P03003

REMOTE project: techno-economic analysis of H2-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 provide a reliable, cost-effective and decarbonized alternative to on-site electricity generation through diesel engines.

In this context, the EU REMOTE project aims at demonstrating the technical and economic feasibility of H_2-based energy storage solutions in remote locations: four demonstration sites have been selected in four different locations across Europe. According to the site, different RES sources are exploited: solar, wind, biomass or hydro. Their usage is optimized thanks to the operation of an H_2-based Power-To-Power (P2P) technology. In fact, surplus RES energy can be supplied to the electrolyzer for H_2 production. The fuel cell is then employed to generate electricity back during renewable power shortages. A battery bank is also adopted as complementary shorter-term electricity energy buffer. A centralized controller on-site will perform the management of the whole hybrid EES.

The aim of this study is to develop a preliminary 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 is compared with the current/alternative one. Main input data for the analysis were provided by the REMOTE project partners: techno-economic data from the technology suppliers, whereas electricity consumption and RES production values from the end users of the four isolated locations. Results from preliminary energy simulations revealed that the need for an external source is significantly reduced thanks to RES coupled with the hybrid storage system. Moreover, for all DEMOs 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.

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]-[3]. Hydrogen, in particular, can represent an interesting storage solution because of its high energy density and long-term storage capability [4].
Concerning off-grid and micro-grid environments, diesel engines are the dominant technology for electricity generation with more than 23 GW of installed capacity [5], mostly in island and large territorial states, despite the related high production costs and pollution problems [6]. Exploiting local renewable energy could be an alternative. 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 can become an interesting choice [7]-[8] providing a reliable, cost-effective and decarbonized alternative to the common on-site electricity generation through diesel engines [9].
The presented work is performed within 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 [10]. REMOTE objective is to demonstrate the techno-economic feasibility of hydrogen-based energy storage solutions in isolated micro-grids and off-grids remote areas, in the 5-200 kW range of fuel cell power [11]. As shown in Figure 1a, four DEMOs will be installed in four different locations across Europe: Ginostra (South of Italy), Agkistro (Greece), Ambornetti (North of Italy) and Froan Islands (Norway). The last DEMO will be temporarily host in the mainland in Rye (Norway) for a 2-year testing period before being moved to Froan. Each installation will complement locally available RES (i.e., solar, wind, biomass or hydro) with a hybrid energy storage system based on hydrogen and batteries, as schematically reported in Figure 1b. Stationary batteries are in fact commonly used to store energy on daily basis smoothing down the RES high-frequency variability [12]. However, when the energy storage is required for a longer period, batteries become expensive and the integration with H_2-Power-To-Power (P2P) systems with medium/long-term capabilities can be a viable and reliable option [13]. The adoption of a proper Energy Management Strategy (EMS) is thus essential for a correct interaction of the various sub-systems with the aim of achieving good energetic and economic performances [14]. 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). During the course of the project, data from real-life experience will be made available giving the possibility to define specific control strategies for each DEMO and providing valuable information for the system modeling. The variety of the involved DEMO cases will allow to gain significant learning from integration with existing infrastructure in real sites paving the way for the deployment of the P2P storage system at large scale.
The aim of this study is to define the use cases of the four DEMOs, analyzing the technical solution proposed for each DEMO in order to evaluate how to improve the local situation. The various demonstration sites are described and the main technical data of the innovative RES + hybrid P2P system are presented. Preliminary energy simulations are carried out to demonstrate the effectiveness of the hybrid energy storage solution in reducing the usage of external sources (e.g., diesel engines). Finally, potential economic benefits are outlined comparing costs for the current or alternative and the suggested renewable solutions.

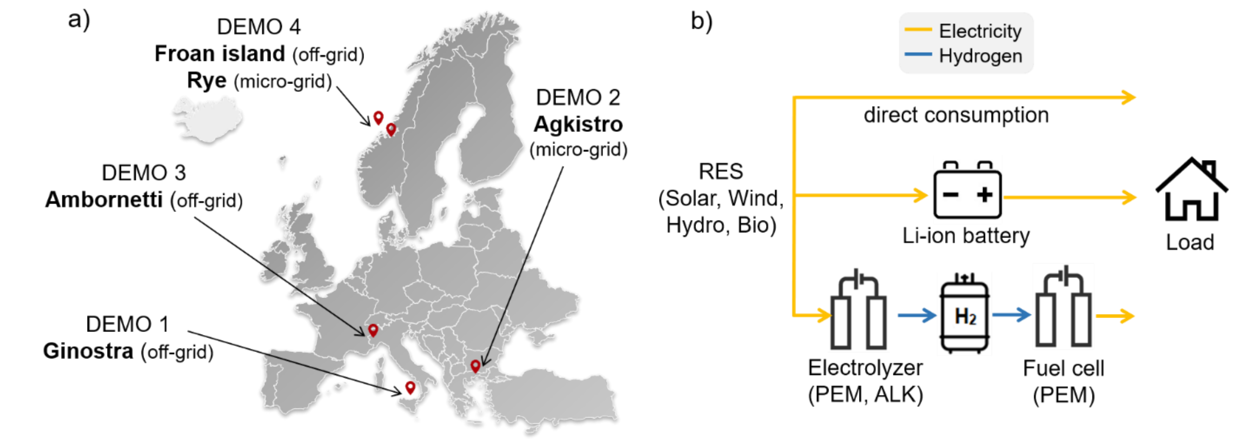

Figure 1. *a) Geographical location of the four demonstration sites. b) Operational sketch of the P2P system with H2 and batteries as energy storage mediums*

1. DEMO's description

A summary of the main components involved in the suggested innovative solution for each DEMO is reported in Table 1.

		1. Ginostra	**2. Agkistro**	**3. Ambornetti**	**4. Rye**
RES	Typology	PV	Hydro	PV + Biomass	PV + Wind
	Size	170 kW	0.9 MW	75 kW PV 49 kW Biomass	85 kW PV 225 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	25 kW	18 kW	55 kW
	G2P				
	Technology	PEM	PEM	PEM	PEM
	Rated Power	50 kW	50 kW	85 kW	100 kW
	H_2 storage				
	Gross energy (LHV)	1793 kWh	996 kWh	498 kWh	3333 kWh
	Battery				
	Technology	Li-ion	Li-ion	Li-ion	Li-ion
	Rated energy	600 kWh	92 kWh	92 kWh	550 kWh

Table 1. *Components of the RES+H_2-based storage solution*

1.1 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) [15] 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 and 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 Systems (EPS) [16]. 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. 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 171.6 MWh. The new PV power plant is estimated to produce yearly about 273.2 MWh. Analyzing the hourly PV estimated energy production and load profiles along the year, it was seen that only slightly less than one third of the overall annual energy from PV, i.e., 82.4 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 RES energy to use when a renewable energy deficit occurs, thus reducing or even avoiding the intervention of the diesel generator.

1.2 DEMO 2: Agkistro

Agkistro is a remote village situated in Serres region, North Greece closed to Bulgaria. At the DEMO site there is a hydroelectric plant, which is owned by Horizon SA (HOR) [17], with connection to the grid to sell the produced electricity. HOR company, which is the DEMO 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 case of grid connection, besides the expensive and invasive work due to 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 with no 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 and 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 DEMO benefits from continuous availability of renewable

source (hydro plant). Two fuel cell units of 25 kW 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 3166 MWh, whereas the total yearly electrical energy required by the new facility is estimated to be approximately 87 MWh. In a framework with high RES electricity generation and quite predictable and stable DEMO load, the P2P system is thus conceived as a backup unit in case of emergency or scheduled hydro plant downtime due to maintenance.

1.3 DEMO 3: Ambornetti

The mountain hamlet Ambornetti is an off-grid site located in North Italy, Piedmont. 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 lead by IRIS [18], 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 and 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 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 approximately 41 kW of electric power (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 Ballard Power Systems Europe (BPSE) [19] 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 349 MWh. 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. 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.

1.4 DEMO 4: Froan/Rye

Froan is an archipelago of four islands located off the west coast of Norway, near 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 [20]. Since the cable is outdated, there is the urgency to replace it or consider other alternatives.
The exploitation of local RES sources, i.e., solar and wind, together with a H_2-battery storage system has been chosen as a solution. 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 and 3) learning from the H_2-based system operation in Nordic countries climate and evaluating whether to propose it to other remote areas.

The complete P2P system will be validated and tested at Rye on the mainland first, before shipping it to Froan. The farm site in Rye will be supplied by a 225 kW wind turbine and a 85 kW PV power plant. A non-integrated P2P solution with a 55 kW air-fed PEM electrolyzer from Hydrogenics (HYG) [21] and a 100 kW PEM fuel cell from BPSE has been considered. The hydrogen storage tank has about 100 kg of hydrogen capacity and is provided by Powidian (POW) [22]. 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. Regarding the Froan site, the technical sizing of the RES and storage systems is still ongoing and depends on authorization issues.
The annual electrical consumption at Rye is about 126.8 MW. Concerning the wind and solar yearly production, around 209.7 MWh and 74.9 MWh have been estimated, respectively. The analysis of PV/wind production and load hourly profiles shows that about 81.6 MWh of the total RES production (i.e., PV + wind) are directly used to cover the farm load. The high amount of surplus RES energy can be thus stored through batteries and hydrogen and later used during the occurrence of energy shortages so as to maximize local solar and wind energy exploitation.

2. Method

2.1 Control strategy

A preliminary energy management strategy for the hybrid storage system has been defined in order to perform energy simulations (on yearly basis with 1-hour time step) and prove the usefulness of the proposed RES plus P2P solution in covering the electrical end-use demand. The 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.
The State Of Charge (SOC) of the battery (SOC_{bat}) represents the main key decision factor for the EMS. The maximum and minimum battery SOC levels ($SOC_{max,bat}$ and $SOC_{min,bat}$, respectively) are considered as indicators to evaluate when switching on/off the fuel cell and the electrolyzer. When the battery 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 SOC_{bat} has reached its maximum allowed level, the electrolyzer is switched on to convert the surplus RES energy into hydrogen. By contrast, during discharging (RES power lower than the load demand), the fuel cell is employed in order not to allow the battery SOC to go below $SOC_{min,bat}$. Information about the hydrogen SOC 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 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 SOC limits.

2.2 Economic analysis

Building on the data of the four DEMO sites, an economic analysis has been carried out in order to evaluate the economic viability of the scenario with RES coupled with H_2-based storage. Net present costs (NPC) for the current or alternative and renewable solutions were thus computed as follows:

$$NPC = \sum_{i=1}^{n}\left[\frac{\mathrm{CAPEX}_i}{(1+d)^i}+\frac{\mathrm{OPEX}_i}{(1+d)^i}+\frac{\mathrm{RC}_i}{(1+d)^i}\right]$$

Where:

- n: analysis period, in years.
- d: corrected discount (considering an expected inflation rate).
- CAPEX_i: capital expenditures (including transport and installation costs) due to investments in the system in year i. It refers to the investment costs at the beginning of the strategic periods (for the first period $i = 1$).
- OPEX_i: operational and maintenance costs of the system in year i.
- RC_i: regeneration 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 (LCOE) is also defined to calculate unit costs of the NPC divided by the updated energy delivery with the discount rate:

$$\mathrm{LCOE} = \frac{\sum_{i=1}^{n}\left[\frac{\mathrm{CAPEX}_i}{(1+d)^i}+\frac{\mathrm{OPEX}_i}{(1+d)^i}+\frac{\mathrm{RC}_i}{(1+d)^i}\right]}{\sum_{i=1}^{n}\frac{\text{Energy delivery}_i}{(1+d)^i}}$$

NPCs and LCOEs were calculated over different time horizons: 10, 20, 25 and 30 years. The nominal discount rate was set equal to 7%. It was adjusted assuming an expected inflation rate of 2%, such that the real discount rate is 4.9%. Specific data about investment, replacement and operating costs were provided by the project partners.

3. Results

3.1 Energy simulation

Energy balance simulations on a yearly basis have been performed for DEMOs 1, 3 and 4 by implementing the operation strategy models described in Section 2.1. The hourly profile of RES production and load provided by the end-users of each DEMO were used. Main results are summarized in Table 2. For Agkistro site, a RES supply failure is instead simulated assuming the storage system at full capacity. Nominal values for equipment sizes and efficiencies from the technology suppliers were considered. 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.

In Ginostra, simulations show that the proposed hybrid P2P solution enables to drastically decrease the use of current operating diesel generators to a value of around 4.4% 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 44.3%), acting as shorter term storage. The fuel cell instead only accounts for approximately 3.5% of the load; but its presence is required due to its longer term storage capability. The fuel cell is in fact mainly used in the summer period, which is characterized by a higher energy demand because of tourism. Figure 2a shows the hydrogen level within the storage to be sharply reduced in summer because of fuel cell operation.

Regarding Agkistro site, 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. During winter and summer, the daily load required by the facility is around 400 kWh. During autumn and spring, instead, when there are no heating and cooling needs, the load demand to be covered each day is lower, approximately 170 kWh. Applying the control strategy for the discharging case previously reported, in case of RES failure (i.e., RES power set equal to zero), the storage system is found to be able to sustain the energy demand for slightly more than one day in the summer and winter period and for almost three days for the rest of the year.

In Ambornetti, considering a reference day (i.e., no biomass device maintenance) 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 daily 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. Instead, 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. The fuel cell intervention is clearly shown in Figure 2b, where the H2 SOC periodically drops during maintenance of the biomass generator. Approximately 87.1% of the total load is directly provided by RES. The battery share accounts instead for around 11.7%. Batteries need in fact to operate on a daily basis during the load increment in the morning and evening. The remaining 1.2% 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 the periodic maintenance of the biomass plant.

In Rye, local RES coupled with the hydrogen/battery energy storage systems are effective at significantly decreasing the amount of energy required from external sources (e.g. fossil fuel generators or the grid) to a value lower than 5% of the annual load request. Wind and PV plants directly cover approximately 61.2 % of the total load. Batteries and fuel cells accounts instead for about 25.9% and 8.4%, respectively. The evolution throughout the year of the amount of hydrogen in the tank is represented in Figure 2c: the higher energy deficit in the first part of the year causes the hydrogen level to stay around low values. The reduced deficit in the summer period, together with a high surplus of RES energy, allows to fill the H2 storage, which is then gradually emptied in the second part of the year where an increase of the deficit occurs.

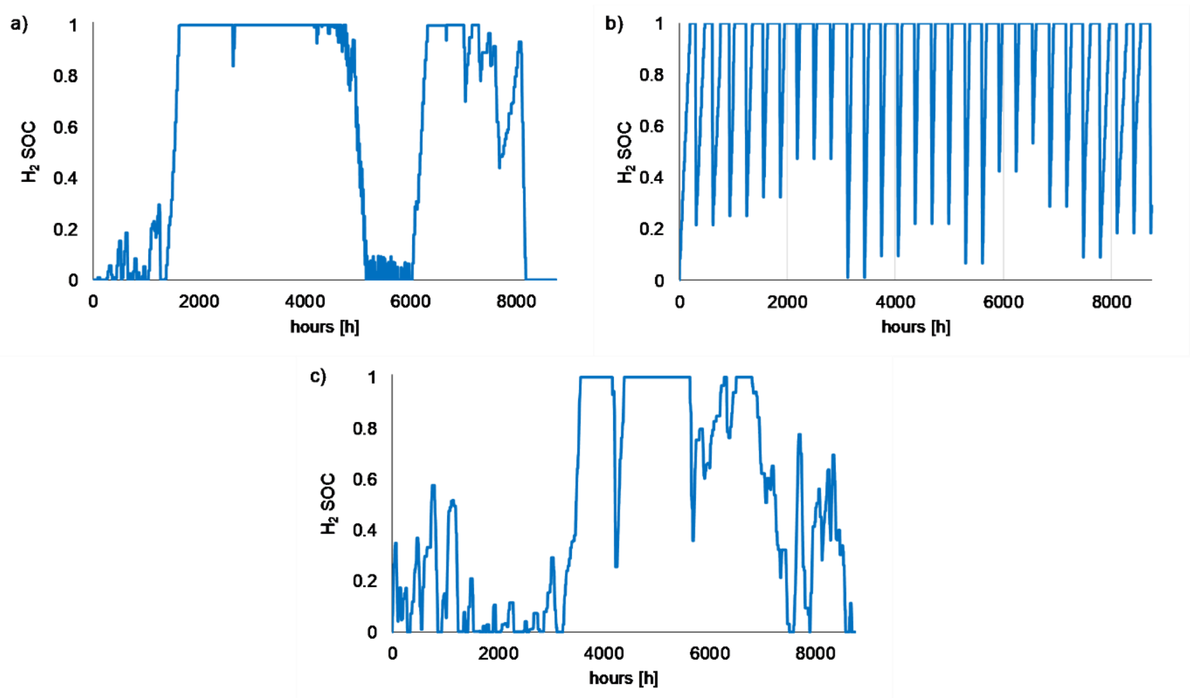

Figure 2. *H_2 state of charge over the year for a) Ginostra, b) Ambornetti and c) Rye*

	DEMO 1		DEMO 3		DEMO 4	
Load directly covered by RES	82.0 MWh	47.8%	303.9 MWh	87.1%	77.6 MWh	61.2%
Load covered by P2P (battery + H_2)	82.0 MWh	47.8%	45.1 MWh	12.9%	43.5 MWh	34.3%
Load covered by external source	7.6 MWh	4.4%	0 MWh	0%	5.7 MWh	4.5%
Total load	171.6 MWh	100%	349 MWh	100 %	126.8 MWh	100%

Table 2. *Annual load coverage results*

3.2 Economic simulation

Regarding the economic analysis, 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. Figure 3 reports the LCOE values for each of the four DEMOs over different time horizons. According to the results, a renewable solution is more profitable than the current or alternative solution, either at short term (e.g., in Agkistro and Froan) or in the longer term (e.g., in Ginostra and Ambornetti where it is after around 10 and 20 years respectively when the RES solution yields lower NPC and LCOE). Concerning the RES configuration, the systems in Agkistro and Froan show values in the range 300-500 €/MWh (Froan is the largest demo and in Agkistro RES is available and thus investment costs are lower); whereas the LCOE is larger in the smaller demos of Ginostra and Ambornetti, between 700 and 1,100 €/MWh depending on the case and investment horizon. In particular, in Ginostra, the LCOE is strongly affected by the high costs for equipment transport and installation due to the remote location that can be reached only by helicopter and without the availability of heavy-work vehicles. It is also observed a steeper decrease in LCOE with investment horizon in the cases with grid connection due to the larger importance of the CAPEX; whereas in Ambornetti and Ginostra the solutions with diesel generators, which are characterized by large OPEX, cause the LCOE to be more constant in all investment horizons.

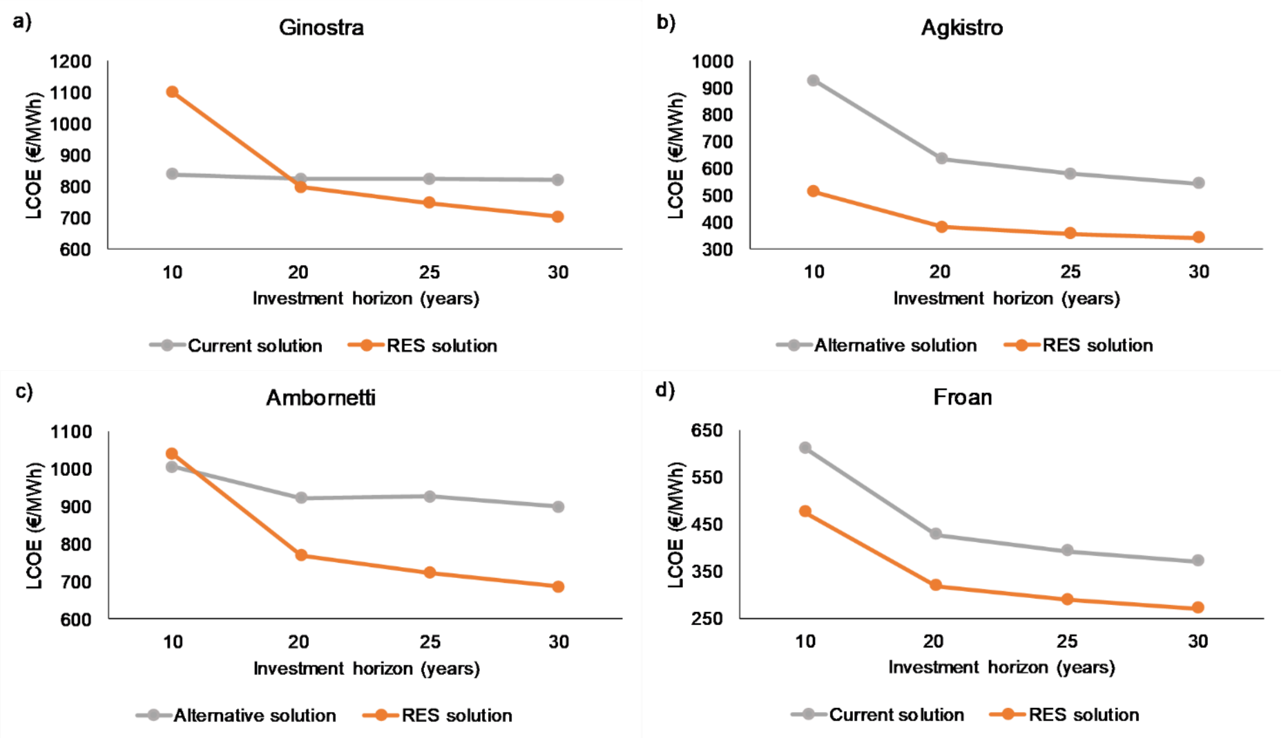

Figure 3. *LCOE values for the current/alternative solution and RES solution for the four DEMO cases of the project, (a) Ginostra, (b) Agkistro, (c) Ambornetti and (d) Froan.*

4. Conclusions

A preliminary EMS for the hybrid P2P system was developed in order to perform energy balance simulations over a reference year with 1 hour time step. Local RES coupled with a battery-H_2 storage system were shown to allow to significantly reduce or even eliminate the usage of external sources. In Ginostra, the renewable configuration enables to decrease the operation of current diesel generators to less than 5% of the total electrical demand of the local community. In Rye, only around 4.5% of the overall annual load has to be supplied by an external source. 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 1-3 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. A preliminary economic analysis was also performed for a comparison between the innovative configuration and the current/alternative one in terms of LCOE. For all the considered DEMOs, the exploitation of local renewables together with the adoption of a P2P system was proved to be more cost effective than traditional options either in the short or longer term. Outcomes of these preliminary simulations have thus shown the usefulness and economic viability of P2P systems. More detailed and refined results will be derived during the project, taking also advantage of real data from operation of the proposed storage solutions.

Acknowledgment

This project has received funding from the Fuel Cells and Hydrogen 2 Joint Undertaking under grant agreement N°779541. This Joint Undertaking receives support from the

European Union's Horizon 2020 research and innovation programme, Hydrogen Europe and Hydrogen Europe research.

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