrne razmere (povprečna letna hitrost vetra po modelih AIOLOS in Aladin – DADA; najprivlačnejša so območja, na katerih je hitrost vetra 5 m/s ali več), površinski pokrov kot dejavnik hrapavosti terena, bližina visokonapetostnega elektroenergetskega omrežja (daljnovodov in transformatorskih postaj), dostopnost – bližina cest, naklon terena, matična podlaga, stabilnost zemljišča, možnost vodne erozije, poplavna območja. Pri modelu ranljivosti smo upoštevali poti velikih zveri, življenjski prostor medveda, podatke Društva za opazovanje in proučevanje ptic Slovenije o življenjskem prostoru ptic, ekološko pomembna območja, varovana območja Natura 2000 po Ptičji in Habitatni direktivi in zavarovana naravna območja, človekovo bivalno okolje (naselja, turistična območja, kulturna dediščina, varstvena območja vodnih virov), vidne kakovosti (izjemne krajine, območja varstva kulturne dediščine, zavarovana območja – še posebej vidno izpostavljena območja, vidna s pogosto obiskanih točk), hidrosfero in pedosfero ter potenciale za rabo in razvoj. Oceno tveganja smo vključili v analizo ustreznosti prostora kot njen tretji del; iz izhodiščnega modela ustreznosti za vetrne elektrarne smo na podlagi ocene tveganja izločili območja z največjo ustreznostjo, ki so bila na območjih večjega tveganja (indeks tveganja 3 ali 4). Za prvo različico ustreznosti (brez upoštevanja tveganj) in drugo (ob upoštevanju tveganj) smo izračunali skupno površino območij, na katera bi lahko umestili veliko elektrarno (z nazivno močjo vsaj 10 MW). Pri tem je bila kot vzorčni tip vetrnice za umestitev v prostor upoštevana vetrna turbina E-70 z nazivno močjo 2,3 MW nemškega proizvajalca Enercon (kakršna je obstoječa vetrna turbina v Dolenji vasi pri Senožečah), iskali pa smo območja, na katera bi lahko postavili najmanj pet tovrstnih vetrnih turbin. Obstoječe vetrne elektrarne zavzamejo v povprečju med 12 in 57 ha/MW (Denholm idr., 2009). Podatki o razdaljah med posameznimi turbinami, ki jih je mogoče najti v literaturi, pa znašajo od 3 do 15 premerov rotorja (Department of Environment, 2007; Christie in Bradley, 2012, ter Meyers in Meneveau, 2011). V analizah smo pri umeščanju vzorčnih vetrnih elektrarn predvidevali, da je razdalja med vetrnicami v vrsti 215 m (trije premeri rotorja), razdalja med vrstami pa 355 m (pet premerov rotorja), kar pomeni, da smo s karte ustreznosti odčitali tiste površine z največjo ustreznostjo, ki so bile velike vsaj 200 m × 1000 m (za postavitev petih vetrnic v vrsto) ali 500 m × 600 m (za postavitev petih vetrnih turbin v gručo). Slovenska praksa sicer pri umeščanju vetrnih elektrarn predvideva manjše gostote stojišč. Tako je bila na Senožeških brdih sprva predvidena postavitev več kot 3–4 turbine na km^2, vendar ker gre za precej razgiban teren, ki ima tudi druge omejitve, vetrnih turbin ni bilo mogoče razporejati s tako gostoto. Zadnji načrt za Senožeška brda predvideva različne gostote na km^2, ponekod samo eno stojišče ali pa tega celo ni. Za obe različici (ustreznost brez upoštevanja tveganj in ustreznost z upoštevanimi tveganji) smo izračunali stroške investicije in vzdrževanja, količino proizvedene energije in za ustreznost brez upoštevanih tveganj tudi stroške zaradi fizične škode zaradi žleda. Obravnavali smo tudi tretjo možnost, pri kateri bi na območja največjih tveganj umestili vetrne elektrarne z vgrajenim sistemom za zaznavanje in preprečevanje nabiranja ledu na turbinah, za druga območja pa smo pri tej različici predvideli postavitev navadnih vetrnih turbin.

3.3 Metoda primerjave stroškov in koristi

Zaradi nabiranja žlednih oblog na vetrnih turbinah lahko pride do zaustavitve turbin ter s tem do izgube proizvodnje električne energije, zmanjšanja moči zaradi spremenjene aerodinamike in hitrejše obrabe posameznih delov, nekontrolirano odpadanje večjih kosov ledu pa pomeni nevarnost za ljudi in objekte v bližini (Dalili idr., 2007, ter Grünevald idr., 2012). Zaradi posledic žlednega dogodka novembra 2013 v Teksasu, ki je povzročil veliko fizično škodo na turbinah in prenosnem omrežju, sta bili ukinjeni vetrni elektrarni s skupno nazivno močjo 78 MW. Upravljavci so izračunali, da stroški za popravilo škode presegajo vrednost oziroma koristi ponovnega zagona (Micek, 2014). Sodobne vetrne turbine lahko imajo vgrajen sistem za zaznavanje ledu in preprečevanje njegovega nabiranja (Deutsche WindGuard, 2011). Za pomoč pri odločanju glede umeščanja v prostor smo za obe različici ustreznosti za postavitev vetrnih elektrarn v Sloveniji izračunali, kako morebitne škode zaradi žleda vplivajo na količino proizvedene energije in kolikšne so finančno izražene škode morebitnih popravil. Pri tem smo analizirali tudi različico, pri kateri imajo



Slika 4: Ustreznost prostora za vetrne elektrarne brez upoštevanja tveganja zaradi žleda (ilustracija: Maruša Matko)



Slika 5: Ustreznost prostora za vetrne elektrarne ob upoštevanju tveganja zaradi žleda (ilustracija: Maruša Matko)

turbine na območjih z največjim tveganjem vgrajen sistem za zaznavanje in preprečevanje nastajanja ledu. Upoštevali smo 25–50-letno obdobje (zaokroženo), saj lahko v tem času pride do dogodkov, pri katerih so lahko škode na elektroenergetski infrastrukturi velike (indeks tveganja 3, kadar lahko na prenosnem in distribucijskem sistemu nastane od 1 milijona do 10 milijonov evrov škode, pogostnost 0,037/leto, in indeks tveganja 4, kadar lahko nastane škoda, višja od 10 milijonov evrov, pogostnost 0,0185/leto). Pri vseh treh različicah – prva z upoštevanjem žlednega dogodka, druga s tehnično izboljšavo (sistem za preprečevanje nabiranja ledu) za vetrne elektrarne na območjih z največjim tveganjem in tretja brez upoštevanja tveganja – so bili upoštevani stroški postavitve, obratovanja in vzdrževanja. Podatek o višini investicije temelji na podatkih o investiciji za obstoječo vetrno turbino v Dolenji vasi pri Senožečah (Ministrstvo Republike Slovenije za infrastrukturo, 2013) in na izračunih nacionalnega laboratorija za obnovljivo energijo ameriškega ministrstva za energijo (ang. *National Renewable Energy Laboratory of the U. S. Department of Energy*; Moné idr., 2015). Ta znesek znaša približno tri milijone evrov. Sistem za detekcijo ledu in preprečevanje njegovega nabiranja na turbinah poveča investicijo za 2–6 %, na stroške obratovanja in vzdrževanja pa ne vpliva bistveno (Eriksson, 2013). V izračunih investicije v take vetrne elektrarne smo uporabili srednjo vrednost – 4 %. Porabljeno energijo za ogrevanje lopatic rotorja smo zanemarili (pulzirajoče, kratkotrajno delovanje). Tudi razpoložljivost tovrstnih vetrnih turbin je nekoliko večja od turbin brez vgrajenega sistema za zaznavanje in preprečevanje nabiranja ledu, kar v izračunih izravna porabljeno energijo za ogrevanje – odtaljevanje oblog. V dostopni literaturi je razpon vrednosti stroškov vzdrževanja in obratovanja zelo velik. Tako Ryan Wiser in Mark Bolinger (2014) v analizi empiričnih podatkov o vetrnih elektrarnah v ZDA ugotavljata, da stroški obratovanja in vzdrževanja za vetrne elektrarne, postavljene po letu 2010, znašajo 23 dolarjev/kW na leto. V podatkih, ki sta jih obravnavala, ni vedno jasno navedeno, kaj je vključeno v te stroške, v večini primerov pa gre za stroške za plače, material in rente. Po drugi strani Christopher Moné idr. (2015) trdijo, da podatek iz prej omenjene študije upošteva le variabilne stroške, ne vključuje pa zavarovanja, davkov, najemnin za zemljišča in amortizacije. Izračunali so, da ob upoštevanju teh stroškov znašajo skupni stroški vzdrževanja in obratovanja 50 dolarjev/kW na leto. Med stroške nenačrtovanega vzdrževanja vključujejo tudi naključne odpovedi, vendar iz prispevka ni jasno razvidno, ali so lahko vzrok za te tudi IVD. V študiji Mednarodne agencije za energijo (ang. *International Energy Agency,* v nadaljevanju: IEA, 2015) so analizirali stroške vzdrževanja in obratovanja vetrnih elektrarn na Danskem, v Nemčiji, na Irskem, Norveškem, v Evropski uniji in ZDA. Leta 2012 je v Nemčiji znašal letni strošek obratovanja in vzdrževanja vetrnih elektrarn 55,9 evra/kW, na Irskem 55 evrov/kW in v ZDA 50 dolarjev/kW. Za nekatere države podatki zaradi nezanesljivosti niso podani. V izračunu smo upoštevali vrednost 56 evrov/kW. Nick Middeldorf in Andreas Düing (2012) sta v svoji raziskavi predvidevala, da se zemljišča za postavitev vetrnih turbin kupijo in da je ta strošek del investicije. Med stroške vzdrževanja in obratovanja pa sta vštela pogodbo o vzdrževanju s proizvajalcem turbin, zavarovanje, stroške energije in upravljanja. Po njunih ugotovitvah znašajo stroški vzdrževanja in obratovanja za turbino Enercon E-70 v prvih dveh letih obratovanja 13 tisoč evrov, v poznejšem obdobju pa 24 tisoč evrov letno. V izračunu smo upoštevali vse štiri vire podatkov in jih primerjali med seboj. Podatki zadostujejo za raven podrobnosti naše obravnave, vendar pa bi bilo treba za natančnejše analize doreči, kateri stroški vzdrževanja in obratovanja se upoštevajo v Sloveniji na podlagi obstoječe elektrarne in predvidenih projektov. Cena električne energije je bila izračunana iz podatkov o tržni ceni električne energije v Sloveniji v obdobju 2009–2015 Javne agencije Republike Slovenije za energijo (Borzen, 2015) in znaša približno 50 evrov/MWh. Za velike vetrne elektrarne sicer obstajajo spodbude s strani države v obliki obratovalne podpore, ki za leto 2015 znašajo 52,64 evra/MWh, vendar smo pri izračunu neto sedanje vrednosti (v nadaljevanju: NSV) zaradi negotovosti v zvezi s podporami v prihodnosti upoštevali le tržno ceno električne energije. Upoštevanje subvencij pri izračunu NSV bi močno vplivalo na rezultat, saj je lahko cena električne energije s podporami tudi do dvakrat višja od tržne. Za obravnavano obdobje smo kot diskontno stopnjo upoštevali dvoodstotno letno inflacijo, kar je cilj Evropske centralne banke za evroobmočje. V primeru žlednega dogodka je treba prenoviti 190 vetrnih turbin, ki so na območjih, na katerih je tveganje zaradi žleda največje. Turbina predstavlja 68 % celotne investicije (Moné idr., 2015), kar znaša skupno 388 milijonov evrov.

4 Rezultati

4.1 Tveganje za elektroenergetsko infrastrukturo zaradi žleda

Rezultat analize žlednih dogodkov na podlagi njihove intenzivnosti in pogostnosti pojavljanja je karta tveganja, prikazana na sliki 2. Na belo obarvanih območjih (v Prekmurju in na Obali) v celotnem obdobju opazovanja ni prišlo do škod zaradi žleda. Nasprotno pa se večje škode (nad 10 milijonov evrov) najpogosteje (več kot 0,2-krat letno) pojavljajo na najtemnejših območjih (Brkini, Idrijsko in Cerkljansko hribovje, okolica Logatca). Večina slovenskega ozemlja ima indeks tveganja 1 (svetlo siva barva), pri katerem so škode na elektroenergetski infrastrukturi majhne, pojavljajo pa se lahko do 0,2-krat letno. Za primerjavo je bila karta tveganja za elektroenergetsko infrastrukturo zaradi žleda prekrita s karto žlednih con po standardu SIST EN 50341-3-21 za gradnjo visokonapetostnih nadzemnih vodov (Slovenski inštitut za standardizacijo, 2009), kot prikazuje slika 2. Standard deli ozemlje Slovenije na tri cone, in sicer glede na obtežbo, ki jo je treba upoštevati pri projektiranju daljnovodov. V coni 1 nastajajo le majhne žledne obtežbe, ki v preteklosti niso povzročale poškodb nadzemnih vodov. V coni 2 se pričakujejo visoke žledne obtežbe, zaradi njih je na teh območjih v preteklosti že prišlo do poškodb daljnovodov. V coni 3 so območja, na katerih se na osnovi vremenskih pogojev, geografske lege in dolgoletnih izkušenj pričakujejo visoke žledne obremenitve. Tovrstne obremenitve so v preteklosti povzročile pomembne škode na nadzemnih vodih. Glede na ugotovitve ocene tveganja bi bilo smiselno posodobiti standard – razširiti cono 3 na območja, na katerih je obtežba zaradi žleda največja. Na osnovi zbranih podatkov, opravljenih analiz in izračunov ter izpeljanih sinteznih rezultatov je bila opravljena tudi primerjava predlaganih različic državnega prostorskega načrta za nadgradnjo 400 kV daljnovoda Beričevo–Divača (slika 3), da bi se prikazala uporaba zadevne ocene tveganja za prostorsko načrtovanje – izbira ustreznejšega koridorja oziroma trase. Ob upoštevanju rezultatov, prikazanih na sliki 2, je za postavitev novega visokonapetostnega daljnovoda Beričevo–Divača primernejši južni koridor.

4.2 Ustreznost prostora za umestitev vetrnih elektrarn

Karta ustreznosti za postavitev vetrnih elektrarn, ki upošteva tudi tveganja zaradi žleda, je prikazana na sliki 4. V Sloveniji je približno 68 km^2 ustreznih površin za postavitev vetrnih elektrarn. Med temi območji smo izbrali tista, na katera bi bilo mogoče umestiti velike vetrne elektrarne – najmanj 5 vetrnic tipa E-70 proizvajalca Enercon (elektrarna v Dolenji vasi). Površina teh območij (brez upoštevanja tveganj) znaša dobrih 31 km^2. Na ta območja bi lahko postavili 405 referenčnih vetrnih turbin. Njihova skupna instalirana moč bi znašala 930 MW, skupna letna proizvodnja pa bi ob domnevi, da bi obratovale 1800 ur na leto, znašala 1,68 TWh. Ob izločitvi območij z največjim tveganjem je najustreznejših površin za umestitev najmanj petih vetrnih turbin 17 km^2. Ta območja so prikazana na sliki 4. Na ta območja bi bilo mogoče postaviti 215 vetrnic s skupno nazivno močjo 495 MW. Skupna letna proizvodnja električne energije bi znašala 890 GWh.

4.3 Primerjava stroškov in koristi

Podatki NSV stroškov in koristi za vse tri različice postavitve vetrnih elektrarn brez upoštevanja pojavljanja žleda in z njim – slednje zunaj območij s tveganji zaradi žleda in z upoštevanjem tehnične izboljšave za odtaljevanje – so prikazani v preglednici 1. Pri prvi različici, po kateri bi postavili vetrne elektrarne tudi na območja z največjimi tveganji (najtemnejša območja na sliki 2), so stroški glede na vse vire podatkov večji od koristi. Različica, ki upošteva tveganja zaradi žleda tako, da uvaja tehnične izboljšave (sistem ogrevanja lopatic rotorja), ima lahko pri upoštevanih nizkih stroških obratovanja in vzdrževanja (Middeldorf in Düing, 2012) pozitivno neto sedanjo vrednost (247 milijonov evrov), upoštevajoč stroške po Wiserju in Bolingerju (2014) je NSV 42 milijonov evrov, upoštevajoč stroške po Monéju idr. (2015) in IEA (2015) pa je NSV vetrnih elektrarn tudi brez žlednega dogodka negativna (–403 milijone evrov oziroma –605 milijonov evrov). Različica, ki upošteva tveganja zaradi žleda tako, da vetrnic na območjih z večjimi tveganji ni, ima ob upoštevanju različnih virov podatkov prav tako lahko pozitivno neto sedanjo vrednost (143 milijonov evrov, Middeldorf in Düing, 2012, ali 34 milijonov evrov, Wiser in Bolinger, 2014) ali pa negativno (–202 milijona evrov, Moné idr., 2015, ali –311 milijonov evrov, IEA, 2015). Praktičen vpliv in rezultat teh ugotovitev sta prikazana na več različicah slike 2, odvisno od stališč investitorjev in upravljavcev vetrnih elektrarn – skladno z odločitvijo o številu, tipu, opremi in lokaciji novih enot se izhodiščna slika 2 o tveganjih ustrezno dopolni, upoštevajoč rezultate ocene stroškov in koristi (NSV). Pričakovani rezultat je, da bi razliko med koristmi in stroški ustrezno prenesli na nove (dopolnjene) karte, in sicer tako, da bi nižje končne stroške prikazali kot nižjo kategorijo posledic. Te karte bi bile osnova za končno potrditev vlaganj s strani investitorjev, bile pa bi tudi osnova za potrjevanje podrobnih prostorskih načrtov. V tem smislu bi moral postopek prostorskega načrtovanja predvidevati ponovitve (iteracije) ocene tveganja zaradi IVD tudi na ravni izdelave podrobnih prostorskih načrtov.

5 Razprava

Rezultati testiranja metode za vključevanje ocene tveganja v prostorsko načrtovanje elektroenergetske infrastrukture, predstavljeni v prispevku, kažejo, da je ta pregledna in operativna ter da lahko služi kot podpora v postopku odločanja. Rezultati ocene tveganja pomembno prispevajo k optimizaciji elektroenergetske infrastrukture in jih lahko uporabimo na več načinov. Optimizacija elektroenergetske infrastrukture ob upoštevanju tveganj zaradi IVD je lahko tehnološka ali prostorska. Tehnološka optimizacija vključuje posodobitve gradbeno-inženirskih standardov ob upoštevanju ocene tveganja (slika 2 – karta tveganja za elektroenergetsko infrastrukturo zaradi žleda). Na ta način bo prihodnji infrastrukturi zagotovljena večja mehanska trdnost oziroma odpornost. Med ukrepe za tehnološko optimizacijo spada tudi postavitev vetrnih elektrarn z vgrajenim sistemom za zaznavanje ledu in preprečevanje njegovega nabiranja. Ocena tveganja lahko služi tudi kot podpora za načrtovanje investicij v posodabljanje posameznih delov na obstoječih objektih. Pri prostorski optimizaciji elektroenergetske infrastrukture lahko oceno tveganja zaradi IVD uporabimo pri presoji že predlaganega načrta oziroma

Preglednica 1: Primerjava stroškov in koristi za postavitev vetrnih elektrarn v 25-letnem obdobju, in sicer brez upoštevanja pojavljanja žleda (različica 1) in ob upoštevanju rezultatov ocene tveganja (različici 2 in 3)

različica	NSV (stroški)		NSV (koristi)	NSV (razlika med koristmi in stroški)	NSV (razlika med koristmi in stroški v primeru žlednega dogodka)
1 (vetrne elektrarne tudi na območjih, na katerih pride do žlednega dogodka)	investicija:	–1,215 milijarde evrov	prodana električna energija: +1,67 milijarde evrov	od –582 milijonov evrov do +270 milijonov evrov	od –118 milijonov evrov do –970 milijonov evrov
	stroški vzdrževanja + obratovanja	–185 milijonov evrov (Middeldorf in Düing, 2012) –390 milijonov evrov (Wiser in Bolinger, 2014) –835 milijonov evrov (Moné idr., 2015) –1,037 milijarde evrov (IEA, 2015)			
	stroški zaradi žlednega dogodka	–388 milijonov evrov			
	stroški skupaj	od 1,4 milijarde evrov do 2,252 milijarde evrov			
	stroški skupaj v primeru žlednega dogodka	od 1,788 milijarde evrov do 2,640 milijarde evrov			
2 (vetrne elektrarne tudi na območjih, na katerih pride do žlednega dogodka, vendar turbine na teh območjih imajo vgrajenega sistema za preprečevanje nastajanja žleda)	investicija:	–1,238 milijarde evrov	prodana električna energija: +1,67 milijarde evrov	od –605 milijonov evrov do +247 milijonov evrov	od –605 milijonov evrov do +247 milijonov evrov
	stroški vzdrževanja + obratovanja	–185 milijonov evrov (Middeldorf in Düing, 2012) –390 milijonov evrov (Wiser in Bolinger, 2014) –835 milijonov evrov (Moné idr., 2015) –1,037 milijarde evrov (IEA, 2015)			
	stroški zaradi žlednega dogodka	0 evrov			
	stroški skupaj	od 1,423 milijarde evrov do 2,275 milijarde evrov			
3 (vetrne elektrarne samo na območjih, na katerih ne pride do žlednega dogodka)	investicija:	–645 milijonov evrov	prodana električna energija: +886 milijonov evrov	od –311 milijonov evrov do +143 milijonov evrov	od –311 milijonov evrov do +143 milijonov evrov
	stroški vzdrževanja + obratovanja	–98 milijonov evrov (Middeldorf in Düing, 2012) –207 milijonov evrov (Wiser in Bolinger, 2014) –443 milijonov evrov (Moné idr., 2015) –552 milijonov evrov (IEA, 2015)			
	stroški zaradi žlednega dogodka	0 evrov			
	stroški skupaj	od 743 milijonov evrov do 1,197 milijarde evrov			

Viri podatkov za izračun: Middeldorf in Düing (2012); Wiser in Bolinger (2014); Moné idr. (2015); IEA (2015) njegovih različic (primer analize predlaganih tras daljnovoda, slika 3), lahko pa jo vključimo v oblikovanje načrta, pri čemer iščemo lokacije, na katerih bodo škode na objektih, ki jih umeščamo v prostor, manjše ali pa do njih ne bo prišlo. Ocena tveganja je v analizo ustreznosti v izvedbenem smislu vključena kot njena tretja sestavina, sicer pa gre konceptualno za sestavino (ne)privlačnosti. Metoda za vključevanje ocene tveganja v prostorsko načrtovanje elektroenergetske infrastrukture je bila razvita v sodelovanju s predstavniki slovenskih podjetij za proizvodnjo, prenos in distribucijo električne energije. Pristop, ki smo jim ga predstavili, so ocenili kot obetaven, zdaj pa tehtajo možnosti za uporabo metode za svoje potrebe. Nadaljnje preverjanje uporabnosti opisane metode bi moralo vključevati tudi prostorske načrtovalce in povezane odločevalce. Vsekakor lahko prikazani rezultati služijo kot spodbuda za javno razpravo o potrebah po elektriki v prihodnosti, njenem zagotavljanju, o energetski mešanici in upoštevanju različnih tveganj pri umeščanju te infrastrukture v prostor.

Rezultat ocene tveganja – karta tveganja za slovensko elektroenergetsko infrastrukturo zaradi žleda – je pokazal, katerim območjem se je pri iskanju lokacij za novo elektroenergetsko infrastrukturo smiselno izogibati, če želimo preprečiti večje škode, in kje je za obstoječo infrastrukturo smiselno izvesti ukrepe za preprečevanje ali zmanjšanje škode. V zadnjih letih so bile posodobljene ali na novo izdelane karte tveganja zaradi žleda tudi za Francijo (Dalle in Admirat, 2011), Italijo (Bonelli idr., 2011), Švico (Grünevald idr, 2012), Kanado (Lamraoui idr., 2013) in Veliko Britanijo (Nygaard idr., 2014). Te karte temeljijo na meteoroloških modelih in/ali na podatkih meteoroloških postaj in prikazujejo območja glede na pričakovano debelino žledne obloge ali njeno trajanje. Bjørn Nygaard idr. (2014) predlagajo uporabo kart pri oblikovanju novih inženirskih standardov, Bernard Dalle in Pierre Admirat (2011) ter Paolo Bonelli idr. (2011) pa pri inženirskem projektiranju daljnovodov, ki so na določenih območjih že predvideni, in pri oblikovanju tehničnih ukrepov za preprečevanje nabiranja žleda ali njegovega odstranjevanja, ne omenjajo pa iskanja lokacij za novo infrastrukturo na podlagi svojih ocen tveganj. Dalle in Admirat (2011) omenjata uporabo karte tveganja tudi pri organizaciji nujnih popravil v primeru pojava dogodkov. Fayçal Lamraoui idr. (2013) trdijo, da lahko karta tveganja služi kot podpora pri odločanju o izvedbi določenih projektov, vendar se z uporabo ocen tveganja v odločevalskih postopkih ne ukvarjajo natančneje. Thomas Günevald idr. (2012) predlagajo uporabo karte tveganja zaradi žleda pri načrtovanju vetrnih elektrarn v kombinaciji s kartami vetrnega potenciala, vendar zamisli ne razvijejo podrobneje. Ker se omenjene raziskave ukvarjajo predvsem s tehnološko optimizacijo in ne z iskanjem lokacij za novo elektroenergetsko infrastrukturo na podlagi ocen tveganj, v nadaljevanju primerjava naših rezultatov z drugimi ni mogoča, zato se bomo osredotočili na prednosti in slabosti metode, s katerimi smo se soočili pri testnem primeru.

Ena od težav, ki so se pokazale pri testiranju metode, je dostopnost podatkov. Beleženje podatkov o IVD in škodah, ki jih povzročajo, ni standardizirano. Podatki podjetij za prenos in distribucijo so zelo heterogeni (lahko beležijo število odjemalcev brez energije, trajanje prekinitev dobave, količino nedobavljene energije, fizično ali finančno škodo), zato jih je treba pred izvedbo ocene tveganja prilagoditi, da so primerljivi. V prikazanem primeru so bili v ustreznem obsegu dostopni samo podatki za direktno (fizično) škodo, zato rezultati kažejo kategorije tveganja za prenosno podjetje in distribucijska podjetja. Če bi bili na voljo tudi podatki o nedobavljeni energiji, bi bilo mogoče ob finančni škodi za prenos in distribucijo omrežja izračunati tudi finančno škodo za odjemalce in posredno gospodarsko škodo. Beleženje podatkov o škodah bi bilo smiselno poenotiti. Tudi po dolžini časovne vrste se razlikujejo od podjetja do podjetja; težko dostopni so predvsem podatki iz časa pred elektronskimi arhivi. To lahko prispeva k manjši natančnosti ocene tveganja, predvsem če se manjkajoči podatki o določenem IVD nanašajo na podjetje, ki deluje na območju, na katerem se ta IVD pojavlja pogosto in povzroča večje škode. Poleg tega lahko tudi škode v okolju (na primer podiranje dreves zaradi žleda) povzročijo še dodatne škode na infrastrukturi. To smo v oceno tveganja zajeli z upoštevanjem škod v gozdovih. Tudi dostopni podatki o stroških za vetrne elektrarne so zelo heterogeni in lahko odločilno vplivajo na to, kakšna je neto sedanja vrednost predlaganega projekta, kot je prikazano v preglednici 1. Obravnavani viri med stroške obratovanja in vzdrževanja namreč zajemajo različne stroške (nekateri na primer predvidevajo najem zemljišč, drugi pa domnevajo, da bo zemljišče kupljeno in bo njegova cena del investicije). Prihaja tudi do razlik med podatki iz različnih držav, ki so bile obravnavane v navedenih študijah. Pred dejanskim odločanjem za umestitev objekta v prostor bi bilo zato treba v Sloveniji sprožiti diskusijo, kateri podatki naj se uporabijo v analizi stroškov in koristi. Dodatne negotovosti se nanašajo na prihodnje spodbude s strani države za uporabo obnovljivih virov energije, zato je bila pri izračunih koristi zaradi prodane električne energije upoštevana tržna cena elektrike v Sloveniji in ne subvencionirana, ki je lahko tudi dvakrat višja. Naša ugotovitev, da v primeru žlednega dogodka stroški prerastejo koristi, je konsistentna s primerom iz prakse, v katerem so raje ustavili obratovanje poškodovanih vetrnih elektrarn, kot da bi jih obnovili (Micek, 2014).

6 Sklep

V članku smo želeli oblikovati, testirati in predstaviti metodo, ki bo povezala oceno tveganja s pristopi iz prostorskega načrtovanja. Izkazalo se je, da je prikazani pristop uporaben tako v prostorskem načrtovanju kot pri odločanju glede ukrepov za povečanje mehanske odpornosti, med katere spadajo tudi odločitve o vzdrževanju in posodabljanju elektroenergetske infrastrukture. Hipoteza, da lahko z vključitvijo ocene tveganja v prostorsko načrtovanje vplivamo na zmanjšanje škod zaradi IVD na energetski infrastrukturi, se je potrdila. Metoda je bila prikazana na primeru tveganj zaradi žleda v Sloveniji in umeščanju vetrnih turbin, uporabiti pa jo je mogoče tudi za druge IVD in različne kombinacije teh dogodkov ter v drugih regijah. Poleg tega njena uporaba ni omejena le na energetsko infrastrukturo, temveč je mogoče na ta način ocenjevati tveganja tudi za drugo kritično infrastrukturo in druge okoljske sestavine – naravne (na primer gozd, tla, vodotoki itd.) in antropogene (na primer naselja, kulturna dediščina itd.). Poleg tega je pri ocenjevanju tveganj mogoče prilagajati merilo – velikost obravnavanega območja in podrobnost analize. V nadaljnje raziskovanje bo treba vključiti vse omenjene vidike in izdelati ocene tveganja tudi za druge IVD, ki povzročajo škodo na elektroenergetski infrastrukturi (močen veter, težek in obilen sneg, toča, močna neurja, zaradi katerih pride do poplav in povečane erozije), za kombinacije teh dogodkov in drugo elektroenergetsko infrastrukturo (fotovoltaični paneli, hidroelektrarne, jedrske elektrarne). Naslednji korak v raziskovanju bi morala biti uporaba ocene tveganja pri oblikovanju vzdrževalnih oziroma posodobitvenih ukrepov za obstoječo infrastrukturo in pri analizi stroškovne učinkovitosti teh ukrepov.

Odpira se vprašanje, kako obravnavati dogodke, s katerimi še nimamo izkušenj. Smiselno bi bilo uporabiti podnebne modele, ki napovedujejo spremembe pogostnosti in intenzivnosti IVD, vendar pa je ločljivost teh modelov groba, poleg tega pa pri modeliranju postopnih podnebnih sprememb in IVD obstajajo številne negotovosti glede prihodnjih izpustov toplogrednih plinov, glede oblikovanja podnebnih modelov, zmanjševanja njihovega merila z globalne ravni na regionalno ali lokalno, kot tudi glede nelinearnih razmerij med povprečnimi vrednostmi podnebnih spremenljivk in izrednimi vremenskimi dogodki (Mearns idr., 1984; Jones, 2001; Mitchell idr., 2006; Fowler idr., 2007; Van Aalst, 2006; Chen idr., 2011; Ceglar in Kajfež-Bogataj, 2012; IPCC, 2012; Sunyer idr., 2012, ter Willems idr., 2012). Gotovost napovedi o pojavljanju IVD je močno odvisna tudi od tipov obravnavanih IVD in od obravnavanih regij (Planton idr., 2008, in IPCC, 2012). Dodaten vir negotovosti pomeni modeliranje vplivov IVD na specifične sisteme, kot so kmetijstvo, gozdarstvo, energetski sektor ipd. (Fowler idr., 2007). Pri prihodnjih napovedih vplivov podnebnih sprememb na elektroenergetsko infrastrukturo bi bilo smiselno upoštevati različne kombinacije podnebnih scenarijev ter scenarijev prihodnjega družbenega in gospodarskega razvoja, kot tudi že izdelane načrte za prihodnji razvoj energetike. Nekateri tipi elektroenergetske infrastrukture so relativno novi (na primer sončne elektrarne), zato je za to infrastrukturo na voljo le malo informacij o tem, kako dovzetna je za škode zaradi različnih IVD. Poleg tega imamo tudi območja, na katerih v preteklosti določene infrastrukture ni bilo, lahko pa bo tja umeščena v prihodnosti. K zmanjšanju negotovosti pri ocenjevanju tveganja lahko prispeva uporaba več zanesljivih podatkov z različnih lokacij in za različno infrastrukturo oziroma druge okoljske sestavine. V prihodnje bi bilo zato upravljavcem elektroenergetske in druge infrastrukture smiselno predlagati standardiziran sistem beleženja podatkov o vplivih IVD na njihove objekte. Obravnava različnih tehnologij za pridobivanje električne energije zahteva previdnost pri razlagi rezultatov – indeks tveganja, izračunan na podlagi škode zaradi IVD in pogostnosti njihovega pojavljanja, je lahko za različne tehnologije enak, v absolutnih številkah pa se lahko škoda zaradi neproizvedene električne energije razlikuje tudi za red velikosti (na primer primerjava med proizvodnjo v hidroelektrarni ali jedrski elektrarni v Sloveniji), drugod tudi za več. Zato je treba pri razlagi indeksov tveganja in stroškov, povezanih z njimi, jasno določiti kontekst. Kako naj bo predstavljena metoda vključena v formalne postopke prostorskega načrtovanja, je treba še preveriti oziroma se dogovoriti s prostorskimi načrtovalci in drugimi udeleženci v teh postopkih. Dogovor s stroko bi bil predvidoma hiter, pri upravnih organih pa je mogoče pričakovati daljša dogovarjanja glede postopka. Menimo, da bi bila vključitev predstavljene metode v obstoječe postopke mogoča že z manjšimi prilagoditvami teh postopkov glede na kontekst prostorskih načrtov, merilo in potrebe (pričakovanja).

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Integration of extreme weather event risk assessment into spatial planning of electric power infrastructure

This article examines practical measures for integrating risk assessment of extreme weather events into spatial planning. An approach that integrates risks due to ice storms into spatial suitability analysis is presented in two case studies: in siting transmission and distribution power lines, and in siting windfarms. Assessment of risks to the power grid due to ice storms is carried out first. The results of the risk assessment are then used as a basis for analysing proposed alternatives for siting high-voltage power lines and as input in analysing the suitability of space for siting windfarms. The results of a cost-benefit analysis of various alternatives for siting windfarms (an alternative that takes risks due to ice storms into account and one that does not) show that the damage caused by extreme weather events has a significant impact on the economic viability of a plan. There are two options for integrating risk assessment results into planning electric energy infrastructure: by updating engineering standards and by avoiding areas where greater damage to infrastructure due to extreme weather events is expected. Risk assessment provides important information that can affect decisions about land use and decisions about technical measures for enhancing the physical resilience of infrastructure.

Keywords: spatial planning, risk assessment, extreme weather events, energy infrastructure, vulnerability

1 Introduction

Gradual climate change with rising mean temperatures and changed precipitation patterns is expected to impact electricity supply and demand as well as its price, accessibility and transmission or distribution (Feeley et al., 2008; Wilbanks et al., 2008; Kopytko & Perkins, 2011; Rübbelke & Vögele, 2011; McColl et al., 2012; Schaeffer et al., 2012). Extreme weather events (EWE) such as strong wind, heavy rainfall or snow, ice storms, hail and so on or various combinations of these extreme conditions may cause damage to hydroelectric power plants, coal-fired power plants, nuclear power plants, wind turbines, solar panels, power lines and substations (Auld et al., 2006; McColl et al., 2012; Schaeffer et al., 2012; International Atomic Energy Agency (IAEA), 2013; Patt et al., 2013; Sieber, 2013). According to the Intergovernmental Panel on Climate Change (IPCC; 2012, 2013), both the intensity of EWE and the frequency of EWE with specific intensities have recently increased, and this trend is expected to continue in the future. Energy infrastructure has a long lifespan and decisions about its location and technical implementation made now will have long-term consequences. This is why gradual climate change and EWE should be taken into account in the planning process, which demands an analysis of various adjustments and adaptation measures (Auld et al., 2006; Wilbanks et al., 2008; Rübbelke & Vögele, 2011; Schaeffer et al., 2012; IAEA, 2013). Building energy infrastructure that is resilient to gradual climate change and EWE is one of the key adaptation measures of the energy sector (Auld et al., 2006; Cortekar & Groth, 2015; Panteli & Mancarella, 2015), which is also pointed out in international and national policies such as the United Nations Framework Convention on Climate Change (2014), the EU Strategy on Adaptation to Climate Change (European Commission, 2013) and the US Draft Climate Change Adaptation Plan (United States Environmental Protection Agency (EPA), 2012a). The Slovenian draft national energy programme (see Jožef Stefan Institute, 2011) listed "reliable energy service in extreme conditions, such as natural disasters" among the goals for reliability of the energy supply. The draft national energy programme prepared in 2011 was not adopted and therefore not implemented. The decision-making process about the draft national energy programme was stopped after public discussion and transboundary impact assessment, and the document remained at the draft level. The energy sector development document still in force is the Resolution on the National Energy Programme (Sln. *Resolucija o Nacionalnem energetskem programu*, Ur. l. RS, no. 57/2004), which was adopted in 2004. It will be replaced by the Energy Concept of Slovenia (Sln. *Energetski koncept Slovenije*), which is being prepared. The Proposal for Guidelines for Preparing the Energy Concept (Sln. *Predlog usmeritev za pripravo Energetskega koncepta,* Ministry of Infrastructure of the Republic of Slovenia, 2015) lists a reliable energy supply among the goals for a sustainable energy sector. This goal should be attained via development of a reliable power grid and the use of dispersed energy sources. The resilience of infrastructure to EWE is not explicitly mentioned.

There are, in general, two approaches to preventing damage to power infrastructure: 1) technical (mechanical) improvement of the components, making them more robust and resistant to physical stress, and 2) considering the physical location of infrastructure and locating it to places where its vulnerability to gradual climate change and EWE is lower (Auld et al., 2006; IAEA, 2013). Operationally, the second option is related to spatial planning. Planning land use that takes into account risks due to various factors is more cost-effective than structural measures for risk reduction (Sudmeier-Rieux et al., 2015). Studies on integrating risk assessment into spatial planning (ARMONIA; Lancaster University, 2007; Sutanta et al., 2010; Storch & Downes, 2013; Prawiranegara, 2014) have concentrated on developing a decision-support system and not specifically on the use of risk-assessment results for allocating new facilities. We focus on this particular issue with the aim of filling the gap by showing how existing approaches in land-use planning can be adjusted to take into account the results of risk assessment of gradual climate change and EWE.

The research background and connected hypothesis is as follows: it is rational and feasible to integrate risk assessment into spatial planning in order to reduce damage to energy infrastructure caused by EWE. The article starts by presenting the importance of spatial planning in reducing risks posed by gradual climate change and EWE and the use of risk assessment in spatial planning. These two fields are then connected by developing a method for integrating them. The use of the method is presented in a case study on risks to energy infrastructure due to ice storms in Slovenia. In the case study, risk assessment is used to support analysis of proposed alternatives of a planned high-voltage power line and for determining the most suitable locations for siting windfarms. This is followed by a cost-benefit analysis of three development alternatives: one that takes risks due to ice storms into account by siting windfarms (no wind turbines are located in areas with high risk); one that includes technical measures for damage prevention or reduction in areas with high risk; and one in which risks are not considered. The presentation of the results is followed by a discussion of the usefulness of the proposed approach and its strengths and weaknesses. The conclusion proposes directions for further research.

2 Theoretical background

2.1 The role of spatial planning in adapting to gradual climate change and extreme weather events

Spatial planning has been recognised as a basis for adaptation to climate change in research literature (Biesbroek et al., 2009; Wilson & Piper, 2010; Hurlimann & March, 2012; Rastandeh, 2015) and in several strategic documents; for example, the Green and White Paper of the European Commission (European Commission, 2007, 2009) and the Territorial Agenda of the European Union (European Commission, 2011). In Slovenia too, spatial planning has explicitly been pointed out as a priority of adaptation because it offers important preventive instruments for adapting to climate change through integrated planning and urban development (Government Office of the Republic of Slovenia for Climate Change, 2011; Kajfež-Bogataj et al., 2012). A great number of studies about the effectiveness of spatial planning in climate change adaptation have been carried out at the international level (e.g., International Commission for the Protection of the Alps, 2010; Pütz et al., 2011; Linkaits, 2013), as well as at the national level (e.g., Rivera & Wamsler, 2014; Flannery et al., 2015; Kumar & Geneletti, 2015), regional level (e.g., Rannow et al., 2010; De Bruin et al., 2013) and local level (e.g., Wilson, 2006; Andersson-Sköld et al., 2015; Dubois et al., 2015). In Slovenia, spatial planning as a tool for adapting to climate change was analysed by Mojca Golobič et al. (2012). The authors of these studies state that spatial planning is an activity with the ability to help society and the economy with adaptation to land-use change, prevention of natural disasters and integration of various fields into planning (Rannow et al., 2010; Pütz et al., 2011; Greiving & Fleischhauer, 2012; Serrao-Neumann et al., 2015). They point out that some spatial-planning instruments already include measures for adapting to climate change but these measures are not sufficient or are not suitably implemented in order to transfer adaptation into practice (Wilson, 2006; Rannow et al., 2010; Golobič et al., 2012, Pütz et al., 2011). The same authors conclude that it is necessary to make a step from the strategic level towards consistent implementation of adaptation by means of spatial planning at the operational level. Sven Rannow et al. (2010) argue that assessment and use of data about the frequency and intensity of extreme events are limiting factors for spatial planners and they propose using findings of other disciplines in order to take EWE into account. In spatial planning legislation, climate change is addressed implicitly – as a part of protection or restoration of the natural environment, protection of settlements against natural disasters, and environmentally and economically suitable spatial development (Government Office of the Republic of Slovenia for Climate Change, 2011).

2.2 Risk assessment and integrating it into spatial planning

A great number of studies about risks due to natural and/or anthropogenic extreme events have been carried out in the past two decades. Many of these studies were carried out with the support of international organisations, such as Nato (Briggs et al., 2002), the European Union (the research projects Accidental Risk Assessment Methodology for Industries, or ARAMIS, 2002–2005; Sharing Experience on Risk Management (Health, Safety and Environment) to Design Future Industrial Systems, or SHAPE-RISK, 2004–2007; ARMONIA, 2004–2007; Early Recognition, Monitoring and Integrated Management of Emerging, New Technology Related Risks, or iNTeg-Risk, 2008–2013; Technology Opportunities and Strategies Towards Climate-Friendly Transport, or TOSCA, 2010–2013; Coordination of European Research on Industrial Safety towards Smart and Sustainable Growth, or SAFERA, 2012–2015), the United Nations Office for Disaster Risk Reduction (UNISDR) and the International Atomic Energy Agency (CRP Techno-Economic Evaluation of Options for Adapting Nuclear and Other Energy Infrastructure to Long-Term Climate Change and Extreme Weather, 2012–2015). The body of scientific literature about risk assessment is also extensive; it studies risks due to various extreme events; for example, erosion (Alder et al., 2015), floods (Camarasa-Belmonte & Soriano-García, 2012; Zhou et al., 2012; Canters et al., 2014; Prawiranegara, 2014; Foudi et al., 2015), forest fires (Thompson et al., 2015) and others. These studies place great emphasis on developing methods to reduce the consequences of various types of extreme events. Melanie Gall et al. (2015) studied interdisciplinary research on risks in the past fifteen years that connected various research fields, methods and stakeholders. They conclude that there is a large gap between research and implementation in practice. Even though most of the these articles stress that the risk-assessment methods they have developed and presented may be used as decision support and could be included in spatial planning (e.g., Camarasa-Belmonte & Soriano-García, 2012; Alder et al., 2015; Foudi et al., 2015; Thompson et al., 2015), this integration is not further explored. Most studies that address integrating risk assessment into spatial planning (Lancaster University, 2007; Sutanta et al., 2010; Storch & Downes, 2013; Prawiranegara, 2014) focus on designing decision support systems based on maps of integrated hazards or risks and not on developing methods for finding suitable locations for specific activities, uses or facilities. Marisa Berry and Todd BenDor (2015) included projections of sea level rise and inundated areas due to storm surges into spatial suitability analysis, but this mostly means siting activities away from the coast and lower lying areas; their study takes into account neither the probability of occurrence of storms nor their consequences. Stefan Greiving et al. (2006) believe that risk assessments carried out by professionals from various fields are not ready to be used in spatial planning; transfer of information about risks into the language of spatial planning is needed in order to use this information in the planning process. This problem was addressed by Davor and Branko Kontić (2008) in a case study of risks due to industrial accidents. The approach presented in this article builds on and further develops their method by focusing on risks due to extreme natural events. We presume that integrating gradual climate change and EWE into the spatial planning of energy infrastructure would optimise their efficiency and prevent or decrease possible damage. This article presents an approach for choosing suitable locations for siting energy infrastructure that was developed and tested in a case study of risk to energy infrastructure due to ice storms in Slovenia.

3 Methods

The method integrating risk-assessment results into spatial planning is based on the approach developed in a case study of risks due to industrial accidents by Kontić and Kontić (2008). By using spatial planning tools, they tried to prevent or minimise the consequences of industrial accidents in the vicinity of organisations in the category of higher risks according to Council Directive 96/82/EC of 9 December 1996 on the control of major accident hazards involving dangerous substances (Seveso II Directive, Official Journal of the EU, no. 10/1997). We further developed their approach and adapted it for risk assessment of extreme events as consequences of natural processes with a focus on risk due to EWE. The terminology used in this article has different meanings in different contexts or fields. In risk assessment the terms *risk*, *hazard* and *vulnerability* are defined as follows:

- A risk is the likelihood of occurrence (expressed in frequency or probability) of specific consequences as a result of exposure to a specific stressor or hazard (EPA, 2012b; UNISDR, 2014);
- A hazard is a dangerous phenomenon, substance or activity that may cause adverse consequences (loss of life, injury or other health impacts, property damage, loss of livelihoods and services, social and economic disruption or environmental damage) in a system exposed to the hazard (UNISDR, 2014);
- The vulnerability of a system (e.g., energy infrastructure, forest, etc.) is the characteristics and circumstances of a community, system or asset that make it susceptible to the damaging effects of a hazard; possibility that the exposed subject or system may be affected by the phenomenon in case of exposure (Cardona, 2003; UNISDR, 2014); the purpose of determining the vulnerability of a system is to reduce risk by using technical measures or adjustment of existing land use.

The IPCC (2007) provides a different definition of vulnerability to climate change. Vulnerability is assumed to be the result of three factors: 1) a function of the character, magnitude and rate of change that a system is exposed to, 2) the sensitivity of a system and 3) its adaptive capability. Each of these factors is assessed based on criteria and indicators that can be described with qualitative or quantitative data. Spatial or environmental vulnerability is a term used in spatial planning defining potential negative effects that the proposed development plan may have on individual environmental components and the environment as a whole at a specific location. This article uses two terms: vulnerability of a system as defined in risk assessment and spatial or environmental vulnerability as defined in spatial planning.

3.1 Method for assessing risk to energy infrastructure due to extreme weather events

The method for assessing risk to energy infrastructure due to extreme weather events was tested in a case study of risk to energy infrastructure posed by ice storms. The method comprises four steps:

1. Determining the geographic scope and intensity level of an extreme weather event based on data from past occurrences. The intensity level of each EWE (e.g., mass, force, temperature, burden due to glaze ice, strong wind, heavy snow, heavy rain storm, etc.) is represented on GIS-based maps (see Figure 1), in which each cell is evaluated on a scale from 1 (low) to 4 (high) for physical burden on the electric energy infrastructure. The size of the cell depends on the size of the area analysed and the detail of the analysis. In the analysis presented here, which was carried out at the level of all of Slovenia, the cell measured 100 m × 100 m. The data were obtained from archives about past EWE. We used data about locations of damaged power lines and elevation above sea level where the damage was present. The events were categorised into classes of intensity based on financial damage caused by a specific event. The thresholds of these categories were determined according to the amount of financial means allocated by transmission and distribution companies for infrastructure maintenance.
2. Analysis of the vulnerability of the electric energy infrastructure and the location and the environment in which the infrastructure is situated to a specific EWE. The purpose of this step is to determine whether the energy infrastructure at a specific location is able to withstand an

Data about the events

Date	Location	Financial loss (€)	Category of intensity	Category of frequency	Risk index
19 Nov. 1972	Tezno	528,000	2	3	2
5 Nov. 1980	Brkini	33.5 million	3	3	3
13 Nov.–14 Nov. 1985	Idrija area, Cerkno area	120,000	2	3	2
30 Jan.–8 Feb. 2014	All of Slovenia except the Littoral and Prekmurje	214 million	4	1	3

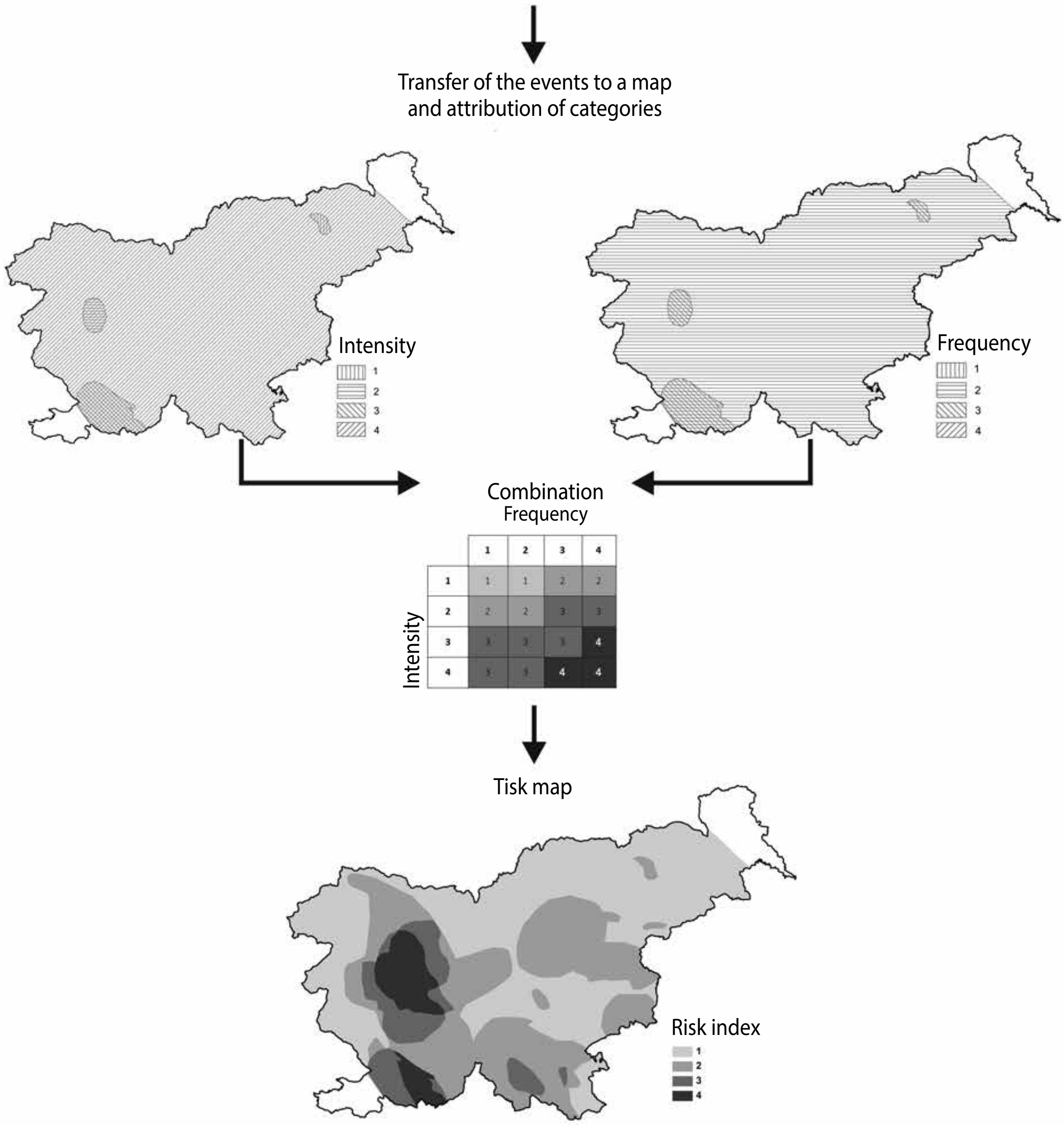

Figure 1: Risk assessment steps (illustration: Maruša Matko).

EWE of a given intensity level. A particular EWE can cause direct, primary damage to energy infrastructure as well as secondary damage due to environmental damage (e.g., falling trees or erosion), which causes additional structural and other damage and loss to the energy infrastructure. The vulnerability of infrastructure, in terms of primary damage, can be specified and evaluated by using construction and other engineering or quality standards, whereas vulnerability due to destruction of environmental features (i.e., secondary damage) is more complex and is affected by several factors. In the case of glaze ice, damage to forests has been used as a determinant or indicator of environment-related vulnerability. Vulnerability is expressed as the ratio of the expected level of damage or loss of the infrastructure to the maximum possible damage or loss and is expressed on a scale of 1 to 4. The results are represented on GIS-based maps for various EWE at specific locations (see Figure 1).

3. Assessment of the probability or frequency of occurrence of an extreme weather event at a particular site or region where specific energy infrastructure is, or will be, located. Based on historical data about EWE, the frequency or probability of occurrence of various types of EWE is calculated. The results are presented on maps.
4. Integration of the three steps above, with the aim of determining physical and other (e.g., economic or health) consequences that will lead to the specification of a risk index pertaining to the particular area and infrastructure. The risk index integrates the intensity of an EWE and the vulnerability of energy infrastructure to the specific intensity level of an EWE, the frequency or probability of occurrence of an EWE and consequences; that is, social damage due to damaged infrastructure. These combinations are similar to the standard risk matrices used for integrating the frequency or intensity of events with the consequences of these events.

Practical implementation of risk assessment of the four selected icing events and the damage caused by them is presented in Figure 1. First, data about the occurrences of ice storms, their locations and the damage they caused were obtained. Each event was then drawn on a map in a GIS environment (see Figure 1) and categorised into a class of intensity based on the damage it caused (which depends on intensity of the event and vulnerability of a system). Each event was categorised into a class of frequency of occurrence. In Figure 1, hatching (line fill) is used to represent the intensity and frequency of selected events in order to show the spatial distribution of events, which has impact on the final result. Only four selected events are presented on intensity and frequency maps to facilitate readability; see the paper by Maruša Matko et al. (2015) for data about all the events. By integrating the categories of intensity and frequency of the events, we obtained a risk index for each event, and risk indices of all the events were then combined into the end result, a risk map. The risk map in Figure 1 takes into account all of the icing events that were considered.

Assessment of risks to electric power lines due to ice storms was carried out using data on the occurrence of damage to forests and electric infrastructure. This is based on data on the occurrence of ice storms between 1961 and 2014 collected by the Slovenian Environment Agency (ARSO) and reports about damage caused by glaze ice (Šifrer, 1977; Radinja, 1983; Kern & Zadnik, 1987; Papler, 1996; Bogataj, 1997; Jakša, 1997; Jakše, 1997; Kastelec, 1997; Lapajne, 1997; Nadižar & Papler, 1997; Šipec, 1997; Trontelj, 1997a; Trontelj, 1997b; Zadnik, 1997; Špehar, 1998; Rebula, 2001; Rebula, 2002; Zadnik, 2006; Habjan & Bahun, 2009; Habjan, 2010; Sinjur et al., 2010; Bahun, 2014; Bahun et al., 2014; Belak & Maruša, 2014; Belak et al., 2014; Jakomin, 2014; Zavod za gozdove Slovenije, 2014 and Elektro Slovenija, 2015), data about the basic characteristics of a specific event (location affected, damage to forests, size of the area where damage occurred and volume of damaged wood biomass) and damage to the transmission and distribution network (length of damaged power lines, number of damaged columns and financial damage as a consequence of physical damage and number of customers that suffered power loss). Financial damage to the power infrastructure was calculated according to the average prices of components of the power grid from Key F (average price in the electric power network grouped by activities; Sln. *Šifrant F – povprečna cena po skupinah del v elektroenergetskem omrežju,* Administration of the Republic of Slovenia for Civil Protection and Disaster Relief, 2014) used for calculating damage caused by the 2014 ice storm. Financial damage to forests was calculated from data on physical damage to forests, using the average price of wood biomass in Slovenia over the last decade, which amounts to about EUR 50/m^3 (Statistical Office of the Republic of Slovenia, 2015). Damage to forests was addressed separately from that to power lines; risk assessment was carried out and a risk map was prepared for each sector separately and then aggregated to yield the final result. Based on physical damage to forests and to the electric infrastructure leading to financial damage, the events were categorised into classes from 1 to 4 (in which class 1 represents the lowest and 4 the highest intensity level of ice storm). The frequency of occurrence of each event in the observation period (1961–2015) was calculated. Based on the frequency of occurrence, events were then categorised into classes from 1 (very low frequency) to 4 (very high frequency). These were then combined with the consequence categories using a matrix and the result was the categorisation of each event into a class of risk index (1 = lowest risk, 4 = highest risk). The events arranged based on the risk index were then drawn on a map, and the end result is the risk map presented in Figure 2.

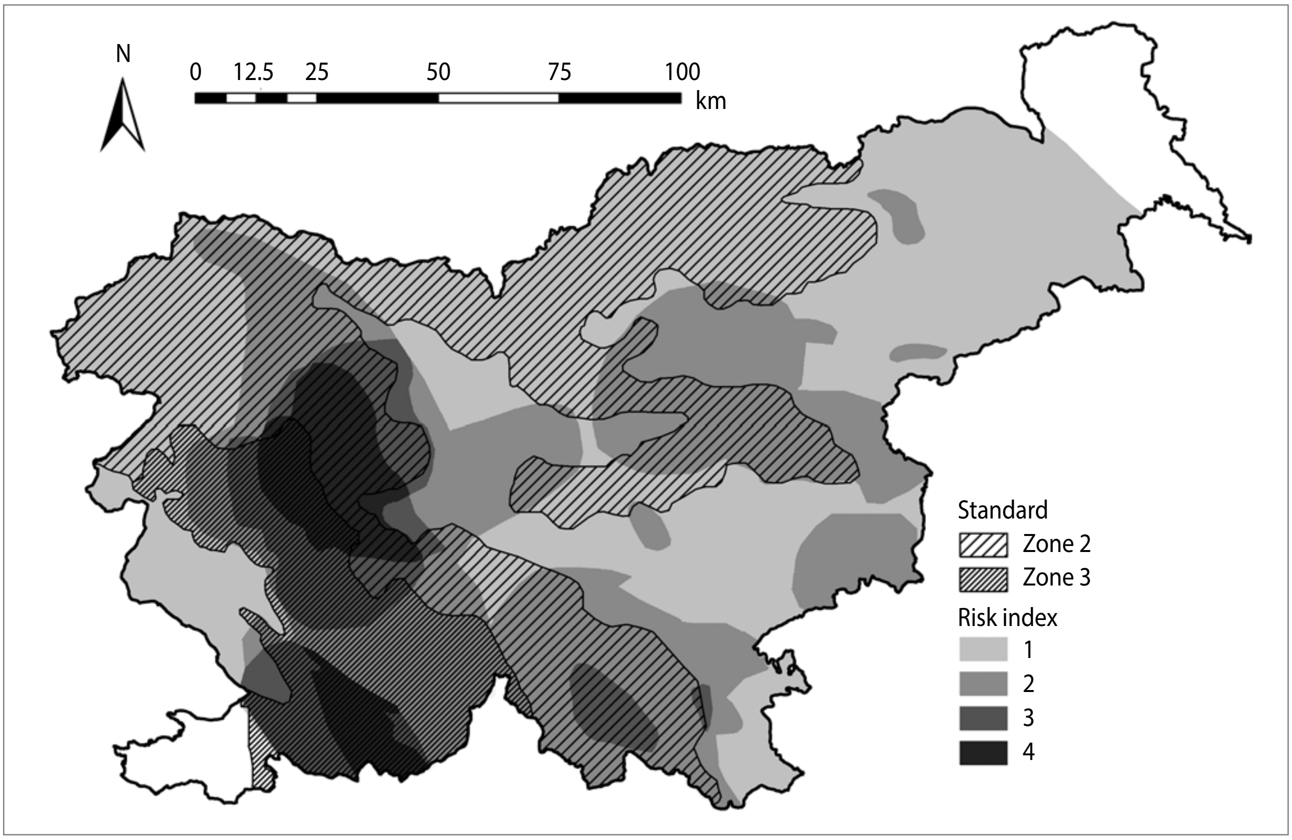

Figure 2: Map of risks to electric energy infrastructure due to ice storms overlaid with standard SIST EN 50341-3-21 for building high-voltage overhead lines (illustration: Maruša Matko).

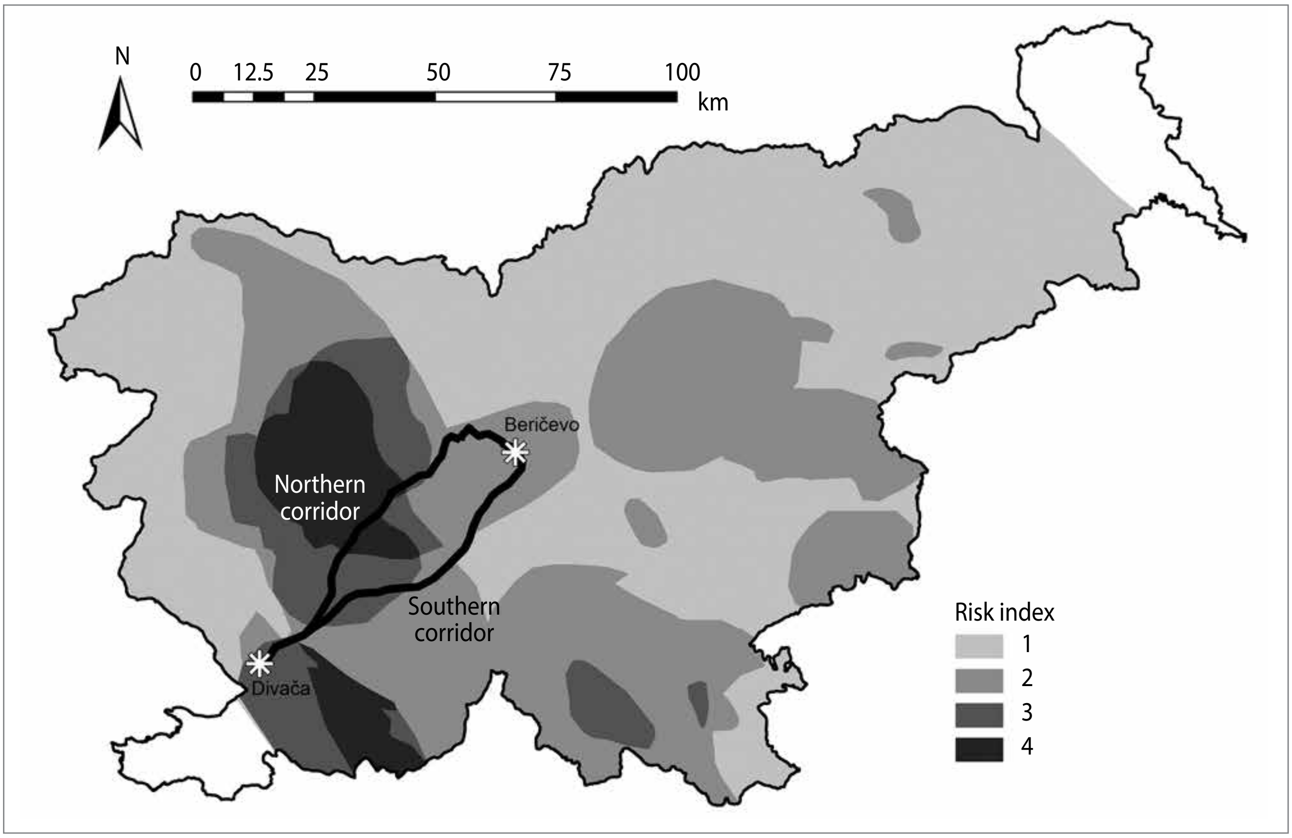

Figure 3: Map of risks to electric energy infrastructure due to ice storms and proposed alternatives of the 400 kV Beričevo–Divača power line (illustration: Maruša Matko).

3.2 Method for integrating the results of risk assessment into a spatial suitability analysis for a specific activity

A spatial suitability analysis for wind farm siting in Slovenia was carried out first. In Slovenia, analysis of suitability of space for a specific activity has been in practice since the early 1990s. It consists of two components: analysis of spatial attractiveness for a specific activity and analysis of vulnerability of the environment to this activity. The analysis of spatial attractiveness evaluates the characteristics of an area in the context of technical and economic feasibility or attractiveness for the proposed development project. Analysis of environmental vulnerability, on the other hand, determines how vulnerable the same area is to this activity and serves as an early warning system to avoid excessive environmental impacts in the area where the project is to be implemented. The synthesis of spatial attractiveness and environmental vulnerability analysis is optimised by means of a suitability matrix into a spatial suitability model. The overall process is GIS-supported. The suitability analysis method and process are not described in detail because they followed standard approaches (Marušič, 1993; Marušič et al., 1993; Koblar et al., 1997; Marušič et al., 2004). The criteria taken into account in the analysis of spatial attractiveness for siting wind farms are: wind conditions (average annual wind speed according to the AIOLOS and Aladin, or DADA, models; areas with a wind speed of 5 m/s or more are the most attractive), land cover as a factor contributing to roughness of surface, the vicinity of a high-voltage electric power grid (power lines and substations), accessibility or the vicinity of roads, slope, geologic material, soil stability, the presence of water erosion and areas subjected to flooding. In the environmental vulnerability model, we took into account wildlife corridors, bear habitats, data on bird habitats prepared by DOPPS (Birdlife Slovenia), ecologically important areas, Natura 2000 sites protected under both the Birds Directive and the Habitats Directive, natural protected areas, the human living environment (settlements, tourist attractions, cultural heritage and water source protection areas), visual qualities (exceptional landscapes, areas under complex protection of cultural heritage and protected areas, especially visually exposed areas visible from frequently visited points), the hydrosphere, the pedosphere and potentials of land for use and development. Risk assessment was incorporated into suitability analysis as its third component; we excluded the most suitable areas where the risk was high (risk index 3 or 4) from the baseline suitability model for siting wind farms. For the baseline version of suitability (which does not take risk into account) and for the second one (which takes risk into account) we calculated the total area of places where wind farms (with an installed capacity of at least 10 MW) could be built. In the calculations we used an E-70 wind turbine with an installed capacity of 2.3 MW produced by the German manufacturer Enercon (like the existing wind turbine in Dolenja Vas near Senožeče). We searched for locations where at least five such wind turbines could be built. Existing wind farms occupy on average between 12 and 57 ha/MW (Denholm et al., 2009). Data about the distance between turbines that can be found in the literature range from three to fifteen rotor diameters (Department of the Environment, 2007; Christie & Bradley, 2012; Meyers & Meneveau, 2011). We assumed that the distance between sample turbines in a row would be 215 m (three rotor diameters) and 355 m between rows (five rotor diameters), which means that we searched for locations measuring at least 200 m × 1,000 m (for siting five wind turbines in a row) or 500 m × 600 m (for siting five wind turbines in a cluster) among areas with the highest suitability on the spatial suitability map for siting wind farms. However, in Slovenian practice wind turbines in plans for siting wind farms are usually spaced wider apart. In the Senožeče Hills, for example, more than three or four turbines per km^2 were planned at first, but due to the diverse terrain with other limitations wind turbines could not be spaced so densely. The last version of the plan for the Senožeče Hills specifies several different densities per km^2, at some locations only one wind turbine and at some even no wind turbines. We calculated the investment and maintenance costs and the amount of energy produced for both versions of spatial suitability (with and without integration of risks) and, for suitability that does not take risks into account, also additional costs due to physical damage as a consequence of a severe ice storm. A third option for siting wind farms was analysed as well; a system for detecting and preventing ice accretion would be integrated into wind turbines in areas with higher risks whereas regular wind turbines would be built in other locations.

3.3 Cost-benefit analysis

Accretion of ice on wind turbines can lead to complete stoppage of turbines, resulting in significant energy loss, decreased power production due to disruption of aerodynamics and shortening the lifetime of the components, and uncontrolled ice throw from rotating blades poses a serious safety issue to people and facilities in the vicinity (Dalili et al., 2007; Grünevald et al., 2012). In November 2013, ice storms caused significant damage to wind turbines and the transmission system in Texas, which led to shutting down two wind farms with a combined capacity of 78 MW. Estimates to fix the damage exceeded the economic value of the projects at both facilities (Micek, 2014). A system for detecting ice accretion on rotor blades and preventing ice accumulation is available for modern wind farms (Deutsche WindGuard, 2011). To support the decision-making process about wind farm siting, we

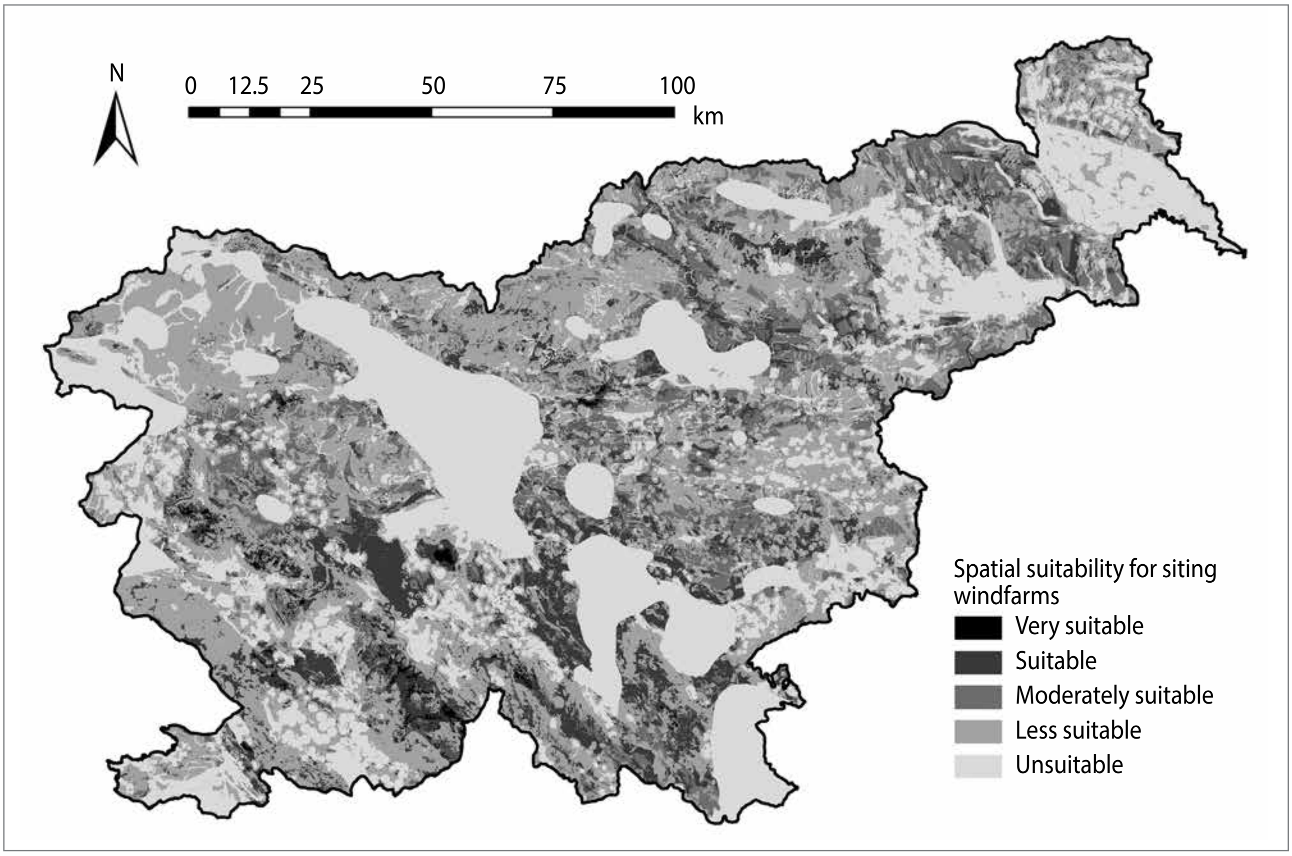

Figure 4: Spatial suitability for siting wind farms without consideration of risks due to ice storms (illustration: Maruša Matko).

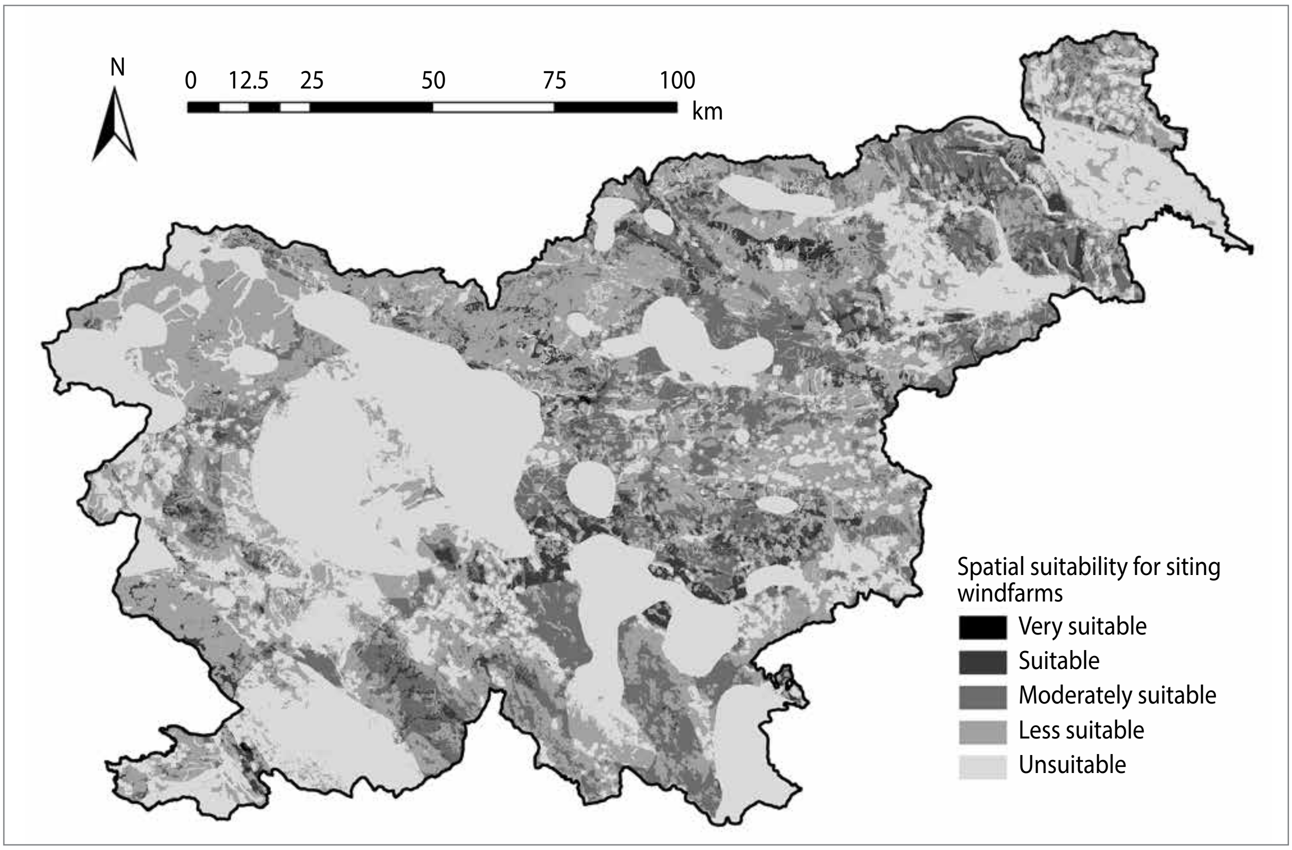

Figure 5: Spatial suitability for siting wind farms with consideration of risks due to ice storms (illustration: Maruša Matko).

calculated how possible damage can affect the amount of energy produced and financially expressed damage due to possible repairs for both spatial suitability alternatives for siting wind farms in Slovenia. We analysed an additional alternative with a system for detecting and preventing ice accretion built into turbines located in the areas with highest risks. We considered a period of 25 to 50 years (rounded figures) because severe damage can occur during this period (risk index 3, when damage to the transmission and distribution system amounts to between EUR 1 million and 10 million, frequency 0.037/year and risk index 4, when damage is higher than EUR 10 million, frequency 0.0185/year). The costs of construction, operation and maintenance were taken into account for all three alternatives for siting wind farms: the first one, which considers risk due to ice storms, the second one with a technical improvement (a system for detecting and preventing ice accretion) for wind turbines in the areas with the highest risk and the third one, which does not consider risk. Calculation of investment costs is based on data about investment in the existing wind turbine in Dolenja Vas near Senožeče (Ministry of Infrastructure of the Republic of Slovenia, 2013) and calculations by the National Renewable Energy Laboratory of the US Department of Energy (Moné et al., 2015). Investment costs amount to approximately EUR 3 million per wind turbine. A system for detecting ice and preventing its accumulation on turbines increases investment costs by 2 to 6% but it does not significantly affect the maintenance and operation costs (Eriksson, 2013). We used an average value of 4% in our calculations. The energy used for heating the rotor blades was not taken into account (pulsing, short-term impact). The availability of such wind turbines is slightly higher than those of turbines without an ice detection and accretion prevention system because of the energy used for heating and thawing glaze ice. The range of operation and maintenance costs is relatively high in the available literature. Ryan Wiser and Mark Bolinger (2014), for example, analysed empirical data about wind farms in the US and found that the maintenance and operation costs of wind farms built after 2010 amount to USD 23/kW annually. The data they considered did not always clearly state what is included in these costs, but in most of these cases maintenance and operation costs consist of wages, materials and rent. Christopher Moné et al. (2015), on the other hand, state that the figure from the aforementioned study considers only variable costs and does not include insurance, taxes, rents and amortisation. They calculated maintenance and operation costs considering these factors and the result was USD 50/kW annually. The costs of unplanned maintenance included random failures, but it is not clear from the study whether their cause can be EWE. In another study by the International Energy Agency (IEA, 2015), analyses of operation and maintenance costs in Denmark, Germany, Ireland, Norway, the European Union and the US were carried out. In 2012, annual costs of maintenance and operation were EUR 55.9/kw in Germany, EUR 55/kW in Ireland and USD 50/kW in the US. Data for some of the countries analysed were not provided due to high uncertainty. We used a value of EUR 56/kW in our calculations. Nick Middeldorf and Andreas Düing (2012) assumed that the land for building wind turbines would be purchased and that these costs are part of the investment. They included the maintenance contract with the turbine manufacturer, insurance, and energy and management costs in the maintenance and operation costs. According to their findings, annual costs of operation and maintenance for the Enercon E-70 wind turbine are EUR 13,000 in the first two years of operation and EUR 24,000 later on. We used all four sources of data in our calculations and compared one to another. These data are sufficient for the level of detail of our research, but for more detailed analyses consensus should be achieved on which maintenance and operation costs should be considered in Slovenia based on existing wind power plants and planned projects. The price of electric energy was calculated based on data on the market price of electric energy between 2009 and 2015 published by the Energy Agency of the Republic of Slovenia (Borzen, 2015), which is approximately EUR 50/MWh. There exists a feed-in tariff for large wind farms (EUR 52.64/MWh in 2015), but due to uncertainties connected to future subsidies only the market price was considered in calculating the net present value (NPV). Consideration of subsidies in calculating the NPV would significantly affect the end result because the price of electric energy that includes subsidies is up to twice as high as the market price. In the period of observation, a discount rate of 2% was taken into account, which is the goal of the European Central Bank for the euro area. In the case of an ice storm, 190 wind turbines located in high-risk areas would be repaired. A turbine represents 68% of the entire investment (Moné et al., 2015), which amounts to a total of EUR 388 million.

4 Results

4.1 Risk to electric energy infrastructure due to ice storms

The result of the analysis of ice storms in terms of their intensity level and frequency of occurrence is the risk map presented in Figure 2. In the areas in white (Prekmurje and the coast), no damage was caused by ice storms in the period observed. On the other hand, greater damage (more than EUR 10 million) occurs most often (more than 0.2 times per year) in the darkest areas (the Brkini Hills, the hilly area near Idrija and Cerkno, and the surroundings of Logatec). Most of Slovenia has a risk index of 1 (light grey): damage to electric energy infrastructure is relatively low and occurs up to 0.2 times per year. The map of risk to electric energy infrastructure due to ice storms was overlaid by the map of glaze ice zones according to standard SIST EN 50341-3-21 for building high-voltage overhead lines (*Slovenian Institute* for *Standardisation,* 2009) as shown in Figure 2. The standard divides Slovenia into three zones based on the burden that should be considered in designing power lines. In Zone 1, the burden due to glaze ice is relatively small and did not cause any physical damage to power lines in the past. In Zone 2, a high burden due to glaze ice is expected, which damaged power lines in the past. In Zone 3, a very high burden is expected based on meteorological conditions, geographic location and long-term experience. Such burdens caused significant damage to power lines in the past. Based on the findings from our risk assessment, it would be recommendable to update the standard: to extend Zone 3 to areas where the risk due to ice storm is the highest. Based on the data obtained, analyses and calculations carried out and the synthesis of results, we compared two proposed national spatial plan alternatives for upgrading the 400 kV Beričevo–Divača power line (Figure 3) in order to present the use of the described risk assessment in spatial planning for selecting the most suitable corridor. Considering the results presented in Figure 2, the southern corridor is more suitable for siting the new high-voltage Beričevo–Divača power line.

4.2 Spatial suitability for siting wind farms

The map of spatial suitability for siting wind farms that takes risk due to ice storms into account is presented in Figure 4. Slovenia has approximately 68 km^2 suitable for building wind farms. Among these are areas suitable for siting at least five E-70 wind turbines manufactured by Enercon (e.g., the wind turbine in Dolenja Vas). The total area of these territories (without consideration of risk) is about 31 km^2. Four hundred five sample turbines could be built there. Their total installed capacity would be 930 MW and their total annual electric energy production (assuming that they would operate for 1,800 hours per year) would amount to 1.68 TWh. If high-risk areas are excluded, there are altogether 17 km^2 suitable for building at least five wind turbines. These areas are presented in Figure 5. Two hundred fifteen wind turbines could be built there with a total installed capacity of 495 MW. Their total annual production of electric energy would be 890 GWh.

4.3 Results of cost-benefit analysis

Table 1 presents data about the NPV of costs and benefits for all three alternatives of siting wind farms without consideration of the occurrence of ice storms and with this consideration (in the latter case, the wind farms would be located outside high-risk areas and technical improvements for de-icing are included in the analysis). In the first alternative, in which wind farms would be located in all the most suitable areas including those with the highest risk (the darkest areas in Figure 2), costs are higher than benefits according to all data sources considered. The alternative that considers risk by including technical improvements (a rotor blade heating system) has a positive net present value (EUR 247 million) if low maintenance and operation costs are taken into account (Middeldorf & Düing, 2012), the NPV is EUR 42 million if costs according to Wiser and Bolinger (2014) are considered, and the NPV is negative if costs calculated by Moné et al. (2015) and IEA (2015) are taken into account (negative EUR 403 million and negative EUR 605 million, respectively). The alternative that considers risk by not locating wind farms in areas subjected to high risk of ice storms has a positive NPV according to some data sources (EUR 143 million, Middeldorf & Düing, 2012, or EUR 34 million, Wiser & Bolinger, 2014) and negative NPV according to others (negative EUR 202 million, Moné et al., 2015, or negative EUR 311 million, IEA, 2015). The practical impact and result of these findings would be presented in several versions of Figure 2, depending on the point of views of investors and operators of wind farms; the primary version of Figure 2 would be adjusted based on the results of risk assessment and cost benefit analysis (NPV) in accordance with the number, type, equipment and location of new units. The expected result would be new maps that would include the difference between costs and benefits by presenting lower total costs as a lower category of damage and consequently lower risk index. These maps would form the basis for investors' final decision about investment as well as the basis for approving detailed spatial plans. To achieve this, the spatial planning procedure at the level of detailed spatial plans should allow for iterations of assessment of risk due to EWE.

5 Discussion

The method for integrating risk assessment into spatial planning of electric power infrastructure that was presented and tested in this study is transparent and operable and can provide support in the decision-making process. There are several ways of applying the risk assessment results to optimise electric power infrastructure. Optimisation of electric energy infrastructure that considers risk can be technical or spatial. In technical optimisation, the risk assessment results can be used to revise building codes (Figure 2: map of risk to electric energy infrastructure due to ice storms), making future facilities physically more resilient. One measure of technical optimisation is building wind turbines with an integrated ice detection and prevention system. The risk assessment results can also serve to support investment planning of maintenance of the existing infrastructure. In spatial optimisation, the approach can be used to compare various alternatives of the plan that has

Table 1: Comparison of costs and benefits of building wind farms in a twenty-five-year period without taking into account risks due to ice storms (option 1) and with consideration of the risk assessment results (options 2 and 3).

Option	NPV (costs)		NPV (benefits)	NPV (difference between benefits and costs)	NSV (difference between benefits and costs in case of ice storm)
1 (wind farms also in areas where ice storms can occur)	Investment:	–EUR 1.215 billion	Electric energy sold: +EUR 1.67 billion	From –EUR 582 to +EUR 270 million	From –EUR 118 million to –EUR 970 million
	Costs of maintenance + operation:	–EUR 185 million (Middeldorf & Düing, 2012) –EUR 390 million (Wiser & Bolinger, 2014) –EUR 835 million (Moné et al., 2015) –EUR 1.037 billion (IEA, 2015)			
	Costs due to ice storm:	–EUR 388 million			
	Total costs:	From EUR 1.4 billion to EUR 2.252 billion			
	Total cost in case of ice storm	from EUR 1.788 billion to EUR 2.640 billion			
2 (wind farms also in areas where ice storms can occur, but wind turbines in these areas have a system for icing detection and prevention)	Investment:	–EUR 1.238 billion	Electric energy sold: +EUR 1.67 billion	From –EUR 605 million to +EUR 247 million	From –EUR 605 million to +EUR 247 million
	Costs of maintenance + operation:	–EUR 185 million (Middeldorf & Düing, 2012) –EUR 390 million (Wiser & Bolinger, 2014) –EUR 835 million (Moné et al., 2015) –EUR 1.037 billion (IEA, 2015)			
	Costs due to ice storm:	EUR 0			
	Total costs:	From EUR 1.423 billion to EUR 2.275 billion			
3 (wind farms only in areas where ice storms do not occur)	Investment:	–EUR 645 million	Electric energy sold: +EUR 886 million	From –EUR 311 million to +EUR 143 million	From –EUR 311 million to +EUR 143 million
	Costs of maintenance + operation:	–EUR 98 million (Middeldorf & Düing, 2012) –EUR 207 million (Wiser & Bolinger, 2014) –EUR 443 million (Moné et al., 2015) –EUR 552 million (IEA, 2015)			
	Costs due to ice storm:	EUR 0			
	Total costs:	From EUR 743 million to EUR 1.197 billion			

Data source for calculation: Middeldorf & Düing (2012); Wiser & Bolinger (2014); Moné et al. (2015); IEA (2015).

already been proposed (as shown in the case study for proposed transmission lines, Figure 3) or it can be integrated into development of the plan itself by searching for locations where damage to the planned facilities will be lower or will not occur. Operationally, risk assessment is included in spatial suitability analysis as its third component, but conceptually it is a part of spatial (un)attractiveness. The method for integrating risk assessment into spatial planning of electric power infrastructure has been developed in cooperation with Slovenian electricity production, transmission and distribution companies. They assessed the approach we presented to them as promising and they are now running further tests to see how it can be applied to meet their needs. Testing the applicability in a wider context should include spatial planners and policy makers. The results presented can by all means stimulate public discussion on future energy demands and how to meet them, the energy mix and the consideration of various risks when choosing appropriate locations for future energy infrastructure.

The risk assessment result (a map of risk to Slovenian electric power infrastructure due to ice storms) showed which areas should be avoided in siting new electric energy infrastructure in order to prevent greater damage and on which existing infrastructure to implement measures to prevent or minimise damage. Recently, new risk maps have been prepared for France (Dalle & Admirat, 2011), Italy (Bonelli et al., 2011), Switzerland (Grünevald et al., 2012), Canada (Lamraoui et al., 2013) and the UK (Nygaard et al., 2014). These maps are based on meteorological models and/or data obtained from meteorological stations and show areas where specific ice load or specific duration of icing is expected. Bjørn Nygaard et al. (2014) propose using risk maps in developing new building codes, and Bernard Dalle and Pierre Admirat (2011) and Paolo Bonelli et al. (2011) propose using them in designing power lines that are already proposed to be built at specific locations and in making decisions about technical measures for preventing ice accretion or its removal, but none of these authors mention searching for locations for future infrastructure based on the results of their risk assessments. Dalle and Admirat (2011) propose using a risk map in organising emergency repairs. Fayçal Lamraoui et al. (2013) state that a risk map can serve as a decision support tool in making decisions about implementing specific projects but they do not elaborate this idea further. Thomas Günevald et al. (2012) propose using a map of risk due to ice storms in planning wind farms in combination with maps of wind potential, but they do not develop the idea in detail. The studies presented mostly address technological optimisation and not searching for locations for new electric power infrastructure based on risk assessments, and this is why it is impossible to compare our results with others and hence we focus on the strengths and weaknesses of our approach that we encountered during its testing.

One of the issues raised during the application of the method presented is the availability of data. Monitoring EWE and the damage they cause is not standardised. The datasets from electric power transmission and distribution operators are very heterogeneous (they can record the number of customers without electricity, duration of interruption of power supply, amount of energy not supplied, and physical or financial loss). Proper assumptions and adaptations are therefore required before risk analyses can be undertaken. In the case presented, suitable data were available only for direct (physical) damage, and therefore the results show risk categories for the transmission and distribution companies. If data about energy not supplied were available, the financial loss suffered by customers and indirect loss suffered by the economy could be calculated. It would make sense to standardise the recording of data about damage. The length of time series of data about damage depends on a company; data recorded before the existence of electronic archives are especially difficult to obtain. This can contribute to lesser accuracy of risk assessment, especially if the operator with such data is responsible for the infrastructure in locations where EWE often occur and cause significant damage. Damage caused by EWE to the environment can cause additional damage to infrastructure. This was taken into account in risk assessment by considering damage in forests. Available data on costs of wind turbines are very heterogeneous as well and the choice of the data source can have a decisive impact on the net present value of the proposed project, as shown in Table 1. The sources of data considered in our calculations differ in their definition of operation and maintenance costs (e.g., some count land rentals among operation and maintenance costs whereas others assume that the land would be purchased and that the land price would be part of the investment costs). There are also differences between the data depending on the countries considered in these studies. This is why a discussion on the data used in the cost-benefit analysis should be held before making decisions about siting wind farms in Slovenia. There are additional uncertainties connected to future incentives for using renewable energy sources and therefore only the market price of electricity in Slovenia was taken into account in calculations of benefits due to electric power sold, whereas the subsidised price (which can be two times higher than the market price) was not considered. In the case of an ice storm, the costs of wind farms are higher than the benefits. This finding is consistent with the actual case from practice when stopping the operation of wind farms was chosen over their repair (Micek, 2014).

6 Conclusion

The aim of this article was to design, test and present a method that would integrate risk assessment into spatial planning tools.

The approach presented proved to be useful in spatial planning as well as in making decisions about enhancing mechanical resilience, which includes decisions about maintaining and reconstructing electric power infrastructure. Our hypothesis that integrating risk assessment into spatial planning can reduce the damage to energy infrastructure caused by EWE was confirmed. The approach developed was presented in a case study of ice storms in Slovenia and siting wind farms, but it can be applied to other types of extreme weather events and various combinations of these events as well as to various geographical scales and regions. The application of the method is not limited to energy infrastructure; it can be used to assess risks to other critical infrastructure as well as other elements of the environment, both natural (e.g., forest, soil, watercourses, etc.) and manmade (e.g., settlements, cultural heritage, etc.). The level of detail of the risk assessment can be adjusted both in the geographic scale (size of the area of examination) and in the level of detail of analyses. Future research should include all of the aspects mentioned and assess risks due to other types of EWE causing damage to electric power infrastructure (strong wind, heavy snow, hail and heavy rain that causes flooding and erosion) due to combinations of these events and for other electric power infrastructure (e.g., photovoltaic panels, hydroelectric power plants and nuclear power plants). The next step of the research should include an analysis of application of the approach to designing maintenance and reconstruction measures for existing infrastructure and to cost-effectiveness analyses of these measures; for example, a comparison of the costs of protective measures against potential damage due to extreme events.

During the research, the question was raised how to address events that have not been experienced so far. It would be recommendable to use climate models that simulate changes in the frequency of occurrence and intensity of EWE, but these models usually have coarse resolution and are related to uncertainties in future emission scenarios, design of climate models and their downscaling from the global to regional and local levels, as well as to nonlinear relationships between mean values and extreme weather events (Mearns et al., 1984; Jones, 2001; Mitchell et al., 2006; Fowler et al., 2007; Van Aalst, 2006; Chen et al., 2011; Ceglar & Kajfež-Bogataj, 2012; IPCC, 2012; Sunyer et al., 2012, and Willems et al., 2012). The certainty of projections of the occurrence of EWE depends greatly on the types of extremes and the regions considered (Planton et al. 2008; IPCC 2012). Modelling impacts of EWE on a specific system (e.g., agriculture, forests and the energy sector) constitute an additional source of uncertainty (Fowler et al. 2007). For better prediction of the impact of climate change on electric power infrastructure, various combinations of climate change scenarios and scenarios of future energy and social development, as well as details of planned energy infrastructure, may be used. Some types of electric energy infrastructure are relatively new (e.g., photovoltaic panels) and little information is available about their susceptibility to damage due to various types of EWE. There are also some territories that have had no infrastructure in the past, but it might be located there in the future. To reduce the degree of uncertainty, sufficient reliable data have to be obtained for various locations and infrastructure as well as for other elements of the environment. A standardised system for recording data about the impact of EWE on electric power and other infrastructure should therefore be proposed to operators of these facilities. Appropriate caution is necessary when various types of facilities (i.e., power units) are analysed. The results (i.e., risk index categories) may appear to be equal for all units, but in absolute terms (e.g., energy not delivered) this is not the case: there may be differences in orders of magnitude (e.g., comparison between energy production at a hydroelectric power plant and the nuclear power plant in Slovenia). Therefore, when interpreting risk indices and related costs, the context and energy infrastructure involved should be specified. It has yet to be experienced in practice how the method presented can be applied in formal spatial planning procedures. Consensus with spatial planners and other stakeholders in procedures should be achieved about this. Agreement with experts is expected to be reached quickly, whereas negotiation with administrative authorities may take longer. We believe that integrating the approach presented into existing spatial planning procedures requires only minor adaptations according to specific land-use planning contexts, levels of detail and needs or expectations.

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