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NINA POGLIČ

VREDNOTENJE REŠITEV ZA RAVNANJE Z ODPADNO VODO V PLANINSKIH KOČAH Z METODO ANALIZE ŽIVLJENJSKEGA CIKLA

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EVALUATION OF SOLUTIONS FOR WASTEWATER MANAGEMENT IN MOUNTAIN HUTS USING THE LCA METHOD

Master thesis No.:

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ZAHVALA

Iskreno se zahvaljujem mentorici izr. prof. dr. Nataši Atanasovi in somentorjema Maximilianu Grau-u ter doc. dr. Darji Istenič, ki so me tekom pisanja magistrske naloge usmerjali in mi pomagali. Zahvaljujem se za vaše nasvete in konstruktivne kritike, ki so mi bili v veliko pomoč pri doseganju najboljše različice mojega dela.

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Izvleček

Magistrsko delo analizira okoljske vplive različnih tehnologij čiščenja odpadnih voda in načinov upravljanja v planinskih kočah s poudarkom na Koči pri Triglavskih jezerih, priljubljeni turistični destinaciji, ki se sooča z izzivi prekomernega vnosa hranil v bližnje Dvojno jezero. Z metodo analize življenjskega cikla (LCA) smo ovrednotili dva predlagana scenarija v primerjavi s sedanjim nepravilno delujočim sistemom čiščenja odpadnih voda. Upoštevali smo kategorije vplivov, kot so globalno segrevanje, poraba vode, evtrofikacija sladke vode, ekotoksičnost sladke vode in izraba fosilnih virov.

Pri Scenariju I je predviden sodoben membranski filter, medtem ko so v scenariju II vključene robustne tehnologije, kot so suha stranišča in ratlinske čistilne naprave (RČN). Rezultati LCA so pokazali, da ima scenarij II manjši vpliv na okolje v vseh kategorijah vplivov, zlasti pri izrabi fosilnih goriv, kjer je vpliv scenarija I 25-krat večji od vpliva scenarija II. Analiza je pokazala pomen izbire materialov, saj so solarni paneli v scenariju I prispevali skoraj 60 % celotnega vpliva na sladkovodno ekotoksičnost v fazi gradnje. V obeh scenarijih imajo na okoljski odtis ključno vlogo puhala. Oba scenarija pozitivno vplivata na kategorijo vpliva porabe vode, kot posledica ponovne uporabe vode in uporabe suhih stranišč. Pri Scenariju II je velik pozitivni vpliv prihranka vode zmanjšal celoten okoljski vpliv sistema.

Analiza je pokazala, da se je pri optimizaciji ravnanja z odpadnimi vodami v gorskih kočah potrebno osredotočiti na robustne tehnologije z minimalnimi potrebami po energiji. Po zgledu švicarskih koč, kjer se vse bolj uveljavlja vgradnja suhih stranišč in drugih energetsko učinkovitih rešitev, rezultati predlagajo podoben premik tudi za slovenske planinske koče.

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Abstract

Master's thesis analyses the environmental impacts of different wastewater treatment technologies and management methods in mountain huts, focusing on the Triglav Lakes Hut, a popular tourist destination facing organic and nutrient pollution in the nearby Double Lake. Using Life Cycle Assessment (LCA), we evaluated two proposed scenarios against the current malfunctioning wastewater treatment system. We considered impact categories such as global warming, water consumption, freshwater eutrophication, freshwater ecotoxicity, and fossil resource scarcity.

Scenario I include a modern membrane filter, while Scenario II include robust technologies such as dry composting toilets and constructed wetlands (CW). The LCA results showed that Scenario II had a lower environmental impact in all impact categories, particularly in the scarcity of fossil resources, where the impact of Scenario I is 25 times higher than Scenario II's. The analysis showed the importance of material choices, with solar panels in Scenario I contributing almost 60% of the total impact on freshwater ecotoxicity in the construction phase. In both scenarios, blowers play a vital role in the environmental footprint. Both systems positively impact the water consumption impact category due to water reuse and dry toilets. In Scenario II, the significant positive impact of water savings reduced the overall environmental impact of the system.

The analysis shows that optimising wastewater management in mountain huts should focus on robust technologies with minimal energy requirements. Following the example of Swiss huts, where the installation of dry toilets and other energy-efficient solutions is gaining popularity, the results suggest a similar shift for Slovenian mountain huts.

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LIST OF ABBREVIATIONS

WWTP – Wastewater Treatment Plant

CW – Construction Wetland

SBR – Sequential Batch Reactor

MBBR – Moving Bed Biological Reactor

TF – Trickling Filter Systems

RBC – Rotating biological contactor

MBR – Membrane Bio Reactor

COD – Chemical oxygen demand

BOD_5 – Biochemical oxygen demand

TN – Total nitrogen

TP –Total phosphate

NH4-N – Ammonium

NO3-N – Nitart

NaOCl – Sodium hypochlorite

$FeSO_4$– Iron (II) sulfate

PE – Population Equivalent

TNP – Public Institute of the Triglav National Park

LCA – Life Cycle Assessment

LCI – Life Cycle Inventory

RS – Republic of Slovenia

EPA – Federal Environmental Protection Act

WPA – Water Protection Act

NGO – Non-governmental organisation

SAC – Swiss Alpine Club

1 INTRODUCTION

Mountain regions are known for their scenic beauty and unique ecosystems. Nonetheless, the mounting fascination with mountaineering in these areas has led to a significant hazard from pollution, mainly from wastewater. Many of the mountain huts in Slovenia are grappling with malfunctioning wastewater treatment plants (WWTP), leading to the treated wastewater exceeding the acceptable limits for environmental release. Pollution in sensitive environments like mountains can be very harmful. An example is the Triglav Lakes Hut, where improper wastewater management caused algae blooms in Double Lake.

Mountain huts usually use small on-site treatment plants to treat their wastewater. The most popular technologies in Slovenian huts are Sequencing Batch Reactor (SBR), Trickling Filter (TF), Moving Bed Biological Reactor (MBBR), Septic tank, Constructed Wetland (CW), Membrane Biological Reactor (MBR) and Rotating Biological Contactor (RBC, Biodisk). Picking a wastewater treatment technology for mountain huts is intricate and multifaceted. It calls for a comprehensive approach to balance environmental sustainability, resource efficiency, and practicality, which is crucial to safeguard these unspoiled environments. Life cycle assessment (LCA) can assist in the comprehensive environmental evaluation of technology`s impacts, thus selecting the most appropriate.

The LCA technique focuses on calculating estimates of the environmental effects produced by a process or item during its lifespan. Usually, a "cradle to grave" perspective is adopted, analysing the environmental impact from the start of production to the disposal stage (end of life).

The benefit of using LCA is that it is a widely recognised and well-established technique frequently employed to evaluate the effects of separate wastewater treatment methods and to contrast them. Nevertheless, LCA has disadvantages and restrictions, such as defining the right system boundary to get representative results. Most studies on the life cycle assessment of wastewater treatment evaluate its effects on climate change, water pollution, and ecosystem damage, particularly on marine and freshwater habitats. They also consider the reduction of resources such as fossil fuels and the alteration of soil properties. (Adapted from Laitinen et al., 2017).

The goal of the Master`s thesis is first to evaluate the environmental impacts of different wastewater treatment technologies applied in a particular mountain hut situated in Triglav Lakes Valley as part of the “Vrh Julijcev” project using Life Cycle Assessment (LCA). Secondly, to examine the practice of wastewater treatment in the Swiss Alps and provide the best technologies applicable in Slovenia by considering differences in legislation and practice.

Thus, the research questions of the thesis are:

- Which of the proposed technologies is the least environmentally impactful for wastewater management at Triglav Lakes Mountain Hut?

- Are the proposed technologies more environmentally friendly than the existing technology used in the hut?

- What are the so-called “hot spots” of the proposed technologies, and how can we reduce their environmental impact?

- After examining the treatment technologies and concepts used in the Swiss Alps, can some of those be replicated in Slovenia and applied in Slovenian mountain huts?

2 LEGISLATION

The EU Directive on urban wastewater treatment (Directive 91/271/EEC) is currently in force and was adopted in 1991. This Directive regulates the collection, treatment and discharge of urban wastewater and the treatment and discharge of wastewater from specific industrial sectors. When dimensioning WWTP, it is necessary to consider the prescribed limit values that the treated water can reach when discharged into the environment. Since we were interested in implementing Swiss technologies in the Slovenian mountains, the following subsections present the transposition of the EU Directive into Slovenian legislation and Slovenian and Swiss regulations in this field.

2.1 SLOVENIAN LEGISLATION

The requirements of Slovenian legislation on urban wastewater discharge and treatment align with European legislation's requirements. The main provisions transposed from the Directive into Slovenian law are:

- Decree on the discharge and treatment of urban wastewater (Official Gazette of the RS, No 98/15, 76/17, 81/19, 194/21 and 44/22 - ZVO-2).
- Decree on the emission of substances and heat when discharging wastewater into waters and the public sewage system (Official Gazette of the RS, No. 64/12, 64/14, 98/15, 44/22 - ZVO-2, 75/22 and 157/22).
- Rules on initial measurements and operational monitoring of wastewater (Official Gazette of the RS, No. 94/14 and 98/15).
- Environmental Protection Act (Official Gazette of the Republic of Slovenia, no. 44/22, 18/23 – ZDU-1O and 78/23 – ZUNPEOVE).

The following regulations relating to wastewater management also apply:

- Decree on the management of sewage sludge from the urban wastewater treatment plants (Official Gazette of the RS, No. 62/08 and 44/22 – ZVO-2).
- Decree on the classification of structures (Official Gazette of the RS, No. 96/22).
- Building Act (Official Gazette of the RS, No. 199/21 and 105/22 – ZZNŠPP).

Of the above listed, the most relevant to wastewater management in mountain huts is the Decree on the discharge and treatment of urban wastewater (Official Gazette of the RS, No 98/15, 76/17, 81/19, 194/21 and 44/22 - ZVO-2). Article 21 states that in the case of a mountain hut located within 100 metres of a sewerage connection, where a public water supply system does not provide the drinking water supply, and where the hut is in an area outside the limits of an agglomeration, treatment of urban wastewater must be provided in a small sewage treatment plant with a capacity of less than 50 PE. A small WWTP must consist of a mechanical treatment unit from which the wastewater is discharged via further treatment, filtration, or infiltration. They must be constructed in such a way as to prevent leakage and escape of wastewater into the environment. The aeration of the WWTP or the septic tank must also be ensured. Sludge collection must be provided as prescribed in Article 17 of this Regulation for managing sludge from WWTP with a capacity of less than 50 PE. The public service operator must ensure that the sludge is collected at intervals determined according to the capacity of each WWTP, but at least once every three years.

Article 21 of the Regulation also states that for facilities smaller than 50 PE, the collection of urban wastewater in a septic tank is allowed if the treatment of urban wastewater is not feasible due to a prohibition on the discharge of wastewater into water or specific geographical conditions that may adversely affect the operation of the WWTP (e.g. altitude above 1500 m) or if the urban wastewater is from a facility with no permanent employees.

The Decree on the emission of substances and heat when discharging wastewater into waters and the public sewage system (Official Gazette of the RS, No. 64/12, 64/14, 98/15, 44/22 - ZVO-2, 75/22 and 157/22) sets emission limit values for substances after primary treatment. In the case of a WWTP with a capacity between 50 and 2000 PE, COD must not exceed 150 mg/l and BOD5 30 mg/l. For WWTP with a capacity of up to 50 PE, limit values are set only for COD, namely a value not exceeding 200 mg/l. There is no limit on nitrogen, phosphorus, and microbiological pollution discharge levels. The Decree also stipulates that the direct discharge of urban wastewater into groundwater is prohibited. Indirect discharges are prohibited in water protection areas, catchment areas of natural lakes (unless they are catchment areas of an intermittent lake) and within 300 m of the shore of a natural or artificial lake.

No specific emission limit values exist for nature-protected areas, but they are the same as for other areas in the country. They also do not set out guidelines for selecting and designing treatment systems. Decree on the discharge and treatment of urban wastewater (Official Gazette of the RS, No 98/15, 76/17, 81/19, 194/21 and 44/22 - ZVO-2) only stipulates that anyone disturbing nature or the habitat of populations of plant or animal species must use methods that contribute to the maintenance of the species' favourable status. Among other things, any plan or amendment to a plan adopted by the competent authority for wastewater management that could significantly affect a protected area must be subject to a variability of impact assessment.

Other laws affecting wastewater treatment in sensitive areas:

- Water Act (Official Gazette of the RS, No. 67/02, 2/04 – ZZdrI-A, 41/04 – ZVO-1, 57/08, 57/12, 100/13, 40/14, 56/15, 65/20 and 35/23 – odl. US and 78/23 – ZUNPEOVE).
- Nature Conservation Act (Official Gazette of the RS, No. 96/04, 61/06 – ZDru-1, 8/10 – ZSKZ-B, 46/14, 21/18 – ZNOrg, 31/18, 82/20, 3/22 – ZDeb, 105/22 – ZZNŠPP and 18/23 – ZDU-1O).
- Cultural Heritage Protection Act (Official Gazette of the RS, No. 16/08, 123/08, 8/11 – ORZVKD39, 90/12, 111/13, 32/16 and 21/18 – ZNOrg).
- Decree on the environmental tax on pollution due to wastewater discharge (Official Gazette of the RS, No. 80/12, 98/15 and 44/22 – ZVO-2).
- Rules on sensitive areas (Official Gazette of the RS, No. 98/15 and 44/22 – ZVO-2).

- Triglav National Park Act (Official Gazette of the RS, No. 52/10, 46/14 – ZON-C, 60/17, 82/20 and 18/23 – ZDU-1O).
- Decree on activities affecting the environment that require an environmental impact assessment (Official Gazette of the RS, No. 51/14, 57/15, 26/17, 105/20 and 44/22 – ZVO-2).

The Water Act (Official Gazette of the RS, No. 67/02, 2/04 – ZZdrl-A, 41/04 – ZVO-1, 57/08, 57/12, 100/13, 40/14, 56/15, 65/20 and 35/23 – odl. US and 78/23 – ZUNPEOVE) prohibits the direct discharge of wastewater into groundwater, the release of wastewater into natural lakes, ponds, swamps, and other natural bodies of water which have a permanent or intermittent inflow or outflow of inland or groundwater, and into bodies of water created by the extraction or exploitation of minerals or other similar operations and in contact with groundwater.

The Decree on the environmental tax on pollution due to wastewater discharge (Official Gazette of the RS, No. 80/12, 98/15 and 44/22 – ZVO-2) provides that the person liable to pay the environmental charge for the release of urban wastewater into the environment is the legal or natural person who is the occupier of the building where the urban wastewater is produced. Discharging urban wastewater into the environment causes pollution and pollution.

2.2 LEGISLATION IN SWITZERLAND

The Swiss Parliament has enacted various federal statutes to protect natural resources. The primary laws that consider wastewater treatment management are:

- Federal Environmental Protection Act of 1983 (EPA) and
- Federal Water Protection Act of 1991 (WPA).

Non-governmental organisations (NGOs) are active in Switzerland. They participate in the legislative process, exert influence on the formation of public opinion and initiate legal proceedings. One of the NGOs ensuring that activities in mountain huts are environmentally friendly is the Swiss Alpine Club (SAC). There are 153 huts in the SAC.

On average, the mountain huts that are part of the SAC receive up to one million daily visitors, of which 300,000 and 350,000 spend the night. The use of the huts naturally generates a lot of wastewater. SAC's chalets management, including wastewater management, aims to be as environmentally friendly as possible (Strategie für die Abwasser-und Schlammentsorgung auf SAC-Hütten, 2020). The main goals of SAC are:

- Reducing pollution of surface water and groundwater,
- Reducing the input of pollutants into ecosystems that are particularly vulnerable to pollution,
- Eliminating the direct discharge of untreated wastewater into water bodies,
- Good hygienic and aesthetic conditions in toilets (minimising odours and maximising cleanliness).

In achieving these objectives, the SAC, like all other operators of mountain huts, must comply with the applicable legislation and recommendations for wastewater discharge. The

Water Protection Ordinance specified (WPA 814.201) that: "For communal wastewater from WWTP with 200 PE or fewer and for wastewater from overflows from combined systems, the authorities determine the requirements from case to case, taking local conditions into consideration". The guideline value proposed by the Association of Swiss Wastewater and Water Protection Experts (VSA) and applied by the Canton of Bern states that a small WWTP without nitrification with < 200 PE should not exceed a COD of 90 mg/l (Doll & Etter, 2018). The WPA sets out the requirements for the minimum permissible values of the parameters of treated wastewater that can be discharged back into the environment. For the discharge of treated wastewater into sensitive environments, additional requirements are specified in the WPA, shown in Table 1.

Table 1: Additional requirements for the discharge of treated wastewater into sensitive environments (WPA 814.201)

Parameter	Requirements
Total phosphorus (after conversion to dissolved orthophosphate)	For wastewater from plants: - in the catchment area of lakes, - situated on watercourses downstream of lakes, if this is required for the protection of the watercourse, the following requirements apply: - discharge concentration: 0.8 mg/l P and - removal efficiency, concerning raw wastewater: 80%.
Total nitrogen	Plants for which no discharge concentration and removal efficiency for total nitrogen is specified must be operated so that as much nitrogen as possible is eliminated during wastewater purification and sludge treatment. All possible structural modifications must be undertaken at no significant cost; this applies particularly to plants that already carry out nitrification.

3 THEORETICAL BACKGROUND AND LITERATURE REVIEW

3.1 ENVIRONMENTAL IMPACT OF MOUNTAIN HUTS

Initially, mountain huts were only modest shelters, either to protect against bad weather or to be used by hikers to rest between longer hikes. Mountaineering was established in the 18th century and has become increasingly popular among all populations, increasing the desire for comfort (Bobovnik, 2012). Now, mountain huts in Slovenia are an essential part of the country's tourism industry and offer visitors the opportunity to explore the beautiful natural environment. However, these huts also have a significant environmental impact on their surrounding areas.

Bobovnik (2012) defined the environmental impacts of mountain huts as the sum of the environmental impacts of mountaineering and the environmental impacts of accommodation facilities. He also stressed that the fact that the mountain world is compassionate regarding the landscape should be considered, and the negative consequences could be even more significant. Environmental impacts in the hills can be direct (wastewater discharges, noise, etc.) or indirect (walking on mountain paths causing soil erosion, disturbance to wildlife, etc.) (Bobovnik, 2012).

The environmental impact of mountain huts on water resources can be significant. Mountain huts generate various waste streams that can contaminate nearby water sources, including surface water and groundwater. In addition to waste contamination, mountain huts can impact water resources through increased water use. For example, huts may rely on nearby streams or lakes for their water supply, which can deplete water sources and impact aquatic ecosystems. Moreover, washing dishes, cooking, and cleaning the hut can increase the demand for water resources.

For these reasons, good wastewater management is crucial for protecting the environment in the mountains. LCA is an example of a valuable tool that can help us improve wastewater management systems and support decision-making in favour of more environmentally friendly options.

3.2 WASTEWATER MANAGEMENT IN MOUNTAIN HUTS

If available, higher-altitude huts are often supplied with water via rainwater or nearby water sources. When there is a long period without rain, mainly in the summer, many mountain huts experience water shortages (Duhovnik, 2002). This is also the peak season for mountaineering, so this shortage is even more significant.

One of the significant problems in the mountain huts is wastewater management. As mentioned, wastewater is the resulting water that has been altered during human use; uses can be related to domestic, commercial, agricultural, industrial, etc., human activities.

In mountain huts, wastewater typically consists of organic matter and nutrients (nitrogen and phosphorous), mainly from the kitchen, toilets and washing rooms. Kitchen waste like food scraps and cooking oils must be collected and disposed of separately. The amount of water used and the resulting wastewater generated in mountain huts also depends on the supply in the hut. A wide range of food, showers, laundry, and even flush toilets can significantly increase wastewater generation in huts when there is a high level of hut visitation. Laundry wastewater can contain detergents and other chemicals that harm aquatic life and impact water quality.

The primary purpose of wastewater treatment is to remove organic material, nitrogen and phosphorus compounds and pathogens, thereby preventing eutrophication, ecosystem degradation and the risk of deterioration of human health (Jenssen, 2018). Current trends include reusing wastewater, using biological treatment methods, and achieving zero-waste results to minimise environmental pollution (Gutterer et al., 2009).

One of the primary challenges of wastewater management in mountainous areas is the lack of infrastructure. Many remote communities in the mountains need access to a centralised sewage system, making the disposal of wastewater a challenge. In such cases, decentralised wastewater treatment systems such as septic tanks, composting toilets, and small-scale treatment plants are often used.

In addition to the need for more infrastructure, the rugged terrain of mountainous areas can make the construction and maintenance of wastewater treatment systems challenging. This can result in higher costs and longer construction times. Furthermore, the unique ecosystems in mountainous regions must be considered when designing wastewater treatment systems to prevent environmental harm.

The selection and design of appropriate wastewater treatment in mountain huts is also challenging due to seasonal operation or dormancy and the uneven flow of wastewater, which can vary considerably between seasons (Kaczor et al., 2014).

In his thesis, Čepon (2013) investigated the functioning of WWTP in seven Slovenian mountain huts. He found that chemical oxygen demand (COD) and biological oxygen demand (BOD_5) values exceeded the regulatory limits in all but one of the observed huts, which was equipped with an MBR (Table 2). The malfunctioning of the treatment plants was due to the overloading of all the treatment plants and would require either a system upgrade or an increase in the system capacity.

Table 2: Effluents from the analysed WWTP in Slovenian huts (Čepon, 2013)

HUT	COP (mg/L)	Nt (mg/L)	Pt (mg/L)
Gospodična	6 - 35	48-84	5.3-14.4
Lisca	63-179	15.6-96	3.1-13.7
Lubnik	147-486	105-170	2.1-23.9
Ratitovec	57-682	50.6-209	7.7-24.3
Valvasor	74-149	111-147	15.5-17.4
Ermanovec	72-757	23-175	10.2-28.2
Planina	177-386	107-284	11.1-21.1

Despite these challenges, several effective wastewater management strategies can be implemented in mountainous areas. For instance, greywater reuse can be a sustainable way to manage wastewater in these areas. Greywater is the relatively clean wastewater from bathing, washing, and laundry. This water can be treated and reused for non-potable purposes.

This reduces the demand for freshwater resources and the amount of wastewater that needs to be treated and disposed of.

In 2012, the Slovenian Mountain Association (Planinska Zveza Slovenije – PZS) introduced a special certificate for huts with the least possible negative environmental impact - the Environmentally Friendly Mountain Hut (Figure 1). By 2019, 28 mountain huts had received the certificate. The certificate, which must be renewed every four years, covers seven areas: energy and climate protection, drinking water and wastewater, waste, air, noise, building materials, food in the hut and the surrounding area.

Figure 1: The certificate for the environmentally friendly mountain hut (Source: https://www.pzs.si)

3.3 MOST COMMON WASTEWATER TREATMENT TECHNOLOGIES USED IN SLOVENIAN HUTS

Slovenia has 179 mountain huts, shelters and bivouacs (Figure 2). According to the Act on the Triglav National Park (ZTNP-1), a mountain hut provides accommodation, basic food and drink and is intended for this purpose. In contrast, a bivouac, shelter or similar high mountain facility offers shelter. Table 2 displays the Slovenian huts equipped with some form of WWTP. Please note that dry toilets are not tabulated since their information was not obtained.

Figure 2: Map with all the Slovenian huts, shelters and bivouacs (Source: https://www.pzs.si)

Table 3: List of Slovenian huts with information about the type of treatment system (PZS, 2023)

NAME OF THE HUT	Type of treatment system	Capacity (PE)	Year of establishment	Altitude (m)
Aljažev dom v Vratih	SBR	70	2003	1015
Cojz's Cottage at Kokrski sedlo	Trickling filter	-	1999	1793
Dr. Klement Hugo's house in Lepena	MBBR	50	2008	700
House on Komna	Septic tank	-	2005	1520
House on Lubnik	SBR	14	2010	1002
House on Menina planina	CW	32	1998	1453
House on Peca	Trickling filter	48	2001	1665
House on Šmohorju	MBBR	12-16	2016	784
House on Uršlja mountain	SBR	4	2012	1680
Home of the mountaineers in the Logar Valley	Central WWTP Logarska valley	-	-	837
Home at the source of the Završnice River	SBR	20	2014	1425
Pristava House in Javornišek Rovt	SBR	20	2014	975
Domžale house on Mala planina	SBR	14-16	2011	1534
Erjavec's Cottage on Vršič	SBR	30	2014	1525
Frischauf House on Okrešlj	Trickling filter		1998	1396
Jurek's cottage on Lisca	CW	49	2012	927
Kamnik Cottage on Kamnik saddle	Trickling filter		1999	1864
Anton Bavčer's cottage on Čavno	Septic tank	5-25	2012	1242

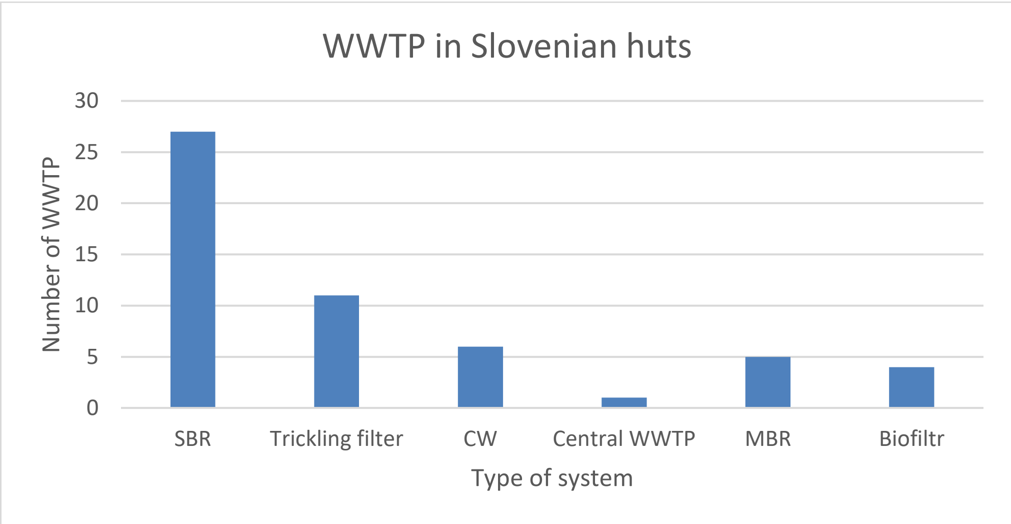
The table continues on the next page…

Cottage on Blegošu	SBR	-	2006	1391
Cottage on Bohorju	MBR	-	2012	896
Cottage on Golici	biofilter	15	2022	1582
Cottage on Grohotu	Trickling filter	40	2005	1460
Cottage on Kriški gori	MBR	4	2019	1471
Cottage on Loka pod Raduho	Trickling filter	40	2001	1534
Cottage on Pikovem	Septic tank	20	2005	992
Cottage on Planina nad Vrhniko	biofilter	6	2012	733
Cottage on Planina pri Jezeru	SBR	30	2007	1453
Cottage on Planina Razor	CW	49	2008	1315
Cottage under Bogatin	Trickling filter	42	2011	1513
Cottage at the source of the Soča River	SBR	20	2013	886
Cottage at Jelen's Spring	biofilter	8	2013	850
Cottage at the Triglav Lakes	SBR	50	2010	1685
Kosije's home on Vogar	biofilter	15	2016	1054
Kranjska hut at Ledine	Trickling filter	65	2002	1700
Cottage of Krek at Ratitovec	SBR	25	2011	1642
Mrzl'k mountain hut	SBR	-	2011	1356
Planinska koča Mrzl'k	MBR	-	2016	971
Mountain hut on Ermanovec	MBBR	2 do 5	2012	968
Mountain hut on Uskovnica	SBR	25	2010	1154
Čemšenik mountain lodge	MBBR	40	2003	840
Košenjak mountain lodge	SBR	20	2014	1169
Mountain Lodge on Boč	SBR	35	2009	658
Mountain Lodge on Bukovica	SBR	6	2013	584
Mountain Lodge on Čreta	MBBR	6	2016	876
Mountain Lodge on Mount Oljeka	SBR	25	2020	725
Mountain Lodge on Kišče	Trickling filter	65	2001	1534
Mountain Lodge on Kum	Septic tank	20	2015	1211
Mountain Lodge on Mirna Mount	SBR	-	2011	1000
Mountain Lodge on Resevna	MBBR	16	2018	636
Planinski dom na Uštah - Žerenku	CW	50	2017	658
Mountain Lodge on Zelenica	SBR	30	2011	1536
Mountain lodge at Gospodična na Gorjancih	MBR	20	2009	828
Mountain Lodge near Krn Lakes	Trickling filter	46	2013	1385
Mountain Lodge at Mount	SBR	16	2016	762
Mountain shelter at Korada	SBR	5	2019	803
Pogačnik's home at Kriški podi	SBR	50	2014	2050
Postman's House at Vršič	MBR	50	2017	1688
Roblek's House at Begunjščićica	SBR	8	2011	1657
Slavkov's home on Golo Brdo	SBR	25	2004	396
Šlajmerjev dom v Vratih	SBR	70	2003	1015
Tonka's house in Lisca	CW	49	2012	927
Tum's Cottage on Slavnik	Septic tank	15	2015	1018

The table continues on the next page…

Valvasor's house under the Stol	SBR	40	2010	1181
Vodnik's house in Velo Polje	Trickling filter	26	2015	1817
Mountain Guard Shelter at Jelenci	CW	-	2023	1185

Of 176 Slovenian mountain huts, 54 are equipped with small WWTP, and two are connected to the public sewerage system (Table 3). Small-scale treatment plants at the huts include SBR (27), Trickling Filter Systems (14), Constructed Wetlands (6), Trickling filters (11), Membrane Biological Reactor (5) and Moving Bed Biological Reactor (6) (Graph 1).



Graph 1: Types and number of WWTP in Slovenian huts

3.4 COMMON TECHNOLOGIES USED IN SWISS MOUNTAINS

Similar to Slovenia, a common approach to wastewater management in Swiss alpine huts uses on-site treatment systems, water conservation measures, and proper sludge management. A significant difference compared with the situation in Slovenia is that wastewater management in Swiss mountain huts has evolved to prioritise sustainable and environmentally friendly solutions. The standard for new renovations encourages dry sanitation systems with urine diversion to ensure minimal water use. Faecal waste is managed through on-site composting or, if necessary, helicopter transport for off-site disposal.

The norm for new renovations of mountain huts in Switzerland favours dry sanitation systems with urine diversion. This approach helps to minimise water and energy consumption and reduces the environmental impact of wastewater discharge. Urine and grey water are combined and disposed of through appropriate treatment systems or soakaways.

As dry toilets are being installed in many Swiss huts, new and improved technologies for composting and managing urine are being developed (Figure 3).

Figure 3: Dry, separate toilet at Lämmerenhut (Source: https://www.sac-cas.ch/it/le-alpi/le-capanne-cas-testano-la-depurazione-delle-acque-del-futuro-33182/)

An example of the development of a new technology is the autarky module, which was designed to stabilise and treat urine. The autarky module was connected to the existing urine line of the Legler hut, which lies 2.273 m above sea level (Figure 4). The urine module converts urine, separated from faeces and rinse water, into fertiliser by stabilising and drying it. Stabilisation fixes essential plant nutrients in the urine, kills pathogenic microbes and prevents odours.

Figure 4: Autarky module at the Legler hut (Source: https://www.eawag.ch/en/info/portal/news/news-detail/testing-the-blue-diversion-autarky-toilet-in-situ/)

Vermicomposting is a standard method of on-site composting that is increasingly used in the Swiss Alps. Vermicomposting composes organic waste using worms, typically red worms (Eisenia fetida) or earthworms, to break down the waste and turn it into nutrient-rich compost. Red worms are highly adaptable and can tolerate a range of temperatures. It is an efficient and sustainable method of recycling organic waste and producing a high-quality soil amendment (Training Material Composting Vermicomposting, 2006). The Vertical Subsurface Flow CW and vermifilter combination are also often installed and proven to be a successful solution for greywater treatment in high mountain areas. An example of such a system is in operation at the Oberes Brüggli mountain restaurant at an altitude of 1159 m. The highest CW in Switzerland is at Martinsmadhütte at 2002m above sea level (Figure 5).

Figure 5: The highest CW in Switzerland (Source: https://vuna.ch/wp-content/uploads/2022/09/Fiches-Vuna-1.pdf)

Using charcoal instead of sand in CW material is becoming more common as it reduces the weight of the material. This makes it easier to transport and install the material. The picture below shows the treatment plant installed at the Chamanna Cluozza hut, which treats the grey water produced by the hut (Figure 6).

Figure 6: CW at the Chamanna Cluozza hut (Source: https://vuna.ch/wp-content/uploads/2022/09/Fiches-Vuna-1.pdf)

Simple and robust systems such as the Biorock system, based on trickling filters for wastewater treatment, are often chosen for cabins where flush toilets are available. The Biorock system uses a combination of biological and physical processes to treat wastewater effectively. It typically consists of a series of tanks or chambers filled with porous media, such as rocks or plastic media, where wastewater is distributed. The porous media provide a large surface area for the growth of beneficial microorganisms that break down organic pollutants. The wastewater trickles through the media and is treated and collected for safe discharge or reuse. This type of system has been installed at the Grialetsch Hut, located at an altitude of 2542 m.

Commonly used technologies are also MBR and SBR. Zermatt ski resort has, for example, the highest functioning MBR in Europe. This system successfully treats wastewater from the renowned ski resort at 3300 meters above sea level (Figure 7). The negative side of this system is energy consumption, which they reduced with the removal of the UV disinfection (Mooser, 2006).

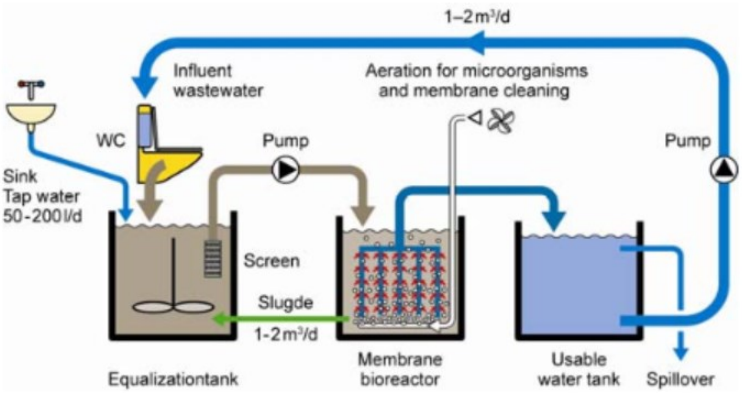


Figure 7: Shame of the wastewater treatment in Zermatt (Mooser, 2006)

The Bächlitalhütte hut (2328 meters above sea level) in the Grimsel area has also replaced its ageing septic tank with a small WWTP, and a new SBR plant went into operation at the end of summer 2017 (Mooser, 2006).

3.5 DESCRIPTION OF TECHNOLOGIES IN MOUNTAIN HUTS

Wastewater management and treatment systems can be divided into less technically demanding or more robust devices, such as a CW and a compost dry toilet, which require little or no energy. Or more advanced and slightly more energy intensive: SBR, MBBR, TF, RBC and MBR.

Constructed Wetland - CW

CW is an engineered system that mimics the natural processes of wetlands to treat wastewater. The system consists of a shallow basin or series of basins planted with wetland plants and filled with soil, gravel, or other porous materials. As wastewater flows through the wetland, it is naturally purified through various physical, chemical, and biological processes.

There are two types of CW, depending on how the water flows:

- Horizontal Flow Constructed Wetland, where wastewater travels horizontally through the cultivated filter bed, where the flora creates an ideal habitat for microbial adherence, promotes the development of aerobic biofilms and facilitates the diffusion of oxygen into the root area. Filtration and decomposition processes are primarily responsible for eliminating organic substances and suspended particles (Figure 8).

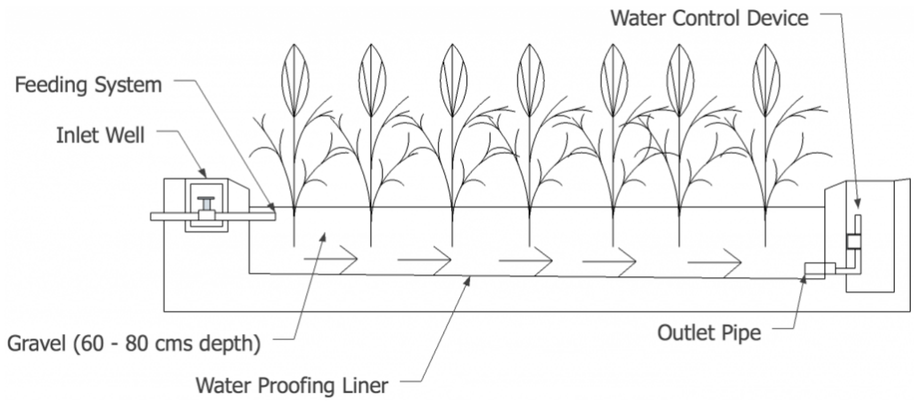


Figure 8: Horizontal flow constructed wetland (Source: https://sswm.info/step-nawatech/module-1-nawatech-basics/appropriate-technologies-0/horizontal-flow-constructed-wetlands-%28hfcw%29)

- Vertical Flow Constructed Wetland is drained at the bottom. Wastewater is applied or dosed from above using a mechanical dosing system, and it descends vertically through the filter matrix to accumulate in a drainage pipe at the basin's base. The important difference between a vertical and a horizontal wetland is the aerobic conditions (Figure 9).

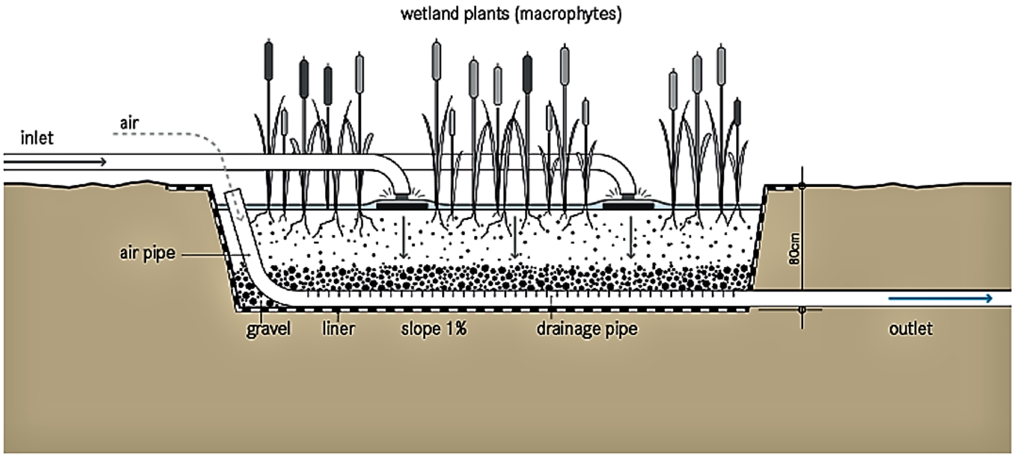


Figure 9: Vertical flow constructed wetland (Source: https://sswm.info/taxonomy/term/3934/vertical-flow-constructed-wetland)

CW offer several benefits for wastewater treatment in mountain regions as they are shown to be efficient. Because they are utilising natural processes to clean water, there is no need for energy and chemicals. However, to treat wastewater successfully, a CW is usually not enough. Therefore, it is often used as a polisher after a biological treatment (such as SBR or TF) to funder remove organic matter.

The most common plants used for CW in the mountains are reeds, hornwort, rushes, sedges, saxifrage and rumex (Bulc et al.,1997). They are characterised by an extensive root system that can absorb large amounts of nutrients, a high oxygen transport capacity and a high tolerance to different climatic conditions. However, the Triglav National Park Act, which only allows the planting of indigenous species, must be considered when constructing treatment plants on Slovenian mountains. Therefore, many species of grasses, sedges, willows, sorrel, nettles and others, which are entirely satisfactory in their purification efficiency, are used in these areas (Bulc et al.,1997).

Compost and dry toilets

Composting toilets were commercialised initially in Sweden and have been an established technology for more than 30 years, and perhaps longer in site-built forms (Anand & Apul, 2014).

The composting toilet is a nonwatery-carriage system (Figure 10) well-suited for remote areas with scarce water or areas with low percolation, high water tables, shallow soil, or rough terrain. Composting toilets eliminate the need for flush toilets, significantly reducing water use and allowing for the recycling of valuable plant nutrients. The choice of how to operate a composting toilet depends on the needs of the location. We can choose from regular dry toilets to ones with separating urine.

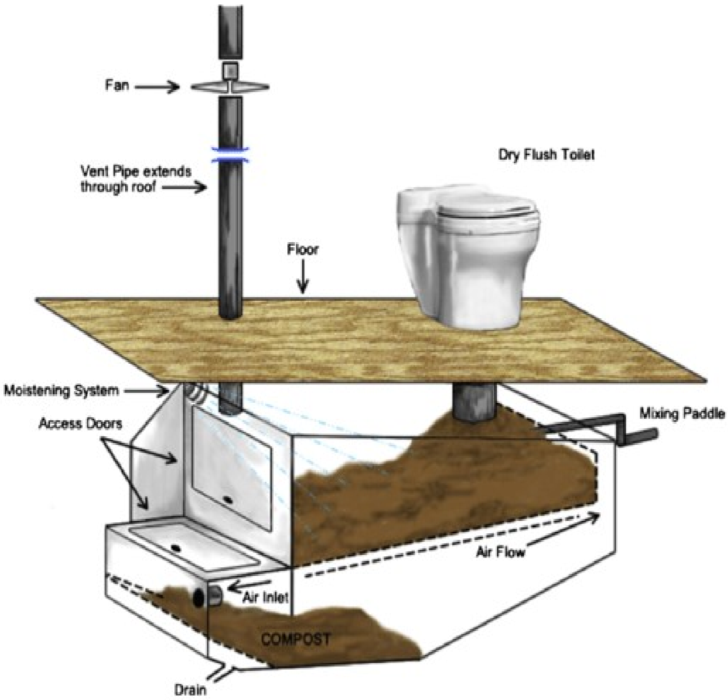


Figure 10: Typical dry toilet with composting (Anand & Apul, 2014)

Composting is the process of breaking down organic matter. Micro-organisms oxidise organic compounds under aerobic conditions, producing carbon dioxide, ammonia, volatile compounds and water. Decomposition releases energy microorganisms use to reproduce and grow; the rest is released as heat. The most common microorganisms that grow are actinomycetes, thermophilic aerobic bacteria and fungi. Actinomycetes are similar to moulds and fungi and are characterised by their ability to break down difficult-to-digest substances such as proteins, cellulose and starch. They also cause the smell of soil in compost. Thermophilic aerobic bacteria thrive at very high temperatures and are therefore adapted to decomposing waste in composting toilets, as heat is one of the by-products of the decomposition process. Fungi such as yeasts and moulds help break solid waste into smaller pieces, which bacteria take up and break down (Figure 11).

Several factors strongly influence the composting processes, such as water volume, temperature, carbon/nitrogen ratio, pH, particle size and porosity, and oxygen concentration. To ensure an optimal environment in composting toilets, bacteria require somewhere between 50-60% humidity, a temperature of around 50°C, sufficient aeration of the material and a carbon/nitrogen ratio of 30 to 35. Achieving these conditions is relatively difficult, which is why various agents are added to compost to bind moisture, increase its volume, and, at the same time, allow new excrements to cover the compost. Examples include sawdust, ash, bark chips and pieces of paper (Esrey, 1998).

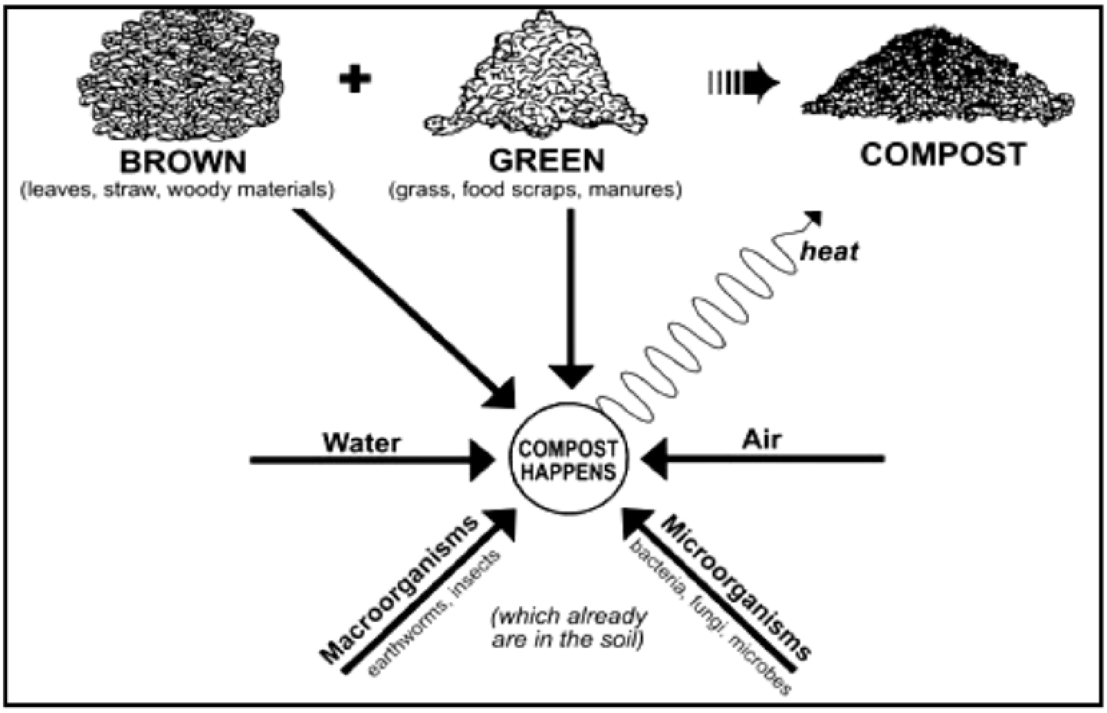


Figure 11: Process Flow Diagram of Composting Process (Training Material Composting Vermicomposting, 2006)

Adequate ventilation for composting is also needed to maintain aerobic conditions. Lack of oxygen in the pile can cause anaerobic conditions, leading to odour problems and reducing the composting rate. On the other hand, excessive airflow is also not recommended as it can remove too much heat and water vapour from the compost (Anand & Apul, 2014). So, a good design is needed to make the composting process work properly.

Sequencing batch reactor - SBR

SBR is a type of wastewater treatment system that uses a sequence of processes in a single tank to treat wastewater. The tank is divided into several compartments or stages, each designed to perform a specific treatment function.

The SBR system operates in batches, meaning the entire treatment process is completed in a single cycle. Each cycle consists of several phases: filling the tank with wastewater, aeration, settling, decanting, and idle time (Figure 12). The wastewater is treated as it moves through each phase (Vouk et al., 2017).

During the aeration phase, air is added to the wastewater, which helps to break down the organic matter in the wastewater. The settling phase follows, where the wastewater is allowed to settle, and the solids are separated from the liquid. The decanting phase involves removing the clear liquid from the top of the tank and leaving behind the settled solids, which are then removed (Vouk et al., 2017).

The idle time phase allows the remaining solids to settle to the bottom of the tank and for the system to prepare for the next cycle. Once the idle time phase is complete, the process begins again by introducing new wastewater (Vouk et al., 2017).

SBR systems are efficient and compact, making them suitable for locations with limited space, such as mountain huts. The negative side is that the system requires energy-intensive equipment, such as aerators and pumps, to facilitate the treatment process and needs regular maintenance with skilled personnel.

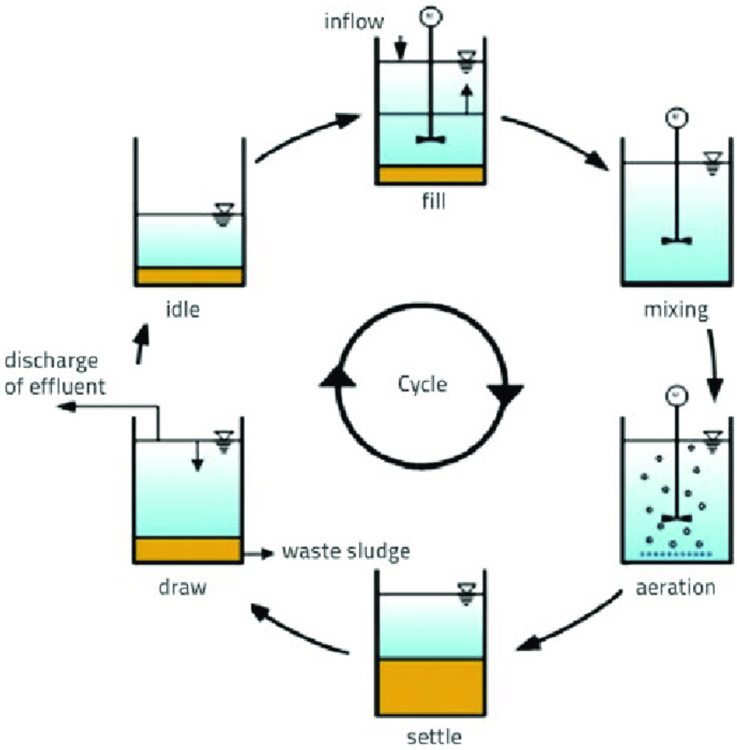


Figure 12: Phases in SBR (Vouk et al., 2017)

Moving Bed Biological Reactor - MBBR

MBBR is a biological process often used due to its efficiency, low operating cost, and sustainability. MBBR is a type of biological wastewater treatment technology that utilises the principles of attached growth. Attached growth refers to the growth of microorganisms on a solid support medium as a biofilm. MBBR uses a carrier material (Figure 13) that provides a surface area for microorganisms to attach and grow. The carrier material is made of high-density polyethene with a specific gravity greater than one, allowing it to remain submerged in water. The carrier material has a large surface area, providing ample microbial growth space. The MBBR technology consists of a tank that houses the carrier material and aeration system. The aeration system provides oxygen to the microorganisms attached to the carrier material, which allows them to break down the organic matter in the wastewater (Leyva-Díaz et al., 2017).

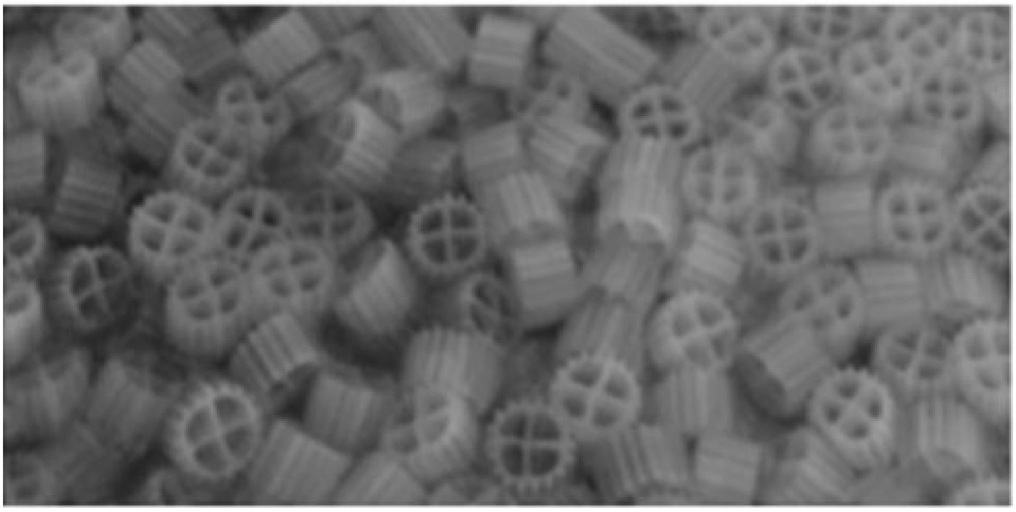


Figure 13: Carrier used in MBBR systems (Leyva-Díaz et al., 2017)

The biofilm on the carrier material acts as a natural filter, removing impurities from the wastewater. The carrier material is continuously in motion, which prevents the biofilm from becoming too thick, allowing for efficient oxygen transfer and preventing clogging (Leyva-Díaz et al., 2017).

The MBBR technology is a highly efficient and effective method of treating wastewater. The technology has several advantages over other treatment methods, including low operating costs, minimal sludge production, and high treatment capacity. The technology is also highly resistant to low temperatures, making it ideal for wastewater treatment in cold climates (Leyva-Díaz et al., 2017).

Trickling filter Systems - TF

TF is a type of biological wastewater treatment technology that uses a medium, such as rocks, gravel, or plastic, to support the growth of microorganisms that break down and remove organic pollutants from wastewater. The wastewater is distributed over the top of the medium and allowed to trickle down through the filter bed. As it passes through the filter bed, microorganisms attach to the surface of the medium and form a biofilm that breaks down and removes organic matter from the wastewater (Figure 14). The treated wastewater then flows out of the bottom of the filter bed and on to further treatment processes or discharge (EPA, 2000).

TF are effective at removing organic matter and suspended solids from wastewater but less effective at removing nutrients such as nitrogen and phosphorus. Therefore, they are often combined with other treatment technologies, such as activated sludge systems or constructed wetlands, to achieve more complete treatment (EPA, 2000).

There are two main types of TF: high-rate and low-rate. High-rate TF is designed to operate at a relatively high flow rate and is typically used for primary treatment or as a pre-treatment step for secondary treatment processes. Low-rate TF are designed to operate at a lower flow rate and provide more complete treatment. After secondary treatment, they are often used as a polishing step to remove remaining organic matter and suspended solids (EPA, 2000).

TF are a cost-effective and reliable technology for treating wastewater, especially in small to medium-sized communities. They are relatively simple to operate and maintain and can be designed to meet a wide range of treatment requirements (Buchanan, 2014).

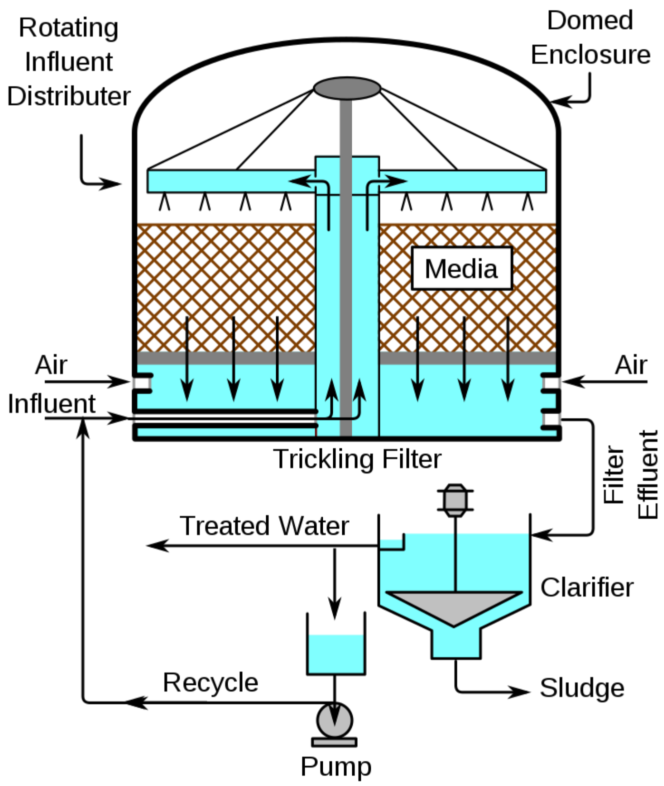


Figure 14: Scheme of Trickling filter (Source: https://www.thewatertreatments.com/wastewater-sewage-treatment/trickling-sewage-treatment/)

Rotating biological contactor - RBC

RBC or Biodisc is a biological treatment process that uses a rotating biological contactor to treat wastewater. The rotating disc provides a large surface area for microbial growth, which facilitates the removal of organic matter from the wastewater (Figure 15) (Waste Treatment, 2023).

The application of Biodisc in the alpine areas has been successful due to its robust design and efficient operation. Biodisc can operate at low temperatures and handle fluctuations in the influent flow rate and composition. This makes it suitable for use in remote alpine regions where access to electricity and other resources may be limited. Biodisc is also a low-maintenance technology crucial in remote areas where access to skilled personnel may be limited. Another advantage of Biodisc is its ability to handle fluctuations in the influent flow rate and composition. Seasonal variations in the volume and design of wastewater characterise the alpine regions. Biodisc can adapt to these changes, ensuring efficient wastewater treatment throughout the year (Waqas et al., 2023).

Although Biodisc has several advantages, some limitations must be considered when designing a wastewater treatment system. One of the limitations of Biodisc is its sensitivity to hydraulic shock. This can occur when there is a sudden increase in the influent flow rate or a change in the wastewater composition. Hydraulic shock can damage the microbial film on the rotating disc, reducing the system's efficiency (Waqas et al., 2023). Another limitation of Biodisc is its susceptibility to clogging. The rotating disc can become clogged with solids and other materials present in the wastewater. This can reduce the system's efficiency and require frequent disc cleaning (Waqas et al., 2023).

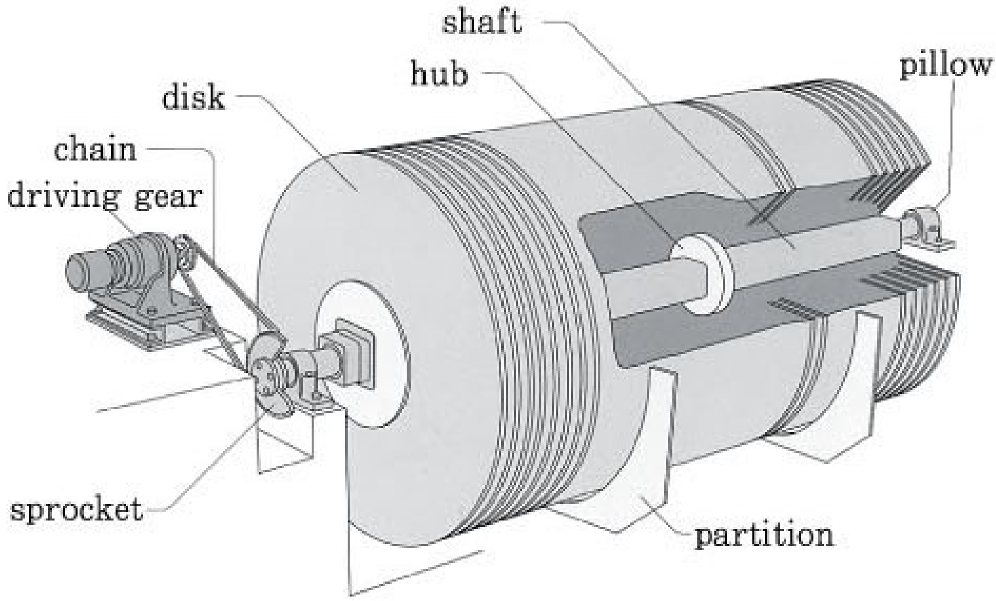


Figure 15: Rotating biological contactor (RBC) (Source: https://www.thewatertreatments.com/wastewater-sewage-treatment/trickling-sewage-treatment/)

Membrane biological reactor - MBR

MBR is a wastewater treatment process that combines biological treatment and membrane filtration in a single unit (Figure 16). The MBR technology consists of a bioreactor where microorganisms degrade organic pollutants and a membrane module that filters the treated water from the mixed liquor.

The biological process occurs in the bioreactor, where microorganisms break down and digest organic matter, including pollutants, in the wastewater. The mixed liquor, which contains the microorganisms, is continuously aerated to maintain optimal conditions for the microorganisms to thrive. The microorganisms form flocs suspended in the mixed liquor and help remove the organic matter from the wastewater.

The membrane filtration occurs in the membrane module containing ultrafiltration or microfiltration membranes. The membranes act as a physical barrier to separate the mixed liquor from the treated water, removing any remaining suspended solids, pathogens, and bacteria. The membrane module is cleaned periodically to remove accumulated solids that may clog the membrane's pores and reduce the filtration efficiency.

MBRs offer high treatment efficiency and excellent removal of contaminants, including suspended solids, bacteria and nutrients. They also have the advantage of reduced sludge production, which can be an advantage in mountainous areas where sludge disposal and management are often challenges. The disadvantage of MBRs is energy consumption. MBRs require energy for aeration and membrane cleaning; the energy supply is usually deficient in mountainous areas. MBR systems also tend to have higher initial capital costs than conventional treatment systems.

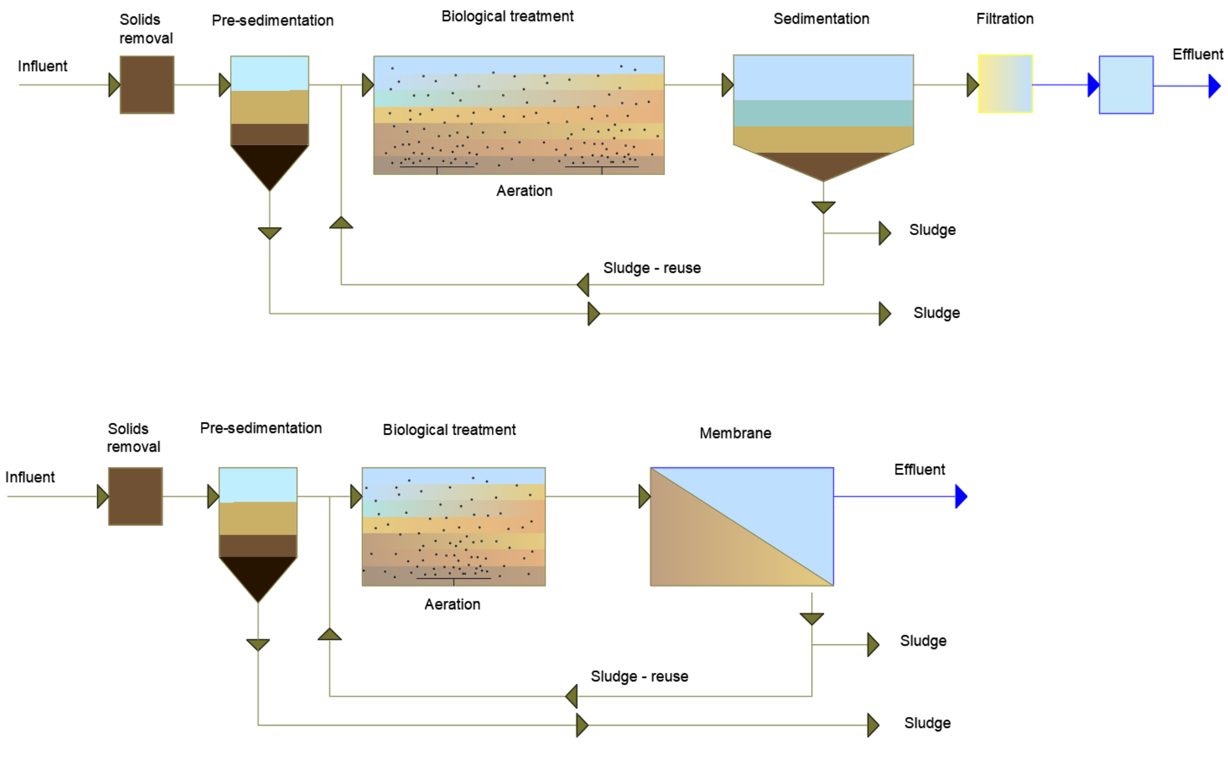


Figure 16: Comparing conventional activated sludge process and MBR

3.6 LIFE CYCLE ASSESSMENT

Life cycle analysis is a good tool for assessing the environmental impacts of individual products and processes. The ISO-led LCA is considered the most integrated and holistic tool to capture WWTP's upstream and downstream impacts. LCA is a tool for measuring the impacts associated with all phases of a product, service or process throughout its life cycle, or so-called "cradle-to-grave".

The main advantages of LCA are:

- It provides information on negative environmental impacts, covering every life cycle stage.
- It helps make decisions and take action to reduce and eliminate negative environmental impacts.
- It offers an analysis of the environmental impacts during the transitions between the different life cycle phases and the total yield (Corominas et al., 2020).

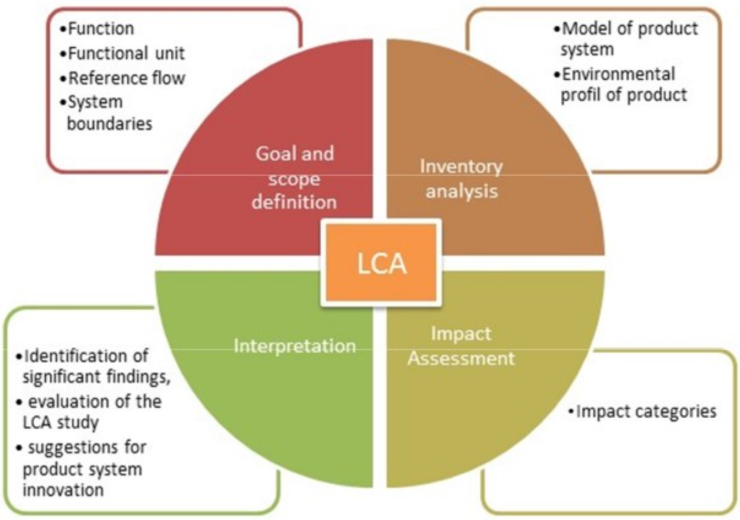


Figure 17: Four LCA phases (Csicsaiová et al., 2019)

ISO 14040-14044 specifies that an LCA study requires four phases (Figure 17):

1. Phase: Objective and Scope:

The first phase of LCA is to define the objective and scope. This involves setting the study's goal, such as identifying environmental hotspots, comparing products or processes, or evaluating sustainability. The scope includes determining system boundaries, functional units, and environmental impacts. System boundaries limit what is included, such as raw materials, energy, transportation, emissions, and waste (Figure 18) (Díaz-Ramírez et al., 2020). The functional unit is a measurable unit for product/process comparison. In this phase, the data requirements and sources of information are also identified. The data quality is critical in LCA, and it should be reliable, relevant, and representative of the product or process being assessed (Díaz-Ramírez et al., 2020).

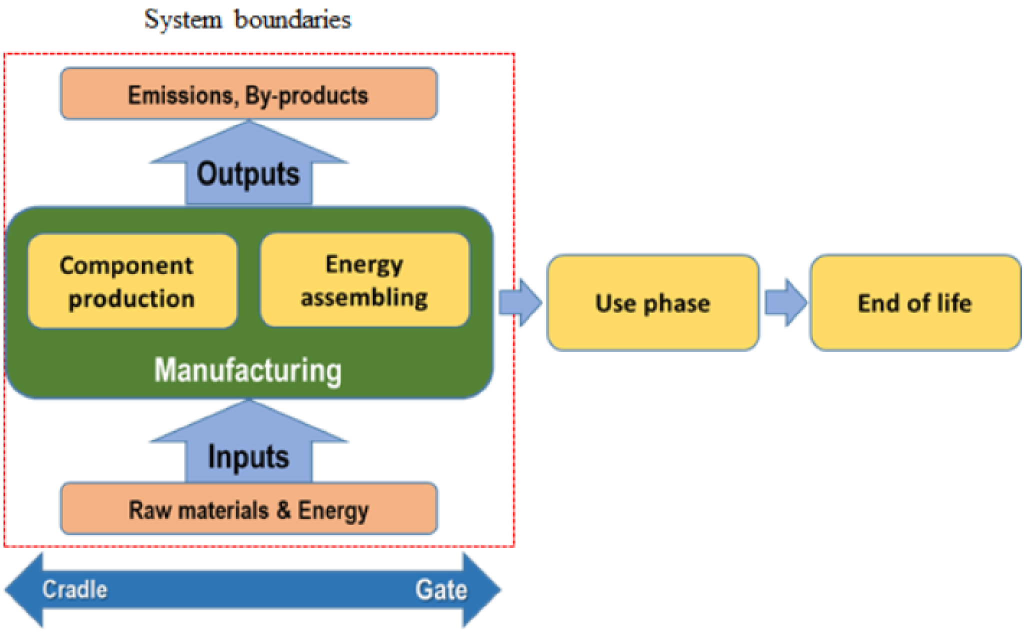


Figure 18: System boundary (Díaz-Ramírez et al., 2020)

2. Phase: Identification of the life cycle inventory:

The second phase of LCA involves the development of a life cycle inventory (LCI). The LCI is a comprehensive list of inputs and outputs associated with the product or process under study. This includes the raw materials, energy, and water inputs and the emissions and waste outputs generated during the different life cycle phases. The LCI is developed using data collected from primary and secondary sources. Primary data is collected directly from the companies and processes involved in producing the product, while secondary data is obtained from publicly available databases, such as Ecoinvent or GaBi.

3. Phase: Impact Assessment:

Impact assessment involves the evaluation of the environmental impacts associated with the product or process. This phase uses the data from the LCI to quantify the environmental impacts using specific impact categories. The selection of impact categories is based on the objectives and scope of the study. LCA's most commonly used impact categories are climate change, human health, ecosystem quality, and resource depletion. In this phase, the environmental impacts are quantified using specific indicators, such as the carbon footprint, water footprint, or ecological footprint.

This phase also characterises the data collected in the LCI, which involves converting the raw data into impact scores using normalisation and weighting factors. Normalisation factors express the data in a standard unit, while weighting factors prioritise the different impact categories based on their significance. Nitrous oxide is, for example, normalised to carbon dioxide equivalents by multiplying the amount of nitrous oxide emissions by a factor of 298, as nitrous oxide has a 298 times more substantial impact on global warming compared with carbon dioxide per kg of emissions of each gas (in a 100-year perspective) (Rahmberg et al., 2020).

4. Phase: Interpretation:

The final phase of LCA is interpretation, which involves the analysis of the results of the assessment. This phase involves identifying the most significant environmental impacts and the sources of uncertainty in the analysis. The results of the LCA can be used to identify opportunities for improving the environmental performance of the product or process, such as the reduction of energy consumption or emissions of greenhouse gases. The results can also be used to compare the environmental performance of different products or processes and inform decision-making. It should also include information on the limitations and assumptions of the study, as well as the sources of uncertainty and sensitivity analysis (Díaz-Ramírez et al., 2020).

3.7 LCA IN WASTEWATER TREATMENT

The operation of WWTP requires a large amount of electricity for pumping or aeration, chemicals for sludge treatment and phosphorus removal, and transportation of waste, sludge, and chemicals. Consequently, WWTP has substantial environmental impacts during its life cycle (i.e., construction, operation, and demolition) due to energy consumption, chemical usage, sludge generation, effluent discharge, and gas emissions (Piao et al., 2016).

The application of LCA in wastewater treatment allows for a comprehensive assessment of the environmental impacts of different treatment options. It helps understand the variations in system boundaries, wastewater composition, and pollutant types. By evaluating the environmental impacts of WWTPs, LCA can provide valuable insights for reducing the environmental footprint of wastewater treatment processes and guide the development of sustainable practices in this field (Nguyen et al., 2020). Since the 1990s, several previous LCA studies have addressed various WWTP-related topics (Corominas et al., 2020).

The advantage of using LCA is that it is a standardised and well-established method often used to determine the impacts of different wastewater treatment technologies and compare them. However, there are drawbacks and limitations to LCA. When LCA results are highly abstract, they provide only generalised information about potential impacts and are not directly linked to the actual situation (Pizzol et al., 2015). Therefore, LCA is useful for comparing alternative solutions but not for assessing environmental impacts and the interactions between natural and manufactured systems (Nika et al., 2020).

In a separate investigation, Vassalle et al. (2023) employed LCA to compare the ecological repercussions of up-flow anaerobic sludge reactors with high-rate algal ponds, which have been attached to wastewater treatment and bioenergy recovery, to the previously established up-flow anaerobic sludge reactors with consolidated technologies. Since they generate biogas, high-rate algal ponds are the most environmentally beneficial option in the four impact categories. Kohlheb and colleagues (2020) tested how eco-friendly and efficient an algal pond and a sequencing batch reactor are throughout their life cycle. Their findings revealed that the high-efficiency algal pond uses less energy and is better for the environment because it causes less global warming and eutrophication. However, the SBR is slightly more beneficial for the environment as it removes more nutrients.

Additionally, Flores and colleagues (2020) found that using nature-based methods to treat wastewater, like through wetlands, has a smaller environmental footprint when compared to standard wastewater treatments (such as the activated sludge system).

Most LCA studies addressing the topic of wastewater treatment include impact categories related to climate change, eutrophication, freshwater and marine acidification, ozone depletion, ecotoxicity, depletion of resources such as fossil fuels, and soil modification (Huijbregts et al., 2017). The most commonly used method for assessing impacts in the EU is the ReCipe method, which analyses mid- and end-streams (Huijbregts et al., 2017).

Most LCA studies investigate industrial WWTP or central WWTP with a higher capacity, and only a few papers deal with decentralised wastewater treatment systems. Garfí et al. (2017) compared conventional wastewater treatment systems (based on activated sludge systems) and natural wastewater treatment systems for small communities. They found that natural wastewater treatment systems are a more environmentally friendly alternative, mainly due to their lower consumption of electricity and chemicals.

Software SimaPro

SimaPro is a computer program designed to determine the impact of products on the environment. The first version of the program was produced in 1990. The program was developed in the Netherlands to help designers and engineers develop new materials, products and services. A demo version is available online (www.pre.nl). Simapro facilitates the assessment by providing a comprehensive framework and analysis capabilities.

Simapro assists in creating an inventory of all inputs (e.g., raw materials, energy) and outputs (e.g., emissions, waste) associated with the system being assessed. This data is often gathered from databases within the program, such as Ecoinvent or GaBi. It offers various impact assessment methods such as ReCiPe 2016 endpoint methods or IMPACT 2002+ and others.

4 CASE STUDY DESCRIPTION - TRIGLAV LAKES HUT

The hut at Triglav Lakes (Figure 19) was built in 1880 by the Austrian Tourist Club after the 2. World War, the Ljubljana Mountaineering Association (Planinsko Društvo - PD) took it over and renovated it to its present appearance (PZS,2023). The hut is situated between the Double Triglav Lake and the artificial lake Močivec below the Tičarice escarpment at an altitude of 1685 m. It is about 150 m from the Double Lake.

Figure 19: Cottage by the Triglav Lakes (Source: https://www.pzs.si/koce.php?pid=35)

The hut is open from June until the end of September. It offers 170 beds in 13 dormitories, 30 beds in 13 individual rooms and 18 beds in a winter room (PZS, 2023). 2019, according to Levstik (2019), the number of daily guests ranged from 58 to 552, with a maximum of 650, and the number of overnight stays ranged from 36 to 147. This translates into around 6,000 overnight stays and around 10,000-day guests over the whole hut operation season. The cottage accommodates 7 employees throughout the season.

Wastewater generation

The facility currently has 5 flush toilets with a 7l flush volume, 2 flush urinals with a flush time of 6 seconds, 5 sinks in the toilets and 1 kitchen sink. There is also 1 shower for staff and 1 for guests (use of a token with a 3-minute operation and water consumption of 15 l). The chalet also has a washing machine. Outside the building is one flush toilet, one flush urinal and one sink with a tap (Rozman, 2020). The indoor toilets are closed after breakfast, and guests can only access the outdoor toilet with a sink.

Water source and consumption

The source of drinking water is a spring above the hut. Water consumption was recorded for August 2018 (1. 8. 2018 - 24. 8. 2018) and amounted to 148 m^3 per month. In 2019, a new water meter was installed to allow separate metering outside and inside the facility and recorded that the average consumption during the operational period in 2019 was 101. 7 m^3 per month inside the facility, peaked in August (161. 2 m^3). Off-site consumption averages 6.87 m^3 and peaks at 10 m^3 in August. Rozman (2020) calculated that the largest share of water consumption is accounted for by outdoor toilets with washbasins (46%) and kitchen and indoor toilets with washbasins (46%).

The cottage is self-supplied with electricity from a generator (diesel), a solar power plant and a battery. Solar power accounts for 50% of the energy produced; the rest is from a liquid-fuelled generator. Under ideal conditions, a solar power plant produces 18. 5 kWh/day (in 5 hours of sunshine). When electricity peaks, it is stored in batteries and used when consumption peaks. The batteries have a nominal capacity of 1500 Ah and can supply the hut for up to 24 hours. On average, 1300 l of diesel are used per season.

There is a wood-burning stove in the common area of the cottage. On average, 4m^3 of firewood is used per season (e.g., 6 months). There is a gas cooker in the kitchen, which uses around eight cylinders of gas per season.

In the event of a power shortage, individual consumers are systematically disconnected from the electricity supply, with the municipal WWTP being switched off first, then the kitchen, lighting and finally the freezers. The largest electricity consumer in the hut is the sewage treatment plant, which has a rated power of 3.5 kW.

Treatment of wastewater

Currently, all wastewater, i.e., water from the kitchen, indoor and outdoor toilets, sinks and showers, is discharged to a small sewage treatment plant (Compact SBR 21000) located on the east side of the building. The treatment plant was installed in 2011.

Through four grease traps, which are designed to keep oils and detergents out of the kitchen, the wastewater from the kitchen overflows into the primary settling tank, which has a capacity of 14 m^3. Wastewater from indoor toilets, washbasins and showers is also discharged into the same cistern. A second smaller primary settling tank with a capacity of 10m^3 carries wastewater from the external toilet and washbasin. In addition to settling larger particles, the primary settling tank is also used to equalise the temperature of the water before it is discharged to the biological treatment plant to allow it to function correctly (Figure 20).

The SBR has a capacity of up to 50 PE. It is sized for a hydraulic load of 150 l/PE/day and an organic load of 60g BOD_5/PE/day. The total maximum capacity of the treatment plant is 12 m^3/day. The biological WWTP also has three separate tanks with filter bags (sludge settling). Finally, the treated effluent from the SBR is discharged into a cascade shaft and further into a soakaway.

Condition of treated water

In 2021, as part of preparing the report for improving the status of the Double Lake, four measurements of the wastewater from the hut were carried out at the end of the season in July, August, and September. The samples were analysed at the Domžale Kamnik Central WWTP. Grey water (i.e., kitchen wastewater) was sampled at the grease traps, and wastewater from the two primary settlement tanks and the effluent from the sewage treatment plant were also sampled.

All samples exceeded the permitted concentrations of the biochemical parameters, the limit values for which are laid down in the Decree on the discharge and treatment of urban wastewater (Official Gazette of the RS, No 98/15, 76/17, 81/19, 194/21 and 44/22 - ZVO-2). Table 4 summarises the analysis results of the individual wastewater parameters. From the results, it can be seen that the values of COD and BOD_5 exceed the permitted levels (COD = 150 mg/l and BOD_5 = 30 mg/l) by 42% and 25%, respectively.

Table 4: Analysed wastewater from the hut (Atanasova, 2021)

	Date	pH [/]	COD [mg/l]	BOD5 [mg/l]	NH4-N [mg/l]	TP [mg/l]	TN [mg/l]
GREASE TRAPS	21.7.2021	6.20	967.00	185.00	8.30	1.53	1543
	12.8.2021	5.13	2442.00	865.00	16.10	4.41	725
	27.8.2021	4.78	2477.00	1775.00	59.00	1.63	327
	9.9.2021	4.95	/	1500.00	193.00	96.80	788
PRIMARY SETTLEMENT TANK (external toilets)	27.8.2021	8.17	923.00	610.00	220.00	18.90	471
	9.9.2021	6.80	8880.00	6415.00	221.00	129.00	361
INFLOW IN SBR	27.8.2021	7.16	1996	310	177	20.80	1960
	9.9.2021	7.33	1074	575	223	99.50	756
OUTFLOW FROM SBR	12.8.2021	6.19	**346.00**	**40.00**	27.70	17.10	385

According to Roš and Levstik (2020), the poor performance of a sewage treatment plant is due to improper sludge discharge. In particular, the unstable loading of the treatment plant leads to so-called floating sludge discharged from the treatment plant, reducing the sludge content and thus impairing the treatment plant's performance. The discharge interval of the excess sludge is vital for the operation of the biological WWTP. That is why it is essential that at the start of the season, untreated activated sludge is fed to the SBR.

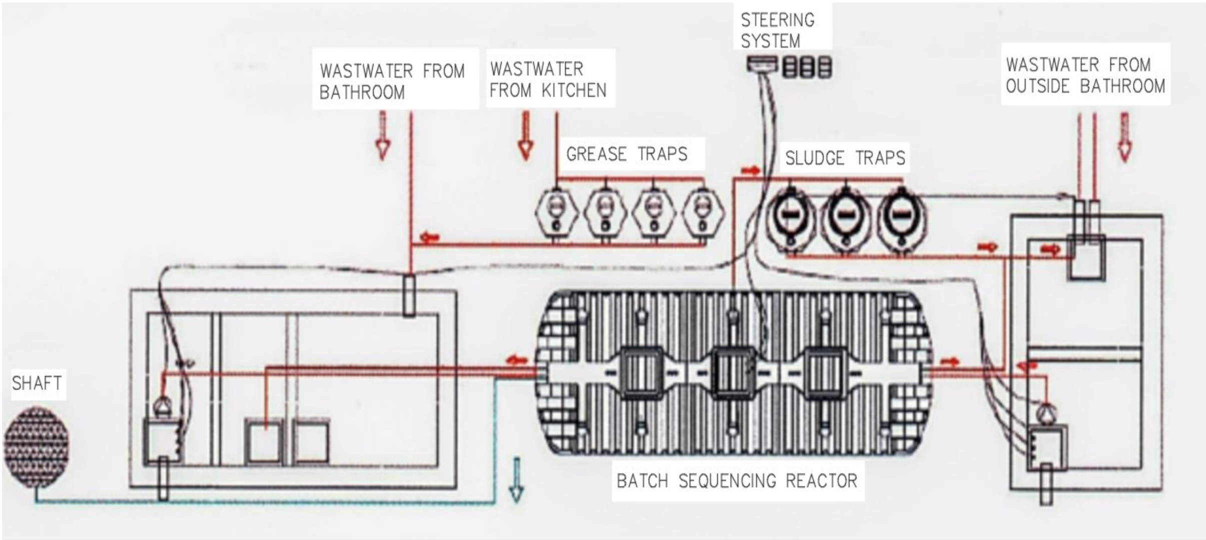


Figure 20: Wastewater treatment from Triglav Lakes hut - status quo (Roš et al., 2020)

Supplying the hut

The hut is only serviced by helicopter. On average, seven helicopter flights are carried out seasonally to supply the hut (food and drink, fuel, etc.) and transport the waste, sludge etc. to the valley.

State of the Double Lake

The Double Lake (Figure 21) comprises the Fifth and Sixth Triglav Lake, part of the Seven Lakes complex. According to the report "Expert Baselines for the Management of Lakes in TNP" (Brancelj, 2019), the lake is among the most endangered. It is designated as a lake with "poor ecological status" and is already in a state where it can no longer return to its original state.

In the hydrogeological report (Rožič et al., 2019), a tracer test found that the treated wastewater drains into a marshy area next to the cottage. The area is made of glacial sediments, which are not very permeable, so the treated wastewater flows directly into the lake.

Filamentous green algae accumulate along the lake's banks, and numerous thread-leaved water crowfoot clumps are found below the algae belt. Another problem is the number of fish, which is too high. The state of the lake has improved somewhat with fish harvesting and algae removal, but this is only a temporary solution.

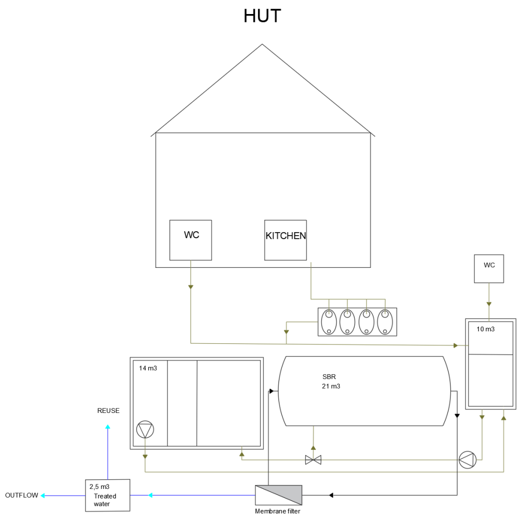
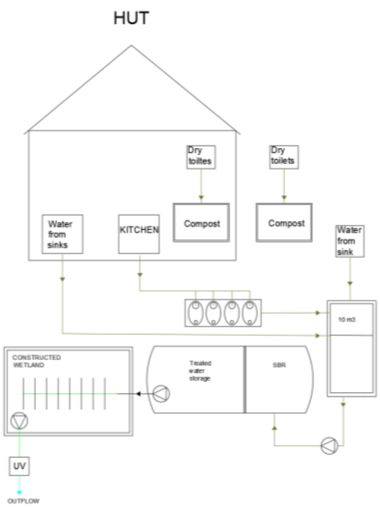
Figure 21: Double Lake (Brancelj, 2019)

The project "VrH Julijcev" - Improving the status of species and habitat types in the Triglav National Park - was launched in 2018 to improve the status of species and habitat types in the Natura 2000 sites in the Triglav National Park, which are assessed as unfavourable or already in an irreversible state. The project's lead partner is the Triglav National Park Public Institute. The project includes various activities that help protect selected endangered species, publicity, and appeals to people to be more nature-friendly when visiting the Triglav National Park. As part of improving the condition of the Double Lake, lake macrophytes, arctic char, and common minnow, which disrupt the functioning of aquatic ecosystems and their structure, were removed. The project also optimised and upgraded the existing small WWTP to mitigate the impact of its operation on the lake. In the following chapters, the optimisation solutions are presented.

4.1 PROPOSED MEASURES

To enhance Double Lake conditions and decrease water usage at the cottage, TNP is considering two solutions to treat the cottage's wastewater more effectively. Both solutions (Scenarios) (Table 5) offer improved results in managing generated wastewater. The first Scenario (Scenario I) is technologically more demanding, whereas the second (Scenario II) is more robust and inspired by the good practices (involving robust solutions) from the Swiss Alps. The measures described were taken from the projects developed as part of the "VrH Julijcev" project.

Table 5: Measures to improve wastewater treatment in Triglav Lakes hut

<table>
<tr><th>MEASURE</th><th>DESCRIPTION</th></tr>
<tr><td>Measure 1 (SCENARIO I)

</td><td>- SBR ventilation upgrade
- Optimization of the SBR system
- Membrane module added
- Dehydration bags added
- Reuse of treated wastewater
- Assembly of the solar system to provide enough energy for the wastewater system</td></tr>
<tr><td>Measure 2 (SCENARIO II)

</td><td>- Optimization of the SBR system (to treat only grey water)
- Dehydration bags added
- Constructed wetland added
- Flush toilets replaced with dry toilets</td></tr>
</table>

4.1.1 SCENARIO I: SBR UPGRADED WITH MEMBRANE MODULE

The wastewater management solution under consideration treats grey water and black water together, as is already the case in the existing wastewater system. An external module for membrane ultrafiltration of the effluent is added to the SBR system (Figure 22). The following changes in the system are foreseen:

- the system for the discharge of excess sludge is abolished,

- the larger septic tank is closed and used as a backup holding capacity in case of failure of the WWTP,

- SBR ventilation is upgraded,

- installation of a membrane filter,

- the addition of a new small basin with a volume of 2,5 m^3 at the outlet of the SBR for the reuse of treated water; and

- dehydration bags are installed to dehydrate the sludge at the end of the season.

Description of the operation of WWT in Scenario I

The kitchen wastewater is taken to grease and oil interceptors and is collected in the existing smaller septic tank with the wastewater from the indoor toilets and washbasins. Water from the outside toilet and the washbasin is drained into the same septic tank. The septic tank allows the retention of one day's influent to the WWTP. The larger existing septic tank is closed during the wastewater treatment process and serves as a backup tank in case of the WWTP's failure. In such cases, wastewater is pumped from a smaller septic tank into a larger one, thus providing a larger holding volume. When the device is restarted, it is pumped back. An existing pump shall be used to pump the wastewater.

By removing the larger septic tank from operation, the wastewater entering the biological WWTP is more organic-rich, as it spends less time in anaerobic conditions. This ensures better operation of the treatment plant. Also, to improve the operation of the WWTP, the system for the discharge of excess sludge is being abolished. As noted above (Roš et al., 2020), the malfunctioning of the plant is due to the lack of activated sludge, and the additional sludge removal is further impairing the plant's performance.

Blowers with a higher capacity are installed. In addition, the performance of SBR cycles is optimised. In the final stage of WWTP, membrane ultrafiltration is switched on to filter the wastewater after aeration. Ultrafiltration through membranes has a size of 0.4 µm, which allows the filtration of bacteria and most viruses. The treated water overflows into the treated water tank. The SBR is sized to treat 9 m^3 of wastewater per day (i.e., three batches in total). However, the system will be programmed to treat a maximum of two batches per day (i.e., 5,6 m^3 wastewater per day), with any excess wastewater being stored in a larger septic tank and treated at lower flows. However, in the case of smaller inflows, the system is periodically aerated to prevent the activated sludge from rotting.

To reduce water consumption, the reuse of treated water is foreseen. The treated water overflows into a sump and is pumped to the external and internal toilets. The drinking water and treated water systems shall be physically separated to avoid contamination of the drinking water. In case of water shortage, up to 1 m^3 of potable water is filled into the reservoir to operate the toilets. The reservoir must be disinfected regularly with an appropriate amount of NaOCl. The treated water flows into an existing soakaway.

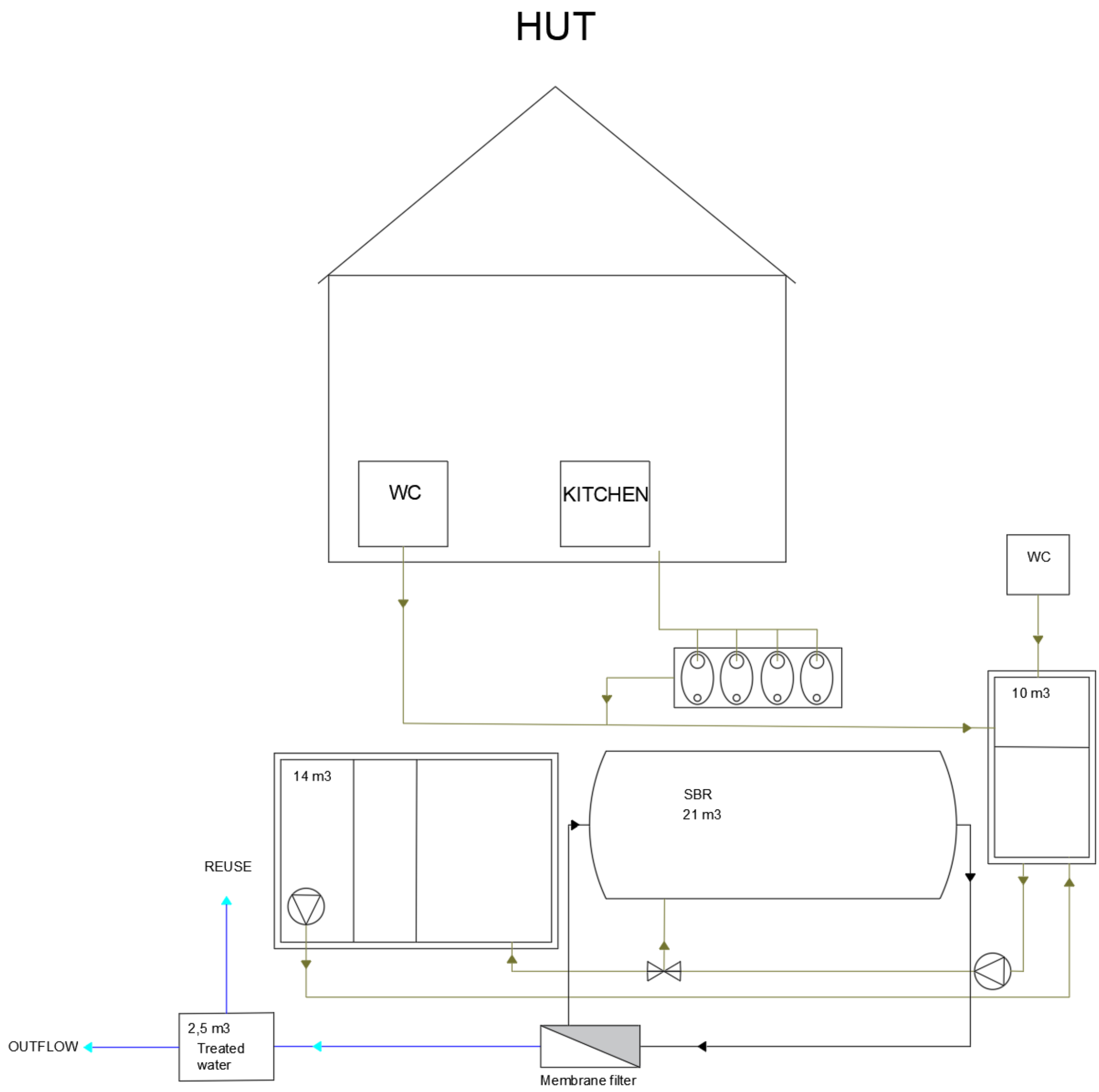


Figure 22: Scenario I

Sludge dehydration bags shall also be included in the wastewater treatment system and filled with sludge at the end of the season. At that point, the WWTP also stops operating. The sacks are stored over the winter on storage racks in the hut. The leachate from the sludge is collected in a catch basin and discharged into a smaller septic tank. The dried sludge, reduced by up to 90% in volume, is transported to the valley at the start of the season.

Due to the lack of power in the hut, the WWTP was often switched off, causing it to malfunction. A separate solar system will be built for this purpose. This will allow the treatment plant to operate without interruption. The collected energy is stored in new separate batteries. The system provides as much daily energy as the treatment plant needs. A gas generator is also replacing the existing diesel generator. This will only power the treatment plant in bad weather when the solar system will not provide enough energy. The control system is also being modernised and digitised.

4.1.2 SCENARIO II: IMPROVING THE SBR SYSTEM WITH A CW AND DRY TOILETS

This solution only treats water from the kitchen, showers and sinks (grey water), replacing existing flush toilets with dry toilets with no waste water outlet (Figure 23). Table 6 presents the greywater characteristics used as input data for the design of the reconstruction of the existing SBR:

Table 6: Composition of grey water (Roš et al., 2020)

Parameters	Area
COD [mg/l]	200-800
BOD5 [mg/l]	90-280
TN [mg/l]	2,1-31,5
NH4-N [mg/l]	0,1-25,4
TP [mg/l]	0,6-31,5
TSS [mg/l]	45-350

A CW and a UV disinfection system are added to improve the quality of the treated water effluent from the SBR. Additional changes to the status quo:

- abolition of the system for extracting excess sludge,
- abolition of flush toilets,
- update of the Control System,
- the SBR system is redesigned with a new coagulant dosing system for phosphorous precipitation,
- dehydration bags are installed to dehydrate the sludge at the end of the season.

Description of the operation of WWT in Scenario II

Wastewater from the kitchen is transferred via oil and grease traps to a smaller septic tank. Wastewater from indoor showers, washbasins, and outdoor washbasins also flows into the same septic tank. An existing pump is installed in the septic tank to pump water to the SBR treatment plant.

The existing SBR shall be divided into two parts. The first chamber is for the biological treatment of wastewater. New blowers shall be installed to ensure sufficient ventilation of the system. The second part of the SBR is a holding tank for treated water with a volume of up to 13 m^3. Aerobic conditions must also be ensured in this system, which is why aerators are installed.

The SBR is sized to treat 4.4 m^3 of wastewater per day (i.e., four batches), but the system is programmed to treat only two batches per day, i.e., 2.2 m^3 of wastewater is treated. In the case of reduced wastewater flow into the system, aeration shall be included to avoid the putrefaction of activated sludge.

The treated effluent is pumped from the SBR to the polishing plant (CW), a reprocessed existing larger septic tank. The purpose of the CW in this system is to remove nutrients further and introduce oxygen into the water. The water flows vertically through the treatment plant in the subsurface to avoid any potential odour. The plants that contribute to water treatment are Alpine dock (Rumex alpinus), seven planted per m^2. A suitable drop at the end of the plant ensures a constant water level in the CW. The CW shall be forced-aerated to ensure sufficient oxygen supply. The treated water from the CW is collected in a collector and discharged via a UV disinfection system into an existing soakaway.

All five existing flush toilets shall be replaced with dry toilets. Two compost bins shall be provided for the interior, one for the hut caretakers and one for the guests. The staff collection tank has a capacity of 7,000 uses/year and provides a multi-seasonal capacity. Meanwhile, the guest container must be emptied annually. Compost bins for indoor sanitation are installed in the basement of the building, where there is currently a storage room. A blower is installed to serve as an extraction fan to suck air through the toilet and the collection tanks into the atmosphere. The speed of the blower is regulated so that the outflow is always slightly higher than the inflow, which prevents odours from returning to the shell and maintains warm air in the collection tanks.

The leachate that settles at the bottom of the compost bin is pumped to the compost, thereby increasing the efficiency of the compost, and the excess is pumped to the IBS bin and, when full, taken downstream for further treatment.

Two dry toilets and one dry urinal shall replace the currently functioning external toilet. The compost collection bin shall be placed under the outdoor toilets in an existing storage area. The space shall be rearranged to allow for the removal of compost bins. The compost bin has a capacity of 7,000 uses per year, so it is planned to empty the bin once or twice a season. The whole container is stored in an enclosed area, and at the end of the season, the containers are emptied into a transport container and transported to the valley for further processing.

The urine from the dry urinal flows into the compost bin and provides an input of nutrients for better composting performance. The compost bins must have sufficient warm air to ensure composting processes and sufficient evaporation. This is provided by a hot-air collector on the hut's roof, from which warm air is fed into the collection tanks. A blower is installed in the compost bin, just like indoor toilets.

It is also necessary to regularly add sufficient dry structural material to ensure adequate moisture and proper composting processes. The structural material draws moisture and transforms the moist compost into a brittle, humus-like material.

No new energy source needs to be added to operate the wastewater treatment system and the dry toilets, as removing black wastewater from the treatment system will reduce the energy consumption for the operation of the SBR. The current amount of energy produced is sufficient to meet the needs of the hut and this wastewater treatment method.

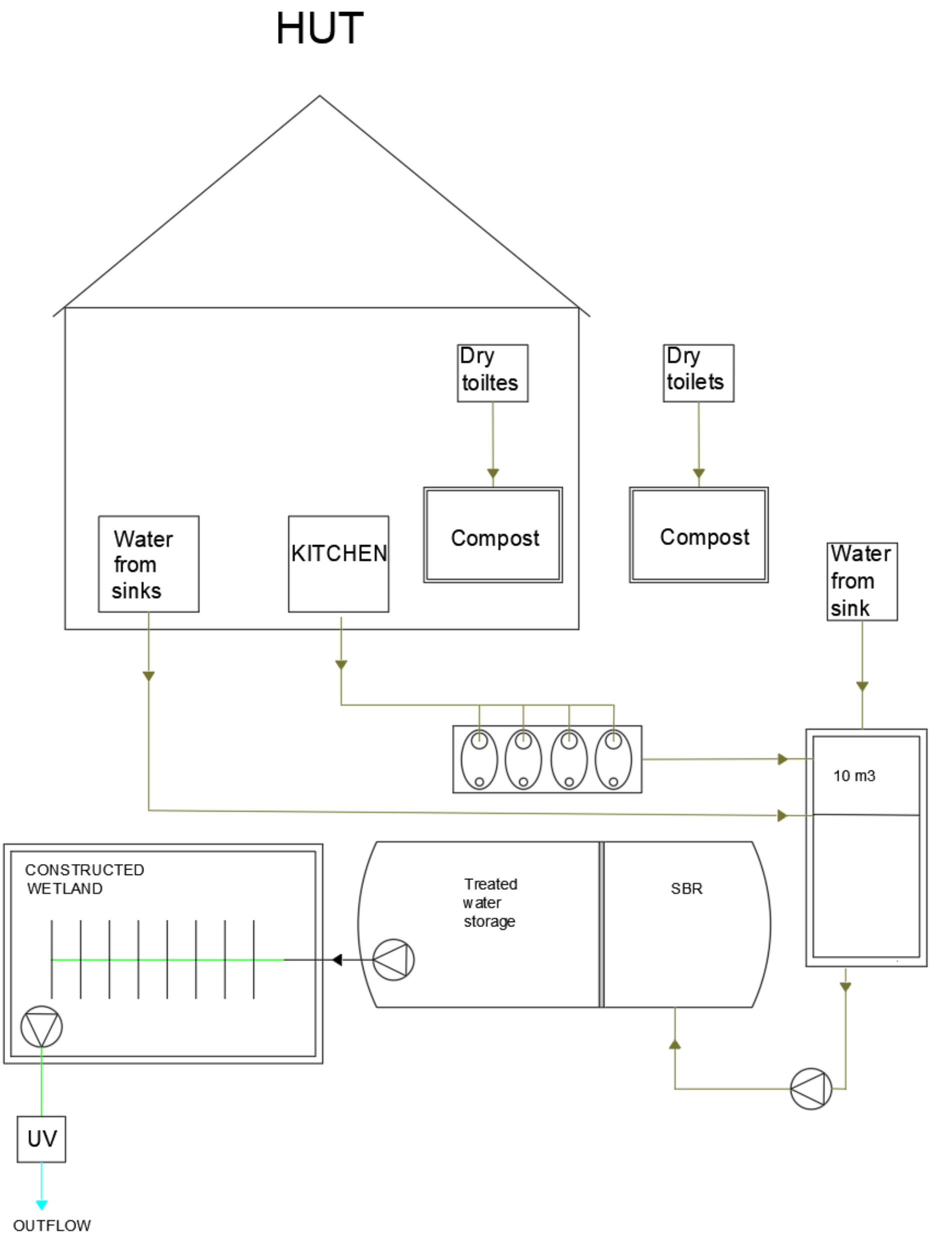


Figure 23: Scenario II

5 LIFE CYCLE ASSESSMENT OF WWTP IN TRIGLAV LAKES

5.1 GOAL AND SCOPE DEFINITION

The objective of the analysis is to assess and compare the potential environmental impact of the construction and operation of the two proposed measures (Scenarios) for wastewater management in Triglav`s Lake Hut.

The functional unit of the study is the volume of water treated by the WWTP during 20 years of operation.

The system boundary of the presented analysis includes all the necessary construction materials, energy and transport needed for the construction of the systems, all the emissions generated during operation, and the energy needed for the operation and maintenance of the equipment installed in the system. The analysis also includes the transport required for operation (sludge, compost removal, etc.) and system maintenance.

For each solution separately, the environmental impact of the individual materials used in the construction of the systems, the impact of the energy required for construction and the impact of the system operation were calculated. The environmental impacts of the two solutions were also compared with each other. The existing situation was also included in the analysis, but due to the lack of accurate data, only the operation of the current operating system was included. None of the scenarios include further sludge treatment, only the transport.

In the inventory analysis, we collected all the materials needed for the construction of the system and for its operation. Most of the inventory data was drawn from the Ecoinvent database of the LCA program SimaPro. Some inventory data, which we could not find in the mentioned database, were drawn from the literature in the inventory tables.

During the construction phase, we considered the production of most components and materials. Since we do not have exact information on the manufacturers of the materials, we excluded their distribution (transport to the dealer and further to the construction site) from the analysis. Due to the lack of data from the manufacturers and some resetting of the calculations, fittings, aeration membranes and the control box are not included in the analysis. Here, we assumed that the mentioned elements would not significantly affect the results.

Due to the lack of reliable data on the decomposition of individual elements and waste materials management, the decomposition phase was also excluded from the LCA analysis. That includes further sludge treatment.

The analysis of the individual measures is described in the following chapters, where the elements included in the calculations (inventory analysis) are described in more detail.

5.2 METHOD AND ENVIRONMENTAL IMPACT CATEGORIES

For calculations, we used the ReCiPe midpoint method. ReCiPe (Revised International Reference Life Cycle Data System) is a widely used life cycle impact assessment (LCIA) method that helps evaluate the potential environmental impacts of a product or process throughout its life cycle. It assesses a broad range of environmental impact categories, as presented in Figure 24 and Table 7.

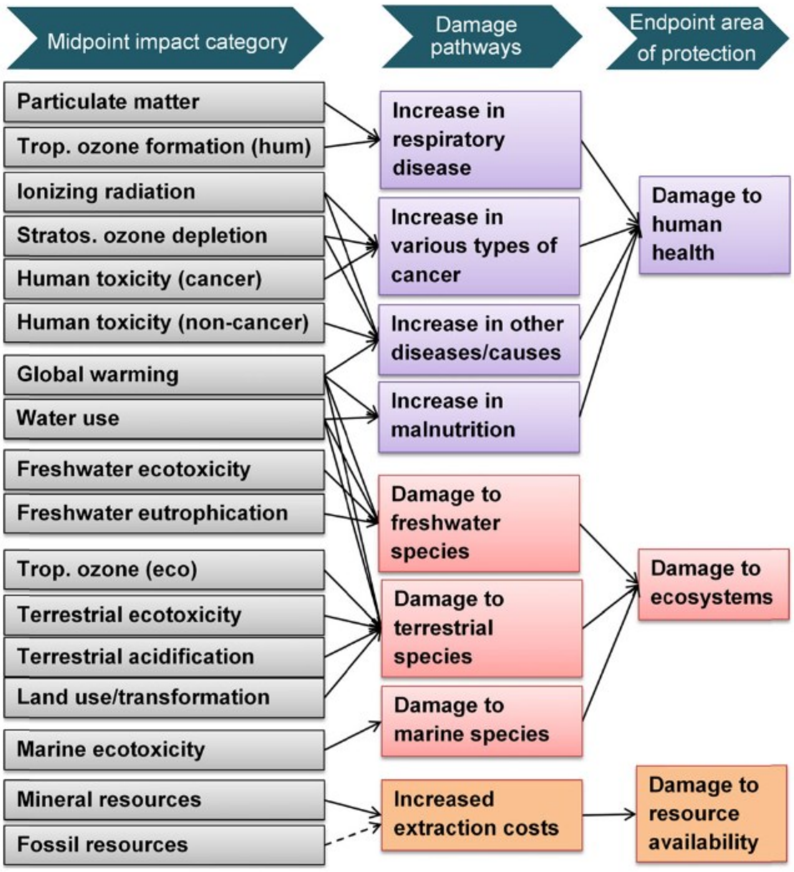


Figure 24: Overview of the impact categories (Huijbregts, 2017)

Table 7: Environmental impact categories of the ReCipe method (Huijbregts, 2017)

Impact category - midpoint	Unit	Description
Global warming	kg CO2-eq	Indicator of potential global warming due to emissions of greenhouse gases to the air. Divided into three subcategories based on the emission source: (1) fossil resources, (2) bio-based resources and (3) land use change.
Ozone depletion	kg CFC-11-eq	Indicator of emissions to air that causes the destruction of the stratospheric ozone layer
Ionising radiation	kBq Co-60 eq	Damage to human health and ecosystems linked to the emissions of radionuclides.
Fine particulate matter formation	kg PM2.5 eq	Indicator of the potential incidence of disease due to particulate matter emissions

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Photochemical ozone formation, terrestrial ecosystems	kg NMVOC-eq	Indicators of emissions of gases that affect the creation of photochemical ozone in the lower atmosphere (smog) catalysed by sunlight.
Photochemical ozone formation, human health	kg NMVOC-eq	Indicators of emissions of gases that affect the creation of photochemical ozone in the lower atmosphere (smog) catalysed by sunlight.
Terrestrial acidification	kg SO2 eq	Indicator of the potential acidification of soils and water due to the release of gases such as nitrogen oxides and sulphur oxides
Freshwater eutrophication	kg P eq	Indicator of the enrichment of the freshwater ecosystem with nutritional elements due to the emission of nitrogen or phosphor-containing compounds
Marine ecotoxicity	kg 1,4-DCB	Damage to marine species.
Terrestrial ecotoxicity	kg 1,4-DCB	Damage to terrestrial species.
Freshwater ecotoxicity	kg 1,4-DCB	Damage to freshwater species.
Marine eutrophication	kg N eq	Indicator of the enrichment of the marine ecosystem with nutritional elements due to the emission of nitrogen-containing compounds.
Human carcinogenic toxicity	kg 1,4-DCB	Impact on humans of toxic substances emitted to the environment and divided into non-cancer and cancer-related toxic substances. Impact on freshwater organisms of toxic substances emitted to the environment.
Human non-carcinogenic toxicity	kg 1,4-DCB	Impact on humans of toxic substances emitted to the environment and divided into non-cancer and cancer-related toxic substances. Impact on freshwater organisms of toxic substances emitted to the environment.
Land use	m2a crop eq	Measure the changes in soil quality (Biotic production, Erosion resistance, Mechanical filtration).
Water consumption	m3	Indicator of the relative amount of water used, based on regionalised water scarcity factors.

Mineral resource scarcity	kg Cu eq	Indicator of the depletion of natural non-fossil resources.
Fossil resource scarcity	kg oil eq	Indicator of the depletion of natural fossil fuel resources.

Not all impact categories have been taken into account in the calculation. We have focused on those most relevant to our study, i.e., those related to impacts on aquatic ecosystems and those subject to environmental considerations in general. We focused only on five impact categories: global warming, freshwater eutrophication, freshwater ecotoxicity, fossil resource scarcity, and water consumption.

5.3 LCA - SCENARIO I

As mentioned in Section 4.1.1, the current system is improved by upgrading the existing SBR with a membrane module. The system boundary of Scenario I is shown in Figure 25.

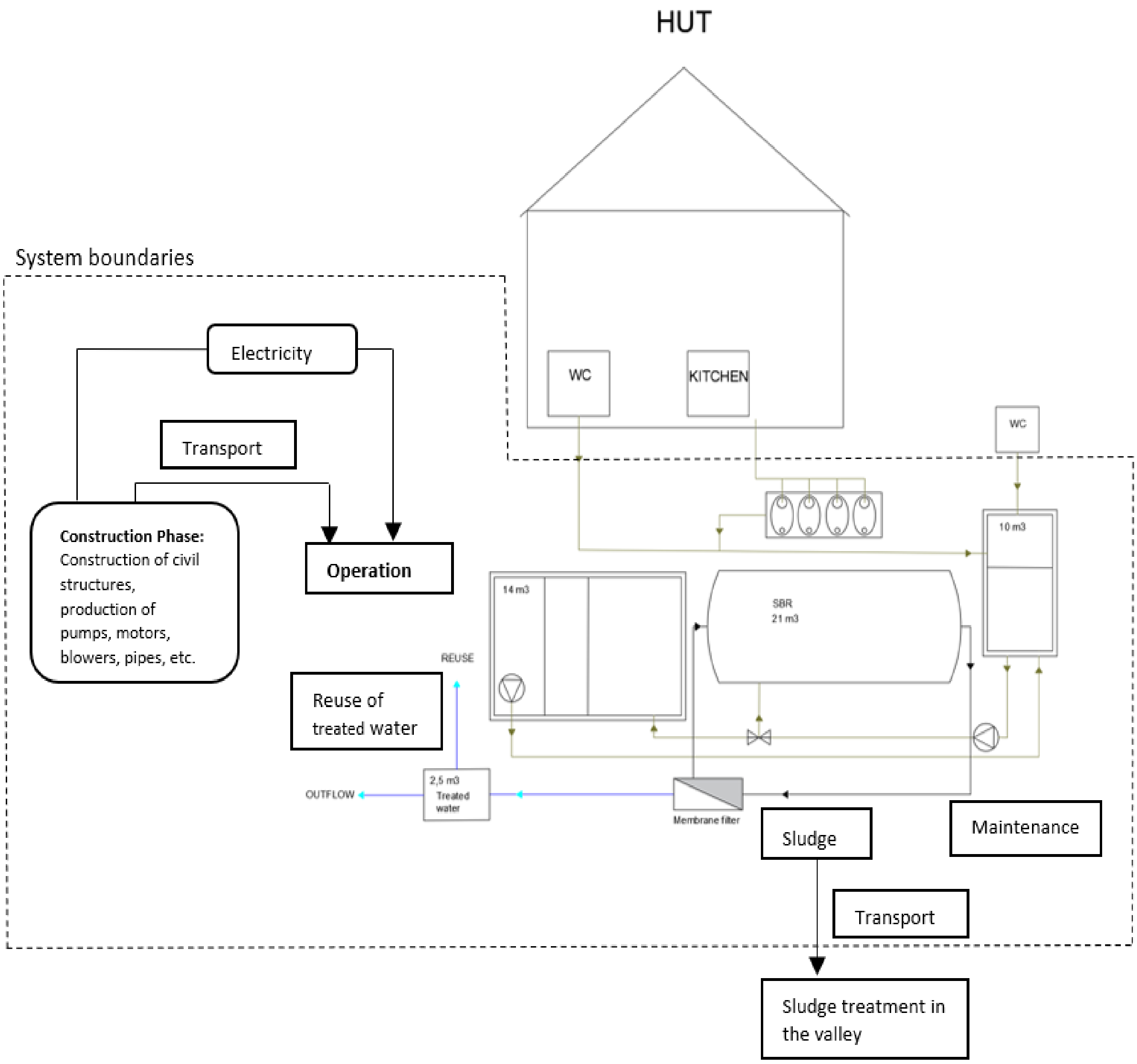

Figure 25: System boundaries of Scenario I

5.3.1 INVENTORY ANALYSIS – SCENARIO I

Table 8 gives an inventory of all the materials used in the construction of the first scenario, while Table 9 shows the amount and type of energy required for the construction phase. These tables also include the Ecoinvent processes selected to describe each material or energy considered in the analysis. In Table 8, we included the lifetime of each element used in the construction phase. This provided the information on the number of elements required to operate the system for its 20-year lifetime. Data on the lifetime of each element was obtained from the manufacturers, but where this information was unavailable, we used the average lifetime obtained from the literature.

For simplicity, we used aluminium pumps with a power of 0.75 kW in our calculations. In reality, pumps of different powers and materials are installed in the system. As the same values have been used for both solutions, it can be assumed that the results are comparable, i.e., none of the scenarios was favoured.

When calculating the energy needed for the construction phase, we have foreseen that all the workers will ride in one helicopter and stay in the cabin during the construction. They will drive to the valley once a week during the 1-month construction schedule. We assumed that one helicopter flight would last 1 hour (up and down) and three consecutive flights would be needed.

Table 8: Inventory of the material consumed for the construction of Scenario I

ELEMENT	MATERIAL	ECOINVENT PROCESS	UNIT	QUANTITY	The life span of the item	QUANTITY IN FU
Membrane module	org. Polymer, PES	Polysulfone {GLO}| polysulfone production, for membrane filtration production | Cut-off, S	kg	115.00	10 years	230.00
Pump	**		piece	6	15 years	8
Blower	Aluminium	Aluminium, primary, ingot {RoW}| market for | Cut-off, U	kg	42.00	3 years	280.00
Tank	PEHD	Polyethylene, high density, granulate {GLO}| market for | Cut-off, S	kg	650.00	20 years	650.00
Diaphragm blower	Stainless Steel	Steel, chromium steel 18/8 {GLO}| market for | Cut-off, S	kg	80.00	5 years	320.00
Fat trapper	PEHD	Polyethylene, high density, granulate {GLO}| market for | Cut-off, S	kg	31.20	5 years	124.80
Pipes	PEHD	Polyethylene, high density, granulate {GLO}| market for | Cut-off, S	kg	14.03	20 years	14.03
Dehydration bags	PVC	Polypropylene, granulate {GLO}| market for | Cut-off, S	kg	76.80		76.80
Tank for technological water	PEHD	Polyethylene, high density, granulate {GLO}| market for | Cut-off, S	kg	11.00	20 years	11.00

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Alumplast pipes	Aluminium	Aluminium, primary, ingot {RoW}| market for | Cut-off, U	kg	21.62	20 years	21.62
Solar Panel		Photovoltaic panel, multi-Si wafer {GLO}| market for | Cut-off, S	m^2	24.00	20 years	24.00

** Morera Carbonell et al., 2020

Table 9: Inventory of the energy used for construction of Scenario I

ELEMENT	MATERIAL	ECOINVENT PROCESS	UNIT	QUANTITY
Excavation/backfilling of material	Excavator	Excavation, hydraulic digger {GLO}| market for | Cut-off, U	m^3	12
Helicopter transportation of equipment, materials and workers	Helicopter	Transport, helicopter {GLO}| market for | Cut-off, U	hr	24**

**Suppose the workers sleep in the cabin: transport once a week (up and down 3 consecutive flights). We assumed 1 monthly term plan: 8 x 1 hour x 3 flights = 24 hours (Messmer et. al., 2016)

Table 10 gives an overview of the operation of Scenario I. The amount of energy in the table represents the energy the system uses over its lifetime. It, therefore, represents the energy required to operate the system for 20 years, treating 13552 m^3 of wastewater, or 5.6 m^3 per day. Most of the energy will come from the new solar system (54450 kWh), but as the new system is more energy-intensive than the current one, a new gas generator must be used. Because solar electricity is considered clean and produces no emissions, it has no impact on the environment during its operational phase.

We anticipated that there would be 40 days of insufficient sunlight per season to generate enough energy to run the WWTP. Consequently, the gas generator will be used during these periods to power the system.

Removing the dehydrated sludge from the hut to the valley is also included in the inventory. It is assumed that one helicopter flight is required per season. We are considering using a military helicopter with a payload of 2,484 kg (Slovenska vojska, 2023).

Values for emissions in treated water released to the environment are taken from the “VrH Julijcev” project and represent the number of emissions in the water that will be treated over the lifetime of the plant.

Table 10: Inventory for the operation of Scenario I

OPERATION		UNIT	AMOUNT	TYPE OF ENERGY	COMMENTS
Energy	Solar power	kWh	54450.00	Solar system (clean energy)	New solar system, except in bad weather; Battery storage = 14 kWh
	Gas aggregate	kg	96969.70	Liquefied petroleum gas {Europe without Switzerland} | market for liquefied petroleum gas | Cut-off, U	We expect that 40 days per season will not be sunny, and the solar system will not provide enough power**

The table continues on the next page…

Sludge removal	Helicopter	hr	20	Transport, helicopter {GLO}| market for | Cut-off, U	1 hr/season (233 kg dehydrated sludge per season)
	Wastewater inflow to treatment plant	m3	13552.00		5.6 m^3/day - average
Avoided material	Recycling water	m3	6050.00	Tap water {GLO}| market group for | Cut-off, S	Average recycled water 2,5 m^3/day
	Outflow from the system	m3	7502.00		Average outflow of treated wastewater 3.1m^3/day
Coagulation additives	$FeSO_4$	l	1060.00	Iron (III) sulfate, without water, in 12.5% iron solution state {GLO}| market for | Cut-off, U	0.53 l/day and 53 l/season
Water emission	BOD	kg	15,00		Outflow: 2mg/l, the amount is in FU (for 7502 m^3 treated water)
	COD	kg	90,02		Outflow: 12mg/l The amount is in FU (for 7502 m^3 treated water)
	TP	kg	0,75		Outflow: 0,1mg/l; the amount is in FU (for 7502 m^3 treated water)
	TN	kg	14,25		Outflow: 1,9mg/l; the amount is in FU (for 7502 m^3 treated water)
	NO3-N	kg	21,01		Outflow: 2,8mg/l; the amount is in FU (for 7502 m^3 treated water)

** Cegnar, 2019

5.3.2 IMPACT ASSESSMENT – SCENARIO I

In the next subchapters, the results of LCA for Scenario I are presented.

Construction – SCENARIO I

Materials and energy in the construction phase significantly impact the global warming impact category (Table 11), where the blowers and solar panels are the most significant contributors. The helicopter transport of material to the hut also significantly impacts global warming.

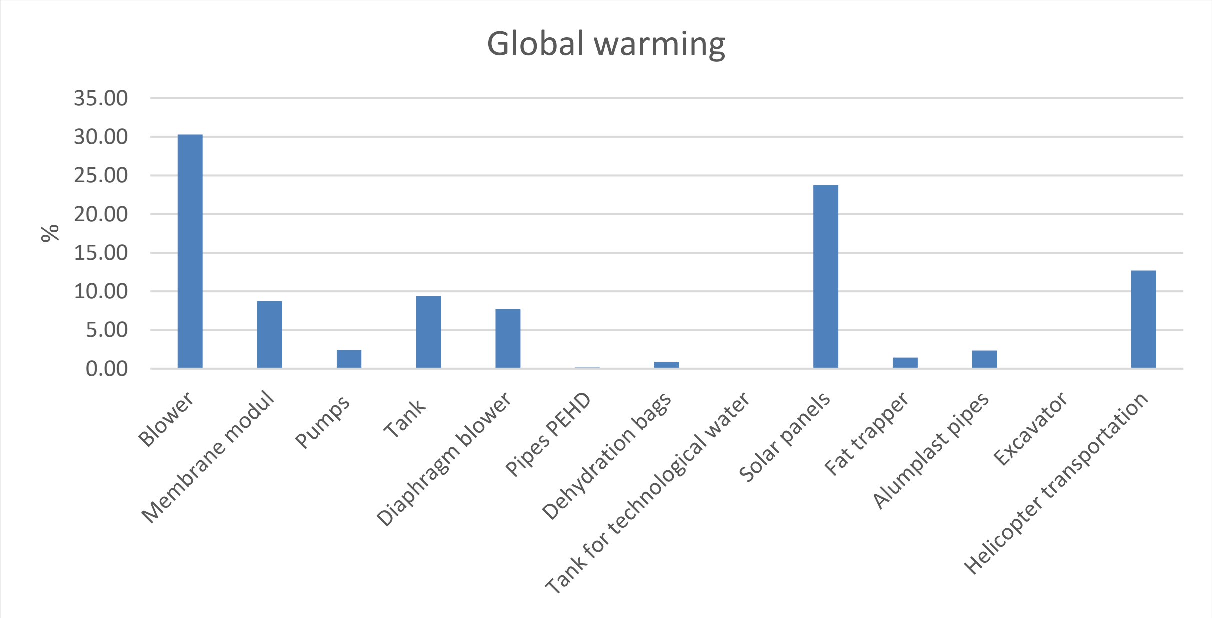
Table 11: Environmental impact from the material used in the construction phase for Scenario I

Impact category	Unit	Total	Blower	Membrane modul	Pumps	Tank	Diaphragm blower	Pipes PEHD	Dehydration bags	Tank for technological water	Solar panels	Fat trapper	Alumplast pipes	Excavator	Helicopter transportation
Global warming	kg CO2 eq	20656.783	6260.000	1800.000	498.683	1950.000	1590.000	33.500	181.000	26.200	4910.000	298.000	483.000	6.400	2620.000
Freshwater eutrophication	kg P eq	9.063	2.340	0.982	0.741	0.333	0.887	0.007	0.038	0.006	3.140	0.064	0.180	0.001	0.344
Freshwater ecotoxicity	kg 1,4-DCB	1033.608	152.000	62.800	4.736	32.400	138.000	0.762	4.090	0.598	614.000	6.780	11.700	0.042	5.700
Fossil resource scarcity	kg oil eq	6418.496	1290.000	901.000	123.976	1090.000	374.000	23.500	131.000	18.500	1320.000	209.000	99.500	2.020	836.000
Water consumption	m3	430.722	20.200	32.400	138.667	15.500	14.200	0.335	1.590	0.263	202.000	2.980	1.560	0.007	1.020

Expectedly, the most minor impact on the global warming category is the energy for the excavator and the pipes, as the quantities used are not significant. Fossil resource scarcity is the second impact category most affected by the construction phase, with solar panels, blowers and PEHD tanks having the most significant impact. Freshwater eutrophication is the impact category least affected by the construction phase. Solar panels are the most significant contributor to all impact categories in the construction phase, except for global warming.

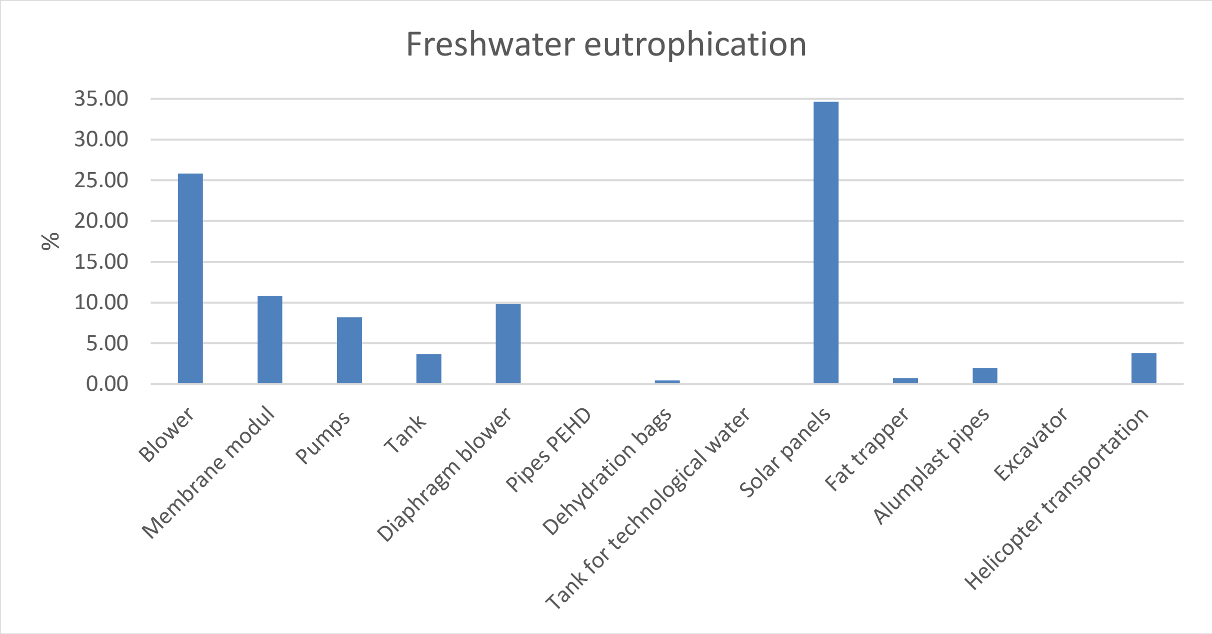
The environmental impact of all materials used in the construction phase is also shown in the graphs (Graph 2 to Graph 6). We can see that solar panels and blowers dominate all the impact categories.

Blowers account for 30% of the total global warming impact, while solar panels account for just under 25% (Graph 2). Helicopter transport accounts for less than 15%, while tanks and diaphragm blowers account for less than 10%. Other materials and energy used in the construction phase have less than a 5 % impact on global warming.



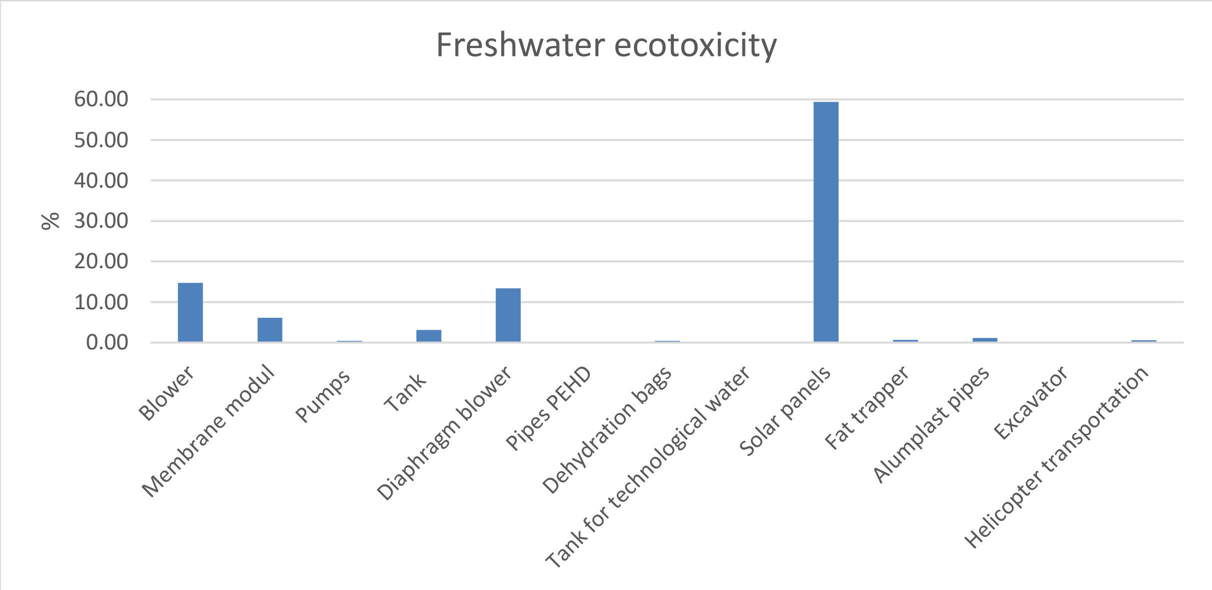
Graph 2: Global warming contribution of each material - Scenario I

For freshwater eutrophication (Graph 3), the order of impact of individual materials is similar to global warming, with solar panels accounting for just under 35% of the total freshwater eutrophication impact, blowers accounting for just over 25%, membrane modules, tanks and blowers accounting for around 10%, and other elements contributing less than 5% to freshwater eutrophication.



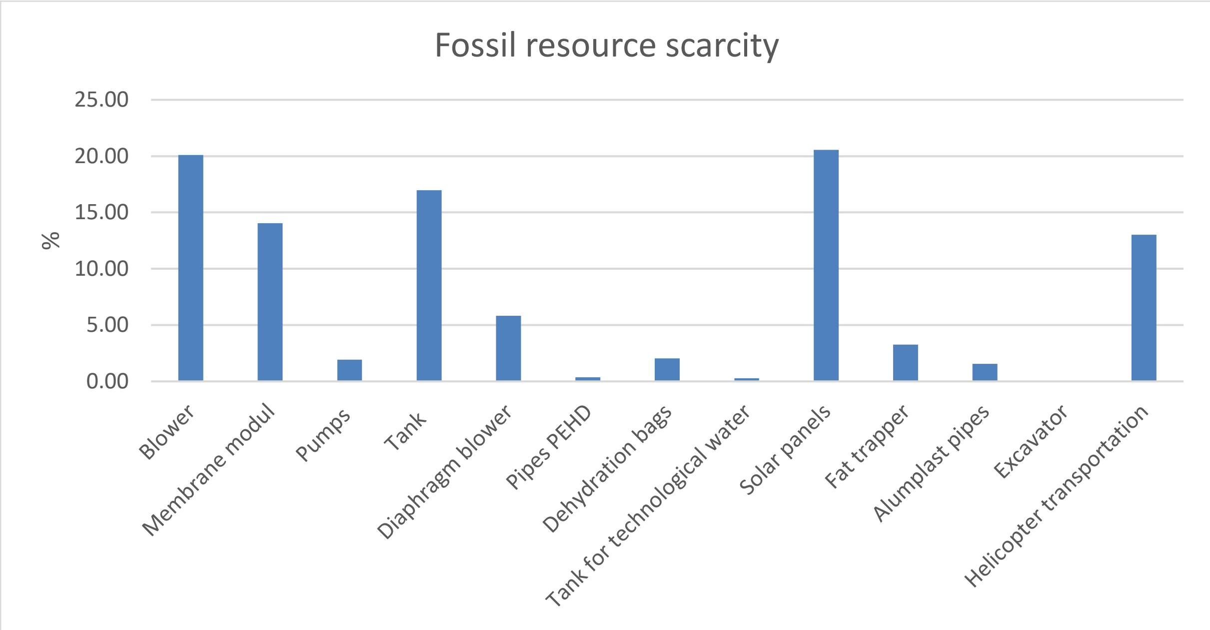
Graph 3: Freshwater eutrophication contribution of each material - Scenario I

59% of the total impact on freshwater ecotoxicity comes from solar panels. Blowers and diaphragm blowers contribute 15% and 13%, respectively, while the other materials used contribute less than 6% to freshwater ecotoxicity, which is the share of the membrane module's impact (Graph 4).



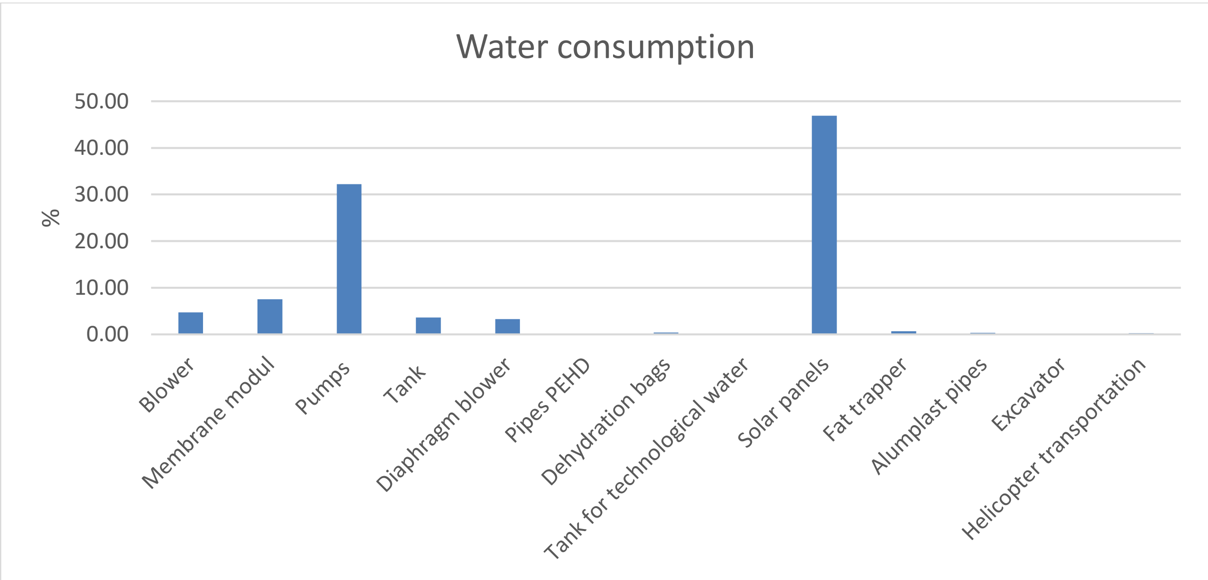
Graph 4: Freshwater ecotoxicity contribution of each material - Scenario I

Solar panels and blowers have the most significant impact on fossil resource scarcity, each accounting for more than 20% of the total impact, followed by tanks at 17%, membrane module at 14% and helicopter transport at 13%. Other materials contribute less than 5% to fossil scarcity (Graph 5).



Graph 5: Fossil resource scarcity contribution of each material - Scenario I

In terms of water consumption impact, solar panels again have the most significant impact (47%). Pumps have an enormous impact in this category, with 32% of the total impact. Membrane modules have an impact of 8%, and blowers have an impact of almost 4%. Other materials used in the construction phase have less than 3% of the total impact (Graph 6).



Graph 6: Water consumption contribution of each material - Scenario I

Operation – SCENARIO I

As mentioned in Section 5.3.1, we only included gas aggregate for cloudy days when there is not enough sun to power the solar panels. The largest energy consumers are the aeration of the membrane module, which accounts for more than 30% of the total energy consumption, and the pumps that supply water to the MBR and pump the treated water for reuse, which account for 20% of the total energy consumption of the system.

In Table 12, we can see the impact of each element in the operation phase on the five impact categories. The operation in Scenario I has the most significant impact on the scarcity of fossil resources, which is expected since gas aggregates represent the most significant amount. The second impact category that is the most affected is global warming, which is the result of gas aggregate and helicopter transport.

Iron sulphate ($Fe_2(SO_4)_3$), added to remove phosphorus compounds from wastewater, significantly contributes to global warming, fossil resource depletion and freshwater ecotoxicity. All categories are positively affected by the reuse of treated wastewater. Of course, the most significant positive contribution is to water consumption but also to global warming and fossil resource scarcity.

Some contaminants in the treated water discharged to the environment still contribute to freshwater eutrophication. However, these amounts are minimal compared to other elements in the treatment plant's operation.

Table 12: Environmental impact of operation for Scenario I

Impact category	Unit	Total	Gas aggregate	Sludge removal	Operation	Water reuse	$Fe_2(SO_4)_3$
Global warming	kg CO2 eq	131579.50	64900.00	1940.00	0	-4658.50*	298.00
Freshwater eutrophication	kg P eq	105.49	50.8	0.26	3.06	-3.05	0.22
Freshwater ecotoxicity	kg 1,4-DCB	933.84	531.00	4.22	0	-215.38	55.00
Fossil resource scarcity	kg oil eq	256506.90	125000.00	619.00	0	-1222.10	110.00
Water consumption	m3	-5879.04	73.60	0.76	0	-6050.00	19.20

*Positive values show the environmental burden, while negative values for each indicator show the environmental burden saved.

Total impact of Scenario I

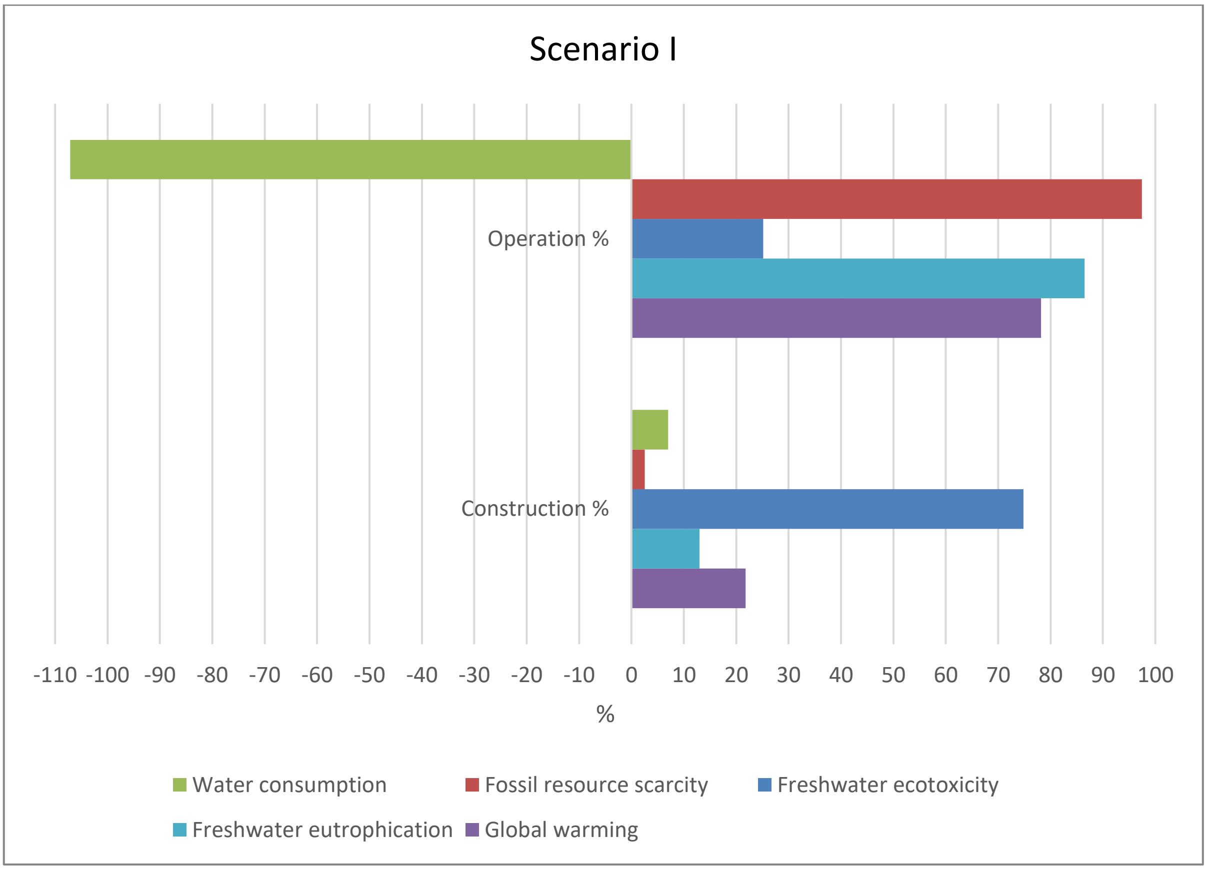
Tables 13 and 14 show that operation significantly contributes to environmental impacts. 96% of the total impact on fossil resource scarcity comes from operation. This was to be expected as the operation phase consumes more energy, especially considering the 20-year life of the system. Furthermore, operation contributes 87% to the total impact on freshwater eutrophication, 78% to global warming and 28% to freshwater ecotoxicity, to which the construction phase contributes 75%. The operation positively impacts water consumption, reducing 107% over 20 years. Graph 7 shows the percentage of each impact category affected by operation and construction.

Table 13: Total impact of Scenario I

	Global warming [kg CO2 eq]	**Freshwater eutrophication** [kg P eq]	**Freshwater ecotoxicity** [kg 1,4-DCB]	**Fossil resource scarcity** [kg oil eq]	**Water consumption** [m^3]
Construction	17433.28	7.75	956.72	5749.25	394.62
Operation	62479.50	51.29	374.84	124506.90	-5956.44
Total	79912.78	59.04	1331.56	130256.15	-5561.82

Table 14: Total impact of Scenario I in percentages

	Global warming	**Freshwater eutrophication**	**Freshwater ecotoxicity**	**Fossil resource scarcity**	**Water consumption**
Construction %	12	13	75	4	7
Operation %	78	87	25	96	-107



Graph 7: Total impact of Scenario I (operation and construction) in percentages

5.3.3 INTERPRETATION – SCENARIO I

Scenario I has the highest impact on fossil resource scarcity, with 96% of the contribution from the treatment plant's operation. The result shows that much energy is needed to run the WWTP. Even though the new solar system provides most of the energy, the demand is too high to operate the treatment plant successfully during lousy weather. In such cases, the energy source is petroleum gas, which has a significant environmental footprint.

Scenario I also impacts freshwater eutrophication, with the operation phase contributing 87% of the total impact, with the most coming from petroleum gas.

The impact of Scenario I on global warming is also high, with 78% of the total impact coming from the operation phase. Again, the highest impact comes from the gas aggregate due to the high energy demand.

The construction phase impacts freshwater ecotoxicity more than the operation phase, with 75% of the total impact. In the construction phase, the solar panels have the highest impact. In the operation phase, the energy consumption of the gas aggregate has the highest impact on freshwater ecotoxicity.

The results show that the energy source strongly impacts all impact categories and can be considered a "hot spot" in Scenario I. With water recycling, Scenario I has a strong positive impact on water consumption. In the last chapter, we will consider different solutions that could help reduce both scenarios' hot spots.

5.4 LCA - SCENARIO II

In Scenario II, the existing flashing toilets are replaced with dry toilets. As a result, no black water is sent to the treatment plant. The current SBR system is modified to treat grey water only, and a CW and UV disinfection are added at the end of the treatment. The system boundary of Scenario II is shown in Figure 26.

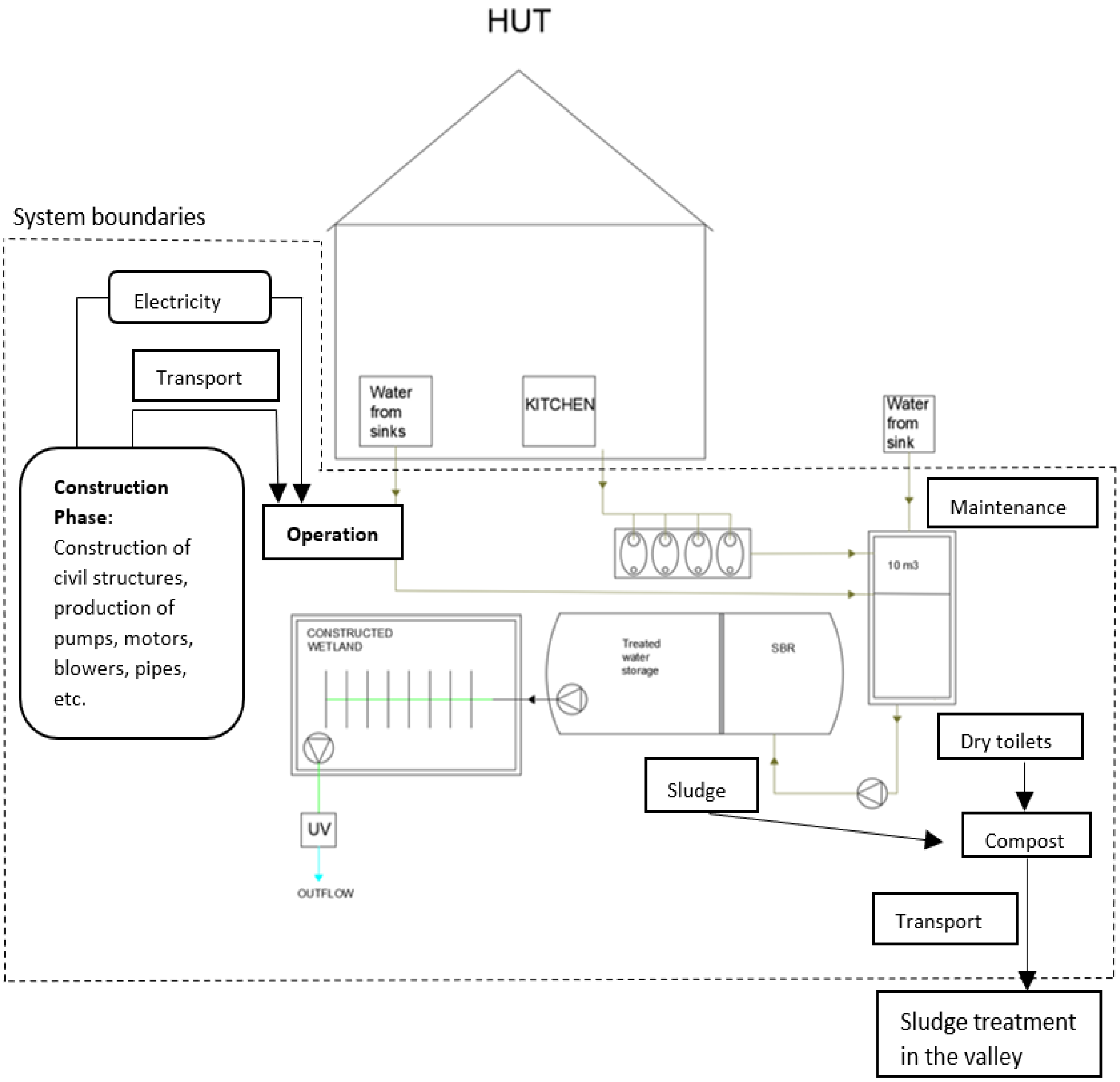


Figure 26: System boundaries of Scenario II

5.4.1 INVENTORY ANALYSIS – SCENARIO II

Table 15 presents all the materials and their amount used in the construction phase of Scenario II. The same as for the first scenario, we included the lifetime of each element used in the construction phase to get an impact on the maintenance of the system. Tables 15 and 16 also include Ecoinvent processes selected to describe each material or energy considered in the analysis.

For the second scenario, we also used aluminium pumps with a power of 0.75 kW for our calculations. The amount of energy consumed for construction can be seen in Table 16. When calculating the energy needed for the construction phase, we assumed three helicopters would be needed for all the material and to transport the workers to the hut. The worker would stay at the hut during the construction and drive to the valley once a week during the 1-month construction schedule. We assumed that one helicopter flight lasts 1 hour (up and down).

In both scenarios, transporting the required materials and workers was assumed to be the same. However, an additional 22 hours of gravel substrate transport was considered in Scenario II. A one-hour one-way flight with a maximum helicopter load of 2484 kg was considered (Slovenska vojska, 2023).

Table 15: Inventory of the material consumed for the construction of Scenario II

ELEMENT	MATERIAL	ECOINVENT PROCESS	UNIT	QUANTITY	The life span of the item	QUANTITY IN FU
Pump	**		piece	5	15 years	6.5
Diffuser	PEHD	Polyethylene, high density, granulate {GLO}| market for | Cut-off, S	kg	1.64	10 years	3.28
Pipes	PEHD	Polyethylene, high density, granulate {GLO}| market for | Cut-off, S	kg	3.45	20 years	3.45
Blower	Aluminium	Aluminium, primary, ingot {RoW}| market for | Cut-off, U	kg	40.50	3 years	270.00
Tubular aerator	PEHD	Polyethylene, high density, granulate {GLO}| market for | Cut-off, S	kg	0.92	10 years	1.85
Distribution pipes	PVC	Polypropylene, granulate {GLO}| market for | Cut-off, U	kg	177.02	20 years	177.02
Fat trapper	PEHD	Polyethylene, high density, granulate {GLO}| market for | Cut-off, S	kg	31.20	5 years	124.80
Pipes	Stainless Steel	Chromium steel pipe {GLO}| market for | Cut-off, U	kg	13.41	20 years	13.41
Drainage pipe	PEHD	Polyethylene, high density, granulate {GLO}| market for | Cut-off, S	kg	47.27	20 years	47.27
Tubular aerator	Stainless Steel	Chromium steel pipe {GLO}| market for | Cut-off, U	kg	53.12	20 years	53.12
UV unit		ultraviolet lamp production, for water disinfection | ultraviolet lamp | Cutoff, U	piece	1	20 years	1
Gravel substrate	Gravel/Sand	Gravel, crushed {GLO}| market for | Cut-off, U	kg	25000.00	20 years	25000.00
Compost bin	PEHD	Polyethylene, high density, granulate {GLO}| market for | Cut-off, U	kg	218.10	20 years	218.10
Dry toilet Clivus	Ceramics	Sanitary ceramics {GLO}| market for | Cut-off, S	kg	150.00	20 years	150.00
Dry urinal Clivus	Ceramics	Sanitary ceramics {GLO}| market for | Cut-off, S	kg	21.00	20 years	21.00
Pipes	PVC	Polypropylene, granulate {GLO}| market for | Cut-off, U	kg	41.50	20 years	41.50

Solar panels		Photovoltaic panel, multi-Si wafer {GLO}| market for | Cut-off, S	m2	2.00	20 years	2.00
Pipes with insulation - for warm air supply	Stainless Steel	Chromium steel pipe {GLO}| market for | Cut-off, U	kg	1082.20	20 years	1082.20
	Synthetic rubber	Synthetic rubber {GLO}| market for | Cut-off, U	kg	7.43	20 years	7.43
Dehydration bags	PVC	Polypropylene, granulate {GLO}| market for | Cut-off, S	kg	38.40		38.40

** Morera Carbonell et al., 2020

Table 16: Inventory of the energy used for construction of Scenario II

ELEMENT	MATERIAL	ECOINVENT PROCESS	UNIT	QUANTITY
Excavation/backfilling of material	Excavator	Excavation, hydraulic digger {GLO}| market for | Cut-off, U	m^3	25.20
Helicopter transportation of equipment, materials and workers	Helicopter	Transport, helicopter {GLO}| market for | Cut-off, U	hr	24*
Helicopter transportation of sand and gravel (gravel substrate for CW)	Helicopter	Transport, helicopter {GLO}| market for | Cut-off, U	hr	22**

*Suppose the workers sleep in the cabin: transport once a week (up and down 3 consecutive flights). We assumed 1 monthly term plan: 8 x 1 hour x 3 flights = 24 hours (Messmer et. al., 2016)

**11 flights needed for 250000 kg of gravel substrate: 11 x 1 hour x 2 flight = 22 hours (Slovenska vojska, 2023)

Table 17 gives an overview of the inventory for the operation of Scenario II. The amount of energy shown in the table is the total energy required to operate the system for 20 years, during which it will treat 4400 m^3 of wastewater or 2.2 m^3 per day. 50% of the energy required to operate the treatment plant and the hut comes from existing solar energy. Since the energy demand for the scenario considered is lower than for the existing system in the hut, the current amount is sufficient to operate the new system. As in Scenario I, we assumed 40 days of operation per season when there is not enough sunshine to generate electricity to power both the hut and the treatment plant. These days, the existing diesel generator is used to produce electricity.

The removal (transport) of compost from the hut to the valley is also included in the inventory. We assumed one flight per season.

As dry toilets replace flush toilets, water is saved. Therefore, we calculated the amount of water saved per flush. From the average number of visitors per season (16098), we calculated the average water saved per toilet flush (Rozman, D. 2020). The water consumption per flush is 7 litres.

Values for emissions in treated water released to the environment are taken from the “VrH Julijcev” project and represent the number of emissions in the water that will be treated over the lifetime of the WWTP.

Table 17: Inventory for the operation of Scenario II

OPERATION		UNIT	AMOUNT	TYPE OF ENERGY	COMMENTS
Energy	Solar power	kWh	4212.00	Solar system (clean energy)	Solar power provides energy for 50% of the whole hut and treatment plant.
	Diesel aggregate	kg	524.40	Diesel {Europe without Switzerland} | market for | Cut-off, U	We expect that 40 days per season will not be sunny, and the solar system will not provide enough power**
Sludge and compost removal	Helicopter	hr	20	Transport, helicopter {GLO}| market for | Cut-off, U	1 flight at the end/start of the season
	Wastewater inflow to treatment plant	m^3	4400.00		2.2 m^3/day - average
Avoided material	Recycling water	m^3	8470.00	Tap water {GLO}| market group for | Cut-off, S	Dry toilets taken into account as water savings – 3.5 m^3/day
	Outflow from the system	m^3	4400.00		The average outflow from the system is 220 m^3/year.
Coagulation additives	$FeSO_4$	l	360.00	Iron (III) sulphate, without water, in 12.5% iron solution state {GLO}| market for | Cut-off, U	18 l/season
Water emission	BOD	kg	0.88		Outflow: 2mg/l The amount is in FU (for 4400 m3 treated water)
	COD	kg	35.20		Outflow: 8mg/l; the amount is in FU (for 4400 m^3 treated water)
	TP	kg	0,44		Outflow: 1mg/l; the amount is in FU (for 4400 m^3 treated water)
	TN	kg	6.60		Outflow: 15mg/l; the amount is in FU (for 4400 m^3 treated water)
	NO3-N	kg	17.60		Outflow: 2,8mg/l; the amount is in FU (for 4400 m^3 treated water)

** Cegnar, 2019

5.4.2 IMPACT ASSESSMENT – SCENARIO II

Construction – Scenario II

From Table 18, we can see that all materials and energy in the construction phase have the most significant impact on global warming, with fans, aluminium-isolated pipes and helicopter transport having the most significant impact. Construction has the most negligible impact on freshwater eutrophication.

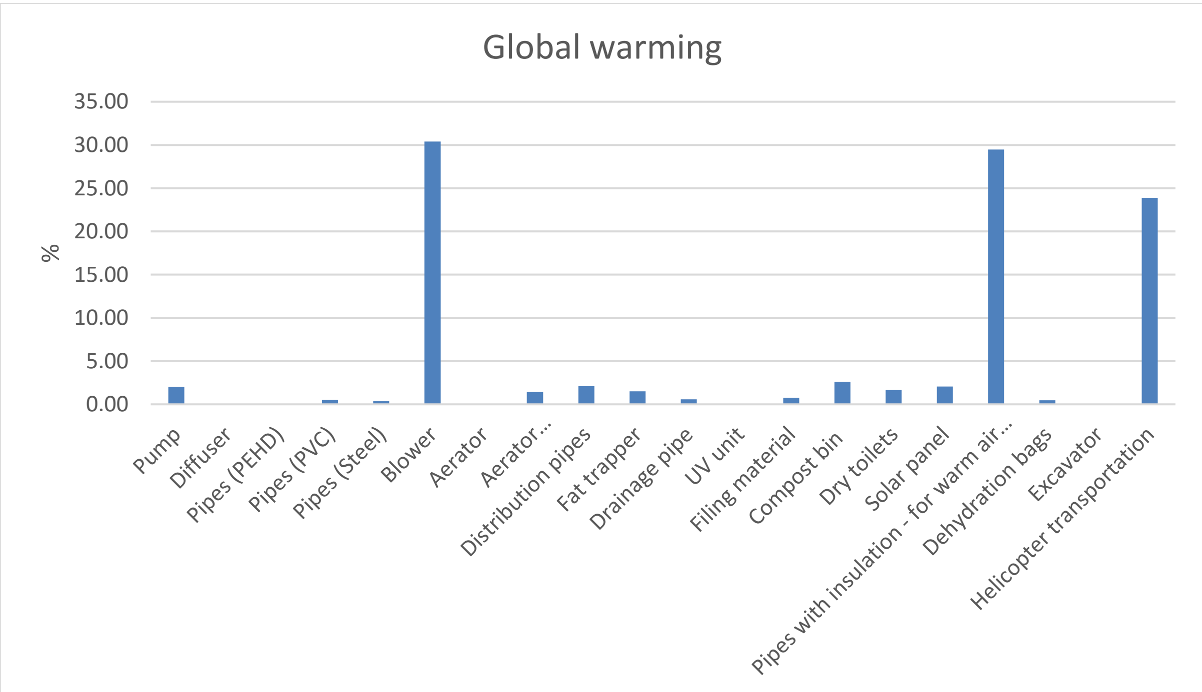
Table 18: Environmental impact of the material used in the construction phase for Scenario II

Impact category	Unit	Total	Pump	Diffuser	Pipes (PEHD)	Pipes (PVC)	Pipes (Steel)	Blower	Aerator	Aerator (Stainless steel)	Distribution pipes	Fat trapper	Drainage pipe	UV unit	Filing material	Compost bin	Dry toilets	Solar panel	Pipes with insulation	Dehydration bags	Excavator	Helicopter transportation
Global warming	kg CO2 eq	19877.66	405.18	7.81	8.23	98.00	72.30	6040.00	4.41	287.00	418.00	298.00	113.00	1.03	153.00	520.00	328.00	409.00	5860.60	90.70	13.40	4750.00
Freshwater eutrophication	kg P eq	7.79	0.60	0.00	0.00	0.02	0.04	2.25	0.00	0.16	0.09	0.06	0.02	0.00	0.04	0.11	0.13	0.26	3.34	0.02	0.00	0.62
Freshwater ecotoxicity	kg 1,4-DCB	791.52	3.85	0.18	0.19	2.21	6.09	147.00	0.10	24.10	9.43	6.78	2.57	0.03	7.41	11.90	13.00	51.20	493.00	2.05	0.09	10.35
Fossil resource scarcity	kg oil eq	5677.67	100.73	5.50	5.80	71.10	16.70	1240.00	3.10	66.10	303.00	209.00	79.30	0.30	46.20	366.00	105.00	110.00	1362.90	65.70	4.24	1517.00
Water consumption	m3	248.83	112.67	0.08	0.08	0.86	0.84	19.40	0.04	3.31	3.67	2.98	1.13	0.01	9.44	5.21	1.81	16.80	67.84	0.80	0.01	1.85

Fossil resource scarcity is the second impact category most affected by the construction phase. As expected, helicopter transport has the highest contribution to fossil resource scarcity. Aluminium insulated pipes and fans also significantly impact this impact category. Freshwater ecotoxicity is also a high-impact category, with aluminium-insulated pipes contributing the most to the impact.

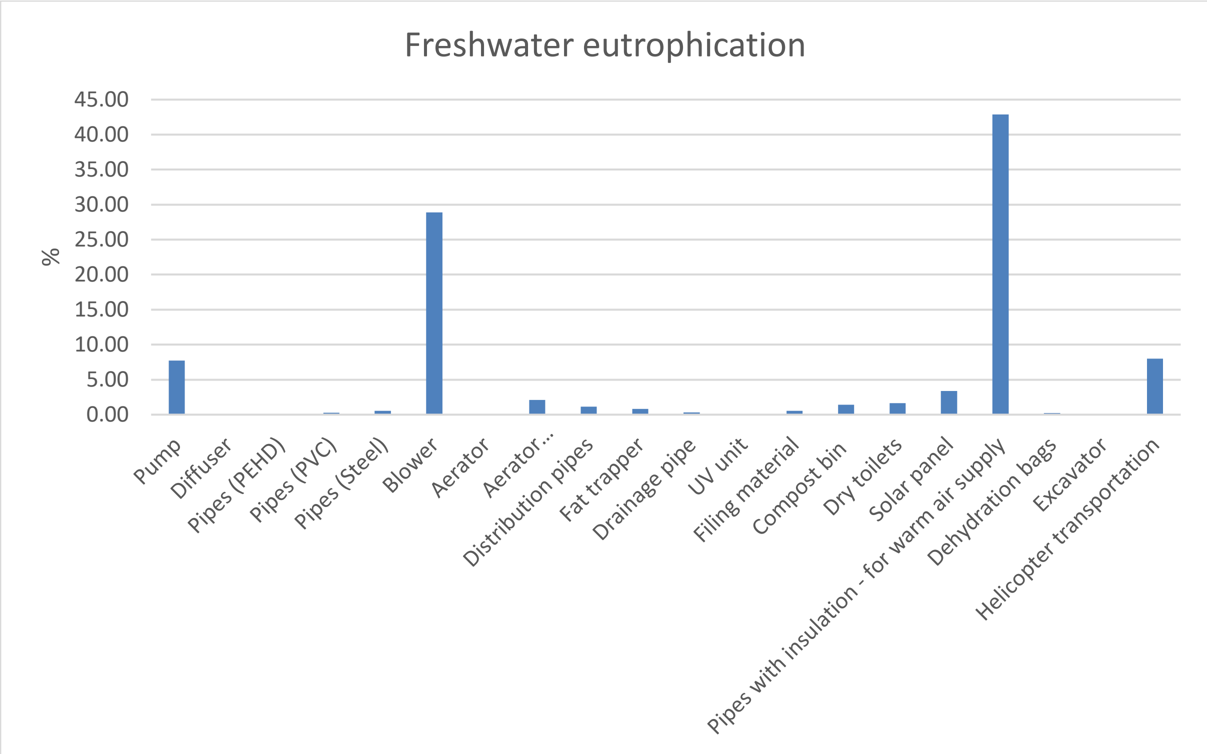
The environmental impact of all materials used in the construction phase is also shown in the graphs below (Graph 8 – Graph 12). We can see that the aluminium-isolated pipes have a high impact in all impact categories.

Graph 8 shows the global warming impact category of each element used in the construction phase. The most significant impact on global warming is caused by the blowers, with a 30% contribution and the aluminium-isolated pipes, with a 29% contribution. Helicopter transport contributes almost 24% to the global warming impact category. Other elements contribute less than 5%.



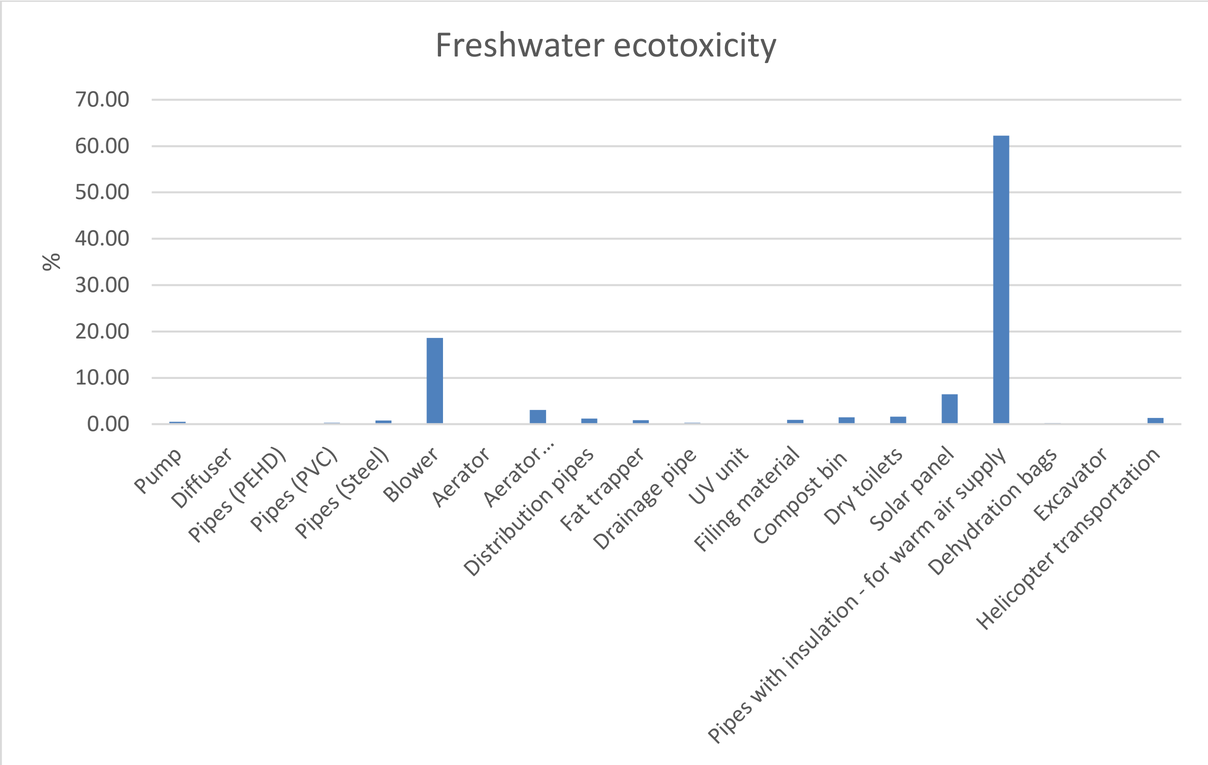
Graph 8: Global warming contribution of each material - Scenario II

Nearly 45% of the total impact on freshwater eutrophication comes from aluminium-isolated pipes and 29% from blowers (Graph 9). Helicopter transport contributes 8%, pumps contribute almost 7% to the freshwater eutrophication impact, and other materials contribute less than 5%.



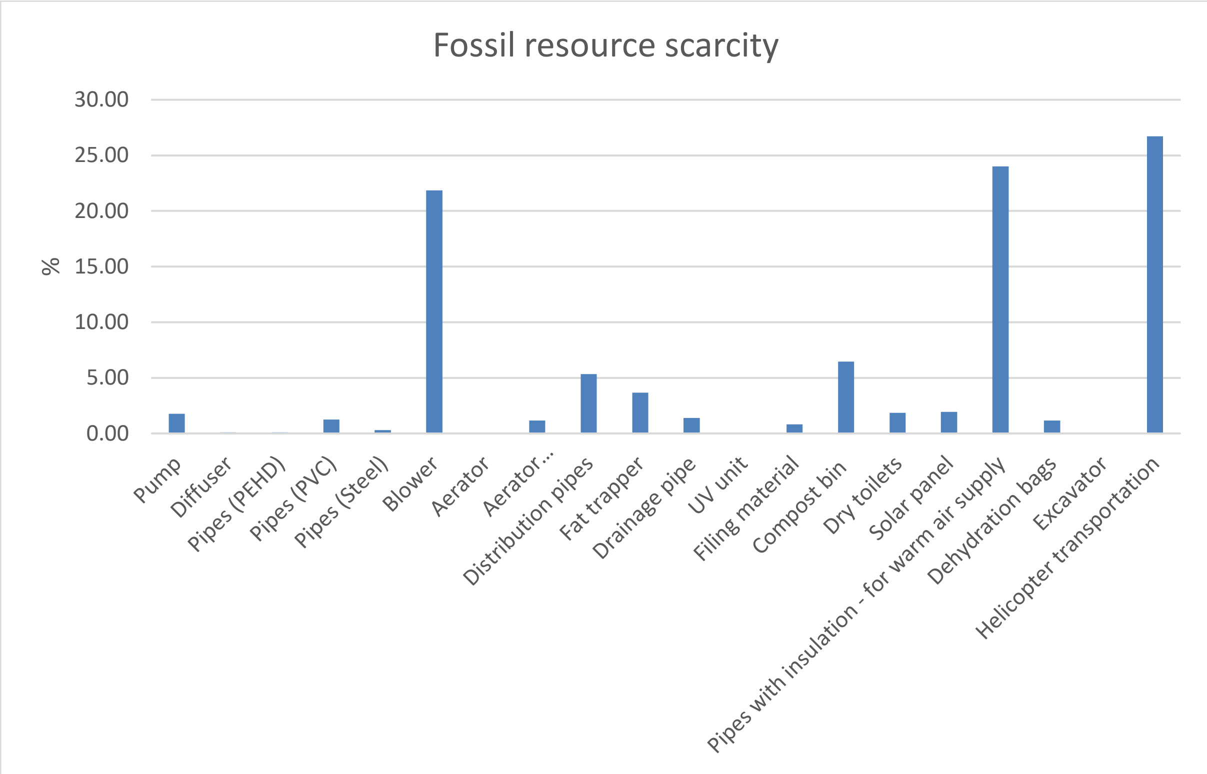
Graph 9: Freshwater eutrophication contribution of each material – Scenario II

Graph 10 shows that aluminium-isolated pipes and blowers contribute most to freshwater ecotoxicity. Aluminium-insulated pipes represent 62% of the total impact, and blowers represent 19% of the total impact on freshwater ecotoxicity. Other materials contribute less than 10% to the freshwater ecotoxicity impact category.



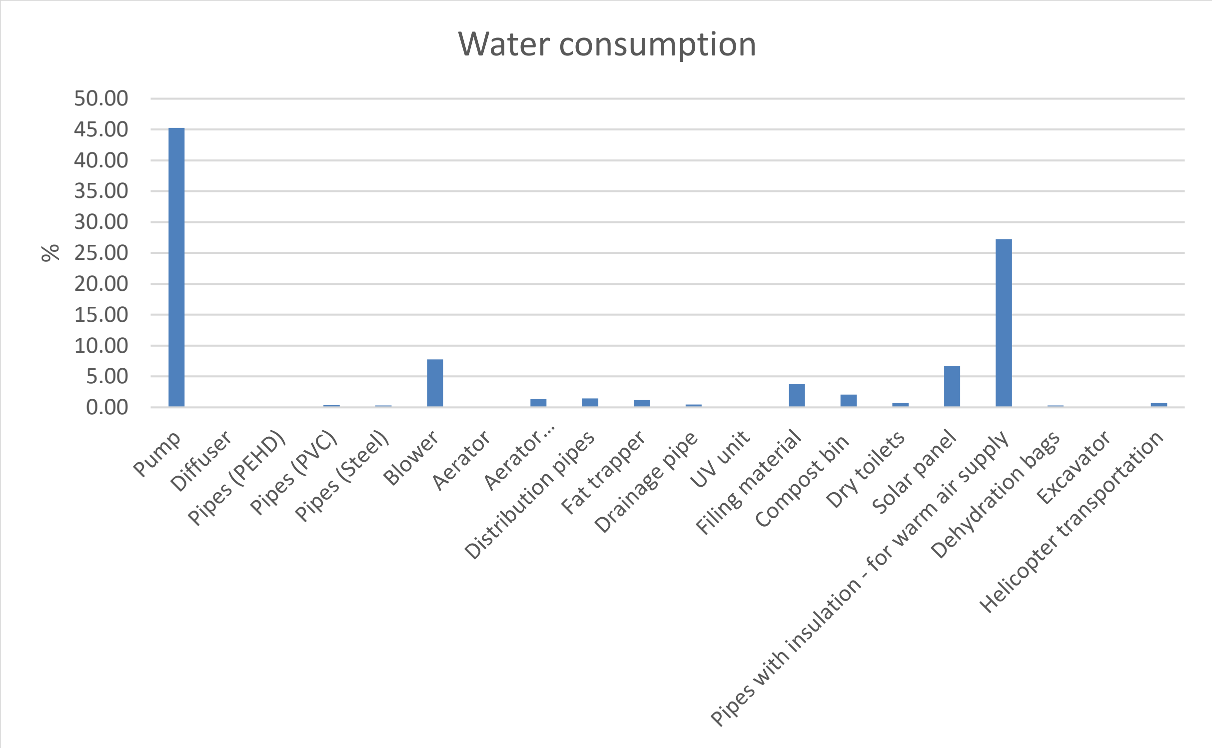
Graph 10: Freshwater ecotoxicity contribution of each material - Scenario II

Graph 11 shows that aluminium-isolated pipes, blowers, and helicopter transport have the highest impact on fossil resource scarcity. Aluminium-isolated pipes contributed 24% to the total impact, blowers contributed 22%, and helicopter transport contributed almost 27% to the total impact on fossil resource scarcity. Compost bind represents almost 7% of the total impact, and distribution pipes made from PVC represent just above 5% of the total impact on fossil resource scarcity. Other materials contribute less than 5% to the total impact.



Graph 11: Fossil resource scarcity contribution of each material - Scenario II

The most significant contributor to water consumption are pumps, which account for 45% of the total water consumption impact (Graph 12). With almost 28% of the total impact, the aluminium-insulated pipes represent the second-highest impact on water consumption. Blowers contribute 8% to the total impact, and solar panels contribute 7% to the total impact on water consumption. All other materials contribute less than 5% to this impact category.



Graph 12: Water consumption contribution of each material - Scenario II

Operation – Scenario II

Similarly, as in Scenario I, we only considered the energy not produced by the solar panels, as they produce clean energy. We have considered the diesel generator, which is assumed to run 40 days per season when there is not enough sunshine to power the treatment plant. The largest energy consumers are the aeration blowers that aerate the SBR, accounting for almost 40% of the total energy consumption. The pumps account for 30% of the total energy consumption, the largest of which are the pumps that transfer the grey water into the SBR.

Table 19 shows the impact of each element in the operation phase on the five impact categories. The operation in scenario II has the most significant impact on global warming and scarcity of fossil resources, with sludge removal by helicopter accounting for the largest share of the total impact.

Iron sulphate ($Fe_2(SO_4)_3$), added to remove phosphorus compounds from wastewater, significantly contributes to global warming, fossil resource depletion and freshwater ecotoxicity. We can see that water saving significantly impacts water consumption and all other impact categories.

Some contaminants in the treated water discharged to the environment still contribute to freshwater eutrophication. However, these amounts are minimal compared to other elements in the treatment plant's operation.

Table 19: Environmental impact of operation for Scenario II

Impact category	Unit	Total	Diesel aggregate	Sludge removal - helicopter	Operation	Water saving	Fe SO4
Global warming	kg CO2 eq	-4224.00	255.00	1940.00	0.00	-6520.00	101.00
Freshwater eutrophication	kg P eq	-2.46	0.25	0.26	1.23	-4.27	0.08
Freshwater ecotoxicity	kg 1,4-DCB	-276.11	2.97	4.22	0.00	-302.00	18.70
Fossil resource scarcity	kg oil eq	-443.70	610.00	619.00	0.00	-1710.00	37.30
Water consumption	m3	-8502.45	0.29	0.76	0.00	-8510.00	6.51

*Positive values show the environmental burden, while negative values for each indicator show the environmental burden saved.

Total impact of Scenario II

Tables 20 and 21 show the total impact of Scenario II, contributed both from the construction phase and operation. Overall, construction has the highest impact on all the categories, with global warming being the most affected. It represents 46% of the total freshwater eutrophication impact, 43% of the total freshwater ecotoxicity impact and 27% of the global warming impact category.

Because the water savings over the 20-year lifetime of the treatment system are so significant, the savings have a major positive impact on all impact categories, with the expected impact on water consumption being the most pronounced and, surprisingly, also on global warming, as well on fossil resource scarcity and freshwater ecotoxicity.

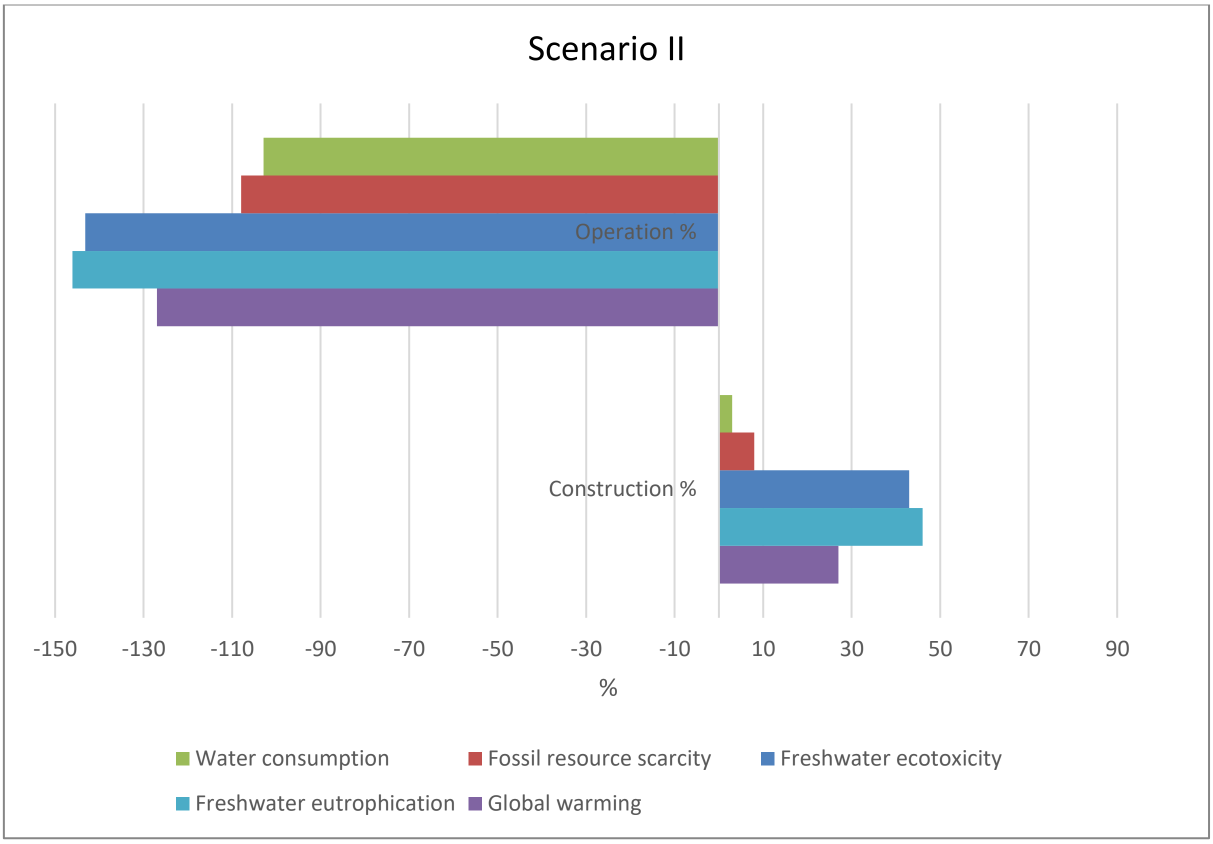
Looking at the total impact of the construction and operation phases (Graph 13), we can see that the operation phase is responsible for more than the total impact of construction and operation combined due to the positive impact of water savings. In other words, the positive impact of the operation phase is so significant that it not only counteracts its negative impact but also contributes to reducing the overall impact of the system.

Table 20: Total impact of Scenario II

	Global warming [kg CO2 eq]	**Freshwater eutrophication** [kg P eq]	**Freshwater ecotoxicity** [kg 1,4-DCB]	**Fossil resource scarcity** [kg oil eq]	**Water consumption** [m^3]
Construction	19877.66	7.79	791.52	5677.67	248.83
Operation	-4224.00	-2.46	-276.11	-443.70	-8502.45
Total	15653.66	5.33	515.41	5233.97	-8253.62

Table 21: Total impact of Scenario II in percentages

	Global warming	Freshwater eutrophication	Freshwater ecotoxicity	Fossil resource scarcity	Water consumption
Construction %	27	46	43	8	3
Operation %	-127	-146	-143	-108	-103



Graph 13: Total impact of Scenario II (operation and construction) in percentages

5.4.3 INTERPRETATION – SCENARIO II

Scenario II has the highest impact on freshwater eutrophication and ecotoxicity, with 46% and 43% of the contribution from the construction phase, respectively. This result tells us that the materials used for the system have a high impact on those two impact categories. We could choose different materials with less environmental impact when looking for better solutions. The high contribution on the highest impacted categories comes from aluminium insulated pipes and blowers.

The impact of Scenario II on the scarcity of fossil resources is also high, with 52% of the total impact coming from the operational phase. The highest impact comes from helicopter transport in the operation and construction phases.

The total impact on all impact categories is lower due to the positive impact of the operation phase and water saving as a result of the installation of dry toilets.

The results show that the material (aluminium insulated pipes especially) and helicopter transport strongly impact the highest impacted categories and can be considered a "hot spot" in Scenario II. We can also see that reducing water consumption has a strong positive impact on all impact categories. This is because reducing water consumption helps to conserve the natural resource that is water, which results in less wastewater and less energy and chemicals needed to treat it.

5.5 COMPARING THE IMPACT OF SCENARIO I AND II

The following sections will compare the impacts of Scenario I and Scenario II for both phases. In the last part of the chapter, we will compare both scenarios with the current operation of the treatment plant in the hut for the operational phase.

Construction phase

From Table 22, it can be seen that overall, the construction phase in Scenario I has a slightly more significant impact on all impact categories than the construction phase in Scenario II, except on global warming, where Scenario II has a more significant impact. The most considerable difference between the two scenarios is in the global warming category.

Table 22: Total impact of the construction phase of Scenario I and Scenario II

	Global warming	Freshwater eutrophication	Freshwater ecotoxicity	Fossil resource scarcity	Water consumption
	kg CO2 eq	kg P eq	kg 1,4-DCB	kg oil eq	m3
SCENARIO I	17433.28	7.75	956.72	5749.25	394.62
SCENARIO II	19877.66	7.79	791.52	5677.67	248.83

Operation phase

Table 23 shows that the operation in Scenario I has a much higher impact on the environment than Scenario II, as it positively impacts all impact categories. Scenario I has a positive impact only on water consumption. The highest difference between the two scenarios is in the global warming category.

Table 23:Total impact of the operation of Scenario I and Scenario II

	Global warming	Freshwater eutrophication	Freshwater ecotoxicity	Fossil resource scarcity	Water consumption
	kg CO2 eq	kg P eq	kg 1,4-DCB	kg oil eq	m^3
SCENARIO I	62479.50	51.29	374.84	124506.90	-5956.44
SCENARIO II	-4224.00	-2.46	-276.11	-443.70	-8502.45

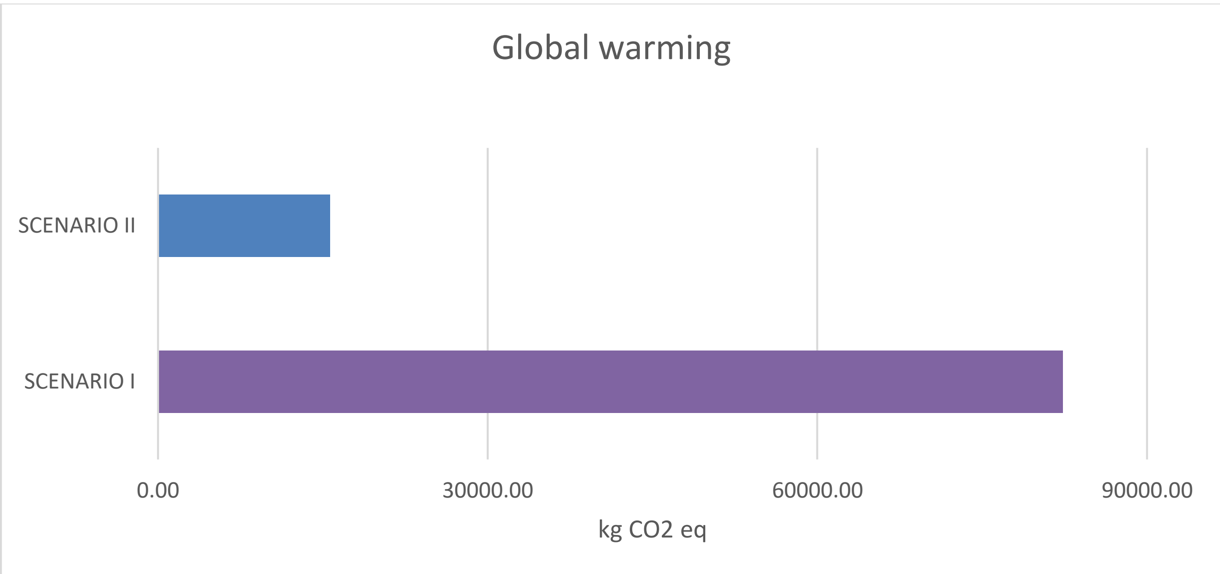
Total Impact

Total impact of both scenarios is shown in Table 24. The most significant difference between the two scenarios is the impact of fossil resource scarcity. The total impact on fossil resource scarcity of Scenario I is 25 times greater than that of Scenario II. This can also be seen in Graph 17. The impact of Scenario I on freshwater eutrophication is also significantly higher (11 times) than that of Scenario II. The difference in impact on the freshwater eutrophication can be seen in the Graph 15.

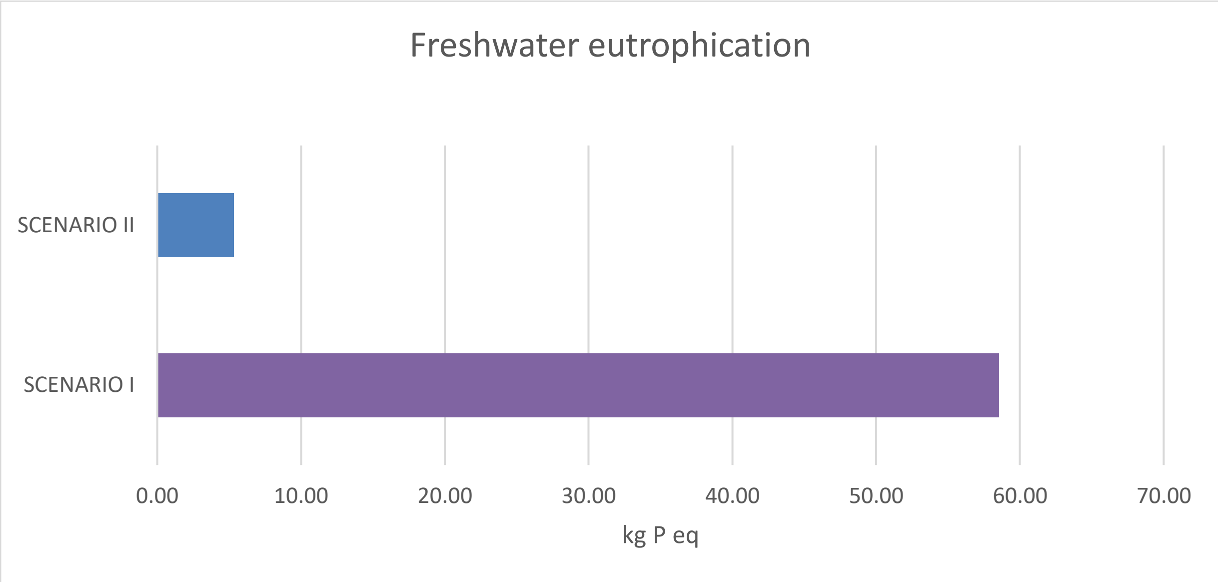
Table 24: Total impact of the Scenario I and Scenario II

	Global warming	**Freshwater eutrophication**	**Freshwater ecotoxicity**	**Fossil resource scarcity**	**Water consumption**
	kg CO2 eq	kg P eq	kg 1,4-DCB	kg oil eq	m^3
SCENARIO I	79912.78	59.04	1331.56	130256.15	-5561.82
SCENARIO II	15653.66	5.33	515.41	5233.97	-8253.62

Scenario I also has a higher impact on global warming than Scenario II. The difference between the two scenarios can be seen in Graph 14, where we can see that the impact of Scenario I is five times higher.

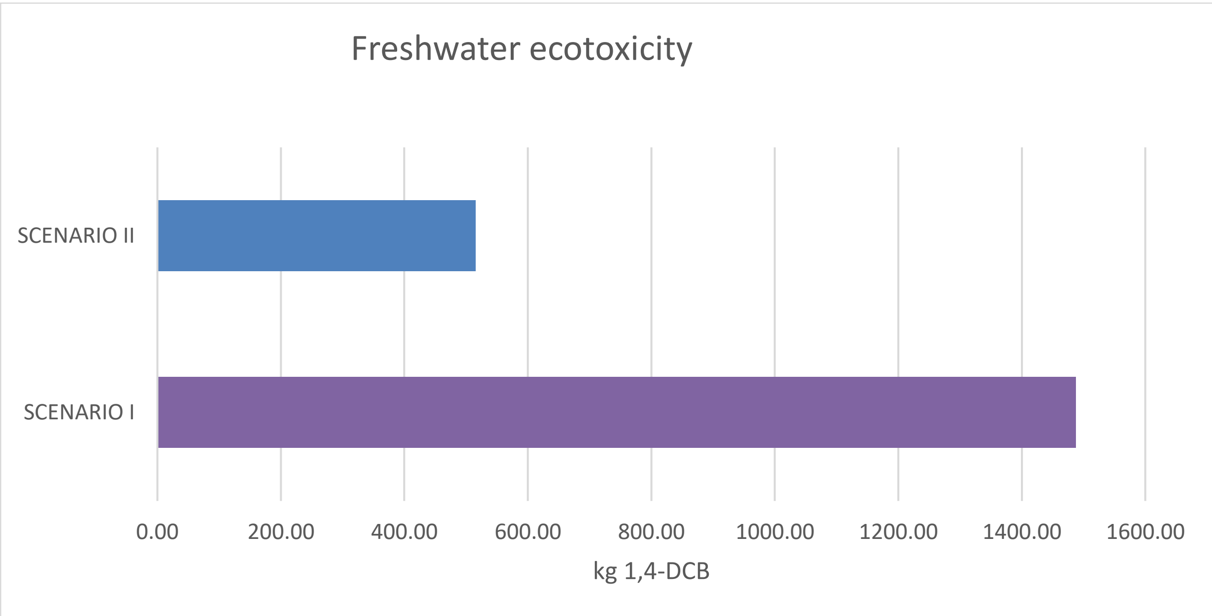


Graph 14: Total impact on global warming from Scenario I and Scenario II

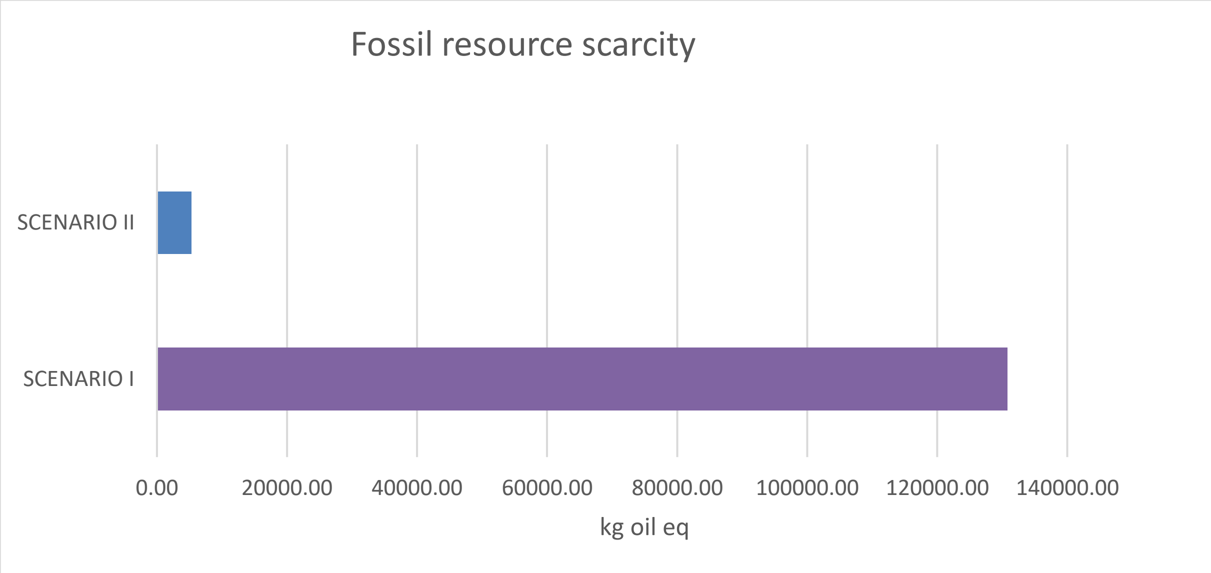


Graph 15: Total impact on the freshwater eutrophication from Scenario I and Scenario II

Scenario I also has a higher impact on freshwater ecotoxicity than Scenario II. The difference between the two scenarios can be seen in Graph 16, where we can see that the impact of Scenario I is three times higher.

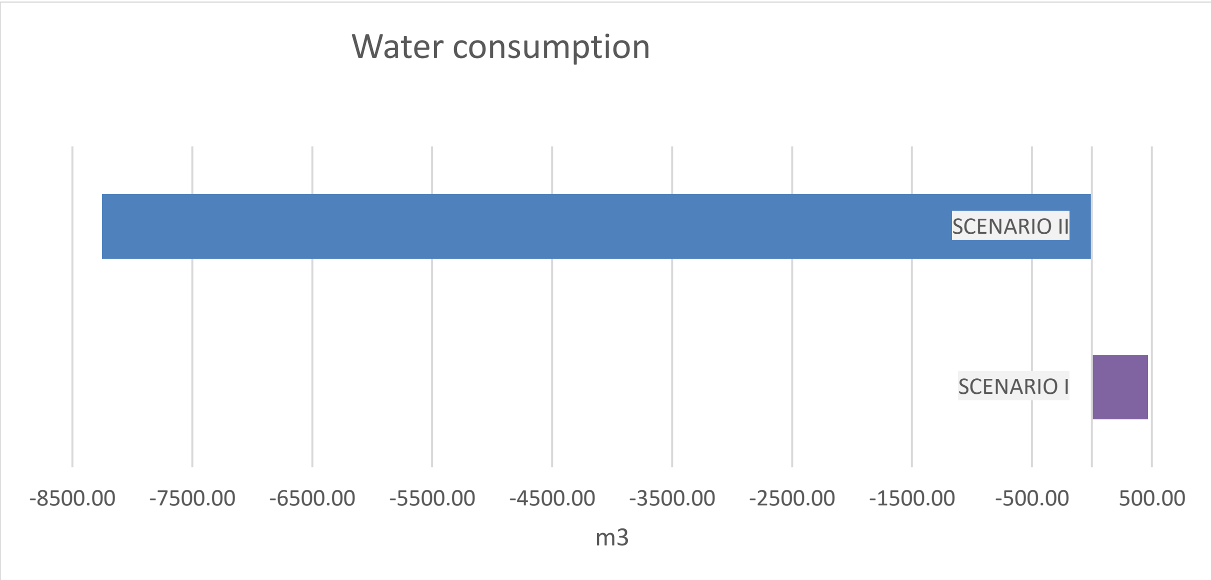


Graph 16: Total impact on the freshwater ecotoxicity from Scenario I and Scenario II



Graph 17: Total impact on the fossil resource scarcity from Scenario I and Scenario II

Both scenarios positively impact water consumption since water is being saved in both cases (Graph 18). Scenario II has a slightly more significant positive impact on the water consumption.



Graph 18: Total impact on the water consumption from Scenario I and Scenario II

Comparing the impact of the operation with both scenarios and the current state

We were also interested in whether the solutions presented were better for the environment than the status quo. As we did not have all the information on the construction of the current wastewater treatment system, we decided to look only at the system's performance. Based on the above results, we also assumed that operation would account for a more significant proportion of the total environmental impact. To calculate how the current situation operates, we have used the data from the input data study (Rozman, 2020).

Table 25 shows the values of all the impacts from the system operation area on all the impact categories. It can be seen that the operation of the system currently in use has a higher impact on all impact categories. We can also see that Scenario I has only slightly less impact on the global warming impact category and fossil resource scarcity impact category compared to the current state. This shows the high energy demand in both systems (status quo and Scenario I).

Table 25 shows that compared to the current state, Scenario II has over 100% less impact on all impact categories and water consumption, even over 10000%. Scenario I also has significantly less impact on the water consumption impact category, with over 7000% less impact in the operation phase.

Table 25: Total impact on all of the categories from operation from both scenarios and current state

	Global warming	**Freshwater eutrophication**	**Freshwater ecotoxicity**	**Fossil resource scarcity**	**Water consumption**
	kg CO2 eq	kg P eq	kg 1,4-DCB	kg oil eq	m^3
SCENARIO I	62479.50	51.29	374.84	124506.90	-5956.44
SCENARIO II	-4224.00	-2.46	-276.11	-443.70	-8502.45
CURRENT STATE	65098.00	183.70	683.60	127440.00	81.91
SCENARIO I The difference compared to the current state (%)	4.02	72.08	45.17	2.30	7371.94
SCENARIO II The difference compared to the current state (%)	106.49	101.34	140.39	100.35	10480.23

Interpretation

Both scenarios are better solutions compared to the current situation and have lower environmental impact. However, the operation of Scenario I still strongly impacts global warming and the scarcity of fossil resources, mainly due to the high demand for energy and the type of energy used in operation. This energy source still contributes significantly to the negative environmental impact despite replacing the old diesel generator with a more efficient gas generator.

Table 25 shows that Scenario II also has a lower or even positive environmental impact than the status quo due to the considerable water savings. On this basis, it can be argued that Scenario II is less environmentally damaging from the point of view of the LCA analysis.

5.6 SUGGESTIONS BASED ON LCA TO IMPROVE SCENARIO II

Even though Scenario II has substantially lower environmental impact than Scenario I, the system could be improved with technology that would provide even better, more environmentally friendly solutions. To improve the system we could focus on good practises implemented in the Swiss Alps.

As most of the impact is due to the construction of the WWTP, i.e., transporting sand material for the CW, replacing the media of the CW with coal-expanded clay aggregate or other lightweight material could be considered to reduce the number of helicopter flights. Blowers in the SBR also contribute to almost all impact categories in the construction phase, so we could, for example, replace SBR with another CW with vertical flow. This would avoid the use of blowers and also reduce the need for electricity.

Another system that does not need electricity is Biorock, presented in Section 3.4. In this case, Biorock could replace SBR. The only source of energy consumption would be the pumps to transport the water into the Biorock and onto the CW. However, if sufficient head could be provided in the field, the water could also flow into the system by gravity. The Biorock units can cover as many PE as required when installed in parallel.

Traditionally, a Biorock consists of two tanks: one for primary anaerobic treatment (1) and one for biological treatment (2) (Figure 27). Solid organic matter settles to the bottom in the primary treatment, while oils and fats float to the surface. In the second part of the reactor, the effluent is distributed over a medium (5) that acts as a medium for aerobic bacteria that purify the water. The treated water flows by gravity through the treatment layers to the bottom of the reactor, where it is discharged to CW (6).

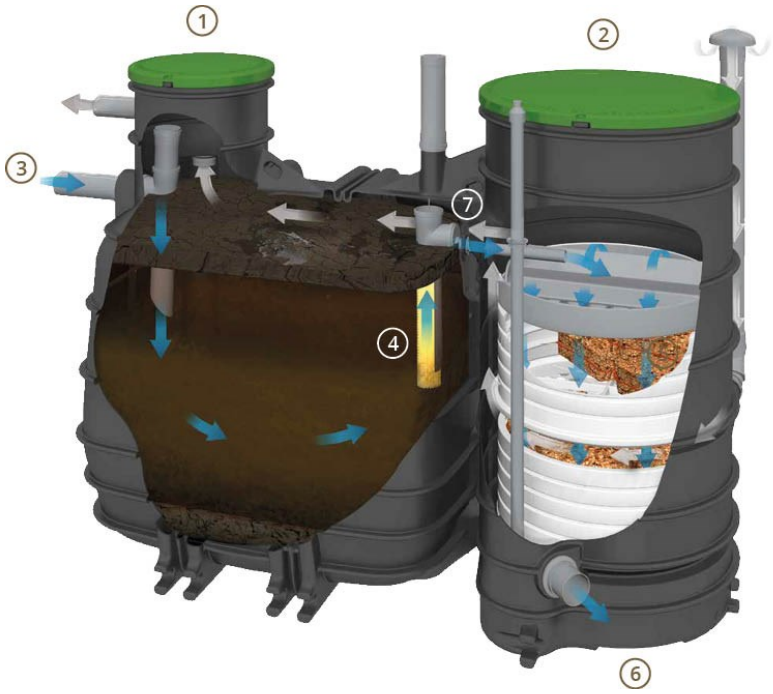


Figure 27: Example of a biorock from a company Biorock Swiss (Source: https://biorock.swiss)

The air required for the system's operation enters the reactor through an aeration pipe installed below ground level (7). The exhaust air is discharged from the reactor through vent pipes, which terminate at a much higher level, creating a constant negative pressure throughout the system. The vent pipes act as a chimney, and electricity is not needed.

Of course, all the proposed solutions and technologies would still need to be developed and evaluated to see if the treatment and implementation would be effective.

6 CONCLUSIONS

The Master's thesis aimed to determine whether the choice of different wastewater treatment technologies and wastewater management methods has different impacts on the environment and, if so, what these impacts are. We focused on wastewater from mountain huts, where water and electricity are often scarce. In addition, such areas are often more vulnerable to pollution. Increasingly, LCA is being used to identify environmental impacts, providing insight into different impact categories such as global warming, water consumption, acidification of clean water, and so on. This allows us to quickly identify which elements included in the calculations have contributed most to the environmental impact.

The most commonly used technology for wastewater treatment in Slovenian huts is the SBR Trickling filter, MBBR, CW, MBR and Biodisk. Similar technologies are also used in Swiss huts, where existing systems are increasingly being replaced by more robust solutions, such as dry toilets with urine separation and biofilters combined with CW.

In this Master's thesis, we focus on the Triglav Lakes Hut, one of the most popular tourist destinations. The Double Lake next to the hut has been suffering from organic and nutrient pollution for several years, reflected in the lake's algae growth. The organic pollution and nutrients come from treated wastewater discharged into the lake through a sinkhole. The current SBR system was found to be malfunctioning and needed to be replaced with a more efficient one. For this reason, the "VrH Julijcev" project presented improved wastewater management and treatment systems at the Triglavs Lake Hut.

The first solution (Scenario I) is a high-efficiency wastewater treatment technology that uses a membrane module with a membrane filter installed after the biological treatment which take place in the SBR. The second solution (Scenario II) involves more robust technologies, such as dry composting toilets and a CW, which work with the SBR to treat grey water. Due to their robustness, these technologies have proven to work well in remote and hard-to-reach locations, such as mountain huts, and are also a common practice in Swiss huts.

In the thesis, we analysed which of the proposed solutions for wastewater management in the Triglav Lakes Hut has a lower environmental impact and whether this solution has a lower environmental impact than the current system in place. We also analysed which installed elements and parts of the system contribute most to the negative environmental impact and whether other alternative solutions for these elements would have a lower environmental impact through their operation and installation. In selecting alternative solutions, we considered technologies commonly used in the Swiss huts as examples of good practice.

The results of the LCA analysis show that the more robust solution (i.e., Scenario II) has a lower environmental impact than Scenario I. Scenario II is shown to have a lower impact than Scenario I for all impact categories considered. The most significant difference is observed for fossil resource scarcity, where the impact of Scenario I is 25 times higher than Scenario II's.

Solar panels have the most significant environmental footprint when building the system in Scenario I. They contribute almost 60% of the total impact on freshwater ecotoxicity, 47% on water consumption, 35% on freshwater eutrophication, 20% on fossil resource scarcity and 24% on global warming in the construction phase.

Only the blowers significantly impact global warming (30% of the total impact) during the construction phase in Scenario I. The system operation in Scenario I has the most significant impact due to the scarcity of fossil resources, with blowers contributing 30% of the total energy consumption. However, due to water reuse, the system in Scenario I positively impacts the water consumption impact category.

In the construction of Scenario II, global warming is the most significant contributor to the total impact, with aluminium pipes with insulation (29%) and blowers (30%) being the most important contributors. In the impact category, water consumption pumps have the highest impact, with a share of 45%. The system's operation has a positive environmental impact due to the significant water savings. The disposal (transport) of sludge and compost by helicopter has the highest impact on global warming.

The choice of materials used has been shown to have a significant impact on the total environmental footprint of each Scenario. The results show that the manufacture of solar panels has a high environmental impact in Scenario I. In Scenario II, the highest contribution to the total impact in the construction phase comes from blowers. This suggested that technologies with less energy demand would give more environmentally friendly solutions. For example, replacing SBR with another CW with vertical flow was suggested to avoid the need for blowers. Other low energy-consuming technologies, such as Biorock, were also suggested.

A comparison of the two scenarios with the existing system shows that the discharge of treated wastewater into the Double Lake does not contribute much to the overall impact, although organic and nutrient pollution due to failures of the current system is high and is the leading cause of the "bloom" of the lake. This shows that the pollution of Double Lake is relatively small on a global scale and does not contribute much to the global environmental impact. This indicates the necessity to take selected system boundaries into account when interpreting the LCA. In our case, we focus only on the impact of the WWTP and its construction and operation at the global level. For example, if we wanted to find out how emissions from the treated wastewater affect the lake, we would need to identify specific impacts on the local ecosystem and consider how emissions from the treatment system are reflected in the local aquatic ecosystem and how the treatment system affects the ecosystem services provided by the lake (natural habitat, recreational opportunities, etc.). This would give us more information on the impact of proper or improper wastewater treatment on the lake.

LCA is a good tool for identifying the so-called "hot spots" for a negative environmental impact. As a result, we can quickly identify it and replace it accordingly to reduce the environmental footprint. However, we need to set clear system boundaries in the calculations, especially when comparing different technologies; otherwise, we may not get a representative result.

The results show that wastewater management in mountain huts should focus more on robust technologies requiring zero or near-zero energy. An essential step in this direction has already been taken in the Swiss huts, where installing dry toilets and other simple energy-saving technologies is becoming more widespread. Given that the weather conditions in the Slovenian mountains are similar to, or even harsher than, those in Switzerland, Slovenian mountain huts could move in a similar direction.

7 ZAKLJUČEK

Cilj magistrske naloge je bil ugotoviti, ali ima izbira različnih tehnologij čiščenja odpadne vode in načinov ravnanja z odpadno vodo različne vplive na okolje, in če ja, kakšni so ti vplivi. Osredotočili smo se na odpadne vode iz gorskih koč, kjer pogosto primanjkuje vode, električna energija pa je omejena. Poleg tega so takšna območja pogosto bolj izpostavljena onesnaževanju. Za ugotavljanje vplivov na okolje se vse pogosteje uporablja metoda LCA, ki omogoča vpogled v različne kategorije vplivov, kot so globalno segrevanje, poraba vode, zakisljevanje čiste vode itd. Tako lahko hitro ugotovimo, kateri elementi, vključeni v izračune, so najbolj prispevali k okoljskemu vplivu.

Najpogosteje uporabljene tehnologije za čiščenje odpadne vode v slovenskih kočah so SBR, precejalniki, MBBR, RČN, MBR in Biodisk. Podobne tehnologije se uporabljajo tudi v švicarskih kočah, kjer se obstoječi sistemi vse bolj nadomeščajo z robustnejšimi rešitvami, kot so suha stranišča z ločevanjem urina in biofiltri v kombinaciji z RČN.

V magistrskem delu se osredotočamo na Kočo Triglavska jezera, ki je ena najbolj priljubljenih turističnih destinacij. Dvojno jezero ob koči že več let trpi zaradi onesnaženja s hranili, ki se kaže v rasti alg v jezeru. Onesnaženje izvira iz prečiščene odpadne vode, ki se v jezero odvaja preko ponikovalnice. Ugotovljeno je bilo, da sedanji sistem SBR ne deluje pravilno in ga bi bilo potrebno zamenjati z bolj učinkovitim. Zato so bili v okviru projekta "VrH Julijcev" predstavljeni izboljšani sistemi za upravljanje in čiščenje odpadne vode v koči ob Triglavskem jezeru.

Prva rešitev (Scenarij I) je sodobnejša in dokazano zelo učinkovita metoda čiščenja odpadne vode, in sicer uporaba membranskega modula z membranskim filtrom, ki je nameščen po biološki obdelavi, ki poteka v SBR. Druga rešitev vključuje robustnejše tehnologije, kot so suha kompostna stranišča in RČN, ki delujejo skupaj s SBR za čiščenje sive vode. Te tehnologije so se prav zaradi svoje robustnosti izkazale za dobro delujoče na oddaljenih in težko dostopnih lokacijah, kot so gorske koče in so pogosta praksa tudi v švicarskih kočah.

V magisterskem delu nas je zanimalo, katera od predstavljenih rešitev za ravnanje z odpadnimi vodami v Koči pri Triglavskih jezerih je manj obremenjujoča na okolje in ali ima ta rešitev manjši vpliv na okolje kot sedanji sistem. Zanimalo nas je tudi, kateri vgrajeni elementi in deli sistema najbolj prispevajo k negativnemu vplivu na okolje in ali za te elemente obstajajo druge alternativne rešitve, ki bi s svojim delovanjem in vgradnjo imele manjši vpliv na okolje. Pri izbiri alternativnih rešitev smo upoštevali tehnologije, ki se običajno uporabljajo v švicarskih kočah kot primeri dobre prakse.

Rezultati analize LCA kažejo, da ima robustnejša rešitev (tj. scenarij II) manjši vpliv na okolje kot sodobnejša rešitev membranskega filtra. Pokazalo se je, da ima scenarij II manjši vpliv kot scenarij I za vse obravnavane kategorije vpliva. Največja razlika je opazna pri vplivni kategoriji pomanjkanje fosilnih virov, kjer je vpliv scenarija I 25-krat večji od vpliva scenarija II.

Sončni kolektorji imajo največji okoljski odtis pri gradnji sistema scenarija I. V fazi gradnje prispevajo skoraj 60 % celotnega vpliva na ekotoksičnost sladkih voda, 47 % na porabo vode, 35 % na evtrofikacijo sladkih voda, 20 % na pomanjkanje fosilnih virov in 24 % na globalno segrevanje. Večji vpliv na globalno segrevanje (30% celotnega vpliva) imajo v fazi izgradnje v scenariju I le še puhala. Delovanje sistema v scenariju I največji vpliv na pomanjkanje fosilnih virov, saj puhala prispevajo 30 % celotne porabe energije. Zaradi ponovne uporabe vode pa sistem v scenariju I pozitivno vpliva na kategorijo vpliva porabe vode.

Pri gradnji po scenariju II k skupnemu vplivu največ prispeva globalno segrevanje, pri čemer največ prispevajo aluminijaste cevi z izolacijo (29%) in puhala (30%). V kategoriji vpliva porabe vode imajo največji vpliv črpalke, in sicer 45% delež. Delovanje sistema ima zaradi velikega prihranka vode pozitiven vpliv na okolje. Odstranjevanje (prevoz) blata in komposta s helikopterjem ima največji vpliv na globalno segrevanje.

Izbira uporabljenih materialov ima pomemben vpliv na celoten okoljski odtis pri obeh scenarijih. Rezultati so pokazali, da ima proizvodnja solarnih panelov velik vpliv na okolje v scenariju I, medtem ko v scenariju II največji prispevek k skupnemu vplivu v fazi gradnje prispevajo puhala. To je nakazovalo, da bi tehnologije z manjšo potrebo po energiji zagotovile okolju prijaznejše rešitve. Predlagana je bila na primer zamenjava SBR z dodatno RČN z vertikalnim pretokom, da bi se izognili potrebi po puhalih. Predlagane so bile tudi druge tehnologije z nizko porabo energije, kot je Biorock z RČN.

Primerjava obeh scenarijev z obstoječim sistemom kaže, da odvajanje očiščene odpadne vode v Dvojno jezero, ne prispeva veliko k skupnemu vplivu, čeprav je onesnaženje s hranili zaradi nepravilnega delovanja trenutnega sistema močno in je glavni vzrok za "cvetenje" jezera. To kaže, da je onesnaževanje Dvojnega jezera v svetovnem merilu precej majhno in ne prispeva veliko k svetovnemu vplivu na okolje. Iz tega je razvidno, da moramo pri razlagi rezultatov LCA upoštevati izbrane sistemske meje. V našem primeru se osredotočamo le na vpliv čistilne naprave ter njeno gradnjo in delovanje na globalni ravni. Če bi na primer želeli ugotoviti, kako emisije iz očiščene odpadne vode vplivajo na jezero, bi morali opredeliti posebne vplive na lokalni ekosistem; preučiti, kako se emisije iz sistema čiščenja odražajo v lokalnem vodnem ekosistemu in kako sistem čiščenja vpliva na ekosistemske storitve, ki jih zagotavlja jezero (naravni habitat, rekreacijske možnosti, itd.). S tem bi pridobili več informacij o tem, kakšen vpliv ima pravilno oziroma nepravilno čiščenje odpadne vode na jezero.

LCA je dobro orodje za relativno hitro prepoznavanje tako imenovanih "vročih točk" negativnega vpliva na okolje. Ker jih lahko hitro prepoznamo, jih lahko ustrezno nadomestimo ter tako zmanjšamo okoljski odtis. Vendar pa moramo pri izračunih določiti jasne sistemske meje, zlasti pri primerjavi različnih tehnologij, sicer morda ne bomo dobili reprezentativnega rezultata.

Rezultati jasno kažejo, da bi se moralo ravnanje z odpadno vodo v planinskih kočah bolj osredotočiti na preproste tehnologije, ki za svoje delovanje potrebujejo nič ali skoraj nič energije. Pomemben korak v tej smeri je bil že narejen v švicarskih kočah, kjer je praksa nameščanja suhih stranišč in drugih preprostih tehnologij za varčevanje z energijo vse bolj razširjena. Glede na to, da so vremenske razmere v slovenskih gorah podobne ali celo ostrejše kot v Švici, bi lahko slovenske planinske koče šle v podobno smer.

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