A study of the techno-economic feasibility of H_2-based energy storage systems in remote areas

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Abstract

The development of efficient and sustainable energy solutions and the attempt to reduce carbon dioxide emissions are leading to an increasing penetration of Renewable Energy Sources (RES). Effective Electrical Energy Storage (EES) solutions need therefore to be developed to deal with the issue of fitting locally available RES and loads. Hydrogen can become an interesting option because of its high energy density, long-term storage capability and modularity. In particular, in isolated micro-grid and off-grid remote areas, intermittent RES integrated with H_2-based storage systems can allow to lower, or even eliminate, the usage of diesel engines and avoid the need for expensive and invasive grid connections. The present study is part of the European REMOTE project, whose main goal is to prove the added value of H_2-based energy storage solutions with respect to alternative technologies in terms of economics, technical and environmental benefits. Four demonstration sites supplied by renewable electricity will be installed in either isolated micro-grids or off-grid remote areas throughout all Europe, from Italy (two sites) and Greece to

Norway. The aim of this work is to perform a techno-economic analysis and demonstrate the effectiveness of the hybrid H_2-battery Power-To-Power (P2P) solution in reducing the usage of external sources (e.g., diesel engines or grid) in a cost-effective way, with different load and environment conditions. The economic viability of the considered scenarios was outlined by computing the Levelized Cost Of Energy (LCOE). For each of the four sites, the innovative renewable configuration was compared with the current/alternative one. The REMOTE project partners provided main input data for the analysis: techno-economic data from the technology suppliers, whereas electricity consumption and RES production values from the end users of the four isolated locations. LCOE values derived using cost inputs both from REMOTE and literature are presented for a comparison. Results from the energy simulations revealed that the need for an external source is significantly reduced thanks to RES together with the hybrid storage system. Moreover, for all the four sites the renewable solution was shown to be more profitable than the current or alternative one, either in the short term or in the longer term.

Keywords

Energy storage; Off-grid; Electrolysis; Hydrogen; Battery; Power-to-power

1. Introduction

Renewable Energy Sources (RES) will represent the major asset in the future energy mix, addressing the problem of fossil fuel progressive depletion and mitigation of greenhouse gas emissions. However, well-known challenges have to be overcome to allow RES widespread diffusion. Effective Electrical Energy Storage (EES) systems are in fact required to deal with the problem of intermittency of electricity production from RES (e.g., wind and solar) [1]–[4]. Hydrogen, in particular, represents an interesting storage solution because of its high energy density per mass and long-term storage capability [5], [6].

Concerning off-grid systems, there is a large market to replace diesel generators with renewable energy sources [7], [8] . Local RES exploitation would be also helpful to avoid the need for unreliable and invasive grid connections. However, EES solutions need to be adopted to better optimize local RES management allowing to achieve higher RES penetration levels. Intermittent RES coupled with H_2-based energy storage systems are an interesting choice [9], [10] that has the potential to provide a reliable, cost-effective (especially in remote areas) and decarbonized alternative to the on-site electricity generation through diesel engines [11]. Off-grid rural areas currently not electrified could also take advantage of this RES-based EES solution to have a reliable access to locally generated electricity.

The presented work is performed in the framework of REMOTE (Remote area Energy supply Multiple Options for integrated hydrogen-based Technologies), a 4-year project (2018-2021) of the EU's Horizon 2020 program [12]. REMOTE objective is to demonstrate the techno-economic feasibility of hydrogen-based energy storage solutions in isolated micro-grids and off-grid remote areas, in the 5-200 kW range of fuel cell power [13]. As shown in Figure 1, four demo systems are going to be installed in different locations across Europe: Ginostra

(South of Italy), Agkistro (Greece), Ambornetti (North of Italy) and Rye (Norway). The last demo will be eventually moved to an off-grid island in Norway, depending on the availability of a suitable site and the timeline of the authorization process. Each installation will complement locally available RES with a hybrid energy storage system based on hydrogen and batteries. Different kinds of local RES will be exploited to cover the electrical end-use loads. The variety of the involved demo cases will thus allow gaining significant learning from integration with existing infrastructure in real sites, paving the way for the deployment of Power-to-Power (P2P) storage systems at large scale.

The storage solution proposed in the project consists of a hybrid configuration based on electrolysers for RES electricity conversion into hydrogen, which is stored as compressed gas and used in fuel cells for electricity generation, including also batteries to ensure both short- and long-term storage. Stationary batteries are indeed used to store energy on daily basis. However, when the energy storage is required for a longer period, batteries become expensive and the integration with H_2-P2P systems with medium/long-term capabilities can be a viable and reliable option [14]. The combination of hydrogen and batteries for storage purposes has been widely analysed in the literature showing great potential in providing power source to customers in a reliable and sustainable manner [15]. The research on such kind of hybrid storage systems is mainly addressed to their optimal design with the aim of achieving the minimum system cost [16]–[18]. Environmental objectives (e.g., reducing CO_2 equivalent emissions) can be also considered in the sizing problem [19]–[21]. The adoption of a proper Energy Management Strategy (EMS) is also essential for a correct interaction of the various sub-systems with the aim of achieving good energetic and economic performances [22]. However, the task is challenging because of the high number of technologies to be integrated (i.e., RES power systems, battery and hydrogen-based devices). Ref. [23] and [24] present a comprehensive review of EMSs for renewable hybrid energy systems with the latter focusing in particular on hydrogen technologies. The main objectives of a P2P control strategy can be summarized as follows [25]:

- Reliable coverage of the electricity loads
- Ensuring the system components to operate under optimal conditions preventing them from operating outside safe working ranges.
- Optimise the average roundtrip efficiency along the year

The intermittent nature of most of RES (e.g., wind and solar) leads to fluctuations in power production that have to be properly faced. Recurrent changes in the operation of the fuel cell and electrolyzer components should be avoided to limit their performance degradation and preserve their lifetime. A battery bank becomes thus useful as an instantaneous and daily energy buffer smoothing down the RES high-frequency variability [26]. However, the battery device should be protected from heavy utilization avoiding excessive over-charging/discharging in order not to negatively affect its life span. EMSs are therefore necessary to properly and safely operate the various P2P subsystems while satisfying the load requirements. Rule-based control strategies are generally defined giving priority to the route with higher transmission efficiency for the energy flow in order to keep the overall system operation efficiency as high as possible [25]. To this aim, a typical hierarchy consists of using the battery and then the hydrogen pathway, i.e., electrolyzer and fuel cell [26]–[29]. The battery State-Of-Charge (SOC) is generally considered as the main key decision factor for the EMS. A control scheme with the presence of hysteresis bands is often also adopted for the regulation of the battery-H_2 system [30]–[32]. In that case, additional key control parameters have to be introduced within the system management strategy providing higher flexibility in the operation of the various components [31]. The implementation of hysteresis bands was shown to be beneficial in further protecting the battery from heavy utilization and preventing the electrolyzer and the fuel cell from being switched on/off too frequently [30],

[32]. During the course of the project, data from real-life experience will be made available giving the possibility to define specific EMS for each demo and providing valuable information for the system modelling.

This article defines the case studies of the four demos, analysing the technical solution proposed for each site in order to evaluate how to improve the local situation. A techno-economic analysis was performed after the definition of a reference energy management strategy. To our knowledge, no literature exists that comprehensively assess H2-battery energy storage systems in different kinds of remote locations in Europe, from alpine to insular, with different typologies of local renewable sources and loads considered. The assessment takes advantage of unique data and information provided and verified directly by international technology developers and end-user actors. Load and RES generation hourly profiles, equipment sizes and main features are in fact provided by project partners directly involved in the demos. LCOE values derived from real costs are also shown. This will thus be helpful to give a wider and more complete insight into the feasibility of these kind of systems in micro grid environments.

The structure of this paper is as follows: in Section 2 the demonstration sites are described and the main technical data of the innovative RES + hybrid P2P system are presented. Section 3 presents the adopted energy management strategy and the main techno-economic assumptions are shown. Results from the EMS implementation are then reported in Section 4, where potential economic benefits by way of Net Present Costs (NPC) are also outlined by comparing costs for the current or alternative and the suggested renewable solutions.

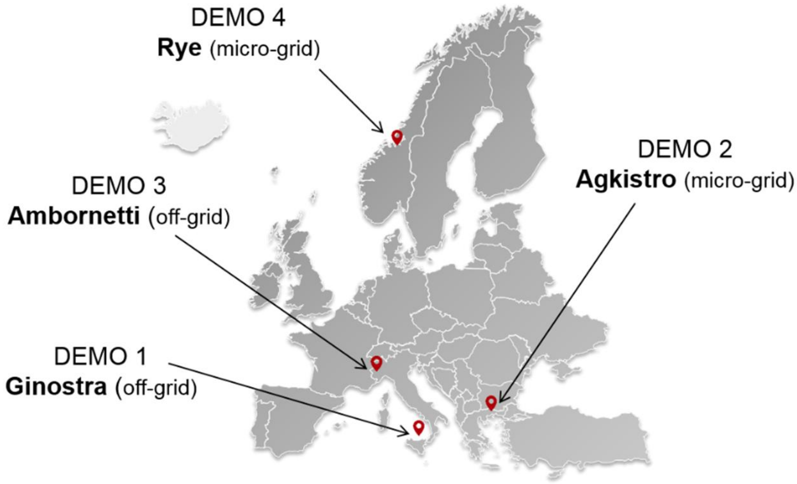

Figure 1. *Geographical location of the four REMOTE demonstration sites.*

2. Demonstration sites description

2.1 General configuration of the hybrid power/storage system

The four demo cases are characterized by different typologies of RES (i.e., solar, wind, biomass and hydro) and user loads (i.e., residential and small industrial), which will affect differently the design and management of the proposed P2P solution.

A general schematic of the adopted stand-alone H_2-based P2P system is shown in Figure 2. Local renewable energy is converted into electricity to satisfy the electrical demand of the final user. Surplus energy, if present, is stored by charging a Li-ion battery bank or producing hydrogen by means of a low temperature electrolyzer (alkaline or Proton Exchange Membrane, PEM). Hydrogen is then stored in pressurized vessels and, when required, sent to a PEM fuel cell for electricity generation. During renewable power shortages, the remaining energy fraction to cover the load is supplied by the battery discharging and/or the fuel cell operation. The energy storage process implies a loss of energy depending on the involved technology: the battery device has a higher efficiency compared to the hydrogen pathway as shown by the technical assumptions of Table 2. In all the four installations, the electrolyzer device operates at 30 bar. It is thus not required the presence of a compressor to store the produced hydrogen into the gas vessel, which works up to 30 bar. Fuel cell instead operates at ambient pressure.

The battery is required to provide electricity for the daily operation of the control unit and auxiliary equipment. It also acts as a daily energy buffer, smoothing down the RES power output and avoiding too frequent start-ups and shutdowns of the electrolyzer and fuel cell. Each component of the P2P system needs to be operated within proper working ranges for safety and efficiency purposes. Dedicated control algorithms will be developed for each P2P plant to optimize the operation and coupling of the various involved subsystems, basing on each site-specific features.

Two different architectures for the storage solution will be developed during the project. Concerning demo 1 in Ginostra and demo 2 in Agkistro, an integrated P2P system supplied by Engie-Electro Power Systems (EPS) [33] has been chosen. This means that the fuel cell and the electrolyzer are completely integrated and managed by the same power electronics, which is remotely controlled. The integrated P2P modules, which are available in units of 25 kW, can be thus connected in parallel to reach the required size making the entire solution flexible and adaptable. Demo 3 in Ambornetti and demo 4 in Northern Europe are instead provided with a non-integrated Power-To-Gas (P2G) + Gas-To-Power (G2P) system. In demo 3, the electrolyzer and the fuel cell are supplied by EPS and Ballard Power Systems Europe (BPSE) [34], respectively. In demo 4, Hydrogenics (HYG) [35] is the electrolyzer supplier, whereas the one for the fuel cell is BPSE, with Powidian (POW) [36] as integrator.

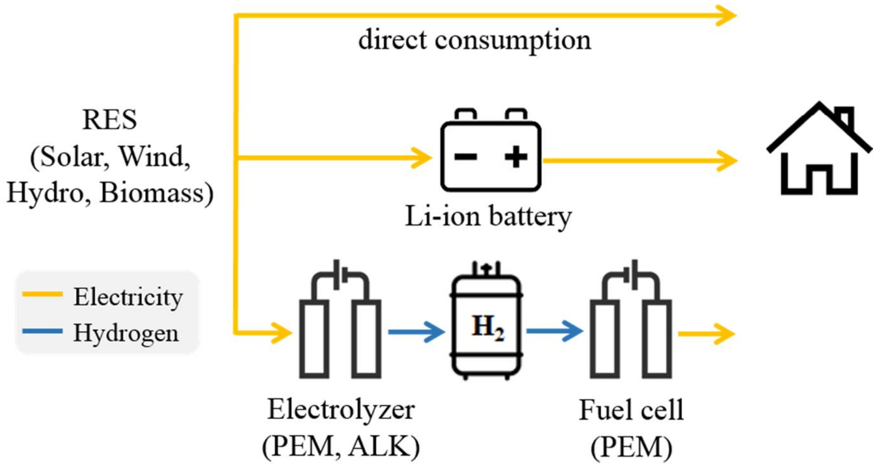

Figure 2. *Operational sketch of the P2P system with H_2 and batteries as energy storage mediums.*

2.2 DEMO sites specifications

A summary of the main components involved in the suggested innovative solution for the four sites is reported in Table 1. A description of each demo is provided in the next sections.

		1. Ginostra	**2. Agkistro**	**3. Ambornetti**	**4. Rye/Froan**[1]
RES	*Typology*	PV	Hydro	PV + Biomass	PV + Wind
	Size	170 kW	0.9 MW	75 kW PV 49 kW Biomass	250 kW PV 675 kW Wind
P2P	*Typology*	Integrated	Integrated	Non-integrated	Non-integrated
	Supplier	ENGIE-EPS	ENGIE-EPS	BPSE, ENGIE-EPS	HYG, BPSE, POW
	P2G Technology	Alkaline	Alkaline	Alkaline	PEM
	Rated Power	50 kW (2 stacks)	25 kW	18 kW	50 kW
	G2P Technology	PEM (O_2 fed)	PEM (O_2 fed)	PEM	PEM

	Rated Power	50 kW (2 stacks)	50 kW (2 stacks)	85 kW (6 stacks)	100 kW (6 stacks)
	H_2 storage Gross energy (LHV)	 1793 kWh	 996 kWh	 498 kWh	 3333 kWh
	Battery Technology Rated energy	 Li-ion 600 kWh	 Li-ion 92 kWh	 Li-ion 92 kWh	 Li-ion 550 kWh

[1] RES data are specific for Froan, the Norwegian archipelago which was used as case study for the techno-economic analysis

Table 1. *Components of the RES+H_2-based storage solution for the REMOTE demo sites.*

2.2.1 Demo 1: Ginostra

Ginostra is a village on the island of Stromboli in Southern Italy. The site is classified as off-grid since not connected to neither the Italian distribution and transmission grid nor the main Stromboli island micro-grid. All loads are residential and currently satisfied by employing one 160 kW and three 48 kW diesel generators. Because of the remoteness of the area, the fuel has to be transported in by helicopter leading to high costs for electricity generation. Enel Green Power (EGP) [37] is the final user of demo 1.

Main drivers to move to the PV + battery-H_2 P2P solution can be summed up as follows:

1) reducing current diesel consumption to lower the cost of electricity production and decrease the local pollution;
2) enhancing the reliability of the electricity service;
3) avoiding prohibitively high costs due to grid connection;
4) gaining experience from the P2P operation to replicate in other European islands.

Main technical specifications of the PV battery-H_2 system are set out below. Regarding the RES power plant, a 170 kW PV system from EGP will be installed. The hybrid energy storage system includes a 600 kWh Li-ion battery bank from EGP and an integrated hydrogen-based solution from Engie-Electro Power System (EPS) [33]. In particular, the H_2 system is composed of a 50 kW alkaline electrolyzer, a 50 kW PEM fuel cell (i.e., two 25 kW P2P modules) and a hydrogen storage with total capacity of 21.6 m^3. An oxygen storage of 10.8 m^3 is also present since the fuel cell is fed with pure O_2 to avoid to send air rich of marine salts in direct contact with the cathode of the cell. Two 48 kW diesel generators will be maintained as a final back-up system.

The total annual electrical load, which is currently covered by diesel generator, is around 172 MWh. As shown in Figure 3 (on the left), Ginostra energy needs are highly seasonal with variations between 10 MWh/month in winter and 30 MWh/month in summer. The new PV power plant is estimated to produce about 271 MWh/year. Analysing the hourly PV estimated energy production and the load profiles along the year, it was seen that only slightly less than one third of the overall annual energy from PV, i.e., 82 MWh, can be directly consumed by the load. An energy storage system is therefore necessary to optimize the RES exploitation and store the remaining excess solar energy to be used when a renewable energy deficit occurs (thus reducing or even avoiding the intervention of the diesel generator). Figure 3 (on the right) shows the total energy surplus and deficit for each month along the year. It suggests that the high amount of excess solar energy during spring could be stored and employed later in the summer to face the load increase because of tourism.

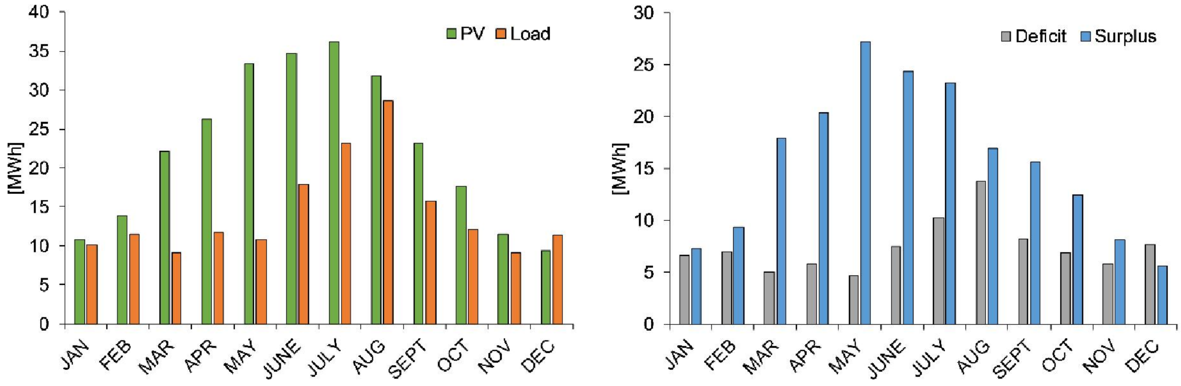

Figure 3. *Monthly distribution of RES and load data (on the left) and energy surplus and deficit (on the right) for Ginostra.*

2.2.2 Demo 2: Agkistro

Agkistro is a remote village situated in the Serres region, in North Greece close to Bulgaria. At the demo site there is a hydroelectric plant, which is owned by Horizon SA (HOR) [38], connected to the grid to sell the produced electricity. HOR company, which is the end user, aims at building an agri-food processing unit very close to its power plant. In order to connect the new facility to the grid, the company should create a separate line directly to a transformer 20 km away since the local one is full. In this scenario, besides the expensive and invasive work due to the connection, the company would buy electricity from the grid at a price higher than the value of the sold hydropower energy.

The aim is therefore to make the new processing unit energy autonomous avoiding the grid connection and relying only on the hydro plant and on the H_2-based P2P storage as a back-up system. Main drivers to move to this solution are thus:

1) avoiding the high expenses due to grid connection works;
2) improving the electrical supply reliability avoiding grid connection problems, i.e., instability and frequent outages due to the site remoteness;
3) avoiding to buy electricity from the grid at high prices;

4) gaining experience in the P2P storage solution for the replication in other remote areas.

The hydroelectric plant has a total capacity of 0.9 MW (with two turbines of 0.65 and 0.25 MW, respectively). Similarly to the Ginostra site, an integrated P2P system delivered by EPS is adopted. The hybrid storage solution includes a 92 kWh Li-ion battery bank, an alkaline electrolyzer and a PEM fuel cell with nominal sizes of 25 kW and 50 kW respectively and a 12 m^3 H_2 storage tank. An oxygen vessel with total capacity of 6 m^3 will be also installed to power the O_2-fed fuel cell. The minimum available electrolyzer size from the manufacturer, i.e., 25 kW, was chosen since the site benefits from continuous availability of renewable source (hydro plant). Two fuel cell units (25 kW each) were instead considered for the G2P section in order to cover the highest load request, which is around 40 kW.

Since the hydro plant works all year-round providing electricity to the main grid, RES electricity production is much higher than the load of the agri-food unit. Considering a medium year, the total annual production from the hydroelectric plant is in fact around 3739 MWh, whereas the total yearly electrical energy required by the new facility is estimated to be approximately 51 MWh. In a framework with high RES electricity generation and quite predictable and stable electrical demand, the P2P system is thus conceived as a backup unit in case of emergency or scheduled hydro plant downtime due to maintenance.

2.2.3 Demo 3: Ambornetti

The mountain hamlet Ambornetti is an off-grid site located in the Piedmont region in North Italy. The aim is to turn this rural area into a completely energy autonomous community with neutral impact to the environment according to the object of a renovation project funded by local private investors including IRIS company [39], which is the demo end user.

Advantages and drivers related to the RES + P2P solutions are:

1) minimizing the overall lifecycle impact based on the renovation project aim;
2) avoiding expensive and invasive works and infrastructures for connection to the grid;
3) avoiding the employment of traditional fossil fuel generators;
4) gaining experience in the P2P storage solution for potential replication in other Alpine areas.

Concerning electrical production from local RES, a 75 kW PV power plant and a 49 kW biomass-based CHP generator [40] will be installed to provide electricity to the off-grid community. The biomass system is able to work up to around 8500 hours per year providing a constant useful electric power of approximately 41 kW (49 kW in total, of which 8 kW are self-consumed). Maintenance of the CHP plant is scheduled around every 300 hours. Biomass will be supplied from surrounding forests management and local agricultural waste. Regarding the storage system, a 18 kW alkaline electrolyzer from EPS and a 85 kW air-fed PEM fuel cell from BPSE are adopted. The hydrogen tank has a volume of 6 m^3. Li-ion batteries with a total storage capacity of 92 kWh are also employed.

The annual electrical energy required by Ambornetti site is around 348 MWh. As shown in Figure 4, no relevant variation in the community demand can be found along the year. The total yearly energy produced by the PV system is estimated to be about 75.5 MWh; whereas the annual electrical energy coming from the biomass CHP system is around 345 MWh (see Figure 4). The biomass plant periodically requires maintenance and needs to be shut down for approximately 10 hours each time. An energy storage system is thus necessary to complement the PV source during maintenance periods and allow the site to depend exclusively on local renewable sources.

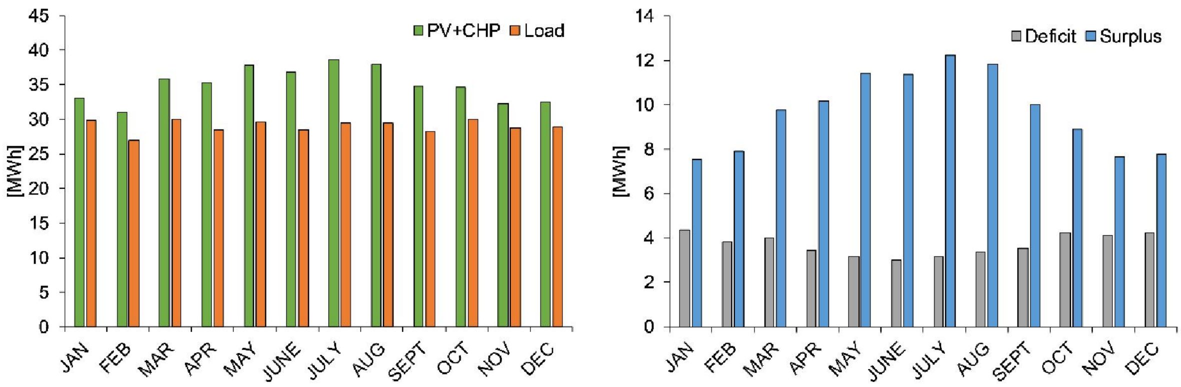

Figure 4. *Monthly distribution of RES and load data (on the left) and energy surplus and deficit (on the right) for Ambornetti.*

2.2.4 Demo 4: Rye/Froan

Norway has a peculiar geography characterized by a large number of islands, many of them located close to the mainland and interconnected to the national grid through sea cables. The outdatedness of subsea connections requires expensive replacements or to consider other alternatives for providing power to the islands. In the REMOTE project, the exploitation of local RES, i.e., solar and wind, together with a H_2-battery storage system has been considered. Main drivers to prefer this alternative are:

1) avoiding the high-priced and invasive replacement of the sea cable;
2) avoiding diesel power generation because of cost and polluting issues;
3) learning from the H_2-based system operation in Nordic countries climate and evaluating whether to propose it to other remote areas.

As a case study to develop the analysis for Norway, the Froan islands have been selected. Froan is an archipelago of four islands located off the west coast of Norway, near the city of Trondheim. The islands are currently interconnected by electric grid with one connection to the mainland through a sea cable, which is owned by the end user TrønderEnergi [41]. Data of RES generation and load are available for Froan and have been used to develop the techno-economic analysis presented in this paper. Within the project, the complete P2P system will be validated and tested at Rye, a site located near the city of Trondheim on the mainland, while a suitable island site is in the phase of identification for the future installation of the demo. The Rye site has characteristics similar to the Froan case study in terms of load and installed RES, thus, the data obtained from the operation in Rye will be relevant for a fair comparison with the simulated case study.

A combination of PV modules and wind turbines is considered for renewable energy generation. Three wind turbines of 225 kW each are supposed to be built in Froan, together with a 250 kWp PV system. Regarding the storage system, a non-integrated P2P solution with a 50 kW PEM electrolyzer from HYG and a 100 kW air-fed PEM fuel cell from BPSE is chosen. The hydrogen storage tank has about 100 kg of hydrogen capacity and is provided by POW. A battery bank consisting of 5 racks of 110 kWh Li-ion is also adopted as a short term and quick-response storage. The whole system is integrated and managed by POW.

Starting from the data provided by TrønderEnergi, a value of around 561 MWh per year of electrical load was computed for the Froan site. Concerning the wind and solar yearly production, around 1315 MWh and 195 MWh have been estimated, respectively (i.e., total annual RES generation of 1510 MWh). The analysis of PV/wind production and load hourly profiles shows that about 445 MWh of the total RES generation are directly used to cover the load. The high amount of surplus renewable energy (accounting for approximately 1065 MWh/year) can be thus stored through batteries and hydrogen and later used during the occurrence of energy shortages to maximize local solar and wind energy exploitation. In Figure 5 the monthly trend of the total RES production and load (on the left) and energy surplus and deficit (on the right) is reported.

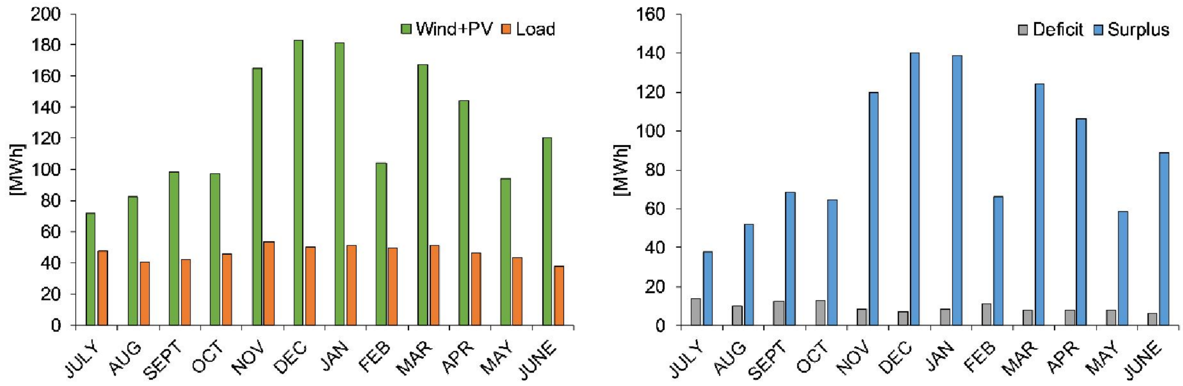

Figure 5. *Monthly distribution of RES and load data (on the left) and energy surplus and deficit (on the right) for Froan.*

3. Methodology

3.1 Energy management of the hybrid P2P system

An Energy Management Strategy (EMS) for the hybrid storage system has been defined in order to perform energy simulations and prove the usefulness of the proposed RES plus P2P solution in covering the electrical end-user demand. Results will be also helpful for the development of the subsequent economic study. The considered control strategy integrates batteries as short-term storage system operating in first instance to absorb/provide electricity when necessary, and hydrogen as longer-term storage medium working when the maximum and minimum operating limits of the battery are reached.

Within the hybrid energy storage system, priority of operation is thus given to the battery component. The state of charge of the battery represents the main key decision factor for the EMS. The maximum and minimum battery SOC levels ($SOC_{,max}$ and $SOC_{,min}$, respectively) are considered as indicators to evaluate when switching on/off the fuel cell and the electrolyzer. When the SOC lies between its lower and upper boundary, priority is given to the battery component. During charging (RES power higher than the load demand), if the SOC has reached its maximum allowed level, the electrolyzer is activated to convert the surplus renewable energy into hydrogen. By contrast, during discharging (RES power lower than the load demand), the fuel cell is employed to prevent the battery SOC to go below SOC_{min}. Information about the Level Of Hydrogen (LOH) within the storage tank is also required: the electrolyzer can operate until the H_2 container is full and the fuel cell can produce electricity only if enough hydrogen is present. Modulation ranges of electrolyzer and fuel cell need finally to be respected for the correct operation. The following constraints have therefore to be checked within the control strategy: 1) battery SOC limits, 2) modulation ranges of the electrochemical devices and 3) hydrogen storage LOH limits.

Figure 6 describes the detailed logical block diagram for the charging case. In case the RES electrical power exceeds the demand of the end-user load, the surplus power is first employed to charge the battery. When the maximum battery SOC is reached, surplus electricity is supplied to the electrolyzer for hydrogen production. The electrolyzer, which is operated within its modulation range, works until the storage tank is completely filled with hydrogen (i.e., a LOH value equal to 1 is reached); whereas the remaining excess RES energy, if present, is curtailed.

The control strategy for the discharging case is instead shown in Figure 7. When the required load is higher than the power available from RES, the necessary additional power for the complete load coverage is provided by the battery or the fuel cell depending on the battery SOC value. In case the minimum SOC of the battery is reached, the fuel cell device is activated to meet the power deficit in order to prevent the over-discharging of the battery. The EMS allows the fuel cell to work between its minimum and maximum operating points ($P_{FC,LB}$ and $P_{FC,UB}$) if enough hydrogen is present inside the pressurized container. If the electric load to be covered is lower than the minimum allowed fuel cell power, the fuel cell is forced to operate at $P_{FC,LB}$ and the excess FC power is employed to charge the battery and/or curtailed. An external source (e.g., diesel generator) has to supply the end users in case both battery and fuel cell are not able together to satisfy the power deficit.

At each time step of the simulation, the battery SOC was computed as follows:

$$SOC(t+1) = SOC(t) + \frac{P_{BT,c}(t) \cdot \Delta t \cdot \eta_{BT,c}}{C_{BT}} - \frac{P_{BT,d}(t) \cdot \Delta t}{\eta_{BT,d} \cdot C_{BT}} \quad (1)$$

Where C_{BT} represents the nominal capacity of the battery, $P_{BT,c/d}$ stands for the battery charging/discharging power, $\eta_{BT,c/d}$ is the battery charging/discharging efficiency and Δt is the time step (which was set to 1 hour in the in the current study).

The maximum charging/discharging power which does not cause the SOC to go above/below its upper/lower limit is, respectively:

$$P_{BT,SOC,c}(t) = C_{BT} \cdot \frac{(SOC_{max} - SOC(t))}{\Delta t} \cdot \frac{1}{\eta_{BT,c}} \quad (2)$$

$$P_{BT,SOC,d}(t) = C_{BT} \cdot \frac{(SOC(t) - SOC_{min})}{\Delta t} \cdot \eta_{BT,d} \quad (3)$$

Analogously, the level of hydrogen (LOH) within the storage tank was defined as:

$$LOH(t) = LOH(t-1) + \frac{P_{EL}(t-1) \cdot \Delta t \cdot \eta_{EL}}{C_{H2}} - \frac{P_{FC}(t-1) \cdot \Delta t}{\eta_{FC} \cdot C_{H2}} \quad (4)$$

Where C_{H2} corresponds to the useful capacity of the H_2 storage tank, $P_{EL/FC}$ is the electrolyzer/fuel cell working power and $\eta_{EL/FC}$ represents the electrolyzer/fuel cell efficiency.

The maximum electrolyzer/fuel cell power which allows not to go above/below the upper/lower LOH is, respectively:

$$P_{EL,LOH}(t) = C_{H2} \cdot \frac{(LOH_{max} - LOH(t))}{\Delta t} \cdot \frac{1}{\eta_{EL}} \qquad (5)$$

$$P_{FC,LOH}(t) = C_{H2} \cdot \frac{(LOH(t) - LOH_{min})}{\Delta t} \cdot \eta_{FC} \qquad (6)$$

The technical input parameters which have been assumed for the model are shown in Table 2. Data about rated power and energy of the various components are instead reported in Table 1.

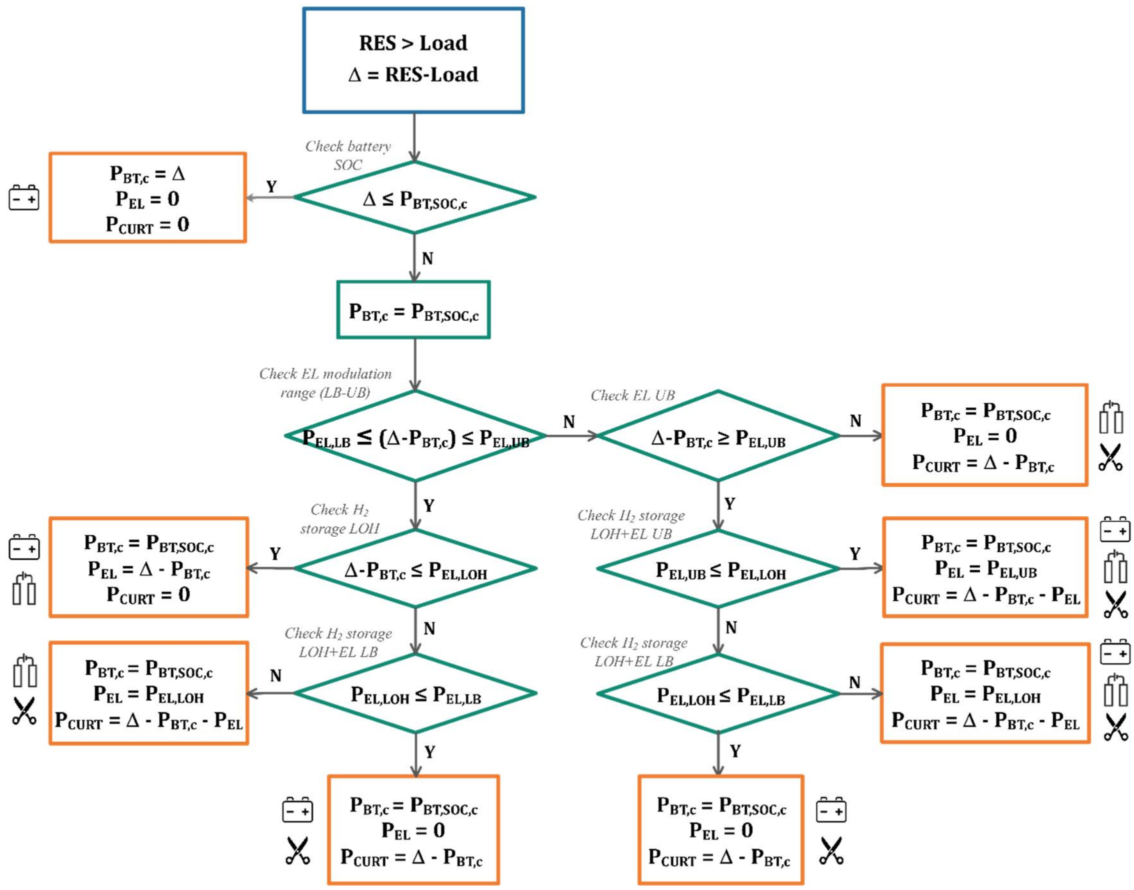

Figure 6. *Logical block diagram for the charging case (RES higher than load).*

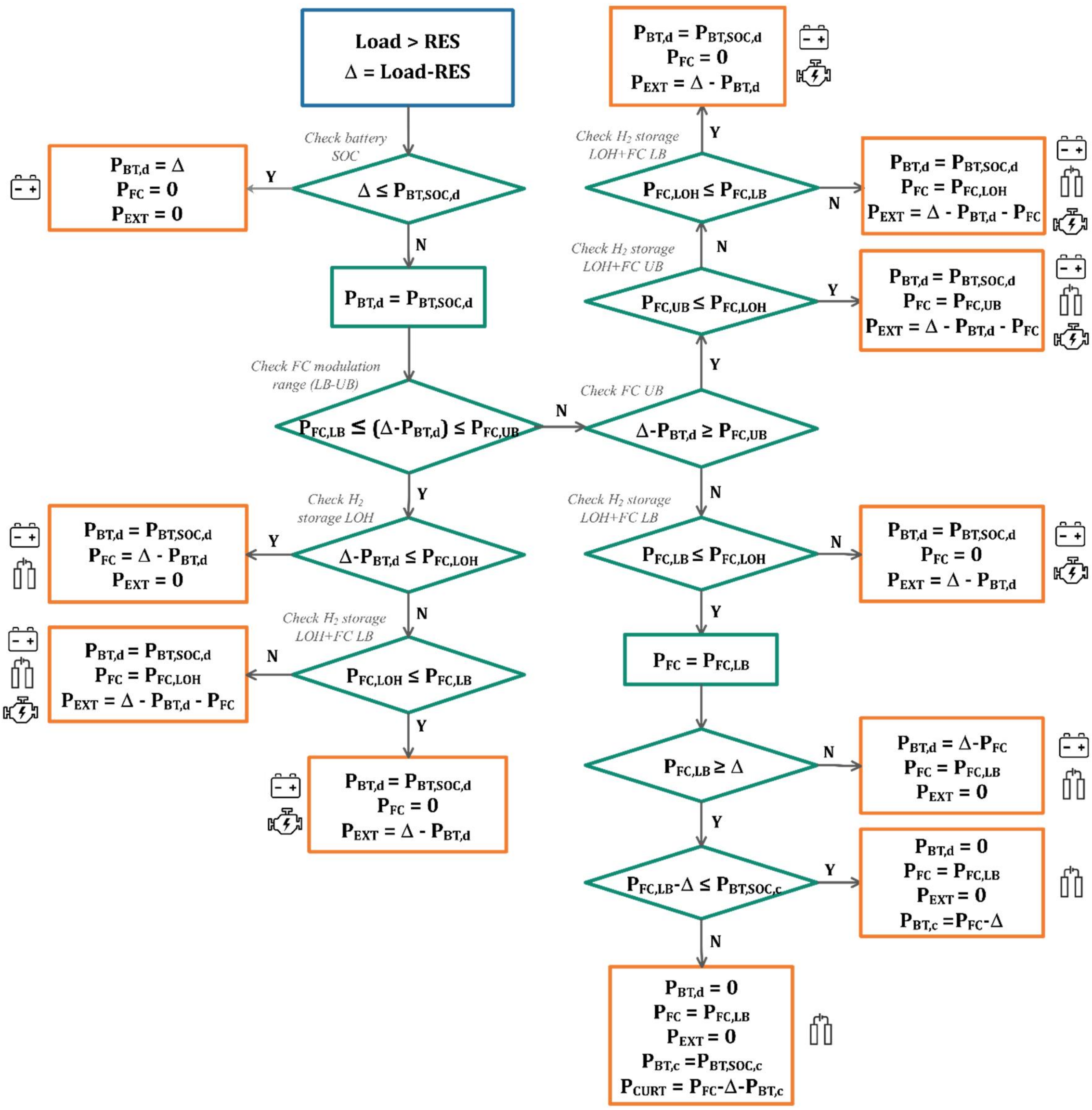

Figure 7. *Logical block diagram for the discharging case (RES lower than load).*

	Demo 1 **Ginostra**	**Demo 2** **Agkistro**	**Demo 3** **Ambornetti**	**Demo 4** **Froan**
		P2G		
System minimum power [42]	10%	10%	10%	10%
Rated system el eff. (HHV, AC current) [42]	70%	70%	70%	68%
		G2P		

Modulation range [43]	0.06-1	0.06-1	0.06-1	0.06-1
Rated system el eff. (LHV, AC current) [42]	45%	45%	45%	45%
Battery				
Charge efficiency [44]	0.92	0.92	0.92	0.92
Discharge efficiency [44]	0.92	0.92	0.92	0.92
SOC limits [44]	0.2-1	0.2-1	0.2-1	0.2-1

Table 2. *Technical input parameters for the EMS analysis.*

3.2 Economic analysis

An economic analysis has been carried out in order to evaluate the economic viability of the configuration with local RES coupled with the H_2-based storage. Three different scenarios were considered and compared in the study:

1) The literature-based RES scenario, corresponding to the renewable P2P solution with costs from literature sources (usually expressed as target data for the technology)
2) The REMOTE-based RES scenario, corresponding to the renewable P2P solution with real costs from the producers involved in the REMOTE project (referring to this case, only the obtained LCOE are reported due to confidentiality issues).
3) Alternative/current scenario, corresponding to the business-as-usual case study, where electricity is provided by diesel generators (for Ginostra and Ambornetti) or by a new cable connection to the national grid (for Agkistro and Froan).

Net present costs (NPC) for the three scenarios were computed as follows:

$$NPC = CAPEX_0 + \sum_{j=1}^{n} \left[\frac{OPEX_j}{(1+d)^j} + \frac{RC_j}{(1+d)^j} \right] \quad (7)$$

Where:

- *n*: analysis period, in years.
- *d*: corrected discount rate (considering an expected inflation rate).
- $CAPEX_0$: capital expenditures (including transport and installation costs) due to investments performed at the beginning of the analysis period (i.e., *j*=0).
- $OPEX_j$: operational and maintenance costs of the system in the *j-th* year.
- *RCj*: replacement costs. They refer to the periodic reinvestment/regeneration to maintain the operation of the system. It includes all related transport and installation costs.

Levelized cost of energy is also defined to calculate unit costs of the NPC divided by the updated energy delivery with the discount rate:

$$\mathrm{LCOE} = \frac{CAPEX_0 + \sum_{j=1}^{n} \left[\frac{OPEX_j}{(1+d)^j} + \frac{RC_j}{(1+d)^j} \right]}{\sum_{j=1}^{n} \frac{\text{Energy delivery}_j}{(1+d)^j}} \quad (8)$$

NPCs and LCOEs were calculated over different time horizons: 5, 10, 15, 20 and 25 years.

The real discount rate *d* was computed as follows:

$$d = \frac{d' - ir}{1 + ir} \quad (9)$$

Where *d'* represents the nominal discount rate; whereas *ir* corresponds to the inflation rate. The *d'* and *ir* terms were assumed to be equal respectively to 7% and 2%, such that the real discount rate is 4.9% [45]. The project partners provided specific data about investment, replacement and operating costs for the REMOTE-based RES scenario. However, due to confidentiality reasons, these details have been omitted from the present work.

The literature-based RES scenario is indeed based on available costs from literature, shown in Table 3. No investment is considered for the hydro plant since already existing.

Component	Investment	Replacement	O&M	Ref.
PV plant	1547 €/kW	80 €/kW (10 y)[1]	24 €/kW/y	[46]
Biomass CHP	6,316 €/kW[3]	245 €/kW (3 y)[2]	0.0333 €/kWh/y + 5.28 €/h[3]	[40]
Wind plant	1,175 €/kW[4]	-	3%/y (of Inv. cost)	[47]
Hydro plant	-	-	20,000 €/y	[38]
PEM fuel cell	Ref. size: 10 kW Ref. specific cost: 3,947 €/kW Cost exponent: 0.7	46% (of Inv. Cost) (5 y)	3%/y (of Inv. cost)	[44], [48], [49]
ALK electrolyzer	Ref. size: 312 kW Ref. specific cost: 2,000 €/kW Cost exponent: 0.7	35% (of Inv. Cost) (9 y)	3%/y (of Inv. cost)	[44], [49]–[51]
PEM electrolyzer	4,600 €/kW[5]	35% (of Inv. Cost) (5 y)	3%/y (of Inv. cost)	[44], [51], [52]
H_2/O_2 storage	470 €/kg	-	2%/y (of Inv. cost)	[51]
Li-ion battery	550 €/kWh	550 €/kWh (10 y)	10 €/kWh/y	[44], [53]
Diesel generator	420 €/kWh	420 €/kWh (16,000 h)	0.4 €/h + 2 €/L[6]	[44]

[1] Replacement cost referred to the inverter component.

[2] Replacement cost referred to the reformer and motor components.

[3] O&M cost referred to the biomass consumption.

[4] Derived from the average of 1000 and 1350 €/kW (upper and lower boundaries of IEA data for different countries) [47].

[5] Derived from [54], considering an electrolyzer rated capacity of 50 kW (the one of Rye/Froan) and converting it into €.

[6] O&M cost referred to the diesel consumption.

Table 3. *Costs of components of the RES + P2P configuration.*

Scale dependencies of costs for the alkaline electrolyzer and PEM fuel cell systems have been considered. In order to evaluate the effect of capacity on purchased equipment cost, the following relationship was employed:

$$cost = \left(\frac{S}{S_{ref}}\right)^n \cdot \frac{cost_{ref} \cdot S_{ref}}{S} \qquad (10)$$

Where *cost* (€/kW) is the specific CAPEX of the equipment and *S* (kW) corresponds to its size. The term $cost_{ref}$ (€/kW) represents instead the specific CAPEX of the same equipment with reference size S_{ref} (kW). The cost exponent *n*- was set equal to 0.7 in agreement with previous studies [47]. As shown in Table 3, a reference specific cost of 2,000 €/kW was considered for the alkaline system with around 300 kW size [50], which is in line with what reported by Proost [54]. Concerning the PEM fuel cell component, the specific investment cost was derived from ref. [48] and the effect of capacity on the equipment cost was computed considering a 10 kW reference size. The values thus obtained are well in accordance with the ones derived from references [55] (after removing the CHP sub-system cost) and [44]. There was no need to apply Equation 10 to the PEM electrolyzer since an investment cost specific to its own rated capacity was found. Li-ion battery cost is not dependent on the size, as shown in ref. [56], but on the C-rate [57]. The cost assumed – 550 €/kWh [8] – is in agreement with the reported cost for energy-designed batteries for stationary storage applications [57]. Overall, all the adopted economic values have been checked and approved by the various project partners.

Concerning the renewable configuration, diesel generators acts as a backup system, which intervenes when no more energy is available from RES and the hybrid storage. The fuel consumption $cons_{DG}$ (in l/h), which depends on the diesel generator output power, was defined as a linear function of its electrical output according to the following equation [58][21]:

$$cons_{DG} = B_{DG} \cdot P_{DG,N} + A_{DG} \cdot P_{DG} \quad (11)$$

Where $P_{DG,N}$ corresponds to the rated power (in kW), P_{DG} is the output power of the diesel generator (in kW), whereas A_{DG} (equal to 0.246 l/kWh) and B_{DG} (equal to 0.08415 l/kWh) are the coefficients of the consumption curve. The hourly cost of the fuel consumption C_{fuel} (in €/h) can be then evaluated as:

$$C_{fuel} = cons_{DG} \cdot cost_{fuel} \quad (12)$$

Where $cost_{fuel}$ is the fuel price (in €/L), whose value is reported in **Errore. L'origine riferimento non è stata trovata.**.

4. Results

4.1 P2P energy management results

Energy balance simulations on a yearly basis have been performed for the demonstration sites 1, 3 and 4 with 1-hour time step by implementing the operation strategy models described in Section 3.1. The hourly profile of RES production and load provided by the end-users of each demo were used. Techno-economic data reported in Table 1, Table **2** and **Errore. L'origine riferimento non è stata trovata.** were adopted. Main results are summarized in Table 4. For Agkistro site, a RES supply failure is instead simulated assuming the storage system at full capacity. The aim is to demonstrate the effectiveness of the H_2-based P2P solution in reducing the usage of external sources (e.g., diesel genset) by maximizing the exploitation of local RES.

	Ginostra		**Ambornetti**		**Froan**	
Load directly covered by RES	81.8 MWh	47.7%	303.9 MWh	87.3%	443.4 MWh	79.0%
Load covered by P2P (battery + H_2)	83.1 MWh	48.4%	44.3 MWh	12.7%	92.2 MWh	16.4%
Load covered by external source	6.7 MWh	3.9%	0 MWh	0%	25.7 MWh	4.6%
Total load	171.5 MWh	100%	348.2 MWh	100 %	561.2 MWh	100%

***Table 4**. Annual load coverage results*

In Ginostra, simulations show that the proposed hybrid P2P solution enables to drastically decrease the use of diesel generators to a value of around 4% of the total yearly demand. When the RES power is not enough to satisfy the load, the shortage is mainly met by the battery (approximately 47%), acting as shorter term storage. The fuel cell instead only accounts for approximately slightly less than 2% of the load; but its presence is required due to its longer term storage capability. The fuel cell is in fact mostly used in the summer period, which is characterized by a higher energy demand because of tourism. This is clearly displayed in Figure 8a, where the hydrogen level within the storage sharply decreases in the period July-August because of fuel cell operation, in concomitance to an increase of the energy deficit (fraction of load not directly met by the PV). It can be seen that the storage tank is quickly filled with hydrogen at the beginning of the year thanks to the conversion of the RES surplus through the electrolyzer. A better exploitation of the local PV source could be achieved by increasing the size of the hydrogen storage (with the chosen P2P configuration around 26% of the yearly available RES is in fact curtailed). In this way the curtailment during the spring period would be reduced because of a greater usage of the electrolyzer with a consequent further reduction of the diesel generation intervention. Unfortunately, it is not possible to further expand the size of the hydrogen storage due to the lack of space in the plant site area.

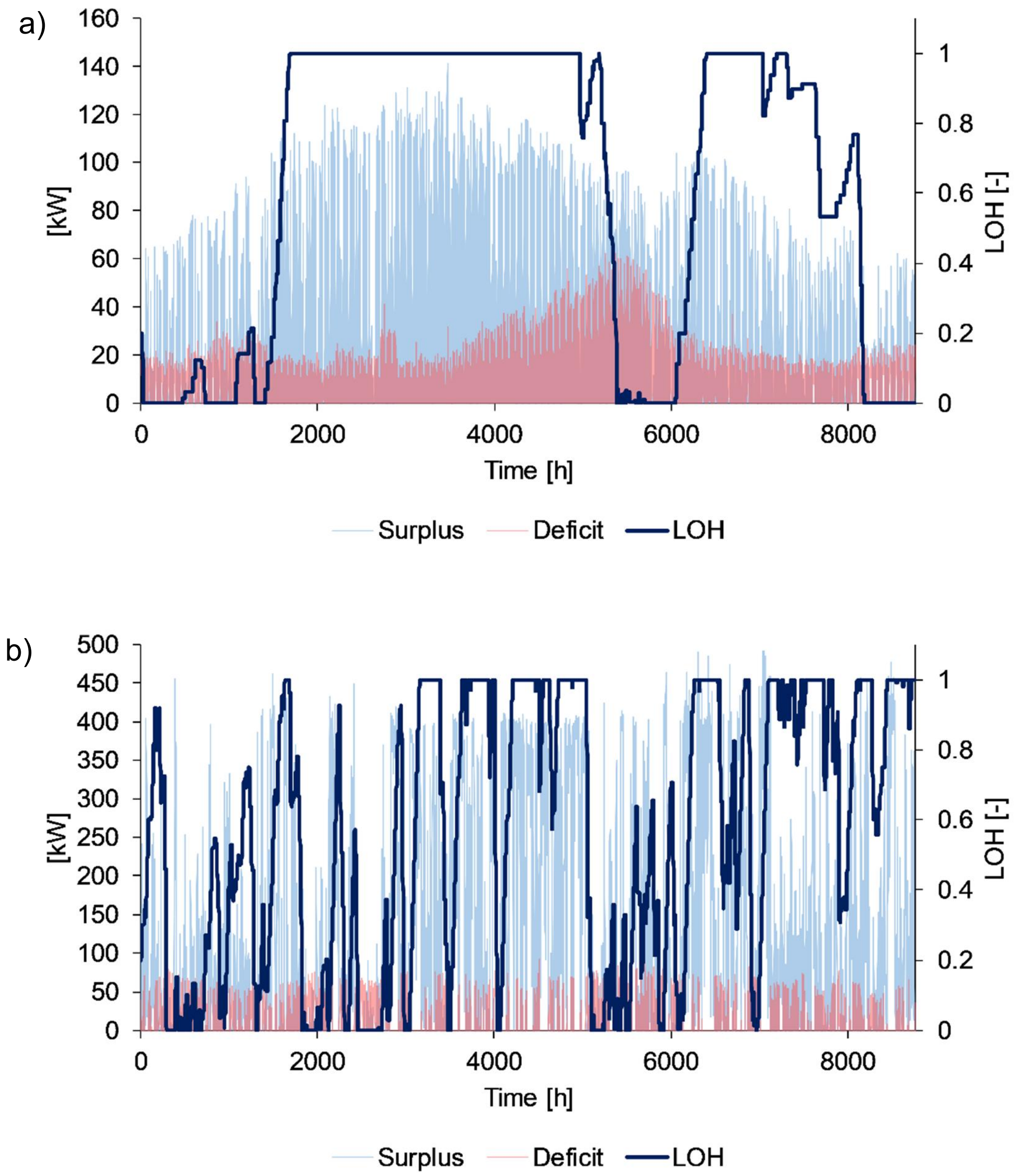

Figure 8. *RES surplus and deficit (x-axis) and LOH (y-axis) along the year for the Ginostra (a) and Froan (b) simulation.*

Regarding the Agkistro demo, since the hydroelectric production is always much higher than the load demand, it is considered that the hybrid storage system is at full capacity all year long. Batteries and hydrogen have a function of back-up in the case of emergency (e.g., RES supply failure or maintenance). Electrical loads of the agri-food building present a seasonal variation. This variability is due to the seasonal use of some mechanical equipment and the summer cooling and winter heating needs. The daily electrical consumption referred to the most demanding working day is approximately 193 kWh. Referring to this load profile and applying the control strategy for the discharging case reported in Figure 7, in case of RES failure (i.e., RES power set equal to zero), the back-up hybrid storage system is found to be able to sustain the energy demand for almost three days, thanks to the H_2 longer-term capability.

In Ambornetti, a June representative day with no maintenance of the CHP biomass device is reported in Figure 9a. The daily RES and load behaviours of any other day with no CHP maintenance present similar trends. As shown in Figure 9c, the biomass system working at rated power together with the PV plant are used to cover the electric load. The battery bank needs also to intervene every day during the morning and evening load peaks when renewable power (i.e., solar plus biomass) is not sufficient alone to satisfy all the electrical demand. The battery SOC is daily regenerated by charging the battery during night (thanks to the excess power production from biomass) and, during the summer months, also in the middle of the day (thanks to the surplus RES power due to the increased PV production).

As displayed in Figure 9d, in the presence of maintenance of the biomass generator, energy within the hydrogen storage system is also required. The battery component in fact quickly reaches its minimum SOC and the fuel cell has to be switched on consuming hydrogen. Figure 9b depicts the level of hydrogen trend along the year: the LOH periodically drops during maintenance of the biomass generator because of the intervention of the PEM fuel cell component.

Solar and biomass sources together with the hybrid storage system were found to be able to completely satisfy the yearly electric demand of the Ambornetti community. Approximately 87.3% of the total load is directly provided by RES. The battery share accounts instead for around 11.1%. Batteries need in fact to intervene of a daily basis during the load increment in the morning and evening. The remaining 1.6% is finally covered by the fuel cell. The hydrogen pathway does not intervene every day; but its function is essential as a backup medium to guarantee energy self-sufficiency during each CHP maintenance interval of 10 hours.

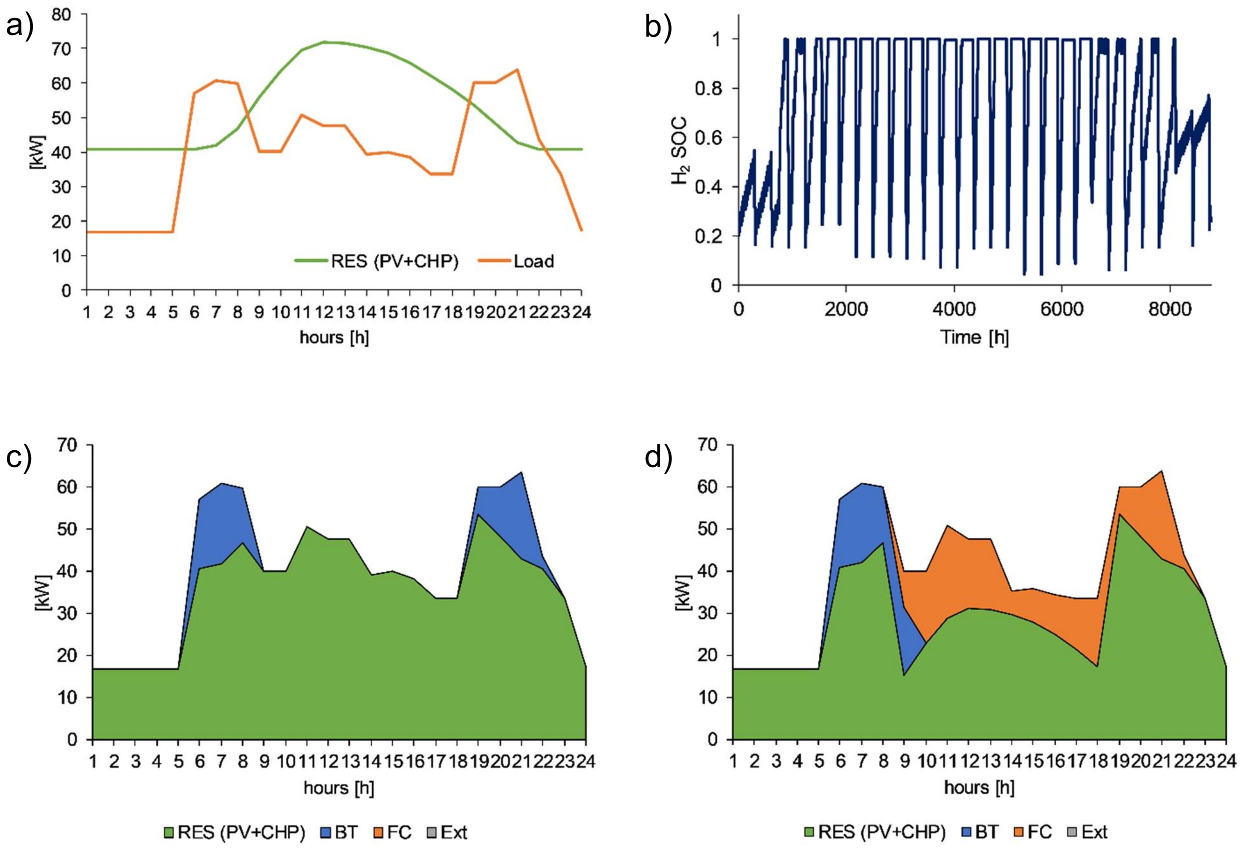

Figure 9. *Ambornetti daily trend of total RES supply and load for a June representative day with CHP (a); LOH along the year (b); load coverage with CHP (c); load coverage with no CHP (d).*

In Froan, local RES coupled with the hydrogen/battery energy storage systems are effective at significantly decreasing the amount of energy required by back-up diesel generator units to a value lower than 5% of the annual load request. Wind and PV plants directly cover approximately 79 % of the total load. Batteries and fuel cells accounts instead for about 11% and 5.4%, respectively. The evolution throughout the year of the amount of hydrogen in the tank is represented in Figure 8b. With respect to the Ginostra case, the fuel cell intervenes more frequently and there is no evident seasonal behavior of the hydrogen level, mainly because of randomness of the wind power. Around half of the annual total available renewable energy is found to be curtailed. It could be thus considered to employ the excess renewable energy for other purposes as well (e.g., hydrogen for local mobility). Further work will also focus on a techno-economic optimization for all the four sites with the aim of evaluating the optimal sizes of the various components, so as to guarantee the total load coverage with the minimum LCOE.

4.2 Economic benefits: cost comparison

Building on the data of the four demo sites, an economic analysis was then performed with the aim of computing LCOE values for the various configurations. For each site the following options are compared to the hydrogen-based one: usage of current diesel generators in Ginostra, connection to the grid in Agkistro, employment of a hypothetic diesel generator set in Ambornetti and replacement of the current sea cable in Froan. Regarding the renewable solution, results in terms of LCOE derived using both economic data from REMOTE partners and from the literature were shown.

Figure 10 shows a graph of the LCOE over different time horizons for each of the four sites. According to the results, a renewable solution is more profitable than the current or alternative one already in the short term for Agkistro, Ambornetti and Froan sites. In Ginostra, instead, the RES + P2P solution becomes economically more attractive in a longer term: after around 15 years, in fact, the LCOE of the configuration based on PV with energy storage becomes lower than the case with only diesel generators.

Concerning the renewable option and considering the case with costs provided by the REMOTE partners, the systems in Ambornetti and Froan present LCOE values at year 20 of around 0.42 and 0.55 €/kWh, respectively. The electricity cost is instead higher for the other two sites: 0.81 €/kWh for Ginostra and up to approximately 1.50 €/kWh for Agkistro. This is mainly due to the high CAPEX of the hydrogen-based energy storage systems, which appear to be less profitable in small systems (i.e., lower electricity demand). The annual load to be covered is in fact around 51, 172, 348 and 561 MWh for Agkistro, Ginostra, Ambornetti and Froan, respectively. Moreover, in Ginostra, the high LCOE is also strongly affected by the expensive costs for equipment transport and installation due to the remote location that can be reached only by helicopter and without the availability of heavy-duty vehicles.

Referring to the same configuration, LCOE results derived by employing cost data from literature sources are a bit lower, with an increase of the discrepancy by reducing the considered investment horizon. This LCOE difference is due to a general slight underestimation of the component costs taken from the literature, in particular of the hydrogen technology which has not yet been fully established and commercialized with a consequent high variability in the production costs. Indeed, since the demos of the project are the first units of this type to be deployed, they suffer higher assembly costs and other costs related to the not completely optimized BoPs. Moreover, costs referred to transport and installation of the various equipment can become relevant for remote locations and differ from site to site. This contribution is thus difficult to properly quantify from the literature.

Regarding the current/alternative solution (i.e., orange curves of Figure 10), it is observed a steep decrease in LCOE with investment horizon for Agkistro and Froan sites due to the relevant contribution of the initial investment (i.e., $CAPEX_0$) for connection to the grid. In Ambornetti and Ginostra, instead, the solutions with diesel generators present very large OPEX, causing the LCOE to be more constant in all investment horizons. Costs related to the usage of diesel generators are in fact mostly due to operational expenses caused by the consumption of fossil fuel, whose cost is high due to transportation and logistics issues in remote locations (a specific consumption cost of 2 €/L was in fact supposed [44], in accordance also with project partner's knowledge).

Figure 11 shows the various items contributing to the LCOE, considering the 20-year time horizon. It can be seen that the hybrid energy storage system, i.e., battery plus hydrogen (electrolyzer, gas storage tank and fuel cell), represents a relevant share of the total electricity cost, mainly because of the high H_2 equipment cost. However, as shown in Section 4.1, the presence of an energy storage solution is required for a better exploitation of local renewable sources and hydrogen becomes useful for its higher energy capacity, even though batteries contribute most to the load coverage. The role of hydrogen was also investigated in Ref. [59], where a techno-economic optimization was performed for the Ginostra site analysing different technology combinations. When no diesel generator is available for technology mix, energy storage hybridization (i.e., battery plus hydrogen) resulted in the lowest LCOE, compared to the case with only battery and only hydrogen. In particular, hydrogen was shown to be useful as a seasonal energy storage providing power mainly in the summer period during which an increased electricity demand occurs due to tourism (as visible in Figure 3). Hydrogen appears thus to be helpful to store energy over a longer period of time and avoiding the over-dimensioning of batteries.

It should also be noted that possible local utilization of by-products from H_2-based devices operation, such as heat and oxygen, has not been taken into account in the present economic analysis. In the Froan islands, as an example, the oxygen produced by the electrolyzer could be employed in local fish farms, thus increasing the potential income of the RES + hybrid-P2P configuration. Moreover, environmental advantages are also linked to these types of hybrid energy storage systems since they represent an interesting low carbon alternative to the usage of traditional fossil fuels. Indeed, the economic evaluation of emissions reduction would improve further the results for RES scenarios.

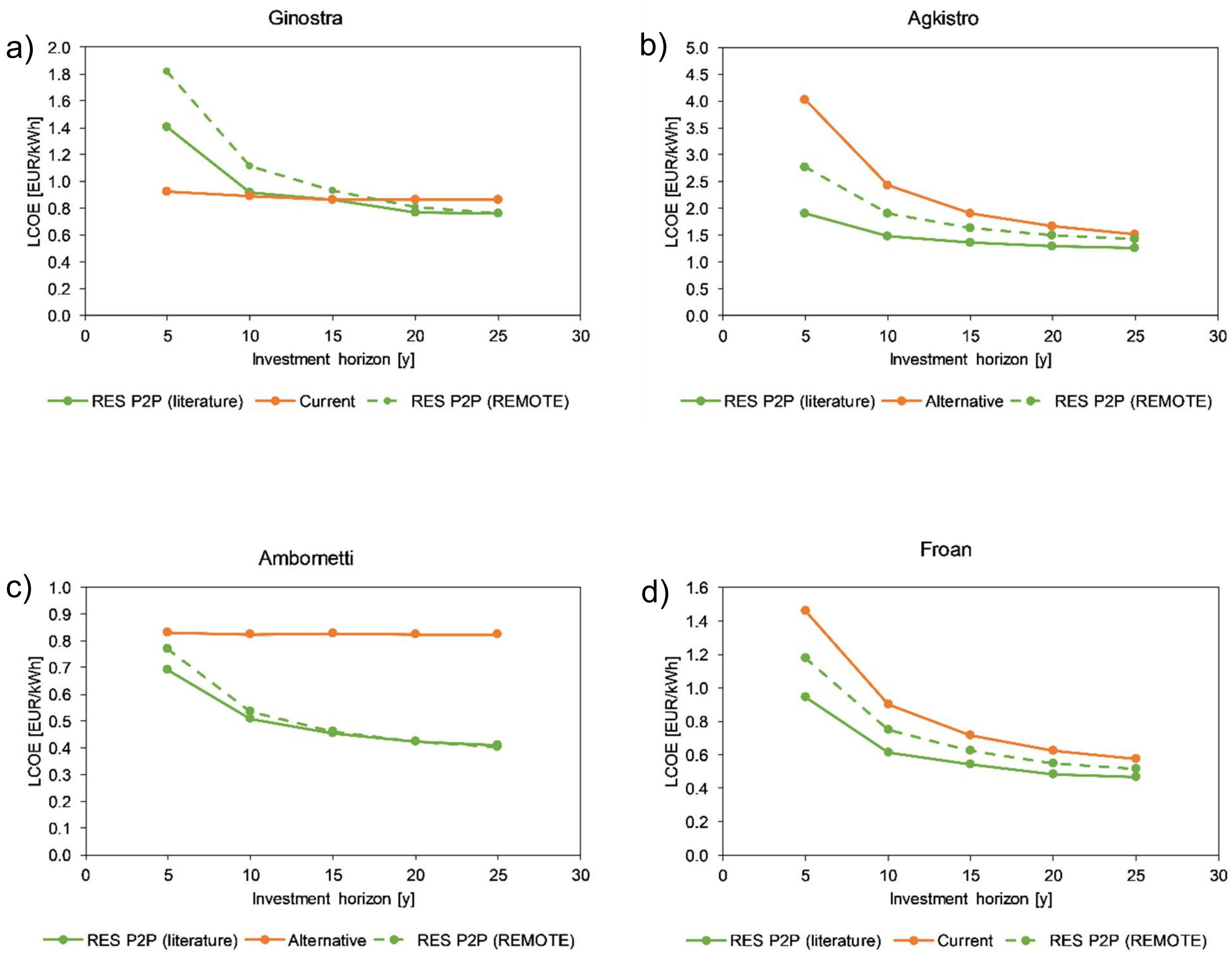

Figure 10. *LCOE for the current/alternative and suggested RES + P2P solution for Ginostra (a), Agkistro (b), Ambornetti (c) and Froan (d)*

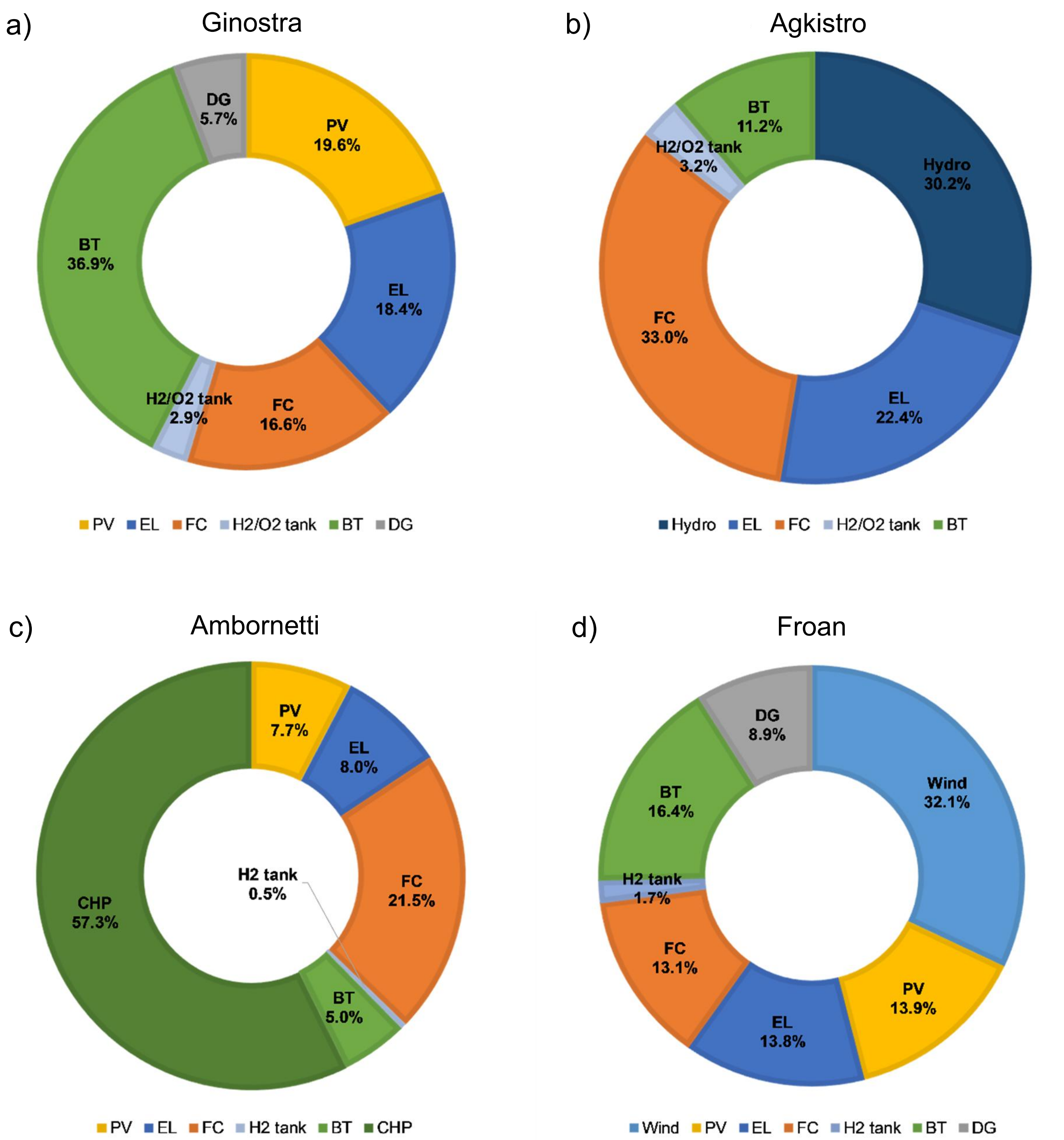

Figure 11. *Contributions to the LCOE at 20 years for Ginostra (a), Agkistro (b), Ambornetti (c) and Froan (d)*

Conclusion

A techno-economic analysis has been performed for the four demos. Energy balance simulations over a reference year with 1-hour time step were carried out after defining an energy management strategy for the hybrid P2P system. Local RES coupled with a hybrid battery-H_2 storage system were shown to allow to significantly reduce or even eliminate the usage of fossil-based power generation. In Ginostra, the renewable configuration enables to decrease the operation of current diesel generators to less than 4% of the total electrical demand of the local community. In Froan, only around 4.6% of the overall annual load has to be supplied by diesel genset. A completely energy autonomy was found to be possible in Ambornetti thanks to the exploitation of local solar and biomass sources. Finally, in Agkistro, the P2P configuration was verified to be effective as a backup solution, guaranteeing almost three days of energy autonomy in case of emergency or maintenance of the hydro plant. Generally, the hydrogen solution is useful for its longer-term storage capability intervening mainly during maintenance, emergency or periods of the year with a higher electrical demand. An economic analysis was then performed for a comparison between the innovative configuration (using costs both from literature sources and REMOTE partners) and the current/alternative one in terms of LCOE. For all the considered demo sites, the exploitation of local renewables together with the adoption of a hybrid P2P system was proved to be more cost effective than traditional options either in the short or longer term. Outcomes of these simulations have thus shown the usefulness and economic viability of P2P systems located in remote stand-alone micro-grid areas. Environmental benefits such as reduced CO_2 emission due to the lower diesel generator share and avoidance of invasive works because of grid connections have to be considered as well. It is also important to note that demonstration systems developed within the REMOTE project do not represent mass produced units. Their costs are thus expected to decrease with further development of hydrogen technologies and their market diffusion, making P2P systems increasingly more attractive.

Acknowledgement

This project has received funding from the Fuel Cells and Hydrogen 2 Joint Undertaking under grant agreement No 779541. This Joint Undertaking receives support from the European Union's Horizon 2020 research and innovation programme, Hydrogen Europe and Hydrogen Europe research.

The authors want to thanks the REMOTE project partners for their contributions in terms of input data for the modelling. In particular, we would like to thank the demonstration sites end users (Enel Green Power for Ginostra, Horizon SA for Agkistro, IRIS srl for Ambornetti and Trønder Energi for Froan) and the power-to-power systems developers (ENGIE EPS Elvi Energy, Ballard Power Systems Europe, Hydrogenics and Powidian).

Nomenclature

Symbols:

C_{BT}	Battery capacity (kWh)
C_{H2}	Hydrogen storage capacity (kWh)
$P_{BT,c}$	Battery charging power (kW)
$P_{BT,d}$	Battery discharging power (kW)
$P_{BT,SOC,c}$	Maximum battery charging power which allows not to go above the upper battery SOC (kW)
$P_{BT,SOC,d}$	Maximum battery discharging power which allows not to go below the lower battery SOC (kW)
P_{CURT}	Curtailed power (kW)
P_{DG}	Diesel generator power (kW)
$P_{DG,N}$	Diesel generator rated power (kW)

P_{EL}	Electrolyzer power (kW)
$P_{EL,LB}$	Minimum electrolyzer power (kW)
$P_{EL,SOC}$	Maximum electrolyzer power which allows not to go above the upper H_2 storage SOC (kW)
$P_{EL,UB}$	Maximum electrolyzer power (kW)
P_{FC}	Fuel cell power (kW)
$P_{FC,LB}$	Minimum fuel cell power (kW)
$P_{FC,SOC}$	Maximum fuel cell power which allows not to go below the lower H_2 storage SOC (kW)
$P_{FC,UB}$	Maximum fuel cell power (kW)
P_{EXT}	Power provided by an external source (grid, engine or others) (kW)
$\eta_{BT,c}$	Efficiency of the battery charging
$\eta_{BT,d}$	Efficiency of the battery discharging

Acronyms and abbreviations:

ALKE	Alkaline Electrolyzer
BPSE	Ballard Power System Europe
BT	Battery
CAPEX	Capital Expenditure
CHP	Combined Heat and Power
DG	Diesel Generator
EGP	Enel Green Power
EL	Electrolyzer
EMS	Energy Management Strategy
EPS	Electro Power System
FC	Fuel Cell

G2P	Gas-to-Power
HOR	Horizon SA
HYG	Hydrogenics Europe
LHV	Lower Heating Value
LOH	Level Of Hydrogen
NPC	Net Present Cost
OPEX	Operational Expenditure
PEM	Proton Exchange Membrane
PEME	Proton Exchange Membrane Electrolyzer
PEMFC	Proton Exchange Membrane Fuel Cell
POW	Powidian
PV	Photovoltaic
P2G	Power-to-Gas
P2P	Power-to-Power
RC	Replacement Cost
RES	Renewable Energy Source
SOC	State Of Charge
TREN	TrønderEnergi

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