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Department of Environment,
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MASTER'S DEGREE THESIS

**Integrated Solutions for the Energy and
Environmental Sustainability of Alpine Huts**

Toesca Refuge Case Study

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ABSTRACT

Italian Version

Il presente lavoro di tesi, svolto nell'ambito della *Challenge@PoliTo_by Firms "Innovative Solutions for the Sustainability of Alpine Huts by Club Alpino Italiano Torino"*, affronta il tema della sostenibilità energetica e ambientale dei rifugi alpini di proprietà del Club Alpino Italiano (CAI), Sezione di Torino. Il contesto di ricerca riguarda le difficoltà tipiche delle strutture isolate in ambiente montano, spesso non collegate alle reti pubbliche di approvvigionamento idrico, fognario ed elettrico, e caratterizzate da accessibilità limitata, condizioni climatiche severe e forte variabilità stagionale dell'afflusso turistico.

Lo studio si è focalizzato su un rifugio attualmente esistente, quale il Rifugio Toesca, situato a 1710 m s.l.m. nel territorio del Comune di Bussoleno, all'interno della Città Metropolitana di Torino, al fine di migliorare l'autonomia, la resilienza e la sostenibilità dello stesso. Le principali criticità del caso di studio analizzato riguardano il sottodimensionamento dell'attuale sistema di trattamento dei reflui tramite vasca Imhoff e la vulnerabilità dell'approvvigionamento elettrico, basato prevalentemente su una turbina idroelettrica integrata da un generatore diesel di supporto.

L'obiettivo della tesi è valutare una soluzione integrata, intervenendo sia sulla gestione delle acque reflue, sia sulla produzione di energia elettrica da fonti rinnovabili. La metodologia utilizzata si basa sull'analisi del caso studio e delle relative criticità. A partire dalle informazioni ottenute, si è provveduto al dimensionamento del sistema di trattamento dei reflui attraverso il calcolo degli abitanti equivalenti e dei carichi inquinanti, considerando di utilizzare un sistema SBR per la depurazione delle acque reflue, integrato con un essiccatore solare per la gestione dei fanghi. Al fine di garantire un approvvigionamento certo di energia elettrica, si è simulata l'installazione di un impianto fotovoltaico dotato di accumulo. In ultimo, è stata considerata la fattibilità economica degli interventi proposti mediante l'analisi del Valore Attuale Netto, tenendo conto di costi di investimento, costi operativi evitati e vita utile degli impianti.

I risultati mostrano che il sistema SBR proposto è in grado di trattare efficacemente i reflui prodotti dal rifugio, garantendo concentrazioni in uscita di BODs, COD e solidi sospesi inferiori ai limiti normativi previsti per lo scarico al suolo. L'integrazione dell'essiccatore solare consente inoltre di ridurre significativamente il volume dei fanghi, limitando la frequenza degli interventi di trasporto e smaltimento. Dal punto di vista energetico, la simulazione di diverse configurazioni fotovoltaiche ha permesso di individuare quella capace di ridurre il ricorso al generatore diesel di back-up, corrispondente ad una potenza di picco pari a 6.3 kWp, un inverter e una batteria da 15 kWh.

In conclusione, la soluzione proposta dimostra come un approccio integrato alla gestione di energia, reflui e fanghi possa contribuire in modo concreto alla sostenibilità dei rifugi alpini isolati. Tale approccio, grazie alla combinazione di tecnologie adatte a contesti remoti e ambientalmente sensibili, può inoltre rappresentare un modello di riferimento potenzialmente replicabile, con i necessari adattamenti, in altri ambienti montani caratterizzati da criticità analoghe.

English Version

The present thesis work, carried out within the framework of the *Challenge@PoliTo* by *Firms* initiative “*Innovative Solutions for the Sustainability of Alpine Huts by Club Alpino Italiano Torino*”, addresses the issue of the energy and environmental sustainability of alpine huts owned by the Italian Alpine Club (CAI), Turin Section. The research context concerns the typical difficulties of isolated facilities in mountain environments, which are often not connected to public water supply, sewerage and electricity networks, and are characterized by limited accessibility, severe climatic conditions and strong seasonal variability in tourist inflow.

The study focused on an existing mountain hut, namely Toesca Refuge, located at 1710 m a.s.l. in the Municipality of Bussoleno, within the Metropolitan City of Turin, with the aim of improving its autonomy, resilience and sustainability. The main critical issues of the case study concern the undersizing of the current wastewater treatment system based on an Imhoff tank, and the vulnerability of the electricity supply, which is mainly based on a hydroelectric turbine integrated with a diesel backup generator.

The objective of the thesis is to evaluate an integrated solution, acting both on wastewater management and on the production of electricity from renewable sources. The methodology used is based on the analysis of the case study and its related critical issues. Starting from the information obtained, the wastewater treatment system was sized through the calculation of population equivalents and pollutant loads, considering the use of an SBR system for wastewater treatment integrated with a solar dryer for sludge management. In order to ensure a reliable electricity supply, the installation of a photovoltaic system equipped with storage was simulated. Finally, the economic feasibility of the proposed interventions was carried out through a Net Present Value analysis, taking into account investment costs, avoided operating costs and the useful life of the systems.

The results show that the proposed SBR system is able to effectively treat the wastewater produced by the hut, ensuring outlet concentrations of BOD₅, COD and suspended solids below the regulatory limits established for discharge to soil. The integration of the solar dryer also makes it possible to significantly reduce the volume of sludge, limiting the frequency of transport and disposal operations. From an energy perspective, the simulation of several photovoltaic configurations made it possible to identify the one capable of reducing the use of the diesel backup generator, corresponding to a peak power of 6.3 kWp, one inverter and a 15 kWh battery.

In conclusion, the proposed solution demonstrates how an integrated approach to the management of energy, wastewater and sludge can make a concrete contribution to the sustainability of isolated alpine huts. Thanks to the combination of technologies suitable for remote and environmentally sensitive contexts, this approach may also represent a potentially replicable reference model, with the necessary adaptations, in other mountain environments characterized by similar critical issues.

CONTENTS

1. Introduction	1
2. Case Study: Toesca Refuge.....	3
2.1 Water and energy supply system.....	3
2.2 Wastewater treatment system	4
3. State of the Art.....	5
4. Design of an Integrated Sustainable System for Toesca Refuge.....	7
4.1 Proposed Solution for Wastewater treatment system	7
4.1.1 Hybrid Sequencing Batch Reactor (SBR)	8
4.1.2 SBR Model applied to Toesca Refuge	11
4.1.3 Sludge Management Solution with the Solar Dyer technology.....	15
4.1.4 Economic analysis for the wastewater treatment system	17
4.2 Proposed Solution for Energy system optimization.....	20
4.2.1 Rooftop photovoltaic plant with BESS	23
4.2.2 Economic analysis for the energy system	24
4.3 Economic analysis of the integrated system: Wastewater treatment plant and Rooftop photovoltaic plant with BESS.....	32
4.4 Development status of the solution.....	34
5. Business Analysis	35
5.1 Definition of Value Proposition	35
5.1.1 Wastewater treatment plant (SBR).....	35
5.1.2 Rooftop Photovoltaic plant with BESS	35
5.2 Business Model Canvas	35
5.3 S.W.O.T. Analysis.....	37
5.4 Competitors.....	39
6. Conclusions	40
Bibliography.....	42

LIST OF TABLES

Table 1: Generalities of Toesca Refuge.....	3
Table 2: Main known products analyzed.....	5
Table 3: Advantages of aerobic SBR Technologies.	10
Table 4: The ISEA E.I.30 SBR technical characteristics (8).....	12
Table 5: The ISEA E.I.30 SBR removal efficiencies (8).....	13
Table 6: Average daily outgoing load.	13
Table 7: Outgoing effluent concentrations.	14
Table 8: Economic evaluation of the wastewater treatment plant along the project lifetime.	19
Table 9: Data for the calculation of the total weight of the photovoltaic system components.	25
Table 10: Data for the calculation of the helicopter transport cost.	26
Table 11: I_0 calculation – CASE 1: 28 photovoltaic modules.....	26
Table 12: Data for the calculation of the diesel consumption annual cost.....	27
Table 13: NPV calculation – CASE 1: 28 modules photovoltaic system.	28
Table 14: I_0 calculation – CASE 2: 14 photovoltaic modules.....	30
Table 15: NPV calculation – CASE 2: 14 modules photovoltaic system.	31
Table 16: TRL classification for the components of the proposed integrated solution for the Toesca Refuge.	34

LIST OF FIGURES

Figure 1: Scheme of the wastewater management system in Toesca Refuge (2).	4
Figure 2: Wastewater treatment plant proposed. In light blue the “water line”, while in orange the “sludge line”. The red box indicates the heart of the process.	8
Figure 3: SBR (Sequencing Batch Reactor) design principle (4).	8
Figure 4: The ISEA SBR System by Aliaxis (8).	11
Figure 5: Sketch of the proposed solar sludge dryer.	16
Figure 6: NPV of the wastewater treatment plant along the project lifetime.	20
Figure 7: Electrical energy consumption estimation in a type-day of summer season.	20
Figure 8: Electrical energy consumption estimation in a type-day of winter season.	21
Figure 9: Monthly average water flow through Rio Gerardo.	22
Figure 10: Pelton turbine monthly power production.	22
Figure 11: SOC of the Battery Energy Storage System (BESS) for the PV Plant made of 14 modules.	24
Figure 12: NPV trend during the investment useful lifetime – CASE 1: 28 modules photovoltaic system.	29
Figure 13: NPV trend during the investment useful lifetime – CASE 2: 14 modules photovoltaic system.	32
Figure 14: NPV of the new wastewater management system and photovoltaic system (14 modules).	33
Figure 15: General scheme of a Business Model Canvas.	36
Figure 16: S.W.O.T. Analysis for the integrated solution developed for the Toesca Refuge case study.	39

CHAPTER 1

1. Introduction

In recent years, the issue of the sustainability of isolated structures has taken on an increasingly significant role, especially in fragile natural contexts such as the Alpine environment. Mountain huts are, in fact, essential places for tourist accommodation, hiking, and the enhancement of the territory, but at the same time they pose major challenges from a technical, environmental, and economic perspective. Their location, often far from main settlements and public water and energy distribution networks, makes the management of essential resources such as water, electricity, and wastewater treatment particularly complex.

The objective of the *Challenge@PoliTo_by Firms “Innovative Solutions for the Sustainability of Alpine Huts by Club Alpino Italiano Torino”*, the framework within which the present thesis work was developed, is to identify innovative and sustainable solutions for the Alpine huts owned by the *Club Alpino Italiano (CAI), Turin Section*. In this context, water and energy management represents a complex challenge that requires the contribution of several disciplines in order to address the issue in a comprehensive and multidimensional manner. For this reason, the work was developed by a multidisciplinary group of engineers and architects, with the aim of analysing the technical and management criteria necessary to ensure proper water supply, efficient energy management, and effective wastewater treatment in Alpine huts.

The operational difficulties of these structures are linked to several factors. First, Alpine huts are often located in isolated and high-altitude areas, where access is limited and, in some cases, impossible for most means of transport. This makes both the transport of materials and ordinary and extraordinary maintenance operations complex, especially during winter periods or following severe weather events. Furthermore, many huts are not connected to electricity, water, or sewage systems, making the identification of autonomous and sustainable solutions even more important.

In addition to these critical issues, there are the climatic conditions typical of the mountain environment, such as low temperatures, frost, snow, and strong weather variability, which can reduce the efficiency of the systems and increase the risk of malfunctions. A further determining factor is the high variability of tourist flows, both seasonal and weekly, which directly affects water and energy consumption as well as wastewater production. During certain periods of the year, the number of users can increase rapidly, generating peaks in demand, whereas in other months the facility may be scarcely used or closed. This aspect makes it necessary to adopt a flexible and efficient management system, capable of adapting to different levels of use without compromising the sustainability of the available resources.

Within this context lies the case study of Toesca Refuge, located at 1710 m a.s.l. in the territory of the Municipality of Bussoleno, within the Metropolitan City of Turin. The hut represents a significant example of the issues that characterise many isolated Alpine structures. In particular, the analysis of the current state reveals two main critical aspects. The first concerns the wastewater treatment system, currently based on an Imhoff tank that is undersized

in relation to the actual number of visitors and, consequently, is not always adequate to ensure effective treatment of the wastewater produced. The second critical aspect concerns energy supply: the hut relies mainly on a hydroelectric turbine, but the availability of energy may be compromised both by periods of reduced water flow and by damage or obstructions to the supply pipes, making it necessary to use a backup diesel generator.

In light of these issues, the present thesis aims to analyse and develop an integrated solution to improve the energy and environmental sustainability of Toesca Refuge. The main objective is to identify a system capable of increasing the autonomy of the facility, reducing its environmental impact, and ensuring more efficient management of the available resources. The approach adopted is not limited to the replacement of individual plant components, but considers the hut as a complex system in which energy production, wastewater treatment, and sludge management must be designed in a coordinated manner.

The proposed solution is therefore configured as an integrated and interconnected system, consisting of several complementary technologies. It combines advanced wastewater treatment through an SBR system, more efficient sludge management through solar drying, and an enhancement of renewable energy production through a photovoltaic system with storage. These elements are designed to operate synergistically, jointly addressing the main critical issues of Alpine huts in terms of water, energy, and waste, with the aim of optimising resource use and ensuring greater environmental protection in an isolated and sensitive context.

Despite the fact that this thesis work was developed in relation to the Toesca Refuge case study, the proposed solution is applicable to a range of isolated and environmentally sensitive locations. Key application areas include:

- *Alpine Huts and Mountain Refuges*: This is the primary and most direct application, as the solution is specifically designed to address the unique challenges of sustainability in remote, high-altitude mountain environments that lack conventional utility infrastructure.
- *Remote Tourist and Residential Facilities*: Any tourist accommodations, lodges, or residential buildings situated in off-grid or difficult-to-access areas could benefit from this self-sufficient system.
- *Eco-Tourism and Sustainable Development Projects*: Projects focused on minimizing environmental impact in natural landscapes, where grid connection is not feasible or desirable, present ideal application areas.

CHAPTER 2

2. Case Study: Toesca Refuge

The Toesca Refuge is located in the Municipality of Bussoleno and at 1,710 m a.s.l. in the Rio Gerardo valley, a tributary of the Dora Riparia, in the Susa Valley, within the Municipality of Bussoleno, inside the Orsiera–Rocciavre Natural Park, in an area of particular significance from a landscape, botanical, and faunal perspective; the structure, owned by the Turin Section of the *Club Alpino Italiano (CAI)*, has 25 beds and, during the summer opening period, which varies according to the season and generally runs from the beginning of June to the end of September, is equipped with running water, sanitary facilities, a shower, and electric lighting.

According to the updated 2024 data, the refuge is open from 1 June to 30 September, as well as on holidays and every weekend in April, May, October, November, and December; it records approximately 4,000 visitors per season, uses hydroelectric energy supply, and relies on spring water supply. The general information regarding the refuge under study, according to the updated data (2024), has been summarised in Table 1.

Table 1: Generalities of Toesca Refuge.

Municipality	Bussoleno (TO)
Owner	Sezione CAI Torino
Height (m a.s.l.)	1710
Opening Periods	- 1 June – 30 September and holidays - All the weekends of April, May, October, November and December
Beds	25
Visitors per season	4000
Energy supply	Hydroelectric
Water supply	Water spring

2.1 Water and energy supply system

The potable water supply system is based on a spring intake work (1): the aqueduct is supplied by a spring from which the water, at an almost constant temperature of approximately 2 °C, is conveyed through a pipe conduit to a first settling tank and subsequently to a second loading tank; from the latter, the pipeline branches off and, with a hydraulic head of approximately 70 m and a route of approximately 300 m, supplies the refuge. Two circuits branch off from the pipeline entering the refuge: one intended to distribute water to the internal users of the kitchen and sanitary facilities, and one intended to supply the external fountain; the latter has the function of providing visitors with a source of water and, at the same time, ensuring a continuous flow in the main pipeline, sufficient to prevent freezing at the beginning and end of the opening season, when temperatures below 0 °C may occur.

From an energy perspective, the refuge uses as its main source a hydroelectric system with a nominal power of 6 kW, based on the presence of a turbine that is driven by the water

flow and makes it possible to exploit its energy content; furthermore, in order to address any problems relating to the loading tank or the turbine, the structure is equipped with an 8 kW diesel generator and will be provided with a thermal generator from the Nacamuli Refuge, replacing the current generator, which is now obsolete and no longer operational.

2.2 Wastewater treatment system

With regard to wastewater management, the Toesca Refuge relies on a traditional system (2), schematically represented in Figure 1, consisting of preliminary treatments using *bioactivators* (*bioattivatori* in Figure 1), primary treatment through an *Imhoff tank* (*Vasca Imhoff* in Figure 1), and secondary treatment through a *soakaway pit* (*pozzo perdente* in Figure 1).

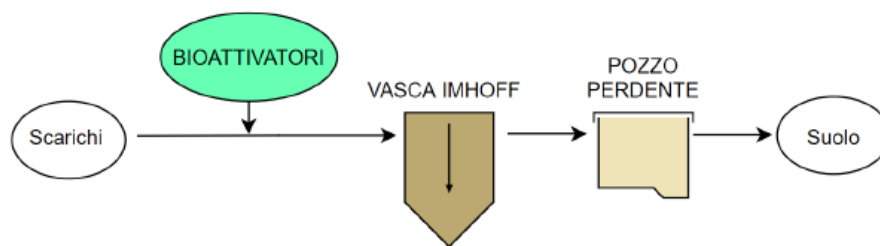


Figure 1: Scheme of the wastewater management system in Toesca Refuge (2).

The preliminary bioactivation treatment, or bioaugmentation, aims to accelerate, even at low temperatures, the rate of contaminant degradation by the existing bacterial colonies; the primary treatment is based on the use of an underground Imhoff tank, which first allows the sedimentation of total suspended solids (TSS) and subsequently the treatment of the settled sludge through anaerobic digestion; the secondary treatment consists of a soakaway pit into which the water exiting the Imhoff tank flows, whose openings allow the wastewater to penetrate into the subsoil, enabling slow biological purification by the microorganisms naturally present in the soil.

The final destination of the wastewater is therefore the ground, while the absence of specific management is reported for sludge management; however, the sludge is usually transported downstream by means of tractors, given the intermediate altitude at which the refuge is located, and only in exceptional cases by helicopter.

CHAPTER 3

3. State of the Art

This section provides an overview of the existing solutions and technologies relevant to the proposed intervention for Toesca Refuge. The analysis focuses on systems and applications related to wastewater treatment and sludge management in isolated or high-altitude contexts. In particular, known solutions reported in literature, existing patents, and commercially available products are examined in order to identify their main technical features, advantages, and limitations.

This preliminary analysis of the products summarized in Table 2 was essential to support the selection of the most suitable technologies for the case study, allowing the proposed solution to be defined on the basis of proven systems, technical feasibility, environmental compatibility, and adaptability to the specific constraints of an alpine refuge. The comparison with the proposed solution as described herein also makes it possible to highlight the specific contribution of the integrated approach adopted in this work, which combines SBR-based wastewater treatment, solar sludge drying, and renewable energy production in response to the operational constraints of alpine huts.

Table 2: Main known products analyzed.

Product Name	Manufacturing Company	Brief description and features of the Product	Differences with the Proposed Solution
<i>Hybrid SBR tank with fixed biofilm reactor</i>	Apex Water Ltd	The key challenge in designing a biological treatment system for the Cardrona Valley is the extreme climate and accordingly low sewage temperatures. Fixed biofilm modules (Bioblock media) were inserted at the bottom of the reactor in order to improve nitrification at low temperatures, which is kept active up to 5 °C. This system is associated with a heating system with thermodynamic solar panels to maintain the reactor temperature above the critical limit.	- The design envelope for the treatment plant was also heavily impacted by the large contribution of the local hotel / restaurant, and the relatively small permanent population. - Referred to a village, not a hut: Cardrona Valley servicing the village, Cardrona Alpine Resort Limited and a 500 house development at Mt Cardrona Station.
<i>Equalization tank</i>	Not specified, used in the Gouter Hut in France	The process involves an initial separation of primary sludge, followed by treatment of the wastewater in a membrane bioreactor using ultrafiltration and high-pressure air injection. The effluent then passes through an activated carbon filter and undergoes UV disinfection, making it suitable for reuse in toilets. The resulting sludge, which comes from grinding, the equalization tank, and membrane retention, is not further treated and is transported downstream by	- Hut located on the Mont Blanc at an altitude of 3835 m and equipped with 120 beds.

Product Name	Manufacturing Company	Brief description and features of the Product	Differences with the Proposed Solution
		helicopter. The system achieves high purification efficiencies (approximately 99% for BOD ₅ , 97% for COD, and 99.55% for suspended solids), but it has high energy demands—particularly for UV treatment and air injection—and faces challenges in sludge management.	
<i>Membrane microfiltration (MBR) plant + Sludge dewatering system</i>	Not specified, used in the Rosa Mount Hütte	It allows purified graywater to be reused to feed toilet and washing machine tanks. Upstream, there are degreasing and fine screening pretreatments. The water, before reaching the membrane bioreactor, undergoes denitrification and nitrification to break down the concentration of nitrogen in the sewage. In this case, the plant is also equipped with secondary treatment with an activated carbon filter that refines the purification process. Also the Sludge dewatering system to reduce the percentage of liquid, the permeate of which is sent back to the denitrification tank, while the solid residue is transported downstream through use of helicopters.	- Hut opened from March to September - Hut located at an altitude of 2880 m and equipped with 120 beds. - Permeate is not returned to the denitrification tank.
<i>Solar drying plant</i>	Not specified, used in Bursa city at the southeast of the Marmara Sea, Turkey	The covered sludge drying plant was constructed as a tunnel type greenhouse with a roof height of 2.5m. It was completely enclosed by two walls, 10mm thick transparent polycarbonate sheet with light transmittance of 80%. The indoor air accumulated in the plant during the day is directed to the rock-bed for energy storage.	- Wastewater sludge was obtained from a municipal plant which has a capacity of 64,000m³ per day. - It was completely enclosed by two walls, 10mm thick transparent polycarbonate sheet with light transmittance of 80%.

CHAPTER 4

4. Design of an Integrated Sustainable System for Toesca Refuge

The solution proposed to solve the problems of Toesca Refuge is a comprehensively integrated system designed to address and overcome the complex sustainability challenges inherent to isolated alpine huts. It represents a cohesive and synergistic approach, where advancements in wastewater treatment, efficient sludge management, and optimized renewable energy generation are interwoven to create a self-sufficient and environmentally responsible operational model. Rather than disparate components, these elements function as an interdependent unit: the robust wastewater treatment system produces a reduced volume of sludge, which is then efficiently handled by the dedicated sludge management unit. Concurrently, the renewable energy system provides the necessary power for both treatment processes and general hut operations, further minimizing external dependencies. This holistic framework ensures enhanced resource autonomy, minimizes ecological impact, and establishes a sustainable operational paradigm for mountain refuges.

The overall goal is to transform alpine huts into self-sufficient and environmentally sustainable entities.

4.1 Proposed Solution for Wastewater treatment system

From the analysis of case studies described above, it can be stated that the choice of suitable technology for Toesca Refuge is based on an integrated and efficient supply chain, whose elements have been selected to ensure sustainability and high performance in a mountainous context. The main selection criteria considered can be summarized as follows:

- *Implementation and optimization of pre-treatment systems*, including degreasing (already in place), grit removal, and screening, with the addition of an equalization process inspired by the Goûter refuge case. This allows regulation of the flow rate and quality of the influent to the primary treatment, preventing hydraulic shocks and excessive organic loads. The removal of coarse solids, oils, and sand not only protects downstream equipment but also improves the efficiency and lifespan of the biological reactor by reducing clogging risks and wear;
- *Selection of a Sequencing Batch Reactor (SBR) as the primary treatment*. It represents a compact and highly versatile technology that allows sedimentation, biological oxidation, nitrification, and denitrification phases to be concentrated in a single tank. This solution, already successfully adopted in the wastewater treatment plant of Cardrona village (New Zealand), ensures high-quality final effluent, compatible with discharge onto the soil or into a receiving water body;
- *Introduction of a sludge treatment system post-SBR*, taking as reference the experience of the Hütte refuge, but installing a small solar dryer. This approach significantly reduces the volume and water content of the produced sludge,

facilitating storage, management, and potential disposal. The use of solar energy also represents a sustainable, low-impact energy solution, perfectly aligned with the needs of an autonomous alpine refuge.

In Figure 2, the whole wastewater treatment chain implemented is shown.

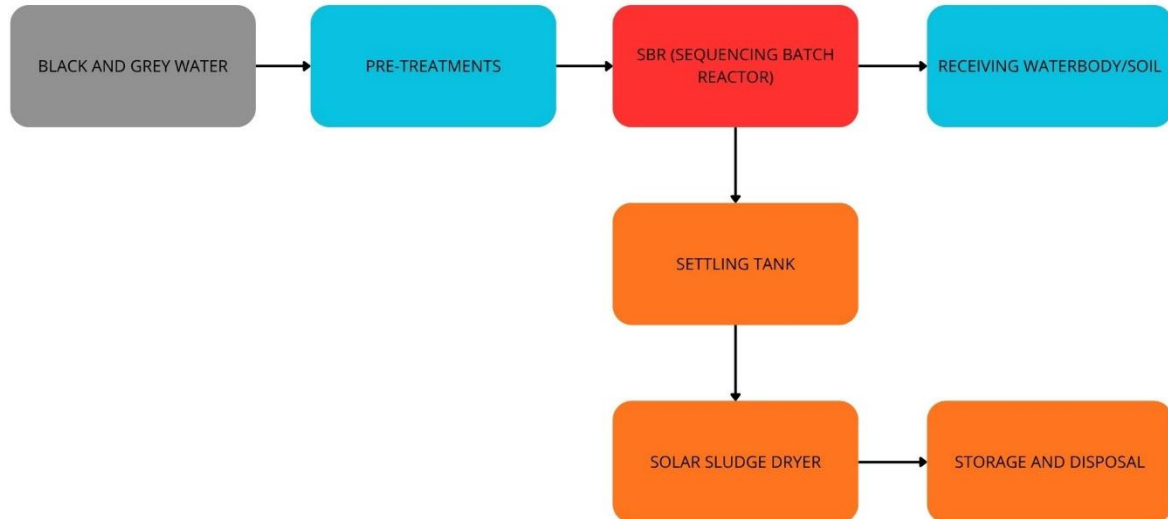


Figure 2: Wastewater treatment plant proposed. In light blue the “water line”, while in orange the “sludge line”. The red box indicates the heart of the process.

4.1.1 Hybrid Sequencing Batch Reactor (SBR)

A Sequencing Batch Reactor (SBR) is a type of activated sludge process used for wastewater treatment that operates in a batch mode within a single tank, performing multiple treatment stages sequentially over time. Unlike conventional continuous-flow systems, SBRs achieve equalization, biological treatment, and secondary clarification all within the same vessel. This design offers significant operational flexibility and is well-suited for treating wastewaters with fluctuating flow rates and pollutant concentrations, making them particularly effective for both municipal and industrial applications, including in remote or smaller communities (3).

Figure 3 represents the cycle comprising five distinct timed steps, all occurring within the same reactor.

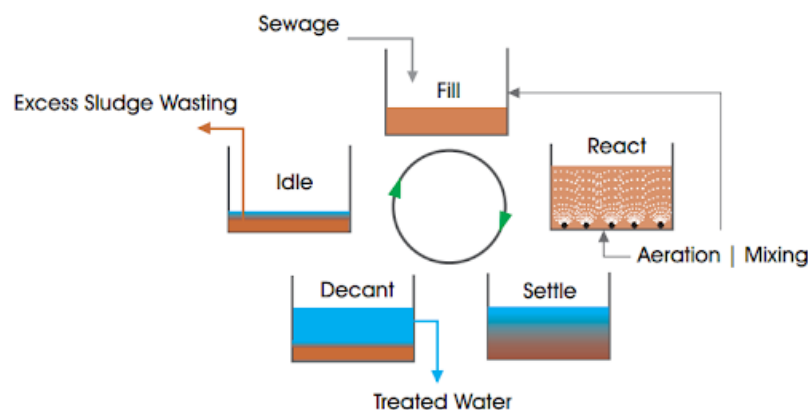


Figure 3: SBR (Sequencing Batch Reactor) design principle (4).

The 5 main phases of the process are detailed as follows (5):

1) Fill Phase

During the Fill Phase, raw or primary-treated wastewater is introduced into the SBR tank. This phase sets the stage for biological treatment. Depending on the operational mode, aeration and mixing may or may not be applied. The reactor typically already contains activated sludge (biomass) from the previous cycle, which immediately begins to interact with the incoming wastewater (3).

2) React Phase (Aeration)

The React Phase is the heart of the treatment process. Here, the wastewater is biologically treated through aeration and mixing, promoting the growth of microorganisms that consume organic pollutants, nitrogen, and phosphorus. This phase can be aerobic, anoxic, or a combination, depending on the treatment goals (e.g., nitrification and denitrification). Dissolved oxygen levels, mixing intensity, and retention time are closely controlled to optimize microbial activity and treatment efficiency. The result is a significant reduction in biochemical oxygen demand (BOD) and nutrient concentrations (6).

3) Settle Phase

In the Settle Phase, all mechanical agitation and aeration are halted, allowing the biomass (sludge) to settle by gravity to the bottom of the tank. The absence of turbulence helps form a clear boundary between the treated water (supernatant) and the settled sludge layer. This phase is crucial for solid-liquid separation and must be long enough to produce a well-clarified effluent. A properly settled sludge blanket ensures that minimal solids are carried over into the next phase.

4) Draw (or Decant) Phase

The Draw or Decant Phase involves the removal of the treated effluent from the top of the tank, just above the settled sludge layer. This is done with a decanter device, which carefully withdraws the clear supernatant without disturbing the settled biomass. The effluent is now sufficiently treated for discharge or further polishing, depending on regulatory requirements. This step is critical for ensuring that high-quality effluent is produced without suspended solids.

5) Idle Phase

The Idle Phase is optional and serves as a buffer period between treatment cycles. This phase can be used to manage flow equalization, adjust for inflow variations, or carry out sludge wasting (removing excess biomass to maintain optimal reactor performance). In multi-reactor systems, idle time allows for synchronized operation across different tanks. While no active treatment occurs during this period, it's important for system flexibility and operational control (7).

The sequential operation of these phases within a single reactor eliminates the need for primary clarification, and secondary clarification basins, often resulting in a reduced footprint and simplified plant design compared to conventional continuous activated sludge systems.

An Aerobic SBR would be an optimal choice for alpine environment for the reasons summarized in Table 3, identified by categories:

Table 3: Advantages of aerobic SBR Technologies.

Category	Feature / Advantage	Details and Alpine relevance
Temperature management	Adjustable react time	In colder conditions, microbial activity slows but SBR allows longer aeration cycles to maintain treatment performance
	Aeration helps retain heat	Continuous or intermittent aeration generates some internal heat, aiding temperature stability inside the tank
	Biological process resilience	Nitrification (by nitrifying bacteria) is temperature-sensitive, but extended aeration in SBR supports nitrifier survival even at $\sim 5-10^{\circ}\text{C}$
System efficiency	High treatment performance	Aerobic SBRs effectively remove BOD, ammonia, and suspended solids, ideal for preserving the alpine environment
	Flexible cycle programming	Timers and controllers adjust aeration/react cycles to match occupancy (e.g., busy summer vs. quiet winter)
	Effective nitrification	Aerobic conditions promote nitrification, converting ammonia to nitrate - important in protecting sensitive alpine soils and streams
Adaptability to refuge conditions	Handles variable flows	Refuge occupancy varies with season and weather. Aerobic SBRs can treat low or peak flows equally well
	On-site sludge reduction	Aerobic SBR systems can stabilize excess sludge, reducing transport frequency, which is critical in areas with limited access
Infrastructure design	Compact footprint	Rifugio Toesca has limited buildable land. SBR combines all treatment steps in one tank, saving space
	Minimal mechanical components	Aerobic SBRs can operate with just a blower, mixer, and decanter—simpler for remote maintenance
	Low maintenance needs	Components like diffusers and timers can be easily checked by staff or seasonal operators, even in basic conditions
Environmental protection	Effluent quality for natural discharge	Rifugio Toesca is in a sensitive alpine setting. Aerobic SBR systems can meet stringent effluent standards for discharge into mountain soil or surface water without any other treatment
	Low odour emissions	Aerobic processes naturally produce fewer odors, preserving the visitor experience and avoiding wildlife disruption

Important aspects to be highlighted of the mentioned above are: the efficiency at low temperatures, adaptability to variable flows, the compact footprint and the reduced sludge produced.

4.1.2 SBR Model applied to Toesca Refuge

The *ISEA E.I.30 SBR* (8) system has been selected for the treatment of domestic wastewater at Toesca Refuge due to its suitability for remote, high-altitude environments with variable and seasonal loads. This third-generation aerobic systems are constituted by the following components, represented in Figure 4:

- two tanks (*SBR Serbatoio* in Figure 4), one for pre-treatments coupled with equalization and the other one for the biological oxidation;
- a control unit (*Unità di controllo SBR* in Figure 4);
- an air blower (*Soffiante d'aria* in Figure 4).



Figure 4: The ISEA SBR System by Aliaxis (8).

This compact, fully integrated solution offers advanced aerobic biological treatment within a small footprint, making it ideal for limited-space settings, as Toesca Refuge. Its robust design ensures reliable operation in harsh weather conditions, with tested functionality down to -20°C , while its modular and programmable operation accommodates fluctuations in visitor numbers throughout the year. Additionally, the system is certified under EN 12566-3, demonstrating compliance with European standards for small-scale wastewater treatment. Its ease of maintenance, low energy consumption, and high treatment efficiency allow to release of the supernatant directly into mountain soil or surface water without any other treatment.

The main technical specifications of the SBR extracted from the technical datasheet (8) are listed in Table 4.

Table 4: The ISEA E.I.30 SBR technical characteristics (8).

Category	Specification	Details
Model code	IS30SBR	Third-generation SBR unit
Max flow capacity	4500 L/day	Equal to 30 equivalent inhabitants
Organic load capacity	1.80 kg BOD ₅ /day	-
Tank Volumes	2 x 7,25 m ³	Separate tanks for pre-treatment and biological treatment
Operating Temperature of the control unit	From - 20°C to + 50°C	-
Treatment performance	BOD ₅ : 98% COD: 93% SS: 97%	Based on full capacity tests by PIA Lab (Germany)
Tank material	HDPE	Corrosion-resistant, child-safe anti-opening lids (A15 class)
Energy consumption	~5.25 kWh/day	For normal operation; up to 7.5 kWh/day in total with blower
Hydraulic design	Equalized SBR	Includes airlift pumps for internal flows

With a capacity of up to 30 equivalent inhabitants and tested for extreme temperatures down to -20°C, it is particularly well-suited for remote or high-altitude environments such as Toesca Refuge.

For the sizing of the wastewater management system, the calculation of the population equivalent (PE) is based on the methodology described in (9), specifically developed for alpine refuges. According to this report, 1 PE is assigned for every 5 staff members, 1 PE for each room with an area less than 14 m², and an additional number of PEs calculated by taking the difference between dining seats and sleeping accommodations, divided by eight, is used to account for visitors who do not stay overnight.

In the analyzed refuge, the following values were obtained:

- *1 PE for staff*: Internal sources at the refuge report a maximum of 3 staff members present for most of the open season, with occasional additional personnel (up to 6 workers) for no more than 6–7 days per season.
- *10 PE for rooms*: Equal to the number of rooms, as each has an area smaller than 14 m².
- *2.5 PE for the dining area (excluding overnight guests)*: Calculated as the number of seats in the dining room (40) minus the number of beds (20), divided by 8.

The total population equivalent is therefore PE = 13.5, given by the sum of the aforementioned values.

Additionally, the following assumptions were made:

- 200 L/day·PE of sewage production

- 60 gBOD₅/day·PE hydraulic load
- 120 gCOD/day·PE (Chemical Oxygen Demand)
- 90 gTSS/day·PE (Total Suspended Solids)

Multiplying these values by the number of inhabitants results in an average daily load of:

- 2,700 L/day
- 810 gBOD₅/day
- 1,620 gCOD/day
- 1,215 gTSS/day

A peak flow rate was then calculated by assuming again 200 L/day·PE, but using 1 PE per bed (20 PE) and 1 PE for every 4 additional dining seats over the number of beds, resulting in a total of 22.5 PE, representing a scenario where the refuge hosts its maximum visitor capacity. The corresponding peak flow is 4,500 L/day.

To verify the effectiveness of the SBR reactor in this specific case, given the calculated influent flow and pollutant load, the previously described SBR reactor (model ISEA E.I.30 (8)) removal efficiencies were considered, as represented in Table 5

Table 5: The ISEA E.I.30 SBR removal efficiencies (8).

Average removal efficiency [%]		
BOD ₅	COD	TSS
98%	93%	97%

The average daily outgoing load for each pollutant (BOD₅, COD, TSS) was subsequently assessed using the following equation:

$$\text{Average daily outgoing load} \left[\frac{g}{day} \right] = \text{average daily incoming load} * (1 - \text{average reduction})$$

The results are reported in Table 6:

Table 6: Average daily outgoing load.

Average daily outgoing load [g/day]		
BOD ₅	COD	TSS
16,2	113,4	36,45

Finally, to verify whether these values comply with legal limits, pollutant concentrations were calculated by comparing the daily pollutant load with the effluent flow rate (evaluated as the difference between the influent flow and sludge volume), as shown in Table 7.

Table 7: Outgoing effluent concentrations.

Effluent concentrations calculated [mg/L]		
BOD ₅	COD	TSS
6,13	42,9	13,8
Maximum allowable values according to Legislative Decree 152/06, Part III, Attachment 5, Table 4		
BOD ₅	COD	TSS
20	100	25

It was found that, based on the expected flow rates, the pollutant concentrations in the treated effluent were significantly lower than the emission limits for soil discharge, as established in *Table 4, Attachment 5 of Part III of Legislative Decree No. 152 of April 3, 2006*. Therefore, it was concluded that there is no need to implement an additional post-treatment stage after the SBR reactor.

The reactor used for this analysis has a maximum capacity equivalent to the estimated peak flow (4,500 L/day), which means that its energy consumption and spatial footprint can also be reasonably adopted for the design under consideration:

- Dimensions: 230 × 570 × 230 cm
- Electric consumption: 12.75 kWh/day, of which:
 - 7.5 kWh/day for the control unit (display, blower, air discharge)
 - 5.25 kWh/day for the reactor (including pre-treatment, equalization, sludge recirculation and purge)

As for the oxygen required to sustain the biofilm's metabolic processes, it was calculated as:

$$\Delta O_2 = k \cdot \alpha \cdot BOD_{5,removed} + \beta \cdot X \cdot V$$

Where:

- $k = 1.5$ (safety factor);
- $\alpha = 0.5 \text{ kgO}_2/\text{kg BOD}_{5,removed}$ (oxygen demand for organic matter degradation);
- $\beta = \beta_{20^\circ\text{C}} \times 1.084^{(T-20)}$, where $\beta_{20^\circ\text{C}} = 0.1 \text{ kgO}_2/(\text{kg TSS} \cdot \text{day})$;
- X = suspended solids concentration, assumed as $0.3 \text{ kgSS}/\text{m}^3$;
- V = reactor volume (m^3).

This resulted in an oxygen demand of $\Delta O_2 = 3.313 \text{ kg/day}$, corresponding to $2.32 \text{ m}^3/\text{day}$ of oxygen, or $11.04 \text{ m}^3/\text{day}$ of air. To estimate the related energy consumption of the compressor, the following formula was used:

$$P = \frac{(p \cdot V)}{\eta \cdot t}$$

With a pressure $p = 2 \text{ bar}$ and efficiency $\eta = 0.7$, the resulting energy requirement is $P = 0.85 \text{ kWh/day}$.

4.1.3 Sludge Management Solution with the Solar Dyer technology

Following biological treatment via a Sequencing Batch Reactor (SBR) at Toesca Refuge, the excess sludge produced is managed through a system of primary decantation and subsequent solar drying.

The solar sludge dryer is a *passive* greenhouse-like structure designed to dehydrate sewage sludge using solar energy and natural ventilation. It consists of:

- Transparent polycarbonate or glass roofing for optimal solar gain;
- Insulated side panels to retain heat;
- Drying floor (supposing metal trays) where sludge is spread in thin layers;
- Manual or automated mixing tools to enhance drying;
- Ventilation system (natural in this case, which does not require energy) to evacuate moisture-laden air.

The first part of the system is designed to operate continuously, in line with the regular functioning of the SBR unit. In particular, the production of liquid sludge was estimated based on the quantity of total suspended solids (TSS) removed daily by the SBR system. Specifically, the production of the sludge at the refuge is around 1,215 kgss/day, based on typical suspended solids generation per inhabitant; assuming as mean production of TSS 90 gss/day per PE (where PE is equal to 13.5 for the case study). After that, considering the average removal efficiency of 97% for the SBR system, the amount of suspended solids effectively separated and accumulated as excess sludge is 1,178 kgss/day. Assuming a sludge concentration of 20g/L, this corresponds to a daily sludge volume of 58.9 L/day. This value was used to dimension the downstream storage and drying units.

Therefore, an underground cylindrical decantation tank with a volume of approximately 26 m³ has been proposed to store the sludge produced throughout one full year. All the main calculations are reported in the following points:

- *Annual volume of thickened sludge:* $58.9 \text{ L/day} \times 365 \text{ days} \approx 21,500 \text{ litres/year} (\approx 21.5 \text{ m}^3)$;
- A *safety margin* of 20–25% is applied to account for operational variability, resulting in a total required volume of $\sim 26 \text{ m}^3$, with a total area of 10.5 m² and a diameter of 3.08 m;
- *Annual production of sludge:* $1.178 \text{ kgss/day} \times 365 \text{ days} \approx 430 \text{ kgss/y}$.

With this configuration, the sludge is transferred automatically from the SBR to the decantation tank, considering that the tank is sized to accumulate the full annual volume, allowing the sludge to be removed only once per year for solar drying. In addition, this system reduces the need for frequent handling or manual intervention in a remote location and minimizes the risk of accidental discharge.

The solar sludge dryer is designed so that the dryer accumulates and dries three annual sludge batches, meaning that the dryer is emptied only once every three years. This approach minimizes the need for frequent intervention and enables a single removal operation at the end

of the cycle. Thickened sludge (at 5% solids) is spread over the floor once a year. Operationally, solar radiation heats the interior, while ventilation promotes evaporation. Moisture is reduced from ~95% to 10–20%, lowering sludge volume by up to 80–90%.

Once a year, the sludge is extracted from the decantation tank, so there's a process of thickening and the sludge now is at approximately 5% TSS and transferred to a solar drying greenhouse for dehydration and volume reduction.

Every year, the total amount of dry solids to be handled is estimated to be approximately 430 kgss/y and assuming a concentration of 5-7%, the corresponding volume of sludge to be dried is calculated as:

$$\text{Annual wet sludge volume} = \frac{430 \text{ kg}}{0.06} = 7,200 \frac{\text{L}}{\text{year}} \approx 7,2 \frac{\text{m}^3}{\text{year}}$$

The proposed solar drying system is designed to accumulate and treat sludge over three years, therefore the total dry solids produced are 1290 kgss. Considering a final drying to 85%-90% dryness, the expected dry sludge mass becomes approximately 1,500 kg (as dry sludge). With an assumed bulk density of 800 kg/m³, this corresponds to a final dried volume of 1.8-2.0 m³ over three years. This dried mass can be easily stored within the same solar dryer, typically in a designated corner or rear zone of the greenhouse structure.

To effectively evaporate the water content from ~7.2 m³/year of thickened sludge, the required drying surface depends on solar exposure and climatic conditions and in cooler climate with lower sun, it would be about 12 m². In terms of volume, it is hypothesized as follows: 3.0 m × 4.0 m × 2.0 m. A possible schematic representation of the solar sludge dryer is represented in Figure 5.

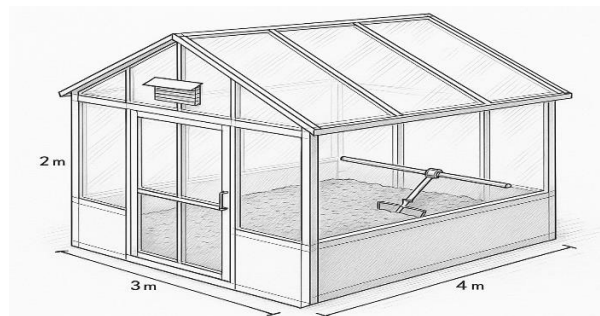


Figure 5: Sketch of the proposed solar sludge dryer.

In summary, the key benefits of the solar sludge dryer are primarily related to the significant reduction in sludge volume and weight, making the material much easier to handle, store, and manage on-site. Since the dried sludge occupies far less space, it only needs to be transported to a disposal facility once every three years. This results in substantial savings in transportation and disposal costs.

Additionally, the system operates entirely on solar energy, requiring *no external power supply*, which means it is a zero-emission and energy-free solution, ideal for off-grid mountain locations. Its low-maintenance design, combined with the environmental advantages such as odor reduction and pathogen die-off, make it a highly sustainable and cost-effective option.

4.1.4 Economic analysis for the wastewater treatment system

Once the technical feasibility of the system has been demonstrated, the analysis proceeds with the evaluation of its economic feasibility. For this purpose, the Net Present Value (NPV) method was adopted, as it allows for the assessment of the investment's economic viability.

The NPV is calculated as the sum of the expected cash flows CF_t , discounted using a discount rate r , over a time horizon n corresponding to the useful life of the initial investment I_0 . The equation used for the calculation is as follows:

$$NPV = -I_0 + \sum_{t=0}^n \frac{CF_t}{(1+r)^t}$$

For an intervention to be considered economically sustainable, it is necessary to verify that the point at which the NPV becomes positive—referred to as the Discounted Payback Period (DPP)—falls within the useful life of the investment n .

Therefore, the two essential conditions for an investment to be deemed economically advantageous are:

- $VAN > 0$;
- $DPP < n$.

Compliance with both conditions indicates that, over the investment's useful life, the proposed technical intervention for Toesca Refuge is capable of generating net economic benefits.

The starting point is the estimation of the costs for the components of the above described system, allowing to calculate the capital expenditures (CAPEX), as detailed below:

- ***Removal of the Existing Imhoff Tank:***

The cost for removal was estimated at 180 €/m² (10). Given a tank surface area of 8 m², the removal cost amounts to 1,457 €. Additionally, dismantling the tank will generate approximately 288 kg of waste. This waste will later be considered in terms of transport logistics to the valley.

- ***Installation of the SBR Reactor:***

Based on the technical specifications of the selected reactor (8), the purchase cost is 13,400 €. Transport costs for the reactor (652 kg) must be included, along with installation labor. Installation will require three workers, each paid 40.25 €/h (35 €/h (11) plus a 15% surcharge for work in a non-standard environment), for a total of 40 hours. This results in a labor cost of 4,830 €.

- ***Sedimentation Tank:***

For a polyethylene sedimentation tank weighing 1,800 kg, a capital cost of 8,000 € has been assumed. Installation will require two workers for 24 hours, using the same hourly rate as for the SBR installation. This leads to an installation cost of 1,932 €.

- ***Solar Dryer:***

The purchase price for the solar dryer is 10,000 €, with a weight of 600 kg. Installation will require three workers for 16 hours, also resulting in a labor cost of 1,932 €.

- ***Material Transport Costs:***

The total weight of materials to be transported to the site (SBR reactor, sedimentation tank, and solar dryer) is approximately 3,000 kg. Additionally, the dismantled Imhoff tank (2,880 kg) must be transported away. Since a standard helicopter can carry up to 1,000 kg per trip, three trips will be necessary. The helicopter call-out fee is 800 €, with a flight cost of 30 €/min. A one-way flight takes approximately 15 minutes. The total transport cost is estimated at 2,150 €.

- ***Equipment Rental and Site Transport:***

An additional 6,000 € has been budgeted for the rental and transport of equipment required for installation.

Based on those assessments described, the total CAPEX is estimated at 49,700 €.

Three main operational cost components were identified:

- An *annual saving* of 200 € due to the elimination of bioactivators, which were necessary in the previous system but are no longer required.
- An *annual saving* of 1,330 € by avoiding helicopter transport to empty the Imhoff tank, which was previously required once per year. In the new system, this operation is only needed once every three years.

Considering a *discount rate of 3%* and a *project lifetime of 30 years*, a discounted cash flow analysis was performed. The resulting NPV is presented in Table 8 and Figure 6 below.

Table 8: Economic evaluation of the wastewater treatment plant along the project lifetime.

<i>Year</i>	<i>Cash flow [€/year]</i>	<i>Cumulated cash flow [€/year]</i>	<i>Discounted cash flow [€/year]</i>	<i>NPV [€/year]</i>
0	1533	-49701	-49701	-49701
1	1533	-48168	-48168	-48168
2	1533	-46634	1489	-46679
3	1533	-45101	1445	-45234
4	1533	-43568	1403	-43831
5	1533	-42034	1362	-42468
6	1533	-40501	1323	-41146
7	1533	-38968	1284	-39861
8	1533	-37434	1247	-38615
9	1533	-35901	1210	-37404
10	1533	-34368	1175	-36229
11	1533	-32834	1141	-35088
12	1533	-31301	1108	-33980
13	1533	-29768	1075	-32905
14	1533	-28234	1044	-31861
15	1533	-26701	1014	-30847
16	1533	-25168	984	-29863
17	1533	-23634	956	-28907
18	1533	-22101	928	-27980
19	1533	-20568	901	-27079
20	1533	-19034	874	-26205
21	1533	-17501	849	-25356
22	1533	-15968	824	-24531
23	1533	-14434	800	-23731
24	1533	-12901	777	-22954
25	1533	-11368	754	-22200
26	1533	-9834	732	-21468
27	1533	-8301	711	-20757
28	1533	-6768	690	-20066
29	1533	-5234	670	-19396
30	1533	-3701	651	-18746

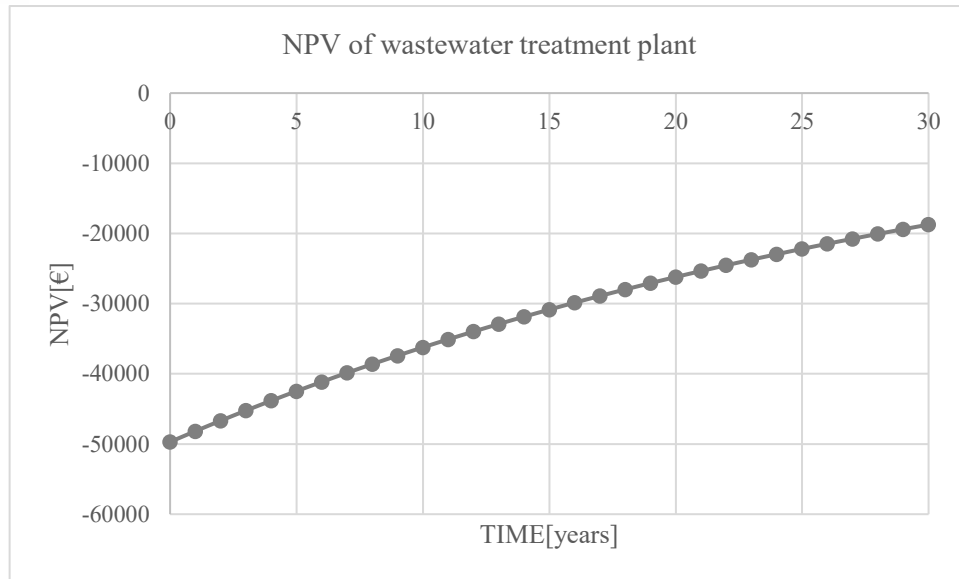


Figure 6: NPV of the wastewater treatment plant along the project lifetime.

4.2 Proposed Solution for Energy system optimization

To perform a detailed energy analysis, the electrical consumption of the mountain hut was estimated for two typical days: one in summer (June 1st – September 30th) and one in winter (weekends in April, May, October, November, and December), with results shown in Figure 7 and Figure 8 respectively.

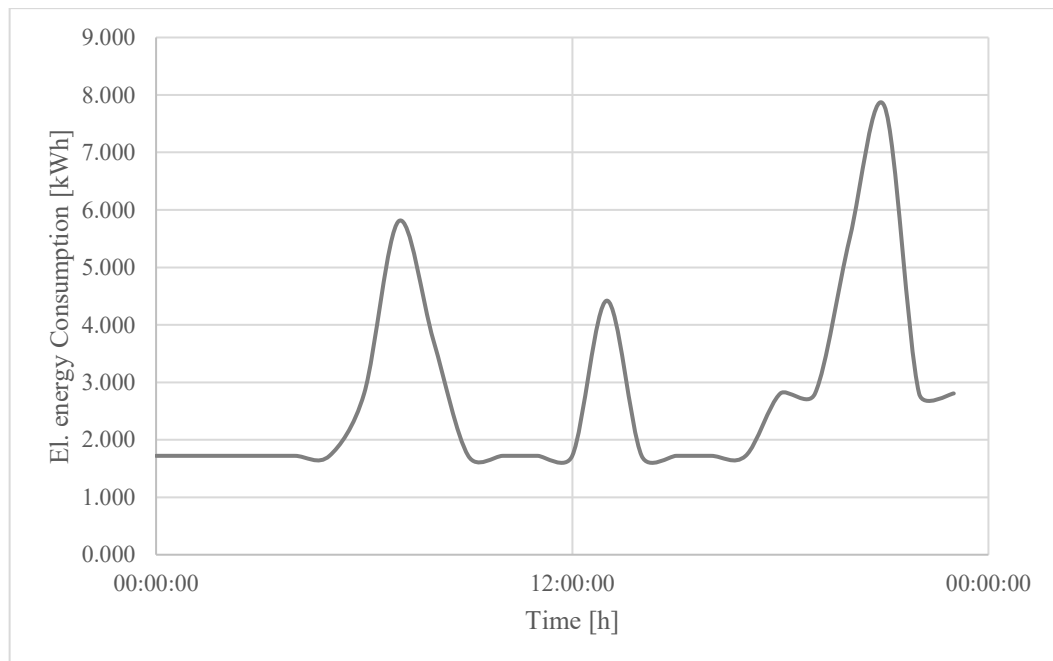


Figure 7: Electrical energy consumption estimation in a type-day of summer season.

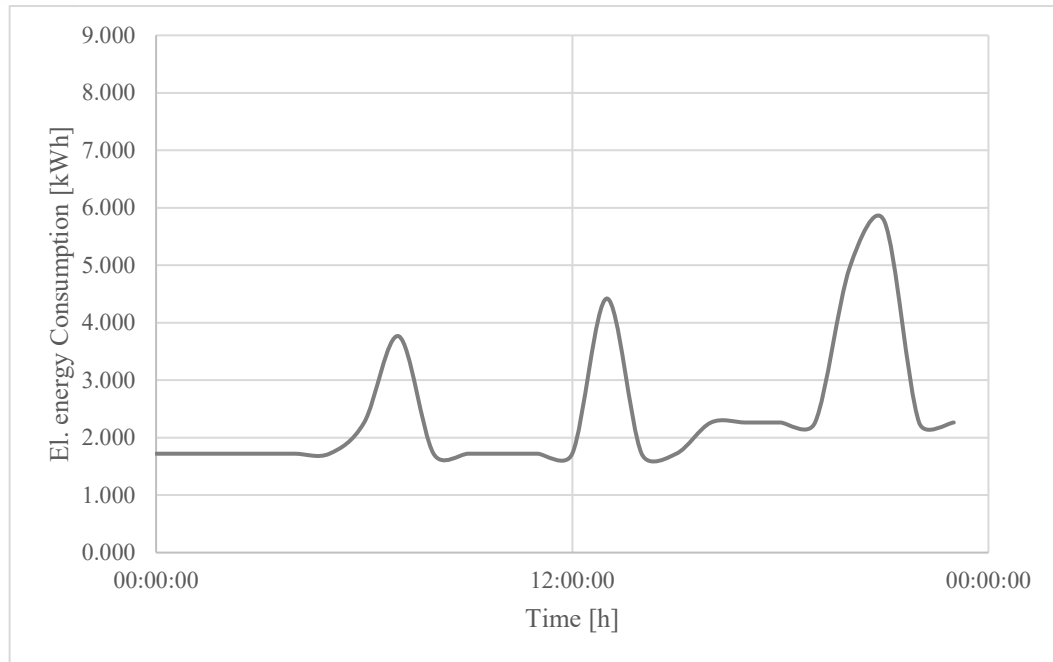


Figure 8: Electrical energy consumption estimation in a type-day of winter season.

In both cases, three consumption peaks were identified: in the morning (due to washing machine, water heater, and lighting use), at lunchtime (dishwasher and beer tap), and in the evening (lighting, dishwasher, beer tap, boiler, and washing machine). Constant loads like refrigerators and freezers were also included, as confirmed by the hut manager. Additionally, the wastewater treatment system previously described generates a constant load of 12.5 kWh/day (0.52 kWh/hour).

The consumption curves of Figure 7 and Figure 8 were used to create an annual load profile, with a total yearly consumption of 10,433 kWh. This analysis supports the assessment of local electricity generation options that can fully meet the load at any given time.

By analyzing monthly precipitation data at Pra Catinat, the average flow rate of the Rio Gerardo—used to power the Pelton turbine serving the mountain hut—was estimated.

The flow pattern shown in Figure 9 and is typical for a mountain stream, with peaks in spring (April and May), due to snowmelt and autumn (October and November), due frequent rainfall, and minimum values in winter (January and February) due to ice and snow.

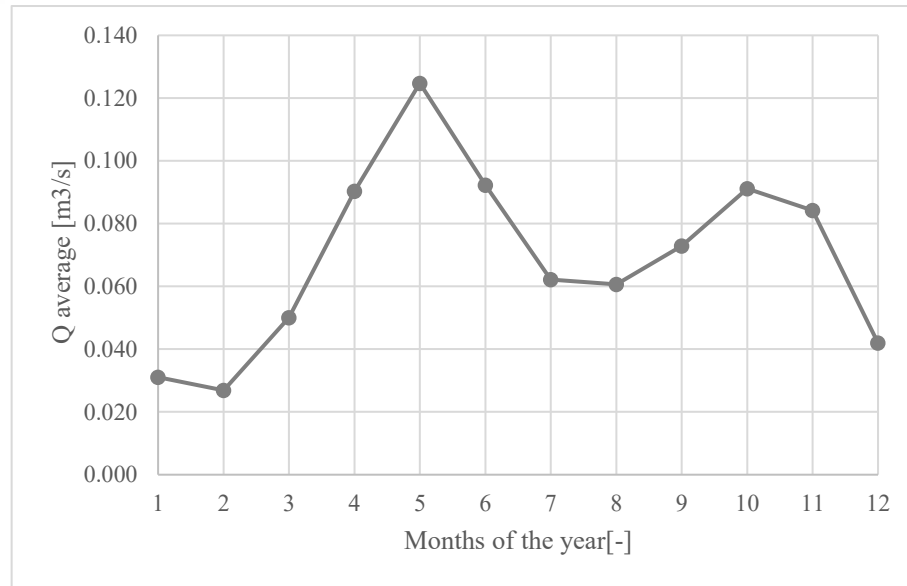


Figure 9: Monthly average water flow through Rio Gerardo.

The turbine's monthly power production is shown in Figure 10 and was calculated starting from the previously described discharge rate, assuming however that the system only uses 10% of the total stream flow, to provide more realistic estimates.

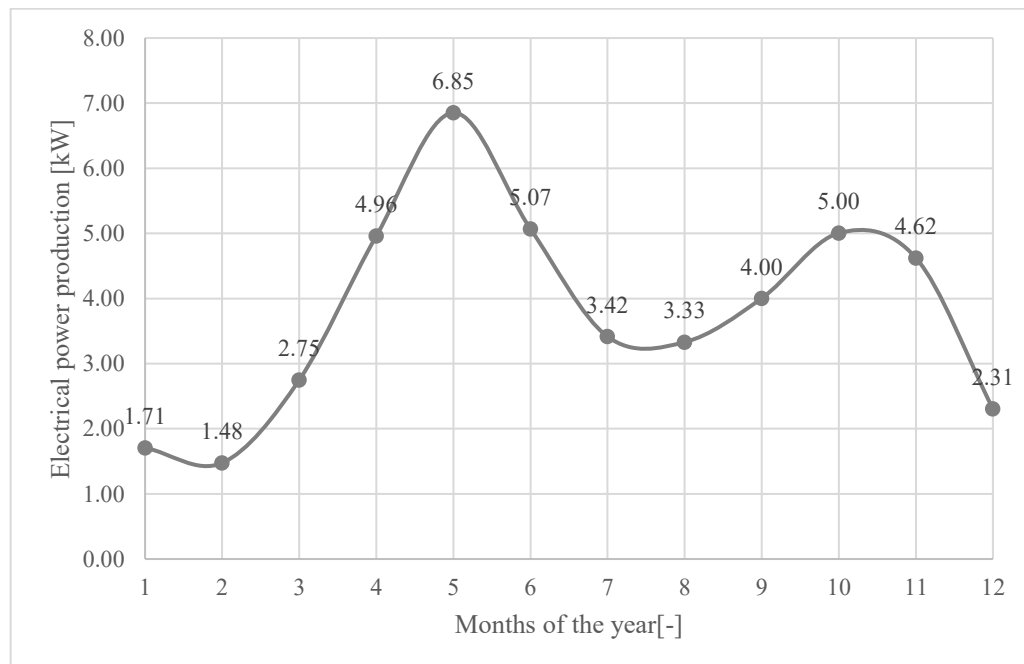


Figure 10: Pelton turbine monthly power production.

Seasonal variation in the producibility is clearly visible in Figure 10: most critical periods are winter months (January, February), when the hut is closed, and summer months (July, August), when energy demand is highest, but water flow is reduced. However:

- The reduction in water flow during the winter months of December, January, and February is not highly problematic, as the hut is closed during this period.

- The reduction in water flow during the summer months could lead to insufficient electricity generation to meet the energy demands of the hut during the summer season, which corresponds to its peak occupancy period.

To mitigate the limited summer hydropower production – likely worsened by debris clogging the intake – a photovoltaic system installation on the hut's south-facing roof has been proposed. This would leverage high solar energy availability in summer to reduce the risk of power shortfalls and potential forced closure of the hut.

4.2.1 Rooftop photovoltaic plant with BESS

To assess the productivity of a potential rooftop photovoltaic system for the hut, the *SolarEdge* (12) online modeling software was used. This tool allowed accurate placement of the hut and 3D modeling of the roof to simulate the PV installation, using the hut's annual consumption profile evaluated as previously described.

In the first phase of the analysis, a system with 28 panels (12.6 kWp), two inverters, and two 9.7 kWh batteries was considered. The report produced by the software following the simulation proved the system is oversized, with 63% of energy production unused due to the hut being off-grid.

It is necessary to underline that the simulation then focused on photovoltaic production alone (without storage), which was later combined with estimated output from the Pelton turbine. A Python script was used to calculate hourly battery charging/discharging behavior and the battery's state of charge (SOC), assuming a safe operating range of 10% to 90% to extend battery lifespan.

Several simulations were carried out to evaluate the energy production of photovoltaic systems of various sizes and in the end, the optimal system was identified as consisting of 14 PV modules (6.3 kWp), a single inverter, and a 15 kWh battery, as recommended by the Onis Visa (13) technical consultant contacted by phone.

The use of the Python code made it possible to analyze the battery's charge-discharge trend, as shown in Figure 11.

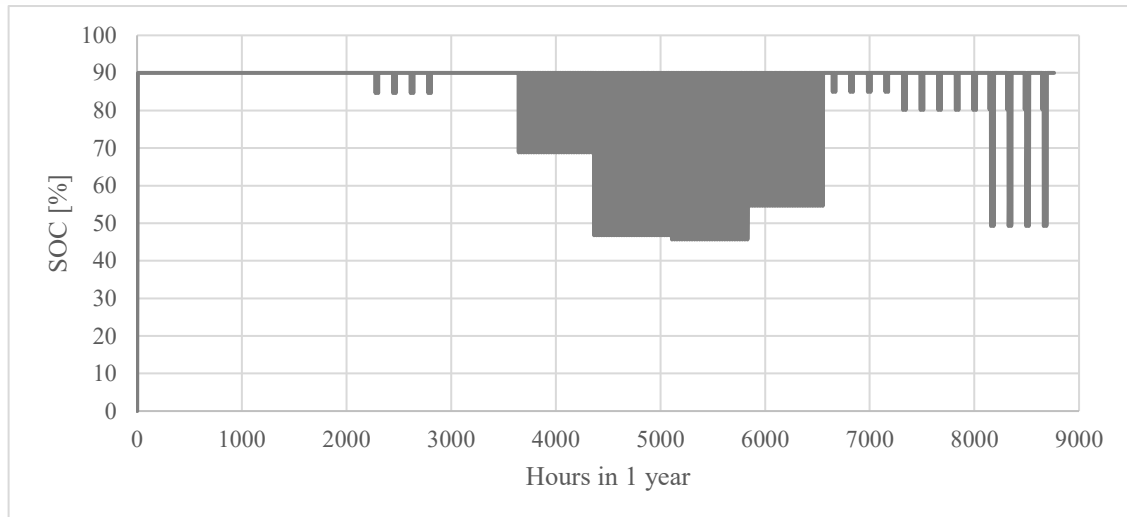


Figure 11: SOC of the Battery Energy Storage System (BESS) for the PV Plant made of 14 modules.

It can be observed that the battery never fully discharges, and that the moments during the year when instantaneous production is insufficient to meet the load—thus requiring the use of stored energy—occur mainly in the summer months. During these periods, the battery discharges down to a minimum of 40%, still ensuring load coverage.

4.2.2 Economic analysis for the energy system

As made overfor in relation to the proposed solution for the wastewater treatment plant, the economic feasibility was evaluated also for the rooftop photovoltaic plant together with the BESS.

The following section proceeds with the analysis of the two case studies previously described from a technical point of view.

CASE 1: Photovoltaic plant made of 28 modules (Peak power: 12.6 kWp)

The first scenario considers the oversized photovoltaic system, aimed at assessing the potential energy yield of this technology at the Toesca Refuge site. The main components of the system are as follows:

- 28 photovoltaic modules (model: AIKO NEOSTAR A450-MAH54W (14));
- 2 inverters (model: SolarEdge SE6000H-RW000BEN4 (15));
- 2 batteries (model: SolarEdge Home Battery 9.7 kWh (16)).

In particular, for the storage batteries, a challenge was encountered in obtaining consistent pricing across different capacities to be used in the second phase of the case study. To ensure scalability of the analysis, a normalized approach was adopted: the unit cost per kWh was calculated based on the price of the 9.7 kWh battery, which can then be applied to batteries of any capacity.

The installation cost estimate was carried out using the hourly labor cost for electrical, plumbing, and heating systems, as specified in the *Prezzario delle Opere Edili ed Impiantistiche*

of the Province of Turin (Edition No. 33, December 2024). A 15% markup was applied to this cost to account for the additional expenses associated with carrying out works at high altitudes (above 1500 m and up to 1800 m a.s.l.) (17).

The total expected duration for the installation was estimated at two working weeks, based on a standard schedule of 5 days per week and 8 hours per day.

The total installation cost was calculated using the following formula:

$$C_{installation} = 1.15 \cdot C_{h,labor} \cdot N_{weeks} \cdot 5 \frac{days}{week} \cdot 8 \frac{hour}{day}$$

Where:

- $C_{h,labor}$: hourly labor cost, equal to 31.16 €/h;
- N_{week} : number of working weeks.

Given the refuge's remote high-altitude location, it is essential to consider transportation costs, assuming the use of a helicopter for delivery. The estimation of helicopter transport costs is based on several assumed factors. First, a company providing material and labor transport services at altitude via helicopter was identified (18). This company is located in the Province of Turin and operates in the Sauze d'Oulx area, approximately 20 km from Toesca Refuge.

Next, a helicopter model from the company's fleet primarily used for high-altitude work was selected, allowing the determination of the aircraft's cruising speed and maximum load capacity, which are 240 km/h and 820 kg, respectively (19).

The total weight of the photovoltaic system equipment was calculated using data summarized in Table 9.

Table 9: Data for the calculation of the total weight of the photovoltaic system components.

Module weight [kg/piece] (14)	$W_{modules}$	20.6
Inverter weight [kg/piece] (20)	$W_{inverter}$	9.9
Battery weight [kg/piece] (16)	W_{batt}	119

After separately calculating the total weight of the photovoltaic system equipment as

$$N_{modules} \cdot W_{modules} + N_{inverter} \cdot W_{inverter} + N_{batt} \cdot W_{batt}$$

totaling 834 kg, and determining the flight distance as that between Bussoleno and Rifugio Toesca, the transport cost was calculated as:

$$C_{trasp} = C_{call} + C_{min} \cdot (T_{path} + T_{op})$$

based on the data shown in Table 10:

Table 10: Data for the calculation of the helicopter transport cost.

Cost of call	Information provided from CAI	C_{call}	1000 €
Cost per minute	Information provided from CAI	C_{min}	31 €
Path duration	Calculated as the ratio between the path length and the aircraft cruising speed	T_{path}	7 min
Charge/discharge operation time	Hypothesis	T_{op}	1 min

The resulting transport cost is equal to 1,139 €.

In Table 11 are summarized the data used to calculate the total initial investment:

Table 11: I_0 calculation – CASE 1: 28 photovoltaic modules

N. modules	$N_{modules}$	28
Module price [€/piece] (14)	C_{module}	446.4
9.7kWh battery cost [€/piece] (16)		628.9
Battery cost [€/kWh]	$C_{battery,kWh}$	628.9
Battery size [kWh]	$Size_{batt}$	19.4
N. inverter	$N_{inverter}$	2
Inverter price [€/piece] (20)	$C_{inverter}$	910
Installation cost [€]	$C_{installation}$	2866.7
Transport cost [€]	C_{trasp}	1139

The investment cost is evaluated as follows:

$$I_0 = N_{modules} \cdot C_{module} + C_{battery,kWh} \cdot Size_{batt} + N_{inverter} \cdot C_{inverter} + C_{installation} + C_{trasp}$$

The total investment cost I_0 for CASE 1 is finally equal to 30,525 €.

It is necessary to consider that:

- The hut operates as an off-grid system and therefore does not incur costs for purchasing electricity from the grid;
- The installation does not generate direct economic revenue.

Since Toesca Refuge operates off-grid, meaning it is not connected to the national electricity grid, it does not bear costs for electricity purchase. Furthermore, the installation of a photovoltaic system does not produce direct income but allows economic savings by reducing the use of fossil fuel sources. Consequently, the estimation of annual cash flows was carried out considering the following elements:

- Avoided cost of diesel fuel, currently used to power a thermal generator supporting electricity production when the Pelton turbine is insufficient;
- Maintenance costs of the photovoltaic system.

Regarding the avoided diesel cost, it was assumed that, in the absence of photovoltaic systems, the hut compensates approximately 20% of its annual electricity demand through a diesel generator, corresponding to a production of about 2,080 kWh/year. Based on the technical data reported in Table 12, this production requires an estimated annual diesel consumption, converted into a cost of €1,284.90 per year.

Table 12: Data for the calculation of the diesel consumption annual cost.

LHP diesel [kWh/kg] (21)	LHP_{diesel}	12.33
Diesel density [kg/l]	ρ_{diesel}	0.835
Thermal engine efficiency	η	25%
Electrical energy produced by thermal engine [kWh/year]	$E_{eng,therm}$	2080
Liters of diesel annually consumed [l/year]	L_{diesel}	808.1
Diesel price [€/l]¹ (22)		1.59

$$L_{diesel} = \frac{E_{eng,therm}}{LHP_{diesel} + \eta}$$

Given the particular high-altitude location of the refuge, fuel transportation entails a significant additional cost to be considered. As simplification, it was hypotized equal to the one calculated for the transportation of the photovoltaic system installation.

The total cost avoided through the adoption of a photovoltaic system is therefore equal to 2,424€/year. This value is considered the annual economic benefit resulting from the installation of the photovoltaic system, as it represents savings on the current operational costs associated with electricity generation.

To estimate the maintenance cost associated with the photovoltaic system, a scheduled intervention every ten years has been assumed. The maintenance activity has been estimated as equivalent to one man-day of work (8 hours), with an hourly labor cost of 31.16€/h, consistent with the rate adopted for the installation cost estimate. Therefore, the total cost for each maintenance intervention amounts to 249.30€.

For the purpose of the economic analysis, this amount will be appropriately distributed over the time horizon considered (the system's useful life) by applying discounting in the NPV calculation.

Considering:

- A useful life of the investment (n) of approximately 30 years;
- A discount rate (r) of 3%;

The NPV equation was applied, and the results are shown in Table 13 and in the chart in Figure 12.

¹ The value of 1.59 €/l refers to the year 2025

Table 13: NPV calculation – CASE 1: 28 modules photovoltaic system.

<i>Years</i>	<i>Revenue</i> [€/year]	<i>Costs</i> [€/year]	<i>CF</i> [€/year]	<i>NPV</i> [€/year]
0	2424.0	30525.0		-30525.0
1	2353.4		2353.35	-28171.6
2	2284.8		2284.81	-25886.8
3	2218.3		2218.26	-23668.5
4	2153.7		2153.65	-21514.9
5	2090.9		2090.92	-19424.0
6	2030.0		2030.02	-17393.9
7	1970.9		1970.90	-15423.0
8	1913.5		1913.49	-13509.6
9	1857.8		1857.76	-11651.8
10	1803.6	185.5	1618.16	-10033.6
11	1751.1		1751.12	-8282.5
12	1700.1		1700.11	-6582.4
13	1650.6		1650.60	-4931.8
14	1602.5		1602.52	-3329.3
15	1555.8		1555.84	-1773.4
16	1510.5		1510.53	-262.9
17	1466.5		1466.53	1203.6
18	1423.8		1423.82	2627.4
19	1382.3		1382.35	4009.8
20	1342.1	138.0	1204.06	5213.8
21	1303.0		1302.99	6516.8
22	1265.0		1265.04	7781.9
23	1228.2		1228.20	9010.1
24	1192.4		1192.42	10202.5
25	1157.7		1157.69	11360.2
26	1124.0		1123.97	12484.2
27	1091.2		1091.24	13575.4
28	1059.5		1059.45	14634.9
29	1028.6		1028.60	15663.5
30	998.6	102.7	895.94	16559.4

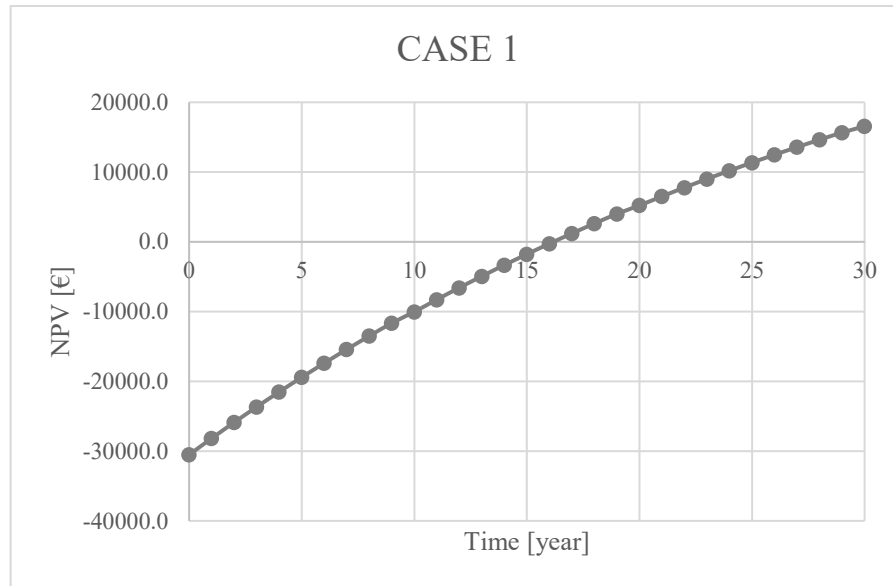


Figure 12: NPV trend during the investment useful lifetime – CASE 1: 28 modules photovoltaic system.

As shown in Table 13 and the graph in Figure 12, the NPV is positive at the end of the photovoltaic system's useful life. This indicates that, over the considered time horizon, the investment is capable of generating economic benefits sufficient to offset the initial and operational costs incurred. However, these benefits only become apparent after the midpoint of the system's useful life, i.e., approximately 15 years after installation. The primary reason for this outcome is attributable to the oversizing of the system, which results in a high investment cost not justified by the achievable energy savings within the specific context of the Toesca Refuge.

CASE 2: Photovoltaic plant made of 14 modules (Peak power: 6.3 kWp)

The second scenario was defined by downsizing the photovoltaic system in order to reduce the associated investment cost, while still providing support for local renewable energy production. The main components of the system are as follows:

- 14 photovoltaic modules (model: AIKO NEOSTAR A450-MAH54W (14));
- 1 inverter (model: SOLAREEDGE SE5000H Home Wavex (15));
- 1 battery with a 15 kWh capacity.

For the NPV calculation using this second configuration of the photovoltaic system, the following parameters were considered equivalent to the previous case:

- Installation cost ($C_{\text{installation}}$) equal to 2,866.70€;
- Maintenance cost (every ten years) equal to 249.30€;
- Annual diesel cost avoided estimated at 2,424€/year.

The investment evaluation was carried out using the data presented in Table 14.

Table 14: I_0 calculation – CASE 2: 14 photovoltaic modules.

N. modules	$N_{modules}$	14
Module price [€/piece] (14)	C_{module}	446.4
9.7kWh battery cost [€/piece] (16)		628.9
Battery cost [€/kWh]	$C_{battery,kWh}$	628.9
Battery size [kWh]	$Size_{batt}$	15
N. inverter	$N_{inverter}$	1
Inverter price [€/piece] (20)	$C_{inverter}$	740
Installation cost [€]	$C_{installation}$	2866.7
Transport cost [€]	C_{trasp}	1139

By applying again the equation used for the calculation of I_0 in CASE 1, an initial investment value of 20,428€ is obtained.

Subsequently, the Net Present Value (NPV) equation was applied once more, using the following assumptions:

- Investment lifetime (n) estimated at 30 years;
- Discount rate (r) equal to 3%.

The results are presented in the corresponding Table 15 and Figure 13.

Table 15: NPV calculation – CASE 2: 14 modules photovoltaic system.

<i>Years</i>	<i>Revenue [€/year]</i>	<i>Costs [€/year]</i>	<i>CF [€/year]</i>	<i>NPV [€/year]</i>
0	2424.0	20428.4		-20428.4
1	2353.4		2353.35	-18075.0
2	2284.8		2284.81	-15790.2
3	2218.3		2218.26	-13571.9
4	2153.7		2153.65	-11418.3
5	2090.9		2090.92	-9327.4
6	2030.0		2030.02	-7297.3
7	1970.9		1970.90	-5326.4
8	1913.5		1913.49	-3412.9
9	1857.8		1857.76	-1555.2
10	1803.6	185.5	1618.16	63.0
11	1751.1		1751.12	1814.1
12	1700.1		1700.11	3514.2
13	1650.6		1650.60	5164.8
14	1602.5		1602.52	6767.3
15	1555.8		1555.84	8323.2
16	1510.5		1510.53	9833.7
17	1466.5		1466.53	11300.2
18	1423.8		1423.82	12724.0
19	1382.3		1382.35	14106.4
20	1342.1	138.0	1204.06	15310.5
21	1303.0		1302.99	16613.4
22	1265.0		1265.04	17878.5
23	1228.2		1228.20	19106.7
24	1192.4		1192.42	20299.1
25	1157.7		1157.69	21456.8
26	1124.0		1123.97	22580.8
27	1091.2		1091.24	23672.0
28	1059.5		1059.45	24731.5
29	1028.6		1028.60	25760.1
30	998.6	102.7	895.94	26656.0

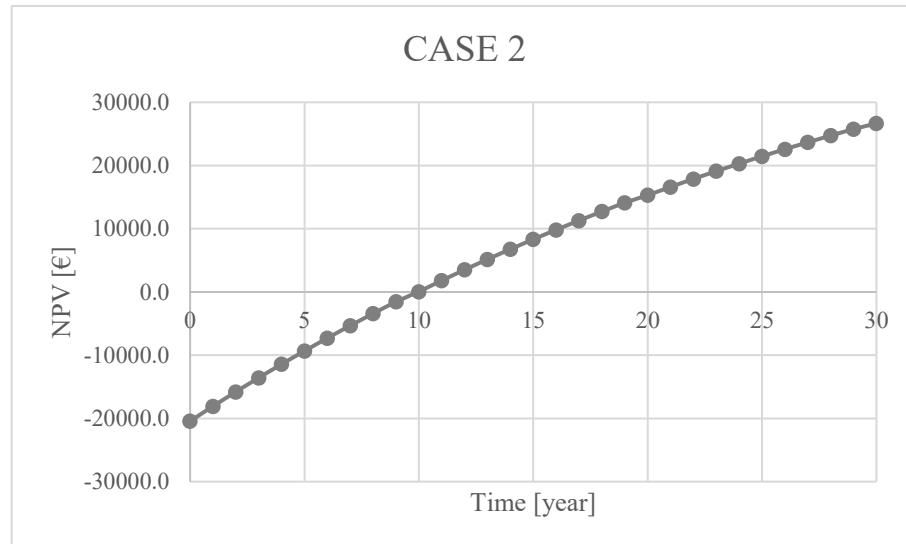


Figure 13: NPV trend during the investment useful lifetime – CASE 2: 14 modules photovoltaic system.

As shown in the results presented in Table 13 and Figure 13, in this second scenario the investment reaches the economic break-even point in the tenth year of the system's useful life. Consequently, the Discounted Payback Period (DPP) is equal to 10 years.

By the end of the system's lifetime, the investment yields a net gain of 26,656€, primarily attributable to the avoided cost of purchasing and transporting diesel fuel, previously used to meet the electrical demand not covered by the Pelton turbine. This outcome highlights that the adoption of a properly sized photovoltaic system can significantly enhance both the economic and environmental sustainability of the refuge, generating a positive financial return over the long term.

4.3 Economic analysis of the integrated system: Wastewater treatment plant and Rooftop photovoltaic plant with BESS

In order to assess the economic viability of the planned interventions for the Toesca Refuge under study, it was decided to calculate the overall NPV, based on the data presented in the previous sections, considering both the wastewater treatment system and the 14-panel photovoltaic system.

The trend of the combined NPV over the 30-year useful life is therefore shown Figure 14:

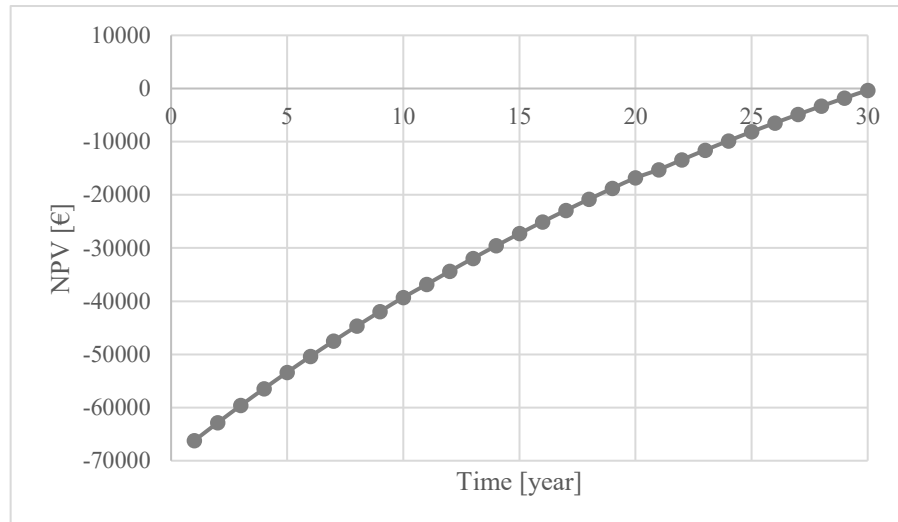


Figure 14: NPV of the new wastewater management system and photovoltaic system (14 modules).

The NPV graph of Figure 14 related to the combined investment in the wastewater treatment system based on SBR technology and the 14-panel photovoltaic system shows that, at the end of the 30-year useful life, the overall NPV amounts to 888€, against a total initial investment of 70,100€ (49,700€ for the SBR system and 20,400€ for the photovoltaic system).

This result indicates that, although the total investment breaks even precisely at the 30th year, the resulting economic gain is extremely limited. As already highlighted in the previous analyses, the photovoltaic system demonstrates a significantly more favorable economic performance: its NPV turns positive as early as the 15th year of operation and continues to grow in the following years, contributing substantially to the achievement of overall economic viability.

Conversely, the SBR wastewater treatment system shows a consistently negative NPV throughout the analysis period. This is primarily due to the difficulty in quantifying the direct economic benefits associated with its installation, as the value of such a system is more appreciable in environmental, regulatory, and sanitary terms rather than through immediate financial returns.

In summary, the analysis shows that the main limitation to the economic sustainability of the integrated intervention lies in the high cost of the SBR system, whose utility – while essential from an environmental and hygiene-compliance perspective – does not directly translate into measurable savings or revenues. On the other hand, the properly sized photovoltaic system proves to be a sound and advantageous investment in the long term, contributing significantly to reducing the operational costs associated with the energy supply of the refuge.

4.4 Development status of the solution

The Technology Readiness Level (TRL) is supposed to be, depending on the technology considered, as described in Table 16.

Table 16: TRL classification for the components of the proposed integrated solution for the Toesca Refuge.

<i>Technology</i>	<i>TRL</i>
<i>SBR (Sequence Batch Reactor)</i>	<i>9 - Actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies)</i>
<i>Solar sludge dryer</i>	<i>7 - System prototype demonstration in operational environment</i>
<i>Photovoltaic system</i>	<i>9 - Actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies)</i>
<i>Overall</i>	<i>8 - System complete and qualified</i>

CHAPTER 5

5. Business Analysis

Beyond the technical design, the proposed solution must also be assessed in terms of practical applicability, economic relevance, and potential value for the stakeholders involved. For this reason, the business analysis focuses on the benefits that the integrated system could provide to Toesca Refuge, considering environmental, operational, and managerial aspects. In this Chapter, value proposition, Business Model Canvas, S.W.O.T. analysis, and comparison with alternative solutions, were analyzed for the solution, in order to evaluate the overall feasibility and strategic relevance of the intervention.

5.1 Definition of Value Proposition

5.1.1 Wastewater treatment plant (SBR)

Regarding the replacement of the actual wastewater management system with an improved one, the Value Proposition could be “*Modern, eco-efficient wastewater management for mountain huts, ensuring electricity throughout the day without relying on the grid*”. *Modern* refers to the fact that recent developments in the wastewater management field made it possible for new technologies and solutions that face the same problems but from a different perspective. The *eco-efficient* aspect of it refers to the fact that it minimizes the risks of polluting in fragile mountain ecosystems.

5.1.2 Rooftop Photovoltaic plant with BESS

For the section of the project concerning the introduction of a photovoltaic system, completed with a storage system for the excess energy produced, the Value Proposition could be “*Reliable, autonomous, and sustainable energy for remote, mountain huts, ensuring electrical independency*”. It grants the possibility of using electricity even if far away from the electric grid, doesn’t require high levels of maintenance and relies on as a sustainable source of energy that is sunlight.

5.2 Business Model Canvas

The Business Model Canvas is a graphical framework composed of nine building blocks, as shown in Figure 15. Each block represents a fundamental component of the business model. As a visual tool, its purpose is to provide a clear and structured representation of the business model, thereby supporting a critical reflection on its main elements (23). This process facilitates the validation of the model and, hopefully, its future implementation.

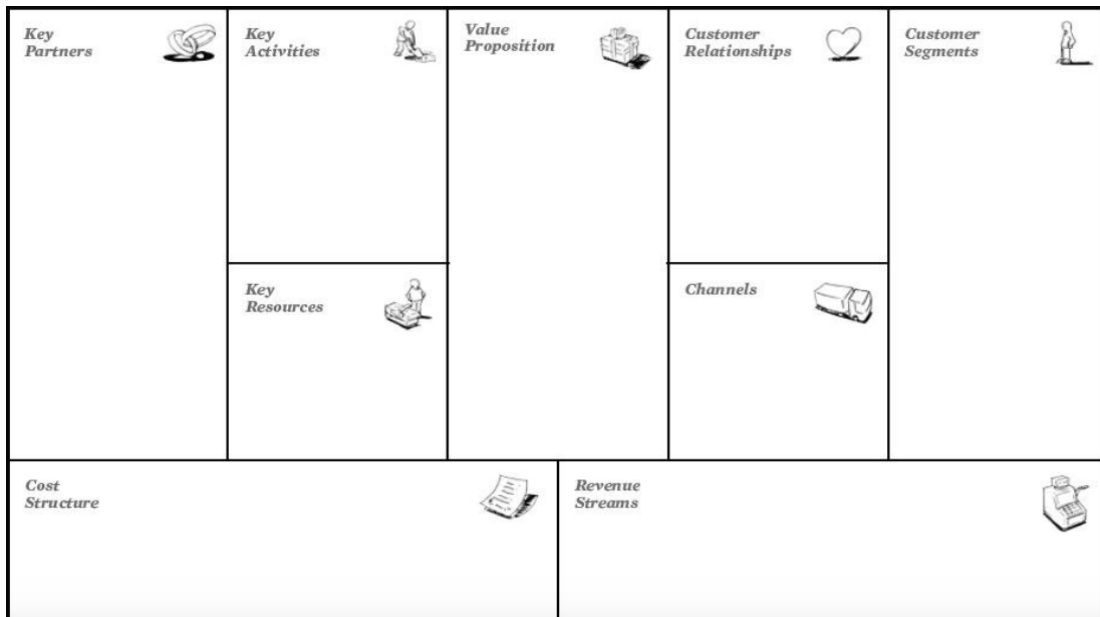


Figure 15: General scheme of a Business Model Canvas.

For the solution described above, the single components of the canvas are compiled as follows:

1) Key Partners:

The key partners in the development of this project were:

- The CAI members who made available the information regarding the hut, such as the turbine model, the structure of the water intake and the Imhoff tank.
- The hut keeper who was able to disclose the practical information about the energy consume and the need for a storage system.
- Prof. A.V. Riggio, whose consult was necessary to determine the applicability of a SBR system in the constraints of the case study.
- Dr. G. Cerino, who devised technical advice on the developing of the photovoltaic system.
- Dr. E. Costamagna, who we consulted for the decision of implementing a new method of wastewater treatment.
- Dr. R. Bosio, who we consulted for the hydroelectric analysis of the case.
- Dr. T. Monti, who we consulted for the economic analysis of the project.

2) Key Activities:

The key activities in the development of the project are:

- a) The installation of a SBR system followed by a sedimentation tank and a solar drier;
- b) The installation of a photovoltaic system of 14 panels, 1 inverter, 1 storage battery.

3) Value Proposition:

The main value proposition of the project is a resilience increase of the hut, a major sustainability due to the loss of the necessity of the usage of the thermic generator, and an easier managing of the sludge coming from the wastewater treatment.

4) Key resources:

The key resources necessary to the project realization are:

- 14 solar panels.
- 1 inverter.
- 1 battery (15 kWh).
- 1 SBR system.
- 1 sedimentation tank.
- 1 solar drier.

5) Customer Relationship:

At the moment of the installation, the hut keeper who will benefit from the project will be informed of the necessities of the new systems and will be taught how to look after them.

6) Channels:

The project is communicated and made possible through the collaboration of CAI and the Politecnico di Torino.

7) Customer Segments:

The main beneficiaries of the project will be:

- The hut customers who will experience with lower probability the absence of electricity or warm water during their staying.
- The hut keeper who will be able to manage more easily the wastewater and its relative muds, and will have less to worry about energetic shortages.

8) Cost Structure:

The main costs relevant to the project realization are:

- The photovoltaic system components, the inverter, the battery and their installation which sum up to around 20.400 €.
- The Wastewater system composed of the SBR system, the sedimentation tank, the solar drier and their installation which sum up to around 49700€.

9) Revenue:

CAI funds.

5.3 S.W.O.T. Analysis

The S.W.O.T. analysis is a strategic planning tool developed by Albert Humphrey between the 1960s and 1970s, during his research on corporate planning and change management at the Stanford Research Institute. The purpose of this analysis is to identify the development opportunities of a business system by enhancing its strengths and mitigating its weaknesses, while taking into account the opportunities and threats that generally arise from the external environment (24).

For the proposed solution described above, the components of the S.W.O.T. analysis can be defined as follows:

- **Strengths**

- *Energy Autonomy*: The photovoltaic system ensures off-grid functionality, reducing energy costs and increasing sustainability.
- *Seasonal Optimization*: System operates during months with higher solar radiation (March–September), improving PV efficiency and drying performance.
- *Low Environmental Impact*: No fossil fuels used; the system aligns with sustainable development goals and alpine environmental standards.
- *Compact and Modular Design*: The SBR and solar dryer configuration is suitable for remote or space-limited areas like mountain refuges.

- **Weaknesses**

- *Limited Operating Season*: The system is inactive in colder months, which may require specific maintenance procedures before/after winter.
- *Solar Dependence*: The solar dryer and PV system depend heavily on weather; performance may drop during cloudy or stormy periods.
- *Sludge Drying Time*: Solar drying is slower compared to mechanical methods, potentially requiring more storage space during peak usage.
- *Battery Capacity Limits*: A single 15 kWh battery might be insufficient during consecutive cloudy days, limiting energy availability.

- **Opportunities**

- *Replication in Other Sites*: Even if the model is specifically structured for the case study, it may be regarded as example by other hut experimenting with similar problems.
- *System Scalability*: Can be upgraded with additional panels, batteries, or treatment capacity based on future demand.

- **Threats**

- *Extreme Weather Events*: Hail, snow, or heavy rainfall may damage infrastructure or reduce system efficiency.
- *Maintenance Accessibility*: Harsh terrain and isolation might complicate repairs or routine maintenance, especially in emergencies.

Figure 16 graphically summarizes the S.W.O.T. analysis just described.

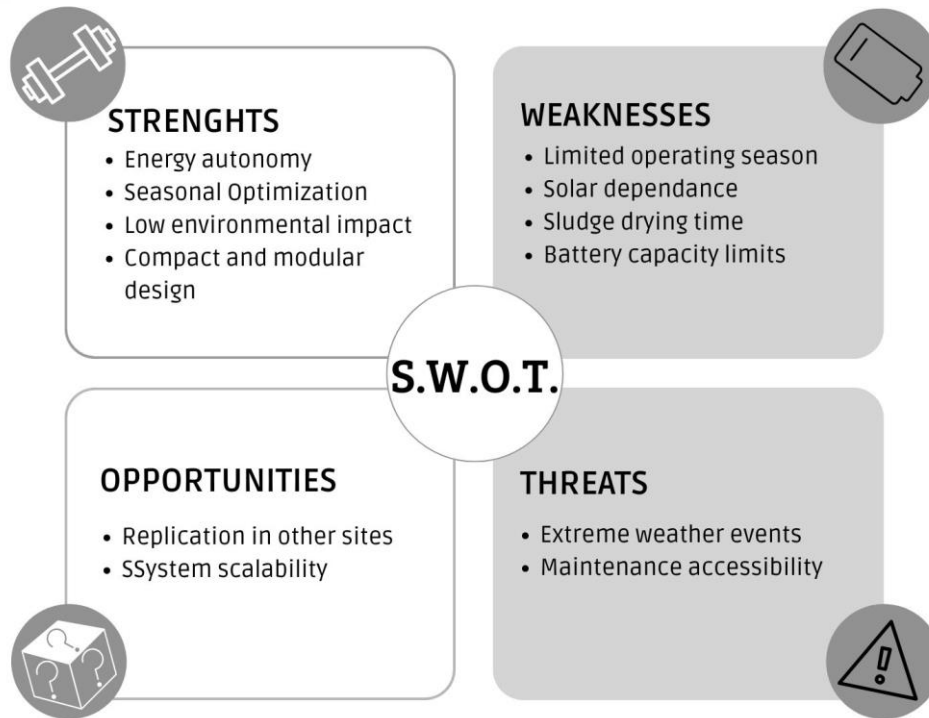


Figure 16: S.W.O.T. Analysis for the integrated solution developed for the Toesca Refuge case study.

5.4 Competitors

Traditional wastewater treatment systems, such as continuous-flow activated sludge plants, may be offered by established engineering firms, though they often require more energy and maintenance – making them less suitable for remote mountain environments. Similarly, mechanical sludge dryers and diesel-powered systems may compete in the field of sludge management, but they typically involve higher operational costs and carbon emissions.

In terms of energy supply, competitors may include hybrid systems using fossil fuels or off-grid diesel generators. However, these alternatives lack the sustainability, low maintenance, and long-term cost efficiency offered by a photovoltaic-powered system.

CHAPTER 6

6. Conclusions

The present thesis work, developed in the context of the *Challenge@PoliTo_by Firms* initiative “*Innovative Solutions for the Sustainability of Alpine Huts by Club Alpino Italiano Torino*”, addressed the issue of sustainability in isolated alpine huts, focusing on Toesca Refuge, in the Municipality of Bussolengo (Metropolitan City of Turin) as a representative case study. The analysis highlighted the main technical and environmental criticalities affecting the refuge, particularly the limitations of the existing wastewater treatment system and the vulnerability of the current energy supply, which mainly relies on hydropower and backup diesel generation. In response to these challenges, an integrated solution was proposed, combining an advanced wastewater treatment system based on Sequencing Batch Reactor technology, a solar sludge drying unit, and a photovoltaic system with battery storage.

The proposed intervention was developed with the aim of improving the autonomy, resilience, and environmental performance of the refuge. From a wastewater management perspective, the replacement of the existing Imhoff tank with an SBR system would allow a more efficient and controlled treatment process, better suited to variable tourist flows and harsh mountain conditions. The integration of a solar sludge dryer would further reduce the volume and moisture content of the produced sludge, simplifying its storage and transport and limiting the need for frequent downstream disposal. From an energy perspective, the photovoltaic system, combined with storage and the existing hydroelectric plant, would contribute to reducing the dependence on diesel generation, improving the overall sustainability of the refuge and increasing the reliability of the energy supply during periods of reduced water availability.

The economic assessment showed that the photovoltaic system represents the most favourable component from a financial point of view, as it is capable of generating long-term savings by reducing fuel consumption and transport costs. Conversely, the wastewater treatment system presents a less immediate economic return, mainly because its benefits are more evident in environmental, regulatory, and sanitary terms rather than in direct financial revenues. Nevertheless, its implementation remains essential for ensuring proper wastewater treatment, reducing the ecological impact on a fragile alpine environment, and improving the overall management of the refuge.

Future developments could further enhance the circularity and sustainability of the proposed system. In particular, the solid residue produced by the solar dryer could be fully valorised through additional treatment steps, with the aim of improving its quality and enabling its potential use as biofuel or as a fertilising material for the surrounding vegetation. This perspective would allow the wastewater management chain to move beyond simple treatment and disposal, transforming waste into a potentially useful resource and further reducing the environmental footprint of the refuge.

Overall, the work demonstrates that the sustainability of alpine huts cannot be achieved through isolated technical interventions, but requires an integrated and multidisciplinary approach. The combination of engineering, environmental and managerial considerations proved to be fundamental for defining a solution capable of responding to the specific constraints of Rifugio Toesca. Although the proposed system is strongly tailored to the

characteristics of the case study, it may represent a valuable reference model for other mountain huts facing similar issues related to water, energy, wastewater, and sludge management. In this sense, the thesis contributes to the broader objective of supporting the transition of alpine refuges toward more autonomous, resilient, and environmentally responsible operational models.

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