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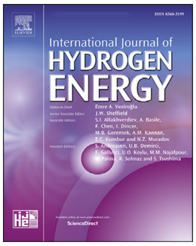

Life cycle assessment of a renewable energy system with hydrogen-battery storage for a remote off-grid community

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HIGHLIGHTS

- An LCA of an off-grid hybrid battery-hydrogen system is performed.
- A comparison with the current scenario based on a diesel generator is performed.
- Low impact on climate change for the Renewable scenario (0.197 kg CO_2 eq./MWh).
- The Renewable scenario can save more than 260 t of CO_2 eq. per year.
- The impact due to transport by helicopter to the remote site is negligible.

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ABSTRACT

Remote areas usually do not have access to electricity from the national grid. The energy demand is often covered by diesel generators, resulting in high operating costs and significant environmental impacts. With reference to the case study of Ginostra (a village on a small island in the south of Italy), this paper analyses the environmental sustainability of an innovative solution based on Renewable Energy Sources (RES) integrated with a hybrid hydrogen-battery energy storage system. A comparative Life Cycle Assessment (LCA) has been carried out to evaluate if and to what extent the RES-based system could bring environmental improvements compared to the current diesel-based configuration. The results show that the impact of the RES-based system is less than 10% of that of the current diesel-based solution for almost all impact categories (climate change, ozone depletion, photochemical ozone formation, acidification, marine and terrestrial eutrophication and fossil resource use). The renewable solution has slightly higher values only for the following indicators: use of mineral and metal resources, water use and freshwater eutrophication. The climate change category accounts for 0.197 kg CO_2 eq./kWh in the renewable scenario and 1.73 kg CO_2 eq./kWh in the diesel-based scenario, which corresponds to a reduction in GHG emissions of 89%. By shifting to the RES-based solution, about 6570 t of CO_2 equivalent can be saved in 25 years (lifetime of the plant). In conclusion, the hydrogen-battery system could provide a sustainable and reliable alternative for power supply in remote areas.

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List of acronyms

CTU	Comparative Toxic Unit
EF	Environmental Footprint
EOL	End-Of-Life
GHG	Greenhouse Gas
LCA	Life Cycle Assessment
LCIA	Life Cycle Impact Assessment
NMVOC	Non-Methane Volatile Organic Compounds
PEF	Product Environmental Footprint
PEM	Polymer Electrolyte Membrane
P2P	Power to Power
PV	Photovoltaic
RES	Renewable Energy Sources
SOC	State-of-Charge
UPS	Uninterruptible Power Supply

Introduction

Climate change is a global challenge of the current century. Greenhouse Gas (GHG) emissions from human activities are the main cause of the observed climate change since the mid-20th century. These anthropogenic emissions originate mainly from the use of fossil fuels for electricity generation, industry and especially heating. Fossil fuels, represented by oil, coal and natural gas, provide more than 80% of the world's energy needs [1]. However, they are not well distributed globally and will not be able to meet future energy demand as they are subject to depletion and will be limited due to their direct link with greenhouse gas emissions. Renewable Energy Sources (RES) could represent one of the solutions: their widespread use has become a key target for the near future in all European and international climate actions (Fit For 55, EU Green Deal [2]). RES can be an effective solution to both energy supply and climate change problems, as they do not emit pollutants into the atmosphere [3].

The main problem related to RES is that they are characterized by intermittent production, which leads to a mismatch between energy supply and demand [4]: for this reason, the use of an energy storage system is necessary [5,6]. In this context, hydrogen (H_2) is expected to play an important role in achieving the main decarbonization goals [7,8]. Hydrogen is characterized by long-term storage capability, high volumetric storage density, flexibility with respect to site topography, suitability for decentralized applications, and limited GHG emissions [9]. Hydrogen can be coupled with RES – e.g. photovoltaic (PV) panels or wind turbines – to store electricity according to the so-called Power-to-Power (P2P) concept [10]. In a hydrogen-based P2P system, the renewable energy generated, when not needed for immediate consumption, can be used to produce hydrogen through water electrolysis [11,12]. At a later stage, the stored hydrogen can be converted back into electricity using fuel cells.

With regard to off-grid areas, renewable H_2-based energy storage systems become essential to achieve energy independence from imported fossil fuels and avoid solutions that are very expensive from both economic and environmental perspectives [13]. Indeed, cost-effective long-term hydrogen storage plays a key role in reducing energy costs when off-grid renewable systems are considered [14].

The optimal design of combined RES and hydrogen-based energy systems for remote areas was studied by Suresh et al. [15] using genetic algorithm: the authors pointed out that the optimal mix of renewable energy sources consists of both programmable (biogas and biomass) and non-programmable (PV, wind) sources, combined with batteries and fuel cells. A more focused study on the choice of optimal battery technologies for hybrid remote storage systems has recently been explored by Babaei et al. [16]. Hydrogen-based storage solutions are also being investigated for energy supply in rural communities in developing countries, as shown by Ayodele et al. [17]: in their case study (health clinic), the breakthrough distance between power cable and RES-H_2 solution was about 8.8 km.

Life Cycle Assessment (LCA) is a quantitative and standardized methodology (ISO 14040-44) [18,19], capable of quantifying the potential environmental impacts of products and services throughout their life cycle. It provides impact data that can help identify opportunities to improve the environmental performance of products and inform industry decision-makers. The LCA literature on energy storage systems (such as batteries or hydrogen-based technologies) is quite extensive, even though these studies are generally very heterogeneous and difficult to compare [20], mainly due to the necessarily high number of assumptions, the lack of primary data on some components and the use of different LCA approaches.

Stropnik et al. [21] conducted a cradle-to-grave LCA analysis of a fuel cell Uninterruptible Power Supply (UPS) system. They showed that a large reduction in environmental impacts can be achieved with circular economy strategies. Petrillo et al. [22] developed a comprehensive but practical and reliable tool for systematic sustainability assessment, based on LCA. Their methodology was applied to a real case study, with different plant configurations, including one with electrolysers, fuel cells, and storage tanks. Belmonte et al. [23] considered two alternative integrated power systems: one based on photovoltaic combined with a hydrogen-based technology (electrolyser and fuel cell), the other based on photovoltaic and batteries. The two systems were compared from a technical and economic point of view and a preliminary LCA was carried out. These energy system configurations were further investigated by the same authors in Ref. [24] with an LCA for stationary (i.e. energy storage for a single family house) and mobile applications. The use of renewable hydrogen for office buildings was recently investigated by Peppas et al. [25]: the hydrogen-based solution showed a 40% reduction in the global warming potential compared to the Greek electrical energy mix, and a similar reduction in acidification potential and photochemical oxidant formation categories. It was also found that wind turbines were preferred over photovoltaic systems due to their lower environmental impact.

Hydrogen-based storage for remote applications was investigated by Zhao et al. [26]: the authors conducted a detailed cradle-to-grave life cycle analysis of hydrogen production and consumption in an isolated area. In their study, hydrogen was produced on-site using Polymer Electrolyte Membrane (PEM) water electrolysers powered by electricity from wind turbines, and then used to provide electricity and heat through fuel cell stacks. They concluded that the introduction of hydrogen into the energy system led to a significant reduction in climate change category, but greater impacts were found in other categories (like ozone depletion, human toxicity, and non-renewable resource depletion). The same authors also analysed the hydrogen-based system from an economic perspective, employing a life cycle cost analysis [27]. Mori et al. [28,29] investigated a hybrid hydrogen-battery storage system for mountain huts, which are typically off-grid and have daily and seasonal load variations. They considered different micro-grid configurations and performed a technical, economic and environmental assessment: the advantages of batteries and hydrogen for short- and long-term storage, respectively, were demonstrated, and a reduction in environmental impact of up to 70% compared to the fossil fuel scenario was found. Their model was based on experimentally-validated data for the hydrogen technologies (fuel cells and electrolysers), as shown in a previous publication by the authors [30]. Bionaz et al. [31] also analysed a remote hybrid (hydrogen + battery) storage system from a techno-economic and environmental point of view. They compared the renewable scenario with other scenarios based on fossil fuels and submarine connection to the mainland grid. It was found that the environmental sustainability of the hydrogen-based configuration is strongly dependent on the CO_2 emission intensity of electricity and on the length of the submarine cable. However, their work focused only on CO_2 emissions, while other environmental impacts were not assessed.

The literature review revealed that there are several scientific papers aiming to analyse energy storage systems based on batteries or hydrogen using LCA approaches, and even dealing with different RES and hydrogen production methods. However, insufficient attention has been paid to the assessment of integrated systems with batteries and hydrogen technologies.

The aim of this work is to perform a comparative LCA assessment between a reference scenario, where the energy supply relies on fossil fuels (diesel generator), and a renewable-based scenario. The latter includes a hybrid energy storage (i.e., both batteries and hydrogen) combined with photovoltaic panels and a diesel generator as a final back-up to reliably meet the electrical demand of an off-grid island community. The analysis is based on a real site (Ginostra, in southern Italy) and is part of the European project REMOTE, aimed to demonstrate the technical and economic feasibility of H_2-based storage solutions in isolated environments [32]. The data on energy flows come from a detailed energy management strategy for the Ginostra case study, implemented and discussed in a previous work by the authors [33]. The whole analysis is based on hourly profiles supplied by the project partners regarding electricity demand and PV production for the Ginostra site. Finally, insights are provided into the environmental impacts associated with air transport (helicopter), which – to the best of the authors' knowledge – is not considered in previous literature.

The study is structured as follows: Section 'Case study description' describes the case study under investigation and introduces the two analysed scenarios. Section 'Methodology' is dedicated to the description of the LCA methodology, with details on the system boundary and the functional unit adopted. Section 'Results and discussion' presents and discusses the main results of the two scenarios, including an assessment of the contribution of transport to the overall system impacts. Finally, conclusions are reported in Section 'Conclusions' .

Case study description

The case study for the LCA analysis is an energy system located in Ginostra, a small village on the island of Stromboli (north of Sicily, southern Italy), which is accessible only from the sea and by helicopter [33]. The site is classified as off-grid since it is connected neither to the Italian distribution and transmission grid nor to the main Stromboli island micro-grid. The electrical load profile during the year is highly seasonal, mainly due to tourism, which leads to an increase in load during the summer. As shown in Fig. 1a, all consumers are residential and are currently supplied by a diesel generator that can meet the peak demand in the summer. Because of the

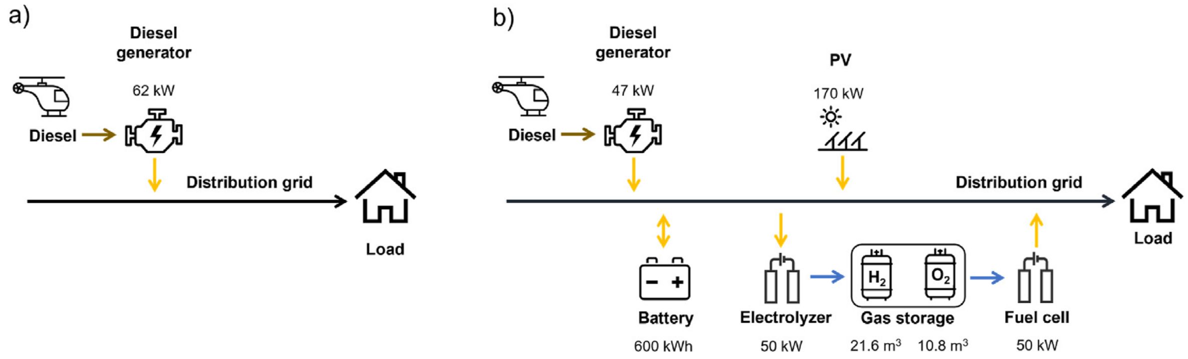

Fig. 1 – Configuration of the Reference scenario that relies on a diesel generator (a), and configuration of the Renewable scenario, which includes a stand-alone renewable hydrogen-battery system (b).

remoteness of the area, fuel must be transported by helicopter, resulting in high costs for electricity generation. The key drivers and benefits of switching to the new renewable power-to-power solution are the following:

- Reduce diesel consumption to decrease local pollution
- Reduce diesel consumption to lower the cost of electricity
- Improve the reliability of the electricity service
- Avoid a costly and invasive connection to the electrical grid

The configuration of the proposed stand-alone renewable H_2-battery system is shown in Fig. 1b. The sizes of the components have been defined within the framework of the REMOTE project and also depend on the sizes of the products that are available from the project suppliers, i.e., Engie-Electro Power System (Engie-EPS) for the hydrogen-based P2P solution and Enel Green Power (EGP) for the photovoltaic and battery systems [33]. The RES power plant consists of a 170 kW PV system. The hybrid energy storage system includes a 600 kWh Li-ion battery bank integrated with a hydrogen-based solution. Specifically, the hydrogen system is composed of a 50 kW alkaline electrolyser (which enables the production of hydrogen and oxygen from water through the process of water electrolysis), a 50 kW PEM fuel cell (which converts hydrogen to electricity), and a hydrogen storage tank with a total capacity of 21.6 m^3 (maximum pressure of 28 bar). Both the electrolyser and the fuel cell (from Engie-EPS) are available as 25 kW modules. A 10.8 m^3 oxygen storage tank is also provided, as the fuel cell is fed with pure O_2 to avoid sending air rich in marine salt into direct contact with the cell cathode. A 47 kW diesel generator is maintained as the final back-up system. The diesel generator has been sized to provide the maximum energy deficit during the year (the deficit was computed based on the results of the energy simulation discussed below).

Fig. 2 shows the profiles over the year (with hourly resolution) of PV production and electrical demand in Ginostra [33]. The annual PV production and electrical demand are about 270.8 MWh and 171.5 MWh, respectively. As can be seen in Fig. 2b, the load shows a seasonal behaviour with a higher demand in summer due to tourism, with a peak load of about 62 kW.

Based on the profiles of PV production and electrical load, the energy simulation of the RES P2P system was carried out over a time horizon of one year and with hourly resolution. A control strategy was thus defined to manage the operation of the hybrid energy system. This provides the energy input data that are needed for the subsequent LCA analysis.

According to the selected control strategy, when the renewable power is insufficient to satisfy the load (discharging case), the shortage is first covered by the battery, which acts as a short-term storage. Once the minimum State-Of-Charge (SOC) of the battery is reached, the fuel cell component intervenes if there is enough hydrogen in the pressurized tank. The diesel generator operates as a final back up system if battery and fuel cell are not sufficient to cover the entire power shortage. Instead, if the renewable power exceeds the end-user load (charging case), the excess power is first used to charge the battery. When the maximum SOC of the battery is reached, surplus electricity is supplied to the electrolyser for hydrogen production until the storage tank is completely filled with hydrogen, while the remaining excess renewable energy, if any, is curtailed. The modulation ranges of the fuel cell and the electrolyser were also considered in the control strategy for an efficient and safe system operation. The detailed logical block diagrams of the discharging and charging case are reported in the Supplementary data, together with the main technical specifications of the P2P components.

The main results, on an annual basis, on renewable energy use and electrical load coverage are listed in Tables 1 and 2. It can be noted that solar energy, together with the hybrid storage system, can significantly decrease the use of the diesel generator to a value of about 3.9% of the total annual electrical demand. Especially, when the energy from PV is not enough to cover the load, the deficit is mainly met by the battery, which serves as a daily energy buffer. The high-capacity hydrogen storage, on the other hand, is necessary to cope with the seasonal variation of the electrical load and is mainly used in the summer when the load increases. More information about

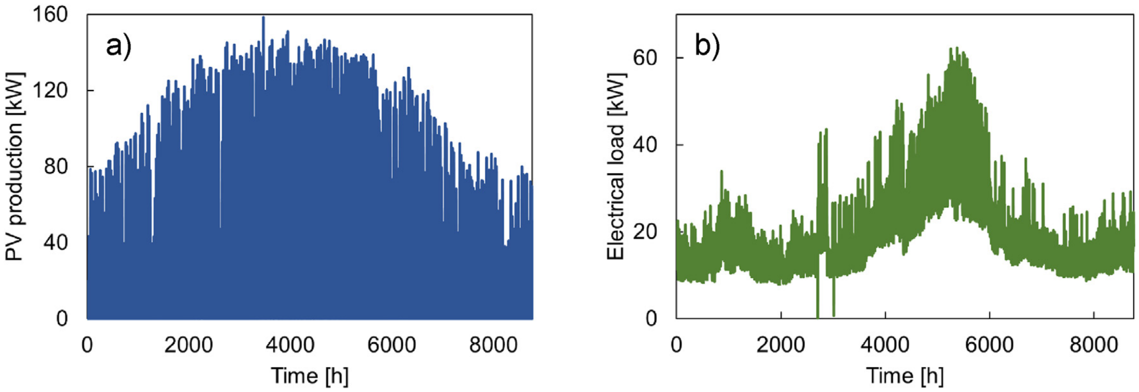

Fig. 2 – Profile over the year (with hourly resolution) of the PV production (a) and electrical load (b) in Ginostra.

Table 1 – Breakdown of the RES use in Ginostra (on an annual basis) for the Renewable scenario.

RES use breakdown	Value
RES to load	88.71 MWh/year
RES to electrolyser	8.44 MWh/year
RES to battery	103.28 MWh/year
RES to curtailment	70.39 MWh/year
Total RES	270.83 MWh/year

Table 2 – Breakdown of the load coverage in Ginostra (on an annual basis) for the Renewable scenario.

Load coverage breakdown	Value
Load directly covered by RES	81.76 MWh/year
Load covered by fuel cell	2.40 MWh/year
Load covered by battery	80.70 MWh/year
Load covered by diesel generator	6.69 MWh/year
Total electrical load	171.54 MWh/year

the control strategy and the energy simulation can be found in a previous work of the authors [33], which demonstrated the effectiveness of the proposed solution from an economic point of view.

Methodology

A life cycle assessment (LCA) approach has been considered to assess the environmental sustainability of the off-grid energy system. The analysis was carried out using SimaPro® software [34] and Ecoinvent database.

The LCA methodology includes four different phases [18,19,35], as described below.

1. Goal and scope definition: to define the goal, scope, system boundaries, functional unit, and assumptions of the study.
2. Inventory analysis: to quantify the input and output flow of the processes (in terms of raw materials, resources, energy, waste, and emissions).
3. Impact assessment: to evaluate the potential impacts of a product system.
4. Interpretation and improvements: to check the consistency of the study and provide conclusions and recommendations.

The overall objective of this study is to evaluate and compare the main environmental impacts associated with (i) the current diesel-based energy system (Reference scenario) and (ii) the proposed RES-based energy system (Renewable scenario). This comparison will show whether the renewable solution is an environmentally sustainable alternative, already knowing its effectiveness from a techno-economic perspective [33]. In addition, this LCA also aims to identify the processes or components responsible for the greatest environmental impact in order to understand possible future improvements that companies or decision-makers should focus on.

In line with previous studies and the PEF (Product Environmental Footprint) Category Rules for batteries [36], the functional unit considered is 1 kWh of electricity provided by

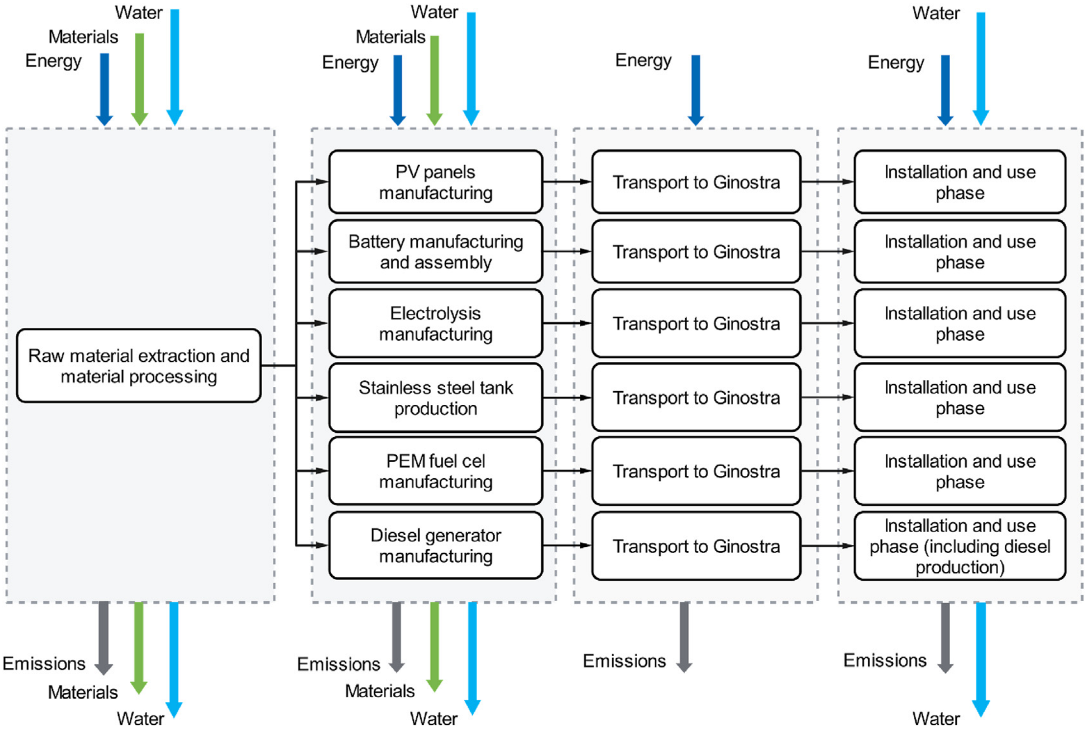

Fig. 3 – System boundary for the LCA analysis of the Renewable scenario.

Table 3 – Main specifications of diesel generators for the Reference and Renewable scenarios.

	Reference scenario	Renewable scenario
Diesel generator size	62 kW	47 kW
Weight of a single genset	1250 kg	1250 kg
Lifetime	16,000 h	16,000 h
Fuel consumption[a]	88,630 l/year	3639 l/year
Operating hours	8758 h/year	504 h/year

[a] Fuel consumption curve from Ref. [38].

the energy system in the Renewable scenario and diesel-based Reference scenario.

As shown in Fig. 3, the boundaries of the study for both the scenarios are "from-Cradle-to-Utilization", including extraction and processing of raw materials, manufacturing, transport to Ginostra, construction, installation and the use phase. Due to the high variability of End-Of-Life (EOL) scenarios, the assessment of this phase usually involves a considerable number of assumptions, leading to a high degree of uncertainty in the environmental impact results. For this reason, the present study excludes the EOL phase from the analysis. Furthermore, as various components of the renewable scenario could be reused or recycled, the exclusion of the EOL phase can be considered as a precautionary measure.

The potential impacts of the two scenarios were assessed using the Environmental Footprint (EF) 3.0 method, in accordance with the PEF guidelines. Life Cycle Impact Assessment (LCIA) methods, such as EF 3.0, provide the so called "characterisation factors" to convert the inventory data into a set of potential impacts. EF 3.0 method is the most recent method (November 2019) developed by the European Commission [37]. The impact categories were selected according to the most relevant aspects for the analysed scenarios. Specifically, the following impact categories were considered: Climate Change, Ozone Depletion, Photochemical Ozone Formation, Particulate Matter, Acidification, Freshwater Eutrophication, Terrestrial Eutrophication, Marine Eutrophication, Freshwater Ecotoxicity, Water Use, Resource Use – fossils, Resource Use – minerals and metals.

Inventory of the Reference and Renewable scenarios

Reference scenario

The Reference scenario refers to Ginostra's current energy system (Fig. 1a), where electricity demand (171.54 MWh per year) is met by a 62 kW diesel generator. According to energy simulations of the diesel-based system, the total diesel consumption is 88,630 L per year, which was evaluated considering a fuel consumption curve that depends on the output power of the diesel generator [38]. The operating hours amount to 8758 h per year. The lifetime of the diesel generator was assumed to be 16,000 h, which means that it needs to be replaced every 22 months. The main characteristics of the diesel genset are summarized in Table 3.

It was assumed that the transport of the generator and diesel fuel from Milazzo (on the Sicily coast) to Ginostra is carried out by helicopter. The travel time (approximately 30 min) was calculated based on the distance and the average helicopter speed. The number of flights required was determined taking into account the maximum capacity of the helicopter and the weight of the various components. An average value of 2000 kg was hypothesized for the maximum capacity of the helicopter.

Based on these data, the life cycle model was developed using background data sets from the Ecoinvent 3.7 database. In order to ensure the reproducibility of this study, the quantities of input flows and the proxy datasets used are listed in Table 4.

Renewable scenario

The Renewable scenario evaluates the impact of electricity generation with the renewable hydrogen-battery system (Fig. 1b). Table 5 shows the inventory of this system for the production of 1 kWh of electricity in Ginostra. Data from the

Table 4 – Inventory of the reference scenario for 1 kWh of electricity produced.

Flow	Quantity	Proxy dataset in Ecoinvent 3.7	Notes
Generators [p]	$1.11 \cdot 10^{-5}$	Diesel-electric generating set, 18.5 kW {GLO}| market for | Alloc Rec, S	• Diesel generator size: 62 kW • Lifetime: 16,000 h • 1 diesel generator (62 kW) + 13 replacements are required during the project lifetime (25 years).
Diesel [kWh]	5.16	Modified from: Diesel, burned in diesel-electric generating set, 18.5 kW {GLO}| market for | Alloc Rec, S	The dataset has been modified by deleting the input of "Diesel-electric generating set", since this input has been calculated with specific reference to the case study of Ginostra (88,630 l/year).
Transport with helicopter [h]	$1.11 \cdot 10^{-4}$	Transport, helicopter {GLO}| processing | Alloc Rec, S	Helicopter flights include both the diesel generator and the diesel fuel supply to the island. The average number of flights per year is 38.

Table 5 – Inventory of the renewable scenario for 1 kWh of electricity produced.

Flow	Quantity	Proxy dataset in Ecoinvent 3.7	Notes
Photovoltaic panel [m^2]	$2.15 \cdot 10^{-4}$	Photovoltaic panel, single-Si wafer {GLO}| market for| Alloc Rec, S	• PV systems size: 170 kW • PV total area: 922.23 m^2 • No replacements are needed during the project lifetime (25 years).
Photovoltaic plant [p]	$6.95 \cdot 10^{-8}$	Photovoltaic plant, electrical installation for 570 kWp open ground module {GLO}| market for photovoltaics, electrical installation for 570 kWp module, open ground | Alloc Rec, S	
Photovoltaic mounting system [m^2]	$6.41 \cdot 10^{-5}$	Photovoltaic mounting system, for 570 kWp open ground module {GLO}| market for | Alloc Rec, S	
Generators [p]	$5.92 \cdot 10^{-7}$	Diesel-electric generating set, 18.5 kW {GLO}| market for | Alloc Rec, S	• Diesel generator size: 47 kW • Lifetime: 16,000 h • 1 diesel generator (47 kW) is required during the project lifetime (25 years). No replacements are needed during the project lifetime.
Diesel [kWh]	$2.12 \cdot 10^{-1}$	Modified from: Diesel, burned in diesel-electric generating set, 18.5 kW {GLO}| market for | Alloc Rec, S	The dataset has been modified by deleting the input of "Diesel-electric generating set", since this input has been calculated with specific reference to the case study of Ginostra (3639 l/year).
Battery [kg]	$2.3 \cdot 10^{-3}$	Battery, Li-ion, rechargeable, prismatic {GLO}| market for | Alloc Rec, S	• Lifetime: 10 years. • 1 battery (600 kWh) + 2 replacements are required during the project lifetime (25 years). • Energy density: 150 Wh/kg.
Fuel cell [p]	$2.91 \cdot 10^{-5}$	Fuel cell, stack polymer electrolyte membrane, 2 kW electrical, future {GLO}| market for | Cut-off, S	• Lifetime: 5 years. • 1 fuel cell (50 kW) + 4 replacements are required during the project lifetime (25 years).
Alkaline electrolyser [kWe]	$3.50 \cdot 10^{-5}$	Alkaline electrolyser	• Data from literature [39]. • Lifetime: 9 years. • 1 electrolyser (50 kW) + 2 replacements are required during the project lifetime (25 years).
Steel - H_2 storage [kg]	$3.65 \cdot 10^{-3}$	Steel, chromium steel 18/8 {GLO}| market for | Alloc Rec, S	• Total volume: 21.6 m^3. • Mass: 15,652 kg.
Steel - O_2 storage [kg]	$1.82 \cdot 10^{-3}$	Steel, chromium steel 18/8 {GLO}| market for | Alloc Rec, S	• Total volume: 10.3 m^3. • Mass: 7826 kg.
Transport with helicopter [h]	$9.50 \cdot 10^{-6}$	Transport, helicopter {GLO}| processing | Alloc Rec, S	It is considered the transport of PV panels, batteries, electrolyser, hydrogen storage, oxygen storage, fuel cell, diesel generator and diesel fuel to Ginostra, including both the delivery of the initial system and the replacements.

literature were used to model the alkaline electrolyser [39]. The replacement of components was also included in the analysis, considering a lifetime of 5 years for the fuel cell, 9 years for the alkaline electrolyser and 10 years for the battery [33].

As far as transport is concerned, it should be noted that diesel fuel and the various components of the energy system must be transported to Ginostra by helicopter due to remoteness of the site. Through this LCA analysis, it is possible to understand if the transport phase is relevant compared to the overall life cycle impacts, also taking into account that regular trips are required for fuel supply and replacement of components. Analogously to the Reference scenario, the helicopter route from Milazzo to Ginostra was considered. The travel distance and the average speed of the helicopter were used to determine the travel time (about 30 min). The number of trips was then evaluated by knowing the weight of the components and the maximum helicopter capacity (2000 kg). The specifications of the diesel generator for the Renewable scenario are shown in Table 3. The diesel consumption corresponds to 3639 L per year with an operation of 504 h per year.

Results and discussion

This section compares the potential impacts of the Reference and Renewable scenarios. A breakdown analysis is then carried out for each scenario to identify the processes that are mainly responsible for the various environmental impacts.

Comparison of the two scenarios

The resulting impacts of the two scenarios are summarized and compared in Table 6 and Fig. 4. It can be noticed that the improvement with the new renewable-based solution is significant for almost all the analysed impact categories, except for the categories of resource use (mineral and metals), water use and freshwater eutrophication.

Table 6 – Impacts associated with 1 kWh of electricity produced in the Reference and Renewable scenarios.

Impact category	Unit	Electricity – Reference scenario	Electricity – Renewable scenario
Climate change	kg CO_2 eq.	1.73	$1.97 \cdot 10^{-1}$
Ozone depletion	kg CFC11 eq.	$3.63 \cdot 10^{-7}$	$5.18 \cdot 10^{-8}$
Photochemical ozone formation	kg NMVOC eq.	$2.98 \cdot 10^{-2}$	$1.81 \cdot 10^{-3}$
Particulate matter	disease inc.	$3.55 \cdot 10^{-8}$	$1.02 \cdot 10^{-8}$
Acidification	mol H^+ eq.	$2.36 \cdot 10^{-2}$	$2.06 \cdot 10^{-3}$
Eutrophication, freshwater	kg P eq.	$6.30 \cdot 10^{-5}$	$1.07 \cdot 10^{-4}$
Eutrophication, marine	kg N eq.	$1.04 \cdot 10^{-2}$	$6.14 \cdot 10^{-4}$
Eutrophication, terrestrial	mol N eq.	$1.14 \cdot 10^{-1}$	$6.76 \cdot 10^{-3}$
Ecotoxicity, freshwater	CTUe	$1.57 \cdot 10^{+1}$	$1.24 \cdot 10^{+1}$
Water use	m^3 depriv.	$2.89 \cdot 10^{-2}$	$7.43 \cdot 10^{-2}$
Resource use, fossils	MJ	$2.31 \cdot 10^{+1}$	2.49
Resource use, minerals and metals	kg Sb eq.	$5.69 \cdot 10^{-6}$	$2.89 \cdot 10^{-5}$

As the climate change indicator is concerned, the Renewable scenario performs 9 times (−88.6%) better than the Reference scenario, and in 25 years (lifetime of the plant) the saving of greenhouse gases in the atmosphere would be about 6570 t of CO_2 equivalent. Similarly, the impacts of the Renewable scenario are below or close to 10% of those of the Reference scenario for the categories of ozone depletion, photochemical ozone formation, acidification, marine eutrophication, terrestrial eutrophication and resource use (fossil). The environmental benefit of the renewable solution is also visible for the categories of freshwater ecotoxicity (−21%) and particulate matter (−71%). On the contrary, the Renewable scenario has higher impacts than the Reference scenario for the following indicators: use of mineral and metal resources (+80%), water use (+61%) and freshwater eutrophication (+41%). This is mainly due to the manufacturing of the electrolyser, battery and PV panels.

Reference scenario

The chart in Fig. 5 shows the breakdown of the climate change impact in the Reference scenario. Currently, the production of 1 kWh of electricity in Ginostra corresponds to the emission of 1.73 kg CO_2 eq., of which 94% is due to the production and combustion of diesel. The transport of fuel by helicopter, on the other hand, hardly influences the result (0.6% of total emissions).

As shown in Fig. 6, diesel burned in the generator is also the main contributor for most of the other impact categories under analysis. The only exceptions are the categories of freshwater eutrophication, water use and resource use (minerals and metals), where the genset manufacturing is the main share. The impact of transport is negligible (less than 1%) for all the categories analysed.

Renewable scenario

As shown in Fig. 7, 1 kWh of electricity produced in the Renewable scenario is responsible for 0.197 kg CO_2 eq. The main contributors to the climate change category are the diesel burned in the diesel generator (37%) and the PV panels (33%).

Fig. 8 shows the contribution of the different plant components on the impact categories. The diesel generator share includes the manufacturing phase and the operation (diesel consumed), while the PV system includes the PV panels, the

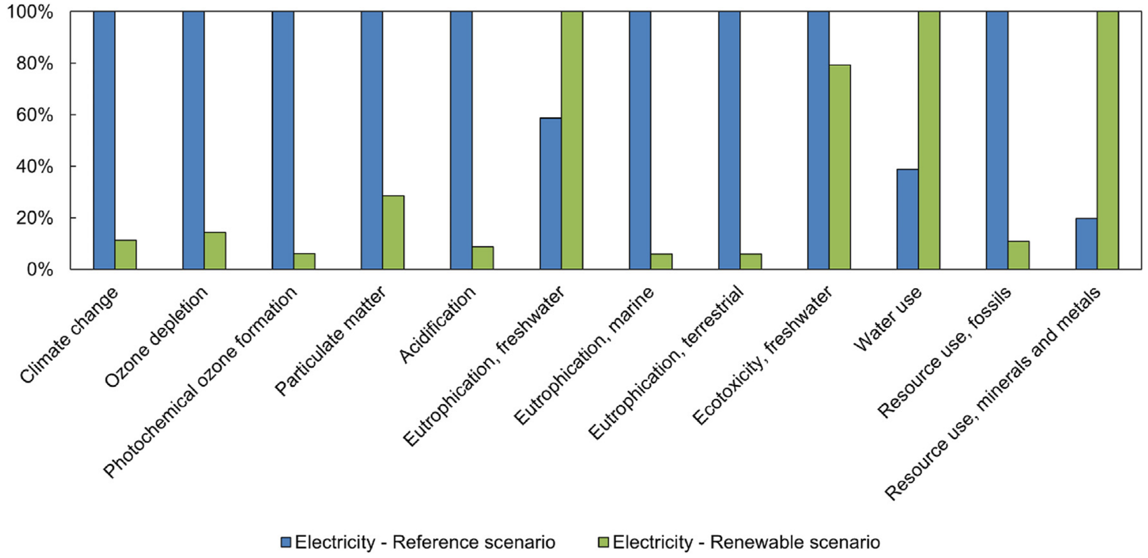

Fig. 4 – Relative comparison of the impacts of the Reference scenario (blue columns) and Renewable scenario (green columns). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

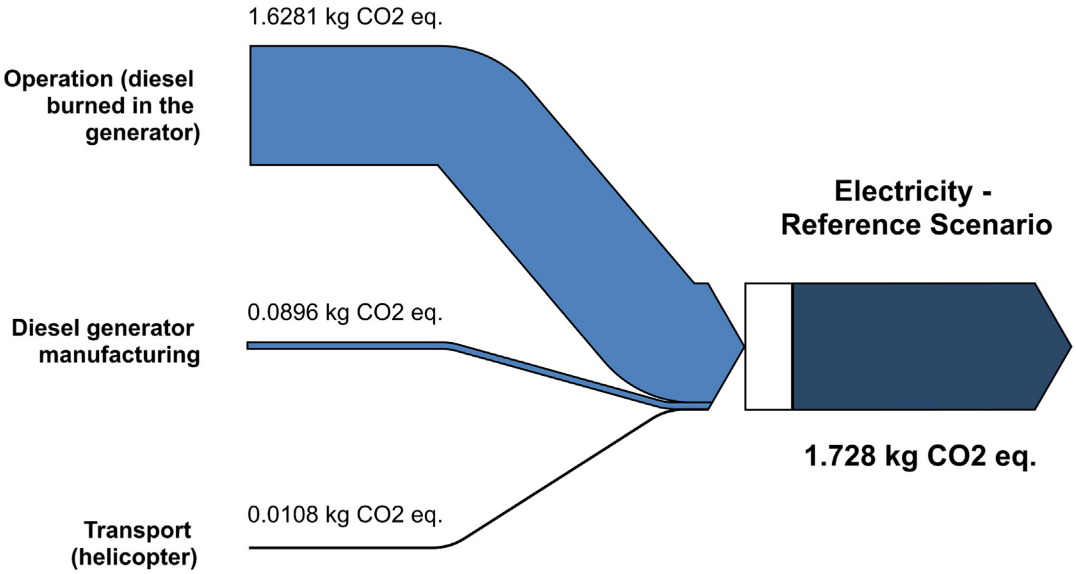

Fig. 5 – Breakdown of climate change impact associated with 1 kWh of electricity produced in the Reference scenario.

mounting system and the electrical installation, as previously described in Table 5. Although the diesel generator provides only about 3.9% of the total energy demand, it is responsible for the largest impact not only on climate change, but also on the following indicators: photochemical ozone formation, acidification, marine/terrestrial eutrophication and resource use (fossil). The impact on the use of mineral and metal resources is mainly related to the production of the alkaline electrolyser (59%), due to the silver needed for its construction, and the battery (26%). The contribution of PV panels is quite relevant for all the indicators, ranging from 10% to 67% of the total impacts. The contribution of helicopter transport is always negligible and amounts to less than 0.5% in all impact categories.

The results were further investigated, focusing on the components with the highest environmental impact, i.e., the PV panels and the diesel generator. More specifically, a study of the emissions divided for each phase of the LCA was carried out, starting from the extraction of the materials to the use phase. Four impact categories were selected for this analysis: climate change, ozone depletion, particulate matter and acidification.

The LCA outcomes are shown in Fig. 9 for the solar PV system. The inventory includes manufacturing, electrical installation, the mounting system and transportation. The PV panel manufacturing process is responsible for the largest impact in each of the four categories (it is always above 87%). The transport phase, on the other hand, is always negligible,

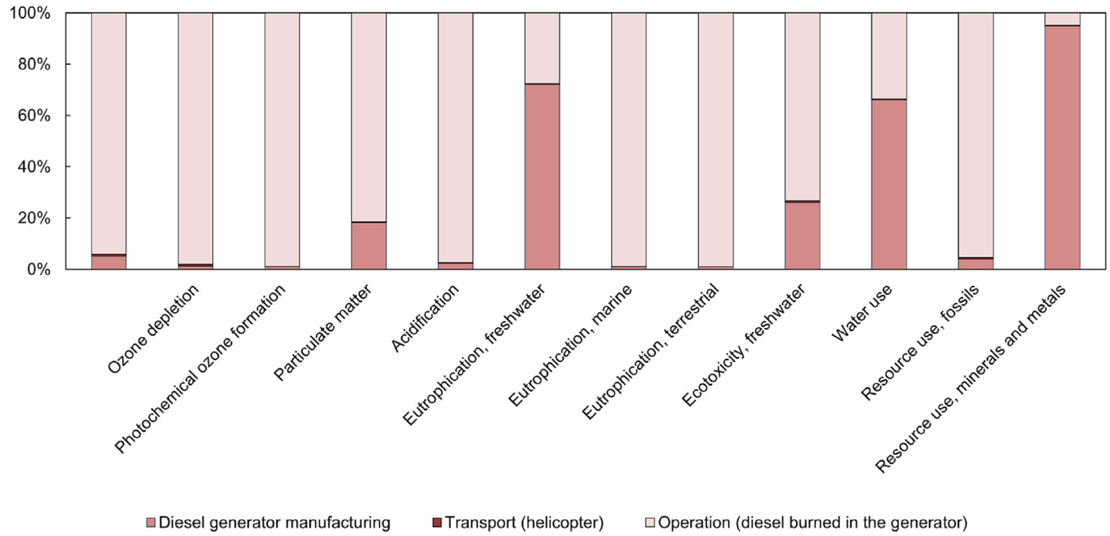

Fig. 6 – Breakdown of the impact categories in the Reference scenario.

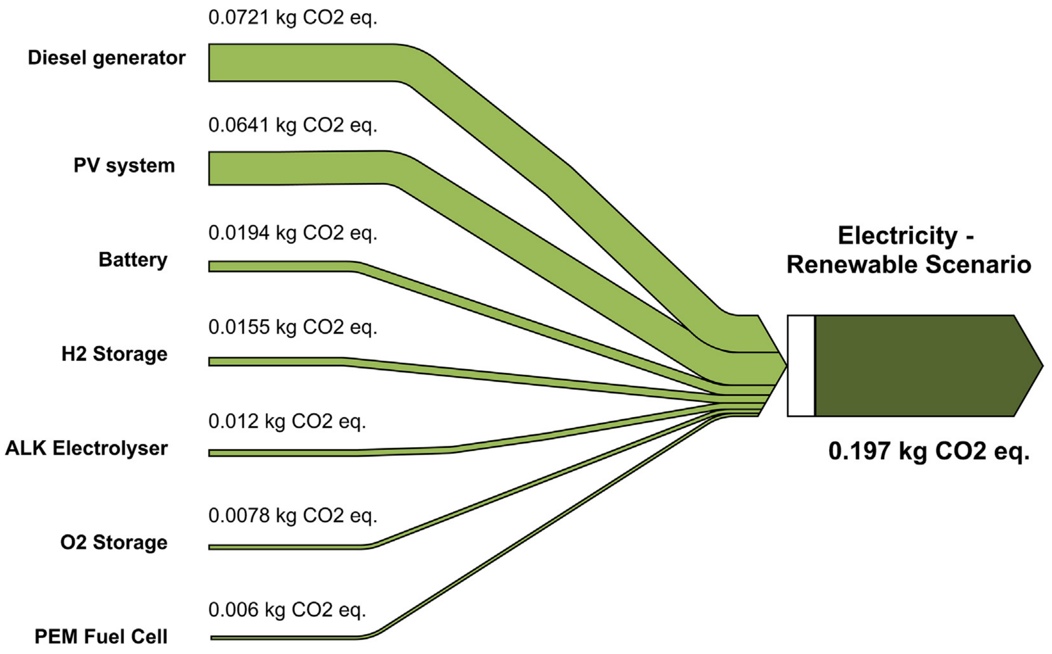

Fig. 7 – Breakdown of climate change impact associated with 1 kWh of electricity produced in the Renewable scenario.

thanks also to the fact that PV panels do not need to be replaced during the lifetime of the project (they are insured for 30 years). The contribution of the PV mounting system is higher than that of the electrical installation, but never accounts for more than 11% in the four categories.

The diesel generator is one of the main sources of emissions from the plant. In fact, it accounts for about 48% of emissions for acidification potential, 37% for climate change, 15% for particulate matter and 29% for ozone depletion. As shown in Fig. 10, diesel fuel combustion is the largest contributor, even though it only covers a small fraction of the total electrical load of Ginostra (about 3.9%) in the Renewable scenario. The second main contributor is the diesel genset manufacturing, especially in the category of particulate matter. Although the number of helicopter flights is greater compared to the other components of the energy system (due to the regular transport of the fuel to the island), the transport phase is still negligible.

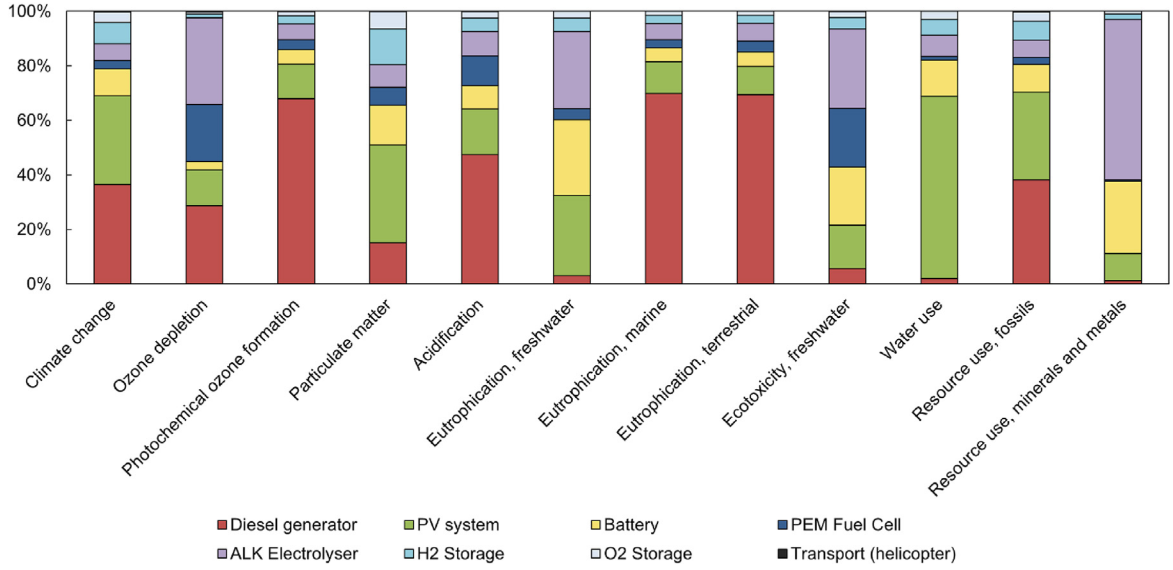

Fig. 8 – Breakdown of the impact categories in the Renewable scenario.

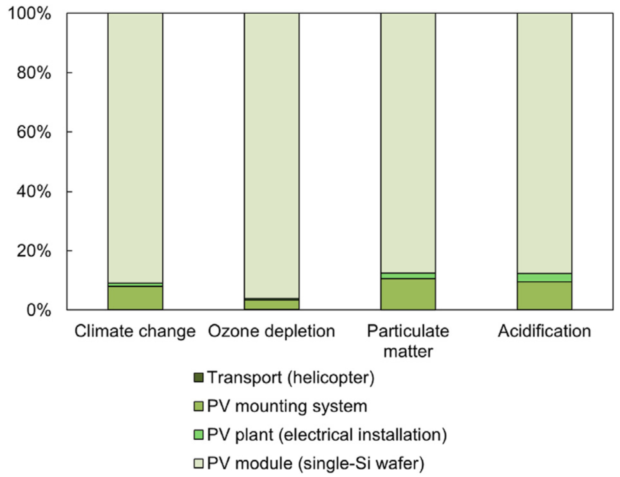

Fig. 9 – Breakdown of the PV panels impacts (Renewable scenario).

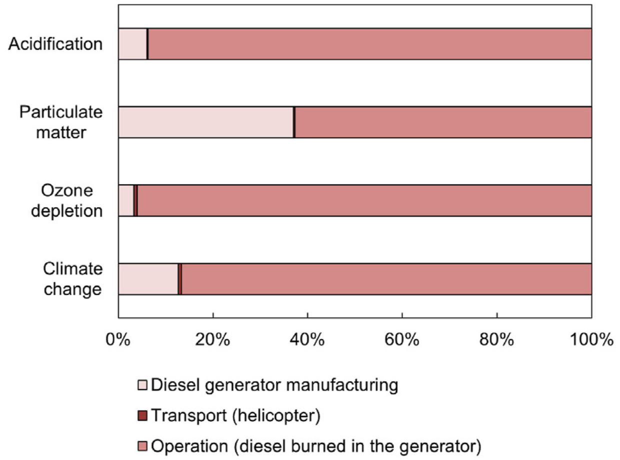

Fig. 10 – Breakdown of the diesel generator impacts (Renewable scenario).

Conclusions

In this study, the environmental sustainability of electricity generation in Ginostra, a remote island located in the south of Italy, was assessed using an LCA analysis. Specifically, two scenarios were investigated: a diesel-based energy system (Reference scenario) and an innovative solution based on a photovoltaic plant combined with a hydrogen-battery energy storage (Renewable scenario). The results refer to 1 kWh of electricity (functional unit) supplied by each of the two energy systems, considering a time horizon of 25 years (i.e., the lifetime of the project).

The results show that the renewable P2P system leads to an improvement over the current diesel configuration for most impact categories. In terms of climate change, the potential impact is 0.197 kg CO_2 eq./kWh for the Renewable scenario, compared to 1.73 kg CO_2 eq./kWh for the Reference scenario. The Reference scenario performs slightly better than the RES-based alternative only for the indicators of water use, freshwater eutrophication and use of mineral and metal resources.

The diesel generator was found to be responsible for a significant share of the impacts even in the Renewable scenario: it accounts for about 37% of the climate change impact, while it reaches almost 70% of the impact on photochemical ozone formation and eutrophication (both marine and terrestrial). For the diesel generator, the most impactful phase is operation (combustion), while for all other plant components, the manufacturing phase plays an important role.

Even if the Ginostra site requires the use of helicopters to provide the necessary materials and fuels, the results show that the emissions due to transport can be considered negligible. In fact, it accounts for less than 1% of the total emissions in both scenarios and for all impact categories analysed.

This environmental study, together with the previous economic study in the framework of the REMOTE project [33], is intended to promote the development of sustainable integrated systems capable of providing electricity in remote areas. From these studies, it appears that the exploitation of renewable energy sources in combination with hydrogen-based storage systems can represent an effective and viable solution from both an economic and environmental perspective. To complete the sustainability analysis, future research could also investigate the social implications of this solution, taking into account the advantages and disadvantages for the local community and for all the actors involved in the value chain.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijhydene.2022.07.199.

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