

Green infrastructure in settlements and cities of the future – two case studies; green roof and treatment wetland

Zelena infrastruktura naselij in mest prihodnosti – dva primera; zelena streha in rastlinska čistilna naprava

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ABSTRACT

The aim of this paper is to present green infrastructure in the context of climate resilience of settlements and cities of the future by two examples; green roofs and treatment wetlands in order to understand more fully their technical operation and to evaluate their efficiency from the perspective of decrease of heat island intensity and reduction of wastewater pollution. The performance of green infrastructure was evaluated on the basis of systematic literature review as well as with project-field measures. The results showed that the introduction of green roofs in future settlements and cities may result in decreased heat island intensity. The temperature decrease depends on climatic characteristics, amount of vegetation and urban geometry. The promising results regarding treatment wetlands performance will be helpful in preparing guidelines for treatment wetlands with practical information about operational and legislation requirements, and performance efficiency to meet new legislation for settlements below 2000 inhabitants, which will enter in force in 2015.

Key words: green infrastructure, green roofs, treatment wetlands

POVZETEK

Članek je namenjen predstavitvi zelene infrastrukture in njenega pomena pri zagotavljanju odpornosti naselij in mest prihodnosti na podnebne spremembe s pomočjo dveh primerov; zelene strehe in rastlinske čistilne naprave. Pri obeh tehnologijah smo želeli bolje razumeti njihovo delovanje ter hkrati ovrednotiti njihovo uspešnost pri zmanjševanju učinka vročinskih otokov in onesnaženja vode. Učinkovitost delovanja zelene infrastrukture smo ovrednotili, tako na osnovi sistematičnega pregleda literature, kot na osnovi terenskih meritev. Rezultati so pokazali, da zelena infrastruktura lahko pripomore k zmanjšanju učin-

ka vročinskih otokov v naseljih in mestih prihodnosti., pri čemer temperatura pada v odvisnosti od podnebnih značilnosti, biomase vegetacije in geometrije urbane površine. Vzpodbudni rezultati delovanja rastlinskih čistilnih naprav bodo tudi v pomoč pri pripravi smernic za rastlinske čistilne naprave s praktični informacijami glede delovanja, učinkovitosti in doseganju zakonodajnih zahtev pri čiščenju odpadne vode iz naselij pod 2000 prebivalci, ki se bodo začele izvajati leta 2015.

Ključne besede: zelena infrastruktura, zelene strehe, rastlinske čistilne naprave

INTRODUCTION

Growing urbanization and increasing resource consumption combined with climate extremes (droughts, extreme heat, and extreme rain events and floods) calls for resilient planning of our settlements and cities. This requires a certain level of decentralization of the urban infrastructure, leading to the application of green infrastructure, innovative green technologies or combination of technologies for integrated management of water, food and energy within the settlements and cities. Re-use of water resources results in “closing material flows” and recycling, which consequently leads to the sustainable management, i.e. sustainable development. There is no other better solution in the long run. Integrated water resource management in urban areas, including rainwater harvesting, recycling of wastewater, as well as a recovery of nutrients and a processing of organic waste holds a great potential for a positive shift to a new paradigm [1-3] that maximizes ecosystem services, minimizes environmental footprint and increases the cities’ adaptive capacity to changing climate, demographic and socio-economic conditions. The aim of this new paradigm is also to enhance the synergy of urban blue (water) and green (vegetation, energy efficiency) systems and to provide effective urban adaptation to future climatic changes.

Engineering and ecological resilience

Holling defined engineering resilience as the ability of a system to return to an equilibrium or steady-state after a disturbance [4-6], which could be either a natural disaster, such as flooding or earthquakes, or a social upheaval, such as banking crises, wars or revolutions. In this perspective, the resistance to disturbance and the speed by which the system returns to equilibrium is the measure of resilience. The faster the system bounces back, the more resilient it is. Ecological resilience, however, was defined as “the magnitude of the disturbance that can be absorbed before the system changes its structure” [7]. Here, resilience is defined not just according to how long it takes for the system to bounce back after a shock, but also how much disturbance it can take and remain within critical thresholds. Ecological resilience focuses on “the ability to persist and the ability to adapt” [8]. Researchers, planners and decision-makers lately often discuss about resilience of the cities, however they rarely clarify at the outset how their system of concern is being defined, what its boundaries are, and how it interacts with other systems beyond these boundaries [9].

Urbanisation and its problems

Increased industrialization and urbanization in recent years have affected dramatically the number of urban buildings with major effects on the climate of urban spaces and the energy consumption in building sector [10]. The fact is that the building sector labels the 40 % rule on world-wide scale, which means that world's building industry uses 3 million tons of materials per year, 40 % of the total world' materials and raw materials; buildings use 40 % of the total required energy and natural resources in the world during their construction and use; after closed production-consumption circle building wastes presents on average 40 % of the total wastes in the world [11].

With the Industrial Revolution, urban spaces expanded dramatically, much faster and with much more significant changes than in their previous evolutionary periods. The large areas modern settlements and cities occupy, their structure, materials and the general lack of vegetation cannot but have altered the climatic characteristics of urban spaces. These changes have a direct effect on the local climate of urban spaces, specially the central parts of the settlement and/or city, causing a significant rise of the urban temperature and other alterations, known as the urban heat island effect (Fig. 1). The term "heat island" refers to urban air and surface temperatures that are higher than nearby rural areas.

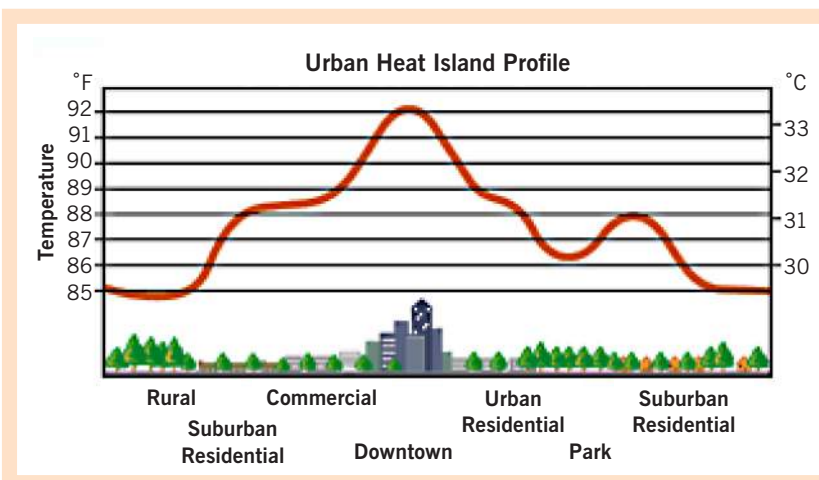


Figure 1:

Sketch of a typical heat-island urban profile [12].

The 'heat island' phenomenon is a reflection of the microclimatic changes brought about by man-made alterations of the urban surface [13] (Table 1). This may cause serious local climatic unpleasant conditions and even imperil human health, especially for cities in climates with a distinctively hot season [14]. In this context the introduction of green infrastructure can play an important role to minimise urban heat island effect, improve microclimate conditions, reduce air and water pollution, increase biodiversity and aesthetic and as such enable conditions supporting wellbeing environment.

The heat island phenomenon may occur during the day or the night period, during winter or summer season. The intensity of the heat island is mainly determined by the thermal balance of the urban region and can result in up to 10 degrees of temperature difference, particularly in

summer, during clear and still-air night [15]. Intergovernmental Panel on Climate Change (IPCC) has completed data from various cities, where temperature increase due to the heat island varies between 1.1 °C and 15 °C [16-18] (Table 1).

Table 1:
Heat-island intensity in some cities [16-18].

City	Heat island intensity ¹ [°C]
30 US cities	1.1
New York	2.9
Moscow	3.0 – 3.5
Tokyo	3.0
Shanghai	6.5
Athens	6.0 – 15.0
London	8
Ljubljana	1.0 – 3.0

¹ The maximum temperature difference between the city and the surrounding area.

Green building systems have been gaining popularity over the last years as a solution to the environmental problems that modern cities face. But “Does green system contribute to solving the problems of heat island effect?”

GREEN INFRASTRUCTURE

In the context of urbanization and all consequences (e.g. heat island effects) and increasing resource consumption on one side and in the context of resilience and its ecological function on the other side the application of green infrastructure solutions including treatment wetlands, buffer zones, waste stabilisation ponds, sludge red beds, vegetated ditches, flood bypasses, green roof, green walls and green building envelope, and urban gardens that mimic natural ecosystems could become vital. The green building systems, such as green roof, green walls and green building envelope, are passive techniques that can be used to solve the problems of modern cities and in such manner contribute to sustainable development of the urban environment [19]. Some of these systems also aim to remediate and revitalize degradation areas, close the loop and e.g. return resources back to the source through the understanding of human-environmental relations in the context of integrated comprehension of the nature's self-cleaning mechanisms and knowledge, upgrading them by the latest scientific developments in reducing environmental degradation and increasing the flexibility, as well as through existing relations that are not necessarily ecologically problematic but may, on the contrary, have beneficent effect on ecosystems.

Green infrastructure systems and technologies are often called natural, nature-near or naturally-based technologies due to the fact that these treatment systems use natural processes (such as biological, physical or solar elements or else) to achieve a desired level of wellbeing goals.

Green systems can be also low cost systems and are often also defined as:

- Achieving acceptable levels of treatment;
- Requiring low capital investment;
- Requiring low on-going operation and maintenance costs;
- Requiring less-skilled operator knowledge than many conventional technologies;
- Potentially having longer life-cycles than conventional electro-mechanical technology;
- Minimally relying on civil works and mechanical and electrical equipment;
- Providing robust, reliable, and long-term efficient treatment/conversion technologies/processes;
- Offering plainness of operation and maintenance;
- Achieving self-sufficiency in many respects;
- Providing maximal recovery and re-use of treated water and by-products obtained from the pollution substances;
- Providing simplicity and universality of design at any scale from very small to very big.

Green roofs

There are two major types of rooftop greenery, extensive system and intensive green roofs. Extensive green roofs are not designed for public use and are mainly developed for aesthetic and ecological benefits. An extensive green roof has between 50 and 150 mm of growing medium to support plant life. This limits the size not plants that can be used on the roof, thus limiting the weight of the green roof on the building structure. They are distinguished by being low cost and lightweight (50–150 kg/m²). Minimal maintenance is required and inspection is performed 1–2 times per year. Plants selected tend to be of the low maintenance and self-generative type. Intensive green roofs are usually called 'roof gardens' that generally have from 150 to 1200 mm of growing medium, for supporting larger plant life. They involve a greater load of more than 150 kg/m² [14]. They are developed so as to be accessible to people and are used as parks or building amenities [14]. The added weight, higher capital cost, intensive planting and higher maintenance requirements characterize intensive green roofs [19].

The green system advantages

Studies showed that green systems have important advantages from environmental, health, social and economic point of view and in such manner contribute to sustainable development (Table 2).

**Table 2:**

Issue of sustainable development with green system advantages [14, 15, 20-25].

Issue of sustainable development	Viewpoint	The green system advantages
Environmental	Allocation of rainwater	<ul style="list-style-type: none"> – Holding 15 to 90 % of rainwater (av. 50–60 %), depending on rainfall intensity and substrate thickness. – 8 cm of vegetative layer holds 35 mm of rain water [20].
	Purification of rainwater	<ul style="list-style-type: none"> – Elimination of more than 95 % of cadmium, copper and lead and 16 % zinc. – Decrease of contained nitrogen compounds (greater amount of humus (15 %) causes decreased amount of nitrogen compounds in run-off) [20].
	Air quality	<ul style="list-style-type: none"> – Elimination of 0.2kg particulate matter per m² of vegetation per year. – Absorption of gasses and toxins (medium-sized tree could purify 10m³ of air per day) – 10–32 % increase in canopy layer could reduce ozone concentrations by about 4 ppb [21]. – Production of oxygen, cooling and humidifying the surrounding air.
	Sound isolation	<ul style="list-style-type: none"> – Sound absorption. – 12 cm layer of soil substrate reduces noise in indoor spaces by 40 db [22].
	Reduction of urban heat island effect	<ul style="list-style-type: none"> – Direct and indirect thermal benefit (mentioned in results) [15].
	Energy efficiency: global, regional, local	<ul style="list-style-type: none"> – Direct and indirect thermal impacts (78 less gain, 60 % decrease of thermal fluxes [23, 24] – Over 75 % of the total building energy savings were from direct effects of cool roofs and shade trees [24]. – Reducing the consumption of non-renewable energy sources – In US filled all urban tree spaces, covered rooftops and parking lots with lighter colours reduce electricity consumption by 50 billion kWh/year and reduced amount of CO₂ by 35 million tons/year [26].
	Green roofs as a substitute for lost areas of landscape	<ul style="list-style-type: none"> – A substitute for sacrificed landscaped areas. – Prescribed in the development plan [20].
	Natural habitat for animals and plants	<ul style="list-style-type: none"> – Reducing the quantity of sealed surfaces. – Encourage limited wildlife development [20]. – The Toronto City Hall Demonstration Project features a black oak prairie ecosystem and native plant butterfly plot [27].
Health	Decrease of Sick Building Syndrome (SBS)	<ul style="list-style-type: none"> – Positive effect on the interior climate, increase thermal comfort, and users' productivity [20].
Economical	Reduced renovation costs	<ul style="list-style-type: none"> – Increased waterproof life span (up to 40 years) with protection from UV-rays, hail and extreme temperature differences [28].
	Reduced energy costs	<ul style="list-style-type: none"> – Thermal insulating green roof build-ups with official property-values are allowed to be added to the conventional thermal insulation. – Effect of shading and evapotranspiration: one tree per house causes 12 % to 24 % cooling energy savings three trees per house reduce the cooling load between 17 % and 57 % [14, 25] – Direct effects of shading: 10–35 % of the total cooling energy savings.
	Reduced sewer costs / Storm water-management	<ul style="list-style-type: none"> – 30–80 % reduced the water run-off. The remaining water flows off with a time difference. – Rainwater remains in the natural water cycle thereby reducing sewer costs [20].
	Use of space	<ul style="list-style-type: none"> – Additional space for leisure activities, without spending money on new and expensive building grounds [20].

Decreasing heat island effect

The heat island phenomenon is due to many factors, the more important of which are summarized by Oke et al. [29]:

- Canyon Radiative Geometry contributes to decrease the long wave radiation loss from within street canyon due to the complex exchange between buildings and the screening of the skyline.
- Thermal properties of materials that may increase storage of sensible heat in the fabric of the city (Table 3).
- Anthropogenic heat released from combustion of fuels and animal metabolism.
- Urban greenhouse, that contributes to increase the incoming long wave radiation from the polluted and warmer urban atmosphere.
- Canyon radiative geometry decreasing the effective albedo of the system because of the multiple reflection of short wave radiation between the canyon surfaces.
- Reduction of evaporating surfaces in the city putting more energy into sensible and less into latent heat.
- Reduced turbulent transfer of heat from within streets.

Table 3:

Hydrothermal properties of plants, soil, building materials (concrete) and street materials [14]

Characteristic	Concrete	Asphalt	Soil	Plants
Specific thermal capacity (MJ/m ³ K)	1.60	2.00	1.15	2.60
Thermal conductivity (W/mK)	1.70	1.30	—	—
Vapour diffusivity (10 ⁻⁶ m ² /s)	0.55	1.58	—	—
Ratio of vapour diffusion coefficient to total moisture diffusion coefficient	0.20	0.10	—	—
Emissivity	0.94	0.81	0.94	0.94
Albedo	0.23	0.10	0.23	0.30
Hydraulic conductivity (10 ⁻⁴ m/s)	—	—	0.01	—
Moisture potential, when soil is saturated (cm)	—	—	-49.0	—
Maximum volumetric water content (m ³ /m ³)	—	—	0.492	—
Coefficient b	—	—	10.40	—
Convective heat resistance (s/m)	—	—	—	200
Resistance expressing the plant type (s/m)	—	—	—	100
Canopy extinction coefficient	—	—	—	1.4
Level of soil moisture below which permanent wilting of the plant occurs (m ³ /m ³)	—	—	—	0.25

Green systems may cause the decrease of heat island as a result of:

A. Direct impact:

- decrease of air temperature above the roof
- decrease of canyon air temperature in case of green envelope/green wall/green roof
- decrease of surface temperature in case of roof / green south wall

B. Indirect impact:

- decrease of surface temperatures of non-vegetated surfaces.

Good bioclimatic design always proceeds from location characteristics (i.e. geometry, orientation, and climatic data). Alexandri and Jones [25] performed a study on temperature decreases in a urban canyon due to green walls and green roof in diverse climates. They showed that temperature decrease depends on climatic characteristics, amount of vegetation, urban geometry. The largest decrease was proven in hot and dry climate, minimal in cold and wet climate (i.e. 11.3 °C in Riyadh, 3.6 °C in Moscow). If we compare air canyon temperature decrease between green-all case (green envelope, where both roofs and walls are covered with vegetation) and green-wall case (only walls are covered with vegetation), we can see that the decrease is larger for green-all case, especially in hotter climates.

Air inside a canyon with vegetated walls is reduced due to the evapotranspirational rate from plants and the lower surface temperatures of vegetated surfaces. The latter are responsible not only for lowering the air temperature but also for lowering surface temperatures of surfaces not covered with vegetation. This is indirect cooling effect. This radiative cooling of the street asphalt has additional effect on lowering air temperatures, apart from evapotranspirational and convective cooling effects. Temperature decrease is very important for the comfort of the city. For this reason the use of materials, which deteriorate the urban thermal conditions, is allowed only where necessary e.g. road surfaces. However, on building envelope green vegetation should be used [25].

Two types of green roofs, intensive and extensive were compared by Hien et al. [23]. The results of the study showed that the temperature of the substrate surface measured under vegetation on extensive roofs was lower than surface temperatures on exposed concrete roof. Possible reasons were related to dark colour of the substrate, dry substrate, rare vegetation, and small thermal capacity of substrate.

Green systems have important advantages for whole city. The study of environmental benefits of green roof technology for the City of Toronto found that using a green roof coverage on 50 % of available roof areas would reduce local ambient temperature from 0.5 to 2 °C [30]. Vegetated building surfaces present only one small step in solving the problems. Research of mitigating New York city's heat island with urban forestry, living roofs, and light surfaces, was carried out by Columbia University Centre for Climate Systems Research. The results show that a combined strategy that maximizes the amount of vegetation in New York City by planting trees along streets and in open spaces, as well as by green roofs, offers more potential for cooling than any individual strategy. A combined strategy of urban forestry and green roofs has the greatest city-wide temperature impact that ranges from 0.1 °C for open space planting to 0.4 °C for ecological infrastructure, if 100 % of the available area is redeveloped [31].

TREATMENT WETLANDS

Wetlands are ecosystems that have shallow standing water or a water table at or near the surface and that have a prevalence of vegetation adapted for life in saturated soil conditions. The vegetation uses solar energy to assimilate carbon from the atmosphere and to produce organic matter, which in turn provides energy for heterotrophs (animals, bacteria, and fungi).

Wetlands also have a high capacity to decompose and transform organic matter and other substances. Treatment wetlands (TWs) use this capacity to enhance water quality (treatment of municipal, industrial, agricultural, and urban runoff wastewater). Wetlands are the “kidneys of the landscape” because of their functions in the hydrologic and chemical cycles, as the downstream receivers of waste from both natural and human sources [32]. While water treatment is the primary goal of these systems, some of them provide side benefits for public use and wildlife habitat and have a high aesthetic value as follows [33]:

Food chain support

The type of plant produced and thus the type of food chain that can be supported depend on the physical habitat in the wetland. Natural wetlands are among the most productive ecosystems on earth because of the ample provision of water and nutrients from adjacent uplands [32].

Wildlife habitat

One of the most obvious ancillary benefits of constructed wetlands is the potential for enhancing wildlife. No matter how small the wetland is and how it is designed and constructed, it will provide habitat for some animals. Creating some physical heterogeneity in the wetland can increase faunal diversity.

Human uses

Humans can use constructed wetlands for hunting, plant harvesting, aquaculture, and public recreation. Some large constructed wetlands are open for hunting to public or private groups, and edible crops, such as water chestnut, can be cultivated in treatment wetlands. There are no reported cases, however, where the products produced in wetlands are harvested on a significant basis.

The primary human use function is for recreation activities such as hiking, jogging, biking, and wildlife study. Some large constructed wetlands designed with public use in mind have been incorporated into park settings that encourage public use. Trails, boardwalks, and observation towers allow the public to observe the diversity of the wetland habitat and the resulting wildlife population. These human uses, including the satisfaction of having a wetland and wildlife at the edge of town, may be the most important factors behind public support for protecting and restoring existing wetlands.

Constructed wetlands (CWs) are intentionally created for the sole purpose of wastewater or storm water treatment, whereas *created wet-*

lands are intentionally created to produce or replace natural habitat [34]. Until the late eighties, the literature used artificial wetlands instead of constructed wetlands or treatment wetlands; today, most wetland scientists prefer the last term. Restored wetlands usually refer to the rehabilitation of wetlands that may be degraded or hierologically altered. Mitigation wetlands refer to wetlands that are built to replace the wetland “function” lost by development projects, such as highway construction and commercial development.

DEVELOPMENT AND RESEARCH OF TREATMENT WETLANDS IN SLOVENIA

Treatment wetlands (TW) have been used in Slovenia for the last 25 years [35, 36]. During this period horizontal, vertical, and hybrid systems were constructed, consisting of two or more interconnected beds. Pre-treatment was mostly comprised tanks or sedimentation basins. Excavations were sealed with 2 mm thick HDPE membranes. The medium was mostly a mixture of different material (peat, sand, gravel), varying in grain size and proportion. The depths of the TW varied from 0.4 to 0.8 m. and the bottom slope from 0 to 3.6 %. Most systems were covering between 200 and 1000 m² large surface area. Systems were planted with rhizomes or clumps of different wetland species, predominately with *Phragmites australis*. In 2014 approximately 120 TW were recorded to be in operation in Slovenia, mostly with horizontal subsurface flow. However, since 2013 most of the TW for municipal wastewater treatment were constructed as a vertical flow system, showing a need for more detailed evaluation of vertical system performance. Twenty of recently constructed vertical flow TW were novel single stage vertical flow (VFTW) systems from 4 to 15 population equivalent (PE) for single households, following the same TW design, of which some were recently selected for detailed monitoring regarding hydraulic and pollution load in order to understand more fully their technical operation and to evaluate their performance.

DESIGN AND PERFORMANCE EFFICIENCY OF NEW VERTICAL TREATMENT WETLANDS IN SLOVENIA

The design of twenty VFTW was based on Danish guidelines [37, 38] and targeted for the removal of BOD and COD only, to meet Slovenian legislation limits for wastewater treatment plants < 50 PE, which are 30 mg/l and 150 mg/l, respectively [39]. Since they were only constructed for COD and BOD removal, the surface area assumed for the VFTW is smaller for about 50 % in comparison with Danish guidelines, and varies between 1.2 to 1.5 m² per PE (Fig. 2). Regarding other design factors, such as hydraulic conductivity, sand composition, distribution and drainage systems, VFTW followed the Danish guidelines. The medium of VFTW is 1 m deep, consisting of 3 main layers; 15 cm drainage gravel (16–22 mm) at the bottom, 70 cm of fine sand (0.2–4 mm) and 15 cm of gravel (8–16 mm) on the top for inlet distribution. Systems were planted, as in the past 20 years, with common reed



clumps (*Pragmites australis*) [40]. Performance of VFTW was monitored regarding hydraulic load and hydraulic retention time (HRT), and pollution reduction, following Standard methods [41].

The performance efficiency of the selected VFTW systems showed that effluent concentrations for COD and BOD₅ were below Slovenian legislation limits. It can be assumed that the redesigned and 50 % scaled down Danish VFTW met outlet concentrations for COD and BOD₅, required with Slovenian legislations showing that a surface area was appropriate regarding the efficiency for COD and BOD₅.

CONCLUSIONS

Literature review showed that green infrastructure has an important health, social, ecological and economic benefits. The green building systems, such as green roof, green walls and green building envelope are passive techniques that can be used to solve the problems of modern settlements and cities and in such manner contribute to sustainable development of the urban environment. Introduction of green infrastructure in future settlements and cities may result in decreased heat island intensity, while treatment wetlands can efficiently reduce water pollution. Both examples; green roofs and treatment wetlands can be seen as a multifunctional infrastructure to mitigate several negative impact of urbanisation, climate change and other urban activities. Green infrastructure should be therefore adequately considered in future urban planning and construction to contribute to wellbeing development of our cities and settlements.

Figure 2:
VFTW for wastewater treatment from single household with capacity of 4 PE. Photography taken by Iztok Ameršek.

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