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IVO UŠAJ

NAČRTOVANJE PONOVNE UPORABE SIVE VODE V KOMBINACIJI S SOLARNIMI TOPLOTNIMI SISTEMI ZA TURISTIČNI OBJEKT

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Magistrsko delo št.:

GREYWATER REUSE CONCEPT DESIGN IN COMBINATION WITH SOLAR THERMAL SYSTEMS APPLIED TO A TOURISTIC FACILITY

Master thesis No.:

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Izvleček

Turistični objekti pomembno vplivajo na ekološki odtis predvsem zaradi prekomernega izkoriščanja vodnih in energetskih virov. Magistrsko delo predstavlja načrtovanje nekaterih ukrepov in njihovo oceno izvedljivosti za zmanjšanje porabe pitne vode in energije v Hotelu Salinera (Slovenija). Obravnavani ukrepi vključujejo: ločevanje sive vode in njeno čiščenje z membranskim bioreaktorjem (MBR), ločevanje sive vode in čiščenje z rastlinsko čistilno napravo (RČN) ter zasnovo in oceno izvedljivosti solarnega toplotnega sistema za zmanjšanje energetske porabe. Obe tehnologiji za čiščenje in ponovno uporabo sive vode imata podobne stroške investicije. Obratovalni stroški MBR sistema so veliko višji v primerjavi z RČN. Medtem ko je povratek investicije za RČN manjši od 8 let, je ta doba bistveno daljša za MBR, cca 30 let. Oba ukrepa zmanjšata porabo pitne vode za ocenjenih 45%. Zasnova solarnega toplotnega sistema upošteva omejitve zaradi omejenih razpoložljivih površin. Edina izvedljiva možnost je vgradnja manjšega števila solarnih kolektorjev, ki lahko zagotavljajo 26% zmanjšanje porabe klasičnega energetskega sistema. Ekonomska analiza solarnega toplotnega sistema potrjuje skoraj takojšnjo donosnost naložbe, zaradi katere je njena implementacija povsem izvedljiva. Ekonomska analiza sicer ne upošteva širših implikacij trajnostnega upravljanja z viri, ki bi celotno sliko dodatno obogatile. Dodatne koristi, ki jih taki koncepti prinašajo so odpornost na pomanjkanje vode ali energije, manjša poraba virov, manjše onesnaževanje okolja, saj bi hotel proizvajal manj odpadne vode in porabil manj energije iz neobnovljivih virov, pri RČN tudi dodatno hlajenje zaradi evapotranspiracije in povečanje biodiverzitete.

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Abstract

Tourist facilities have a significant impact on the ecological footprint, mainly due to the excessive use of water and energy resources. The thesis provides the design of measures aimed at reducing drinking water and energy consumption in a real case study, Hotel Salinera (Slovenia), along with the assessment of their feasibility. It addresses the following measures: greywater separation and treatment with a membrane bioreactor (MBR), greywater separation and treatment with a constructed wetland (CW), and the design and evaluation of a solar thermal system to reduce energy consumption in the hotel. Both technologies for greywater treatment and reuse have similar investment costs. However, the operating costs of the MBR are much higher compared to the CW. While the investment for the CW is returned in less than 8 years, this period is significantly longer for the MBR, approximately 30 years. Both measures reduce the drinking water consumption by estimated 45%. The implementation of the solar thermal system takes into account the limitations due to the limited available areas. The only viable option is the installation of a smaller number of solar collectors, which can provide a 26% reduction in the consumption of the classic energy system. The economic analysis of the solar thermal system confirms the almost immediate return on investment. The economic analysis does not take into account additional benefits such as resilience, lower consumption of resources, lower environmental pollution, and in the case of the CW also additional cooling and additional green space (biodiversity).

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LIST OF ABBREVIATIONS

ALR	Areal loading rate
ARR	Accounting rate of return
BOD	Biochemical oxygen demand
CAS	Conventional activated sludge
COD	Chemical oxygen demand
CW	Constructed wetland
DHW	Domestic hot water
DPT	Discounted payback time
EPC	Energy Performance Certificate
EPBD	Energy Performance of Buildings Directive
FV	Future value
GW	Greywater
HRT	Hydraulic retention time
IRR	Internal rate of return
LCS	Life cycle solar savings
LMH	Litres per square meter per hour
MBR	Membrane bioreactor
MF	Microfiltration
NBS	Nature-based solutions
NPV	Net present value
NS	Net savings
PV	Present value
PWF	Present worth factor
Q_{HW}	Hot water heat requirement
RBC	Rotating biological contactor
RWH	Rainwater harvesting
SAD	Specific air demand
SBR	Sequencing batch reactor
SF	Solar fraction
SOD	Specific oxygen demand
SPT	Simple payback time
TMP	Transmembrane pressure
UF	Ultrafiltration
UHI	Urban Heat Island
VSB	Vegetated submerged bed
WW	Wastewater
WWTP	Wastewater treatment plant

1 INTRODUCTION

The increase of global energy and water demand has caused concerns over supply difficulties, diminution of energy and water resources, and degradation of ecosystems. One of the largest sources of energy consumption not only in Europe, but also on bigger scale, can be attributed to buildings, which consume energy at each phase of their life cycle. Buildings with at least 50 years long life cycle will share around 40% of total world energy usage and 30% of global greenhouse gas (GHG) emissions (Pan and Zhang, 2020).

As the demand for energy continues to rise, so does the strain on water resources, creating a complex web of interconnected challenges. Climate change, marked by rising temperatures and shifting weather patterns, amplifies these concerns further, accentuating issues such as water scarcity and intensifying droughts. Although Europe is generally seen as having sufficient water supplies, the EU is facing a growing issue of more frequent and widespread water scarcity and droughts, which are being intensified due to overexploitation of existing water sources.

Over the past decades, intensive urbanisation and industrialisation has caused the increase of the ambient temperatures in cities. This phenomenon, called Urban Heat Island (UHI), has been observed in more than 450 cities worldwide and is evident in almost every urban area (Santamouris and Vasilakopoulou, 2021). Also, UHI does not depend on the size of the city or on its geographic climate. Studies indicate that future heat waves are going to last longer and be more frequent. Besides that, additional heat loads in summertime are expected due to climate change (Ward et al., 2016).

It should not be forgotten that even the process of producing energy often requires a significant amount of water resources, contributing to the increasing demand for water. To address the growing water demand and promote sustainability, it's crucial to implement measures like water reuse. These considerations give great importance to the increase of energy and water efficiency because it would mean cut emissions, reduce energy poverty, lower people's vulnerability to energy prices and support the economic upswing.

In alignment with the EU's commitment to tackle both the energy and water crises through initiatives like the European Green Deal, several directives and strategies have been introduced. These encompass policies such as the Water Framework Directive and the Urban Wastewater Treatment Directive, which address critical water resource management and quality concerns. Furthermore, as part of the Green Deal, the EU presented in October 2020 the Renovation Wave Strategy to set out measures, which aims to improve the energy performance of buildings and to at least double the annual energy renovation rate by 2030.

To foster sustainability within the construction and renovation sector, the introduction of energy performance certificates has been a significant step forward. However, to provide a more comprehensive understanding of a building's true value, it is proposed that these certificates be enhanced by incorporating a water efficiency certificate. This addition serves to emphasize the dual importance of conserving both energy and water resources, as discussed in Chapter 1.2.

1.1 Energy performance certificate

The Energy Performance Certificate (EPC) is a certificate which indicates the energy performance of a building or building unit, calculated according to a methodology adopted in accordance with the Energy Performance of Buildings Directive (EPBD) 2010/31/EU of the European Parliament. EPCs contribute to the improvement of the energy performance of buildings and play a central role in the context of providing information on the energy performance certificates, on the inspection reports and on their objectives and purpose. These certificates should also present cost-effective analysis and, where is possible, identify financial instruments to enhance the energy performance of the building for the owners or tenants of the buildings (Directive 2010/31/EU).

In December 2021, the European Parliament received a proposal to recast the EPBD, which includes measures to make EPCs clearer, more reliable, and visible. The proposal underlines the necessity to have easy-to-understand information that benefit building owners, financial investors, and public authorities. The proposed upgrade provides a clearer definition of a good quality EPC and clarify its purpose. There is an improvement in control mechanisms and in the visibility of property advertisement. In addition, the revised EPBD includes a template with a minimum number of common indicators on energy and greenhouse gas emissions, complemented with several elective ones, for example on charging points and indoor air quality (European Commission, 2021a).

The energy performance rated with A should align with buildings emitting zero emissions, whereas the G grade corresponds to the 15% of poorest performing buildings in each nation. The rest of the country's buildings would be distributed proportionally across the intermediate categories. This approach facilitates a more transparent and uncomplicated building classification system and permits to the national characteristics of the building stock the right flexibility and adaptability. In addition, the revision also puts stress on standardized criteria for databases and the availability of public access to databases containing data about the energy efficiency of buildings. This should elevate the quality of accessible information, simplify the tasks of public authorities and financial institutions, and push the building stock towards zero-emission and fully decarbonised status (European Commission, 2021b).

1.2 Water efficiency certificate

In line with the recognised importance of both energy and water efficiency, a reasonable upgrade of the EPC would be a water efficiency certificate. Namely, EPC alone may not be enough to define the energy balance and consequently the energy efficiency of the building. Proper water management can significantly affect the energy balance and act in terms of saving-water and saving-energy measures. This type of certificate could also evaluate the overall impact of the building on the surrounding environment.

The water efficiency certificate could also assume a higher value if its use would be like the EPC use. This means that it would be legally mandatory for all buildings and would consequently affect their market value. This would influence the general recognition of more sustainable water management in buildings and encourage the reuse of wastewater generated in the building. Measures that would bring the building into a higher class of the water efficiency certificate could be financially supported by state or other institutions, as it happens for the measures related to EPCs.

A proposal of water certificate was designed by Blatnik in 2021 on the EPC model. The difference consists basically in the reduction of water consumption instead of an energy reduction. The certificate itself contains instructions for determining the efficiency of the building in terms of water consumption. The efficiency rate, almost like in the EPC, is divided into five classes from A to E, where A indicates the most efficient class and E the class, where no measures are adopted. Classes C and D have included combinations of measures that enable more efficient use of freshwater resources, but do not include measures that would allow the reuse of wastewater. Class A and B included combinations of measures that allow the reuse of wastewater and those that allow more efficient use of freshwater. Given that, the proposed certificate classifies only combinations that apply to single-household buildings (Blatnik, 2021).

Considering legal frameworks of some EU member states and the feasibility of water reuse in buildings, Blatnik claims that rainwater and greywater (water from showers, bathtubs, washing machines and dishwashers) are the most acceptable water fluxes for reuse. The collection and preparation measures are widespread, accessible, and easy to integrate into the building's existing drainage or supply system. This makes them appropriate for general implementation. The amount of potentially usable greywater flowing from dishwashers, showers and bathtubs was assumed to be the same amount that, according to statistics, is used for these two uses (WHO, 2006a; Blatnik, 2021).

Water saving measures and measures for water reuse can be included in the building in combination. This means, for example, that collected rainwater could be used to flush toilets and all taps in the building would be replaced with water-saving taps. Flushing toilets with rainwater would reduce water consumption by 21% and additional 9% would be granted due to water-saving taps. As the measures affect different water fluxes, their effectiveness is added together, which is not the case for all combinations of measures. One such example is the combination of greywater and rainwater reuse measures. These measures reduce the consumption of fresh water, for all uses where no drinking water is required. Since there is a lot of precipitation in Slovenia on average, as well as the amount of greywater in the building, each of these two streams satisfies the needs for non-drinking uses. With this assumption, despite each of the measures reduces drinking water consumption by 48%, they do not reduce the total by 96% (Blatnik, 2021).

In these years a massive effort has been done for the mitigation of negative impacts on the environment, such as greenhouse effect, air pollution, UHI, and others, which cause damage to human health and limit the economic and social development. To contrast fossil-based energies, that represent the main source of environmental pollutants, many countries invested in finding solutions using renewable energy sources, such as hydropower, solar, wind, biomass and solid wastes and geothermal energy (Yüksek and Karadağ, 2021). Numerous investigations have been made also for energy recovery in air conditioning systems, especially in tropical countries (Abd El-Baky and Mohamed, 2007).

Furthermore, circular water management using nature-based solutions (NBS), provides a large range of measures, which can tackle negative environmental impacts and sustain the use of renewable energy sources. Langergraber et al. (2021) and Atanasova et al. (2021) provide a framework for implementing NBS for circular management of resources in cities.

Employing highly efficient technologies in water heating applications or harnessing the ability to recover heat from warm wastewater, for instance, can lead to a substantial reduction in both energy consumption and GHG emissions (Hervás-Blasco et al., 2020). Heat recovery from warm greywater within houses was presented as a novel concept by Meggers and Leibundgut in 2011. The system involves a tank, that receives the hot outflow from greywater sources, and a heat exchanger that supplies the heat to the heat pump. The latter raises the temperature of the recovered heat to a certain level, from which is possible to obtain new hot water. Thus, the regeneration of hot water supply through wastewater leads to a diminution of energy consumption for domestic water heating purposes which constitute 4% of the total European energy consumption (Kristensen and Petersen, 2021). Interestingly, domestic water use represents, on a global scale, 11% of the total water consumption (Mannan and Al-Ghamdi, 2022).

The depletion of the building's energy consumption can be achieved by the implementation of NBS. Besides that, NBS offer a list of other benefits regarding urban biosphere, such as flood prevention, provision of biodiversity and amenity, water treatment and more (Langergraber et al., 2020). Great examples of multiple benefits to urban environment are provided by constructed wetlands, algae ponds and rotating biological contactors, but also by green roofs and green walls (Kisser et al., 2020). These kinds of technologies are clearly becoming more and more important.

1.3 Goal of the thesis

The primary objective of this thesis is to demonstrate the design and feasibility of measures for improving the efficiency of buildings regarding energy and water consumption. The thesis aims to illustrate various strategies for energy and water reuse, with a particular focus on tourist facilities, as they represent significant energy and water consumers. Among various presented measures for wastewater reuse, two technologies were selected and assessed for their applicability on a real case study in Slovenia: a membrane bioreactor and a constructed wetland treatment system. Simultaneously, a conceptual design and installation project for a solar thermal system was carried out for the same facility to enhance energy efficiency and further improve sustainability.

The following chapter presents detailed quantification and characterisation of energy and water fluxes. Chapter 3 outlines the specific measures that can be employed to achieve these efficiency goals. Subsequently, Chapter 4 describes the practical application of these measures within a tourist facility, along with a thorough assessment of their economic feasibility. The thesis will conclude with a summary of key findings and conclusions.

2 QUANTIFICATION AND CHARACTERISATION OF ENERGY AND WATER FLUXES IN BUILDINGS

In this chapter the focus is on quantification and characterisation of energy and water fluxes in buildings. Water supply, water consumption and wastewater characteristics from buildings will be firstly discussed. The chapter than continues with rainwater characterisation and goes on talking about energy consumption and energy end-uses in buildings. Thereafter, stress is put on the importance of energy saving systems and the application of energy efficiency measures. Within all possible renewable technologies, passive and active solar systems will be presented.

2.1 Water fluxes in buildings

Domestic wastewater flow includes the sewage, which comes not only from private homes, but also from commercial activities and institutions that are commonly parts of urban areas. Normally, it is calculated based on domestic water consumption, which is connected to human behaviour and habits in each urban locality. Furthermore, the main influencing factors on water consumption in households are standard of living, quality of water supply system and installations in houses, water price, presence of industry or tourist attractions, climate, and water losses in the water supply system (Butler et al., 2018; Blatnik, 2021).

Water consumption is commonly determined by taking into account the design population and assigning a value for the average daily per capita water usage (Von Sperling, 2007). In fact, water consumption of an average person varies significantly around the globe, e.g. 124 L/PE/d in Europe (EurEau, 2021), 110 L/PE/d in Slovenia (SiStat, 2020), 122 L/PE/d in Germany (Statistisches Bundesamt, 2019), 141 L/PE/d in England and Wales (Brockett, 2019) and up to 215 L/PE/d in Italy (Istat, 2021) and 314 L/PE/d in America (Dieter et al., 2017). Water availability for users strongly differs among developing countries and developing cities as Tamil Nadu and Chandigarh (both in India), where the average water supply varies from 80 L/PE/d to 540 L/PE/d respectively (Gautam, 2009).

2.1.1 Water consumption in hotels – touristic facilities

Tourism undoubtedly brings a lot of advantages to cities and whole countries on several levels, such as economic, opportunistic, infrastructural, cross-cultural, and promotional. Despite all that, it causes various negative impacts on the environment. Especially in regions with scarce water resources, tourism is seen as a source of permanent problems due to the high demand for water. In fact, hotels and other touristic facilities use a lot of drinking water for their needs and they offer a variety of different services, from recreational to hygienic, relaxing and others, which normally operate 24 hours a day, throughout the year. Tourists tend to care less on how much they consume in hotels, because their costs do not depend on their water consumption, which becomes higher due to hygiene maintenance. While people constantly come and go, important amounts of water are used for cleaning rooms, washing bedding, cleaning dishes etc. Apart from that, the main water consuming factors comprehend irrigation of gardens, swimming pools, spa and wellness, but also golf courses, cooling towers and kitchens.

Studies have revealed that water use in tourism can extremely oscillate, from 80 to even 2000 litres per tourist per day (Gössling et al., 2012). Larger resorts and luxurious facilities tend to use significantly more water than smaller hotels. Important fluctuations can occur between countries, but also between hotels in the same country depending, for example, on geographical location, climate conditions and hotel standards (Gössling et al., 2012; Mechri and Amara, 2021). European tourists consume on average 300L per day, which is about three times more than the average European household consumption. Higher water consumption means more wastewater that needs to be treated, which, in other words, means a higher load on the sewerage system and treatment plant.

Severe problems take place in regions characterised by frequent droughts in warm months or by a general lack of water resources. These regions often correspond to coastal areas or islands with a lot of tourists particularly in summertime. Thus, droughts, peak tourists' seasons, and periods when permanent residents need the largest amounts of water (e.g., for agriculture) often coincide. This may increase water prices, elevate the risk of water resources overexploitation and groundwater depletion. To save water and alleviate the pressure to the scarce water resources, it is necessary to implement measures for more sustainable water management and think more about responsible tourism (Atanasova et al., 2017).

2.1.2 Domestic wastewater

Domestic wastewater represents the main flow from households. Thus, some considerations about its management are needed. This kind of sewage is made of almost 99.9% of water, but the remaining part constitutes the reason why the wastewater needs to be treated (Von Sperling, 2007). It includes a complex mixture of organic and inorganic material present in different forms, from coarse grits and fine suspended solids to colloidal particles and soluble substances. Besides that, it may contain a wide range of metals, pharmaceutical products, emerging pollutants, and high levels of (pathogenic) microorganisms that can cause disease. For this reason, safe and efficient wastewater disposal is crucial to protect the environment and maintain public health. However, the wastewater content is very unpredictable due to its high variability. The quality is affected by the contaminants released into the drain by humans, and by the original quality of water from the supply system. In many cases the quality of infiltrating groundwater must be considered too (Butler et al., 2018).

Specific loads on wastewater measured in units per capita per day are presented in Table 1. Domestic wastewaters are characterised by mostly organic wastes, which contain nutrients like nitrogen, phosphorus, and carbon, but include also relatively high concentrations of microorganisms. Therefore, wastewater characteristics from households are given in Table 2. The range of values is expressed in the most convenient way for measuring pollution, i.e., g/PE d, because it allows to compare different communities and different sources of pollution, for example industry and agriculture. The levels of biochemical oxygen demand (*BOD*) typically oscillate around 54 g per person per day when separate sewerage systems are applied. In developing regions, *BOD* values can be lower, typically ranging from 30 to 40 g/PE d because not all the sewage produced in the area enter the sewer system. In case of combined sewerage systems, *BOD* values may be around 40% higher, around 77 g/PE d (Arceivala and Asolekar, 2007).

Some considerations must be done about offices, factories, schools, etc., which are characterised by part-time occupancy. These *BOD* values are normally taken as half of 54 g/PE d or even less. For restaurants, each meal served may contribute one quarter of 54 g of *BOD*, cinemas and theatres may account for one sixth of 54 g of *BOD* per seat. On the contrary, hotels and hospitals may contribute from 1.5 to 2.5 times more than the usual 54 g of *BOD* (Arceivala and Asolekar, 2007).

Table 1: Specific loads on wastewater in g/(PE d) (Rutar Polanec, 2021)

	Parameter	**Unit**	**Load**
Biological oxygen demand	*BOD*	g O_2/(PE d)	60
Chemical oxygen demand	*COD*	g O_2/(PE d)	120
Suspended solids	*TSS*	g/(PE d)	70
Total Kjeldahl nitrogen	*TKN*	g/(PE d)	11
Ammonium nitrate	$NH_4\text{-}N$	%	75
Organic nitrogen	N_{org}	%	25
Total phosphorus	*P*	g/(PE d)	1.8

Table 2: Raw domestic wastewater characteristics (Arceivala and Asolekar, 2007)

Item	**Range of values (g/PE d)**
Biochemical oxygen demand (BOD_5)	45-54
Chemical oxygen demand	1.6-1.9 x BOD5
Total organic carbon	0.6-1.0 x BOD5
Total solids	170-220
Suspended solids	70-145
Grit (inorganic 0.2 mm and above)	5-15
Grease	10-30
Alkalinity (as $CaCO_3$)	20-30
Chlorides	4-8
Total nitrogen N	6-12
Organic nitrogen	~ 0.4 x total N
Free ammonia	~ 0.6 x total N
Nitrate	0.0-0.5 x total N
Total phosphorus, P	0.6-4.5
Organic phosphorus	~ 0.3 x total P
Inorganic (ortho- and polyphosphates)	~ 0.7 x total P
Potassium (as potassium oxide K_2O)	2.0-6.0

2.1.3 Blackwater characteristics

According to the source of generation, two important fractions of domestic wastewater need to be distinguished, i.e., black and greywater. Blackwater is part of the wastewater that is discharged through toilets and can be further divided into faeces and urine. Many times, apart from human excreta diluted with rinsing water, there are various extra wastes that people throw away in the toilet bowls. A large proportion of wastewater can be attributed to human excreta, which contain various microorganisms that may be problematic for wastewater reuse or treatment. According to Butler et al. (2018) the average production of faeces per day is about 200-300 g per an adult person, which accounts for 10-15 g/PE d of *BOD*. The amount of produced urine by an adult goes from 1 to 1.5 kg per day, which contributes about 6 g/PE d of *BOD*. Excreta also represent an important source of nutrients. Most of organic nitrogen (94%) in the form of ammonia and about 50% of phosphorus released in wastewater come from excreta. Moreover, excreta provide around 1 g/PE d of sulphur too (Butler et al., 2018).

Sewage sludge represents a great potential for the reuse of organic nutrients, but society instead prefers to dispose it of as fast as possible because of bad smells and unpleasant views. Besides that, people intentionally or accidentally throw away a wide variety of solids in the toilet, such as tampons, condoms, sanitary towels, diapers, cotton buds, paper towels and a large amount of toilet paper. The presence of cellulose fibres makes the toilet paper very slowly biodegradable, although it usually disintegrates in a few hours in turbulent flows (Butler et al., 2018). Market research data in combination with toilet paper manufacturers' data and retail sales data in the UK, have shown an average usage value of 0.12 toilet rolls per person per day, which, using additional laboratory tests, can be converted to a dry mass of 16.1 g/PE d (Spence et al., 2016). Studies have also revealed that 0.15 sanitary items per person are thrown away through toilets each day. Some considerations need to be done also on disinfecting, cleaning and descaling chemicals regularly discharged in the sewer system. Even though food waste disposers are widely spread in the world by now, a certain amount of undigested food is still flushed through the toilet. This implicates the presence of oils, cooking oils, fats, meats, and grease and consequently an increase of organic nitrogen, phosphorus, and salt in the blackwater.

2.1.4 Greywater characteristics

All wastewater produced in a building excluding wastewater from toilets is defined as greywater. It is called so since it becomes grey when stored for some time without treatment. This lightly polluted wastewater includes household wastewater from showers, dishwashers, sinks, baths and washing machines (Butler et al., 2018). It can be considered as water of higher quality than blackwater, but of inferior quality than drinking water. Moreover, based on greywater source, it can be divided into light and dark greywater; the first one includes wastewater from bathroom sinks, baths, and showers, while the latter comprehend more contaminated waste from laundry, dishwashers, and kitchen sinks (Birks and Hills, 2007).

The German Association for Water, Wastewater and Waste (DWA) has presented a further distinction between two types of greywater, i.e. (DWA, 2017):

Type A: low grade greywater - greywater without drains from washing machines and kitchen.

- A1: greywater from baths and showers.
- A2: greywater from baths, showers, and washbasins.

Type B: high grade greywater - greywater from kitchen drains and/or washing machines.

- B1: greywater from baths, showers, washbasins and washing machines.
- B2: greywater from baths, showers, washbasins, washing machines and/or kitchen.

2.1.4.1 Greywater quantity and quality

Household wastewater comprises approximately 65% to 75% greywater, and this proportion increases to more than 90% when vacuum toilets are in use (Ghaitidak and Yadav, 2013; Li et al., 2009; Rutar Polanec, 2021). Further, around 50% of the total greywater is constituted by light greywater.

Nevertheless, the quantity and composition of greywater generated are closely tied to an individual's average water consumption in households, a factor that varies across the world. Data from different cities around the world regarding greywater quantity produced by different sources have been presented by Rutar Polanec (2021), who has summarized the analyses made by Ghaitidak and Yadav (2013) and Friedler (2004). These data can be seen in Table 3, which also includes a comparation with total wastewater production.

According to Ghaitidak and Yadav (2013) greywater derives mainly from bathroom (47%), kitchen (27%) and laundry (26%) and encloses different substances (Figure 1). Greywater from bathrooms contains toothpaste, soaps, shampoos, body care products, skin, hair, shaving waste, body fats, lint, and traces of urine and faeces. Greywater coming from dishwashers contains soaps, salinity, bacteria, hot water, food particles, foam, oil and grease, odour, high pH, organic matter, turbidity, and suspended solids. Greywater originating from kitchen sinks is full of food residues, oil and fat, and dishwashing detergents. Further, high concentrations of chemicals from soap powders like sodium, nitrogen, phosphorous and surfactants are typical for laundry greywater, which also contains paints, solvents, bleaches, oils, and non-biodegradable fibres from clothing (WHO, 2006a; Rutar Polanec, 2021). Lastly, high pH, hot water, foam, bleach, oil and grease, nitrate, suspended solids, salinity, phosphate, turbidity, sodium, and soaps are representative contents of greywater from automatic clothes washers (Noah, 2002).

Table 3: Greywater distribution from different sources in L/PE/d (Ghaitidak and Yadav, 2013 and the references therein; Friedler, 2004; DWA, 2017; Rutar Polanec, 2021)

	Washbasin	**Shower**	**Bath**	**Washing machine**	**Kitchen sink**	**Dishwasher**	**Total GW**	**Total WW**	**% of GW in WW**
North America	90		-	82	27		196	378	52
England and Wales	33		-	-	63		96	150	64
Jordan (Aman)	20		-	10	29		59	75	79
Oman	83		-	13	64		161	195	83
Queensland	60		-	35	-		95	-	-
Canberra	60		-	40	17		117	173	67
New South Wales	73		-	45	15		133	195	23
Yemen	17		-	5	13		35	40	87
Israel	15	20	34-55	8-13	25	5	98	-	-
Friedler (2004)	8-13	12-20	16	17-60	13-19	2-6	68-134	-	-
Germany*	10-15	10-50	0-30	10-15	5-10	5-10	75	-	-

*(DWA, 2017)

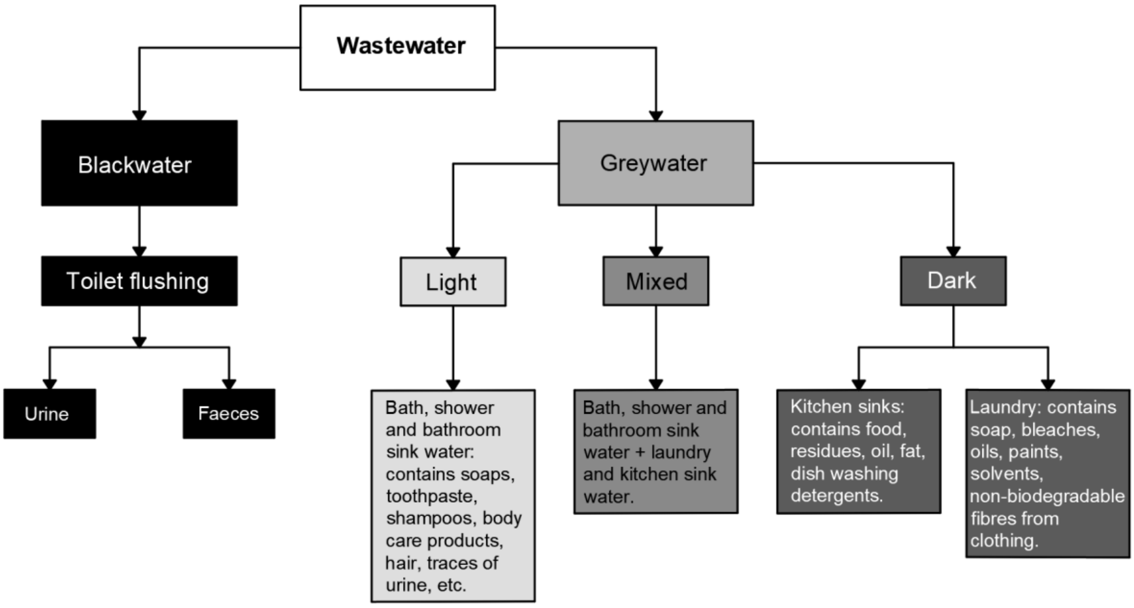


Figure 1: Wastewater division into black and greywater and their contents (Ghaitidak and Yadav, 2013; Li et al., 2009; Noah, 2002; Rutar Polanec, 2021)

2.1.4.2 Greywater composition

Greywater is considered an important alternative water source for non-potable purposes, especially in arid and semi-arid touristic areas, where the peak water demand coincides with the dry period (Atanasova et al., 2017). It is regularly generated in large volumes and its properties make it adapt for reuse in many applications, primarily for irrigation and toilet flushing. For instance, greywater contains a lot less nitrogen than blackwater, which means less complex treatment needed for its reuse. Nevertheless, there may be high concentrations of nutrients and other substances that could be dangerous to aquatic ecosystems, thus treatment is absolutely needed. Proper wastewater characterisation constitutes an important and difficult task to define the most adapt treatment that will be applied. The difficulty stays in the fact that greywater composition varies strongly from case to case, where several factors need to be considered, e.g., the number of inhabitants, the quality of the source water, the age distribution of inhabitants, their lifestyle, their activities, water usage patterns, social and cultural habits and living standards. Other factors that need to be mentioned are the type and quantity of domestic chemicals used (e.g., detergents, soaps, shampoos, toothpastes, etc.), and the length of time until the reuse of water (Ghaitidak and Yadav, 2013; Rutar Polanec, 2021).

Physical, chemical, and microbiological parameters that define greywater quality may strongly differ among the discharges from different domestic sources. Characteristic data at different sources have been collected by Ghaitidak and Yadav (2013), which can be seen in Table 4. Interestingly, this table shows that dishwashers, which contribute the least amount of greywater (2-6 L/PE/d) according to Friedler (2004), may provide up to 4450 BOD mg/L, which is more than the amount produced by kitchen sinks (890 BOD mg/L from) characterised with a larger discharge range. However, it must be pointed out that characteristics of greywater composition differ across research papers; this leads to extended ranges of greywater concentrations. In this sense, different types of greywater treatment can be taken and different types of reuse can be chosen depending on how polluted is that wastewater.

Table 4: Greywater composition at different sources (Ghaitidak and Yadav, 2013; Friedler, 2004; Rutar Polanec, 2021)

Parameters	Wash basin	Bathroom	Shower	Laundry/washing machine	Kitchen sink	Dish washer
pH	7–7.3	7.1–7.6	7.3–7.5	8.3–9.3	6.5–7.7	8.2–8.3
Turbidity (NTU)[a]	164	59.8	84.8–375	328–444	133–211	
EC (mS/m)[a]		43.7	1.4–89	2.9–703	1.4–97	90.61
Tot. solids (TS)	835	777	520–1,090	2,021–2,700	679–1,272	2,819
Tot. Suspended solids (TSS)	153–259	58–78	89–353	188–315	134–625	525
Tot. Dissolved solids (TDS)			279–565	2,140–2,444	312–903	
BOD	155–205	129–173	40.2–424	44.3–462	40.8–890	470–4,450
COD	386–587	230–367	77–645	58–1,339	58–1,340	1,296
Tot. Alkalinity			203	333.6	205.4	
Chlorides	237	166	147–284	205–450	158–223	716
MBAS	3.3	15	14.9–61	42–118.3	41.9–59	11.1
O&G	135	77	164	181	232	328
Tot. N	10.4	6.6	8.7–10.92	14.28	6.44–6.44	
Tot. P			1.12	51.58	0.69	
TC (MPN)[a]	9.42E+03	6,350–5.1E6	2E2–6.8E3	2E2–4.2E6	2E2–5.29E2	4.30E6
FC (MPN)[a]	3.50E+04	1.5E5–4E6	64–4.0E6	13–4E6	200.5–1.2E6	6.0E4–3.2E5
E. coli (MPN)[a]	10	82.7	2E2–1.49E3		2E2	
Boron (B)	0.44	0.41	0.35–0.35	0.4	0.02–0.02	3.8
Calcium (Ca)			15.7–59.9	18.7–24	19.69–23.6	
Magnesium (Mg)			23–56.1	15.1–60.8	16.6–21	
Sodium (Na)	131	112	109.5–184.5	302.1–667	70.1–148.9	641
Arsenic (As)			0.03		0.015	
Copper (Cu)			0.01–0.0127	0.0064–0.01		
Lead (Pb)			0.1036	0.0829	0.0622	
Nickel (Ni)			0.035	0.0352–0.12	0.0352–0.04	
Zinc (Zn)			2.4	0.14	0.039–0.04	

[a] Units in bracket, all other units are in mg/L (except pH)

2.1.5 Rainwater characteristics

First and foremost, it is worth distinguishing between rainwater and stormwater. In fact, stormwater, or surface water runoff, is generated by rainwater or water resulting from any form of precipitation, that falls on a built-up area and runs off from urban surfaces (Butler et al., 2018). Efficient and safe stormwater drainage is essential to maintain or improve public health and flood safety.

In most cases rainwater refers to the rain that falls on a roof, which is drained to the sewerage system. When combined sewerage systems are installed, rainwater gets mixed with wastewater and both get transported to the ultimate destination, which is the wastewater treatment plant (WWTP). In the treatment plant, the wastewater is treated to such an extent that it is suitable for discharge into a nearby watercourse. Alternatively, rainwater is discharged into a separate sewerage system, which makes more sense from the point of view of wastewater treatment, as the water is separated into two fractions with more predictable and uniform concentrations of pollutants. However, there are also other options to manage surface runoff, for example, by means of green roofs, rainwater harvesting and water butts (Butler et al., 2018). The practice of rainwater harvesting was far more common in the past when people were collecting rainwater from roofs for their own needs because water supply systems have not spread yet.

The rainwater quality collected directly from roofs of buildings differs from that from paved surfaces. Rainwater from roofs contains the remains of leaves and moss, bird droppings and insects. However, the type of roofing has the greatest impact on the properties of harvested rainwater. In general, less polluted water drains from sloping roofs due to the shorter retention time of fallen water. Rainwater harvesting may be risky in winter when the snow is in contact with metals in roofing sheets for a long time. Thus, these sheets may contain lead or zinc, which can lead to excessive amounts of heavy metals in the water (Woods Ballard et al., 2015; Blatnik, 2021).

Rainwater harvesting (RWH) systems will be further described in Chapter 3.1.4, where attention will be given to different RWH types and hydraulic design of the storage tank. One of the primary parameters used for proper sizing of the storage is the runoff factor or runoff (yield) coefficient. This coefficient represents the ratio of drained water to water that has fallen on the roof and depends on the slope and material of the surface (Woods Ballard et al., 2015). Table 5 includes suggested values for the average runoff factor based on different types of surfaces. In fact, especially for relatively small rainfall events that fall on flat roofed areas, significant initial wetting losses may occur. This may lead to an overall proportion of runoff referred to an event that is much less than 100%.

Table 5: Recommended initial runoff coefficient for different roofing types (Woods Ballard et al., 2015)

Surface type	**Runoff coefficient**
Pitched roof with profiled metal sheeting	0.95
Pitched roof with tiles	0.90
Flat roof without gravel	0.80
Flat roof with gravel	0.60
Green roof, intensive [a]	0.30
Green roof, extensive [a]	0.60
Permeable pavement	0.60
Pavement/road	0.75

[a] Runoff coefficient is highly uncertain and depend on the season.

2.1.6 Water reuse legislation and standards

The need to minimise the threat to environment and human health due to water reuse has led to the establishment of regulations and guidelines for the safe use of treated greywater and rainwater, which, from a reuse perspective, are considered as a wastewater. Therefore, they must go along with wastewater reuse standards of existing legislation. These standards are globally variable and depend on the intended use of the treated effluent. Generally, limits are set on determined parameters to minimise nuisance smells and algal bloom as well as to preserve human and environmental health. A key benchmark for safe water reuse is represented by the World Health Organization's guidelines published in 2006, which cover only the safe use of wastewater in aquaculture and agriculture (WHO, 2006b). Although these guidelines provide a framework for human safety in wastewater reuse practices, they do not include regulatory aspects.

International ISO standards concerning the use of reclaimed water were issued in the years 2017, 2018 and 2019, as it follows:

- ISO 20760-2:2017, Water reuse in urban areas - Guidelines for centralized water reuse system - Part 2: Management of a centralized water reuse system.
- ISO 20760-1:2018, Water reuse in urban areas - Guidelines for centralized water reuse system - Part 1: Design principle of a centralized water reuse system.
- ISO 20761:2018, Water reuse in urban areas - Guidelines for water reuse safety evaluation - Assessment parameters and methods.
- ISO/DIS 23056:2019, Water reuse in urban areas - Guidelines for decentralized/onsite water reuse system - Design principle of a decentralized/onsite system.

At the EU scale, water reuse is scarcely encouraged in the Urban Wastewater Directive published in May 1991, which however do not oblige the member states to guarantee a certain level of reuse and the development of proper standards. In June 2020, the European Commission issued a new regulation on minimum requirements for water reuse, which came into effect on June 26th, 2023. However, it only applies to the reuse in agricultural applications. Many EU countries have implemented their own regulations or guidelines for the reuse of treated wastewater for non-potable use. Among these there are standards of France, Cyprus, Greece, Italy, and Spain, which are considered as regulations in the national legislation. In Portugal, although the standards are just guidelines, the government considers them when emanating any water reuse permit (Sanz and Gawlik, 2014). The majority of the local standards regarding greywater reuse in these six countries pertain to agricultural, urban, and industrial applications. The intended uses of the standards are summarised in Table 6.

Table 6: Intended uses for water reuse incorporated in the standards of certain EU countries (Sanz and Gawlik, 2014)

Intended use of reclaimed water	**Cyprus**	**France**	**Greece**	**Italy**	**Portugal**	**Spain**
Irrigation of private gardens						√
Supply to sanitary appliances				√		√
Landscape irrigation of urban areas (parks, sports grounds and similar)	√	√	√	√	√	√
Street cleaning			√	√		√
Soil compaction			√			

Fire hydrants			√	√ *		√
Industrial washing of vehicles				√		√
Irrigation of crops eaten raw	√	√	√	√	√	√
Irrigation of crops not eaten raw	√	√	√	√	√	√
Irrigation of pastures for milk or meat producing animals		√	√	√	√	√
Aquaculture						√
Irrigation of trees without contact of reclaimed water with fruit for human consumption	√	√	√	√	√	√
Irrigation of ornamental flowers without contact of reclaimed water with the product		√	√	√		√
Irrigation of industrial non-food crops, fodder, cereals	√	√	√	√	√	√
Water process, and cleaning in industry other than the food industry			√	√**		√
Water process and cleaning in the food industry			√	√**		√
Cooling towers and evaporative condensers			√	√		
Golf course irrigation	√	√	√	√	√	√
Ornamental ponds without public access			√			
Aquifer recharge by localised percolation	√		√			√
Aquifer recharge by direct injection	√		√			√
Irrigation of woodland and green areas not accessible to the public		√	√	√	√	√
Silviculture						√
Environmental uses (maintenance of wetlands, minimum stream flows and similar)						√

*Only for industrial uses.

**Reclaimed water is not suitable for direct contact with food, pharmaceuticals, or cosmetic products.

The guidelines among other cover the requirements for the use of reclaimed water for non-potable applications in urban settings, where public access may be restricted or not restricted. In the former case, the public exposure to the recycled water is controlled, which means that the treatment requirements may not be as severe as those for unrestricted reuse. Irrigation can be also defined as restricted or unrestricted, where the first case comprehends the use of wastewater to grow crops that are not eaten ray by people (WHO, 2006b). In all cases, guidelines and standards set limit values on physical, chemical, microbiological, and disinfection parameters depending on the type of use, as it is seen in Table 8.

In Germany, the quality requirements for the greywater reuse are specified in the DWA's guidelines DWA-M-277E published in 2017 (DWA, 2017). The greywater can be used as service water for different intended uses, which determine the level of treatment to reach specific quality requirements.

The treatment level of greywater can be divided into two categories (C1 and C2) according to the type of use (Table 7):

- C1: mechanical, biological treatment and stabilization of greywater of the Type A (see section 2.1.4).
- C2: mechanical, biological treatment and hygienisation of greywater of the Type A and B (see section 2.1.4)

The physical, chemical, and microbiological quality requirements as well as treatment technologies correspondent to different end-uses of reclaimed water are pointed out in Table 7.

Table 7: Quality requirements for treated greywater, recommended uses and treatment processes (DWA, 2017)

Criteria		**Quality requirements for treated greywater**	
Use category		C1	C2
Treatment method		Treatment/Stabilisation	Treatment and hygienisation
Greywater		Type A	Type A Type B
Biochemical/chemical-physical parameters	Turbidity	–	< 2 NTU
	BOD_5	–	< 5 mg/l
	O_2 Saturation	> 50 %	> 50 %
	pH	6.5 – 9.5	6.5 – 9.5
Hygienic parameters	Total coliforms	No requirement	< 10,000/100 ml
	E. coli		< 1,000/100 ml
	P. aeroginosa		< 100/100 ml
	sampling	–	Reservoir/Consumer
Recommended use	Toilet flushing (private)	+	+
	Irrigation (private) lawn, ornamental plants	–	+
	Irrigation crop plants (for consumption)	–	+
	Laundry (private)*	–	+
	Toilet flushing (public)	–	+
	Exemplary processes and other treatment stages	FB, SF, FLB, Stabilisation	FB, SF, FLB, MBR + UV, UF, RO
	UV UV-system	MBR Membrane bioreactor	FLB Fluidised bed reactor
	UF Ultrafiltration	FB Fixed bed reactor	SF Soil filter system
	RO Reverse Osmosis *UV Transmission > 60 % is recommended.		

Table 8: Water quality guidelines and criteria for different intended uses of the reclaimed water (adapted from Rutar Polanec, 2021; WHO, 2006b; Gross et al., 2007; see the references for details)

		Water quality parameter								**Pathogen criteria**				**Disinfection parameter**		
		pH	*TSS*	*BOD*	*COD*	*TN*	*TP*	*EC*	Turbidity	Tot.	Faecal coliform	E. coli	Poliovirus/ surrogate	UV disinfection	Cl residual	Chlorine CT
Country, reference	**Type of reuse**	/	mg/L					dS/m	NTU	cfu/100mL			log	mJ/cm^2	mg/L	mg/L -min
WHO (WHO,2006b)	Irrigation of ornamentals, fruit, trees, and fodder crops		≤140	≤240							≤1000					
	Irrigation of vegetables likely to be eaten uncooked		≤20	≤20							≤200					
	Toilet flushing		≤10	≤10	≤30						≤10					
Israel (Gross et al., 2007)	Urban reuse		<10													
EU (Regulation 2020/741)	Agricultural irrigation		≤10, 91/271/EEC**	≤10, 91/271/EEC**					≤5			≤10-1000**				
Cyprus (KDP 269/2005, KDP 772/2003)	Irrigation of vegetables likely to be eaten cooked		≤15	≤15							≤100					
	Irrigation of vegetables likely to be eaten uncooked		<10	<10							≤15					

Cyprus	Range from most to least restricted reuses	6.5-8.5	10-30	10-70	70	15	2-10	1.7-2.9				$5\text{-}10^3$				300
France (JORF num.0153, 4 July 2014)	Range from most to least restricted reuses		15		60							$250\text{-}10^5$				
Greece (CMD No 145116)	Range from most to least restricted reuses	6.5-8.5	2-35	10-25		30	1-2	3.0	2-no limit		2	5-200				350
Italy (DM 185/2003)	Range from most to least restricted reuses	6.0-9.5	10	20	100	15	2	3.0				10				250
Portugal (NP 4434 2005)	Range from most to least restricted reuses	6.5-8.4	60					1.0			$100\text{-}10^4$					70
Spain (RD 1620/2007)	Range from most to least restricted reuses		5-35			10*	2*	3.0	1-15			$0\text{-}10^4$				

*Only for aquifer recharge and recreational uses.
**Depending on the wastewater treatment level, crop type and irrigation method.

2.2 Energy fluxes in buildings

Proper design, construction and buildings' operation can reach important energy savings. Energy insufficiency, GHG emissions and their severe threat to environment and human health can be tackled with increasing building energy efficiency. Most people spend about 90% of their everyday life indoors and depending on mechanical heating and air conditioning, causing buildings to be the largest energy consumers on Earth (Cao et al., 2016). In the U.S., for example, building energy consumption compared to the total energy consumption raised for 7.4% between 1980 and 2010. After the U.S., China holds the position of the second-largest consumer of building energy globally. Between 1990 and 2009, China witnessed a significant 40% surge in its energy consumption within the building sector.

Most of the energy consumption in residential buildings involves heating, ventilation and air conditioning (HVAC), as well as water heating. These energy end-uses are followed by appliances, lighting and cooking. On the contrary, the smallest portion of final energy demand is attributed to space cooling. Despite that, it is the fastest growing end-use with a grow rate around 5% between 2017 and 2018. The growth of cooling demand is driven by different factors, such as overpopulation, climate change and higher floor spaces. Even though the residential cooling demand in China is rising vertiginously, the ownership of air condition devices is still low in warm developing counties like Africa and India. The future cooling consumption in these countries will depend mostly on the economic evolution and climatic drivers.

In Europe, the biggest energy end-use is referred to space heating, which accounts for 66% of domestic energy use (Cao et al., 2016). Nevertheless, the average space heating energy has lessened in most E.U. countries since 2000 because of an enhancement of energy efficiency. The energy use normalised by floor area shows significant differences between southern countries and northern countries, where the values go from 60-90 kWh/m^2 to 175-235 kWh/m^2 respectively. Globally seen, the U.S. are the greatest heating energy consumers per unit area, followed by E.U. and China. Despite the increment of 30 billion square meters of buildings in China since 2000 that has led to an increase of the country's heating demand by 10%, the world energy heating consumption has not gotten bigger. The main reasons are associated with important energy conservation measures that have been taken, specially by Western developed countries (Santamouris and Vasilakopoulou, 2021). These measures aim to improve the space heating efficiency through a modernization of existing building envelopes and heating equipment. The latter, together with update appliances, is also instrumental in reducing electricity demand in buildings. For instance, traditional electric heaters should be progressively replaced by efficient heat pumps for space and water heating (Cao et al., 2016).

Lighting and appliances represent a significant portion of the total energy consumption in buildings. The introduction of advanced lighting technologies (e.g., LEDs) and their spread worldwide has brought an improvement of the lighting energy intensity by 15%. On the other hand, the appliance electricity consumption is expected to double its value from 2000 until 2030 mostly due to progressive increasing of economic possibilities in developing countries (Santamouris and Vasilakopoulou, 2021; Cao et al., 2016). Furthermore, the energy demand for appliances is also influenced by inhabitants' behaviour and social guidance.

The final energy consumption in European and U.S. buildings is characterised by a domination of electricity and natural gas, which are the primary fuels sources. The biggest share of the final energy usage is actually covered by electricity, which is mainly used for cooling, heating, lighting, and appliances. Gas is the most used fuel in all European residential buildings and stands for the primary fuel source for water heating in the U.S. Contrarily, Chinese residential sector is dominated by biomass and waste energy sources due to their extensive use for heating and cooking. Renewables, solid fuels, and district heating are becoming popular specially in central and eastern EU regions, while in southern regions solid fuels and district heating are quite uncommon due to low heating needs (Cao et al., 2016). However, renewable energy sources to these days still play a small role in the total building final energy usage.

Energy savings and emission reduction can be obtained through the realization of renewable energy systems and application of energy efficiency measures. The latter are meant to reduce the need for energy, while renewable energy systems are adopted to fulfil the remaining building energy needs. According to Hayter and Kandt (2011) an investment in efficiency measures should be firstly considered, because is roughly half of the cost needed to install renewable systems able to generate the same capacity as efficiency measures. The ability to renew at an equal rate or faster than the depletion rate makes the renewable sources sustainable and preferable to non-renewable energies. Thus, energy sources like solar, wind, biomass and geothermal must be taken seriously into account against negative environmental effects related to overuse of fossil fuels. Before applying a renewable energy technology to retrofit a building, several factors should be considered, such as (Hayter and Kandt, 2011):

- Presence of renewables at or near the building location.
- Allocated space for siting the renewable energy technology.
- Expenses associated with purchased energy from electrical or thermal providers.
- Accessibility to incentives that can mitigate the installation cost of the system.
- Adherence to local regulations impacting renewable energy systems.
- Wish to maintain existing architectural features.

Within all renewable energy technologies applied in buildings, in this thesis the focus is on the use of solar systems and particularly on solar thermal systems. Solar systems used in buildings can be divided into passive and active. Both are fundamental for energy-saving strategies, where different active and passive measures in architecture design can be taken, separately or together. Rezaie et al. (2011) have determined that when the goal is reducing CO_2 emissions of the building, the combined use of both passive and active systems is the most effective. On the contrary, when the target is based on budget, hybrid systems are not a good choice. When selecting the most appropriate system, different factors besides budget and reducing emission goal need to be considered. The main factors include the type of building and its typical energy consumption, the system's reliability, but also the installation, maintenance, and uncomplicated use.

2.2.1 Passive solar design

The concept of passive solar building design consists in the conservation of energy as much as possible. It can support the conservation of energy because of the direct relationship between building design and energy use. Passive solar systems use natural sun's energy and fresh air for heating, cooling, and daylighting without mechanical or electronic equipment. This allows to lower energy needs from other sources and provide good living conditions inside the building. Furthermore, special attention is given by building designers to the possibility to minimize heating and cooling needs. This also requires some knowledge about local climate, solar geometry, and window technology.

Passive solar design principles are built on basic natural processes by means of thermal energy flows connected with natural convection, radiation, and conduction. Basically, when sunlight hits a building, the solar radiation can be reflected, transmitted or absorbed by building's materials. These responses to solar heat influence proper sizing of elements, the selection of materials and placements.

Implementation of passive energy saving technologies can aid the improvement of building energy efficiency. These kinds of technologies involve solar heating and cooling and advanced building envelopes. The aim of all passive solar heating technologies is to capture solar heat and release that heat when is necessary. For example, a typical passive heating device that efficiently captures and transmits solar energy into a building is a solar gain wall, also called Trombe wall. While building's materials are capable capturing heat for later use, solar heat is still available for maintaining comfortable space conditions. Moreover, solar heating systems admit different approaches for their implementation, which are direct gain, indirect gain, and isolated gain (Chel and Kaushik, 2018). For their realization, all of them must include two primary elements: thermal mass for heat absorption, storage and distribution, and south facing glass for northern regions and the other way round.

On the other hand, when talking about passive solar cooling, it can be achieved with a proper combination of ventilation, ground cooling, shading and other elements like operable windows, wing walls or thermal chimneys. Cooling purposes can be also satisfied by installing vents in the upper part of the building to let the warm air to rise by convection and leave the building. Similarly, vents can be installed also in the lower building's level to allow the cooler air to enter. According to Cao et al. (2016), measures like night-time ventilation and passive thermal storage are most widely used in moderate/Mediterranean regions, where large differences in temperature occur during the day in summer. Thermal insulation and passive solar heat gain are typical for cold climates, while in tropical climates mainly prevail ground cooling, solar shading, and green roofs.

2.2.2 Active solar design

Active solar systems utilize mechanical and/or electronic components that convert solar radiation, captured by collectors, into the selected form of energy and permit it to be used in the building. These systems allow solar radiation to be transformed into electricity and heat. Basically, these systems can be divided in two groups with respect to the energy they produce: photovoltaic (PV) systems, which produce electricity, and solar thermal systems, which produce heat energy. PV technology is briefly presented below, while solar thermal systems will be discussed more specifically in the next chapter.

An active solar system can be made by PV cells that turn sunlight into electricity through semiconducting material, which is usually made of silicon, but also other polycrystalline thin films can be used. When sunlight hits the panel, a direct current (DC) is generated. The latter is converted to grid-quality alternating current (AC) electricity to power all the appliances in the building. PV systems are made up of modules, which together assemble arrays that can be placed on or near a building. Traditional solar cells made from silicon are typically flat-plate, which are usually also the most efficient (Hayter and Kandt, 2011). The solar cell efficiency represents an indicator that measures the quality of the conversion from sunlight to DC electricity. Studies have shown that efficiency of PV systems goes from 10% to 23% (Cao et al., 2016; Pandey et al., 2016). The reason is attributed to a large portion of solar radiation incident on PV cells that is converted into thermal energy. This leads to a reduction of conversion efficiency and to an increase of the working temperature of cells. This technical problem can be partially solved by the integration of electricity generation and thermal collection using hybrid photovoltaic-thermal systems (PV/T), which are able to generate heat and electricity at the same time (Chel and Kaushik, 2018).

One of the most used technologies to convert solar energy in electricity consists of integrating PV modules into the building envelope, typically a roof and/or a facade. This technology, called building integrated photovoltaic (BIPV), can seriously raise the total electricity production and reduce the space, material and infrastructural costs of the building (Cao et al., 2016; Pandey et al., 2016). BIPV products are suitable for applications on existing buildings that need major renovations. They can be integrated as rooftop shingles and tiles, building facades or the glazing for skylights. It should be noted that they can add complexity and cost to projects and in some cases may be unavailable (Hayter and Kandt, 2011).

The electricity generation from PV modules strongly depends on local climate conditions. Much research has been done on different climatic regions (Pandey et al., 2013; Eke and Demircan, 2013; Ye et al., 2013). As expected, the efficiency of PV systems results higher in tropical and sunny regions with increased solar irradiation. PV systems are very appropriate for tropical climates, where huge electricity demand is needed for air conditioning. The required energy production can be reliably predicted by means of daily and seasonal patterns. Besides that, by installing sun tracking systems to PV panels, it is possible to lessen the influence of variable sky conditions and consequently increase the efficiency. On the other hand, it causes higher installation costs (Cao et al., 2016).

3 MEASURES FOR THE OPTIMIZATION OF ENERGY AND WATER FLUXES

This chapter presents measures for optimizing energy and waste fluxes, where optimization of fluxes means reduced inflows and outflows to/from buildings, i.e., reduced demand for new resources and reduced waste fluxes as a result of implementing measures for water reuse and renewable energy use.

3.1 Measures for water reuse

The optimization of water fluxes in buildings and the achievement of greater water sustainability and resiliency can be made possible by greywater and rainwater recycling. These approaches need less resource-intensive treatment processes due to their potential to carry less organics, nutrients and pathogens compared to mixed wastewater or blackwater in the absence, for example, of faeces, urine, and toilet paper. Therefore, the source separation approach leads to significant reductions of volumetric burden on the existing wastewater transport and treatment system, as the load of water in WWTP gets lower. The use of systems that separate wastewater into different fractions directly at the source, as well as RWH systems, can also meet some of the building's water demand, deliver sustainability and climate resilience benefits, and help to reduce the water runoff (Woods Ballard et al., 2015). Systems for treatment and reuse of greywater and rainwater will be presented in the following sections.

3.1.1 Measures for greywater reuse

The reuse of greywater requires a system that separates it from other wastewater at the point of origin. Separation, treatment, and greywater reuse can be considered as a great source for non-potable uses, which is also able to reduce the hydraulic load on sewer system and treatment plant. In addition, greywater (and its heat) represents a potential source of heat that can be used to heat various parts of the building or to produce domestic hot water (DHW) (Hervás-Blasco et al., 2020; Rutar Polanec, 2021; Arnell et al., 2017).

Even though greywater is relatively less polluted than blackwater or mixed wastewater, it needs proper treatment before its reuse. According to Ghaitidak and Yadav (2013) none of the untreated greywater characteristics fits to existing reuse standards and guidelines. The technology for greywater reuse must be adapted to the requirements regarding its biochemical composition, quantity, and installation options. Generally, two main groups of technologies can be distinguished: intensive and extensive.

The first group is based on accelerating treatment processes, which is done by introducing more energy into the treatment system. This group include conventional activated sludge (CAS) systems, where energy is used to aerate and return or keeping the sludge in the reactor (Arceivala and Asolekar, 2007). More advanced on-site greywater treatment technologies that currently exist include sequencing batch reactor (SBR), fixed film reactors, and highly automated and energy intensive systems involving biological, chemical and physical treatment mechanisms, such as membrane bioreactors (MBR) or rotating biological contactors (RBCs) and biological aerated filters (BAF) (Atanasova et al., 2017; Arceivala and Asolekar, 2007; Von Sperling, 2007).

Extensive technologies, the second group, refer to NBS, which take advantage of natural processes with minimal inputs of energy and chemicals for their intensification (Boano et al., 2020). The European

Commission defines them as cost-effective solutions supported and inspired by nature, which at the same time provide environmental, economic, and social benefits. Different NBS have been implemented for greywater treatment, including constructed wetlands. Other representatives are green roofs, green walls and urban green spaces like parks and street trees.

3.1.2 Intensive technologies

3.1.2.1 Sequencing batch reactor (SBR)

SBR technology works on the principle of biological treatment with the action of activated sludge, but in contrast with CAS systems, it has intermittent flow and operation. It consists in the incorporation of all units, processes, and operations, which are basically associated to CAS, such as primary sedimentation, biological oxidation and secondary sedimentation, within a single tank. All the treatment stages occur in a complete-mix reactor by means of operating cycles with defined duration. This technology is appropriate for the removal of conventional parameters in small communities and shows considerable operation flexibility for the removal of nutrients (Ghaitidak and Yadav, 2013).

Moreover, the biological mass remains in the reactor, thus, there is no need for separate sedimentation and sludge pumping. The biomass is not withdrawn with the final effluent (supernatant) after the sedimentation but stays in the tank. Typically, the treatment process consists of the following five stages (Von Sperling, 2007):

- Inflow (introduction of the influent into the reactor).
- React (aeration/mixing of the liquid/biomass within the reactor).
- Clarify (sedimentation and separation of suspended solids from the treated sewage).
- Discharge (removal of the treated effluent (supernatant) from the reactor).
- Standby (cycle adjustment and excess sludge removal).

Each stage may have different duration depending on the influent flow variations as well as treatment needs and the sewage and biomass characteristics. The removal of excess sludge normally happens during the last stage, which allows to regulate the stages in the operating cycle of each reactor. In fact, if the greywater is flowing continuously to the plant, more than one reactor is necessary to guarantee the right treatment because only the tank in the first step can receive the incoming sewage. Similarly to CAS flow processes, the quantity and frequency of the sludge, which needs to be removed, depends on performance requirements (Von Sperling, 2007).

3.1.2.2 Membrane bioreactors (MBR)

MBR technology for wastewater treatment combine treatment with activated sludge and membrane separation. The reactor operates similarly to CAS treatment process, but without the need for secondary clarification or tertiary treatment. In fact, it avoids the need of a final filtration step and/or a disinfection step to meet the non-potable reuse standards (Li et al., 2009). The biological treatment is combined with microfiltration (MF) or ultrafiltration (UF) systems using membranes, which are made of semi-permeable materials designed to separate particulate, dissolved, and colloidal substances from liquid solutes. Membranes are typically built-up in four configurations: tubular, plate and frame, spiral wound, and hollow fibre; their replacement is generally required every 3-5 years (Arceivala and Asolekar, 2007).

MBR appears to be very attractive as a technical solution for grey water recycling, especially in collective urban residential buildings with more than 500 inhabitants (Li et al., 2009). The main advantages compared to other technologies are characterised by excellent and stable effluent quality, high organic loading rate, compact structure and low excess sludge production. Nevertheless, there are also some disadvantages including relatively expensive installation and operation, continuous monitoring and frequent maintenance of membranes, and limitations on membrane pressure, temperature, and pH (Yoon, 2015; Blatnik, 2021). General removal efficiencies for MBR can be seen in Table 9.

MBR based greywater reuse involves relatively high costs of the technology and of the greywater separation system. Compared to other small scale biological treatments MBR turns out to be more expensive. Fountoulakis et al. (2016) found out that MBR applied to single household systems requires a water price of at least 10 EUR/m^3 to become feasible. Friedler and Hadari (2006) studied the feasibility of MBR and greywater piping for multi storey buildings. They demonstrated that this technology is economically unrealistic because it becomes feasible when the building size exceeded 37 storeys (148 flats). When several buildings are incorporated together, cluster MBR based systems become feasible when the cluster size comprehends four buildings, each 10 storeys high. Smaller systems would require small subsidies to become feasible. Especially in small size ranges, the payback period largely depends on the building size and on the price of water (Friedler and Hadari, 2006).

In line with Li et al. (2009), Atanasova et al. (2017) confirmed that MBR technology is very promising for medium and high strength greywater recycling, particularly in densely urbanised areas and touristic facilities. They implemented a pilot MBR to a hotel in Loret de Mar (Spain), which was treating greywater for toilet flushing. Experimental data that have been collected for six months have proved that MBR handled well the high variability of the greywater quality. Spanish standards for water reuse were easily achieved except for small microbiological contamination, where minor disinfection was required. Anyway, the results confirmed the usefulness of such a system because a hotel, which produces on average 30 m^3/day of greywater, can yearly save up to 10,000 m^3 of fresh water for toilet flushing. According to the economical evaluation made by Atanasova et al. (2017) the entire MBR based greywater reuse system becomes feasible already for sizes from 5 m^3/day (60 PE) with a payback period of 7 years.

Table 9: Removal efficiencies achieved by MBR systems (Boano et al., 2020; Ghaitidak and Yadav, 2013)

Parameter	**Removal efficiency [%]**
Turbidity	98-99.9
TSS	100
BOD_5	93-97
COD	86-99
TN	52-63
NH_4^+ -N	6-72
TP	19
PO_4^{3-} -P	10-40
Faecal coliforms (*FC*)	99.9 (3 log)

Tank size

Determining the volume of the biological reactor can follow comparable criteria to those used for CAS. However, it is essential to account for the primary process distinctions between MBR and CAS:

- varied kinetic and stoichiometric constants due to distinct growth and decay mechanisms present in each reactor type;
- different applicable operating parameters, including biomass concentrations and sludge age;
- addition of the filtration effect exerted by the membrane on the aerated mixture. This filtration enables complete elimination of the particulate fraction of the substrate and partial removal of the dissolved fraction.

The tank size can be obtained by reordering the equation for sludge concentration in the reactor, which was presented by Wen et al. (1999). Therefore, the tank size expressed in cubic meters can be taken from the equation (1), while the involved parameters can be seen in Table 10.

$$V = \frac{QY\theta_x(C_i - C_e)}{X(1 + k_e\theta_x) - Y\left(C_i - C_{sup}\right)} \tag{1}$$

Then, if assuming a *COD* removal of 85% in the bioreactor and a removal of 12% done by membrane separation, the equation (1) simplifies to (2), because C_{sup}becomes 0.15 C_i and C_e is equal to 0.03 C_i.

$$V = \frac{QY\theta_x\ 0.97C_i}{X(1 + k_e\theta_x) - 0.15YC_i} \tag{2}$$

Table 10: Design parameters for MBR design (Atanasova et al., 2017)

Parameter	**Unit**	**Description**
Q	m^3/day	Flow rate
Ci	g/m^3 (mg/L)	Inflow COD concentration
Ce	g/m^3 (mg/L)	Outflow COD concentration
Csup	g/m^3 (mg/L)	Biomass supernatant COD concentration
Θx	day	Sludge retention time
Y	kg VSS/kg COD	Biomass yield
k_e	1/day	Endogenous decay coefficient
X	g VSS/m^3	Mixed liquor suspended solids (MLSS), biomass concentration
Ni	g/m^3 (mg/L)	Inflow TKN concentration
Ne	g/m^3 (mg/L)	Outflow TKN concentration
λ	gCOD/gMLSS	COD/MLSS; COD assimilated in excess biosolids
i_{xb}	gN/gCOD	TKN content in biosolids: (MLSS expressed as COD)
i_{xb}	gN/gMLSS	
J	LMH	Net membrane flux
SADm	m^3/m^2/h	Specific aeration demand per m^2 of membrane area

Oxygen demand for organic matter and ammonia oxidation

Biological wastewater treatment requires oxygen principally for the satisfaction of carbonaceous and nitrogenous oxygen demands, even though in activated sludge processes a slight amount may be used for the oxidation of inorganic ions, such as manganese ions, ferrous ions, and sulphides. Oxygen consumption depends on the oxidation of the organic matter, which is mainly performed by aerobic heterotrophic bacteria. In aerobic conditions the organic matter is thus converted by these microorganisms into water and carbon dioxide. As a result of the oxidation, there is also an increase in biomass. The chemoautotrophs, on the other hand, can convert ammonia into nitrate using carbon dioxide as a carbon source. Instead of nitrification, which happens in aerobic conditions, in absence of oxygen the nitrate is reduced to nitrogen gas in the process of denitrification. However, excess sludge contains both autotrophs and heterotrophs, but since the first have a slower grow rate, it is expected to have less than 10% of autotrophs in the total biomass (Yoon, 2015).

Carbonaceous O_2 demand and nitrogenous O_2 demand represent two main components that contribute to oxygen demand. The first one is calculated as the difference between the amount of *COD*, which is removed from the raw wastewater, and the *COD* assimilated in excess sludge (equation (3), Table 10). The value of λ for MBR can be assumed as 1.1, while in CAS technology it tends to be slightly higher, between 1.1 and 1.2 (Yoon, 2015).

$$O_{2,carbon} = Q(C_i - C_e) - \lambda YQ(C_i - C_e) \tag{3}$$

The nitrogenous O_2 consumption can be determined by multiplying the rate of the Total Kjeldahl nitrogen (TKN) oxidation, which is used as a measure of nitrogen content instead of total nitrogen, by the factor 4.57, as shown in equation (4).

$$O_{2,nitrogen} = 4.57[Q(N_i - N_e) - i_{XB}YQ(C_i - C_e)] \tag{4}$$

Based on Yoon's research (2015) it is recommended to use for i_{xb} the value 0.086 gN/g *COD*, which is also equal to 0.095 gN/g MLSS. Thereafter it is possible to calculate the total O_2 consumption rate, which comprehends, besides the two components presented above, also the oxygen credit from denitrification (Yoon, 2015). The latter must be considered only in the presence of anoxic conditions in the reactor. Then, the specific oxygen demand (SOD) measured in kg O_2/m^3 is obtained by dividing the $O_{2,total}$ by the wastewater flow rate as follows:

$$SOD = \frac{O_{2,total}}{Q} \tag{5}$$

Membrane area

The design of the membrane area requires to fix the maximum permeate flow in LMH. The latter strongly depends on the type of membrane and on the configuration of the system. The selection is not straightforward because the design flux for membranes must be chosen not too low (high overall surfaces of the membranes and therefore high installation costs for membrane modules), and not too high (high fouling of the membranes and excessive cleaning frequency of the membranes). It must be noted that progressive fouling of the membrane requires the alternation of membrane feeding cycles with physical and/or chemical cleaning cycles.

Moreover, two additional parameters are crucial for the determination of the membrane area, i.e., critical flux and sustainable flux. The first one is defined as that value of the flow, below which the fouling phenomena do not develop and therefore do not cause flow decreases or the increase of transmembrane pressure (TMP) over time. When TMP (despite backwashing) reaches approximately 200 mbar, chemical cleaning is required (Dalmau et al., 2015). In fact, for MBR systems it is more correct to speak of sustainable flux, which is defined as that optimal value of permeate flow to be extracted to minimize chemical cleaning interventions and thus extend the life of the membrane (Viviani, 2013). According to Viviani (2013), the design value for the sustainable flux can be set equal to 80% of the critical flux, which is usually indicated by the manufacturers of membrane modules and assumes values of about 20-50 LMH.

At this point, the membrane area A_m can be easily obtained as the ratio between the maximum feeding flow rate (Q) and the sustainable flux (J), as shown in the following equation:

$$A_m = \frac{Q}{J} \tag{6}$$

Starting from the value of A_m, depending on the type and on the model of membrane adopted, the number of modules required for the system can be successively evaluated.

Aeration of the membranes

Sizing an air scouring system represent a crucial technical challenge in MBR technology. Its purpose consists into limit the membrane fouling phenomena and maintain complete mixing conditions in the reactor. The airflow rate in the reactor must be uniform so that localised membrane fouling can not happen. These kinds of objectives can be achieved by creating a double aeration system with two types of air diffusers: the ones with small pore sizes, which are suitable for the oxygen transfer into water, and the coarse bubble diffusers, which are appropriate for cleaning the membranes (Viviani, 2013).

The determination of the airflow rate for membrane scouring requires the introduction of the specific air demand (SAD). It can be defined in two ways: as SAD per membrane surface area (SAD_m) or SAD per permeate volume (SAD_p). Thus, the scouring airflow (Q_{air}) can be easily calculated by multiplying SAD_m and membrane area, as shown in equation (7).

$$Q_{air} = SAD_m \cdot A_m \tag{7}$$

Moreover, SAD_m depends on membrane configuration and module compactness, while SAD_p is an indicator of the aeration efficiency and an approximate measure for energy efficiency. Both parameters are usually recommended by membrane manufacturers.

Blower power

Air blowers can be classified as either centrifugal blowers or positive displacement blowers. The latter conveys air from the upper inlet port into the stage using two parallel rotary pistons, which are set within a housing also called a conveying chamber. In comparison with centrifugal blowers, these blowers supply constant airflow in a large extent of discharge pressures, but normally require more maintenance and have higher costs. The blowing efficiency depends on the blower type and on the conditions in which they operate (Yoon, 2015).

The air blower power can be calculated based on *SAD_m*, which is utilized as a design factor when calculating the scouring airflow. The equation (8) is valid if assuming quick air compression that permits to maintain intact the internal energy of the blower. Therefore, this leads to an increase in temperature under adiabatic compression conditions. The needed power expressed kW is calculated as follows:

$$P_b = \frac{Q_{air} P_1}{17.4 e_m e_b} \left[\left(\frac{P_2}{P_1} \right)^{0.283} - 1 \right] \quad (8)$$

where:

- e_m is the motor efficiency (–).
- e_b is the blower efficiency (–).
- P_1 is the inlet absolute pressure (kPa).
- P_2 is the outlet absolute pressure (kPa).

Pump

The pump efficiency is determined as the ratio between the power conveyed to the water and the power provided to the pump by the motor. According to Yoon (2015), the efficiencies of centrifugal pumps vary between 75% (for mixed liquor) and 85% (for clean water) under ideal conditions. In field conditions it is expected to have lower overall pump efficiencies. The power of the fluids pump can be calculated considering the differential pressures between pump intake and outtake, and the difference in height between water intake level and the discharge exit. The equation is the following:

$$P_p = \left(\frac{\Delta P}{\rho g} + \frac{v_L^2}{2g} + \Delta \mathrm{h} \right) \frac{\rho g Q_L}{e_m e_p} \quad (9)$$

where:

- P_p: power consumption of the pump (W)
- ρ: liquid density (kg/m)
- g: gravity acceleration (9.8 m/s^2)
- v_L: liquid velocity in pump outlet (m/s)
- ΔP: differential pressure between pump inlet and outlet (Pa)
- Δh: vertical height difference between water intake and discharge (m)
- Q_L: liquid flow rate (m^3/s)

In most cases the velocity head $\left(\frac{v_L^2}{2g}\right)$ is insignificant compared to the pressure head $\left(\frac{\Delta P}{\rho g}\right)$, unless the liquid velocity reaches very high values, which is uncommon for mixed liquor transportation.

3.1.2.3 Rotating biological contactors (RBCs)

Rotating biological contactors represent an attached-growth biological process, where a series of spaced circular discs installed on a horizontal axis rotate slowly through wastewater. The discs are partially submerged in a tank containing the wastewater, so that at each instant around half of the surface is immersed in the sewage and the other part is exposed to the air. This disc rotation helps the attached biomass to absorb organic matter and oxygen from liquid and air respectively. The biomass is thus fixed on the discs (forming a biofilm), which are typically made of low weight plastic like polystyrene or polyvinyl chloride (PVC) (Arceivala and Asolekar, 2007).

In general, the aim of partially submerged RBCs is to remove BOD_5 and to apply carbon oxidation/nitrification of secondary effluents, while completely submerged RBCs also allow denitrification (Boano et al., 2020). This technology has many advantages, such as (Von Sperling, 2007):

- Efficient removal of *BOD*.
- Consistent nitrification.
- Conceptually simpler compared to CAS.
- Straightforward mechanical equipment.
- Reduced potential for unpleasant odours.

On the other hand, there are some disadvantages too, such as (Von Sperling, 2007):

- Inadequate removal efficiency for coliforms.
- Elevated construction and operational expenses.
- Typically recommended for smaller populations to prevent an excessive number of discs.
- Requires protective covers for the discs to shield against rain, wind, and vandalism.
- Relative dependence from the ambient air temperature.

Anyway, the efficiency and the speed of cleaning strongly depend on hydraulic and organic load. According to Ghaitidak and Yadav (2013), RBC systems can efficiently meet reuse standards for non-potable uses, at least with respect to parameters like *pH*, *BOD* and *COD*. Nevertheless, Friedler and Hadari (2006), who analysed the economic feasibility of RBC based systems for on-site greywater reuse in the urban sector, concluded that the RBCs become economically feasible when the building size reach seven storeys (28 flats). To increase the economic feasibility small subsidies should be applied.

3.1.3 Extensive technologies

In contrast to intensive technologies, the use of extensive systems has gained in recent years significant interest due to their low maintenance costs, successful landscape integration and their great environmental, economic, and social sustainability (Matamoros et al., 2016). Typical representatives are soil and plant-based systems like constructed wetlands (CWs) and waste stabilization ponds (WSPs). Beside traditional constructed wetlands, new integrated technologies for greywater treatment and reuse have been implemented, e.g., green walls and green roofs. The green wall technology consists of vegetation that grows directly on a building façade or of vegetation that is cultivated in planter boxes at the base of a building, where the wall or a separate structural system works as a support (Rutar Polanec, 2021).

According to Boano et al. (2020), the most employed NBS/extensive technologies for greywater treatment are CWs, followed by green walls and green roofs. However, it's important to note that both green walls and green roofs can be viewed as altered versions of conventional CW systems. All these systems operate on a fundamental principle: integrating biological, chemical, and physical processes within porous media, amplified by the presence of plants and microorganisms. The strong interaction between plants, substrate, biofilms, atmosphere, and nutrients from greywater characterises the treatment efficiency of these systems. The interaction between roots, substrate, and biofilm promotes various essential mechanisms for the removal of pollutants and pathogens. These include physical processes like sedimentation and filtration, chemical processes such as precipitation and adsorption, and biological processes like microbiological degradation and plant uptake (Boano et al., 2020).

CWs (also called reed beds), based on the reduced energy needs and operational simplicity, are known as a sustainable and low-cost technology for domestic wastewater treatment. Depending on their water surface they are generally divided in two types, i.e.: free water surface type, and submerged/subsurface flow type. The flow direction can be either horizontal or vertical. The horizontal submerged flow type is often used due to its good performance and the possibility to be installed in relatively flat land. It also may prevent mosquito breeding, which is likely for free water surface configurations. Compared to other types, the latter have the highest level of biodiversity (Boano et al., 2020). However, the vertical subsurface flow type is often preferred in steeper slopes, where is no need for pumping. Such configuration is also preferred for larger flows as it is reported to require less land area per person (Arceivala and Asolekar, 2007); more specifically about 1 m^2/PE in cold and temperate climates, and less than 0.5 m^2/PE in warm climates (Masi et al., 2010). In line with Masi et al. (2010), the technical feasibility of CWs to treat greywater has been demonstrated with a removal higher than 91% for BOD_5, 80% for *COD*, 91% for *TSS*, and 60% for *TN* (Estelrich et al., 2021).

3.1.3.1 Green roofs and green walls

Green roof and green wall installation represent two examples of NBS that are very appropriate in densely built urban areas. In comparison with traditional treatment wetlands, which require large land areas for their construction, green roofs and green walls use blank surface spaces of urban buildings and compensate for the lack of space in cities. These applications have many advantages starting with the ability to counterbalance the effects of climate change in the urban environments, as well as the better managing of the water cycle from the household level on (Cross et al., 2021). They are starting to be integrated as parts of modern buildings in many countries offering a lot of benefits, such as: building insulation, carbon sequestration, mitigation of the UHI effect, acoustic comfort, implementation and/or preservation of urban biodiversity, and phytoremediation of air and water pollutants (Rutar Polanec, 2021; Cross et al., 2021). Moreover, they reduce the energy consumption for air conditioning, improve the thermal performance of buildings and provide considerable energy savings (Woods Ballard et al., 2015).

When it comes to green walls, the market globally offers many different types. Numerous designs available in the commercial market prioritize aesthetics and are not designed for wastewater treatment; some even add to the consumption of fresh water. Among the various options, only modular and containerized designs are appropriate for greywater treatment. These designs offer a larger medium capacity, enabling the effective removal of specific particulate and dissolved pollutants (Rutar Polanec, 2021). Nevertheless, Rutar Polanec (2021) in her research has established that linear green wall type, which results from cascading elements attached to the wall, is also very adapt for greywater treatment due to its great similarity to treatment wetland and its ability to reproduce the same pollutant removal mechanism.

Generally, vegetated surfaces on rooftops (green roofs) are more expensive than conventional roofs in terms of construction and maintenance. They are made up of a system, where different materials are layered to obtain the desired vegetative cover and drainage qualities (Woods Ballard et al., 2015). Design elements depend on site restrictions and the green roof type, which includes two main categories: extensive and intensive roofs. Both groups basically consist of a waterproof membrane, an insulation layer, and a vegetation layer cultivated in a growing substrate. The main differences are presented in Table 11.

Table 11: Comparison between extensive and intensive green roof systems (Woods Ballard et al., 2015)

<table>
<tr><th></th><th>Extensive green roof</th><th>Intensive green roof</th></tr>
<tr><td>Access</td><td>Not usually accessible</td><td>Accessible as public space or garden</td></tr>
<tr><td>Growing medium</td><td>Thin (20-150 mm)</td><td>Deeper</td></tr>
<tr><td>Irrigation</td><td>Only during plant establishment</td><td>Occasional to frequent</td></tr>
<tr><td>Maintenance</td><td>Minimal to none</td><td>Low to high</td></tr>
<tr><td rowspan="5">Advantages</td><td>Lightweight</td><td>More favourable conditions for plants, leading to greater potential diversity of plants and habitats</td></tr>
<tr><td>Little or no need for irrigation and specialised drainage systems</td><td>Good contribution to thermal performance of the building</td></tr>
<tr><td>Often suitable for retrofits</td><td>Can be made very attractive</td></tr>
<tr><td>Little management of vegetation</td><td>Recreation and amenity benefits</td></tr>
<tr><td>Relatively inexpensive</td><td>Good surface water retention capacity</td></tr>
<tr><td rowspan="4">Disadvantages</td><td>More stressful conditions for plants, leading to lower potential diversity</td><td>Greater loading on roof structure</td></tr>
<tr><td>Limited insulation provision</td><td>Need for irrigation and drainage systems requiring energy, water, materials</td></tr>
<tr><td>Limited surface water retention benefits</td><td rowspan="2">Higher capital and maintenance costs</td></tr>
<tr><td>Limited aesthetic benefits</td></tr>
</table>

When greywater treatment using green roofs and green walls is desired, there are some crucial aspects that must be considered. The choice of plants must be appropriate to local climatic conditions and high survival capacity must be guaranteed. Other factors connected to plants include aesthetic appearance, low weight, good removal capacity of nutrients, and low space for root growth (Boano et al., 2020). Next, volumes and dimensions of green roof/green wall frame and construction are designed to meet the daily hydraulic (m^3/d), biochemical (g BOD/d), and organic load (mg COD/L and mg BOD/L) (Rutar Polanec, 2021).

The efficiency of green wall systems in treating greywater can decline because of a decrease in hydraulic conductivity due to clogging. Substantially, it can occur with a reduction of the filter media porosity in time, or as a result of biomass production and suspended solids growth. Thus, for the avoidance of clogging and overfeeding, parameters like hydraulic retention time (HRT), hydraulic loading rate (HLR), and organic loading rate (OLR) need to be analysed as design criteria. All of them depend on the flow rate and on the treatment filter's area.

In case of wastewater with a high organic load, the HLR should be reduced to avoid a significant reduction in infiltration capacity. The solution could be done by installing a bigger system or by reducing the feeding quantity. Opting for the second choice would mean having a longer HRT and therefore a better treatment performance. As regards the HLR, its optimum value differs based on a variety of factors, such as: filter media, wastewater strength and dosing method. Studies have shown that several feeding periods within the day lead to more homogeneous delivery of wastewater and nutrients to the plants. Applying smaller and more frequent dosages improves the removal efficiency of pathogens and the nitrification. In addition, this type of dosing stimulates the biomass to develop mostly at the surface of the filter causing higher probability of clogging.

On the contrary, applying larger and less frequent quantities of wastewater may cause a rapid transportation of unoxidized material throughout the filter media. Thus, intermittent dosing requires enough time between applications to allow the right infiltration and redistribution and to avoid a completely saturated flow regime. In addition, a reduced wastewater fractioning load tends to produce a more uniform distribution of biofilm development across the bed's depth (Rutar Polanec, 2021).

3.1.4 Measures and requirements for rainwater use

Rainwater can be used without treatment for uses that do not require a high level of water quality, such as flushing toilets, washing clothes, cleaning floors, watering the garden, and washing the car. The roofs must be properly dimensioned so that water flows to the tank and accumulates. As regards rainwater harvesting, care must be taken to divert water from the main storage tank at the beginning of the rainfall event. A common choice for separating water that contains a higher concentration of pollutants is the first flush diverter. There are several different types of diverters, but in general they all operate on the principle that a certain amount of water coming from the roof is collected in a separate tank from the main reservoir, which has usable rainwater. Different methods can be applied to determine the amount of water needed to be flushed away (Doyle, 2008).

Water from rainwater catchment systems, before being used for non-potable purposes, must meet the minimum quality standards that can be seen in Table 12. To achieve those limits, it makes sense to regularly sample water, perform measurements and based on the results, introduce an appropriate water treatment system before use. Moreover, the storage tank, whose openings may need to be protected to prevent the intake of organic matter, must always maintain aerobic conditions.

Table 12: Minimum quality standards for rainwater before its use (Minnesota Administrative Rules, 2022)

Parameter	**Unit**	**Limit**
E. coli	CFU/100mL	2.2
Odour	/	Non-offensive
Temperature	°C	MR*
Colour	/	MR*
pH	/	MR*

*Measured and recorded only

RWH systems can be designed to reach two different levels of service. Firstly, they can be used only for water supply as water conservation systems. In the opposite case, they can be part of a surface water management, where the tanks are sized for an additional storage capacity to manage larger rainfall events (Woods Ballard et al., 2015). RWH systems can be additionally divided into three different types: gravity-based, pumped based and combined. The first type involves the rainwater collection at sufficient hight so that the water can be carried on by gravity. Nevertheless, there are some constraints related to the temperature of the stored water, the limited operating pressure, and to the structural capacity of the building, which needs to be verified due to the additional load caused by stored water at an elevated position.

Pumped and combined systems result to be much more common types, where a header tank is used in combination with a larger storage tank, which is typically placed underground. The hydraulic design of the storage tank is based on different factors including the daily demand for water from the tank, the roof's catchment area, and the local rainfall characteristics throughout the year. According to Woods Ballard et al. (2015), there are different methods to calculate the tank sizes, but each of them requires the following main parameters:

- The design rainfall depth to be collected.
- The local average annual rainfall quantity.
- The building occupancy.
- The daily consumption of non-potable water.

Most collection tanks are made of plastics, steel, or concrete. Anyway, when choosing materials and product types, considerations involving the need for protection from corrosion, service lifespan, installation and maintenance complexity, and aesthetics should be taken into account.

3.2 Solar thermal systems

The solar thermal system is based on the conversion of the sun's rays into heat. The light that reaches the solar collector installed on roofs, gets through a dark-coated plate - the absorber, which is made up of pipes. These pipes contain a heat transfer medium, usually water or an antifreeze liquid, that warms up and flows towards the hot water store. It is worth mentioning that exist also systems, which operate with air that passes inside the collectors, heats up and is then sent into the rooms with the aim of heating them. Moreover, solar thermal systems with a heat transfer fluid can combine domestic hot water heating and thermal energy production for space heating.

The most common type of solar thermal systems is the one for water heating, where the heat transfer fluid that circulates in the collectors, transfers heat to the domestic or service water through a heat exchanger (closed loop systems). There, the cooled fluid flows back to the collector, while the service water rises in the store forming a stratified system. The warmest water at the top leaves the store when the user opens the taps, as the coldest at the bottom enters from the water supply system. Contrarily, in open loop systems, the water that circulates in the collectors is the same that, once the required temperature is reached, reaches the user. In addition, the heat transfer fluid circulation can be classified into natural (thermosiphon or passive systems) or forced (active systems). The difference between them consists in the use of pumps or fans (in presence of air-to-water heat exchangers), which are not required for natural systems.

Natural circulation systems exploit the natural convection to transport the heat transfer fluid present in the collector, which once heated, has a lower density than the fluid present in the rest of the circuit. This difference in density triggers the circulation of the fluid, which rises to the top of the storage tank. The latter must be placed above the solar collector because the collector, which represents the point where the fluid is the hottest, must not coincide with the highest point of the circuit, otherwise the natural circulation does not occur. In these cases, the installation requires larger pipe sizes than normal to minimise friction losses, since the driving force of the circulation constituted by the difference in density is already small (Axaopoulos, 2011). Considering periods of low solar radiation, usually tanks are sized to carry a hot water supply for two days, if a totally cloudy day happens.

The size of solar systems varies according to the most frequent local weather conditions and hot water requirements. The collector's area is mainly determined by the daily hot water demand, which according to Axaopoulos oscillate from 30 to 75 L per person per day. These values strongly depend on individual lifestyle and local customs. For a four-person family, a thermosiphon solar system usually comprehends one or two modules of collectors with an area between 3 and 4 m^2 and a storage tank with a volume between 150 and 180 L. Certainly, this technology permits to keep the components reduced to a minimum because no pumps or control units are required. This also means low installation and maintenance costs. Contrastingly, this kind of systems negatively affect the aesthetic appearance since the tank must necessarily be placed above the collector.

In many circumstances, when it is not possible or it is inopportune to set the storage tank above the collectors, a forced circulation system is used. Therefore, it is necessary to use a circulating pump, which is utilized to transport potable water (direct systems) or a heat transfer fluid (indirect systems). The presence of the pump implicates the employment of a differential thermostat, which starts the pump when the difference in temperature between the fluid in the collector and the fluid in the tank is greater than a preset value (typically 5-10° C). When opting for an indirect system, which includes a non-potable or toxic fluid, it is mandatory to use a double-wall heat exchanger. In general, heat exchangers can either be placed inside the storage tank or at its outside. External heat exchangers stand out for their higher heat transfer capacity and their possibility to charge several stores from one single exchanger. Moreover, there is almost no reduction in performance due to limescale formation. On the other hand, they have higher costs and often require the installation of an additional pump (Earthscan, 2010).

3.2.1 Collectors

The term solar collector indicates a device capable of capturing energy from the sun. Such energy can be converted into thermal energy or, by means of photovoltaic collectors, into electrical energy. The collector, which is the most important component of any solar system, has many different designs and types with different performances and costs depending on its application (Figure 2 and Figure 3). According to the manufacturer's literature it is important to distinguish different definitions of the collector area (Earthscan, 2010):

- The collector area (gross surface area) is calculable as the product of the external dimensions of the collector. It is used to define the roof surface required for mounting.
- The light entry area (aperture area) is equal to the area through which the solar radiation passes to the collector.
- The absorber area (effective collector area) is smaller than the others and is equivalent to the actual absorber panel's area.

Many times, it is crucial to define the reference area, especially when comparing the energy efficiency or performance between different collectors. In compliance with the standard EN 12975, which is related to tests for measuring the performance of collectors, the reference surface is the aperture area. When measuring the energy yield, usually the absorber area is the one to choose as a reference instead.

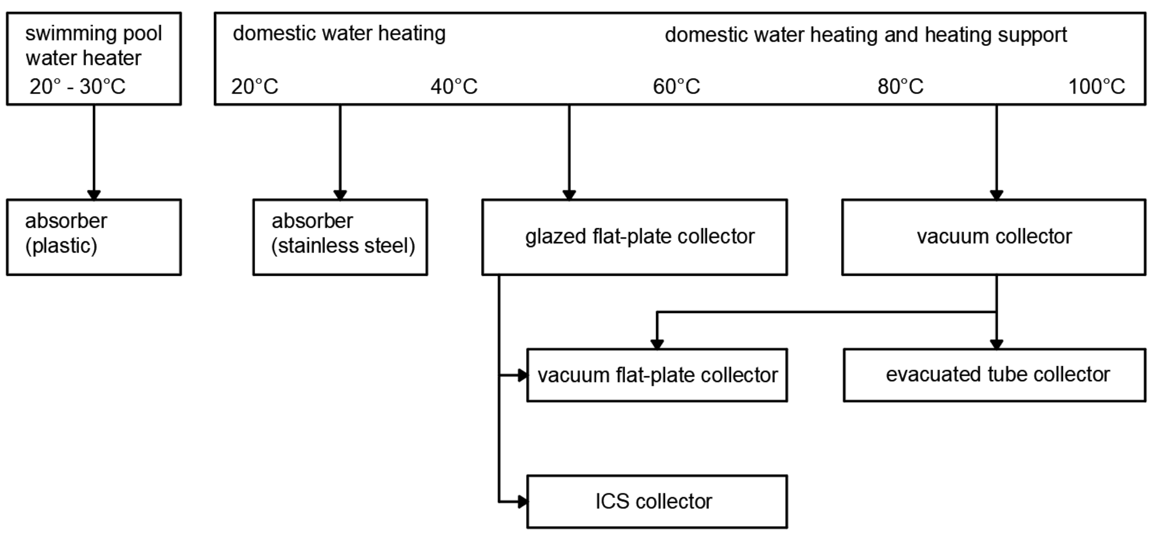


Figure 2: Types of solar thermal collectors (Earthscan, 2010)

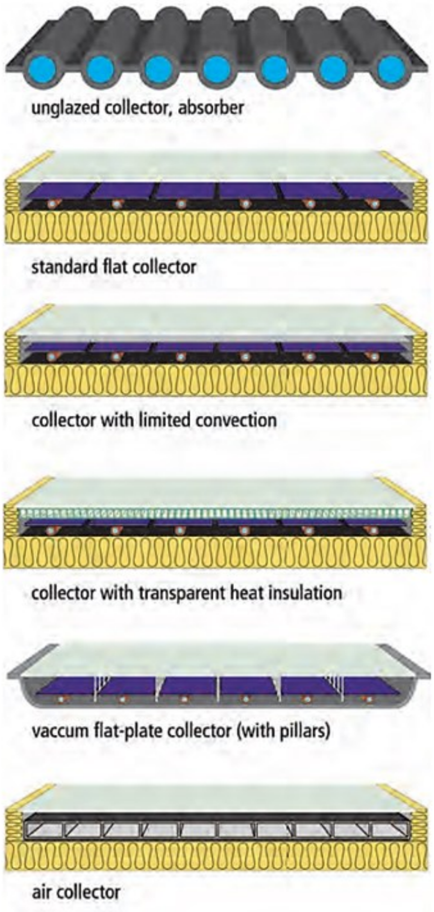


Figure 3: List of collector's designs (Earthscan, 2010)

There are different types of thermal collectors, for example: unglazed, glazed flat-plate, compound parabolic and evacuated tube collectors. Certainly, the simplest ones are the unglazed collectors because they don't have any glazing or an insulated collector box. They are only made up of a wide absorber sheet, which is usually made of plastic, such as polyethylene, polypropylene, and neoprene (Figure 3). These collectors are mainly used for heating of swimming pools or for preheating water in households. In summertime operating conditions when the difference in temperature between the collector and the ambient is small, the efficiency of these collectors can even be better than other more expensive types. Given the low cost and the possibility of satisfying and maintaining, for example for swimming pools, all the temperature needs, they have very short payback times. Moreover, they can be installed on different roof forms from flat ones to curve surfaces.

In cold climates, on the other hand, modest performances are achieved both in terms of efficiencies and the temperatures reached by the heat transfer fluid. In addition to this field-of-use limitation, unglazed collectors need more surface area than glazed collectors to reach similar performances. The rises in temperature are also limited due to higher heat losses.

The most versatile and most widespread type of thermal collectors is the glazed flat-plate. It generally consists of a metal absorber in a flat rectangular casing with one or more glass covers on top and thermal insulation at the back. The latter is used to keep down the conduction heat loss, while the casing is mainly used to maintain the components free from moisture and dust. At the side, there are two tubes for the supply and return of the heat transfer medium from the inlet to the outlet. The absorber plate, because of solar radiation, heats up, transfers heat by conduction to the attached pipes which, by convection, release heat to the heat transfer fluid.

Flat-plate collectors have good efficiency and guarantee the production of hot water with temperatures ranging between 40° and 70° C. But, according to Earthscan, the annual average efficiency of a solar system with glazed flat-plate collectors is only up to 35-40%. With respect to a solar radiation of 1000 kWh/m^2 per year, typical for central Europe (for Italy 1600 kWh/m^2), this stands for an annual energy yield up to 350-400 kWh/m^2. Other strengths and weaknesses are given in Table 13.

Table 13: Advantages and disadvantages of glazed flat-plate collectors (Earthscan, 2010)

Advantages	**Disadvantages**
Cheaper than vacuum collector	Lower efficiency than vacuum collectors
Multiple mounting options	Necessity of a supporting system in flat roofs
Good price/performance ratio	Not suitable for heat generation at high temperatures
Self-assembly possibility	More roof space than vacuum collectors required

To drastically reduce heat losses due to convection between the absorber plate and the cover, experts have decided to create a vacuum between them. The vacuum collectors are made in such a way that the gap between the absorber plate and the transparent cover is almost devoid of air. The volume enclosed in glass cylinders must be evacuated at least to less than 1 kPa (10-2 bar), usually even down to 10-5 bar to prevent losses due to thermal conduction. The collectors are made by several vacuum tubes placed side by side, which are connected and linked at the top by means of an insulated collector box or distributor, in which the supply or return lines are fitted. The tubes are fixed at the lower end to a support. The absorber is installed inside each tube and despite reaching temperatures above 120° C, the glass tube remains at ambient temperature.

In vacuum collectors, the transfer of heat from the absorber plate to the fluid can take place in two different ways based on the exchange that occurs between the fluid that flows along the tubes inside the vacuum areas and the fluid that transports the heat to the user. There it is possible to distinguish two different sorts of evacuated tube collectors: the direct flow-through type and the heat-pipe type (Earthscan, 2010). The first type of tube collectors can be installed either in a vertical position, for example on building's facades, or mounted on flat roofs. In the second type, the heat transfer from the absorber to the heat transfer fluid takes place thanks to another heat exchange mechanism. In particular, the fluid contained in the thin vacuum pipes evaporates by absorbing the heat supplied by solar energy and then releases it by condensing in a special heat exchanger (condenser). Heat-pipe evacuated tube collectors are provided in two versions, one with a dry and one with a wet connection.

Evacuated tube collectors have clearly their advantages and disadvantages, some of them are presented in Table 14. As regards numerical values, the annual efficiency of a complete system with these collectors ranges around 45-50%. Thus, the corresponding energy yield is higher compared to the glazed flat-plate type.

Table 14: Advantages and disadvantages of evacuated tube collectors (Earthscan, 2010)

Advantages	Disadvantages
High efficiency even with large temperature differences between absorber and surroundings	More expensive than a glazed flat-plate collector
More effective support to space heating applications than flat-plate collectors	No horizontal installation for heat-pipe systems (inclination of at least 25° required)
Easily transportable, can be assembled on site	

3.2.2 Sizing of systems for domestic water heating

In temperate climates, when dimensioning a solar system for domestic water heating, a usual design goal is to guarantee the coverage of about 80% of the hot water demand during the year. That leads to economic saves, extended heating boiler's life span, and environment protection. Of course, an auxiliary heating system must be installed and must provide the necessary heat. As regards tropical climates, the general design objective consists of either a fully coverage of hot water demand, or an almost full coverage completed with a back-up heater, which gets into use when needed, only for a few weeks or months per year.

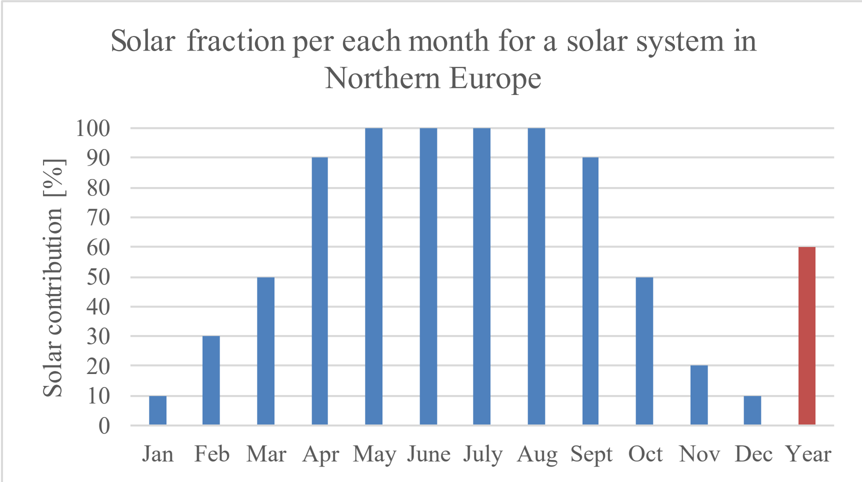
3.2.3 Solar fraction, system efficiency and hot water heat requirement

The ratio between the solar heat yield (Q_S) and the total energy requirement for hot water heating represents the solar fraction (*SF*), which is calculable as follows:

$$SF = \frac{Q_S}{Q_S + Q_{aux}} 100 \tag{10}$$

where Q_{uax} is the auxiliary heating requirement expressed in kWh. In solar energy systems, the higher the solar fraction, the lower is the quantity of fossil energy used for auxiliary heating. Graph 1 shows solar fractions per month for a solar thermal system typical for Northern Europe. It can be noted that the average annual solar fraction reached by the system is 60%.

Interestingly, when a system is designed, for example, to cover almost the total hot water demand in the summer, the addition of extra collectors would not correspond to a higher output. When high levels of irradiation take place, the system would cause excess heat that would lead to high thermal loads on the collectors (causing stagnation) and to a lower efficiency because additional costs would be higher than additional yield. At the opposite, when periods with lower irradiation occur, the current output would be higher, but the annual total output per square metre would be lower than the one with the original system.



Graph 1: Monthly solar fractions in temperate climates (Earthscan, 2010)

The system efficiency (*SE*) represents the ratio between the solar heat yield and the global solar irradiance on the absorber area with respect to a reference time that can be a year:

$$SE = \frac{Qs'}{E_G A}100 \tag{11}$$

where Qs' is the yearly solar heat yield (kWh/a), E_G is the yearly solar irradiance per square metre (kWh/m^{2}a) and A is the absorber area (m^2). The system efficiency strongly depends on the solar fraction because it increases at the lowering of the latter. This happens when the hot water demand is bigger compared to the size of the solar water heater. When the solar fraction starts to increase by expanding the collector area, the system efficiency gets lower, and further energy gain becomes more and more expensive. This can be seen in Figure 4.

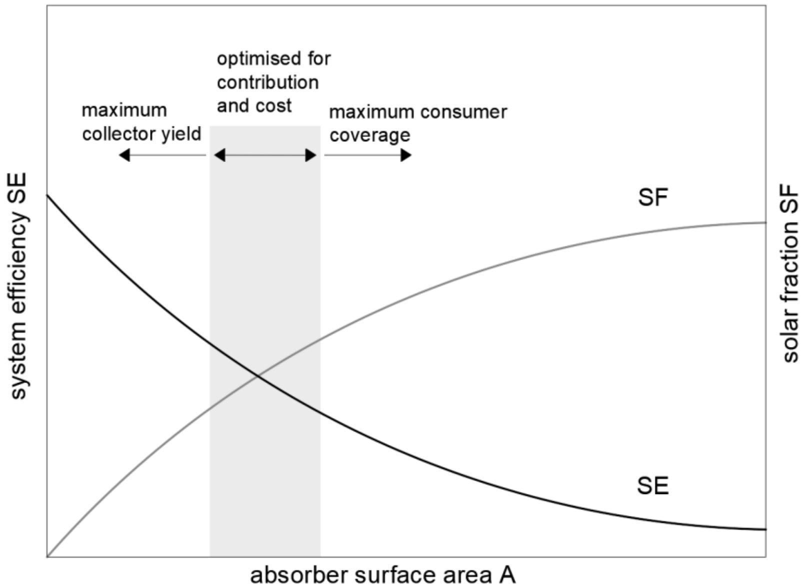


Figure 4: Dependence between solar fraction and system efficiency (Earthscan, 2010)

The hot water heat requirement can be obtained knowing the hot water consumption and using the following equation:

$$Q_{HW} = V_{HW}\, c_W\, \Delta\theta \qquad (12)$$

where V_{HW} is the average daily amount of hot water (kg), c_W represents the specific heat capacity of water (1.162 Wh/kgK), and $\Delta\theta$ is the difference in temperature between hot and cold water (K). The hot water consumption is a key variable for the design of systems for domestic water heating and it should be estimated as accurately as possible considering also the information given in Chapter 2.1 about water consumption in households and touristic facilities.

According to Hervás-Blasco et al. (2020), who collected daily mean greywater temperatures coming from 20 dwellings for a one-year period, the hot water represents around 60% of the total greywater quantity. Moreover, for the determination of the hot water consumption for one- and two-family houses, the following table can be used:

Table 15: Average values for the determination of the hot water consumption (Earthscan, 2010)

Hot water use	**Quantity [L]**
1x hand washing (40°C)	3
1x showering (40°C)	35
1x bathing (40°C)	120
1x hair washing	9
1x dishwashing (50°C)	20
1x washing machine (50°C)	30
Cleaning	3 per person per day
Cooking	2 per person per day

As individual differences are huge, Earthscan (2010) advances three levels of hot water consumption per person per day (considering Table 15 and a usage temperature of water round about 45°C):

- Low consumption (20-30L)
- Average consumption (30-50L)
- High consumption (50-70L)

3.2.4 Annual average method

One shortcut method for solar thermal systems sizing, which is easy to use and provides acceptable estimates of thermal performance, is the annual average method. Its sizing is based on the efficiency of solar collectors, which depends on several factors. These can be included into three main groups:

- external conditions (air temperature and incident solar radiation);
- operating conditions (inlet fluid's temperature or its average temperature);
- construction features (optical properties, overall heat loss coefficient).

The technical datasheets provided by manufacturers are equipped with instantaneous efficiency curves, which represent the performance identity card of solar collectors. With them, knowing the external and operating conditions as input data, it is possible to compute the efficiency of the capturing system. The simplest way to express the collector's efficiency is to use a linear function as follows:

$$\eta = a + b\, P \qquad (13)$$

where a and b are two constants provided by the manufacturer and P represents a parameter defined as:

$$P = \frac{\bar{T}_m - \bar{T}_a}{\bar{G}_c} \tag{14}$$

where $\bar{T}_m$ is the average fluid temperature in the solar collectors, $\bar{T}_a$ is the average temperature of the external air and $\bar{G}_c$ is the average solar irradiation (W/m^2). Thereafter, it is possible to calculate the monthly average daily radiation captured by the solar collector:

$$\bar{E}_{cgi} = \eta\, \bar{E} \tag{15}$$

where $\bar{E}$ is the global solar radiation incident on a sloped surface (Wh/m^2). The captured energy in the i-th month per unit of surface area ($\bar{E}_{ci}$) can be then determined by multiplying $\bar{E}_{cgi}$ with the number of days in the i-th month. To obtain the annual captured energy (E_c) it is only necessary to add up the twelve months. The surface of collectors (A_c) can be found by dividing the required annual energy for domestic hot water production (E_r) with the annual captured energy.

Moreover, to guarantee a good efficiency of the solar plant, the annual solar fraction must be around the value of 0.8. To calculate that, the available ($\bar{E}_{di}$) and auxiliary ($\bar{E}_{in}$) energy per month must be determined using the following equations:

$$\bar{E}_{di} = \bar{E}_{ci}\, A_c \tag{16}$$

$$\bar{E}_{in\,i} = \bar{E}_{ri} - \bar{E}_{di} \tag{17}$$

Based on that, the monthly solar fraction (f_i) is expressed as follows:

$$f_i = \frac{\bar{E}_{ri} - \bar{E}_{in\,i}}{\bar{E}_{ri}} \tag{18}$$

and the annual solar fraction can be determined using equation (19):

$$F = \frac{\sum_{i=1}^{12} f_i\, \bar{E}_{ri}}{\sum_{i=1}^{12} \bar{E}_{ri}} \tag{19}$$

3.2.5 F-Chart method

Both active and passive solar thermal collectors can be designed by means of the f-chart method, which is considered to be the most popular method for its simplicity, user-friendliness, and precision. This method, originally developed in 1976 by Klein, Beckman, and Duffie, is used to estimate the annual thermal performance of either water or space heating systems in buildings, where the minimum temperature of energy delivery is around 20 °C (Axaopoulos, 2011). Moreover, the f-chart method can provide, for a specific solar thermal system, the fraction of the total heating load that is supplied by solar energy. The results are expressed as a function of two dimensionless variables X and Y that represent the ratio of collector losses to heating loads and the ratio of absorbed solar radiation to heating loads respectively (Rosli et al., 2019).

The primary design variable that is used as an input for f-charts is the collector area, which should be taken relatively small as a first attempt value, and then gradually increased until the solar fraction values come around 0.8 (system's good efficiency guaranteed). Figure 5 shows the methodology to obtain the collector area that correspond to the most efficient solar collector.

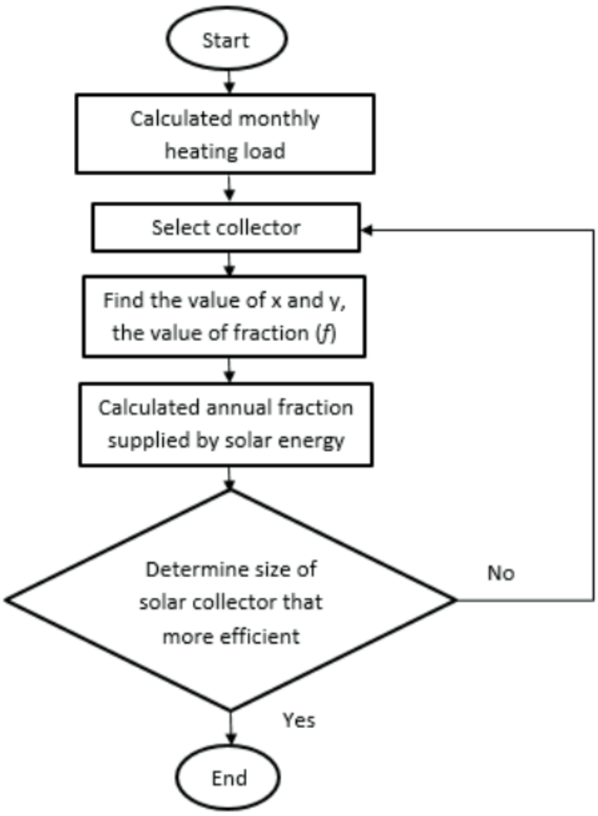


Figure 5: The methodology for the determination of the most efficient solar collector (Rosli et al., 2019)

Firstly, the methodology requires to calculate the total monthly heating load (L) given in Joules, which can be obtained by multiplying the equation (12) by the number of days in the month (N). The dimensionless variable X can be later calculated as follows:

$$X = F_R U_C \frac{F'_R}{F_R} \left(T_{ref} - T_a\right) \Delta t \frac{A_C}{L} \tag{20}$$

where:

- F_R represents the ratio between the power taken from the fluid flow rate and the power that would be drawn from it if the plate would have a uniform temperature equal to that of the fluid inlet,
- U_C is the collector overall loss coefficient (W/m^2 °C),
- $\frac{F'_R}{F_R}$ is the collector heat exchanger correction factor (-),
- T_{ref} is the reference temperature, which is derived empirically (100 °C),
- T_a is the average monthly ambient temperature (°C),
- Δt is the number of seconds in a month, and
- A_C is the collector area (m^2).

The other dimensionless variable Y can be calculated as shown in equation (21):

$$Y = F_R(\tau\alpha_{\mathrm{n}}) \frac{F'_R}{F_R} \frac{(\tau\alpha)}{(\tau\alpha_{\mathrm{n}})} H_T \, \mathrm{N} \, \frac{A_C}{L} \tag{21}$$

where:

- $\tau\alpha_{\mathrm{n}}$ represents the transmittance-absorptance product at normal incidence (-),
- $\frac{(\tau\alpha)}{(\tau\alpha_{\mathrm{n}})}$ represents the ratio of the monthly average to normal incidence transmittance-absorptance product (-),
- H_T is the average daily radiation incident on the collector surface unit area in a month (J/m^2),
- N are the days in a month.

It must be noted that these calculations require some parameters that are specific for each collector's type. They can be measured during standard collector tests or taken from technical sheets supplied by manufacturers. Such is the case for the thermal performance curve slope $F_R U_L$ (W m^2/°C), intercept $F_R(\tau\alpha_{\mathrm{n}})$ (%), and the ratios given by $\frac{(\tau\alpha)}{(\tau\alpha_{\mathrm{n}})}$ and $\frac{F'_R}{F_R}$ (Rosli et al., 2019).

The monthly fraction of the load that can be supplied by solar energy (f) can be determined from the following equation (22) using X and Y:

$$f = 1.029Y - 0.065X - 0.245Y^2 + 0.0018X^2 + 0.0215Y^3 \tag{22}$$

Thereupon, the following equation can be used to calculate the annual solar fraction (F):

$$F = \frac{\sum f_i \, L_i}{\sum L_i} \tag{23}$$

where L_i represents the total heating load for each month and the summation refers to the months in which the system is used.

4 EVALUATION OF THE IMPACT OF MEASURES ON A TOURISTIC FACILITY: HOTEL SALINERA, SLOVENIA

The selected touristic facility Hotel Salinera is located in a coastal Slovenian town called Strunjan, between Izola and Piran. The pleasant natural conditions with Mediterranean climate and a leeward position, attract tourists, who mostly wish a relaxing and calm vacation. The average annual rainfall is about 1000 mm, and the average sunrise-to-sunset duration is around 2346 hours per year. The hotel comprises a total of 101 bedrooms, with 53 of them being four-star rooms and 48 being three-stars rooms. All of them have bathrooms, which are equipped with showers. As a result, the hotel has the capacity to accommodate a maximum of 259 guests per night. Moreover, it offers a range of amenities, including indoor and outdoor pools filled with sea water, a wellness centre, a restaurant, a park, and the direct access to both the beach and the beach bar. The hotel has large green surfaces of 4 ha, which are regularly irrigated with potable water. The hotel operates all year round.

Current management of water and energy fluxes in the hotel follows conventional practices. Drinking water is sourced from the public water system, with an average consumption of 63 m^3 per day throughout the year, including water for irrigation. The daily average greywater amounts to 31 m^3, contributing significantly to an annual total of 11,312 m^3, which represents 49% of the hotel's overall water consumption.

The hotel's energy consumption is significantly influenced by its heating and hot water system. To meet these needs, the hotel employs a heat pump that operates on the water-to-water principle, leveraging the temperature differential between seawater and tap water. During the winter months, this heat pump plays a dual role by providing warmth for both water and indoor spaces. In contrast, during the summer months, it is used for cooling spaces. When this process occurs, the hotel relies on oil as an energy source to heat domestic water. As per data provided by the tourist facility, the average monthly consumption of the heat pump is around 20 MWh, with peaks exceeding 40 MWh in some cases. Additionally, during the summer months of 2022, the consumption of oil amounts to 8,172 L.

In this chapter, various measures are designed and evaluated to optimize water and energy fluxes in the hotel. For water, two alternatives are proposed to separate and treat greywater from all hotel bedrooms. The first alternative involves installing an MBR as a compact greywater treatment solution, while the second alternative incorporates a constructed wetland with subsurface water flow. The latter option necessitates a significant operational area, which is available due to the hotel's approximately 4-hectare green areas. The treated greywater is collected and utilized for irrigation of hotel's green spaces in summer months, which are significant water consumers, and as service water during autumn and winter.

The intensive MBR technology with ultrafiltration doesn't require additional disinfection of recycled water, making it safe for immediate use for non-potable purposes. Moreover, it meets industrial water reuse requirements, allowing it to be used for cleaning both indoor and outdoor surfaces, such as hotel rooms, corridors, parking areas, and other impervious surfaces.

On the other hand, the constructed wetland is chosen as a representative of extensive technologies and is preferred over a green wall because of its ability to integrate very well with the hotel's park and landscape. Moreover, as the hotel produces big amounts of greywater, a large green wall system would be needed for its treating. This would acutely affect the appearance of the building whether it would be placed on an internal wall or as a façade. According to the hotel owners, such change may be too drastic.

The transition of energy usage to renewable sources is ensured through the implementation of solar thermal systems. The proposal consists in the integration of a solar thermal system to one of the two greywater reuse measures presented in Chapters 4.2 and 4.3. The project focuses on the sizing of glazed flat-plate solar collectors for DHW production based on the annual average method and the F-chart method. When sizing such a system, special care must be taken to control boundary conditions given by the building in terms of available space for installation. Besides the ideal sizing of the solar system, which would guarantee the reach of the right solar fraction throughout the year, the stress is put on a more feasible project proposal, which considers the available roof's space for mounting solar collectors and other system's components starting from the boiler and the expansion vessel. The presented solar thermal plant will be also equipped with an economic feasibility analysis further on.

4.1 Quantification of water and energy fluxes in the hotel

Water consumption in the Hotel Salinera amounts to approximately 19400 m^3/year without considering the water for irrigation. The available data refer to a time span from June 2021 to September 2022. Table 16 presents monthly water consumption in the hotel and the estimated amount for irrigation.

Table 16: Water consumption in Hotel Salinera

Month	**Water consumption without irrigation (m^3/day)**	**Irrigation (m^3/day)**	**Total water consumption (m^3/day)**
June 2021	38,0	30,0	68,0
July 2021	64,1	29,0	93,2
August 2021	77,7	29,0	106,7
September 2021	57,1	30,0	87,1
October 2021	46,7	0,0	46,7
November 2021	46,2	0,0	46,2
December 2021	41,3	0,0	41,3
February 2022	33,5	0,0	33,5
March 2022	44,2	0,0	44,2
April 2022	48,4	0,0	48,4
May 2022	58,1	0,0	58,1
June 2022	65,9	30,0	95,9
July 2022	60,7	29,0	89,7
August 2022	71,6	29,0	100,6
September 2022	43,8	30,0	73,8
Average (m^3/day)	53,2	Needed water for irrigation 3600 m^3/year	
Average annual water consumption (m^3/year)	19404		
Total with irrigation (m^3/year)	23004	Average water consumption with irrigation: 63 m^3/day	

Based on the water consumption data from the hotel, it is possible to analyse the quantity of water consumed by water sinks and showers, which are present in every bedroom of the hotel. Two assumptions are made:

- four toilet flushes per day per guest,
- five litres per flush.

The quantity of water used for flushing is estimated in connection with the number of guests per day, where the daily maximum is 259. Considering the total number of bedrooms, it is possible to define the average greywater consumption per room. Moreover, as can be seen in the table below, the maximum water consumption without considering toilets happens in August in both years (45.3 and 41.3 m^3); its average value reaches 31.0 m^3. Considering only the months for which data is available, the average daily consumption per room is about 307 litres, while the average daily consumption per guest is around 151 litres.

Table 17: Estimation of greywater consumption in Hotel Salinera in Strunjan (Slovenia)

	YEAR 2021											
Months (-)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Guests (no/day)	0	0	0	0	0	259	259	259	259	259	176	132
Flushes (m^3/day)	0	0	0	0	0	5.2	5.2	5.2	5.2	5.2	3.5	2.6
Consumption without WC (m^3/day)	0	0	0	0	0	19.5	36.5	45.3	31.9	27.1	28.4	25.9
Avg. greywater consumption (L/day/room)	0	0	0	0	0	193	361	448	316	268	281	257
Greywater consumption (L/day/guest)	0	0	0	0	0	75	141	175	123	105	161	196
	YEAR 2022											
Months (-)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Guests (no/day)	0	75	150	195	259	259	259	259	259	-	-	-
Flushes (m^3/day)	0.0	1.5	3.0	3.9	5.2	5.2	5.2	5.2	5.2	-	-	-
Consumption without WC (m^3/day)	0.0	21.7	27.6	29.6	35.0	37.6	34.2	41.3	23.3	-	-	-
Avg. greywater consumption (L/day/room)	0	215	273	293	346	373	339	409	230	-	-	-
Greywater consumption (L/day/guest)	0	289	183	152	135	145	132	160	90	-	-	-

The project foresees that the greywater from sinks and showers is conveyed and collected in a greywater tank in the basement of the hotel, which also functions as an equalization unit (see Appendix n.1). It regulates raw greywater inflows and outflows to the selected treatment system and equalizes the greywater temperature and quality. Its capacity of 10 m^3 is about one third of the average daily greywater production from bedrooms' sinks and showers. In this case, the collector is planned to be filled up every half or one third of the day with greywater, which would then immediately go on to the treatment. The influent tank must be designed with an overflow pipe that leads the excess water into the existing sewage system.

Treated greywater will be used entirely for irrigation during summer months. Namely, precipitation in this time of the year is not sufficient to irrigate hotel's green surfaces, and thus, the use of recycled greywater ends up being a very good solution. For example, in the summer period from the 1st of June to the 15th of September 2022 (107 days in total), there were only 11 days with more than 1 mm of precipitations (source: Slovenian Environment Agency). Assuming that at least 1 L/m^2 per day is needed to irrigate these surfaces and considering that six days there was enough rainfall that there was no need to water the next day, 90 days of necessary watering remain. Therefore, for an area of 4 ha, such number of days requires 3600 m^3 of water for the irrigation. When irrigation is not necessary, treated greywater is collected and used as service water. Considering that daily greywater volumes exceeding 30 m^3 will be discharged into the sewage system through an overflow pipe, it is possible to estimate the drinking water savings in the hotel (Table 18).

Table 18: Estimated drinking water savings

Month	*Jun 2021*	*Jul 2021*	*Aug 2021*	*Sep 2021*	*Oct 2021*	*Nov 2021*	*Dec 2021*	*Feb 2022*
Treated GW (m^3/day)	19,5	30,0	30,0	30,0	27,1	28,4	25,9	21,7
Drinking water savings (-)	0,29	0,32	0,28	0,34	0,58	0,62	0,63	0,65
Month	*Mar 2022*	*Apr 2022*	*May 2022*	*Jun 2022*	*Jul 2022*	*Aug 2022*	*Sep 2022*	**Average value (%)**
Treated GW (m^3/day)	27,6	29,6	30,0	30,0	30,0	30,0	23,3	
Drinking water savings (-)	0,62	0,61	0,52	0,31	0,33	0,30	0,32	45

For the proper design of solar thermal systems, the consideration of the design parameter of required energy for DHW production and the quantification of the percentage of the daily hot water volume sourced from greywater are both pivotal factors. These aspects ensure that the system is appropriately sized, optimized, and environmentally sustainable, allowing it to efficiently meet DHW demands while reducing reliance on conventional energy sources and conserving freshwater resources.

To verify the validity of the data published by Hervás-Blasco et al. (2020), who reported that the hot water constitutes about 60% of the total greywater volume (see Chapter 3.2.3), the Italian technical specification UNI/TS 11300-2:2019 is used to define the hot water volume and the hot water heat requirement. According to the latter, the daily water volume to meet the DHW demand can be calculated as follows:

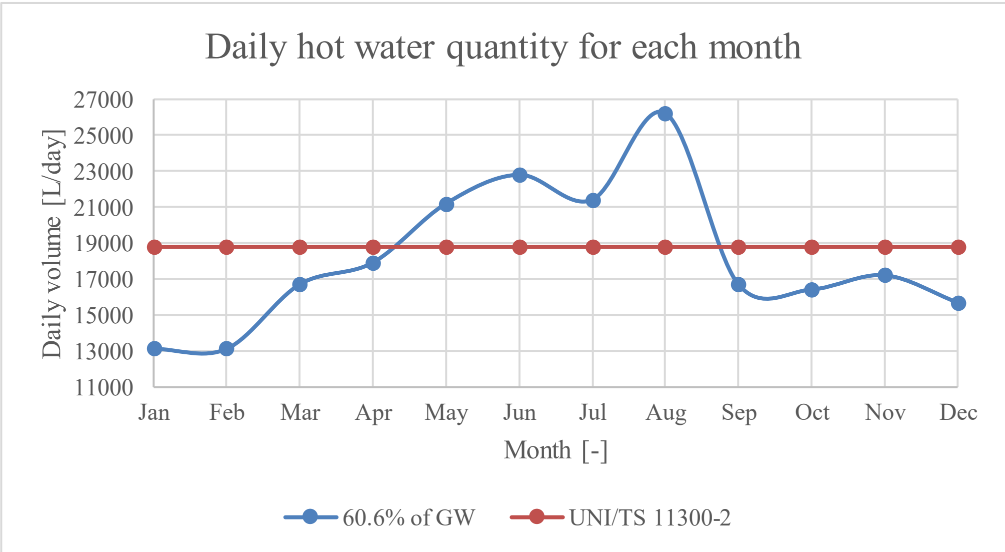
$$V_w = a\, N_u \tag{24}$$

where a is the specific daily requirement in litres and N_u is a variable parameter depending on the type of non-residential building. Their values, which depend on the number of stars of the hotel and the number of beds, are listed in the following table.

Table 19: Values of parameters *a* and *Nu* for some non-residential buildings (UNI, 2019)

Type of non-residential building	***a***	***Nu***
Dormitories, residence, and B&B	40	Number of beds
Hotels up to three stars	60	Number of beds
Hotels up to four stars	80	Number of beds
…	…	…

In this case study, the hotel has 163 beds located in four-star rooms and 96 beds in three-star rooms. Splitting the equation (24) in two parts, the daily volume of hot water results in 18.8 m^3. Thus, considering the temperature of the incoming and outgoing water to be 12 °C and 40 °C respectively, the hot water heat requirement can be calculated using equation (12) and it results in 611.68 kWh per day. This value, multiplied by the number of days in each month, represents the required energy for DHW production E_{ri}. Since it was derived from the Italian technical specification, it is constant every month of the year. Thus, an attempt was made to find a more realistic trend by considering 18.8 m^3 of hot water to be 60.6% of the average daily volume of greywater going from the hotel. Both trends are shown in Graph 2. The blue values indicate the 60.6% of the daily greywater consumption presented in Table 17. Note that, due to missing data, the January value is considered the same as the February value and the June value only refers to June 2022 because the June 2021 value is considered too low. As regards July, August and September, an average between two years was made.



Graph 2: Daily hot water quantity for each month taken from two different procedures

4.2 Design and feasibility of MBR for greywater treatment and reuse

4.2.1 Design of MBR for greywater treatment

The key parameter for the design of both treatment systems is the daily flow rate, which is 30 m^3. All the necessary parameters with their respective values are listed in Table 20. The desired output *COD* concentration of 30 g/m^3 is sufficient to meet the water quality guidelines described in section 2.1.6 (Table 8). In some countries like Italy, Cyprus, and France, that value is well below the limit for greywater reuse, while for WHO's guidelines it represents right the limit value for toilet flushing. Anyway, according to MBR pollutant removal efficiency described in Table 9, such system should eliminate at least 86% of *COD* concentration, which in this case brings a *COD* reduction from 190 mg/L to 26.6 mg/L.

Table 20: Parameters for MBR design

Parameter	Unit	Value	Reference
Q	m^3/day	30	
Ci	g/m^3 (mg/L)	190	Atanasova et al., 2017
Ce	g/m^3 (mg/L)	30	Atanasova et al., 2017
$Csup$	g/m^3 (mg/L)	60	Atanasova et al., 2017
θ_x	Day	22	Atanasova et al., 2017
Y	kg VSS/kg COD	0.3	Fletcher et al., 2007
ke	1/day	0.05	Fletcher et al., 2007
X	g VSS/m^3	3000	Fletcher et al., 2007
Ni	g/m^3 (mg/L)	10	Atanasova et al., 2017
Ne	g/m^3 (mg/L)	6	Atanasova et al., 2017
λ	gCOD/gMLSS	1.1	Yoon, 2015
ixb	gN/gCOD	0.086	Yoon, 2015
ixb	gN/gMLSS	0.095	Yoon, 2015
J	LMH	20	Atanasova et al., 2017
$SADm$	m^3/m^2/h	0.25	Atanasova et al., 2017

Based on the equations presented in section 3.1.2.2 concerning MBR design, specifically from equation (1) to (7), it is possible to determine the biological reactor's volume, the oxygen demand for organic matter and ammonia oxidation, the specific oxygen demand, the required membrane area, and the needed aeration of the membranes. The results are shown in the following table.

Table 21: Results of the MBR design

Volume (m^3)	O_2 carbon (g/day)	O_2 nitrogen (g/day)	O_2 total (g/day)	SOD (g/L)	A_m (m^2)	Qair (m^3/h)
5.80	3216	-18	3198	0.1	62.5	15.6

The MBR treatment system needs for its operation several units that are described in the scheme in Figure 6. Besides the influent tank and the biologic reactor with the membrane compartment included, the plant consists also of a microfiltration unit, a backwash tank, several pumps, blowers and diffusers, and a control cabinet. The proposed placement of the system is shown in Appendix n.1.

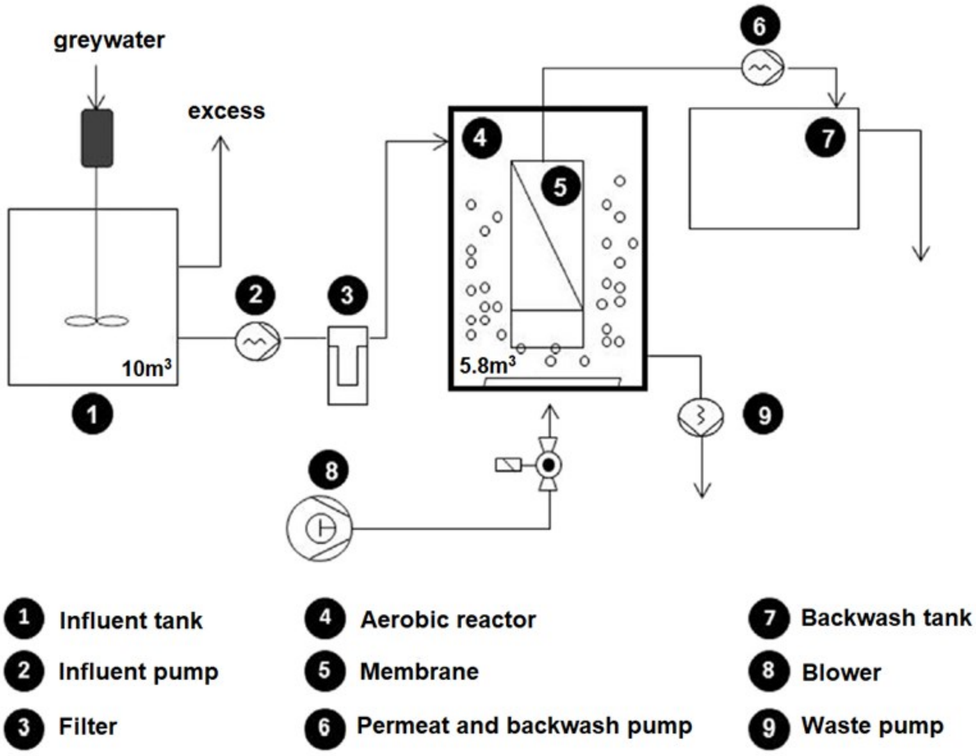


Figure 6: Proposed MBR system plant (adapted from Atanasova et al., 2017)

The proposed plant includes the installation of an immersed ultrafiltration reinforced hollow fibre (UF-HF) membrane with a nominal pore size of 0.02 μm (produced by PCI Membranes company). The membrane is made of Polyvinylidene Difluoride (PVDF), which is an organic polymer that is very robust and flexible. The flow pattern consists in an outside-in configuration, where the feed water passes through the fibres from the outer wall and the permeate is collected in the inside cavity. With respect to the required membrane area (62.5 m^2), it is necessary to mount three modules of 23 m^2.

4.2.2 Feasibility model of the MBR system

The project aims to show the economic feasibility of MBR based greywater reuse system, which includes greywater separation, MBR technology and clean water storage. The evaluation of the feasibility is presented through a model, which involves the design of the MBR based on the daily greywater flow, the size of the greywater separation piping, capital and operational costs, and the payback period of the investment based on water and energy prices in Piran (Slovenia). There, a planning period of 20 years is considered.

The model for cost estimation is created with the assistance of the company CID - Čistilne naprave d.o.o. from Koper (Slovenia), specialized in design, construction, and management of MBR systems. Capital costs (CAPEX) are divided into four main groups:

- GW piping separation.
- Construction works – tank for MBR, influent tank/equalization unit, clean water storage.
- Installation/assembly labour and pipelines.
- Equipment.

The cost of implementing piping separation per bathroom is estimated to be 47% higher compared to the cost outlined in Atanasova et al. (2017) (see Table 22). This increase is attributed to the general rise in prices and the nearly two-fold higher daily greywater consumption per room in the present case.

The consulted company points out that caution is required when estimating the cost of the construction works, as the value is highly dependent on the location, terrain configuration, soil composition, and on tanks' material and configuration. For example, they could be made up from reinforced concrete or reinforced polyester, prefabricated or placed in a container. The latter is a product that contains the entire WWTP. It consists of several components, including the equalization tank with two pumps, rakes for preliminary cleaning, a biological section with membranes for the treatment process. Additionally, there's a reservoir for the treated water with an integrated hydrophore set for the distribution of treated water. The last section of the container functions as a sort of control room with an electrical cabinet housing and blowers underneath, complete with process automation, data transfer capabilities, and dosing pumps for chemicals. All these components are sold as a complete package. However, according to the available data from the company, which are based on their completed projects, construction and craftsmanship costs for MBR systems typically amount to 30 – 35% of the investment value.

The cost of labour for the installation of the intended equipment and all connecting pipelines made of stainless steel and PVC-U plastic (including air extraction from the facility) amounts to approximately 10% of the investment value. Plastic material could be chosen for submerged pipes, while stainless steel could be selected for non-submerged ones. The estimation does not include underground pipelines for draining rainwater (which are not relevant to the project) and pipelines for the discharge of treated water.

The cost assessment of equipment is also highly important. The price of a filter (including installation) for separating larger particles to protect the membranes falls within the range of 9,000 – 12,000 EUR. It is advisable to also add a compactor for filter residues to minimize them as much as possible since the waste cost is calculated based on the weight of the disposed waste. The value of the compactor with waste disposal and a container for waste collection is approximately 6,300 EUR. The purchase and installation of membranes do not differ from the values offered in Fletcher et al. (2007). The price is shown in Table 22.

For safety reasons, it is necessary to include double pumps that operate alternately for all pumps. The system must have two pumps for supplying water from the accumulation tank to the treatment process, pumps for sludge recirculation, pumps for excess sludge removal (screw pumps), and pumps for the permeation of treated water. The total cost for these pumps is 6,500 EUR. This also includes the bases for pump installation, guides for pump extraction from tanks, and chains for submerged pumps. For the distribution of treated water to consumers, a hydrophore set is required, which amounts to an additional 3,500 EUR, including installation.

For membrane cleaning, it is necessary to include dosing pumps for chemicals. Typically, a solution of sodium hypochlorite is used, which is dosed into the treated water flowing counter-current through the membrane. It may also be necessary to add citric acid once a week to prevent the accumulation of limescale. For two dosing pumps, small chemical containers, spill containment, and the installation and automation of the process, an estimated cost of 2,000 EUR is expected.

Moreover, two blowers for membrane cleaning and two blowers for the aeration tank are essential in the system, along with air pipelines, pressure switches (pressostats), and air filters. Their total value amounts to 4,800 EUR. The price does not include any potential soundproof chambers for the blowers. Air diffusers for introducing air into the aeration tank are also required. Based on the calculated airflow requirement (15.6 m^3/h) and the capacity of floor diffusers, approximately 2 – 6 m^3/h for each diffuser, it is reasonable to consider 6 floor diffusers (designed for low load), an air distribution network, and installation on the tank bottom, which costs 1,800 EUR.

A timer switch for regulating the treatment process that operates autonomously is not sufficient. An electrical cabinet is required where all the hardware and technological equipment is connected, along with a controller that will manage the operation of all installed equipment, and software with an operating algorithm for the plant. The total value of electrical installations, including the electrical cabinet and, if necessary, frequency regulators (meaningful for permeation pumps and for the air supply to the aeration tank), amounts to 15% of the investment value.

For equipment control, measuring instruments are also necessary (levels, oxygen, suspended solids concentration, inlet flow, permeate flow, pressure, etc.). The cost for such instrumentation, including installation and parameterization, is estimated to be approximately 6,000 EUR. It is worth mentioning that if the work is to be carried out by an external contractor, he will add approximately 10 - 15% margin to the value of their services.

In the end, the implementation of such a WWTP should cost approximately 90,000.00 EUR. Then, additional costs need to be added for the client's preferences to facilitate maintenance, such as equipment for lifting and positioning the machinery in place (hoists, platforms for easier access to tanks, ladders, stairs, a system for emptying and disposing of excess sludge, etc.). Rounding up to 93,000.00 EUR is a highly realistic estimate of the Capex cost. All the listed items for its estimation are summarised in the table below.

Table 22: List of CAPEX items

Item	**Cost**	**Life, years**	**Price, EUR**
GW separation	250 EUR/bathroom	20	25,250.00
Construction works – tanks	30 – 35% of the investment value	20	/
Installation/ assembly labour	10% of the investment value	20	/
Equipment			
Filter	/	10	11,000.00
Compactor	/	10	6,300.00
Membranes	150 EUR/m^2	10	10,350.00
Pumps	/	5	6,500.00
Hydrophore set	/	5	3,500.00
Instrumentation for chemicals	/	5	2,000.00
Blowers	/	5	4,800.00
Air diffusers	/	5	1,800.00
Measuring instruments	/	10	6,000.00
Electrical installation	15% of the investment value	20	/
Adaptations	/	20	3,000.00
TOTAL without GW separation			93,000.00
TOTAL			118,250.00

On the other hand, annual operational costs (OPEX) involve the cost of consumed energy for all items such as fluid pumps, air diffusers, air blowers and other electrical installation. They also comprise maintenance costs for visits, membrane cleaning and desludging (Table 23). In this case, a 2% increase of OPEX per year is included. The evaluation of the electricity consumption is made under the assumption of 3 kWh per cubic meter and considering Slovenian electricity price of 0.20 EUR/kWh.

Table 23: List of OPEX items

Item	Description and units	Comment	Price, EUR	Reference
Electricity* consumption	kWh	MBRs of approx. 30 m^3/day consume approx. 3 kWh/m^3	6,570.00	Huber Technology data for smart MBR
Check-up visits	1 visit/week	400 EUR/month	4,800.00	CID – Čistilne naprave d.o.o.
Desludging	When needed	180 – 240 EUR/t; approx. 1000 EUR/year	1,000.00	CID – Čistilne naprave d.o.o.
Membrane cleaning	When needed	300 EUR/year	300.00	CID – Čistilne naprave d.o.o.
Membrane conservation	1 month/year	300 EUR	300.00	CID – Čistilne naprave d.o.o.

*Please note that some research indicates significant energy optimisation of MBR (Atanasova et. Al, 2017). In this case the OPEX would drastically reduce.

The lifetime of MBR elements is crucial to define yearly depreciation costs, which are calculated for each element and summed up over the planning period. By doing that, the lifetime capital costs (CAPEX_20), which are related to the replacement of the material, can be obtained. Average OPEX per year, CAPEX_20 and the total costs for 20 years can be seen in the following table.

Table 24: Average annual OPEX, capital costs for 20 years and total costs for the planning period

Avg. OPEX per year (EUR)	CAPEX_20 (EUR)	Total costs for 20 years (EUR)
16,059.00	184,700.00	505,880.00

At the end, the payback period (PP) of the initial investment can be calculated as follows:

$$PP = \frac{CAPEX\_0}{\left(Q\ WP - (YD + OPEX)\right)} = \frac{118{,}250.00\ EUR}{\left(10{,}950\,\frac{\mathrm{m^3}}{\mathrm{year}}\,2.61\,\frac{\mathrm{EUR}}{\mathrm{m^3}} - \left(9{,}235.00\,\frac{\mathrm{EUR}}{\mathrm{year}} + 16{,}059.01\,\frac{\mathrm{EUR}}{\mathrm{year}}\right)\right)} = 36.4\ years \quad (25)$$

where Q is the treated greywater flow (m^3/year), WP is the water price (EUR/m^3), YD are the depreciation costs and OPEX are the operational costs (EUR/year). As for the OPEX, a yearly increase of 2% in the water price is considered.

4.3 Constructed wetland design and feasibility

4.3.1 Design of CW for greywater treatment

Besides the application of an MBR system for the greywater treatment at the Hotel Salinera, a second option is presented in this thesis, i.e., the vegetated submerged bed (VSB) system. Its design is based on the U.S. EPA Manual of Constructed Wetlands Treatment. The proposed VSB system (Figure 7) has four zones: the inlet, the outlet, and the treatment zone, which is divided into the initial and the final treatment zone. The initial treatment zone occupies 30% of the total area and have a big decrease in hydraulic conductivity. The final treatment zone occupies the remaining 70% of the area and undergoes a small change in hydraulic conductivity.

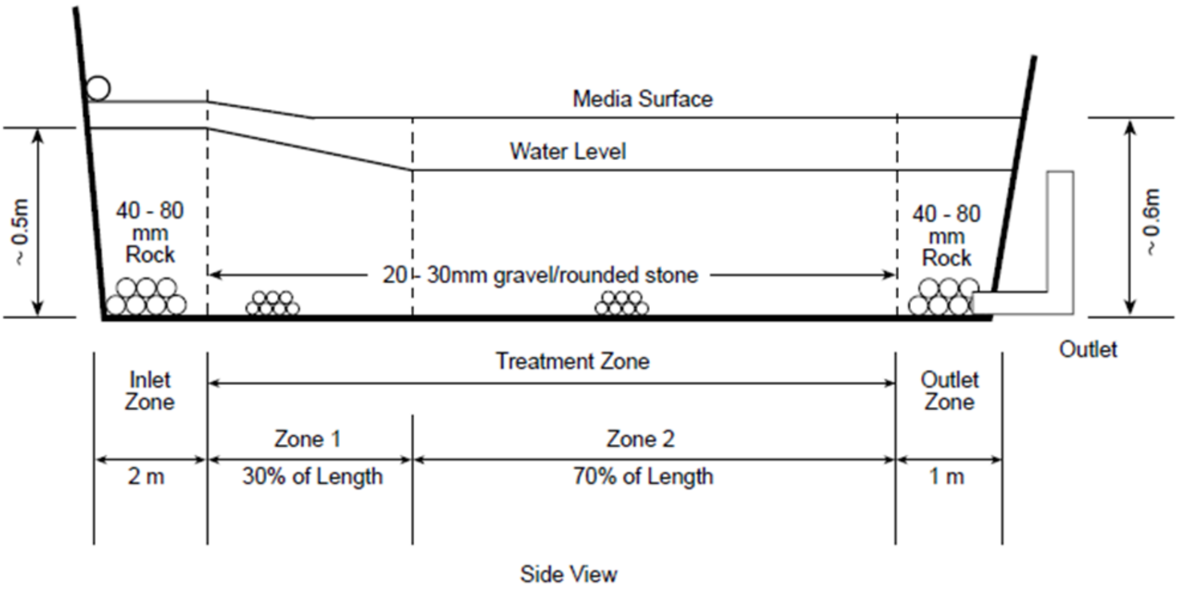


Figure 7: Side view of the proposed VSB system (U.S. EPA, 2000)

The media of the VSB system have four main functions: they represent rooting material for vegetation, permit to evenly distribute or collect the flow at inlets or outlets, supply surface area for microbial growth, and trap and filter particles. It is recommended that the media at the inlet and outlet should range between 40 and 80 mm in diameter to minimize clogging. They should extend from the top to the bottom, and the ideal inlet and outlet length should be 2 m and 1 m respectively. For the design of the treatment zone, gravel and rock media should be strongly preferred over soil and sand due to the susceptibility to clogging and surfacing flows of the latter. Larger gravel or rocks should also be avoided because they are difficult to handle during construction and maintenance. Studies have shown that within the size range of 10 to 60 mm there is no distinct advantage in pollutant removal. Therefore, it is recommended to choose an average diameter between 20 and 30 mm considering the compromise between the ease of handling and the potential for clogging.

The VSB system must be waterproof and protected by a membrane. The diameter of the planting media should not exceed 20 mm and the depth should be at least 100 mm. The systems are most often planted with common reed (*Phragmites australis*). Tufted sedge (*Carex elata*), black sedge (*Carex nigra*) and common bulrush (*Typha latifolia*) also grow well. The recommended planting density is 3 to 5 seedlings per square meter.

The design of the VSB system requires the determination of parameters listed in Table 25.

Table 25: Parameters for VSB system design

Parameter	Unit	Value	Description
Q	m^3/day	30	Maximum Flow
C_0	g/m^3 (mg/L)	95	Maximum Influent BOD
C_i	g/m^3 (mg/L)	100	Maximum Influent TSS
C_1	g/m^3 (mg/L)	30	Required discharge limits BOD
C_e	g/m^3 (mg/L)	30	Required discharge limits TSS
ALR BOD	g/m^2 day	6	Recommended Areal loading rate
ALR TSS	g/m^2 day	20	Recommended Areal loading rate
K	m/d	100000	Clean hydraulic conductivity
K_i	m/d	1000	Hydraulic conductivity of initial treatment zone (1% of clean)
K_f	m/d	10000	Hydraulic conductivity of final treatment zone (10% of clean)
s	%	0.005	Bottom slope
D_{w0}	m	0.4	Design water depth at inlet
D_{wf}	m	0.4	Design water depth at beginning of final treatment zone
D_m	m	0.6	Design media depth
dhi	m	0.06	Maximum allowable headloss through initial treatment zone (10% of D_m)
L_i	m		Length of initial treatment zone

Firstly, the needed surface area is determined using recommended areal loading rates for *BOD* and *TSS*, as follows:

$$A_s = \frac{Q\ C_0}{ALR\ BOD} = \frac{30\frac{m^3}{day} * 95\frac{g}{m^3}}{6\ \frac{g}{m^2 day}} = 475\ m^2 \tag{26}$$

$$A_s = \frac{Q\ C_i}{ALR\ TSS} = \frac{30\frac{m^3}{day} * 100\frac{g}{m^3}}{20\ \frac{g}{m^2 day}} = 150\ m^2 \tag{27}$$

Considering the larger area requirement, the choice is to construct three cells, each of 158 m^2. The surface area of the initial and final treatment zone is 48 m^2 and 111 m^2 respectively. Then, using the Darcy's law and the recommended values for the initial treatment zone, it is possible to determine the minimum width for maintaining the flow below the surface (equation (28)).

$$Q = K_i\, W\, D_{w0}\, \frac{d_{hi}}{L_i} \tag{28}$$

Considering that $L_i = A_{si}/W$, the equation can be rearranged and be solved for W, as is shown:

$$W^2 = \frac{Q\ A_{si}}{K_i\ d_{hi}\ D_{w0}} = \frac{30\frac{m^3}{day} * 48m^2}{1000\ \frac{m}{day} * 0.06m * 0.4m} = 60\ m^2 \tag{29}$$

and $W = 7.7$ m

Next, the design requires to calculate the length and the head loss of the initial and the final treatment zone with the following equations:

$$L_i = \frac{A_{si}}{W} = \frac{48m^2}{7.7m} = 6.2\ m \tag{30}$$

$$L_f = \frac{A_{sf}}{W} = \frac{111m^2}{7.7m} = 14.4\ m \tag{31}$$

$$d_{hi} = \frac{Q\ L_i}{K_i\ W\ D_{w0}} = \frac{30\frac{m^3}{day} * 6.2m}{1000\ \frac{m}{day} * 7.7m * 0.4m} = 0.06\ m \tag{32}$$

$$d_{hf} = \frac{Q\ L_f}{K_f\ W\ D_{wf}} = \frac{30\frac{m^3}{day} * 14.4m}{10000\ \frac{m}{day} * 7.7m * 0.4m} = 0.01\ m \tag{33}$$

The bottom elevations, water surface elevations, water depths, and the media depth-to-water throughout the VSB are collected in the following Table 26. The possible location of the constructed wetland is depicted in Figure 8. The CW's side view is presented in Appendix n.2.

Table 26: Bottom elevations, water surface elevations, water depths and media depths of the VSB system

	Parameter	Unit	Value	Description
Bottom Elevations	*Ebe*	m	0	Elevation of the bottom at outlet (reference point for elevations)
	Ebf	m	0.07	Elevation of the bottom at beginning of final treatment zone
	Eb0	m	0.10	Elevation of the bottom at inlet
Water Surface Elevations	*Ewf*	m	0.47	Elevation of the water surface at beginning of final treatment zone
	Ewe	m	0.46	Elevation of the water surface at outlet
	Ew0	m	0.53	Elevation of the water surface at inlet
Water Depths	*Dw0*	m	0.43	Depth of the water at inlet
	Dwf	m	0.40	Depth of the water at beginning of final treatment zone (Equal to design Dwf)
	Dwe	m	0.46	Depth of the water at outlet
Media Depths	*Em0*	m	0.63	Elevation of the media surface at inlet
	Emf	m	0.57	Elevation of the media surface at beginning of final treatment zone
	Eme	m	0.56	Elevation of the media surface at outlet
	Dm0	m	0.53	Depth of the media at inlet
	Dmf	m	0.50	Depth of the media at beginning of final treatment zone
	Dme	m	0.56	Depth of the media at outlet

Figure 8: Satellite's view of the CW composed of 3 cells

4.3.2 Feasibility of the CW technology

To assess the feasibility of implementing a CW for greywater treatment we consulted a specialized company in Slovenia (Limnos d.o.o.) regarding the cost of installation and operational costs. According to the company, the investment cost of the CW construction along with primary sedimentation tank is estimated to 90,000 EUR with additional 6,000 EUR for the project implementation. The approximate OPEX cost for such a WWTP would be 3000 EUR/year. This price includes:

- Electricity needed for water supply to the CW and recirculation, if the terrain does not allow for gravitational flow of water throughout the entire system.
- Operator who would conduct inspections (considering 16 hours per month).
- Maintenance work (service and replacement of pumps in case of malfunction).

The items for calculating the investment are listed in the table below. The cost for the purchase and installation of the clean water reservoir is taken from Fletcher et al. (2007).

Table 27: Capex items, Opex and the value of the initial investment

Item	Value	Unit
Construction cost	90,000.00	EUR
Clear water tank	6,680.00	EUR
Project documentation	6,000.00	EUR
GW separation	25,250.00	EUR
TOTAL	**127,930.00**	**EUR**
OPEX	3,000.00	EUR/year
Depreciation rate	5	%
Yearly depreciation costs	6,096.50	EUR/year

Using equation (25) it is possible to calculate the PP of the investment. In this case as well, a 2% growth in OPEX costs per year is considered, while yearly depreciation costs are calculated based on a 5% depreciation rate.

$$PP = \frac{127{,}930.00\ EUR}{\left(10{,}950\ \frac{\mathrm{m^3}}{\mathrm{year}} 2.61\ \frac{\mathrm{EUR}}{\mathrm{m^3}} - \left(6{,}096.50\ \frac{\mathrm{EUR}}{\mathrm{year}} + 3{,}714.50\ \frac{\mathrm{EUR}}{\mathrm{year}}\right)\right)} = 6.8\ years \tag{34}$$

4.4 Solar thermal system design

The design of the solar system starts with the determination of the monthly daily average global radiation on an inclined surface ($\bar{E}$) based on the values of the monthly daily average global radiation incident on a horizontal surface ($\bar{H}$). This procedure, presented by Liu and Jordan in 1960, involves an empirical relationship between beam and diffuse radiation. The needed values of $\bar{H}$ were taken from the solar radiation database PVGIS, which provides such information for any location in Europe and Africa, but also for a large part of America and Asia. This database can be found as an online tool on the official website of the European Commission. As concerns values of the total daily radiation expressed in Wh/m^2, the latter is calculated by the integration of irradiation values evaluated at regular intervals during the day. The effects of sky obstruction by local terrain features like hills or mountains are considered and are calculated by means of a digital elevation model.

The monthly daily average global radiation incident on a horizontal surface is determined by the sum of the monthly daily average beam and diffuse radiation ($\bar{B}$ and $\bar{D}$ respectively). The latter are related by the equation (35):

$$\frac{\bar{D}}{\bar{H}} = 1.39 - 4.027\bar{K} + 5.531\bar{K}^2 - 3.108\bar{K}^3 \tag{35}$$

where $\bar{K}$ is the monthly average daily clearness index and is obtained from the division between $\bar{H}$ and $\bar{H}_{ex}$, which represents the daily radiation incident on a horizontal surface located outside of the atmosphere. It can be calculated by the following equation:

$$\bar{H}_{ex} = \frac{24}{\pi} I_{cs}\left[1 + 0.033\, cos\left(\frac{2\pi n}{365}\right)\right](\cos(L)\cos(\delta)\sin(h_a) + h_a \sin(L)\sin\,(\delta)) \tag{36}$$

where:

$$h_a = arcos(-\tan(L)\tan(\delta)) \tag{37}$$

and L is latitude, I_{cs} is the solar constant (1394 W/m^2), h_a is the hour angle relative to sunrise, δ is the solar declination angle calculated by the Cooper formula and n represents the day of the year in which the declination is equal to the monthly average value. The assumption that it occurs every 15-th day of the month has been made. The Cooper formula approximates the solar declination as follows:

$$\delta = 23.45 \sin\left[360\left(\frac{284+n}{365}\right)\right] \tag{38}$$

Once determined $\bar{H}_{ex}$ for the hotel's latitude and longitude of 45.524 and 13.598 decimal degrees respectively, $\bar{K}$ and successively $\bar{D}$ can be calculated. The beam radiation is then given by the following relation (39):

$$\bar{B} = \bar{H} - \bar{D} \tag{39}$$

To find the global solar radiation incident on a sloped surface, geometric factors of beam (R_b), diffuse (R_d) and reflected radiation (R_r) must be considered, as it is shown in equation (40):

$$\bar{E} = R_b\bar{B} + R_d\bar{D} + R_r(\bar{B} + \bar{D}) \tag{40}$$

where:

$$R_d = \frac{1+\cos\,(\beta)}{2} = \frac{1+\cos\,(24)}{2} = 0.96 \tag{41}$$

$$R_r = r\left(\frac{1-\cos(\beta)}{2}\right) = 0.33\left(\frac{1-\cos(24)}{2}\right) = 0.01 \tag{42}$$

$$R_b = \frac{\cos(L-\beta)\cos(\delta)\sin(h_a')+h_a'\sin(L-\beta)\sin(\delta)}{\cos(L)\cos(\delta)\sin(h_a)+h_a\sin(L)\sin(\delta)} \tag{43}$$

The coefficient R_d depends only on the inclination of the surface β (24 degrees), R_r includes the albedo of the environment (0.33 for red clay roofs), R_b instead varies from moment to moment since it is a function of the angle of incidence i and the solar altitude α. The problem is solved by considering the average daily values evaluated in the middle of the month. For a surface with south exposure, as it is in this case, the last coefficient can be calculated using equation (43) considering the hour angle determined by the following equation:

$$h_a' = \min|h_a(\alpha = 0°), h_a(i = 90°)| \quad (44)$$

where (for sloped surfaces with south orientation):

$$h_a(i = 90°) = \arccos[-\tan(L - \beta)\tan(\delta)] \quad (45)$$

The intermediate results and the final values of the monthly daily average global radiation on the hotel's roof, which is inclined at 24 degrees, are presented in Table 28 and Table 29.

Table 28: Needed values of parameters for the reach of the monthly daily average global radiation

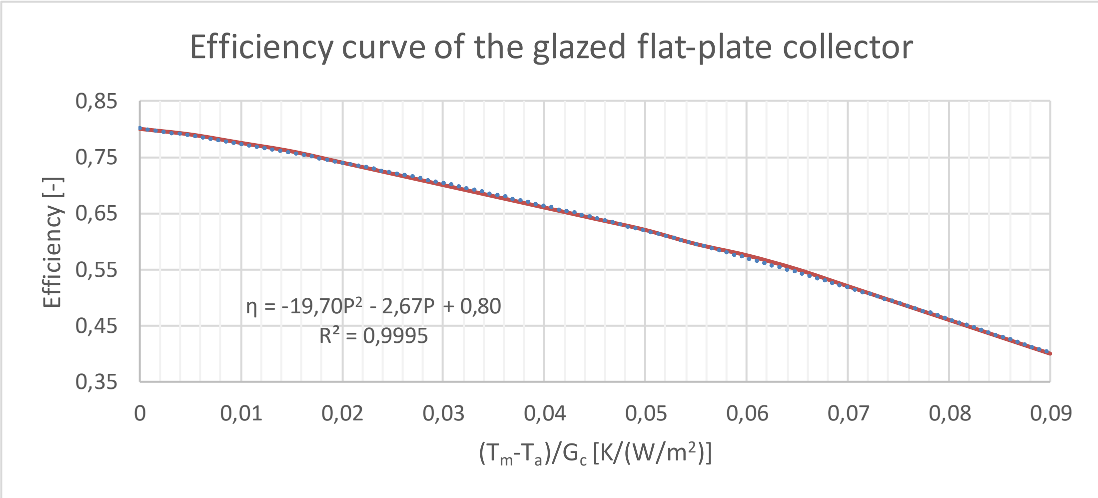
Month	**$\bar{H}$ (Wh/m^2)**	**δ (°)**	**h_a (°)**	**h_a (i=90°) (°)**	**h_a' (°)**
January	1118.94	-21.27	66.64	81.17	66.64
February	2104.26	-13.29	76.08	84.66	76.08
March	3488.18	-2.82	87.13	88.89	87.13
April	5012.57	9.41	99.72	93.75	93.75
May	5989.22	18.79	110.28	97.71	97.71
June	6852.49	23.31	116.04	99.79	99.79
July	7050.59	21.52	113.67	98.95	98.95
August	5939.16	13.78	104.47	95.55	95.55
September	4297.53	2.22	92.26	90.87	90.87
October	2564.95	-9.60	80.08	86.18	80.08
November	1304.97	-19.15	69.29	82.13	69.29
December	780.25	-23.34	63.94	80.20	63.94

Table 29: Intermediate results and the values of the monthly daily average global radiation

Month	**$\bar{H}_{ex}$ (W/m^2)**	**$\bar{K}$**	**$\bar{D}$ (Wh/m^2)**	**$\bar{B}$ (Wh/m^2)**	**R_b**	**$\bar{E}$ (Wh/m^2)**
January	3281.72	0.34	600.60	518.34	2.15	1704.47
February	4884.71	0.43	911.53	1192.73	1.73	2961.82
March	7101.20	0.49	1318.84	2169.34	1.40	4337.92
April	9728.97	0.52	1796.27	3216.30	1.15	5477.63
May	11710.74	0.51	2164.54	3824.68	1.01	6015.95
June	12650.83	0.54	2313.25	4539.24	0.95	6632.09
July	12278.11	0.57	2205.92	4844.67	0.97	6930.47
August	10657.11	0.56	1934.00	4005.16	1.08	6255.24
September	8183.67	0.53	1506.13	2791.40	1.28	5074.07
October	5655.56	0.45	1055.15	1509.80	1.59	3448.16
November	3696.17	0.35	679.75	625.22	2.01	1927.61
December	2887.02	0.27	502.71	277.54	2.31	1131.96

4.4.1 Application of the annual average method

For the solar system sizing the choice fell on a glazed flat-plate collector manufactured by a large Italian company from Teramo named Cordivari. The collector is composed by an aluminium frame, a mineral wool insulation, a selective absorber based on titanium oxides, and by a tempered glass cover against hail. All data were taken from the manufacturer's technical datasheet, from its gross area of 2.5 m^2 and its aperture area of 2.32 m^2 to the collector's efficiency curve. Between two possible orientations of the collector, the vertical one was chosen.



Graph 3: Efficiency curve of the selected glazed flat-plate collector and its polynomial trendline

As it is seen from the Graph 3, the efficiency curve is approximated with a second-order polynomial function:

$$\eta = cP^2 + bP + a \tag{46}$$

where a = 0.80, b = -2.67 and c = -19.70 are constant. To determine the collector's efficiency equation (5) must be solved considering $\overline{T}_m$ = 45°C. The average daily values of the external air temperature for each month are taken from the solar radiation database PVGIS, while the average solar irradiation $\overline{G}_c$ is calculated dividing the values of $\overline{E}$ (see Table 29) by the average sunshine hours (heliophany). These values are taken from literature and are representative of the city of Trieste, which is close to the hotel's site (less than 20 km as the crow flies). The calculated collector's efficiency is shown in Table 30.

Table 30: Efficiency of solar collectors per each month

Month	$\overline{T}_a$ **(°C)**	**Heliophany (h)**	$\overline{G}_c$ **(W/m^2)**	***P*** **(-)**	η **(-)**
January	7.44	2.7	631.28	0.06	0.57
February	7.50	3.6	822.73	0.05	0.64
March	9.56	4.9	885.29	0.04	0.66
April	13.41	6.1	897.97	0.04	0.68
May	17.66	7.5	802.13	0.03	0.69
June	22.12	7.9	839.50	0.03	0.71
July	24.66	9.3	745.21	0.03	0.71
August	24.45	8.4	744.67	0.03	0.71
September	21.04	6.8	746.19	0.03	0.70

October	16.82	5.7	604.94	0.05	0.63
November	12.83	3.2	602.38	0.05	0.60
December	9.12	3.2	353.74	0.10	0.33

Once the efficiency is known, it is possible to apply the annual average method using equations from (15) to (19). To reach the solar fraction of 0.80 the calculated surface of collectors amounts to 167 m^2. This value comprehends the procedure taken from the Italian technical specification, which includes constant monthly values of required energy for DHW production (see Table 31).

Table 31: Results of captured, available, required, and auxiliary energy throughout the year

$\bar{E}_{cgi}$ (Wh/m^2 day)	$\bar{E}_{ci}$ (Wh/m^2 month)	$\bar{E}_{di}$ (Wh/month)	$\bar{E}_{ri} = Q_{HW}$ (Wh/month)	$\bar{E}_{in}$ (Wh/month)	fi
976	30,263	5,053,850	18,605,169	13,551,320	0.27
1892	52,972	8,846,346	18,605,169	9,758,824	0.48
2876	89,148	14,887,638	18,605,169	3,717,531	0.80
3742	112,253	18,746,210	18,605,169	-141,041	1
4136	128,218	21,412,346	18,605,169	-2,807,177	1
4735	142,061	23,724,214	18,605,169	-5,119,044	1
4947	153,372	25,613,142	18,605,169	-7,007,973	1
4458	138,207	23,080,558	18,605,169	-4,475,389	1
3528	105,848	17,676,566	18,605,169	928,604	0.95
2187	67,797	11,322,077	18,605,169	7,283,092	0.61
1162	34,845	5,819,126	18,605,169	12,786,043	0.31
371	11,499	1,920,406	18,605,169	16,684,764	0.10
	TOTAL (kWh/year)	178,102	223,262	45,160	

The second approach involves the same captured energy per unit area, but the other parameters are different. However, as it can be seen from the Table 32, all values, including the annual, are very similar. In fact, the needed surface of collectors for the same solar fraction is 163 m^2, thus only 4 m^2 smaller than the previous.

Table 32: Results of available, required, and auxiliary energy considering variable hot water quantity

Month	$\bar{E}_{di}$ (Wh/month)	$\bar{E}_{ri} = Q_{HW}$ (Wh/month)	$\bar{E}_{in}$ (Wh/month)	fi
January	4,932,799	13,244,729	8,311,929	0.37
February	8,634,457	11,962,981	3,328,524	0.72
March	14,531,048	16,860,441	2,329,393	0.86
April	18,297,199	17,497,688	-799,510	1
May	20,899,475	21,389,196	489,721	0.98
June	23,155,969	22,262,257	-893,712	1
July	24,999,654	21,603,124	-3,396,530	1
August	22,527,731	26,458,390	3,930,659	0.85
September	17,253,175	16,317,637	-935,538	1
October	11,050,889	16,570,407	5,519,517	0.67
November	5,679,746	16,808,980	11,129,234	0.34
December	1,874,408	15,838,518	13,964,110	0.12
TOTAL (kWh/year)	173,837	216,814	42,978	

4.4.2 Application of the F-chart method

In the sizing of solar collectors using the F-chart method, only the variable values of the required energy for DHW production were taken into account. Following the methodology, the initial value for the collector surface area is determined using the annual average method, which amounts to 163 m^2. For solar plants that produce only DHW, equation (20), which is used for the determination of the dimensionless parameter X can be written as:

$$X = F_{sc} F_R U_c \frac{A_c}{L} \Delta t \,(11.6 + 1.18 T_{del} + 3.68 T_{net} - 2.32 T_a) \tag{47}$$

where:

F_{sc} is the de Winter factor (0.9), F_R is the heat removal factor, $L = \bar{E}_{ri} = Q_{HW}$ expressed in J/month, T_{del} is the delivery temperature of the hot water (40 °C), T_{net} is the temperature of the water from the hydraulic network (12 °C) and T_a is the monthly average temperature of the external air.

Knowing the efficiency curve of the selected solar collectors, equation (46) can be written as follows:

$$\eta = F'(\tau\alpha) - F' U_c \frac{\bar{T}_m - \bar{T}_a}{\bar{G}_c} - c\left(\frac{\bar{T}_m - \bar{T}_a}{\bar{G}_c}\right)^2 \tag{48}$$

where:

F' represents the ratio between two thermal resistances:

- the one between the absorbent plate and the external air (in the hypothesis of uniform plate temperature) and
- that between the fluid flowing in the ducts and the external air.

τ is the transmission coefficient of the cover and α is the absorption coefficient of the plate. Therefore, $F'(\tau\alpha)$ is equal to the coefficient a and $F' U_c$ is equal to the coefficient b. It can be also demonstrated that:

$$F_R(\tau\alpha) = k\, F'(\tau\alpha) \tag{49}$$

$$F_R U_c = k\, F' U_c \tag{50}$$

where:

$$k = \frac{1}{1 + \frac{F' U_c}{2G\, c_p}} \tag{51}$$

and G represents the specific flow rate (0.015 kg/m^2 sec) and c_p represents the specific heat (4186 J/kg °C). As regards the parameter Y, equation (21) can be rewritten as follows:

$$Y = \frac{F_{sc} F_R (\tau\alpha)\, A_C \bar{E}\, N}{\bar{E}_{ri}} \tag{52}$$

Table 33 presents the values of X and Y, and it's important to note that their correlations are valid within the following ranges:

$0 \leq X \leq 18$ and $0 \leq Y \leq 3$

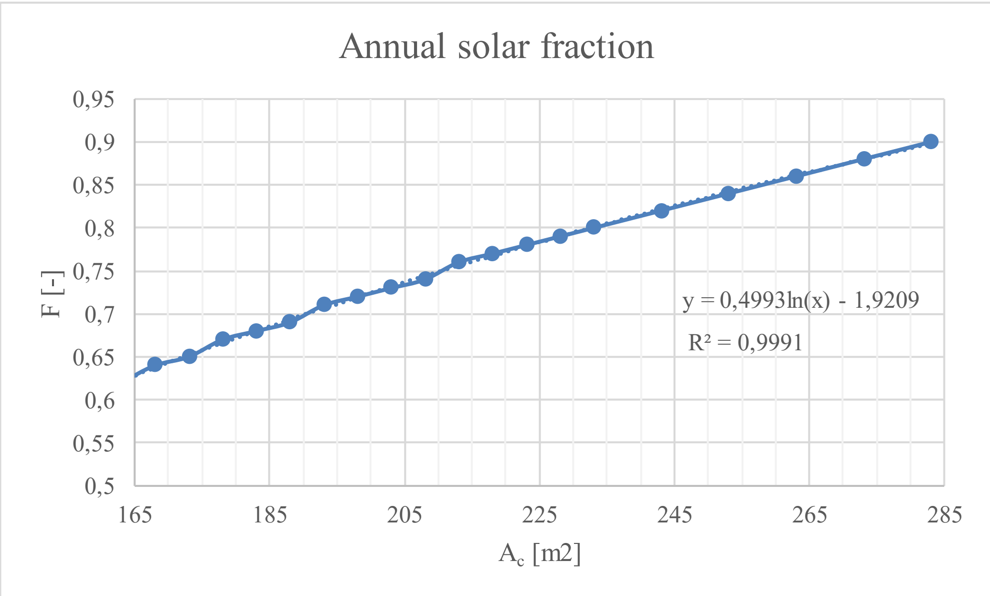
Once these conditions are met, the solar fraction can be calculated using equation (23).

Table 33: Results of the calculation of X and Y

Month	**$\bar{E}$ (MJ/m^2)**	**$\bar{E}_{ri} = Q_{HW}$ (MJ/month)**	**X**	**Y**	**fi**	**fi *$\bar{E}_{ri}$**
January	6.14	47,681	1.85	0.46	0.31	14,735
February	10.66	43,067	1.85	0.80	0.56	24,217

March	15.62	60,698	1.37	0.92	0.67	40,628
April	19.72	62,992	1.14	1.08	0.78	49,252
May	21.66	77,001	0.83	1.00	0.76	58,153
June	23.88	80,144	0.64	1.03	0.78	62,662
July	24.95	77,771	0.60	1.14	0.85	66,152
August	22.52	95,250	0.50	0.84	0.67	64,268
September	18.27	58,743	0.92	1.07	0.79	46,470
October	12.41	59,653	1.10	0.74	0.57	33,909
November	6.94	60,512	1.20	0.40	0.29	17,841
December	4.08	57,019	1.48	0.26	0.15	8,832
TOTAL		780,532				487,121

Generally, the determination of a small surface A_C is the first step. In fact, the first-attempt value leads to a solar fraction of 0.62, which is too low. The surface needs to be incremented until the solar fraction is around 0.80. The obtained data can be represented using a graph, which provides the relation between the area of the collectors and the solar fraction. As it is shown in Graph 4, the curve has a logarithmic trend, and its mathematic expression can be derived by interpolation.



Graph 4: Relation between the annual solar fraction and the area of collectors

The solar fraction of 0.80 corresponds to an area of 233 m^2, which exceeds the available surface on the south side of the roof, which is approximately 225 m^2. To accommodate the available space, it would be necessary to install an aperture area of 208 m^2, resulting in a total collector surface of 225 m^2 and an annual solar fraction of 0.74. However, installing such an area would require a boiler of 10,400 litres, considering that 50 litres per square metre of collector are needed. The boiler must be installed in a closed technical room in the basement floor, which, in this specific case, is not that large.

As a result, the driving factor for the dimensioning of the solar system becomes the available surface and the available height in the basement for the boiler's installation. After consulting the boiler catalogue of the same company that manufactures the collectors, it is found that the largest suitable option is a vertical boiler with two removable inox heat exchangers. This boiler has a volume of 2928 litres, a diameter of 1350 mm, a weight 464 kg and requires a height of 3.13 m for proper installation. This type of boiler allows the installation of 25 modules of solar collectors with the aperture area of 58 m^2 and a total surface of 62.5 m^2, achieving a solar fraction of 0.26.

Based on literature data, an internal heat exchanger with tubes typically requires 0.20 m^2 per unit area of absorbing surface, which in this case means an exchange of 11.6 m^2. This condition is met as the surface area of the exchangers is 12 m^2.

To optimize the arrangement of solar collectors on the roof, a combination of collectors connected in series and in parallel has been considered. This approach is necessary since it is not feasible to place many collectors in series. Having an equal number of collectors in each parallel string results in an enhanced hydraulic balance, leading to consistent flow rates and pressure drops throughout the system. The chosen configuration is illustrated in Figure 10, while Figure 9 shows the roof after the installation of collectors. The floor plan of the basement, including the technical room, can be found in Appendix n.1.

Figure 9: Top view of the collectors' configuration

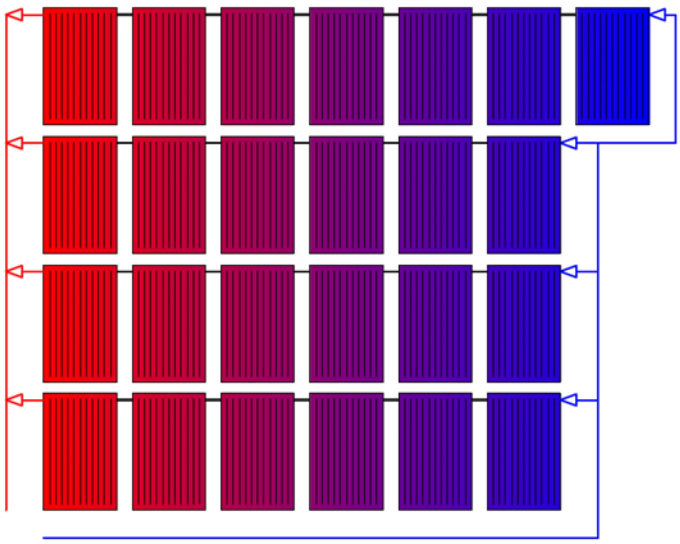


Figure 10: The circuit of collectors

4.4.3 Sizing of other components

In this chapter, the focus is on the proper sizing of pipes, circulation pump, and expansion vessel, as these components play a crucial role in the efficient and reliable operation of solar thermal systems. By correctly sizing these components, it is possible to optimize the system's performance, ensure proper flow rates, minimize energy losses, and maintain safe operating conditions.

The pressure loss in the solar circuit emerges as a critical factor affecting heat transfer. Minimizing this loss becomes very important, necessitating attention to the flow velocity, which should not surpass 0.7 – 1 m/s. Surpassing this threshold would lead to excessive flow resistance. Furthermore, flow speeds exceeding 0.7 m/s may result in undesirable noise disturbances, while velocities of 1 m/s or higher could cause abrasion in copper pipes. Conversely, it is essential to ensure an adequate volumetric flow to facilitate the transfer of heat from the collector to the storage unit. Experience suggests that solar thermal systems tend to perform optimally when maintaining a volumetric flow of approximately 40 L/h per square meter of collector area (Earthscan, 2010).

The calculation of the solar circuit pipe diameter relies on two variables, namely the volumetric flow rate $\dot{m}$ and the flow speed v. Considering the volumetric flow rate of 2320 L/h (58 m^2 x 40 L/h) and the flow speed limit of 0.7 m/s, the diameter can be calculated as follows:

$$D = \sqrt{\frac{4\frac{\dot{m}}{v}}{\pi}} = \sqrt{\frac{4\frac{0.64x10^{-3}\frac{m^3}{s}}{0.7\frac{m}{s}}}{\pi}} = 0.034\ m \cong 35\ mm \qquad (53)$$

Therefore, a minimum internal diameter of 34 mm is necessary in accordance with the requirements. Since this diameter is generally unavailable in the market, a standard outside diameter of 42 mm would be selected. The thickness may vary depending on the manufacturer, but for this diameter the most common are 1.2 mm and 1.5 mm. Considering the larger value, the volumetric flow rate results in 52 L/(h m^2), which generally allows good results.

The nominal volume of the expansion vessel can be calculated using the following equation:

$$V_{nv} = V_u \frac{p_{max}+1}{p_{max}-p_{in}} \tag{54}$$

where V_u represent the useful volume of the vessel (L), p_{max} is the maximum allowable operating pressure (bar) and p_{in} is the initial vessel's filling pressure (bar). The parameter V_u can be calculated with a safety coefficient 1.1 as follows:

$$V_u = (\Delta V + V_{coll})\ 1.1 \tag{55}$$

where ΔV is the expansion of the heat transfer fluid volume obtained by the following equation:

$$\Delta V = \left(V_{coll} + V_{pipes} + V_{hex}\right) e \tag{56}$$

where:

- V_{coll} is the collector volume,
- V_{pipes} is the pipeline volume,
- V_{hex} is the heat exchanger volume and
- e is the volumetric expansion coefficient of the fluid ($e = 0.07$ for a solution of water and glycol).

In this case, the collector volume is 47.5 L (25 modules per 1.9 L), the pipeline volume is 59.7 L (considering 50 m length), and the heat exchanger volume is up to 632 L (two heat exchangers of 316 L). Applying these values to the equation (56) yields the expansion of the heat transfer fluid volume of 51.7 L. Then, V_u can be determined using equation (55), resulting in a value of 109.2 L.

The minimum pressure requirement for the system dictates that the working pressure at the highest point should be a minimum of 0.5 bar. Additionally, the system height ($h_{sys} = 19\ m$) determines the static pressure p_{stat}:

$$p_{in} = 0.5\ bar + p_{stat} = 2.4\ bar \tag{57}$$

$$p_{stat} = h_{sys}\ 0.1\ {}^{bar}/_{m} = 1.9\ bar \tag{58}$$

Moreover, it is recommended to maintain the maximum allowable operating pressure approximately 0.3 bar below the response pressure of the safety valve. Since for this specific case a 5.5 bar safety valve is taken, it leads to a maximum pressure p_{max} of 5.2 bar. Once the useful volume and the pressures are known, the nominal volume of the expansion vessel can be calculated using equation (54), which ends up being 241.8 L. Considering that this value represents the minimum required volume, the subsequent standard size of 250 L is selected.

The circulation pump is generally selected as a component within the pump group, which is given by the manufacturer based on the volumetric flow rate per minute. The manufacturer typically specifies a recommended pump that is suitable for the specific requirements of the system, including the desired flow rate and pressure. The specific components of the pump group may vary depending on the design and configuration of the system, but the common elements typically include (Earthscan, 2010):

- the circulation pump;
- the flow control valve;
- the safety valve, which helps protect the system from excessive pressure;
- the check (non-return) valve;
- the pressure gauge;

- the temperature sensors and
- the control unit, which provides the interface for system monitoring and control settings.

Considering the specific volumetric flow rate of approximately 50 L/min for this case, a pump group within the discharge range of 20-70 L/min would be chosen from the catalogue of the Italian company.

4.4.4 Economic analysis

Solar thermal systems require a significant initial investment but are designed to replace traditional energy systems, reducing overall energy costs. Solar systems generally have much lower operating expenses than conventional systems, but at the same time the latter may have many times less purchase and installation costs. When assessing the economic viability of solar thermal systems, different economic measures can be used, such as payback time, return on initial investment, and life cycle savings. The results obtained from these various indicators usually align, indicating the system's economic feasibility and reaching credible conclusions about the potential cost-effectiveness of a solar thermal system.

In economic terms, a solar energy system is defined by its initial capital investment, yearly expenses, and the advantages it offers. The initial investment includes the cost of solar collectors, storage tank, heat exchanger, piping, circulating pump, and all other items reported in Table 34. It is important to note that installation costs for these components must also be accounted for.

Table 34: Initial investment of the solar thermal system

COST OF THE SOLAR THERMAL PLANT[1]		
	Quantity	Cost (EUR)
Solar circuit		
Collectors*	62.5 m^2 (618.54 EUR/collector)	15,463.50
Fittings kit for 3 collectors*	205.25 EUR x 8	1,642.00
Fittings kit for 2 collectors*	190.48 EUR	0.00
Fittings kit for 1 collector*	175.70 EUR x1	175.70
Fixing kit for 3 collectors*	415.44 EUR x 8	3,323.52
Fixing kit for 2 collectors*	310.35 EUR	0.00
Fixing kit for 1 collector*	203.61 EUR x1	203.61
Pump group*	2,000 EUR	2,000.00
Expansion vessel*	250 L (385 EUR)	385.00
Pipes*	50 m (35.76 EUR/m)	1,788.00

[1] The prices of nearly all components listed are cross-referenced with products in Cordivari's 2022 catalogue, which can be accessed at https://www.cordivari.it/en/product-category/integrated-solar-system/collectors-and-components/ .
However, there are exceptions, such as the expansion vessel obtained from: https://termoidraulica.elbi.it/products/expansion-tanks-for-heating-systems/erce-fixed-diaphragm-expansion-tanks-35-500-litres-/, and the pipes from: https://www.hmemetal.com/en/products/plumbing-tubes/sanco/ (all three websites were accessed on 20.08.2023).

Tank and accessories		
Boiler with heat exchanger*	15,000 EUR	15,000.00
Thermostatic mixing valve*	350 EUR	350.00
Other components		
Miscellaneous parts*		500.00
Total materials		**40,831.33**
Design and documentation		250.00
Transport		0.00
Installation		
Solar circuit	24h (30EUR/h) x 2 installers	1,440.00
Tank	7h	420.00
Electrical system	5h	480.00
Test and user instructions	2h	120.00
Total workforce		**2,710.00**
Total workforce with VAT	22% (in Slovenia)	**3,306.20**
Total with VAT		**44,137.53**

*Taxes included

The economic analysis usually begins with the introduction of simplified financial indicators, as simple payback time (SPT) and accounting rate of return (ARR), which play an important role in evaluating the profitability of investments. They do not involve complex calculations, but their limitations lie in their suitability only for cases with steady cash flows. SPT measures the length of time required for the initial investment to be recovered through cash inflows. The shorter it is, the more favourable the investment. It is calculated by dividing the initial investment (I_{sc}) by the annual net savings (NS). To calculate I_{sc}, the costs of the conventional system, which provides the 74% of the load (1 - 0.26 SF), are not considered. In case of NS, only the avoided fuel cost needs to be calculated as the product of the annual required energy for DHW production, the solar fraction, and the cost of electricity.

The accounting rate of return is described in the following manner:

$$ARR = \frac{(NS, after\ depreciation)}{(Initial\ investment)} \tag{59}$$

It provides insight into the speed at which the initial investment is recouped. However, it's worth noting that this indicator doesn't consider the timing of the net savings, making it less precise and only serving as a rough estimate. Nevertheless, it offers a rapid assessment of the potential profitability. A higher rate of return makes the investment more appealing. The depreciation can be expressed either as a fixed annual amount or as a declining rate, which reflects the reduction in equipment value over time. In this case, estimating a 20-year life period of the project and a salvage value of equipment as zero, the annual depreciation rate is assumed to be 5%. The annual maintenance costs of the solar system are typically expressed as a fixed portion of the initial investment, which in this case are assumed to be 2%.

All the parameters mentioned are available in Table 35, including the determination of SPT and ARR. The annual required energy for DHW production has been calculated in Chapter 4.4.1 (see Table 32). Notably, the auxiliary energy source is a heat pump responsible for supplying both domestic hot water and heating for indoor spaces.

Table 35: Parameters of the economic analysis

Definition	Parameter	Value	Unit
Initial capital investment	Isc	44,138	EUR
Cost of electricity (Slovenia)		0.20	EUR/kWh
Life period of the project	N	20	year
Salvage value of equipment		0	EUR
Annual depreciation rate of equipment		5	%
Annual required energy for DHW production	$\bar{E}_r = Q_{HW}$	216,814	kWh/year
Annual maintenance cost for solar system	2% of investment	883	EUR/year
Solar fraction	F	0.26	/
Fuel savings	K_c	11,274	EUR/year
Annual net savings	NS	10,392	EUR/year
Simple payback time	**SPT**	**4.2**	**year**
Annual depreciation costs		2,207	EUR/year
Accounting rate of return	**ARR**	**18.5**	**%**

The simplified approaches assume that the value of money remains constant over time. This means that the timing of a payment or saving, whether it occurs now or in the future, is considered irrelevant. However, this assumption is inaccurate because the present value of money we currently possess holds greater worth than the same amount expected to be received later. The connection between present and future amounts is represented by an interest rate denoted as the discount rate *r*. Typically, this rate is expressed on an annual basis, and it determines the future value FV that a present value PV will have after *n* years:

$$FV = PV\ (1 + r)^n \tag{60}$$

Over an extended period, such as the entire project life, various computations are necessary to discount all significant payments and savings. However, if a constant amount AP of future payments or savings is taken into account for each year over the next *n* years, the total present value of these payments can be determined using the following formula (Axaopoulos, 2011):

$$PV_{total} = AP\frac{(1+r)^n-1}{r\ (1+r)^n} = AP\ PWF(n, r) \tag{61}$$

where $PWF(n, r)$ is the present worth factor defined for $r > 0$ and $n \geq 1$.

Different additional factors must be included in the appraisal of solar systems, such as loans, grants, fuel prices and inflation. Loans provide an opportunity to pursue an investment when the available funds are not enough. In some situations, borrowing money might be preferred over using private capital, either to maintain sufficient working capital or to take advantage of incentives offered with the loan like low interest rates.

Subsidies are very favourable for investors and make investments more attractive. They are usually provided by governments to encourage a positive impact on the economy, to support growth and innovation, and to promote sustainable practices. In this case it is assumed that the touristic facility does not need any loans. Besides that, grants are intentionally excluded to create a less-convenient scenario than it might be.

The variation of energy prices over time can be extremely important especially in these years. The second factor that must be included in the analysis is certainly the inflation – the rate at which the value of money decrease in time. Therefore, investors are required to pay more for the same goods and services. Considering the inflation rate g equation (60) becomes:

$$FV = PV\ (1 + r_G)^n \tag{62}$$

where r_G represents the gross discounting rate obtained as:

$$r_G = g + r + (g\ r) \tag{63}$$

Moreover, according to Axaopoulos (2011) the equation (61) can be adapted, as follows:

$$PV_{total} = AP\ PWF'(n, r_G, g) = \frac{PWF(n,r)}{(1+g)}\ with\, r = \frac{1+r_G}{(1+g)} - 1 \tag{64}$$

The determination of the life cycle solar savings (LCS) involves the calculation of the net present value (NPV) of the investment, which, n years after it is realized, equals the accumulated savings during this period, subtracted by the cumulative costs and initial investment, with all amounts defined with their present values. The NPV of an investment varies depending on the reference year. At the start of system operation (n = 0), the NPV is equal to the negative value of the initial investment. At the end of the life period, it constitutes the LCS. They can be also presented on an annual basis, leading to the calculation of annualized life cycle savings (ALCS), as follows:

$$ALCS = \frac{LCS}{PWF'(N, r_G, g)} \tag{65}$$

In relation to this project, it is anticipated that both energy and maintenance costs will increase at a rate of 6%. The discounting rate employed is 5%, while the inflation rate, specifically 8.4%, belongs to Slovenia as of May 2023. The calculations of the entire life cycle of the project are shown in the following Table 36. Net solar savings are obtained by subtracting the maintenance costs from fuel savings. Discounting net solar savings allows the determination of the present value of all savings, leading to the evaluation of the investment's net present value over time. At the end of the life period, the NPV equals 155,964 euros. Additionally, the ALCS amount to 13,566 EUR/year.

Table 36: Calculation of NPV of the project for the entire life cycle

Year	Fuel savings (EUR/year)	Maintenance costs (EUR/year)	Net solar savings (EUR/year)	PWF'(n,r_G,g)	PV of savings (EUR)	NPV of the project (EUR)
0	0	0	-44,138	0	-44,138	-44,138
1	11,274	883	10,392	0.88	9,130	-35,008
2	11,951	936	11,015	1.72	9,217	-25,791
3	12,668	992	11,676	2.51	9,305	-16,486
4	13,428	1,051	12,377	3.27	9,393	-7,093
5	14,234	1,114	13,119	3.99	9,483	2,390
6	15,088	1,181	13,906	4.68	9,573	11,963
7	15,993	1,252	14,741	5.34	9,664	21,627
8	16,952	1,327	15,625	5.96	9,756	31,383

9	17,970	1,407	16,563	6.56	9,849	41,232
10	19,048	1,491	17,556	7.12	9,943	51,175
11	20,191	1,581	18,610	7.66	10,038	61,212
12	21,402	1,676	19,726	8.18	10,133	71,346
13	22,686	1,776	20,910	8.67	10,230	81,575
14	24,047	1,883	22,165	9.13	10,327	91,902
15	25,490	1,996	23,494	9.58	10,425	102,328
16	27,020	2,116	24,904	10.00	10,525	112,853
17	28,641	2,242	26,398	10.40	10,625	123,478
18	30,359	2,377	27,982	10.78	10,726	134,204
19	32,181	2,520	29,661	11.15	10,828	145,032
20	34,112	2,671	31,441	11.50	10,931	155,964

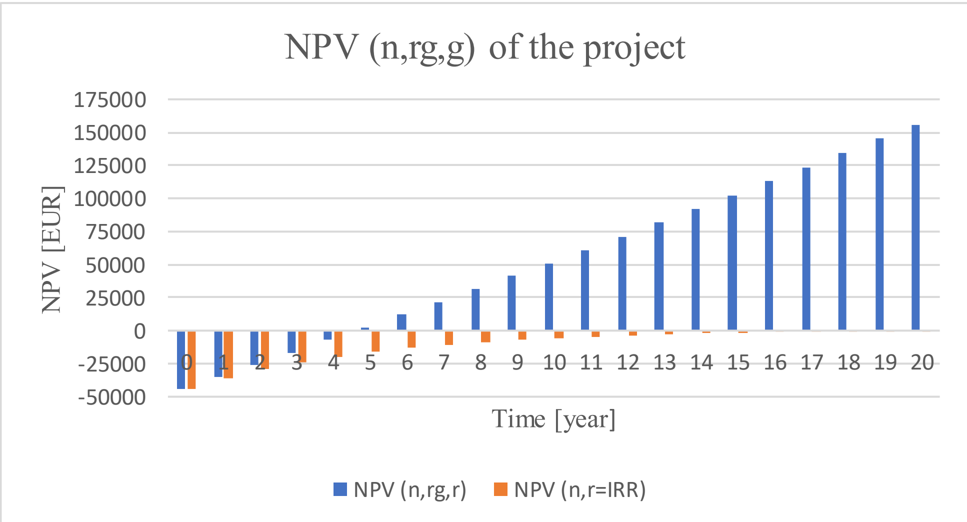
Using linear interpolation between the NPV at years 4 and 5 it is possible to calculate the discounted payback time (DPT) – the needed time to recover the initial investment. It ends up being 4.75 years. In addition to the DPT, the rate at which the invested capital is recovered holds significant importance. This is quantified by the internal rate of return (IRR), also known as return on investment (ROI). It represents the discount rate at which the NPV of the investment becomes zero at the end of the system's life (Axaopoulos, 2011):

$$NPV(N, IRR) = 0 \tag{66}$$

To find IRR, a trial process is needed. Since the NPV decreases when the discount rate decreases, exist two successive trial values of r, denoted as r_i and r_{i+1}, that NPV (N, r_{i+1}) < 0 < NPV (N, r_i). Then, the IRR can be linearly interpolated based on these values, as follows:

$$IRR = r_i + \frac{(r_{i+1} - r_i)\ NPV(N, r_i)}{NPV(N, r_i) - NPV(N, r_{i+1})} \tag{67}$$

Once $r_i = 0.29$ and $r_{i+1} = 0.30$ are found, the estimated IRR of the investment equals 29.1%. The following graph represents the NPV of the project over time.



Graph 5: Development of NPV over time

4.5 Summary of solutions

This chapter offers an overview of proposed solutions for optimizing water and energy fluxes in the Hotel Salinera. Table 37 presents the key features of all three designed measures, along with their economic parameters, which are instrumental in determining the feasibility of their implementation.

Table 37: Characteristics of designed measures

Characteristics		Value	Unit	ADDED VALUE
WATER				
	Design GW discharge	30	m^3/day	
MBR SYSTEM	Biological reactor's size	5.8	m^3	Water security, high quality alternative water source, reduced amount of wastewater, reduced pressure to water sources
	Initial investment	118,250.00	EUR	
	Avg. Annual OPEX	16,059.01	EUR	
	Payback period	36.4	Year	
CW PLANT	Design surface	475	m^2	Water security, alternative water source, reduced amount of wastewater, reduced pressure to water sources, biodiversity and evapotranspirative cooling if properly designed
	Proposed surface	400	m^2	
	Initial investment	127,930.00	EUR	
	Avg. Annual OPEX	3,714.50	EUR	
	Payback period	6.8	Year	
	Avg. Potable water savings	45	%	
ENERGY				
SOLAR THERMAL SYSTEM	Annual required energy for DHW production	216,814	kWh/year	Reduced energy consumption, energy security
	Ideal surface of collectors	225	m^2	
	Actual surface of collectors	62.5	m^2	
	Obtained solar fraction	0.26	/	
	Initial investment	44,137.53	EUR	
	Annual maintenance cost	883.00	EUR	
	Simple payback time	4.2	Year	
	Discounted payback time	4.75	Year	
	Internal rate of return	29.1	%	

5 CONCLUSIONS

The tourism industry and its associated facilities are recognized to have a substantial ecological footprint, primarily due to the overexploitation of water and energy resources. This issue is particularly acute in regions characterized by water scarcity, such as the Mediterranean. During the summer months, in particular, the demand for both energy and water resources can surge to such levels that the available resources may prove insufficient to meet the burgeoning needs of this sector.

The thesis presents the design and the feasibility of measures aimed at reducing energy and water consumption in a real case study, Hotel Salinera in Slovenia. Three measures/concepts were successfully analysed for their design and feasibility: (1) greywater separation, treatment with MBR and reuse, (2) greywater separation, treatment with CW and reuse and (3) a solar thermal system for energy use reduction.

Subsequent discussions with end-users have revealed a pronounced demand for these solutions. However, the economic assessment presents two contrasting scenarios. Both the MBR system and the CW plant exhibit remarkably similar investment costs, differing by a mere 7.6%. However, the operational costs associated with MBR technology are so high that the investment becomes not feasible, with a return period of more than 30 years. On the other hand, the results show that the CW implementation for greywater treatment and reuse would be economically justified. The return period of the investment would be approximately 7 years. In the case of further optimizing the MBR process to the extent that it consumes half as much energy per cubic meter of water, the return-on-investment period would be significantly reduced by more than half, specifically to 16.2 years.

To reduce energy consumption while ensuring energy stability and efficiency, the thesis project offers a comprehensive design and assessment of a solar thermal system. Using the information regarding water consumption, the proportion of hot water within daily greywater, and technical specifications, an appropriate design of this system becomes attainable. However, due to constraints imposed by limited available surfaces in the basement, the installation of a reduced number of solar collectors emerges as the sole viable option. This configuration results in a reduction of 26% in the consumption of the conventional energy system. Its economic analysis confirms a nearly immediate return on investment, rendering this implementation highly feasible. All together the hotel would reduce potable water use by 45% and energy use by 26% by implementing one of the proposed greywater reuse measures and the solar thermal system.

The economic analysis does not take into consideration that, in line with European strategies, governments should invest in such measures, which would increase the feasibility and the uptake of presented concepts. Furthermore, the economic analysis does not take into account the broader implications of sustainable resource management. For instance, it does not consider the positive impacts on existing water systems, the enhanced reliability of water supply during droughts, or the reduction of pressure on freshwater resources.

Additionally, economic analysis overlooks the supplementary benefits of CW, such as increased greenery, biodiversity, and evaporative cooling. It would be also essential to incorporate the costs of all environmental taxes associated with wastewater, which are presently included in the billing structure for potable water. Contemporary billing practices encompass not only the cost of potable water supply but also expenses related to wastewater collection, treatment, and all associated environmental levies. This occurs regardless of the subsequent use of the water, such as for irrigation. Although such practices effectively reduce potable water consumption, the resulting benefits are not considered in the calculation of potable water bills. If all these benefits were factored in, the overall picture would be significantly more favourable.

6 SUMMARY

The increasing demand for energy and water raises concerns regarding stable supply of resources, diminishing energy and water resources, and ecosystem degradation. One of the major sources of energy consumption, not only in Europe but globally, can be attributed to buildings, which consume energy in every phase of their life cycle. As the demand for energy continues to rise, the pressure on water resources is also escalating, creating a complex web of interconnected challenges. Climate change, characterized by rising temperatures and shifting weather patterns, further exacerbates concerns and emphasizes issues such as water scarcity and intensifying droughts.

In recent decades, the European Parliament has adopted various strategies and directives to address the energy and water crises. The introduction of energy certificates under the Energy Performance of Buildings Directive represents a significant step forward. However, these certificates need to be complemented by the inclusion of a water certificate to ensure more efficient water use and a comprehensive understanding of the true value of buildings. Proper water management can significantly impact the energy balance and contribute to water and energy conservation. A water certificate could gain greater prominence if its benefits were like those of the energy certificates. This implies that it would be legally mandatory for all buildings, thereby influencing their market value. Such an approach would also encourage the reuse of wastewater. Measures that would elevate a building to a higher class of the water certificate could receive financial support from the state or other institutions, like measures associated with energy certificates.

Reducing energy consumption in buildings can be achieved through the implementation of nature-based solutions (NBS). These solutions bring numerous other benefits related to the urban biosphere, such as flood prevention, biodiversity conservation, improved aesthetics, water purification, and more (Langergraber et al., 2020). Langergraber et al. (2021) as well as Atanasova et al. (2021) present a framework for the implementation of NBS for circular resource management in cities. Excellent examples of multiple benefits for the urban environment include constructed wetland (CW) treatment systems, wastewater treatment plants (WWTP) with rotating biological contactors, as well as green roofs and green walls.

Domestic wastewater includes sewage originating not only from private homes but also from commercial activities and institutions typically located within urban areas. The quantities of wastewater are calculated based on the consumption of drinking water, which is associated with people's behaviour and habits in each urban environment. Factors influencing water consumption in households include the standard of living, the quality of the water supply system and installations in houses, water prices, the presence of industry or tourist attractions, climate, and losses in the water supply system. Water consumption varies slightly across Europe, specifically: 124 L/PE/d in Europe (EurEau, 2021), 110 L/PE/d in Slovenia (SiStat, 2020), 122 L/PE/d in Germany (Statistisches Bundesamt, 2019), and 215 L/PE/d in Italy (Istat, 2021). Studies have shown that water consumption in tourism can vary greatly, ranging from 80 to as much as 2000 L per tourist per day (Gössling et al., 2012). Larger resorts and luxury facilities typically consume significantly more water than smaller hotels. Significant variations can occur between countries and even among hotels in the same country, depending, for example, on the geographical location, climatic conditions, and hotel standards. European tourists consume an average of 300 L per day, which is approximately three times more than the average household water consumption.

Domestic wastewater is primarily characterized by organic waste containing nutrients such as nitrogen, phosphorus, and carbon, but it also contains relatively high concentrations of microorganisms. The biochemical oxygen demand (BOD) values typically range around 60 g per person per day. It is important to distinguish between two significant fractions: blackwater and greywater. Blackwater is a portion of wastewater discharged through toilets, further categorized into faeces and urine. Greywater includes household wastewater from showers, dishwashers, sinks, baths, and washing machines (Butler et al., 2018). Depending on its source, greywater can be classified into light and dark greywater; the former encompasses wastewater from sinks, baths, and showers, while the latter includes wastewater from washing machines, dishwashers, and the kitchen. Domestic wastewater contains approximately 65% to 75% of greywater, and this proportion increases to over 90% when vacuum toilets are used (Ghaitidak & Yadav, 2013; Li et al., 2009; Rutar Polanec, 2021).

Greywater is considered a significant alternative water source for non-potable purposes, especially in arid tourist areas, where the peak demand for water coincides with the driest periods (Atanasova et al., 2017). Its properties make it suitable for reuse in many applications, primarily for irrigation and toilet flushing. Physical, chemical, and microbiological parameters defining the quality of greywater can vary significantly among sources of domestic wastewater. Ghaitidak and Yadav (2013) compiled characteristic data on greywater from various sources. It was found that the greywater composition characteristics differ among research articles, resulting in wide ranges of concentrations. Hence, depending on the level of contamination, various types of greywater treatment and reuse can be chosen.

In Europe and around the world, various regulations and guidelines are in place to protect human health and the environment regarding the reuse of wastewater, including the safe use of treated greywater and rainwater. Both types are classified as wastewater that need to comply with reuse standards outlined in existing national legislation. Laws and standards vary among countries, particularly concerning the intended use of the treated effluent. The guidelines of the World Health Organization are a critical reference point, although they address the safe use of wastewater only in aquaculture and agriculture (WHO, 2006b).

At the European level, water reuse is scarcely encouraged in the Urban Wastewater Directive, which was published in May 1991. However, this directive does not impose obligations on EU member states to ensure a specific level of water reuse or to develop appropriate standards. In June 2020, the European Commission issued a new regulation that sets out minimum requirements for water reuse, but it focuses exclusively on agricultural applications. Several European member states have introduced their own regulations or guidelines for the reuse of treated wastewater for non-potable purposes. Most notably those of Cyprus, France, Greece, Italy, and Spain, which are considered as regulations in national legislation.

With proper planning, construction, and operation, we can optimize energy fluxes and reduce energy consumption. Addressing energy insufficiency, greenhouse gas emissions, and their serious threats to the environment and health can be achieved through measures aimed at increasing energy efficiency in buildings. The largest share of final energy consumption in buildings in both Europe and the USA is attributed to electricity usage, primarily for heating, cooling, lighting, and household appliances. Following electricity, natural gas constitutes the second-largest source, being heavily utilized in residential buildings across Europe and serving as a primary energy source for water heating in the USA. However, renewable energy sources still play a minor role in the total final energy consumption in buildings.

The reuse of greywater allows for the optimization of water fluxes in buildings and promotes greater sustainability and resilience. Through separation and treatment, greywater serves as an excellent source of non-potable water, simultaneously reducing hydraulic load on the sewerage system and WWTP. Broadly, there are two main groups of processing technologies: intensive and extensive. The first group is based on accelerating cleaning processes by introducing a greater amount of energy into the system. Conventional activated sludge (CAS) systems fall into this category, where energy is used for aeration and for returning or keeping sludge in the reactor (Arceivala & Asolekar, 2007). Among the more advanced technologies for greywater treatment are sequencing batch reactors (SBR), fixed film reactors, and highly automated and energy-intensive systems that involve biological, chemical, and physical cleaning mechanisms, such as membrane bioreactors (MBR), rotating biological contactors (RBC), and biological aerated filters (BAF).

MBR technology for wastewater treatment combines activated sludge treatment with membrane separation. The reactor operates similarly to the CAS treatment process but without the need for a secondary clarifier or tertiary treatment. In fact, there's no requirement for a final filtration and/or disinfection step to meet the standards for non-potable reuse (Li et al., 2009). Biological treatment is combined with microfiltration (MF) or ultrafiltration (UF) using membranes made of semi-permeable materials designed to separate particles, dissolved substances, and colloidal matter from dissolved liquids. Membranes are typically manufactured in four configurations: tubular, flat sheet, spiral, and hollow fibre. The main advantages of this technology over others include excellent and stable effluent quality, high organic loading rate, compact design, and low excess sludge generation. However, there are also some drawbacks, including relatively high installation and operating costs, the need of continuous monitoring, frequent membrane maintenance, and limitations regarding pressure, temperature, and pH (Yoon, 2015; Blatnik, 2021). To size an MBR system, equations presented in Wen et al. (1999) and Atanasova et al. (2017) can be used. This allows the determination of the appropriate size of the bioreactor, the oxygen requirements for the oxidation of organic matter and ammonia, membrane area, necessary aeration, as well as blowers and pumps.

Extensive technologies encompass solutions that harness natural processes with minimal energy input and the use of chemicals for their intensification (Boano et al., 2020). The European Commission defines them as cost-effective solutions that are supported and inspired by nature, providing environmental, economic, and social benefits simultaneously. Various natural solutions have been implemented for greywater treatment, including CWs. Other representatives include green roofs, green walls, and urban green areas such as parks and street trees.

CWs are typically classified based on their water surface into two types: free water surface type and submerged/subsurface flow type. The flow direction can be either horizontal or vertical. CWs with horizontal subsurface flow are often utilized due to their efficiency and suitability for relatively flat terrains. Additionally, they help prevent mosquito breeding, a common issue in free water surface configurations. The design of subsurface flow CWs is described in the U.S. EPA Manual of Constructed Wetlands Treatment (U.S. EPA, 2000). The proposed system consists of four zones: inlet, outlet, and a treatment zone divided into initial and final zones. The initial treatment zone occupies 30% of the total area and has a significant drop in hydraulic conductivity. The final treatment zone covers the remaining 70% of the area and has a minor change in hydraulic conductivity. Studies indicate that there is no significant advantage in pollutant removal for gravel and stone material in the size range of 10 to 60 mm. Therefore, a diameter selection between 20 and 30 mm is recommended, representing a good compromise between ease of management and the possibility of clogging.

Among all renewable energy technologies used in buildings, the emphasis is on the use of solar thermal systems. These systems are based on the conversion of solar radiation into heat. Light that reaches the solar collector passes through a dark-coated plate - the absorber, which is equipped with tubes. These tubes contain a heat transfer medium, usually water or an anti-freeze fluid, which is heated and flows towards the hot water tank. The most common use of such systems is for water heating, where the heat transfer medium, circulating through the collectors, transfers heat to sanitary or service water through a heat exchanger.

The size of solar thermal systems varies based on the most common local weather conditions and the hot water needs. The collector area is primarily determined by the daily hot water demand, which, according to Axaopoulos (2011), ranges from 30 to 75 L per person per day. In many circumstances where it's not possible or appropriate to install the tank above the collectors, forced circulation systems are used. In such cases, a pump is needed to circulate either drinking water (direct systems) or the heat transfer fluid (indirect systems).

In temperate climates, when designing a solar hot water system, a common goal is to provide approximately 80% of the hot water needs throughout the year. This leads to economic savings, an extended lifespan of the heating boiler, and environmental protection. One of the simplified methods for determining the size of solar thermal systems, which is easy to use and provides acceptable estimates of thermal efficiency, is the annual average method. Its application is based on the efficiency of solar collectors. The most versatile and widely used type of solar collectors is the glazed flat-plate collector. It typically consists of a metal absorber in a flat rectangular case with one or more glass covers on top and thermal insulation on the back. Manufacturers provide technical data sheets for all collectors, equipped with efficiency curves over time. With this information, and known input data, external and operating conditions, the efficiency of the capturing system can be calculated. The most popular method, due to its simplicity, user-friendliness, and accuracy, is the F-chart method. It is used to estimate the annual thermal performance of water or space heating systems in buildings, where the minimum energy delivery temperature is around 20 °C (Axaopoulos, 2011).

This method for a specific solar thermal system provides the percentage of the total heat load supplied by solar energy. The main input for such design is the collector area, initially chosen to be relatively small and then gradually increased until the solar fraction reaches approximately 0.80.

The goal of the master's thesis was to present the design and feasibility assessment of various measures to improve the efficiency of buildings concerning energy and water consumption. The thesis aimed to showcase different measures for the reuse of energy and water, with a specific focus on tourist facilities, as they are significant consumers of energy and water. Initially, attention was devoted to quantifying and characterizing the water and energy fluxes within the buildings.

To assess the impacts of the measures and optimize water and energy fluxes, we selected the tourist facility Hotel Salinera, located in the Slovenian coastal town of Strunjan. The hotel has a total of 101 rooms that can accommodate a maximum of 259 guests per night. It operates year-round and offers various amenities, including indoor and outdoor pools, a wellness centre, and a restaurant. The hotel also features extensive green areas covering 4 ha, which are regularly irrigated with potable water.

The current management of water and energy fluxes in the hotel follows conventional practices. Potable water is supplied from the public water supply, with an average consumption of 63 m^3 per day throughout the year. Of this, the average amount of greywater is 31 m^3. The heating system for spaces and hot water preparation significantly impacts the hotel's energy consumption. To meet these needs, the hotel uses a heat pump, consuming approximately 20 MWh per month, with occasional peaks exceeding 40 MWh. During the summer months, the hotel also uses oil, with a total consumption of 8172 L annually.

For the separation and treatment of greywater from all hotel rooms, we proposed two options. The first option involves installing an MBR system as a compact solution for greywater treatment. The second option involve the CW’s placement with subsurface flow. The treated greywater is collected and used for irrigating the hotel's green areas, which constitute significant water consumers, as well as for service water during the autumn and winter seasons.

The transition to the use of renewable energy sources was aimed to be facilitated through the implementation of solar thermal systems. The proposal included integrating such a system with one of the two options for greywater reuse. The project focused on sizing glazed flat-plate solar collectors to produce domestic hot water based on the annual average method and the F-chart method. Besides ideal sizing of the solar system that would ensure an adequate solar fraction throughout the year, emphasis was put on a more feasible project proposal, considering the available roof area for installing solar collectors and other system components, starting from the boiler and expansion vessel.

The project foresaw that greywater from sinks and showers would be collected in a water tank in the hotel's basement. This tank regulates the raw inflow and outflow of greywater into the selected treatment system, balancing the temperature and quality of greywater. Its 10 m^3 capacity represents approximately one-third of the average daily greywater production from sinks and showers in the rooms. To appropriately design the solar system, we verified the data on the proportion of hot water in greywater (Hervás-Blasco et al., 2020) using Italian technical specifications. We found that 18.8 m^3 of daily hot greywater is an acceptable value and aligns with the literature.

Within the project, we calculated the required size of the biological reactor, which amounts to 5.8 m^3, the specific oxygen demand, membrane area, and necessary aeration. With the assistance of the company

CID - Čistilne naprave d.o.o. from Koper (Slovenia), we determined the initial investment and operational costs for the project's duration of 20 years. It turned out that the initial investment amounts to 118,250.00 euros, while the average OPEX costs are 16,059.00 euros. Assuming an electricity consumption of 3 kWh/m^3 and considering the Slovenian electricity price of 0.20 EUR/kWh, we calculated that the payback period for the investment would be 36.4 years. In the case of further optimizing the MBR process to the extent that it consumes half as much energy per cubic meter of water, the return-on-investment period would be significantly reduced by more than half, specifically to 16.2 years.

The CW's design revealed that an area of 475 m^2 is required for its placement. Based on this area, we decided to accommodate three cells with a width of 7.7 m and a length of 20.5 m. In assessing the project's reliability for the CW, we received assistance from Limnos d.o.o., and we determined the initial investment to be 127,930 euros. Considering a 5% depreciation rate and a 2% annual increase in operational costs, we estimated the OPEX costs to be 3,714.50 euros. It turned out that the payback period for the investment is 6.8 years. Both MBR and CW measures would contribute to an estimated reduction of approximately 45% in potable water use.

Before applying the average annual method and the F-chart method, we first determined the values of monthly daily averages of global radiation on the inclined surface. Then, based on the technical data of the collector, we used the first method and obtained a collector surface area, which represents the input for using the more widely used F-chart method. We calculated that a solar fraction of 0.80 corresponds to an area of 233 m^2, exceeding the available surface area on the south side of the roof, which is approximately 225 m^2. Adjusting to such an area would mean ensuring an annual solar fraction of 0.74. Due to the limited available space in the basement, we determined the installation of a reduced number of solar collectors, which proved to be the only feasible option. The configuration of the collectors with an area of 62.5 m^2 resulted in a 26% reduction in energy consumption of the conventional system. The economic analysis of the solar thermal system ultimately showed that the investment of 44,137.53 euros can be recovered in a very short period. The discounted payback period was 4.75 years, while the internal rate of return was 29.1%.

In the economic analysis, we did not consider the fact that, in line with European strategies, the government should invest in such measures. If it did, these measures would prove to be even more economically favourable. In the economic analysis, we also did not take into account the broader implications of sustainable resource management, such as the positive impacts on existing water systems, improved water supply reliability during droughts, reduced pressure on freshwater resources, and enhanced energy stability. If we were to consider all these benefits, the overall picture would be significantly more favourable.

7 POVZETEK

Povečanje potrebe po energiji in vodi sproža skrbi glede težav pri oskrbi, zmanjšanju energetskih in vodnih virov ter degradaciji ekosistemov. Enega največjih virov porabe energije, ne le v Evropi, temveč tudi po svetu, je mogoče pripisati zgradbam, ki porabljajo energijo v vsaki fazi svojega življenjskega cikla. Ker se povpraševanje po energiji še naprej povečuje, se povečuje tudi pritisk na vodne vire, ki ustvarja zapleteno mrežo povezanih izzivov. Podnebne spremembe, ki jih zaznamuje dvigovanje temperatur in spreminjajoči se vremenski vzorci, skrbi še poglobijo in poudarjajo težave, kot so pomanjkanje vode in podaljšanje sušnih obdobij.

V zadnjih desetletjih je Evropski parlament sprejel različne strateške ukrepe in direktive za obvladovanje energetske in vodne krize. Uvedba energetskih certifikatov v okviru Direktive o energetski učinkovitosti stavb predstavlja pomemben korak naprej. Le-ti pa potrebujejo dopolnitev z vklučitvijo vodnega certifikata, da bi zagotovili učinkovitejšo rabo vode in celovitejše razumevanje prave vrednosti objektov. Ustrezno upravljanje z vodo lahko pomembno vpliva na energetsko bilanco in deluje v smislu varčevanja z vodo in energijo. Vodni certifikat bi lahko tako pridobil večjo veljavo, če bi bila njegova uporaba podobna kot pri energetskih certifikatih. To pomeni, da bi bil zakonsko obvezen za vse stavbe in bi posledično vplival na njihovo tržno vrednost. Tako ravnanje bi spodbudilo tudi ponovno uporabo odpadne vode. Ukrepi, ki bi stavbo uvrstili v višji razred vodnega certifikata, bi lahko prejeli finančno podporo države ali drugih institucij, podobno kot pri ukrepih, povezanih z energetskimi certifikati.

Zmanjšanje porabe energije v stavbi je mogoče doseči z izvajanjem naravnih rešitev. Le-te prinašajo številne druge koristi v zvezi z urbano biosfero, kot so preprečevanje poplav, zagotavljanje biotske raznovrstnosti, urejenost okolice, čiščenje vode in še več (Langergraber in sod., 2020). Langergraber in sodelavci (2021) ter Atanasova in sodelavci (2021) predstavljajo okvir za implementacijo naravnih rešitev za krožno upravljanje virov v mestih. Odlični primeri večstranskih koristi za urbano okolje so rastlinske čistilne naprave (RČN), čistilne naprave z rotirajočimi kontaktorji, pa tudi zelene strehe in zelene stene.

Gospodinjske odpadne vode vključujejo odplake, ki ne izvirajo le iz zasebnih domov, temveč tudi iz komercialnih dejavnosti in ustanov, ki so običajno del urbanih območij. Njihove količine se izračunavajo na podlagi porabe pitne vode, ki je povezana z obnašanjem ljudi in navadami v vsakem urbanem okolju. Med dejavnike, ki vplivajo na porabo vode v gospodinjstvih štejemo tudi standard življenja, kakovost vodovodnega sistema in inštalacij v hišah, cena vode, prisotnost industrije ali turističnih znamenitosti, ter podnebje in izgube v vodovodnem sistemu. Poraba vode se po Evropi nekoliko razlikuje, in sicer: 124 L/PE/dan v Evropi (EurEau, 2021), 110 L/PE/dan v Sloveniji (SiStat, 2020), 122 L/PE/dan v Nemčiji (Statistisches Bundesamt, 2019) ter 215 L/PE/dan v Italiji (Istat, 2021). Študije so pokazale, da se poraba vode v turizmu lahko izjemno spreminja, in sicer od 80 do celo 2000 litrov na turista na dan (Gössling in sod., 2012). Večja letovišča in razkošni objekti običajno porabijo bistveno več vode kot manjši hoteli. Pomembna nihanja se lahko pojavijo med državami, pa tudi med hoteli v isti državi, odvisno na primer od geografske lege, podnebnih razmer in standardov hotela. Evropski turisti v povprečju porabijo 300 litrov na dan, kar je približno trikrat več kot povprečna poraba vode v gospodinjstvih.

Odpadne vode iz gospodinjstev so značilne predvsem po organskih odpadkih, ki vsebujejo hranila, kot so dušik, fosfor in ogljik, vendar vsebujejo tudi relativno visoke koncentracije mikroorganizmov. Vrednosti biokemijske potrebe po kisiku se običajno gibljejo okoli 60 g na osebo na dan. Razlikovati je treba med dvema pomembnima frakcijama, in sicer črno in sivo vodo. Črna voda je del odpadne vode, ki se izloči preko stranišč in jo je mogoče nadalje razdeliti na fekalije in urin. Siva odpadna voda pa vključuje gospodinjske odpadne vode iz tušev, pomivalnih strojev, umivalnikov, kadi in pralnih strojev (Butler in sod., 2018). Glede na njen izvor lahko sivo vodo razdelimo na rahlo onesnaženo in višje onesnaženo; prva vključuje odpadne vode iz umivalnikov, kadi in tušev, medtem ko druga obsega še odpadne vode iz pralnih in pomivalnih strojev, ter kuhinje. Gospodinjske odpadne vode vsebujejo približno 65% do 75% sive vode, ta delež pa se poveča na več kot 90%, ko se uporabljajo vakuumska stranišča (Ghaitidak in Yadav, 2013; Li in sod., 2009; Rutar Polanec, 2021).

Siva voda velja za pomemben alternativni vodni vir za nepitne namene, zlasti v sušnih turističnih območjih, kjer največje povpraševanje po vodi sovpada z najbolj sušnim obdobjem (Atanasova in sod., 2017). Njene lastnosti so primerne za ponovno uporabo v mnogih aplikacijah, predvsem za zalivanje in splakovanje stranišč. Fizikalni, kemijski in mikrobiološki parametri, ki opredeljujejo kakovost sive vode, se lahko močno razlikujejo med viri gospodinjske odpadne vode. Ghaitidak in Yadav (2013) sta zbrala njene karakteristične podatke iz različnih virov. Izkazalo se je, da se značilnosti sestave sive vode razlikujejo med raziskovalnimi publikacijami, kar vodi do razširjenih razponov koncentracij. Zaradi tega lahko v odvisnosti od stopnje onesnaženosti izbiramo med različnimi vrstami obdelave sive vode in njene ponovne uporabe.

V Evropi in po svetu veljajo za zaščito zdravja ljudi in okolja pri ponovni uporabi odpadne vode raznorazni predpisi in smernice, ki zajemajo tudi varno uporabo predelane sive in padavinske vode. Obe vrsti sta odpredeljeni kot odpadna voda, zato morata slediti standardom ponovne uporabe odpadnih voda v obstoječi državni zakonodaji. Zakoni in standardi se med državami razlikujejo tudi glede na namen uporabe obdelanega iztoka. Pomembno točko pri tem prestavljajo smernice Svetovne zdravstvene organizacije (WHO, 2006b), ki sicer obravnavajo varno uporabo odpadne vode le v ribogojstvu in kmetijstvu.

Na evropski ravni spodbujanje ponovne uporabe vode ostaja omejeno na direktivo o čiščenju komunalne odpadne vode, ki je bila objavljena maja 1991. Direktiva sicer državam članicam ne narekuje obveznosti zagotavljanja določene ravni ponovne uporabe vode ali razvoja ustreznih standardov. Evropska komisija je junija 2020 izdala novo uredbo, ki določa minimalne zahteve za ponovno uporabo vode, a le za kmetijske aplikacije. Več evropskih članic je uvedlo lastne predpise ali smernice za ponovno uporabo obdelane odpadne vode za nepitne namene. Med njimi izstopajo standardi Cipra, Francije, Grčije, Italije in Španije, ki so v njihovi državni zakonodaji obravnavani kot predpisi.

S pravilnim načrtovanjem, gradnjo in obratovanjem lahko optimiziramo energetske tokove oziroma zmanjšamo porabo energije. Pomanjkanju energije, emisijam toplogrednih plinov in njihovemu nevarnemu ogrožanju okolja in zdravja, lahko nasprotujemo z uvedbo ukrepov za povečanje energetske učinkovitosti stavb.

Največji delež končne porabe energije v stavbah Evrope in ZDA pokriva poraba električne energije, ki se večinoma uporablja za hlajenje, ogrevanje, razsvetljavo in gospodinjske aparate. Drugi je zemeljski plin, ki je najbolj uporabljen energent v vseh evropskih stanovanjskih stavbah ter predstavlja osnovni vir energije za ogrevanje vode v ZDA. Obnovljivi viri energije pa še vedno igrajo majhno vlogo v skupni končni porabi energije stavb.

Ponovna uporabo sive vode omogoča optimizacijo vodnih tokov v stavbah ter doseganje večje trajnosti in odpornosti. Z ločevanjem in čiščenjem velja le-ta za odličen vir nepitne vode, ki hkrati zmanjša hidravlično obremenitev na kanalizacijski sistem in čistilno napravo. Na splošno lahko razlikujemo med dvema glavnima skupinama tehnologij za predelavo: intenzivnimi in ekstenzivnimi. Prva skupina temelji na pospeševanju procesov čiščenja z vnosom večje količine energije v sistem. Sem spadajo konvencionalni sistemi aktivnega blata (CAS), kjer se energija uporablja za aeracijo ter vračanje ali zadrževanje blata v reaktorju (Arceivala in Asolekar, 2007). Med naprednejšimi tehnologijami za čiščenje sive vode so sekvenčni šaržni reaktor (SBR), reaktorji s pritrjeno biomaso, ter visoko avtomatizirani in energijsko intenzivni sistemi, ki vključujejo biološke, kemijske in fizikalne mehanizme čiščenja, kot so membranski bioreaktorji (MBR), rotacijski biološki kontaktorji (RBC) in biološki aerirani filtri (BAF).

Tehnologija MBR za čiščenje odpadnih voda združuje obdelavo z aktivnim blatom in ločevanje z membrano. Reaktor deluje podobno kot proces CAS obdelave, vendar brez potrebe po sekundarnem usedalniku ali terciarni obdelavi. Pravzaprav ni potrebe po končnem koraku filtracije in/ali koraku dezinfekcije za izpolnjevanje standardov za ponovno uporabo v nepitne namene (Li in sod., 2009). Biološka obdelava je kombinirana z mikrofiltracijo (MF) ali ultrafiltracijo (UF) z uporabo membran, ki so izdelane iz polprepustnih materialov, namenjenih ločevanju delcev, raztopljenih snovi in koloidnih snovi od tekočih raztopljenih snovi. Membrane so običajno izdelane v štirih konfiguracijah: cevaste, ploščate, spiralne in votle vlaknine. Glavne prednosti te tehnologije v primerjavi z drugimi vključujejo odlično in stabilno kakovost iztoka, visoko obremenitev z organskimi snovmi, kompaktno zgradbo in nizko tvorbo odpadnega blata. Kljub temu pa obstajajo tudi nekatere slabosti, vključno z relativno visokimi stroški namestitve in delovanja, stalnim spremljanjem ter pogostim vzdrževanjem membran ter omejitvami glede tlaka, temperature in pH (Yoon, 2015; Blatnik, 2021). Za dimenzioniranje MBR sistema se poslužujemo enačb predstavljenih v Wen in sod. (1999) in Atanasova in sod. (2017). Predpišemo lahko ustrezno velikost biološkega reaktorja, potrebo po kisiku za oksidacijo organske snovi in oksidacijo amonijaka, površino membran, potrebno aeracijo, ter puhala in črpalke.

Med ekstenzivne tehnologije spadajo rešitve, ki izkoriščajo naravne procese z minimalnim vnosom energije in kemikalij za njihovo okrepitev (Boano in sod., 2020). Evropska komisija jih opredeljuje kot stroškovno učinkovite rešitve, ki se zgledujejo po naravi in hkrati zagotavljajo okoljske, gospodarske in družbene koristi. Pri čiščenju sive vode lahko uporabljamo različne naravne rešitve vključno z RČN, zelenimi strehami in stenami ter mestnimi zelenimi površinami, kot so parki in drevoredi.

RČN se glede na njihovo vodno površino običajno delijo na dve vrsti: tiste s prosto vodno površino in tiste, ki delujejo podpovršinsko. Smer toka je lahko horizontalna ali vertikalna. RČN s horizontalnim podpovršinskim tokom se pogosto uporablja zaradi svoje učinkovitosti in možnosti namestitve na relativno položnem terenu. Poleg tega preprečujejo razmnoževanje komarjev, kar se pogosto dogaja pri konfiguracijah s prosto vodno površino. Dimenzioniranje RČN s podpovršinkim tokom opisuje ameriški priročnik o čiščenju RČN (U.S. EPA, 2000). Sistem, ki ga predlagajo američani, vsebuje štiri cone: vtok, odtok ter obdelovalno cono, ki je razdeljena na začetno in končno. Začetna cona zavzema 30% celotne površine in ima velik padec hidravlične prevodnosti. Končna cona zavzema preostalih 70% površine in ima majhno spremembo hidravlične prevodnosti. Študije kažejo, da v velikostnem območju od 10 do 60 mm gramoznega in kamnitega materiala ni opazne prednosti pri odstranjevanju onesnaževal. Zato priporočajo izbiro premera med 20 in 30 mm, pri čemer velja dober kompromis med enostavnostjo upravljanja in možnostjo zamašitve.

Med vsemi tehnologijami obnovljivih virov energije, ki se uporabljajo v stavbah, je poudarek na uporabi solarnih toplotnih sistemov. Le-ti temeljijo na pretvorbi sončnih žarkov v toploto. Svetloba, ki doseže solarni kolektor, prehaja skozi temno obarvano ploščo - absorber, ki je opremljen s cevmi. Te cevi vsebujejo prenosnik toplote, običajno vodo ali tekočino proti zamrzovanju, ki se ogreje in teče proti rezervoarju za toplo vodo. Najpogostejši tip takih sistemov je tisti za ogrevanje vode, pri čemer prenosnik toplote, ki kroži po kolektorjih, prenaša toploto na sanitarno ali tehnološko vodo preko toplotnega izmenjevalnika.

Velikost solarnih toplotnih sistemov se razlikuje glede na najpogostejše lokalne vremenske razmere in potrebe po topli vodi. Površino kolektorja določa predvsem dnevna potreba po topli vodi, ki po Axaopoulosu (2011) znaša med 30 in 75 litrov na osebo na dan. V mnogih okoliščinah, ko ni mogoče ali ni primerno namestiti rezervoarja nad kolektorji, uporabljamo sisteme s prisilno cirkulacijo. Takrat je potrebna uporaba črpalke za kroženje pitne vode (direktni sistemi) ali prenosnika toplote (indirektni sistemi).

V zmernih podnebjih, pri načrtovanju sončnega sistema za ogrevanje sanitarne vode, je običajen cilj načrta zagotoviti približno 80% potrebe po topli vodi skozi leto. To vodi k ekonomskemu prihranku, podaljšanju življenjske dobe ogrevalnega kotla in zaščiti okolja. Eden od poenostavljenih načinov za določanje velikosti solarnih toplotnih sistemov, ki je enostaven za uporabo in zagotavlja sprejemljive ocene toplotne učinkovitosti, je letna povprečna metoda. Njena uporaba temelji na učinkovitosti sončnih kolektorjev. Najbolj vsestranski in najbolj razširjen tip solarnih kolektorjev je ploščati kolektor s stekleno ploščo. Običajno sestoji iz kovinskega absorberja v ravnem pravokotnem ohišju z enim ali več steklenimi pokrovi na vrhu ter toplotno izolacijo na hrbtni strani. Vsem kolektorjem izdajajo proizvajalci tehnični podatkovni list, ki je opremljen s krivuljami učinkovitosti v času. S tem je mogoče, ob poznanih vhodnih podatkih ter zunanjih in delovnih pogojih, izračunati učinkovitost sistema za zajem toplote.

Najbolj priljubljena metoda, zaradi svoje preprostosti, uporabniške prijaznosti in natančnosti, je metoda F-chart. Le-to uporabljamo za oceno letne toplotne učinkovitosti sistemov za ogrevanje vode ali prostorov v stavbah, kjer je minimalna temperatura dostave energije okoli 20 °C (Axaopoulos, 2011). Ta metoda za določen solarni toplotni sistem poda delež skupne toplotne obremenitve, ki jo zagotavlja sončna energija. Glavni začetni podatek za načrtovanje sistema je površina kolektorja, ki jo na začetku izberemo v manjših dimenzijah in jo nato postopoma povečamo, dokler vrednosti sončne frakcije ne dosežejo približno 0,80.

Cilj magistrske naloge je bila predstavitev načrtovanja in ocena izvedljivosti nekaterih ukrepov za izboljšanje učinkovitosti stavb glede na porabo energije in vode. Naloga si je prizadevala prikazati različne ukrepe za ponovno uporabo energije in vode, pri čemer je bil poseben poudarek na turističnih objektih, saj so veliki porabniki energije in vode. Pozornost smo najprej namenili kvantifikaciji in karakterizaciji vodnih in energetskih tokov v stavbah.

Za oceno vplivov ukrepov in optimizacijo vodnih in enegretskih tokov smo izbrali turistični objekt Hotel Salinera, ki se nahaja v slovenskem obmorskem mestu Strunjan. Hotel ima skupno 101 sob, ki lahko sprejmejo največ 259 gostov na noč in obratuje skozi vse leto. Nudi različne ugodnosti, vključno z notranjimi in zunanjimi bazeni, wellness centrom in restavracijo. Hotel je obdan z obsežnimi zelenimi površinami velikosti 4 hektarjev, ki jih redno zalivajo s pitno vodo.

Trenutno upravljanje vodnih in energetskih tokov v hotelu sledi konvencionalnim praksam. Pitno vodo oskrbuje javni vodovod, povprečna poraba znaša 63 m^3 na dan skozi vse leto. Od tega znaša povprečna količina sive vode 31 m^3. Sistem ogrevanja prostorov in priprave tople vode znatno vpliva na porabo energije v hotelu. Za zadovoljitev vseh potreb uporablja hotel toplotno črpalko, ki mesečno porabi približno 20 MWh, pri čemer se v nekaterih primerih pojavijo presežki nad40 MWh. V poletnih mesecih se hotel poslužuje tudi nafte, katere skupna poraba znaša 8172 litrov letno.

Za ločevanje in čiščenje sive vode iz vseh hotelskih sob smo predlagali dve možnosti. Prva možnost vključuje namestitev MBR sistema kot kompaktna rešitev za čiščenje sive vode, druga možnost pa umestitev RČN s podpovršinskim tokom. Očiščena siva voda se zbira in uporablja za zalivanje zelenih površin hotela in kot tehnološka voda jeseni in pozimi.

Tranzicijo na uporabo obnovljivih virov energije smo želeli zagotoviti z implementacijo solarnih toplotnih sistemov. Predlog je vključeval integracijo takega sistema z eno od dveh možnosti za ponovno uporabo sive vode. Projekt se je osredotočil na dimenzioniranje solarnih kolektorjev s steklenimi ploščami za proizvodnjo tople sanitarne vode na osnovi letne povprečne metode in metode F-chart. Poleg idealnega dimenzioniranja solarnega sistema, ki bi zagotovil ustrezno sončno frakcijo skozi celo leto, je bil poudarek na bolj izvedljivem predlogu projekta, ki upošteva razpoložljivo površino strehe za namestitev solarnih kolektorjev in drugih komponent sistema, začenši od kotla in ekspanzijske posode.

Projekt je predvideval, da se siva voda iz umivalnikov in tušev zbira v vodnem rezervoarju v kleti hotela. Le-ta uravnava surovi dotok in odtok sive vode v izbrani čistilni sistem ter temperaturo in kakovost sive vode. Njegova kapaciteta 10 m^3 predstavlja približno tretjino povprečne dnevne proizvodnje sive vode iz umivalnikov in tušev v sobah. Za ustrezno načrtovanje solarnega sistema smo preverili podatke o deležu tople vode v sivi vodi (Hervás-Blasco in sod., 2020) tudi s pomočjo italijanske tehnične specifikacije. Ugotovili smo, da je 18,8 m^3 dnevne tople sive vode sprejemljiva vrednost in se ujema s podatki iz literature.

V okviru projekta smo izračunali potrebno velikost biološkega reaktorja, ki znaša 5,8 m^3, specifično potrebo po kisiku ter površino membran in potrebno zračenje. S pomočjo podjetja CID - Čistilne naprave d.o.o. iz Kopra (Slovenija) smo določili potrebno začetno investicijo in operativne stroške za življenjsko dobo 20 let. Izkazalo se je, da začetna investicija znaša 118.250,00 evrov, medtem ko povprečni OPEX stroški pa 16.059,00 evrov. Ob predpostavki porabe električne energije 3 kWh/m^3 in ob upoštevanju slovenske cene električne energije v višini 0,20 EUR/kWh smo določili povratno dobo investicije, ki znaša 36,4 let. V primeru dodatne optimizacije MBR procesa, ko bi porabil pol manj energije na kubični meter vode, bi se povratna doba investicije zmanjšala za več kot polovico, in sicer na 16,2 let.

Dimenzioniranje RČN je pokazalo, da je potrebna površina za njeno umestitev enaka 475 m^2. Na podlagi te površine smo se odločili za umestitev treh celic širine 7,7 m in dolžine 20,5 m. Pri oceni zanesljivosti projekta RČN nam je pomagalo podjetje Limnos d.o.o., s katerim smo določili začetno investicijo na 127.930 evrov. Ob upoštevanju 5% stopnje amortizacije ter 2% povišanju operativnih stroškov na leto smo ocenili OPEX stroške v višini 3.714,50 evrov. Izkazalo se je, da je povratna doba investicije enaka 6.8 let. Ocenili smo, da bi bodisi RČN kot MBR doprinesla 45% zmanjšanje porabe pitne vode.

Pred aplikacijo povprečne letne metode in F-chart metode smo najprej določili vrednosti mesečnega dnevnega povprečja globalnega sevanja na nagnjeno površino. Nato smo na podlagi tehničnih podatkov kolektorja uporabili prvo metodo in dobili začetno površino kolektorjev, ki predstavlja vhodni podatek za uporabo bolj razširjene metode F-chart. Izračunali smo, da sončna frakcija 0,80 ustreza površini 233 m^2, kar presega razpoložljivo površino na južni strani strehe, ki znaša približno 225 m^2. Prilagoditev taki površini bi pomenila zagotavljanje letne sončne frakcije 0,74. Zaradi omejene razpoložljive površine v kleti, smo določili namestitev zmanjšanega števila sončnih kolektorjev, ki se izkaže kot edina izvedljiva možnost. Konfiguracija kolektorjev površine 62,5 m^2 je privedla do zmanjšanja porabe energije klasičnega sistema za 26%. Ekonomska analiza solarnega toplotnega sistema je pokazala, da se investicija v višini 44.137,53 evrov lahko povrne v zelo kratkem času. Čas diskontiranega povračila investicije je znašal 4,75 let, medtem ko je bila donosnost naložbe enaka 29.1%.

Pri rezultatih ekonomske analize nismo upoštevali dejstva, da bi vlada, v skladu z evropskimi strategijami, morala vlagati v take ukrepe. Če bi to storila, bi se ti ukrepi izkazali še bolj ekonomsko ugodni. V ekonomski analizi nismo upoštevali niti širših implikacij trajnostnega upravljanja z viri, ki bi celotno sliko dodatno obogatili. Dodatne koristi, ki jih taki koncepti prinašajo, so odpornost na pomanjkanje vode ali energije, manjša poraba virov, manjše onesnaževanje okolja, saj bi hotel proizvajal manj odpadne vode in porabil manj energije iz neobnovljivih virov; pri RČN še povečano hlajenje zaradi evapotranspiracije in dodatna biodiverziteta.

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