REMOTE

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"Remote area Energy supply with Multiple Options for integrated hydrogen-based TEchnologies"

Deliverable number 2.2

Technical specification of the technological demonstrators

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Abstract:

This work described the activities performed in the framework of the Task 2.2 "HOW to improve the local situations: detailed technical specification of the four demonstrators".
Following the analysis of the local technical (end users, loads, RES availability), economic and regulatory context (described in Deliverable D2.1 "Analysis of the economic and regulatory framework of the technological demonstrators"), Task T2.2 had the aim of defining the technological specifications of each DEMO. The analysis is started from the benchmark analysis of every isolated micro-grids (detailed information on the system operation before the deployment of the new storage system), then considering the single situation:
- isolated micro grid or off-grid application,
- urban or rural application,
- type of renewable sources locally available,
- typology of end users,
- type of loads (electrical),
- amount and time distribution of the loads,
These data have been deeply analysed to clearly define the technical details of the optimized storage solution. The outcomes are the specific technical parameters of each demonstrator: according to the specific features of each DEMO site, a dedicated sizing strategy has been defined and verified. Outputs of a first-level operation strategy model, developed in Matlab®, are shown to justify the sizes of the DEMOs.

Keyword list:

Storage, hydrogen, fuel cell, electrolyser, modelling, sizing strategy, operation strategy

Contents

1. Introduction

The main objective of WP2 is to define the use cases of the 4 DEMOs. After a preliminary analysis of the economic and regulatory framework of the four demonstrators carried out in Task T2.1 (Analyses of the economic and regulatory framework for the four demonstrators), the main objective of Task T2.2 is to analyse the technical solution proposed for each DEMO to evaluate how to improve the local situation.

Figure 1. Geographical location of the four DEMOs.

1.1 Configuration of the hybrid power/storage system

Possible layouts of the hybrid power systems under analysis are shown in Figure 2 and Figure 3. According to the location, different renewable energy sources are exploited: solar, wind, biomass, or water fall. They are converted into electricity to meet the energy demand of a specific load. Surplus energy can be used to charge the battery or can be supplied to an electrolyser for hydrogen production (energy storage in form of a chemical). Hydrogen is then stored in a pressurized container and, when needed, sent to a fuel cell for electricity generation. Therefore, in case of lack of energy from the Renewable Energy Source (RES), the remaining energy fraction to satisfy the load can be provided by the fuel cell through hydrogen consumption or by discharging the battery device.

The battery bank is used to provide electricity for the daily operation of the control unit and auxiliary equipment. It can be also employed (e.g. in the case of Ginostra and Rye/Froan sites) as a daily electricity energy buffer, smoothing the RES output and reducing the intermittency. Maximum and minimum battery State of Charge (SOC) need to be considered: overcharging/discharging should in fact be controlled to protect the battery from being damaged [1]. The hydrogen tank level has to lie in a specific range for a correct operation as well: minimum pressure (to overcome downstream pressure drops) and maximum pressure (for safety reasons) need to be carefully selected. Also electrochemical devices have to stay within specific boundaries for a safe and efficient operation. Working outside the proper operating range leads in fact to a reduced efficiency (moreover low partial loads can cause an enhancement of the gas cross-diffusion effect through the diaphragm for alkaline electrolyzers). Upper and lower operating boundaries for each component are reported in Section 2.

Figure 2 shows the general configuration of a stand-alone RES/H_2/battery-based hybrid system for the DEMOs 1, 2 and 3. The battery component is exploited as energy buffer only in DEMO 1 (i.e. Ginostra), whereas in Agkistro and Ambornetti it serves as a support for the system operation. All the various components are electrically attached to a common Direct Current bus. DC/DC converters are used for the connection to make the different sub-systems to exchange the correct amount of energy. In particular, since an integrated P2P system is employed, there is a single DC/DC section for the P2G and G2P devices. A DC/AC inverter is also required for the user load. Efficiencies for DC/DC and DC/AC converters are usually in the range 95-98% and 94-97%, respectively (average values will be employed for the hybrid system modelling).

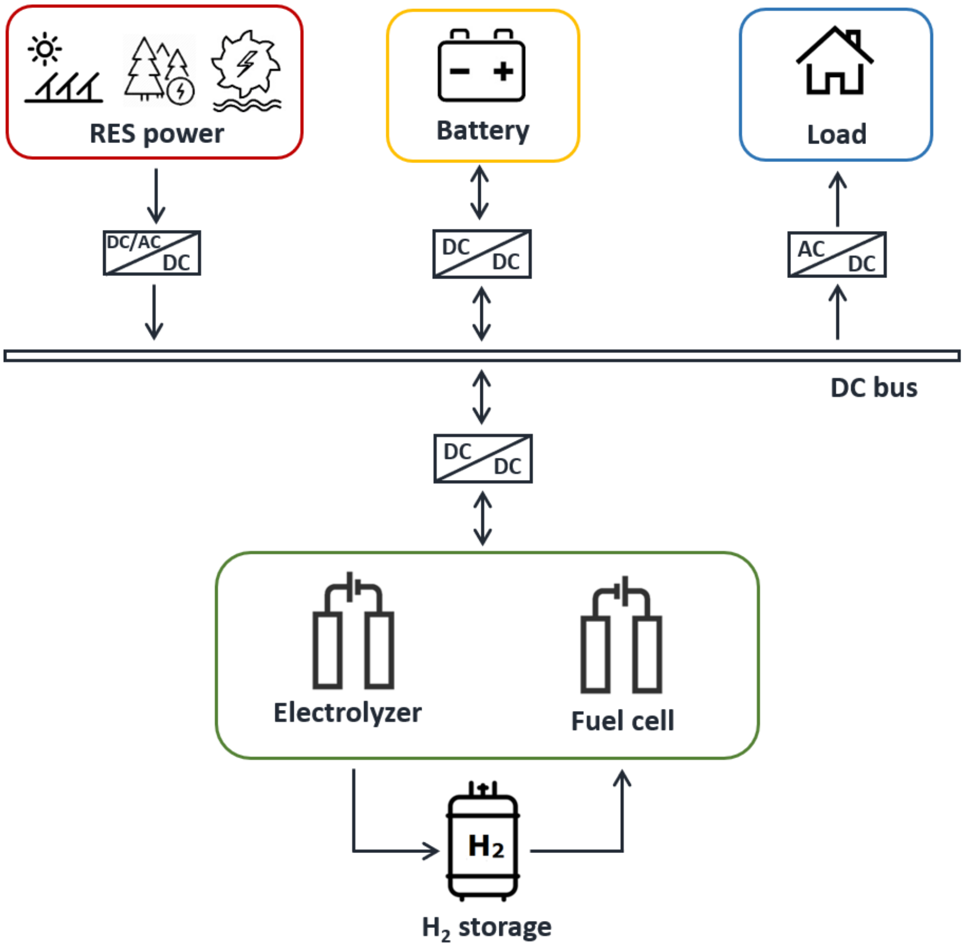


Figure 2. General configuration of a hybrid stand-alone RES H_2 system for DEMOs 1, 2 and 3 (integrated P2P).

In Figure 3, instead, a simplified layout of the hybrid system of DEMO 4 is reported. The main difference with respect to the previous configuration is given by the presence of the AC bus. Moreover, a non-integrated P2P solution is adopted. The electrolyzer component is directly connected to the AC bus (AC/DC converter integrated in the device), whereas the fuel cell is electrically integrated in DC, similarly to the battery device. Here the battery, as for the Ginostra site, is used to alleviate the high-frequency variability of the RES.

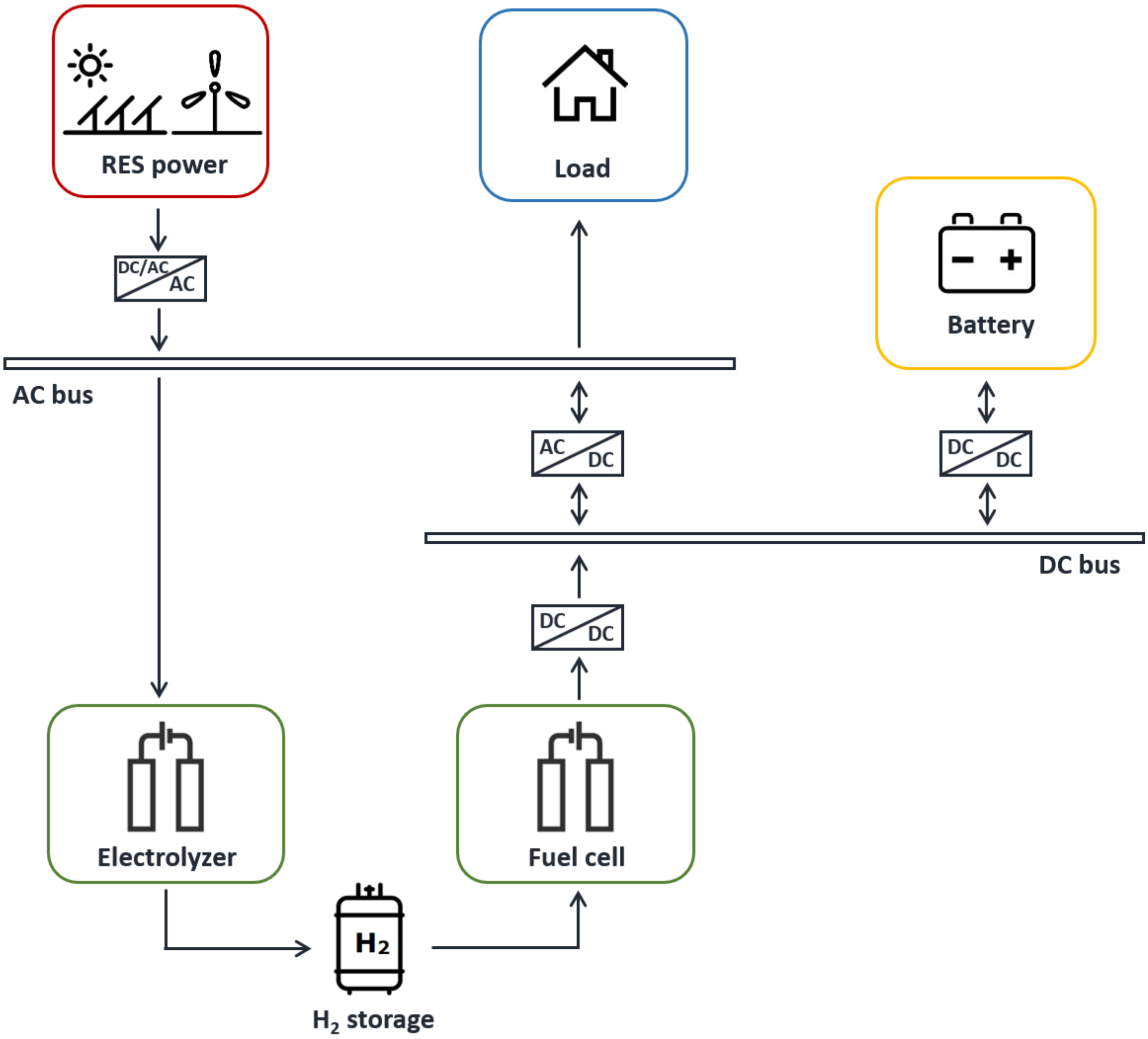


Figure 3. General configuration of a hybrid stand-alone RES H2 system for DEMO 4 (non-integrated P2P).

In the subsequent section, specific technical data of the various equipments involved will be defined for each DEMO. Information related to the local RES sources and loads are also provided to underline the importance of the adoption of an energy storage solution.

2. DEMO sites description

In this section, the system description of the various DEMOs performed in the deliverable D2.1 is integrated with more technical data about the devices adopted and information about local RES and loads.

2.1 DEMO 1: Ginostra

Site description and drivers

Ginostra is a small village located in the island of Stromboli, north of Sicily (Southern Italy). It is regarded as off-grid since not connected to the Italian distribution and transmission grid and also disconnected from the main grid of Stromboli Island.

Currently the load of the site is satisfied by using three 48 kW diesel generators and one 160 kW diesel generator.

Main drivers and advantages derived from moving to the new Power to Power (P2P) solution are:

- Increase and optimize the exploitation of local renewable energy sources
- Reduce diesel consumption to decrease local pollution
- Reduce diesel consumption to lower the cost of electricity (related to transportation and logistics issues of fossil fuels due to DEMO remote location)
- Improve the reliability of the electricity service
- Gain experience from this site improving the P2P concept to subsequently replicate in other European minor islands.

Technical specifications

Main technical data of the proposed innovative solution are reported below.

- <u>RES sources</u>

A PV power plant of 170 kW is employed. It consists of 39 strings, each of them composed of 12 modules, which are made of mono-crystalline silicon and characterized by a rated power of 365 W.

- <u>Integrated P2P system</u>

A system composed of the Hybrid Energy Storage System (HyESS™) from EPS with Li-Ion battery from EGP and a hydrogen storage equipment from EPS is adopted in the Ginostra location.

The HyESS™ solution presents an innovative modular configuration where both the fuel cell and the electrolyser are available in units of 25 kW to make the system more flexible to the user requirements. Main data for the chosen configurations are shown in Table 1. Properties for the battery bank and the hydrogen energy storage are also reported in Table 2 and Table 3 respectively.

	Technology	Nominal size [kW]	Efficiency (LHV) [%]	Modulation range [%]	Max operating pressure [barg]
P2G	Alkaline	50 [a]	63	20-100 [b]	30
G2P	PEM	50 [a]	50	15-100 [b]	0.5

[a] 2 units of 25 kW
[b] referred to the single unit of 25 kW

Table 1. Main technical data of the HyESS™ solution.

Rated energy [kWh]	Charge/discharge rate [kW/kWh]	Efficiency [%]	SOC_{min} [%]	SOC_{max} [%]
600	0.5C	95	20	80

Table 2. Main technical data of the battery bank.

Tank volume [m^3]	Pressure range [bar]	Total gross energy (LHV) [kWh]	Useful gross energy (LHV) [kWh]
21.6	3-28	1793 (28-0 bar)	1538 (28-3 bar)

Table 3. Main technical data of the hydrogen storage.

RES supply and load data

The total yearly load to be satisfied accounts for around 171.5 MWh. The proposed P2P solution aims at reducing the use of diesel generators with consequent advantages from an economic and environmental point of view. The energy which can be potentially produced on a yearly basis by the PV power plant is around 273.15 MWh. The monthly distribution of the energy required by the residential load and the energy produced by solar RES is reported in Figure 4.

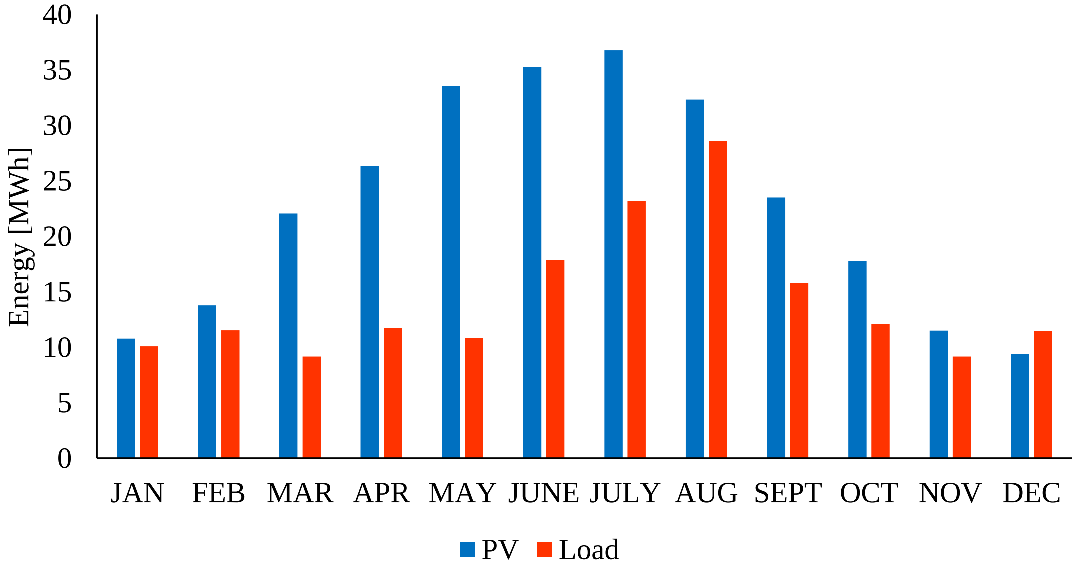


Figure 4. Monthly distribution of PV production and load.

More in detail, the table below reports the yearly values of the total consumption, RES production, direct RES consumption, surplus and deficit (converter efficiencies are still not taken into account):

	Energy
Total load	171.54 MWh
RES production	273.15 MWh
Direct RES consumption	82.39 MWh
RES surplus	190.76 MWh
Deficit	89.15 MWh

Table 4. Load and RES supply data on a yearly basis

Where the total load is equal to the sum of the direct RES consumption and the deficit; whereas the RES production is given by the direct RES consumption plus the RES surplus.

Concerning the load to be covered, besides the total residential load (i.e. 171.54 MWh), additional loads should also be considered for a more precise modelling: they mainly consist in the power consumption due to the operation of auxiliary components of the hybrid system. In particular, the constant consumption of around 1 kW has to be taken into account because of the control and gas unit. Moreover the following terms are also present when the fuel cell and the electrolyzer are running:

$$AUX_{FC} = 2 + 4 \cdot \frac{P_{FC}}{P_{FC,NOM}}$$

$$AUX_{EL} = 2 + 7 \cdot \frac{P_{EL}}{P_{EL,NOM}}$$

AUX_{FC} and AUX_{EL}, which are expressed in kW, are a function of the fuel cell and electrolyzer power. They represent the consumption of power due to the safety ventilation system and the dry cooler and pump required for the stack heat removal.

From Table 4 it can be seen that the PV production is approximately 60% more than the annual energy consumption. Nevertheless, instantaneous energy consumption from RES is less than half of the energy required by the load and slightly less than a third of the total PV energy production. The deficit and surplus behaviours along the year are shown in the following figure:

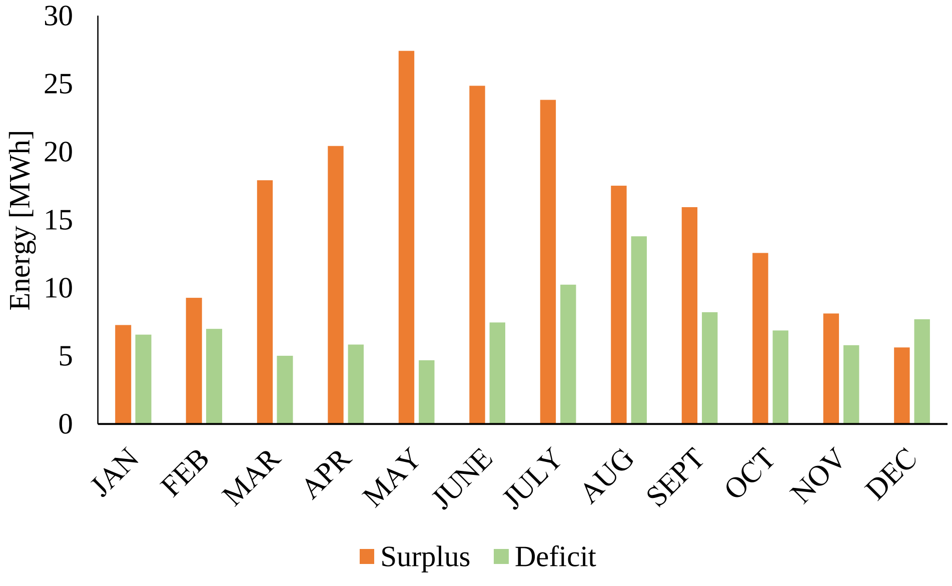


Figure 5. Energy surplus and deficit along the year

An appropriate storage system needs therefore to be designed maximizing the exploitation of RES sources and minimizing the intervention of diesel generators. When surplus RES energy occurs, it must be stored through the battery or the hydrogen system in order to use it later when the solar PV is not sufficient alone to satisfy the load (i.e. during an energy deficit). In particular, the long-term energy storage through hydrogen could be employed to store the high amount of PV surplus in the period March-July (Figure 5), reconverting it into electricity in the subsequent period of the year. In the results section it will be shown how the PV energy can be exploited and how the total load can be covered employing common energy management strategies with the chosen equipment sizing.

2.2 DEMO 2: Agkistro

Site description and drivers

Agkistro is located in Serres region, in North Greece closed to Bulgaria. Horizon, which is the owner of a 0.9 MW hydroelectric plant since 2002, wants to build an agri-food processing unit close to the power plant. The aim is to make the building completely energy autonomous avoiding grid connection. Energy is supposed to be provided directly by the hydroelectric power plant and by the P2P system acting as a sort of backup system.

Main drivers and advantages derived from adopting the hydroelectric + P2P solution are:

- Avoid an expensive investment cost for connection to the grid (20 km away)
- Avoid buying electricity from the grid at a high price (higher than the value of the sold hydropower energy)
- Improve the reliability of the electricity service avoiding problems and frequent outages derived from an eventual grid connection because of the remoteness of the site
- Gain experience from this site improving the P2P concept to subsequently replicate in other remote Greek areas.

Technical specifications

Main technical data of the proposed innovative solution are reported below.

- <u>RES sources</u>

A 0.9 MW hydroelectric power plant is used to produce electricity from water. Currently, it provides electricity to the main grid. From now on, the power plant will be also employed to directly feed the agri-food building with electricity.

- Integrated P2P system

Similar to the Ginostra scenario, the Hybrid Energy Storage System (HyESS™) technology implemented with a hydrogen storage from EPS is chosen. Main data for the configuration considered are shown in the tables below:

	Technology	Nominal size [kW]	Efficiency (LHV) [%]	Modulation range [%]	Max operating pressure [barg]
P2G	Alkaline	25	63	20-100	30
G2P	PEM	50 [a]	50	15-100 [b]	0.5

[a] 2 units of 25 kW
[b] referred to the single unit of 25 kW

Table 5. Main technical data of the HyESS™ solution.

Rated energy [kWh]	Charge/discharge rate [kW/kWh]	Efficiency [%]	SOC_{min} [%]	SOC_{max} [%]
30	2C	95	20	80

Table 6. Main technical data of the battery bank.

Tank volume [m^3]	Pressure range [bar]	Total gross energy (LHV) [kWh]	Useful gross energy (LHV) [kWh]
12	**3-28**	996 (28-0 bar)	854 (28-3 bar)

Table 7. Main technical data of the hydrogen storage.

With respect to the Ginostra DEMO, here the battery has a rated energy of only 30 kWh. Its main function is in fact related to the support of the system start-up and operation of the control unit and auxiliary equipment. There is not the necessity to make it work as an energy buffer storing the fluctuating power coming from intermittent RES sources (as in the case of solar and wind).

Since Agkistro site benefits from a continuous availability of renewable source, it has been possible to choose the minimum available electrolyzer size of 25 kW. In order to be able to cover the highest load request, which is slightly lower than 40 kW as shown in Figure 7, and considering also the efficiency of electronic equipments, a 50 kW fuel cell is also adopted (available in units of 25 kW from the manufacturer) . Considering an average of the four reference days of Figure 7, a daily load value of 282.5 kWh to be covered is computed. The calculation is performed conservatively by considering only working days. By simply taking into account the efficiency of the inverter, the DC/DC converter and the fuel cell, a value of around 615 kWh of hydrogen is found to be required for the satisfaction of the load request of a single day. A hydrogen storage of about 996 kWh has been therefore chosen to be installed to guarantee backup energy for 1-2 days.

RES supply and load data

Since the hydroelectric plant produces electricity to be supplied to the grid, RES electricity production is much higher compared to the load of the agri-food unit. Considering three indicative years (a wet, a medium and a dry year), the annual energy from RES hydroelectric is around 3165.7 MWh for dry year (2017), 3739 MWh for medium one (2016) and 4232.3 MWh for wet on. The overall annual energy required by the load, i.e. the food production company, is instead of 87.4 MWh. For each month, the energy produced by the hydro power plant and the requested load are shown in Figure 6. It can be noted that a higher energy consumption occurs between December-February and June-August. This can be better understood by looking at Figure 7 where the hourly consumption loads for four reference days are reported to show the seasonal variation along the year. This variability is due to the seasonal use of some mechanical equipment (e.g. drying of herbs performed is specific periods of the year) and the summer cooling and winter heating needs. For non-working days, instead, only 5 kW consumption due to refrigerators is considered.

Additional loads should be also taken into account because of the operation of auxiliary components of the P2P system. Their estimation is similar to the one described in section 2.1 for the Ginostra site.

To sum up, in a framework characterized by a RES production much higher than the load request and a quite predictable and stable load, the P2P system has been treated as a back-up unit. The P2P sizing has been performed in line with the range of technical solutions available from the manufacturer (trying to satisfy the peak load request and providing back up energy for 1-2 days).

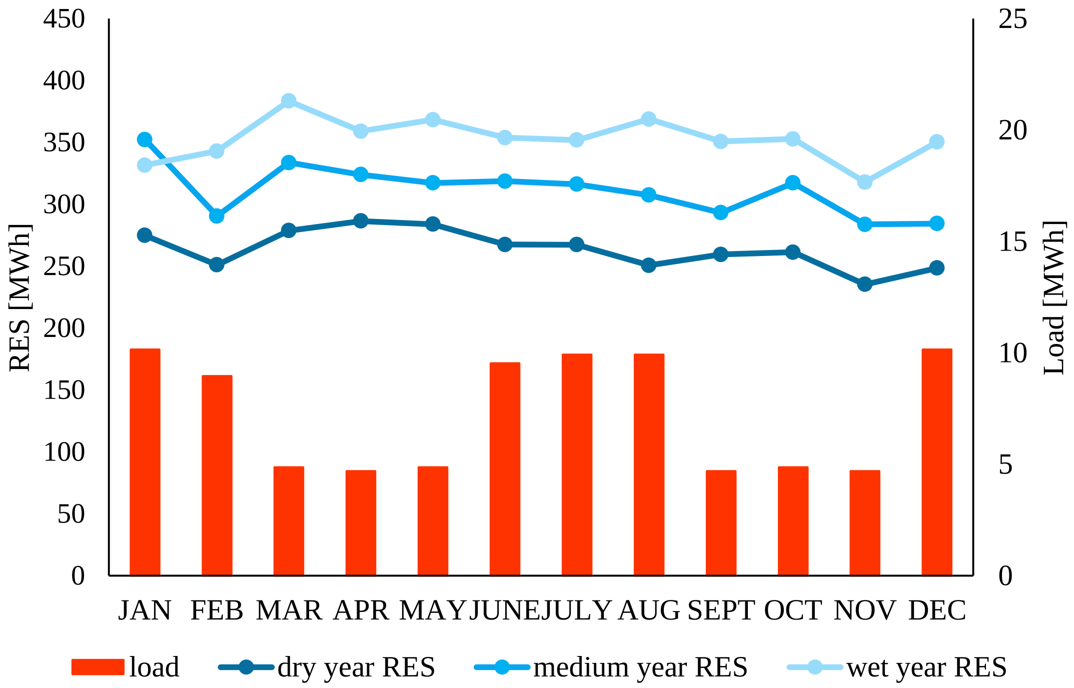
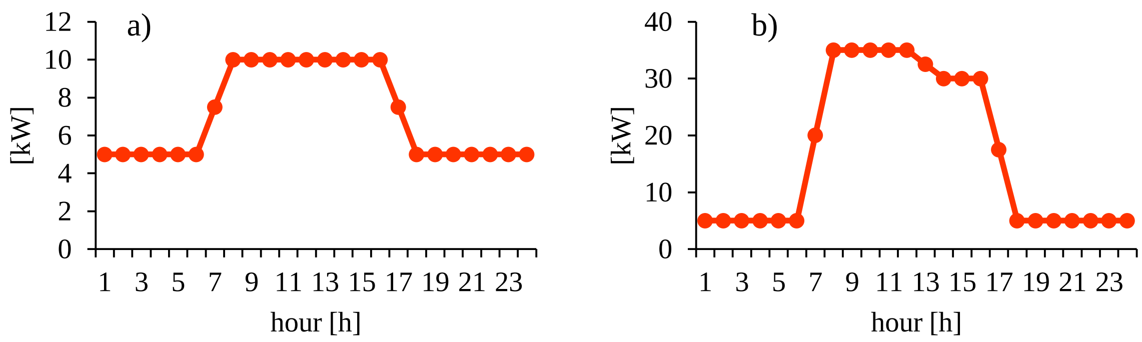


Figure 6. Monthly distribution of hydroelectric production and load.



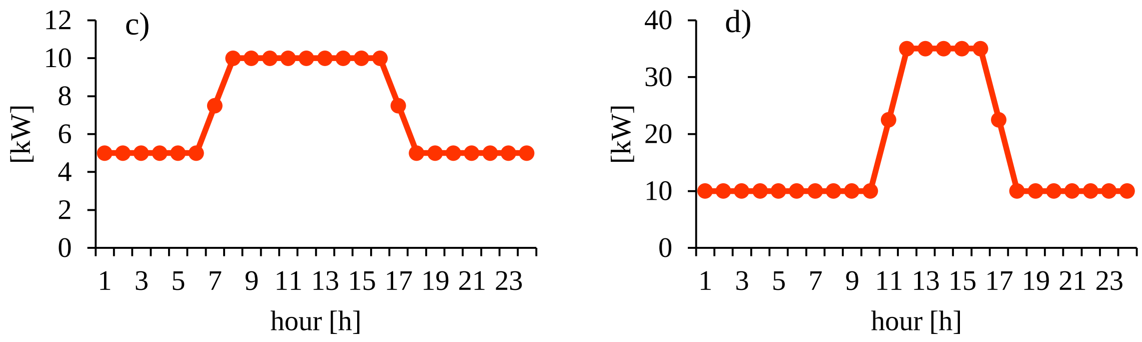


Figure 7. Indicative hourly consumption loads for: a) October, b) January, c) April and d) July.

2.3 DEMO 3: Ambornetti

Site description and drivers

Ambornetti is a mountain hamlet located in North Italy, Piedmont. This site, abandoned for more than 50 years, is now object of a project aiming at making the site a completely off-grid community powered by RES sources with no need of any kind of fossil fuel back up. Biomass and sun as renewable sources will cover the load, together with the help of a P2P system with hydrogen storage.

Main drivers and advantages derived from adopting the PV/biomass + P2P solution are:

- Avoid an expensive investment cost for connection to the grid
- Avoid invasive works and infrastructures due to the grid connection
- Avoid the usage of any kind of polluting traditional fossil fuel sources

Technical specifications

Main technical data of the proposed innovative solution are reported below.

- <u>RES sources</u>

A 40 kW PV plant – together with a 50 kWe biomass-based Combined Heat and Power (CHP) generator consisting of an innovative concept of modular gasification – are employed for the coverage of the community load.

- <u>Integrated P2P system</u>

As for the DEMO 1 and 2, the Hybrid Energy Storage System (HyESS™) technology implemented with a hydrogen storage from EPS, is chosen. Main technical specifications are reported in the following tables:

	Technology	Nominal size [kW]	Efficiency (LHV) [%]	Modulation range [%]	Max operating pressure [barg]
P2G	Alkaline	25	63	20-100	30
G2P	PEM	50 [a]	50	15-100 [b]	0.5

[a] 2 units of 25 kW
[b] referred to the single unit of 25 kW

Table 8. Main technical data of the HyESS™ solution.

Rated energy [kWh]	Charge/discharge rate [kW/kWh]	Efficiency [%]	SOC_{min} [%]	SOC_{max} [%]
30	2C	95	20	80

Table 9. Main technical data of the battery bank.

Tank volume [m^3]	Pressure range [bar]	Total gross energy (LHV) [kWh]	Useful gross energy (LHV) [kWh]
6	**3-28**	498 (28-0 bar)	427 (28-3 bar)

Table 10. Main technical data of the hydrogen storage.

RES supply and load data

The annual energy estimated to be required by the community is approximately 96.6 MWh. The annual energy which can be provided by the PV source is instead around 86.8 MWh (energy from the 50 kWe biomass CHP generator is also available for the load coverage). In Figure 8, their monthly distribution is reported.

In a more detailed analysis, the presence of additional loads related to the P2P system (e.g. control unit, ventilation, system for the removal of heat from the stack) have to be considered. They can be evaluated similarly to the Ginostra and Agkistro cases.

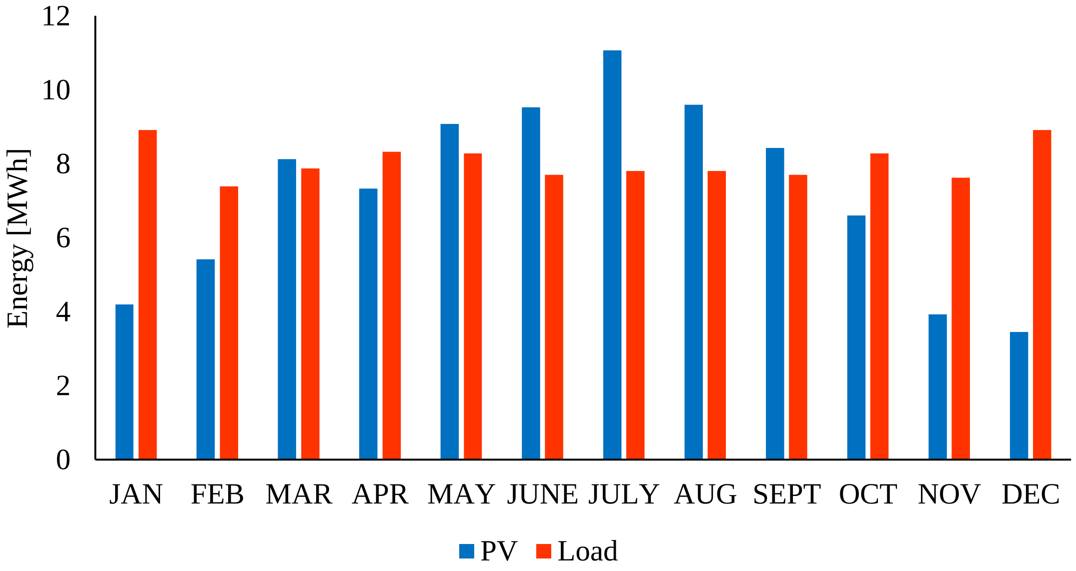


Figure 8. Monthly distribution of PV production and load.

Data related to the amount of PV energy directly consumed by the load, energy surplus (from PV) and deficit are summarized as follows:

	Energy
Total load	96.63 MWh
PV RES production	86.75 MWh
Direct RES consumption	54.01 MWh
PV surplus	32.74 MWh
Deficit	42.61 MWh

Table 11. Load and RES supply data on a yearly basis

As shown in Table 11, slightly more than half of the total load is directly met by the solar source. Moreover, more than one-third of the annual energy coming from the PV system is in excess. In particular, as shown in Figure 9, PV energy surplus is higher in summer than in winter; whereas the energy deficit is characterized by an opposite behaviour with higher values in the winter season.

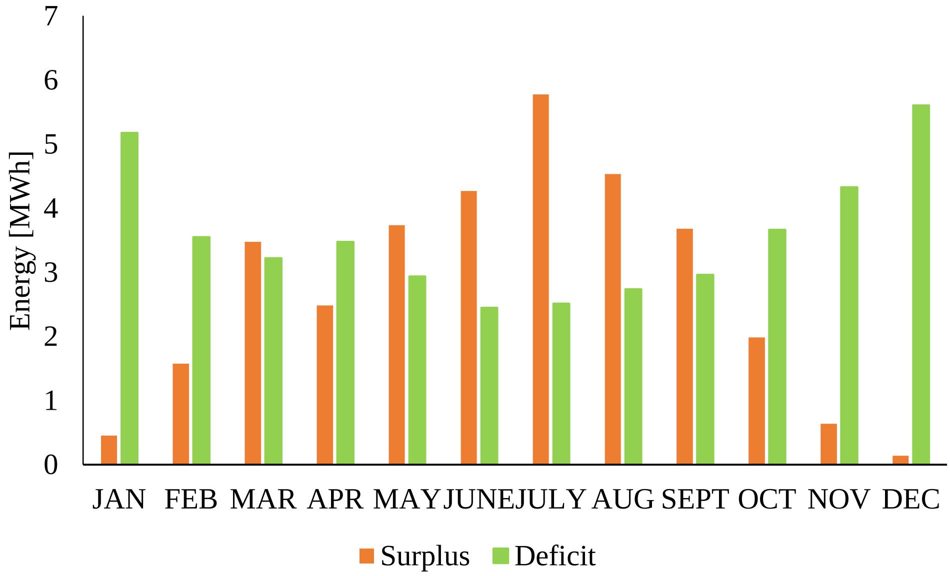


Figure 9. Energy surplus and deficit along the year

An energy storage system can be therefore useful to store the RES excess energy in terms of hydrogen exploiting it when a deficit occurs. In the case energy both directly from the PV and from hydrogen is not able to meet the load request, the biomass generator is employed to cover the remaining fraction of load (considering the availability of biomass on site all year long). The battery component is instead mainly used for the system start-up (not acting therefore as energy buffer). Detailed data about the RES usage and the load coverage employing a basic energy management strategy are reported in the results section.

2.4 DEMO 4: Froan/Rye

The four Norwegian islands of Froan are located off the west coast of Norway. They are interconnected through electric grid and currently connected to the mainland by an outdated sea cable, owned by TrønderEnergi. With the aim of making the islands energy independent, local renewable sources (e.g. solar and wind) coupled with hydrogen and battery as energy storage have been chosen as a solution. Main drivers and advantages derived from adopting the PV/wind + P2P solution are:

- Avoid the expensive and invasive replacement of the outdated sea cable
- Avoid the adoption of diesel generation because of the related polluting issues (not contemplated since Froan is a natural reserve)

- Avoid the adoption of diesel generation because of the high costs (due to the transportation and logistics of fuels)

Initial tests (the first two years) will be however performed in the Rye site, on the mainland. It consists of a micro-grid connecting two farms with a wind turbine and a hydrogen-based energy storage. After the two years operation in Rye, the P2P system will be moved to Froan.

The size of the various devices belonging to the P2P system are at present validated for the Rye location. No relevant technical changes are supposed to be performed after the transfer in Froan. Since the overall Froan load is higher than that of Rye, the southernmost Froan island (connected to the other three further north islands through a sea cable) will be excluded from the project to make the loads of the two sites more similar. There will be, if necessary, some minor changes to adapt the P2P system to the new location (e.g. because of the particular weather conditions in Froan).

Technical specifications

Main technical data of the proposed innovative solution are reported below. Information related to the RES sources are referred to the Rye site. Sizes for RES power plants in Froan are still to be defined. Procedures are, in fact, currently in place to obtain environmental permits. Concerning instead the P2P system, technical data are valid for both the sites.

- <u>RES sources</u>

A 85 kW PV plant together with a 225 kW wind turbine are employed for the load coverage of the two farms located in Rye.

- <u>Non-integrated P2P system</u>

PEM fuel cell and PEM electrolyser provided respectively by Ballard and Hydrogenics are merged in a system known as SAGES (Smart Autonomous Green Energy Station). The hydrogen-based energy storage is instead supplied by Powidian. 5 racks of 110 kWh Li-ion battery are also used as energy buffer to add more flexibility. The total system is managed by the Master Controller technology from Powidian.

Main technical specifications are reported in the tables below.

	Technology	Nominal size [kW]	Efficiency (LHV) [%]	Modulation range [%]	Max operating pressure [barg]
P2G	PEM	55	63	10-100	30
G2P	PEM	100	50	6-100	0.5

Table 12. Main technical data of the non-integrated P2P solution.

Rated energy [kWh]	Efficiency [%]	SOC_{min} [%]	SOC_{max} [%]
550	96	20	90

Table 13. Main technical data of the Li-ion battery bank.

Pressure [barg]	Useful gross energy (LHV) [kWh]
30	3333 (~100 Kg)

Table 14. Main technical data of the hydrogen storage.

RES supply and load data

Since data are not yet available for the Froan location, information provided below are referred to Rye.

The annual energy required by the load in the Rye site is around 126.8 MWh. Considering the wind RES production, until now operation and maintenance of the wind turbine has been performed by the farmer. This leads to almost zero power production between July and August (see light blue bars in Figure 10) by downtime due to maintenance or waiting time for spare parts. In this configuration, the annual energy produced by the wind turbine accounts for 175.1 MWh. From now on, the company TrønderEnergi will be in charge of the operation and maintenance of the turbine keeping it available for production as much as possible. The annual production from wind will be therefore increased reaching an estimated value of around 209.7 MWh. For both cases (farmer and TrønderEnergi maintenance), approximately 74.9 MWh from the 85 kW PV plant need to be also taken into account. The PV and wind energy production for each month is shown in Figure 10. Regarding the old configuration with the turbine maintenance from the farmer, as previously said, it can be noticed no wind production in July and August.

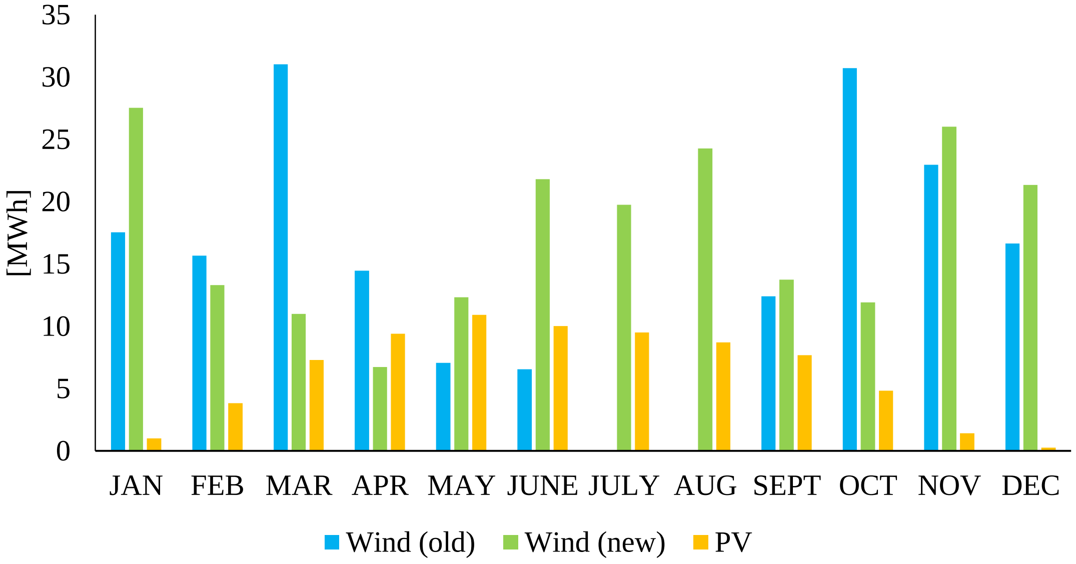


Figure 10. Monthly distribution of PV and wind production in Rye.

Regarding the new configuration, the total yearly energy from RES is about 284.7 MWh (209.7 from wind and 74.9 from PV). Its monthly distribution, together with that of the load, is reported in the Figure 11 below.

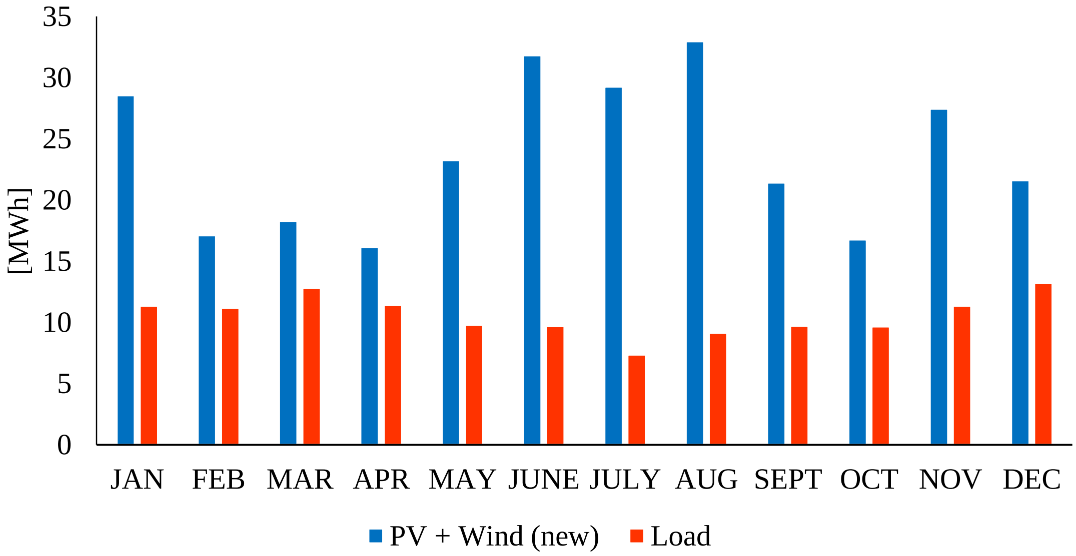


Figure 11. Monthly distribution of RES production and load in Rye.

The data in Table 15 express the total load consumption, the RES (PV + wind) production, the RES energy directly consumed by the load, and then the balance in terms of surplus and deficit:

	Energy
Total load	126.75 MWh
RES (PV + wind) production	284.68 MWh
Direct RES consumption	81.55 MWh
RES (PV + wind) surplus	203.13 MWh
Deficit	45.21 MWh

Table 15. Load and RES supply data on a yearly basis

More specifically, the deficit and surplus trends throughout the year are shown in the following graph:

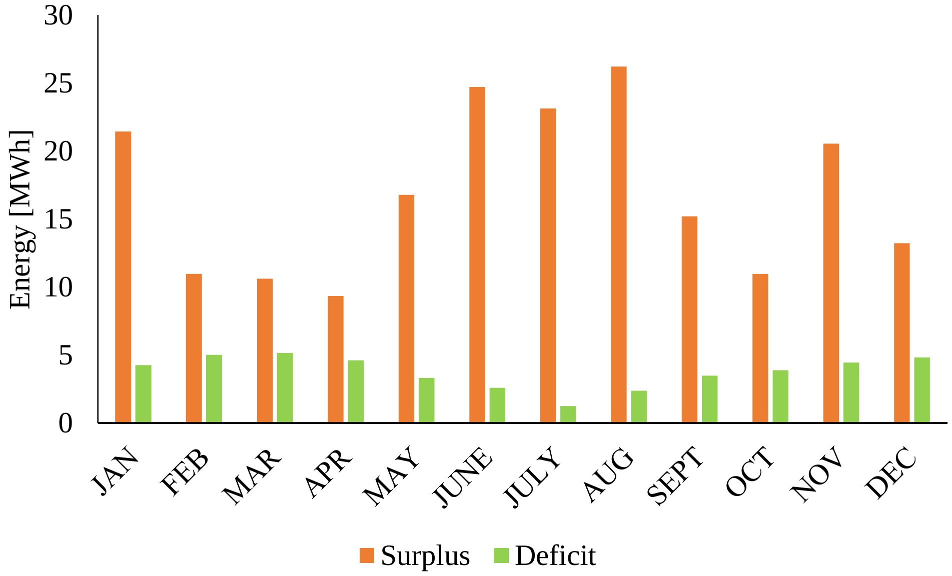


Figure 12. Energy surplus and deficit along the year

In Table 15 it can be seen that more than one third of the load demand cannot be directly satisfied by the PV and wind turbine systems. However, the high amount of surplus RES energy (more than four times the deficit) can be exploited by storing it by means of batteries and hydrogen in order to convert it again into electricity when an energy shortage occurs.

Because of the high value of the excess energy compared to the deficit, it could be considered to use the excess energy also for other purposes (e.g. hydrogen for mobility through the P2G pathway or heating).

Estimated RES data referred to the operation of TrønderEnergi will be used to carry out the model of the hybrid system since the hydrogen/battery energy storage system will be installed in the framework of this new scenario.

3. P2P system model description

The regulation of the energy flows within the hybrid system has to be optimized since it has a significant impact on the overall energy efficiency. Different energy management strategies have been investigated to improve the system performance [1]–[6]. The main objectives of the P2P system management strategy are:

- The reliable coverage of the load request.
- To protect the various components and avoiding their operation outside safe working ranges.

Local RES sources (e.g. solar, wind, biomass and water) are required to meet the load demand of the specific site. Any surplus of energy can be stored by battery charging or in the form of hydrogen through water electrolysis. By contrast, any shortage of power can be covered by the discharge of the battery or by the fuel cell operation. The intermittent nature of most of the RES (in particular the wind behaviour) introduces relevant fluctuations in the power production. Fuel cell and electrolyser devices should be protected from recurrent start-ups and shut-downs, which could accelerate performance degradation and lifetime reduction. The battery component becomes therefore useful to smoothen the high-frequency variability of the RES. However, excessive operation and over-charging/discharging of the battery should be avoided not to negatively affect its life span (with a consequent economic impact). Operation of the battery is required to stay within its SOC limits. Appropriate power management strategies, as well as being required for the load satisfaction by properly manage the local available RES source, are therefore also essential for a correct operation of the different subsystems.

The control strategies adopted in the current study are described below, whereas results from their implementation to the various DEMOs are reported in the following section. In particular, DEMOs 1, 3 and 4 have been considered; whereas the Agkistro case, in which the P2P solution acts as a back-up system, has already been described more in detail in section 2.2.

The aim is to show the benefits derived from the P2P system operation reducing the energy required from an external source (e.g. electric grid or traditional fossil fuel-based generators).

Efficiencies of the various components (DC/DC converters, battery, electrolyser, fuel cell and DC/AC converters), whose values can be found in the technical specifications previously reported, have also been considered in the model. However, for the sake of simplicity, they are not reported in the discussion below. Moreover, nominal values for equipment sizes and efficiencies are adopted in this preliminary analysis. Real data from the P2P system operation in the various DEMOs will be then employed for a refinement of the model in the subsequent work packages.

3.1 Strategy 1 (no battery)

The first strategy which is described is the simplest one to be implemented: the battery component is not operated as energy buffer (help to store excess energy and cover shortages). Energy is stored only in form of hydrogen through the electrolyser, hydrogen storage and fuel cell pathway. This strategy allows the hydrogen level to stay within the chosen range for the correct operation.

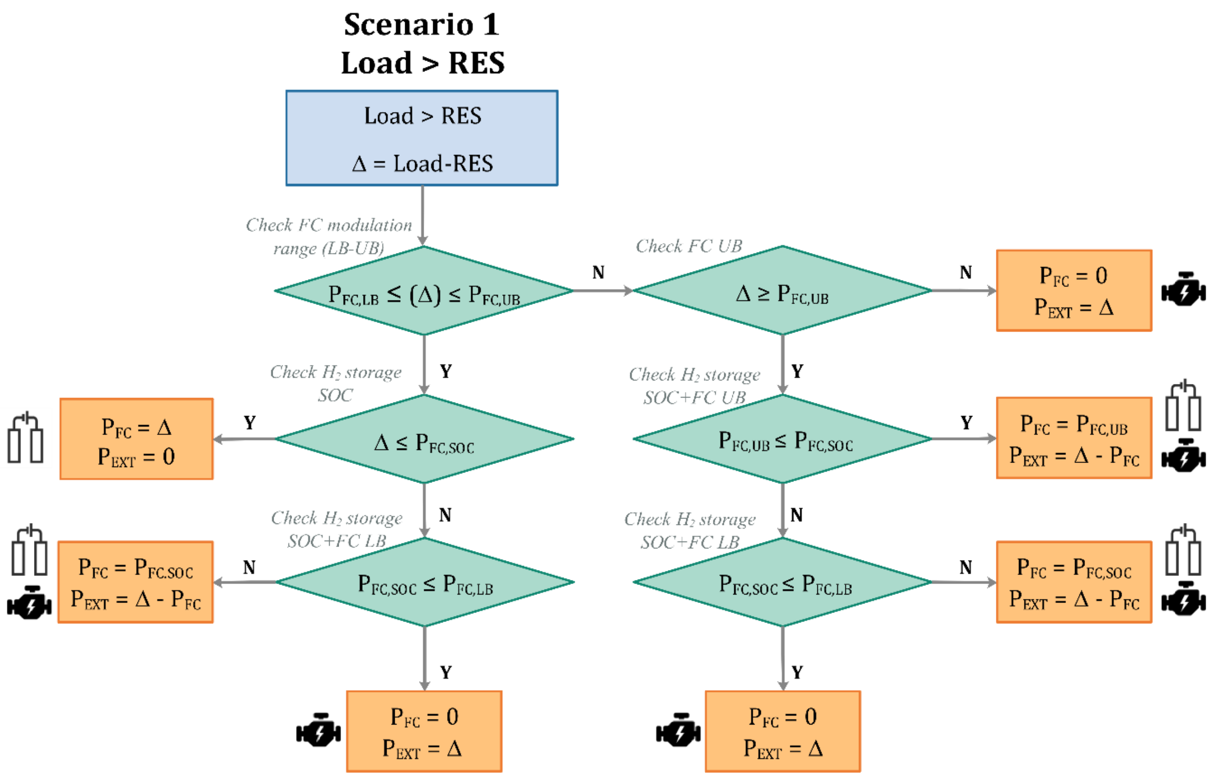


Figure 13. Logical block diagram for the discharging case (RES lower than load) of strategy 1.

When the required load is higher than the power available from RES, firstly it is checked if the fuel cell is able to cover the remaining power fraction (Δ). If the requested additional power is in the fuel cell modulation range, fuel cell is operated at a power not to cause the hydrogen SOC to go below its SOC_{min}. If a remaining power fraction to be covered is still present, an external source is employed. If instead Δ is below the fuel cell lower limit, then an external source has to intervene. Finally, if Δ is higher than the fuel cell upper limit, the fuel cell works at its maximum power if this does not lead the H_2 level to go below its lower limit (otherwise the fuel cell power has to be reduced, even becoming null if lower than $P_{FC,LB}$). The residual power is then provided by the external source. The detailed logical diagram for the discharging case is shown in Figure 13.

If instead the power demand is lower than the output power from RES, the excess RES power (Δ) is stored in terms of hydrogen through the electrolyser or, if not possible, curtailed. In particular, if Δ lies in the electrolyser modulation range, the P2G device operates so as to convert and store that power surplus. In case the H_2 SOC_{max} would be exceeded, the electrolyser power is reduced (or even stopped if becoming lower than $P_{EL,LB}$). The remaining fraction of RES excess power is then curtailed. If instead Δ is lower than the electrolyser minimum power, all the RES power not consumed by the load is curtailed. Finally, if Δ is higher than the nominal power of the P2G system, the electrolyser is operated at its maximum power if not leading to the exceedance of the H_2 storage upper limit (otherwise a lower working power is imposed). The flow chart of this charging case is reported in Figure 14.

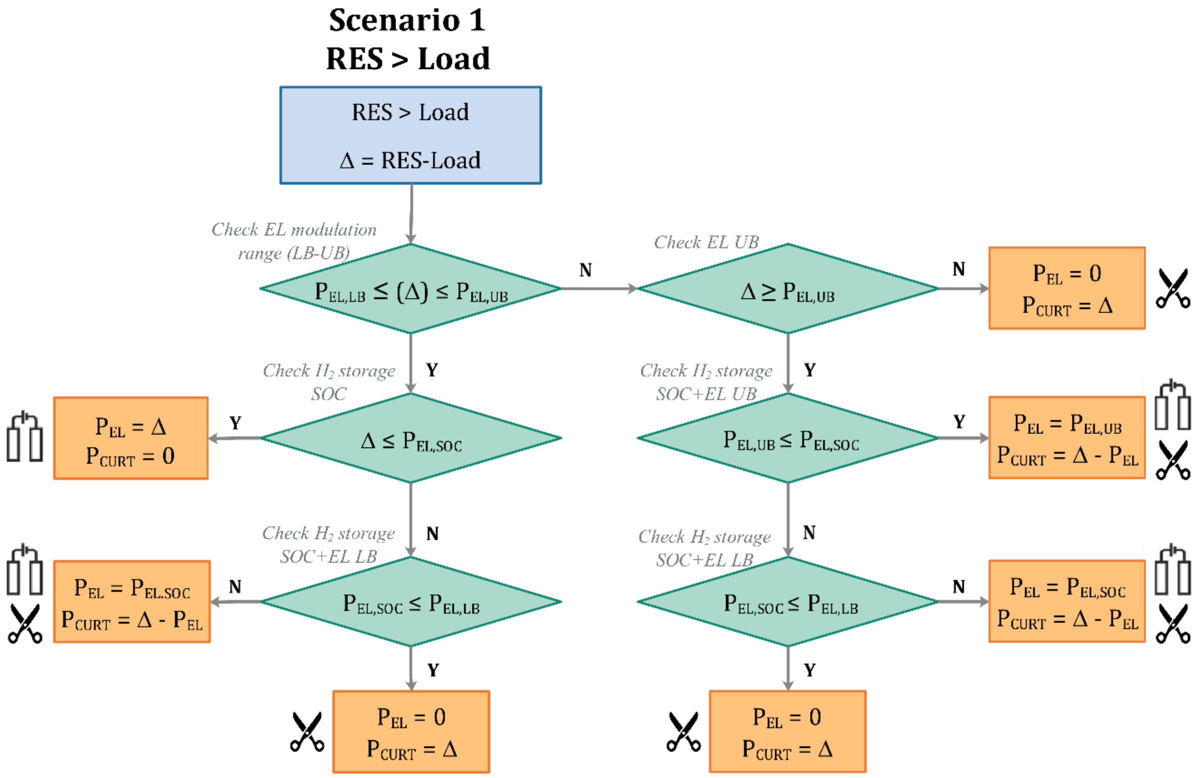


Figure 14. Logical block diagram for the charging case (RES higher the load) of strategy 1.

The power management strategy described above is employed for the P2P system model of DEMO 3. Ambornetti site is in fact equipped with a 30 kW battery, which is not intended to alleviate the variability of local RES outputs.

3.2 Strategy 2 (with battery)

The second power management strategy is referred to a configuration where both the battery and the hydrogen technology are employed as storage solutions. As already mentioned, battery aims at alleviating the RES output, avoiding too frequent interventions of fuel cell and electrolysers. Overcharging/discharging of both the storage options are prevented by imposing proper maximum/minimum SOC values as input parameters. The following control strategy is considered for the Ginostra and Rye/Froan locations, characterized by intermittent wind and/or PV power sources.

When the output power from RES is not sufficient to completely cover the load, the battery first intervenes to meet the required additional power. If the battery SOC would go below the lower boundary imposing that discharging power, the battery power is reduced (to stay above the battery SOC_{min}) and the remaining fraction to be satisfied is managed by the fuel cell or an external source. From now on, the control process becomes similar to the one described for the first strategy.

By contrast, when excess RES power is produced, the surplus is first used to charge the battery. If the maximum battery SOC would be exceeded, the power to the battery is lowered and the remainder is sent to the electrolyser or curtailed according to the logical process described for the first strategy.

Figure 15 and Figure 16 show the flow charts for the charging and discharging configurations of strategy 2, respectively.

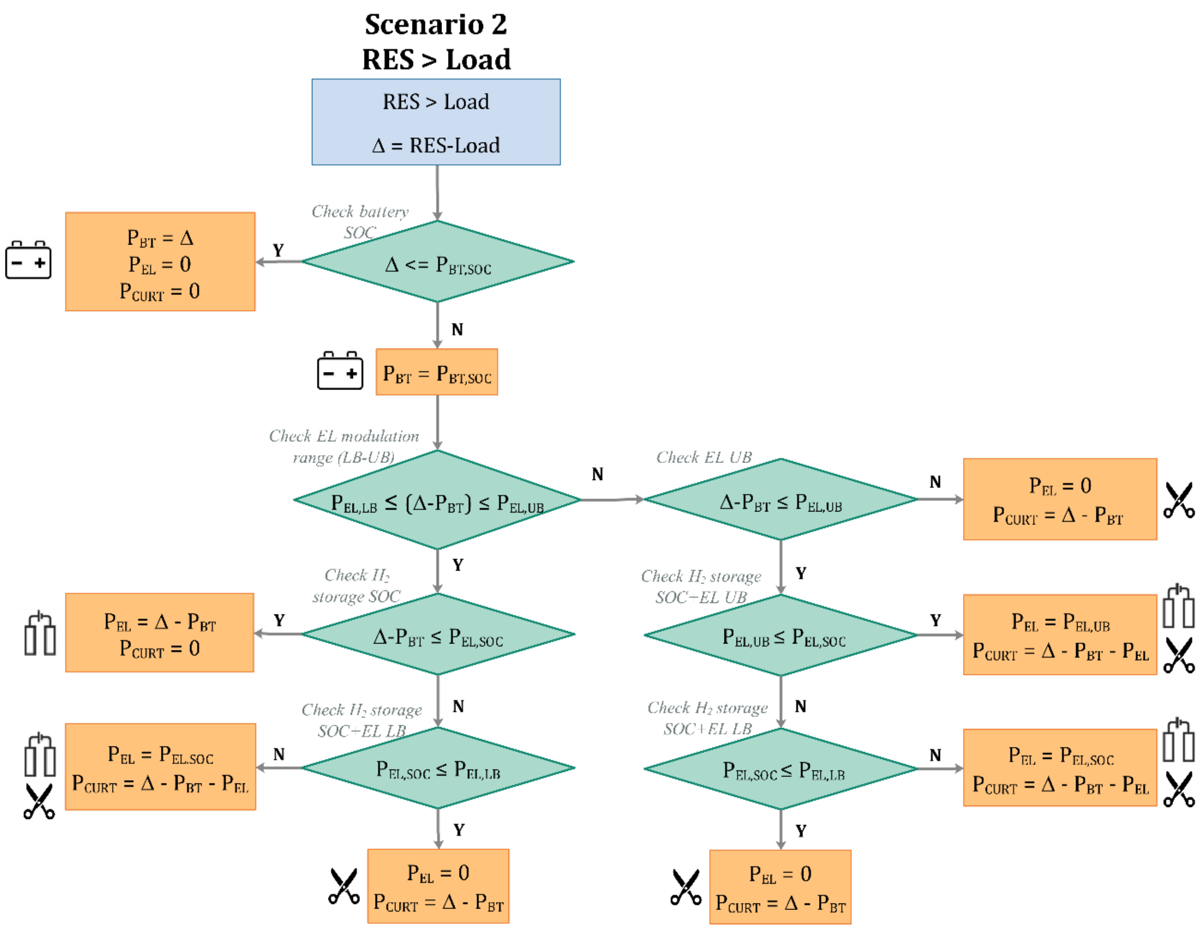


Figure 15. Logical block diagram for the discharging case (RES lower the load) of strategy 2.

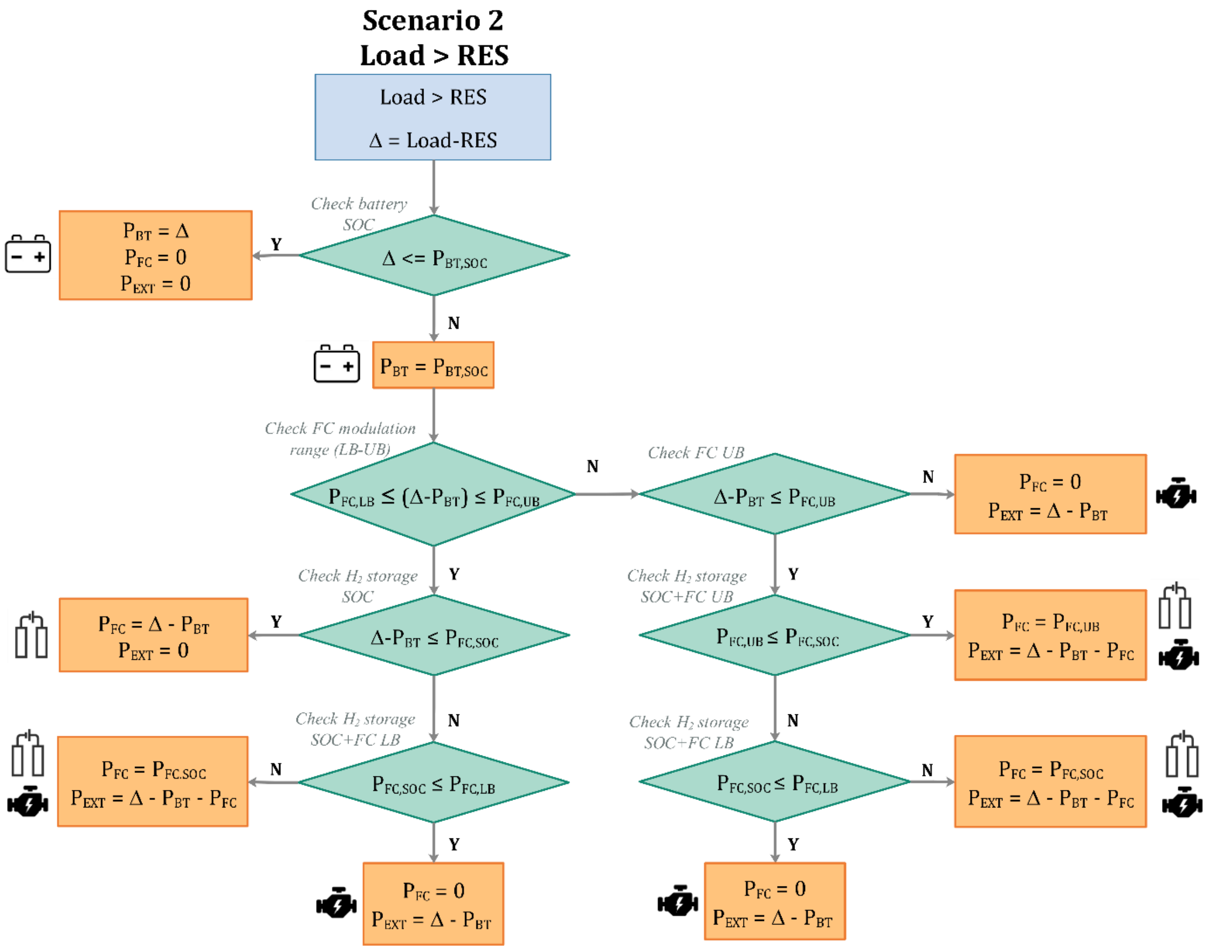


Figure 16. Logical block diagram for the charging case (RES higher the load) of strategy 2.

Moreover, for the sake of comparison, the hysteresis concept is also introduced for the operation of the integrated system.

In a system configuration without hysteresis, the minimum and maximum SOC of the battery are used as indicators to establish the switching on/off of the fuel cell and the electrolyzer (strategy 2). In particular, between the upper and lower battery SOC, the priority of operation is given to the battery device. During the charging phase and above the battery SOC_{max}, the battery is not charged and the electrolyzer is employed. Instead, in the discharging mode and below the battery SOC_{min}, the energy requirement is satisfied by the fuel cell.

Figure 17. Operation of the hybrid system without the hysteresis band

With the introduction of the hysteresis band, the new key control parameters SOC_{fc} and SOC_{el} have also to be considered in the power management strategy. Between SOC_{fc} and SOC_{el}, priority is given to the battery. In the discharging case and in the range SOC_{min}-SOC_{fc}, it is first used the fuel cell and then the battery. Similarly, in the charging phase and between SOC_{el}-SOC_{max}, priority is given to the electrolyzer.

Figure 18. Operation of the hybrid system with hysteresis bands for fuel cell and electrolyzer

The use of the hysteresis band is supposed to protect the battery from heavy utilization, consequently increasing its lifetime, at the expense, however, of a more intense exploitation of the electrolyzer and the fuel cell. On the other hand, the hysteresis band can also help to reduce the possible frequent start-ups and shut-downs of electrolyzer and fuel cell that could occur in the presence of high variability in the RES energy generation [1][7].

Variable	Reference
P_{BT}	battery discharging (case 1) and charging (case 2) power
$P_{B,SOC}$	Case 1: max battery discharging power which allows not to go below the lower battery SOC Case 2: max battery charging power which allows not to go above the upper battery SOC
P_{FC}	fuel cell power
P_{EL}	electrolyzer power
$P_{FC,UB}$	maximum fuel cell power
$P_{FC,LB}$	minimum fuel cell power
$P_{EL,UB}$	maximum electrolyzer power
$P_{EL,LB}$	minimum electrolyzer power
$P_{FC,SOC}$	maximum fuel cell power which allows not to go below the lower H_2 storage SOC
$P_{EL,SOC}$	maximum electrolyzer power which allows not to go above the upper H_2 storage SOC
P_{CURT}	Curtailed power
P_{EXT}	power provided by an external source (grid, engine or others)

Table 16. Nomenclature for Fig. 9-12.

4. Results of control strategies implementation

Main results derived from the employment of the control strategies previously discussed are presented hereafter. Specific examples of the model results for some reference days for each DEMO are reported in the Appendix.

4.1 DEMO 1: Ginostra

The annual energy available from PV RES is about 273.15 MWh, whereas the annual energy required by the load is equal to 171.54 MWh.

On a yearly basis, results of the load coverage and RES usage are shown below for the second power management strategy with the introduction of a hysteresis band (with maximum and minimum battery SOC taken from Table 2, SOC_{fc}=0.3 and SOC_{el}=0.7):

Load coverage	Energy	Share
Load directly covered by RES	82.02 MWh	47.8%
Load covered by fuel cell	6.05 MWh	3.5%
Load covered by battery	75.92 MWh	44.3%
Load covered by external source	7.56 MWh	4.4%
Total residential load	**171.54 MWh**	**100%**

Table 17. Annual load coverage (strategy 2 + hysteresis)

RES usage	Energy	Share
RES to load	85.89 MWh	31.4%
RES to electrolyzer	21.58 MWh	7.9%
RES to battery	87.96 MWh	32.2%
RES to curtailment	77.73 MWh	28.5%
Total RES	**273.15 MWh**	**100%**

Table 18. Annual RES usage (strategy 2 + hysteresis). Values are referred to the DC input of RES to the system

In particular, the monthly distribution is reported in Figure 19 and Figure 20.

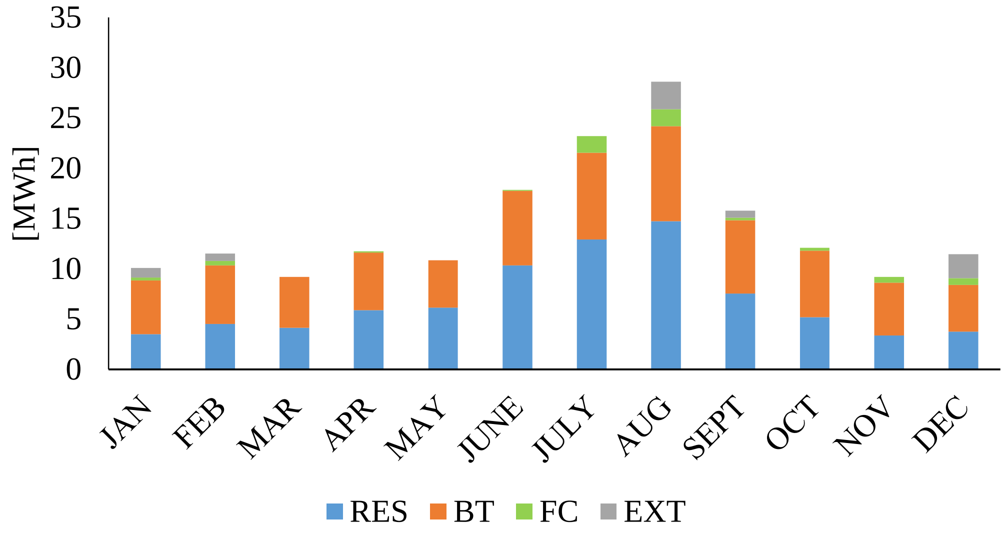


Figure 19. Monthly distribution of the load coverage (strategy 2 + hysteresis)

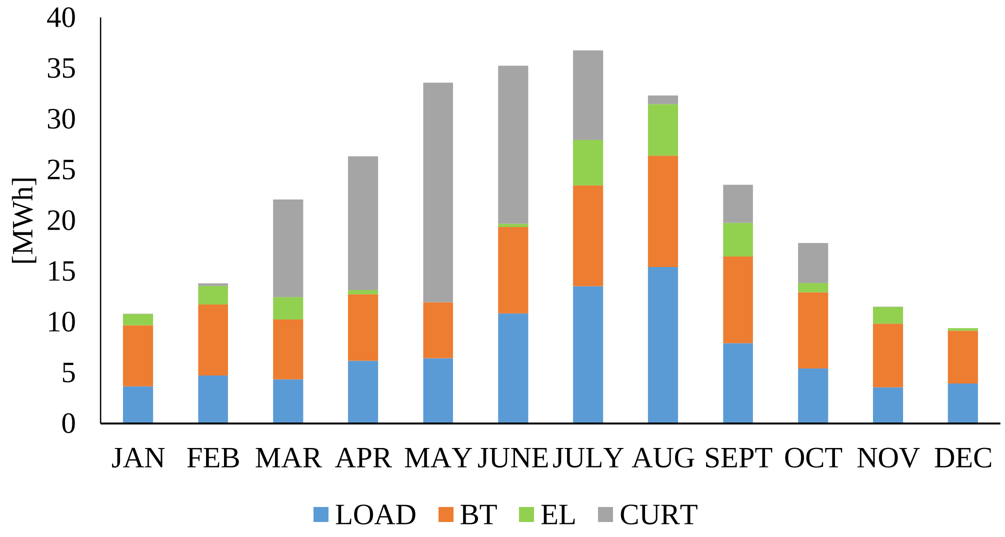


Figure 20. Monthly distribution of the RES usage (strategy 2 + hysteresis)

When not considering the hysteresis bands, a slightly lower intervention of the fuel cell and electrolyzer is observed, together with a higher battery usage (2.8% instead of 3.5% for the fuel cell and 6.2% instead of 7.9% for the electrolyzer). The presence of the hysteresis band, in fact, allows to reduce the frequency of the battery employment when the battery SOC is near SOC_{min} and $SOC_{max.}$

According to the proposed basic control strategy, the hybrid P2P solution enables to drastically decrease the use of current operating diesel generators to a value of around 4.4%. Since the Demo1's target is to cover 100% of load thanks to RES and the hybrid storage, during the experimental operation of the plant all the possible optimization strategies will be adopted in order to reach the goal to switch off the diesel genset for the entire year.

Looking at Table 17, it can be noticed that, when the RES power is not enough to satisfy the load, the shortage is mainly met by the battery, which is the most efficient storage pathway. Moreover, as shown in Figure 19, the fuel cell is used especially in the period July-August, which is characterized by a higher energy demand (and consequently also higher energy deficit as reported in Figure 5). The fuel cell operation leads to the consumption of the stored hydrogen: the hydrogen SOC is in fact sharply reduced in the summer period with the exploitation of almost all the useful gross energy stored in the H_2 tank as presented in Figure 21. This figure clearly shows the useful function of the hydrogen solution as longer term energy storage:

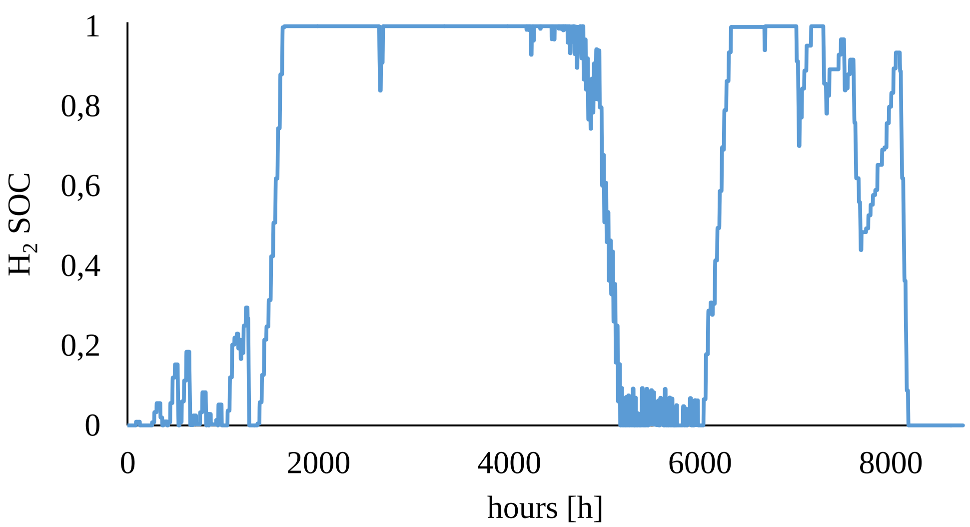


Figure 21. H_2 state of charge over the year

The tank is quickly filled with hydrogen at the beginning of the year thanks to the conversion of the RES surplus through the electrolyzer. A high amount of the RES energy occurring in the spring season needs therefore to be curtailed as it can be observed from Figure 20 (period March-June). A better exploitation of the local RES sources could be achieved by increasing the size of the hydrogen storage. In this way the curtailment during the spring period would be reduced because of a greater use of the electrolyzer. Unfortunately, it is not possible to further expand the size of the hydrogen storage due to the lack of space where to install it in the only area available for the plant.

When considering also the additional loads because of the P2P operation (e.g. control, ventilation and cooling system), the following three terms need also to be covered:

- Control and gas unit: 8.76 MWh per year
- Ventilation and heat removal system when the electrolyzer is running: 4.04 MWh per year
- Ventilation and heat removal system when the fuel cell is running: 1.11 MWh per year

In particular, the new annual RES usage and residential load satisfaction are detailed as follows:

Load coverage	Energy	Share
Load directly covered by RES	81.35 MWh	47.4%
Load covered by fuel cell	4.65 MWh	2.7%
Load covered by battery	74.32 MWh	43.3%
Load covered by external source	11.23 MWh	6.5%
Total load	**171.54 MWh**	**100%**

Table 19. Annual load coverage (strategy 2 + hysteresis) with additional loads

RES usage	Energy	Share
RES to load	89.53 MWh	32.8%
RES to electrolyzer	25.65 MWh	9.4%
RES to battery	90.49 MWh	33.1%
RES to curtailment	67.49 MWh	24.7%
Total RES	**273.15 MWh**	**100%**

Table 20. Annual RES usage (strategy 2 + hysteresis) with additional loads. Values are referred to the DC input of RES to the system

In this case, when trying to meet the energy deficit with the hydrogen pathway, the fuel cell has to operate satisfying also the additional consumptions due mainly to ventilation and cooling. Moreover, a fraction of the surplus RES energy sent to the electrolyzer, instead of being converted into hydrogen, is employed to cover the additional loads due to the auxiliary components when the electrolyzer is running.

As already stated, the battery pathway is generally more favoured than the hydrogen one according to the current strategies. This is reasonable considering the higher efficiency of the battery charging/discharging with respect to the electrolyzer/fuel cell operation. However, hydrogen is still necessary because of its capability to perform a longer term storage (as shown in Figure 21).

A refinement of the model could be further performed, for example taking into account also degradation phenomena (that would affect especially the battery according to the proposed strategies because of its greater utilization). For instance, the fuel cell could be forced to operate more frequently taking care to avoid too many start-ups and trying to make it works in a range where its efficiency is higher. At the same time the battery would still operate as daily energy buffer, but managing smaller power variations (thus reducing the occurrence of deep cycling). These issues has been already partially considered in the current study introducing the hysteresis bands.

More detailed control strategies will be further developed in other WPs based on the specific site requirements to better optimize the plant operation.

4.2 DEMO 3: Ambornetti

The total energy which can be yearly provided by the PV power plant is around 86.75 MWh, whereas the yearly load requirement by the community is equal to 96.63 MWh. Besides the solar source, also energy from a 50 kW biomass generator is employed to meet the community load.

On a yearly basis, results of the load coverage and RES (PV) usage are shown below for the power management strategy 1 (no battery).

Load coverage	Energy	Share
Load directly covered by PV	53.26 MWh	55.1%
Load covered by fuel cell	8.00 MWh	8.3%
Load covered by biomass	35.37 MWh	36.6%
Load covered by external source	0 MWh	0%
Total load	**96.63 MWh**	**100%**

Table 21. Annual load coverage (strategy 1)

RES usage	Energy	Share
PV to load	55.77 MWh	64.3%
PV to electrolyzer	28.55 MWh	32.9%
PV to curtailment	2.43 MWh	2.8%
Total RES	**86.75 MWh**	**100%**

Table 22. Annual RES (PV) usage (strategy 1). Values are referred to the DC input of RES to the system

For each month, the way the load is satisfied and the available solar RES is exploited is shown below.

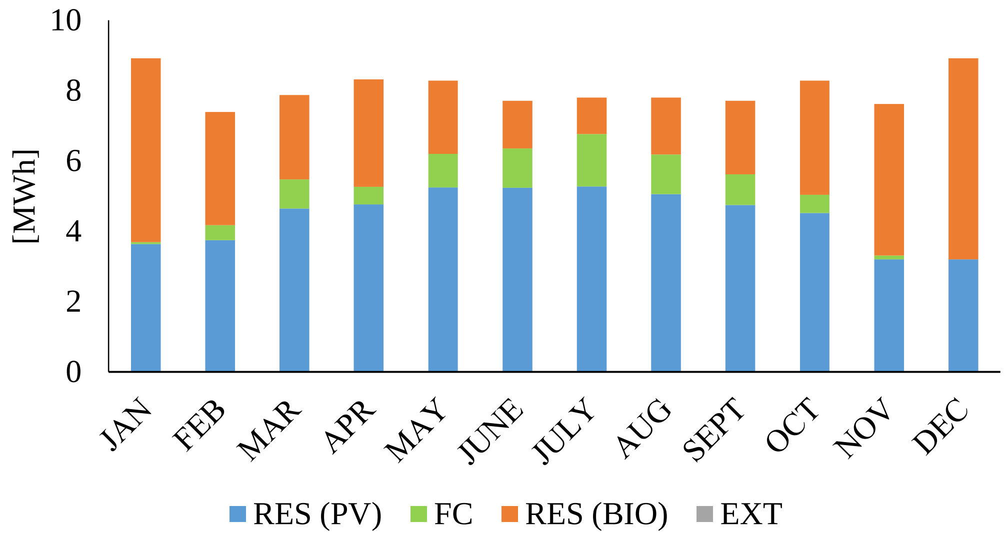


Figure 22. Monthly distribution of the load coverage (strategy 1)

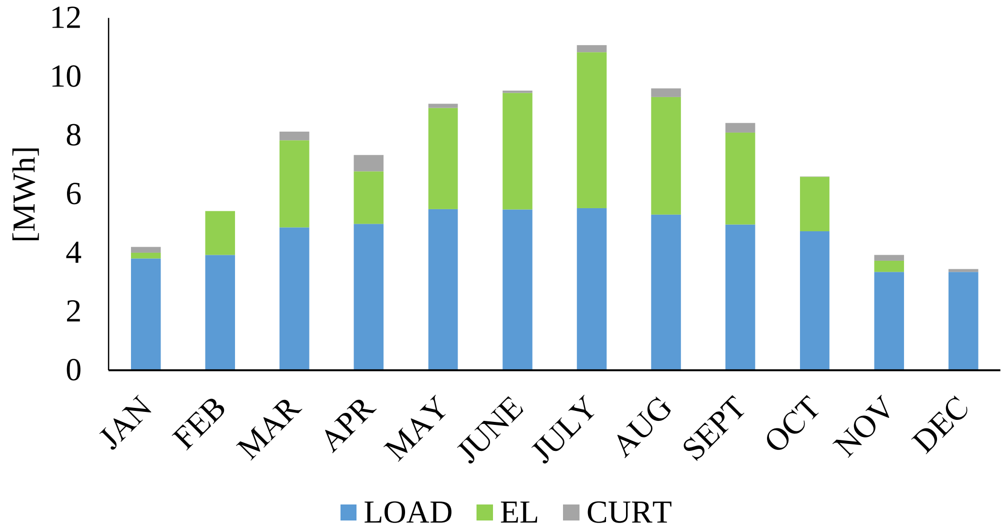


Figure 23. Monthly distribution of the RES usage (strategy 1)

It can be seen from Table 21 that the solar and biomass energy are sufficient to make the community energy autonomous since no additional power is required from external sources. The biomass generator is enough for the site since no power higher than 50 kW is required by its operation.

The hydrogen storage system is also effective at maximizing the RES exploitation since, as shown in Figure 23, almost no curtailment occurs. Almost all the surplus energy is in fact employed by the electrolyzer to produce hydrogen. The small amount of curtailed energy (around 2.8% of the total RES) is mainly due to the inability of the electrolyzer to work at low partial loads (below around 20% of the nominal power of the alkaline electrolyzer).

With the proposed solution, the integration of the biomass source is more consistent (around four times more) than the usage of the fuel cell to supply the remaining fraction of power not provided directly from RES. Within a framework characterized by a low availability of biomass, it could be appropriate to increase the PV size in order to increment both the fraction of load covered directly by the PV and by the fuel cell (with a consequent lower intervention of the biomass-based generator).

By analogy with what done for Ginostra, also for the DEMO 3 it is evaluated the influence of the additional loads due to the presence of auxiliary components. The results are shown below:

Load coverage	Energy	Share
Load directly covered by PV	51.60 MWh	53.4%
Load covered by fuel cell	2.56 MWh	2.6%
Load covered by biomass	42.47 MWh	44.0%
Load covered by external source	0.00 MWh	0.00%
Total load	**96.63 MWh**	**100%**

Table 23. Annual load coverage (strategy 1) with additional loads

RES usage	Energy	Share
PV to load	58.93 MWh	67.9%
PV to electrolyzer	21.75 MWh	25.1%
PV to curtailment	6.07 MWh	7.0%
Total RES	**273.15 MWh**	**100%**

Table 24. Annual RES (PV) usage (strategy 1) with additional loads. Values are referred to the DC input of RES to the system.

With respect to the case without additional loads, here the P2P pathway with hydrogen storage is more inefficient. In fact when the electrolyzer is running to store the excess energy from the PV plant, a fraction of the RES power is consumed by ausiliaries. Moreover, when the fuel cell is operated to meet the deficit, a higher operating power of the device is required to cover also the additional loads of the P2P system.

4.3 DEMO 4: Froan/Rye

The following preliminary modelling is referred to the Rye site since, as previously reported in Section 2.4, data for the RES supply and load are still not available in Froen.

Taking into account the framework in which the P2P system will start to operate (i.e. operation and maintenance of the wind turbine by TrønderEnergi), the annual load required in the Rye site is about 126.75 MWh, whereas the yearly energy globally available from RES (solar and wind) is 284.68 MWh. The yearly load coverage and RES usage computed by running the second power management strategy with the introduction of the hysteresis concept (maximum and minimum battery SOC from Table 13, SOC_{fc}=0.3 and SOC_{el}=0.8) are shown hereafter.

Load coverage	Energy	Share
Load directly covered by RES	77.63 MWh	61.2%
Load covered by fuel cell	10.67 MWh	8.4%
Load covered by battery	32.75 MWh	25.8%
Load covered by external source	5.69 MWh	4.5%
Total load	**126.75 MWh**	**100%**

Table 25. Annual load coverage (strategy 2 + hysteresis)

RES usage	Energy	Share
RES to load	95.85 MWh	33.7%
RES to electrolyzer	49.92 MWh	17.5%
RES to battery	54.05 MWh	19.0%
RES to curtailment	84.87 MWh	29.8%
Total RES	**284.68 MWh**	**100%**

Table 26. Annual RES (PV) usage (strategy 2 + hysteresis) Values are referred to the DC input of RES to the system

Figure 24 and Figure 25 show the way in which energy from RES is exploited and the load is met for each month.

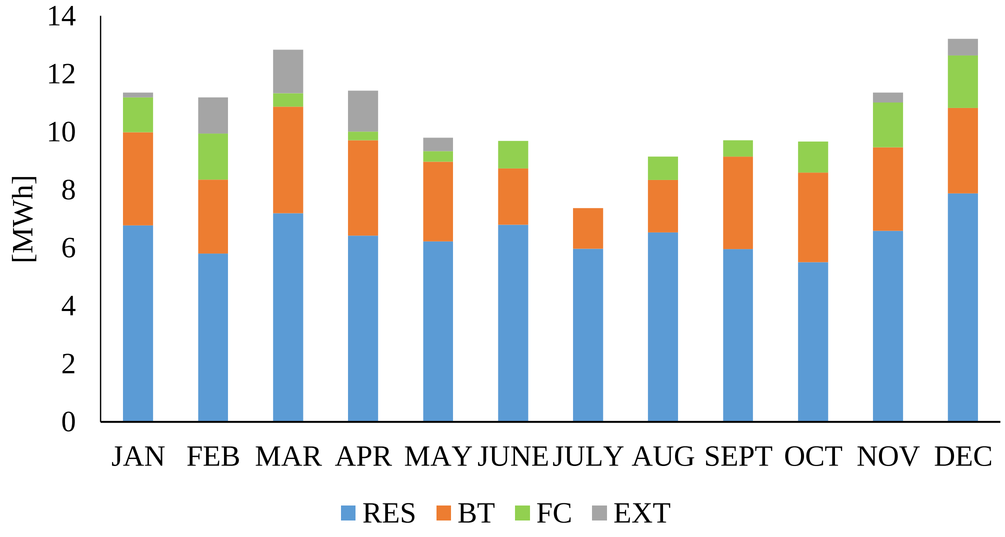


Figure 24. Monthly distribution of the load coverage (strategy 2 + hysteresis)

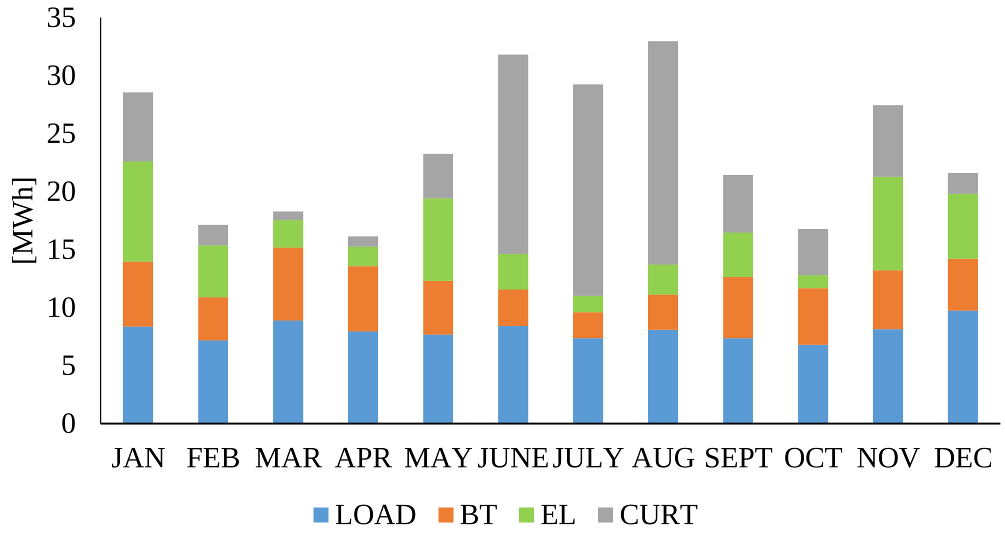


Figure 25. Monthly distribution of the RES usage (strategy 2 + hysteresis)

A slightly lower utilization of the fuel cell and electrolyzer is observed when hysteresis is not considered (7.8% instead of 8.4% for the fuel cell and 16.3% instead of 17.5% for the electrolyzer). This is due to the fact that the battery device is used a bit more increasing the occurrence of its over-charging/discharging.

Unlike for the other sites, the influence of additional loads due to auxiliary components has not been considered for DEMO 4. However, the following evaluation will be performed in subsequent works together with a refinement of the model.

In order to show the longer term energy storage capability of H_2, the evolution throughout the year of the amount of hydrogen in the tank is represented in the figure below:

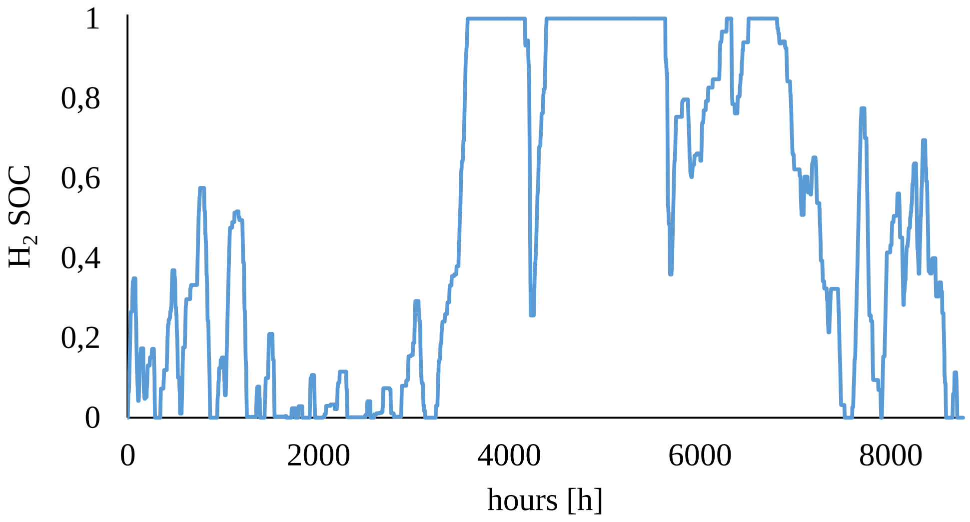


Figure 26. H_2 state of charge over the year

The trend of the H_2 state of charge is in line with data of Figure 12. 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 H_2 storage, which is then gradually emptied in the second part of the year where an increase of the deficit occurs.

According to the reported results, local RES coupled with the hydrogen/battery energy storage 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.

In a scenario with the only availability of power from wind, the annual energy required from an external source would be increased from 5.69 to 29.42 MWh, corresponding to 23.21% of the total load. The wind production is in fact characterized by a very high variability and the support of another source, such as solar which is more predictable and costant, is suggested.

Conclusion

The main aim of Task T2.2 is to provide detailed technical specifications of the four demonstrators underling how the local situation is improved with the operation of the P2P solution. A brief description of each site has been carried out including technical data of the battery/hydrogen storage system and information related to local RES and loads. The usefulness of the adoption of an energy storage solution has been also underlined by evaluating the energy deficit and RES surplus along the year for the various DEMOs.

These data were then used as an input for a first level operation strategy model, developed in order to show the effectiveness of the proposed innovative solutions. Different control strategies were considered to take into account both the configuration in which the battery is employed as daily energy buffer and the one in which the battery is only used as a support for the system operation. The hysteresis concept was also introduced to try to reduce battery heavy utilization by increasing the intervention of the hydrogen pathway.

Preliminary results reveal that the employment of an external source (e.g. a fossil fuel generator or the grid) is significantly reduced. Ambornetti community was found to reach a completely energy autonomy thanks to the exploitation of local solar and biomass sources. In Ginostra and Rye, the usage of an external source can be reduced to around 4.4% and 4.5% of the total load, respectively (values which can be further decreased with more refined models).

A relevant use of the battery component (as, in particular, in the case of Ginostra), which could accelerate its degradation process with consequent economic impacts, could be alleviated by reasonably increasing the fuel cell intervention according to different and more specific control strategies.

Finally, in Agkistro, the P2P configuration, acting as a backup system, was verified to be effective in its task, guaranteeing 1-2 days of energy autonomy and with the capability of meeting the highest load request.

Outcomes of these preliminary simulations have therefore proved the utility derived from the operation of the proposed storage solutions. A more detailed modelling and the improvement of the currently analysed power management strategies will be the objective of subsequent tasks.

The technical solutions derived in the current deliverable, together with the contexts presented in D2.1, will allow for subsequently defining the economics (expected economic outcomes and the business cases) of the DEMOs.

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Appendix

Daily RES usage and load coverage are shown for some reference days for the various DEMOs.

DEMO 1: Ginostra

The results are referred to strategy 2 + hysteresis.

Reference winter day

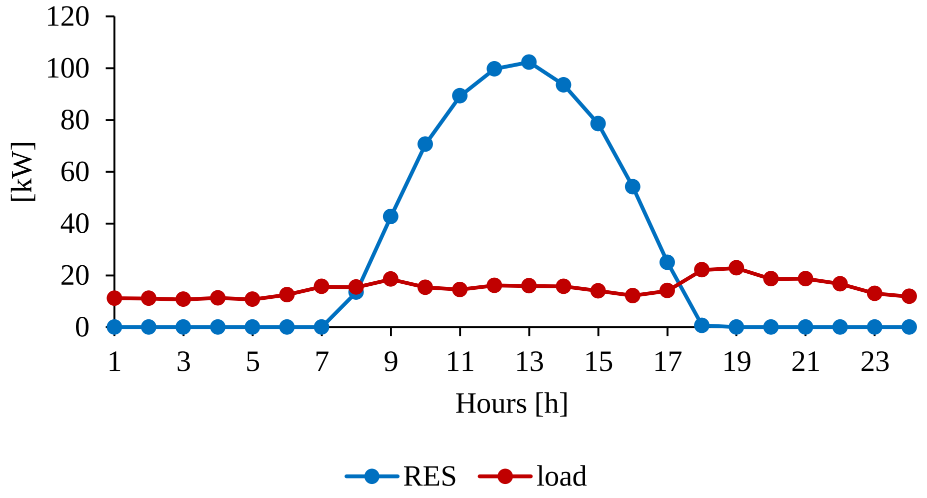

Figure 27. RES and load hourly profiles for a reference winter day in Ginostra

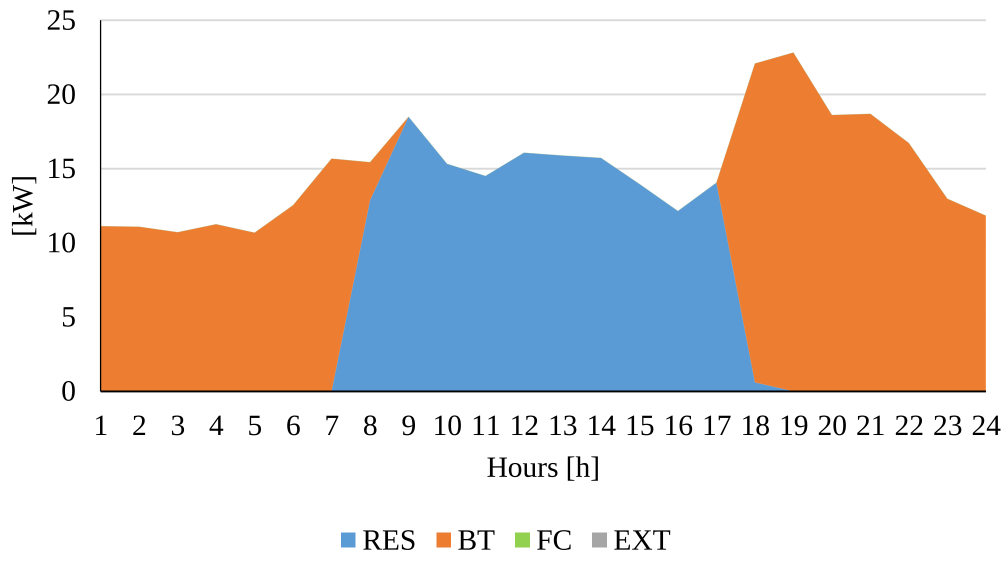

Figure 28. Daily load coverage for a reference winter day in Ginostra

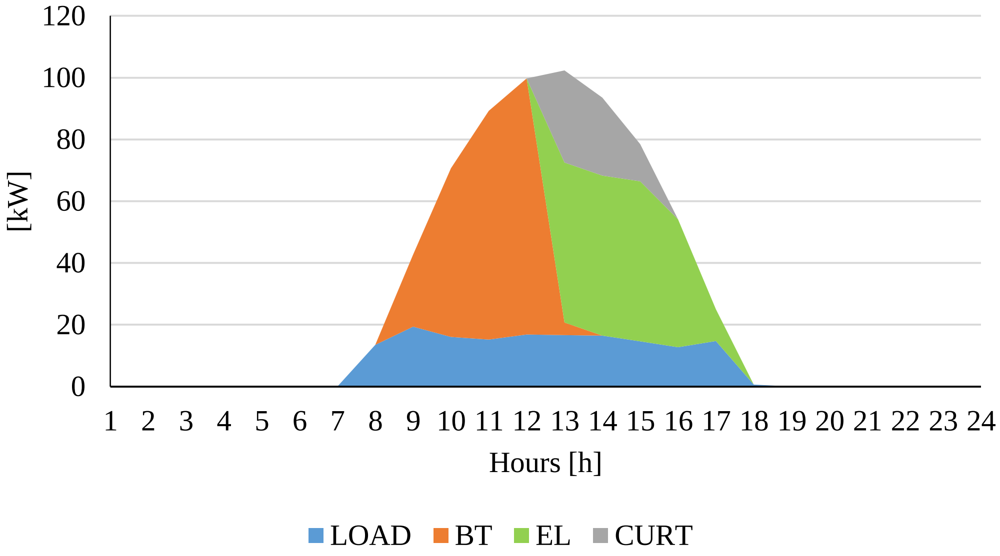

Figure 29. Daily RES usage for a reference winter day in Ginostra

Reference summer day

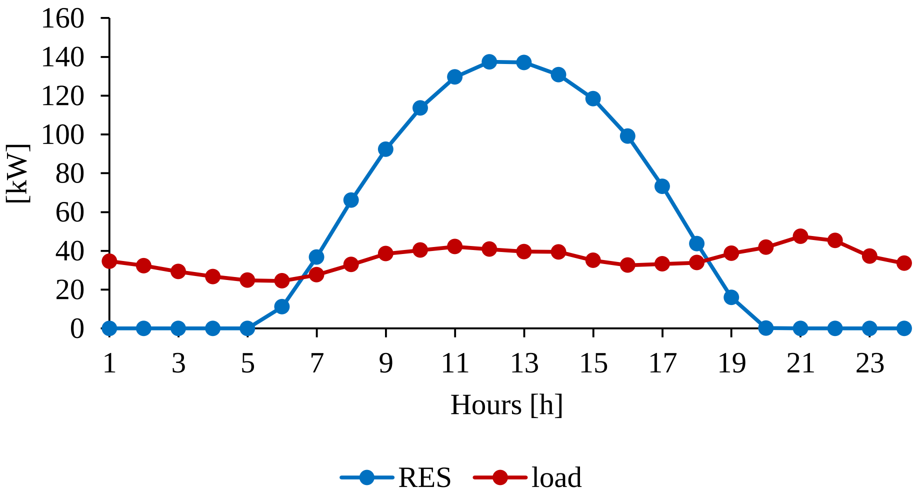

Figure 30. RES and load hourly profiles for a reference summer day in Ginostra

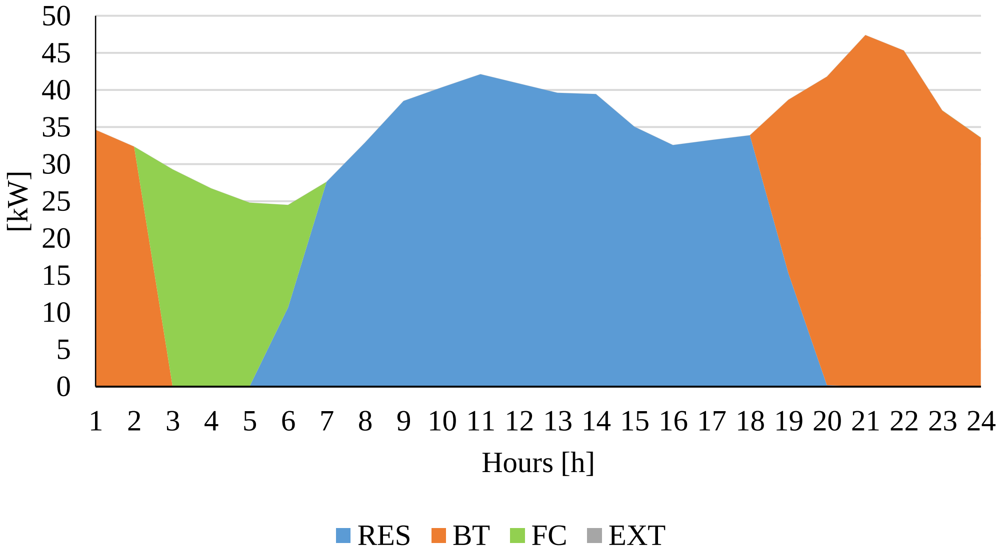

Figure 31. Daily load coverage for a reference summer day in Ginostra

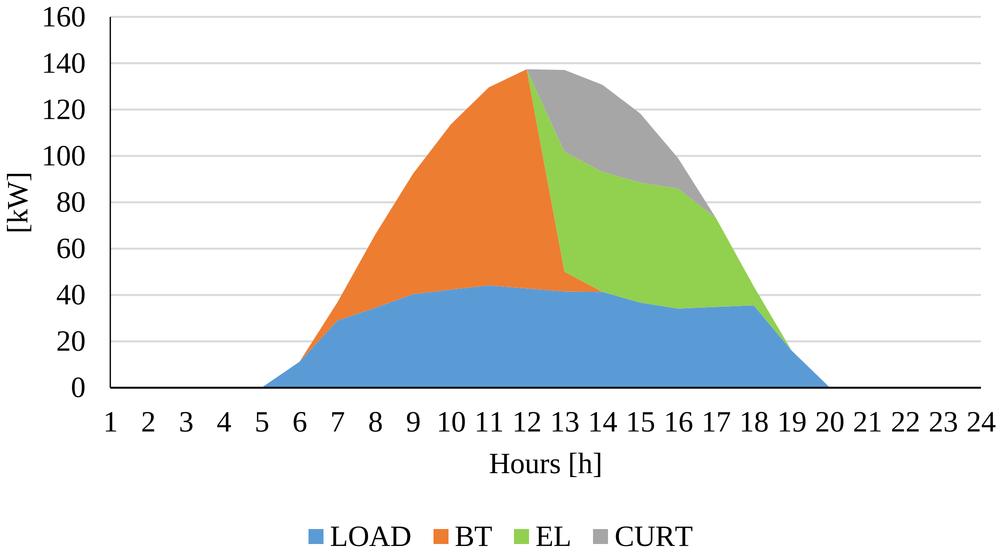

Figure 32. Daily RES usage for a reference summer day in Ginostra

DEMO 3: Ambornetti

The results are referred to strategy 1.

Reference winter day

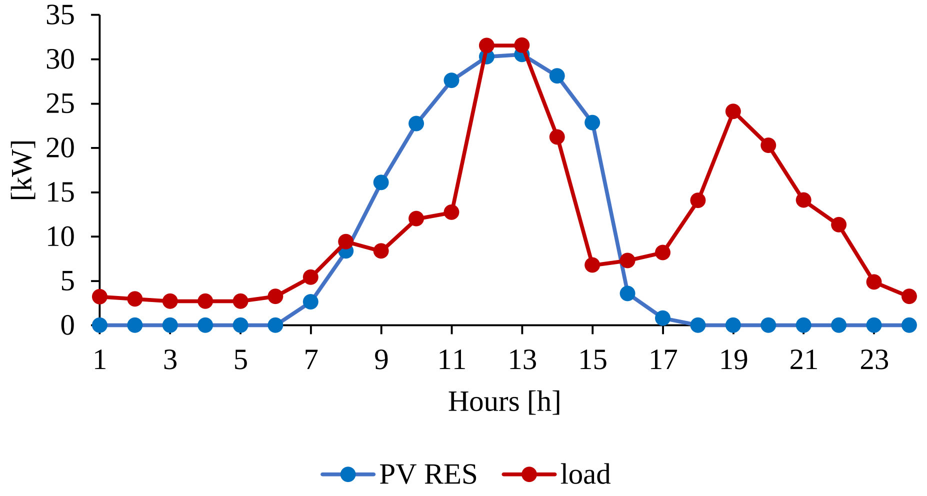

Figure 33. RES and load hourly profiles for a reference winter day in Ambornetti

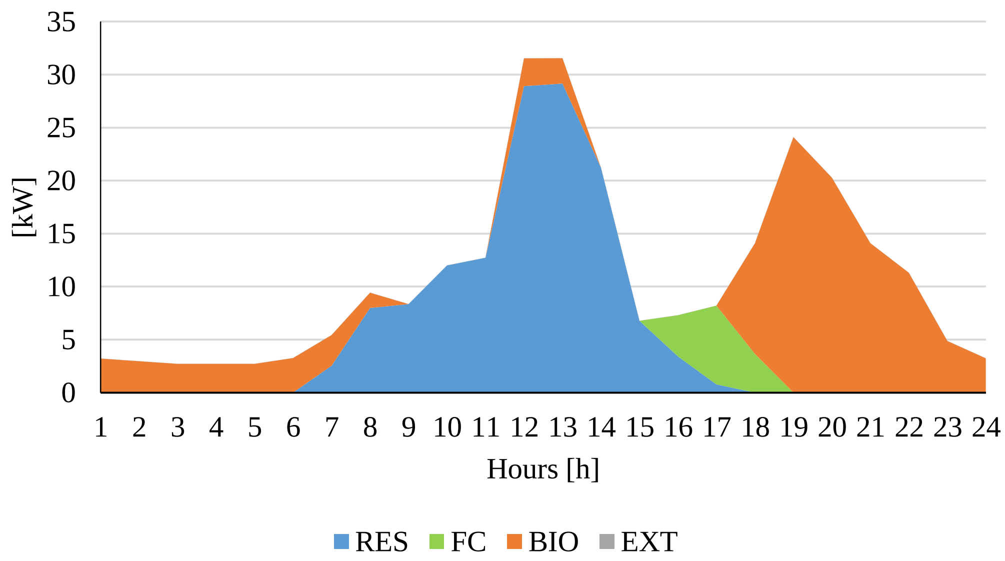

Figure 34. Daily load coverage for a reference winter day in Ambornetti

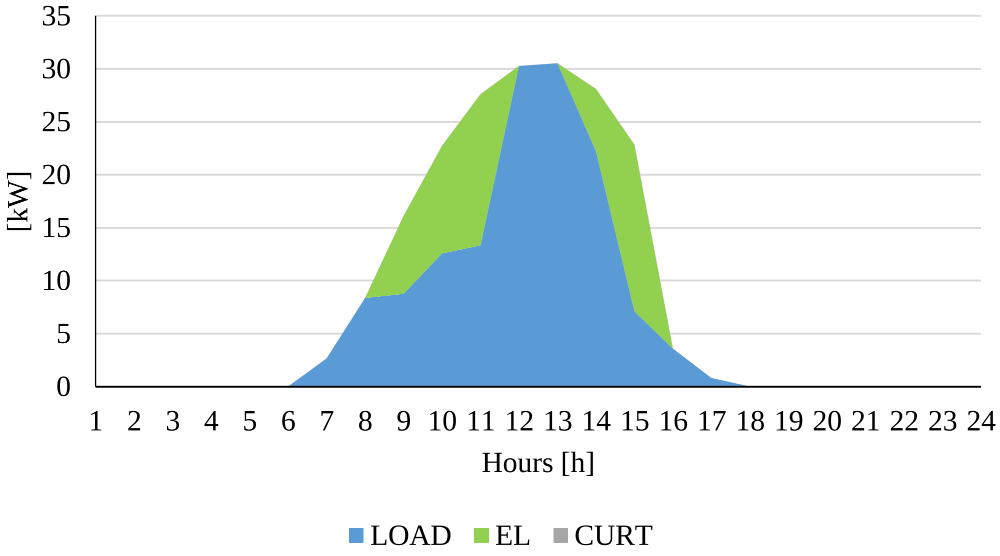

Figure 35. Daily RES usage for a reference winter day in Ambornetti

Reference summer day

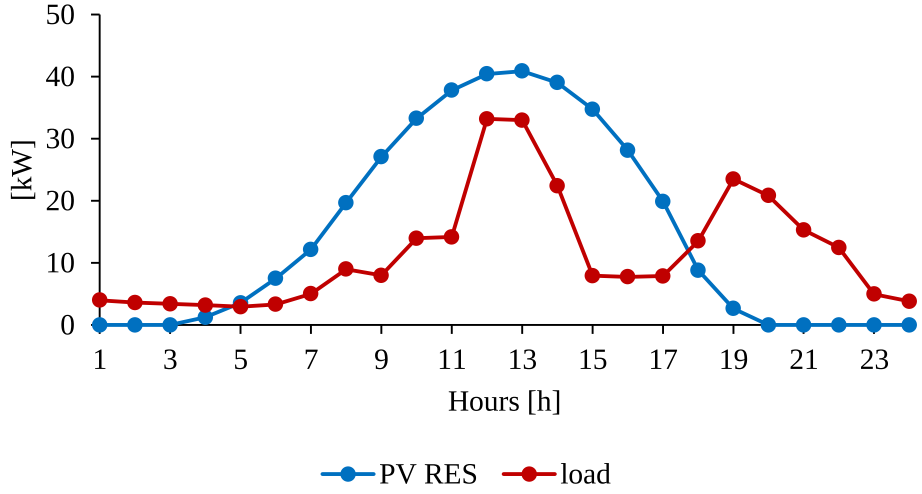

Figure 36. RES and load hourly profiles for a reference summer day in Ambornetti

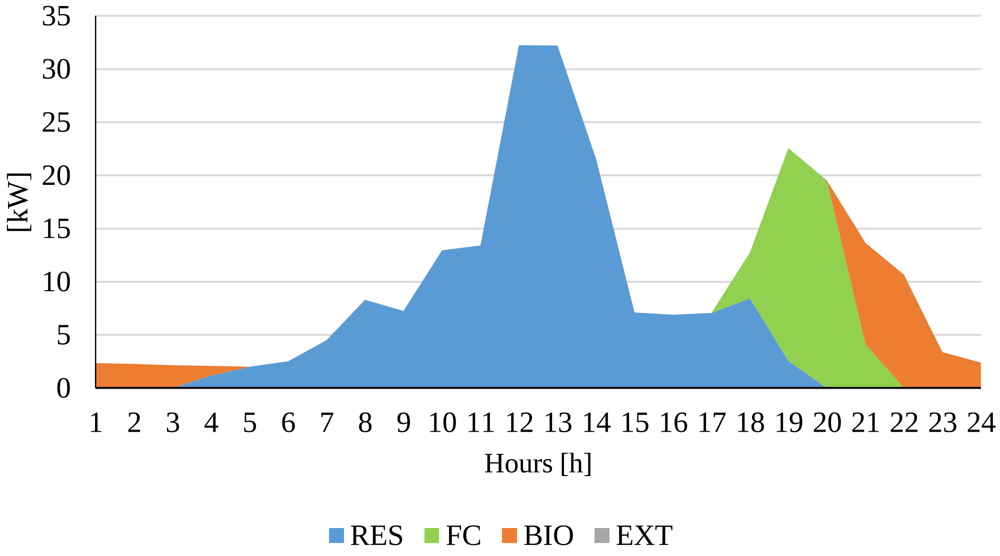

Figure 37. Daily load coverage for a reference summer day in Ambornetti

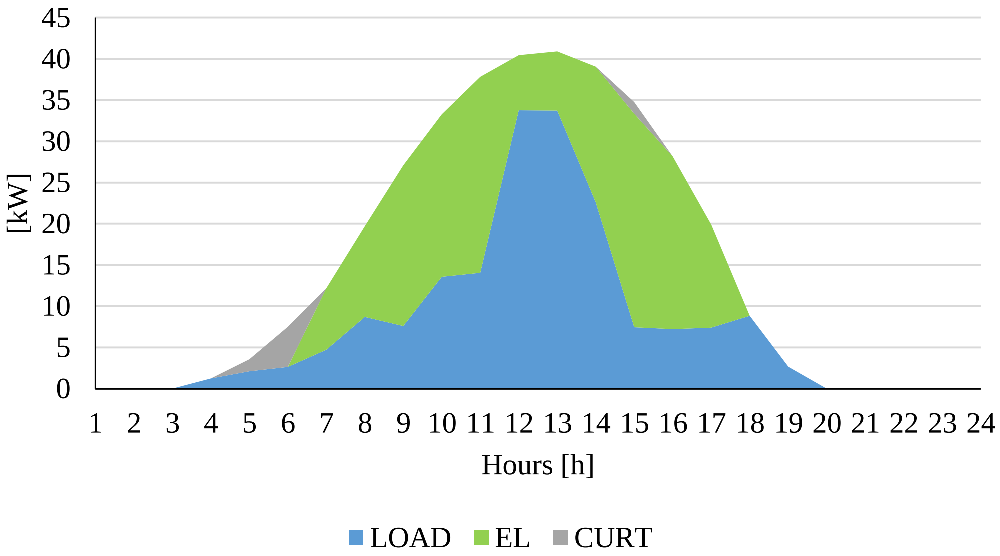

Figure 38. Daily RES usage for a reference summer day in Ambornetti

DEMO 4: Froan/Rye

The results are referred to strategy 1.

Reference winter day

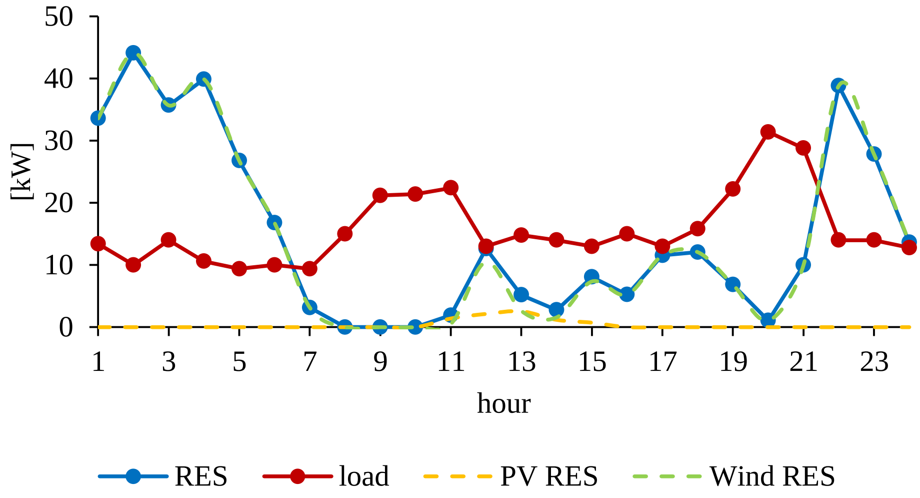

Figure 39. RES and load hourly profiles for a reference winter day in Rye

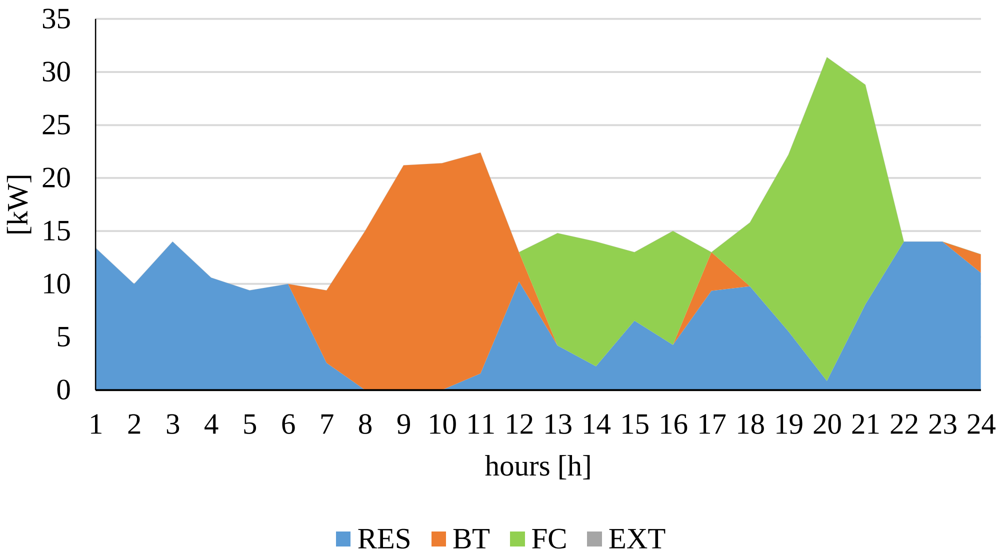

Figure 40. Daily load coverage for a reference winter day in Rye

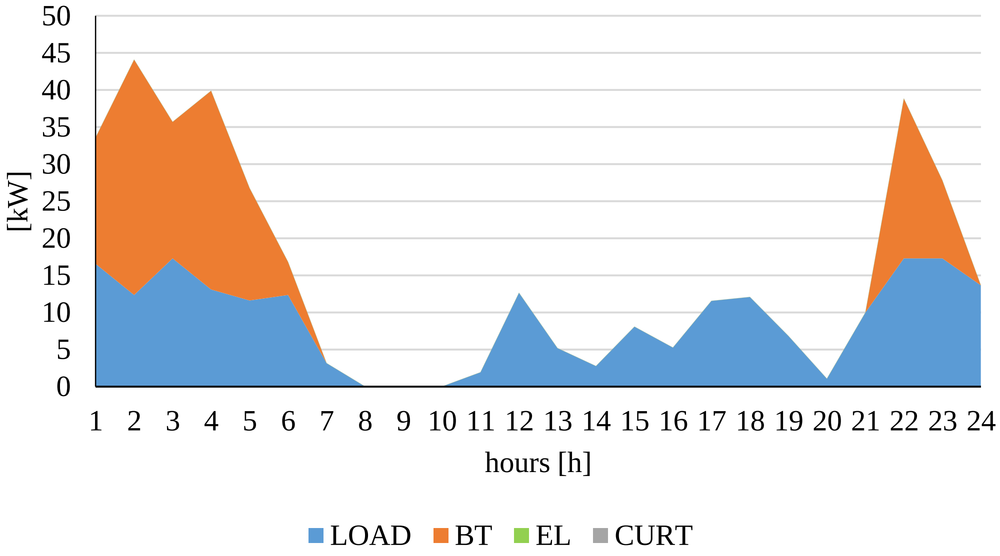

Figure 41. Daily RES usage for a reference winter day in Rye

Reference summer day

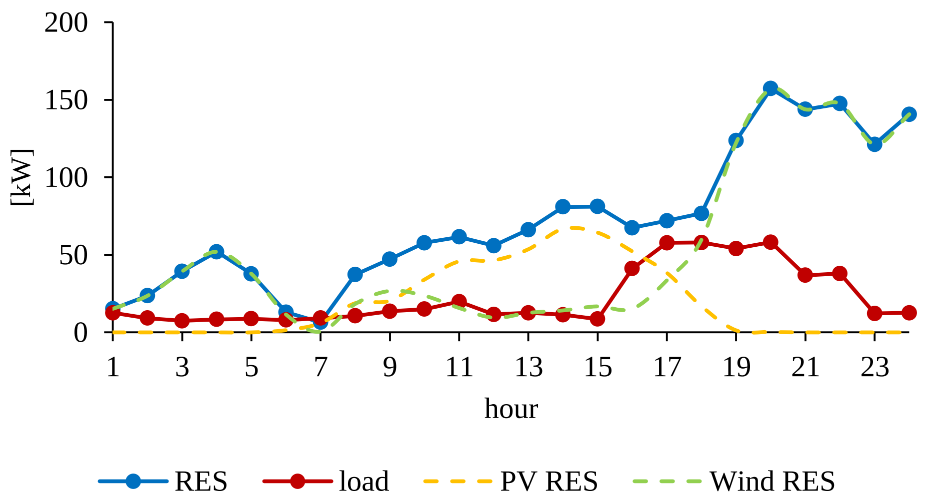

Figure 42. RES and load hourly profiles for a reference summer day in Rye

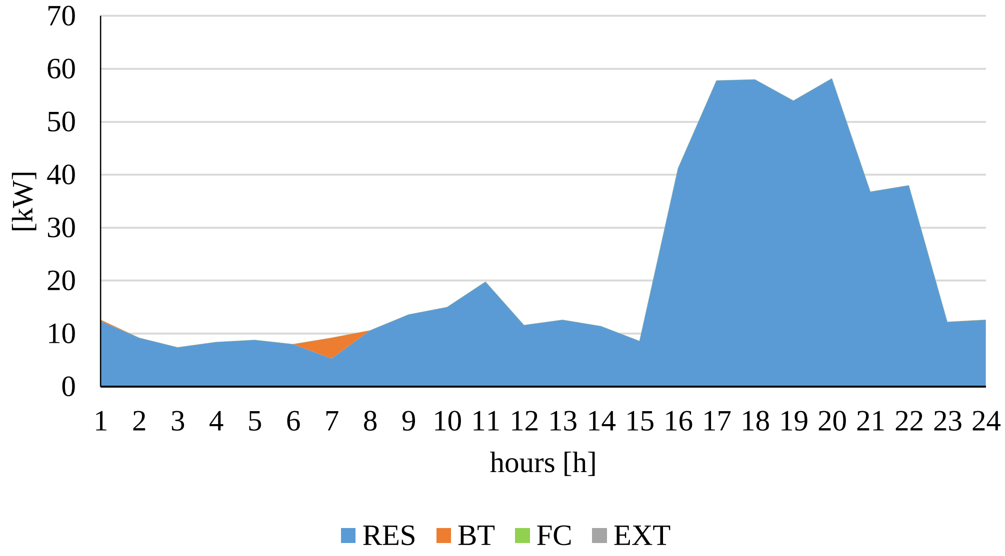

Figure 43. Daily load coverage for a reference summer day in Rye

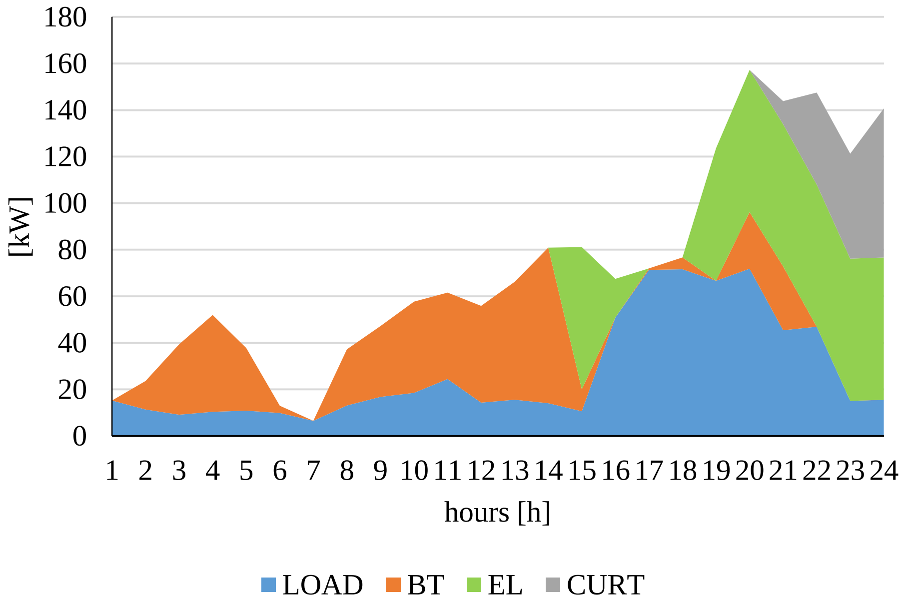

Figure 44. Daily RES usage for a reference summer day in Rye