REMOTE

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“Remote area Energy supply with Multiple Options for integrated hydrogen-based Technologies”

Deliverable number 2.5

Control strategies of the 4 DEMOs

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Abstract:

This work describes the activities performed by the activities of Task 2.4 “Control strategies of the 4 DEMOs”. Initially the definition of the technological specifications of each DEMO is performed by using information from Deliverable D2.2. Subsequently the objective of Task 2.4 was to formulate the control strategies for each DEMO. The analysis includes the development of a generic methodology for the energy management of the hybrid systems which is based on Finite State Machine (FSM) algorithms and propositional based logic.

A set of representative operation scenarios were performed and evaluated, along with the analysis of extreme cases of operation based on the nature of the DEMOs. The results revealed the challenges and potential issues of each DEMO, as well as, some suggested solutions to address the identified issues. A number of Key Performance Indicators (KPIs) was introduced, in order to establish a base case scenario analysis for every DEMO site that will be used for the future development of the control strategies.

Keyword list:

Energy Management, Power to Power (P2P), Renewable Energy, Control Strategies, Finite State Machine (FSM)

Contents

1 Introduction

The main objective of WP2 is to define the use cases of the 4 DEMOs. After a preliminary analysis of the use cases performed in Task T2.2 (Technical specification of the technological demonstrators), the main objective of Task T2.4 is to develop the control strategies for each DEMO plant. The purpose of Deliverable 2.5 is to develop a generic methodology for the energy management of the isolated P2P systems that will be deployed at the four demo sites. The generic methodology is implemented with control strategies that can be adapted to the specific use cases of each DEMO. This document describes the formulation of the generic energy management strategy (EMS) which was developed in conjunction with the formulation of a decision making algorithm. This algorithm, namely Finite State Machine (FSM), incorporates a propositional-based logic that aims to evaluate the state of each individual subsystem of the plants and result in the transition to a new state according to the operation principles of the integrated system.

The **main objectives** of the activities that were performed by Task T2.4 are:

- Presentation of the use cases for each DEMO.
- Definition of the energy management framework.
- Definition of the finite state machine algorithm.
- Formulation of the control cases.
- Evaluation of the results to indicate possible issues for the operation of the DEMOs.
- Proposition of possible solutions for the emerged issues.
- Definition of key performance indicators to set a base case for future development of the control framework.

The developments of Deliverable D2.5 will be updated and refined with the acquisition of real performance data after the deployment of the four demo stations.

1.1 Document structure

Following this introductory section, the remaining part of the document is structured as follows:

- Chapter 2 provides a general overview of the existing DEMOs and their technical specifications
- Chapter 3 describes the methodology used in the energy management strategy, including the definition of the finite state machine.

- Chapter 4 includes an overview of the control strategies that were developed. Also a thorough analysis of each separate use case of the DEMOs is conducted, based on the results of the control strategies.
- Chapter 5 presents an analysis of the operation results based on the defined key performance indicators (KPIs).

Finally, Chapter 6 provides general conclusions and guidelines on how the results included in this deliverable will be further elaborated in forthcoming stages of the project activities.

2 Use cases

In this section, a brief description of the four DEMOs is performed showing the main technical characteristics of the various subsystems. For there to be a link between the deliverables, tables and figures are taken from Deliverable 2.2. Information about local RES and loads is presented in order to fully understand the basis upon which the control cases in Section 4 are designed.

2.1 DEMO 1 (Ginostra)

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^{TM}) from EPS with a Li-Ion battery from EGP and hydrogen storage equipment from EPS is adopted in the Ginostra location.

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

Table 1. Main technical data of the HyESS^{TM} solution.

Rated energy [kWh]	Charge/discharge rate [kW/kWh]	Efficiency [%]	SOCmin [%]	SOCmax [%]
600	0.5C	95	20	80

Table 2. Main technical data of the battery bank.

Tank Volume [m3]	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

The monthly distribution of the energy required by the residential load and the energy produced by solar RES is reported in Figure 1. The table below reports the yearly values of the total consumption and production of power.

	Energy [MWh]
Total Load	171.54
RES Production	273.15
RES Surplus	190.76
RES Deficit	89.15

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

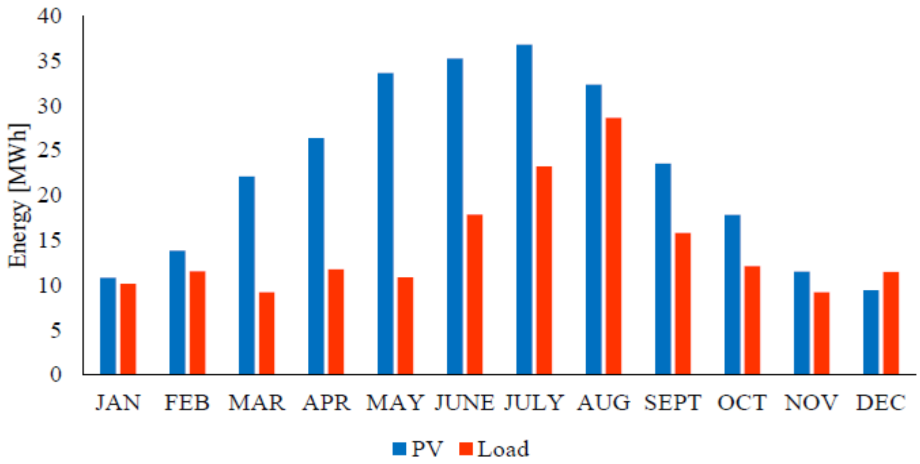


Figure 1. Monthly distribution of PV production and load

The deficit and surplus behaviours along the year are shown in the following Figure 2.

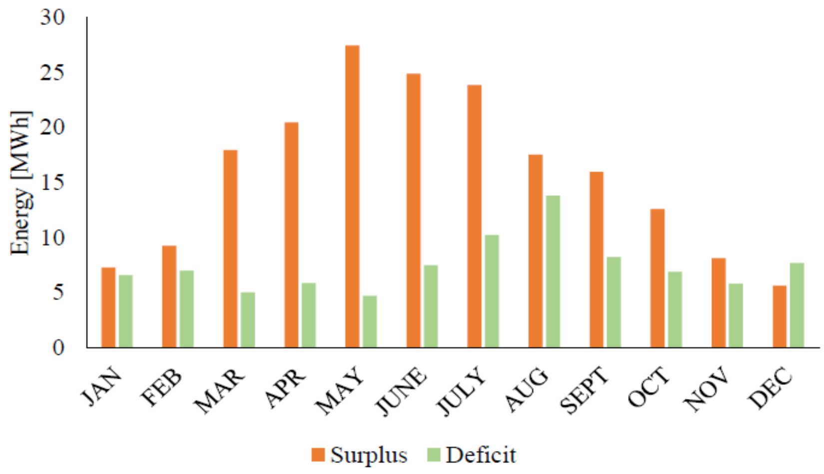


Figure 2. Energy surplus and deficit along the year

2.2 DEMO 2 (Agkistro)

Technical specifications

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

- RES sources

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^{TM}) 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	50	15-100	0.5

Table 5. Main technical data of the HyESS^{TM} solution.

Rated energy [kWh]	Charge/discharge rate [kW/kWh]	Efficiency [%]	SOCmin [%]	SOCmax [%]
30	2C	95	20	80

Table 6. Main technical data of the battery bank.

Tank Volume [m3]	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.

RES supply and load

For each month, the energy produced by the hydro power plant and the requested load are shown in Figure 3.

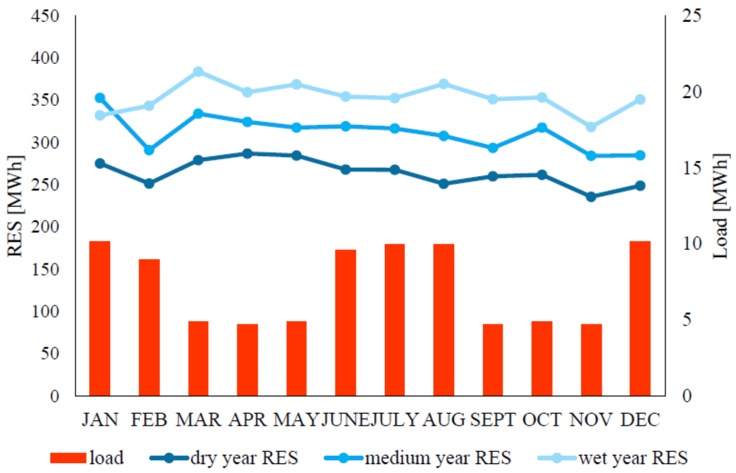


Figure 3. Monthly distribution of hydroelectric production and load.

2.3 DEMO 3 (Ambornetti)

Technical specifications

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

- RES sources

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.

- Integrated P2P system

Similar to DEMOs 1 and 2, the HyESS^{TM} 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	50	15-100	0.5

Table 8. Main technical data of the HyESS^{TM} solution.

Rated energy [kWh]	Charge/discharge rate [kW/kWh]	Efficiency [%]	SOCmin [%]	SOCmax [%]
30	2C	95	20	80

Table 9. Main technical data of the battery bank.

Tank Volume [m3]	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

In Figure 4, the monthly distribution is reported. The table below reports the yearly values of the total consumption and production of power.

	Energy [MWh]
Total Load	96.63
RES Production	86.75

RES Surplus	32.74
RES Deficit	42.61

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

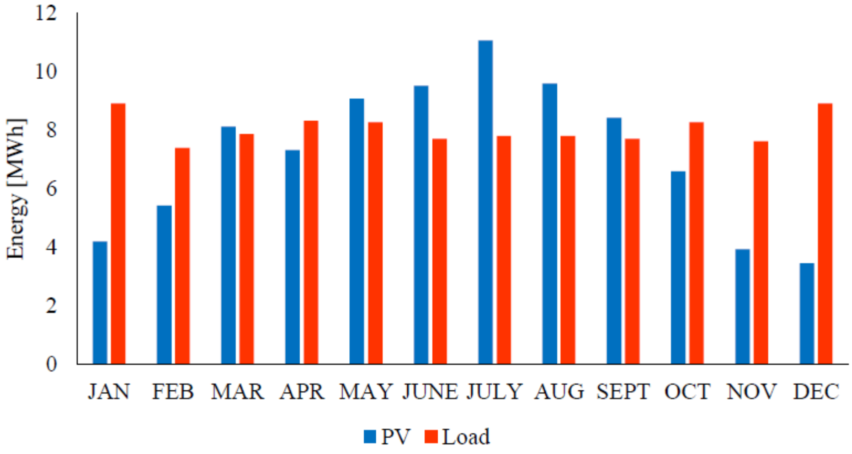


Figure 4. Monthly distribution of RES production and load.

The deficit and surplus behaviours along the year are shown in the following Figure 5.

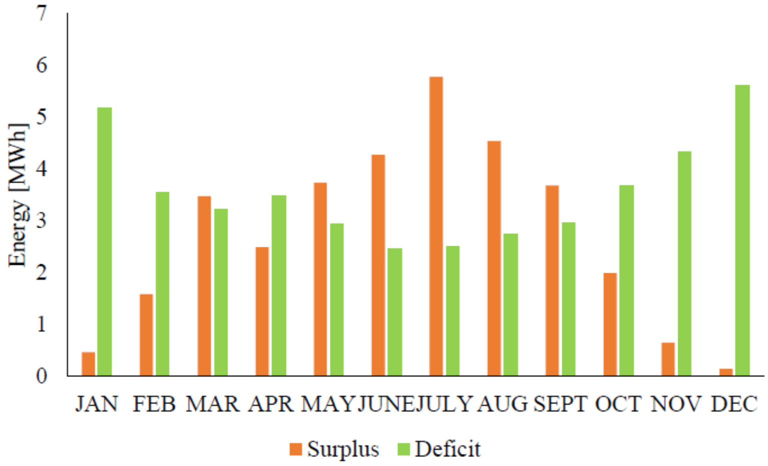


Figure 5. Energy surplus and deficit along the year.

2.4 DEMO 4 (Froan/Rye)

Technical specifications

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

- RES sources

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

- Non-integrated P2P system

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	96-100	0.5

Table 12. Main technical data of the HyESS™ solution.

Rated energy [kWh]	Efficiency [%]	SOCmin [%]	SOCmax [%]
550	95	20	90

Table 13. Main technical data of the battery bank.

Pressure [bar]	Useful gross energy (LHV) [kWh]
30	3333(~100kg)

Table 14. Main technical data of the hydrogen storage.

RES supply and load

The PV and wind energy production for each month is shown in Figure 6. Table 15 reports the yearly values of the total consumption and production of power.

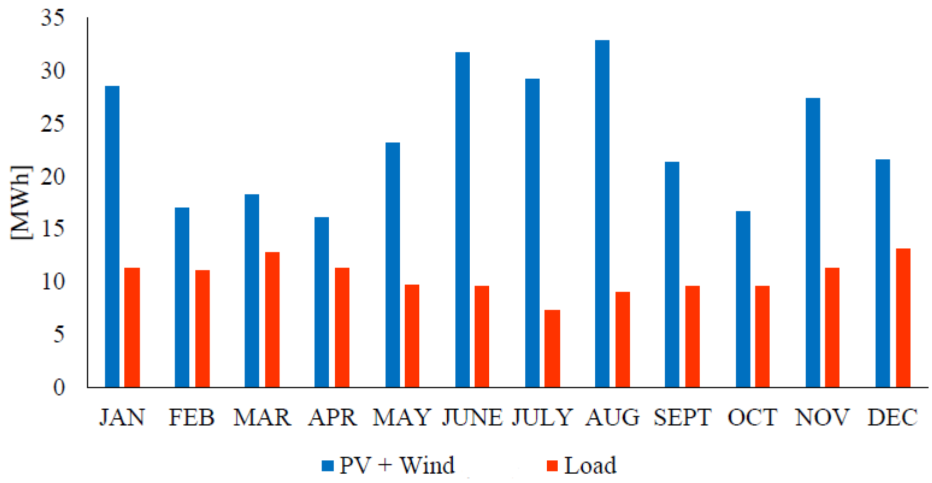


Figure 6. Monthly distribution of RES production and load in Rye.

	Energy [MWh]
Total Load	126.75
RES (PV+Wind) Production	284.68
RES (PV+Wind) Surplus	203.13
RES Deficit	45.21

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

The high amount of surplus RES energy (more than four times the deficit) is shown clearly in Figure 7.

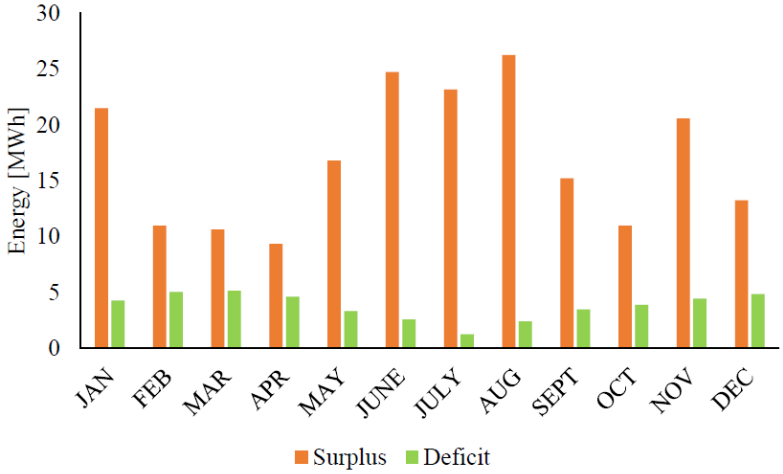


Figure 7. Energy surplus and deficit along the year.

3 Methodology - Energy management framework

The scope of this chapter is to present the generic methodology that was developed for the energy management of the hybrid systems. For this purpose a FSM was formulated and the decision making was assisted by propositional–based logic where each involved system and possible state was included and formulated accordingly.

3.1 Energy management strategies (EMS)

Energy management strategies (EMS) are needed to supervise the operation of each integrated system (DEMO), to evaluate the RES storage efficiency and coordinate the subsystems operation. Thus the development of a suitable EMS is necessary to assess the performance and operation of each DEMO. The purpose of the EMS is twofold, to supervise the status of each subsystem and to be able to adjust to system operational modes. The derived set of rules can be used for the control of the operation of the subsystems, namely the electrolyzer (EL), the fuel cell (FC), the battery bank (BAT), the diesel generator (DSG) and the hydrogen storage tank (HT). The EMS consists of a series of switching actions in order to drive the system from its initial state to an operating mode appropriate to satisfy the load demand taking into consideration each subsystem's or/and device's specifications and the constraints. This methodology is called Finite State Machine (FSM).

3.2 Finite State Machine (FSM)

A finite-state machine (FSM) or finite-state automaton is commonly used in computer science (e.g. for parsing, compiler design and formal verification) and in the design of digital logic circuits [1]. In this work a FSM is used to describe the realization of the EMS for the operation of our hybrid P2P energy storage system. A FSM is a dynamic approach that describes the evolution in time of a set of discrete and continuous state variables. The solar hydrogen system exhibits two kinds of dynamics completely different in nature, namely discrete (e.g. start or stop of the fuel cell) and continuous dynamics (e.g. State of Charge of the battery). The interaction between discrete and continuous operating states motivates the use of the hybrid approach and thus the FSM appears as a powerful analysis tool for the realization of a generic EMS. A FSM is defined by a tuple $(Q, q_0, \delta, \lambda, X, Y)$ in which Q is a finite set of states, $q_0 \in Q$ is the initial state, δ is the state transfer function, λ is the output function, X is the finite input alphabet; and Y the finite output alphabet. The alphabet (X, Y) represents the rules of operation that will be explained in the following section. If FSM receives input x while in state q it produces output $y = \lambda(q, x)$ and moves to state $q' = \delta(q, x)$. This defines a transition $(q, q', x/y)$.

3.3 Logical representation of the operating rules

The transitions between the states are described using a formal propositional-based logic. The output function can enable or disable the operation of a subsystem (EL, FC, BAT, DSG and HT) based on the status of its energy storages, the accumulators (BAT) and the hydrogen tank (HT). The State of Charge (SOC) of the accumulator and the level of the hydrogen storage tank are the main parameters that drive the operating decisions of the EL and the FC. The level of energy in each storage (BAT, HT) defines a set of Boolean variables (β) which are related with the operation of the subsystems. The value of each Boolean variable can be true or false and based on that, the respective subsystem is allowed to operate or not.

In this propositional based approach every logical function can be expressed as a combination of the logical operations (AND: ^, OR: ∨, NOT: !) and the status of each subsystem or the level of stored energy and subsequently compared to the respective level or to each other using the respective operand (Greater: >, Less: <, Equal: =). Furthermore a hysteresis band is used in the boundary limits of the accumulator to avoid irregular operation (reduction of frequent start-ups and shut-downs). For example the operation of the FC depends on the level of H_2 in the HT. A Boolean variable (β_{HT}) represents the level of H_2 in the HT (Table 1).

Variable status	Description
$[\beta_{HT} = 1] \leftrightarrow [\mathrm{HT} \geq HT_{high}]$	Variable β_{HT} is true (=1) if and only if the pressure of H_2 in the HT is greater/equal to HT_{high} (4bar)
$[\beta_{HT} = 0] \leftrightarrow [\mathrm{HT} \leq HT_{low}]$	Variable β_{HT} is false (=0) if the pressure drops below HT_{low} (3bar)

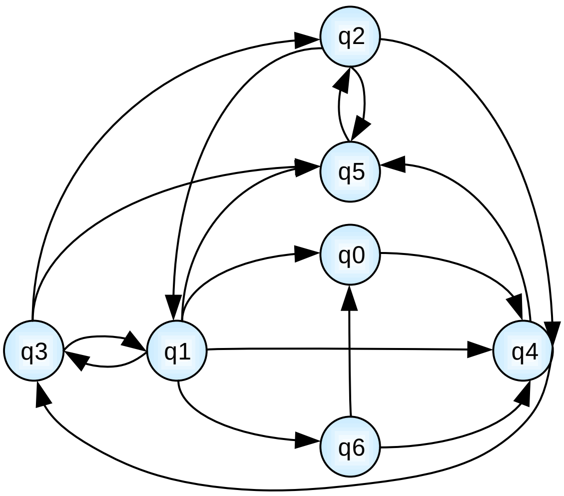
Table 16. Hydrogen Tank Status Variable

In a similar way a set of Boolean variables are defined for the fuel cell operation (β_{FC}), the electrolyzer operation (β_{EL}), the diesel generator operation (β_{DSG}) and the SOC of the accumulators $(\beta_{\min}, \beta_{FCoff}, \beta_{ELon}, \beta_{ELoff}, \beta_{\max})$. In order to define the transitions of the FSM these variables are combined into propositional rules to provide the reasoning behind the subsystems operation. In Table 17 a subset of the FSM's input alphabet is presented that corresponds to the transitions for the hydrogen production and consumption.

Propositional rule	Description
$x_2 : [\mathrm{P} > 0] \wedge (\beta_{ELoff} \wedge \beta_{HT})$	There is a surplus of RES power (P) and the accumulators are charged to the point where the electrolyzer is allowed to operate while the H_2 tank pressure is lower than its maximum level (28bar)
$x_3 : [\mathrm{P} < 0] \wedge !\beta_{\min} \wedge !\beta_{HT}$	There is a deficit of RES power (P), the H_2 tank pressure is lower than its minimum level (3bar) and the SOC of the accumulators is below the minimum (SOC<20%)

Table 17. Propositional Rules and Input alphabet

Each rule constitutes a letter of the input alphabet. These set of rules are derived by the operation of the unit's subsystems. The FSM that describes the operation of our system is shown in Fig 8.



q0: System standby (System curtails excess RES)

q1: Charge BAT by RES

q2: Preserve battery by FC or DSG

q3: FC covers load

q4: BAT covers load

q5: DSG covers load

q6: Electrolyzer produces H_2

Figure 8. Finite State Machine for the operation of the system

The use of the FSM that realizes the EMS enables the study of the behaviour of integrated systems in a flexible way due to its flexibility and adaptability. Overall the proposed EMS is able to incorporate engineering and computational knowledge and techniques for the application on the actual system and it can incorporate various operating modes. Additionally, it offers a theoretical context for the analysis and design of complicated energy systems involving multiple energy sources and loads.

4 Control Cases of the 4 DEMOs

4.1 Overview of the Control Strategies

In this section, the control studies of the 4 DEMOs are presented. The purpose of this study is to apply a systematic methodology that decides about the power distribution actions among the subsystems considering the individual subsystems of each hybrid station. For this purpose, the EMS that was described at Chapter 3 was used in order to achieve this objective. A system level modelling approach was adopted for the purpose of this study. A more detailed and generic approach will be employed after the acquisition of data from the demonstration sites operation.

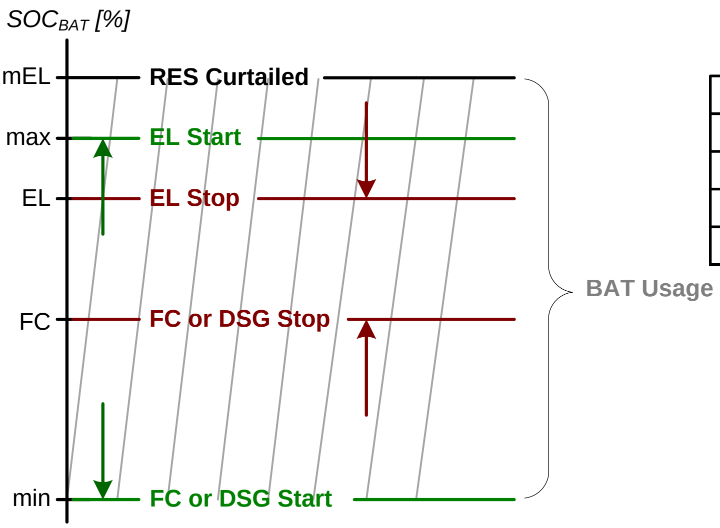
The overall objectives of the hybrid P2P energy storage system are:

- The preservation of battery life (main controlled variable: SOCbat)
- The safe operation of the other subsystems (operation within the limits of FC and EL)
- Optimal exploitation of the energy produced by the RES regarding load fulfilment and energy storage.

According to the needs of each demo site the appropriate scenario configuration was applied. Overall the conditions upon which the scenarios were simulated were:

- Seasonal analysis on selected cases
- Monthly analysis
- Extreme case of RES shortage for 3 days
- Time interval of 1h for the simulation

In this particular framework, the energy sources are the fuel cell (FC), the battery (BAT), the diesel generator (DSG) and the available RES in each DEMO. The load demand defines whether the RES is sufficient to cover it or there is a need of power from another source (FC, BAT, DSG). In other words, the energy surplus or deficit (P) determines the operation of the individual subsystems. In case there is a surplus of RES power, this amount of energy can be stored in the form of electricity by the battery or in the form of H_2 in the pressurized tank (through water electrolysis, EL). Which of the two takes place, depends on the state of charge of the battery (SOC). If the battery SOC has reached its maximum level, then and only then, the EL will operate to produce H_2. Instead, when the SOC is below its max, the battery is charged up to its maximum point. In case there is a deficit of RES power, then the battery covers the occurring shortage of power. If the SOC drops below its minimum point then the FC starts in order to cover the load. The diesel generator acts like a back-up energy source when the battery is discharged and the hydrogen tank is empty. In the extreme case where a long lasting power deficit occurs, if the SOC of the battery is below 20% then the FC (and DSG when the H_2 in storage is consumed) has the role of charging the battery up to a point that it can operate to satisfy the load (>50%). In any other case, the battery is only charged by the RES surplus. The operational zones of every subsystem are shown in Figure 9. The arrows indicate whether the battery is being charged or discharged. The operational zone of the battery is set from 20 to 80%, only surpassing its maximum point when the EL has filled up the hydrogen tank and there is still surplus in the RES production. Then, the battery stores energy until it reaches 90%, which is the point where RES curtailment occurs.



mEL	90 %
max	80 %
EL	70 %
FC	50 %
min	20 %

Figure 9. Finite State Machine operational zones

Every subsystem is correlated to a variable that forces its start/stop operation or its continuous operation. For example, the fuel cell's operation depends on the level of available H_2 in the storage tank as it is shown in Figure 10.

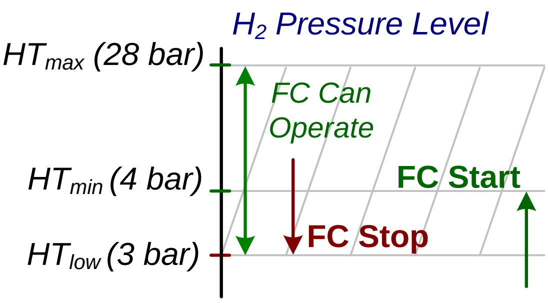


Figure 10. FC operation with regard to H_2 pressure level.

The case studies for each DEMO are described below.

4.1.1 DEMO 1 (Ginostra)

As mentioned in Chapter 2, the Ginostra DEMO site benefits from a large amount of available power coming from PV (yearly surplus = 190 MWh, yearly deficit = 89 MWh). The 600 kWh battery bank plus the 1793 kWh hydrogen tank integrated in the HyESS^{TM} system from EPS are responsible for the energy storage. This case scenario aims to preserve, under nominal operation, the battery life as well as to avoid frequent start-ups and shut-downs of the EL and FC. The battery SOC, which is the main controlled parameter, fluctuates within its specified limits. The addition of the hysteresis bands in the control strategy secures the continuous operation of the EL and FC. The data for RES availability throughout the year exhibit seasonal fluctuations, therefore the results shown in this case refer to the middle month of each season (January, April, July and October) to better understand the seasonal behaviour of the demo.

4.1.2 DEMO 2 (Agkistro)

The hydroelectric plant is characterized as energy storage means by its nature. Under this framework the RES power produced by the plant is much higher than the loads that need to be satisfied and also the loads are predictable (agro-food unit). This means that the P2P station acts as a back-up unit in case of a maintenance of the hydro plant or other malfunctions that can cause power shortage for a couple of days. The case study for this demo site demonstrates the response of the hybrid system when an event as mentioned occurs. Three different simulations show the response under different seasonal loads.

4.1.3 DEMO 3 (Ambornetti)

The demo site in Ambornetti although it integrates a 30kWh battery bank, it is mainly used for the system start-up and therefore not acting as an energy buffer. A 50kW biomass CHP generator (BIO) is integrated to the system. Based on available published information [2] and own experience such biomass gasification/generator system have low availability (ability to run throughout the year). It was assumed that a properly set system would provide an availability on 80% of the time, meaning that 20% of the days it will be out of service. Accordingly, a different control strategy was formulated for this demo's site simulation. So, for this demo's case, the battery will no longer supply power with priority to the other sources (FC, BIO, DSG). Instead, the primary energy source will be the biomass generator, with the fuel cell operating only when the BIO is unavailable. In case of both low hydrogen storage and BIO non-availability then a hypothetical DSG will take over to secure the continuous supply of power to the load. The results for the simulation of this case study are shown for four indicative months of each season (January, April, July, October) just like DEMOs 1 and 4.

4.1.4 DEMO 4 (Froan/Rye)

The demo site in Rye (data not available for Froan) has throughout the year, as shown in Chapter 2, a much bigger surplus of power than deficit. This translates to large amounts of power being curtailed. Similar to the case of the Ginostra site, the nominal operation of the P2P system is considered. The coupled wind turbine with the PV adds much higher fluctuations in the RES supply. The data for RES availability throughout the year exhibit seasonal fluctuations, therefore the results shown in this case refer to the middle month of each season (January, April, July, and October) to better understand the seasonal behaviour of the demo.

4.2 Analysis of the Operation Results for each Demo Site

The operation of the four stations is explored using the aforementioned EMS with the FSM through the results of the yearly operation of each one (except for the Agkistro case where it is explored through a week of operation). In order to have a more distinct picture of the results, only four typical months, one during each season, are shown in this section. The results produced from the employment of the control strategies are shown for one month in this section and the rest are reported in the Appendix.

4.2.1 DEMO 1 (Ginostra)

For the Ginostra station the results refer to one month (January). The RES supply for this month is low, almost the same as the load demand. The control strategy employed focuses on the energy management and distribution among the subsystems with the battery SOC being the main controlled variable. The initial conditions of the system display a low storage level for the hydrogen and battery as a result of the low RES supply of the previous month. The results produced by the FSM simulation are shown in the figures below.

In Figure 11, in particular, the results refer to the whole month (left side) and to three consecutive days of the month (right side).

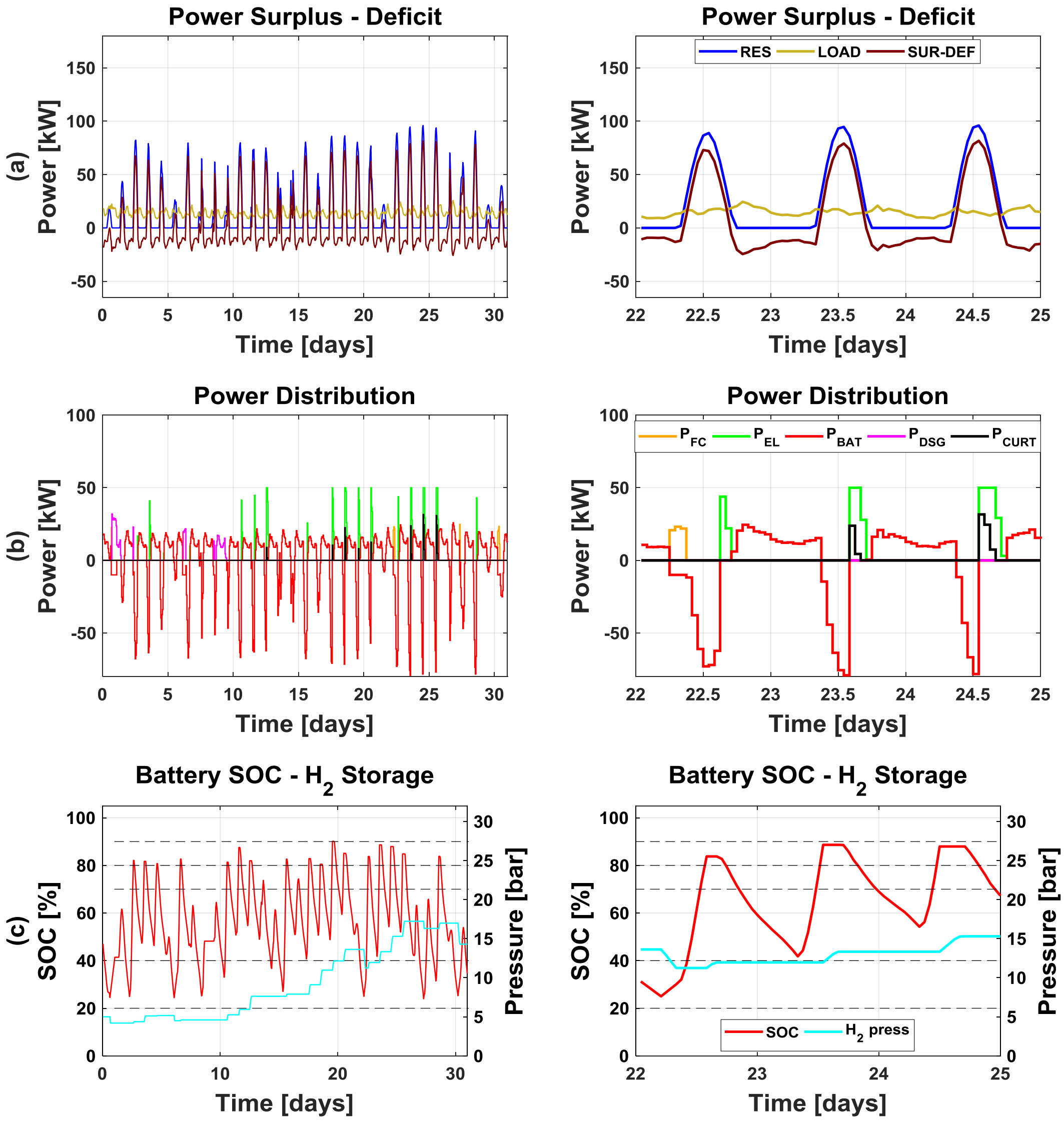


Figure 11. (a) Available RES, load and surplus-deficit, (b) Power distribution, (c) Battery SOC and hydrogen storage level. (left) Whole January and (right) 3 days in January.

The hourly distribution of power among the subsystems is displayed in Figure 11b. On the negative side of the y axis, when there is a surplus of RES power, the battery is being charged. When the state of charge of the battery is in the hysteresis zone (20-30%) and there is a load demand greater than the RES available, then the fuel cell takes on the load but also is responsible to charge the battery up to a point where it can operate safely within the zone of 40-70%. If there was a shortage of hydrogen in the tank then instead of the FC, the DSG would operate in its place covering the load and charging the battery. As displayed in Figure 11c, the battery is the main module that meets the load duty, sitting idle only when it is charged above 80% and allowing the EL to produce H_2 by exploiting the RES surplus. The power being curtailed in Figure 11b is a result of the RES surplus being greater than the maximum modulation range limit of the EL (50 kW). The hourly operation of each module is shown in the next figure (Figure 12).

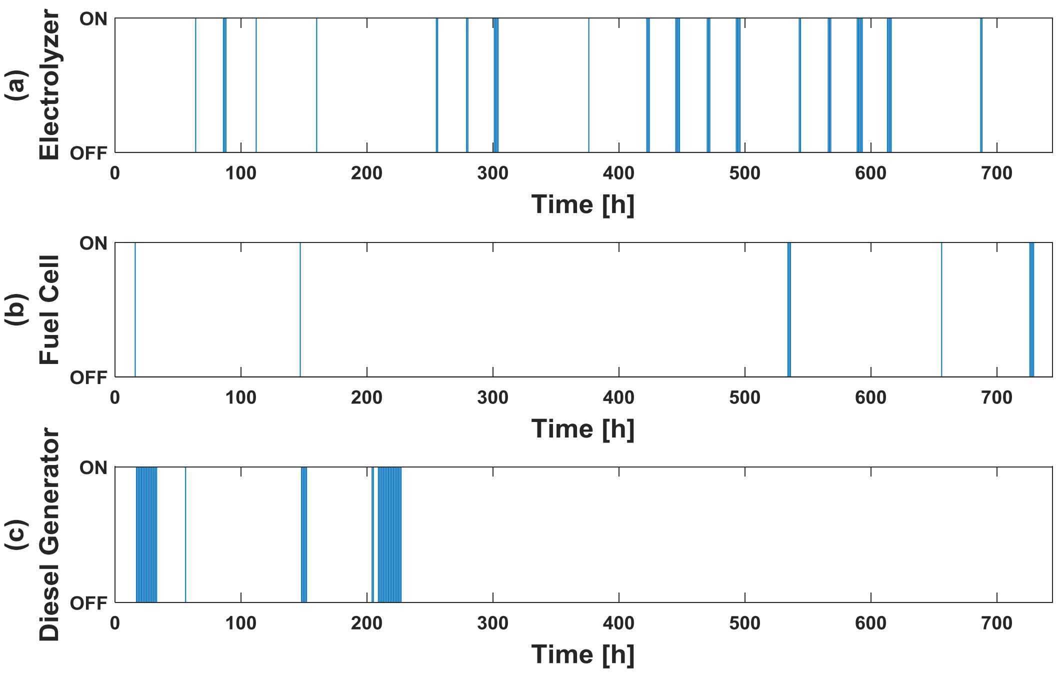


Figure 12. Hourly state (ON/OFF) of the EL (a), the FC (b) and the DSG (c)

In Figure 13c, as stated before, the battery mainly meets the load duty, sitting idle only 6% of its operational time. Furthermore, in this part of the year coming from a month (December) where the most power deficits occur, the diesel generator operates more than the fuel cell compensating for the hydrogen shortage. Coming to the end of the month, the RES supply is increasing as well as the hydrogen storage level (Figures 11a and 13b). For the same reason (low RES in winter), the electrolyzer comes second when there is available surplus, with the battery being initially charged and if there is enough RES power (after the SOC reaches max) then the electrolyzer gets to work.

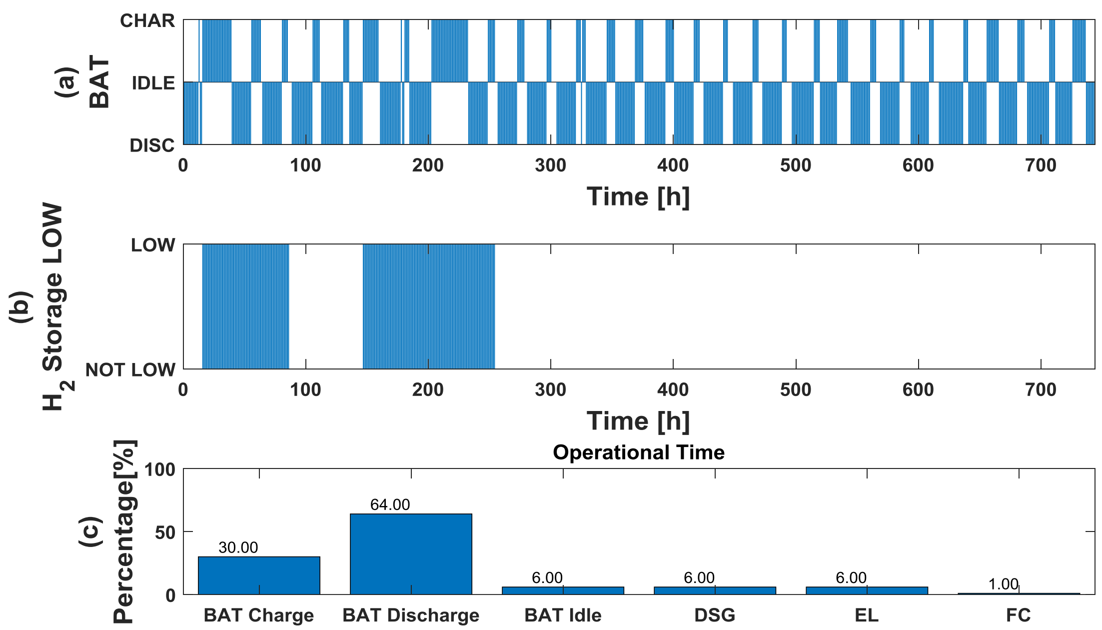


Figure 13. Hourly state(Char/Idle/Disc) of BAT (a), hourly state(Low/Not low) of HT (b), operational time percentage for each subsystem(c)

When considering the yearly operation, it is clear that the hydrogen production from the electrolyzer is favoured in the period between March and November. The tanks are kept almost full through this period, justifying the use of hydrogen for long term storage (see results for other months in the Appendix). The results produced by the strategy in this case, are indicative of the need of bigger hydrogen storage in order to fully curtail the use of a diesel generator in the winter period. This aspect is well known to the project developer Enel Green Power who, however, could not plan the installation of a hydrogen storage volume greater than 24m^3 (currently expected) due to the limited space available in the plant area and to the geometric limits for the positioning of hydrogen storage imposed by Italian law. Moreover, these results offer a base case scenario for the further development of the strategies employed for this DEMO. The models used will be refined after the acquisition of dynamic performance data, taking also into consideration the degradation phenomena of the battery and the efficiency of the EL and FC. An addition to the strategy will be the implementation of optimization-based techniques into the EMS that will decide the best possible distribution of power among the modules, considering health degradation and optimal efficiency.

4.2.2 DEMO 2 (Agkistro)

Since the hydroelectric production in the Agkistro site is always much higher than the load demand, as seen in Figure 3, it is assumed that the hybrid storage system is at full capacity all year long. The control strategy implemented in this case is the same as in DEMO 1 but it is particularly tested in the extreme case of a RES supply failure or a system maintenance. The seasonal loads display a seasonal variance that’s why the results below refer to two months (January and April) with their representative loads.

In Figure 14, the P2P system’s response is shown in the course of the 6 days that the RES failure lasts in January.

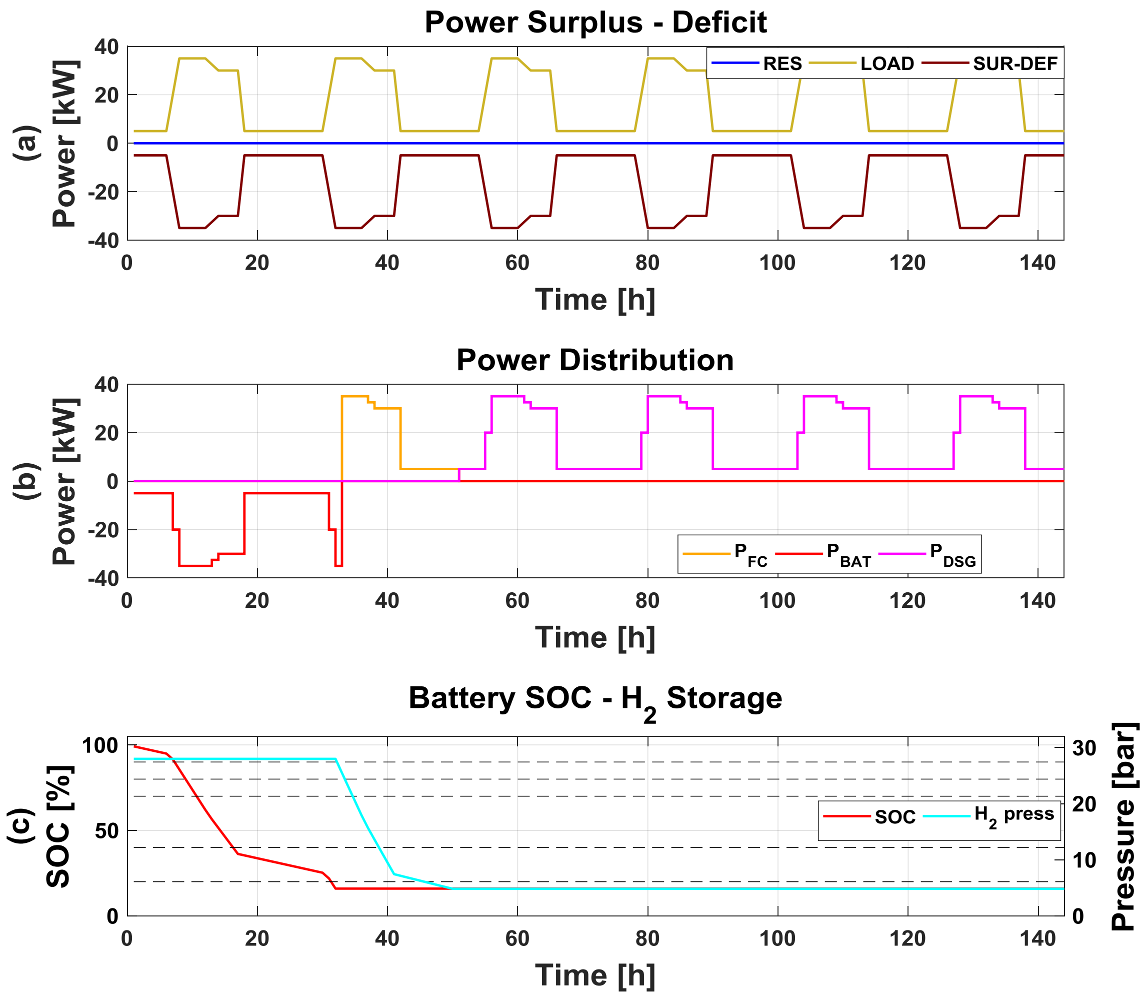


Figure 14. (a) Available RES, load and surplus-deficit, (b) Power distribution, (c) Battery SOC and hydrogen storage level. Month January.

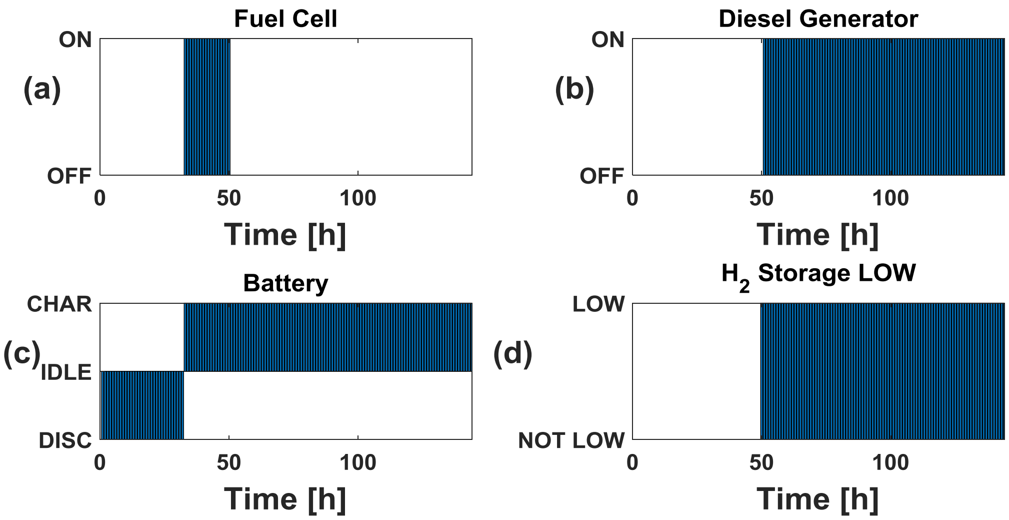
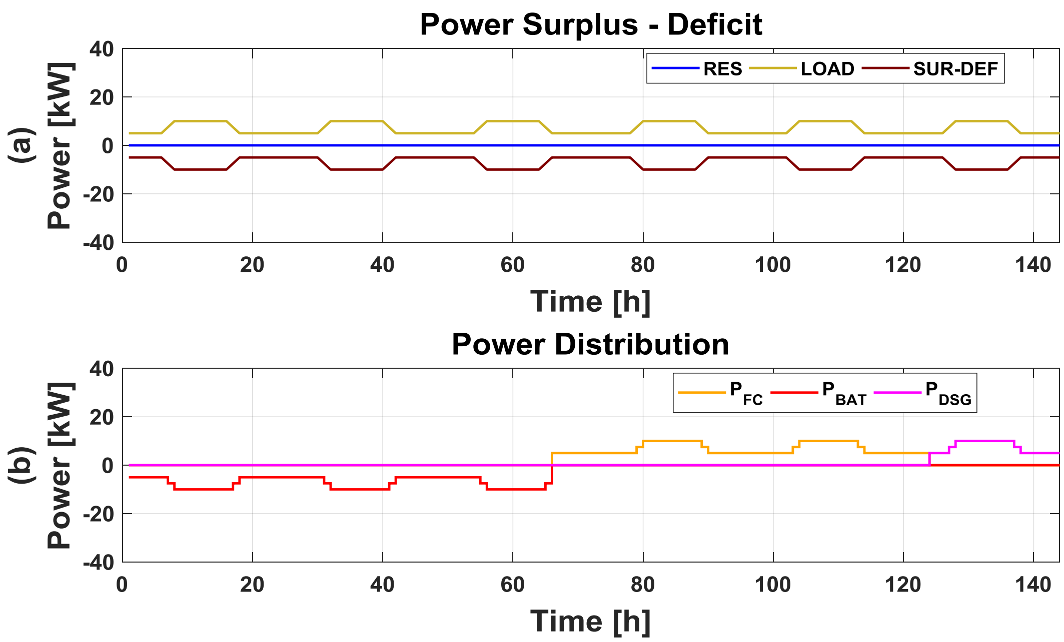


Figure 15. Hourly state (ON/OFF) of the FC (a), the DSG (b), hourly state(Char/Idle/Disc) of BAT (c), hourly state(Low/Not low) of HT (d). Month January

It is clear that the RES storage system is able to supply constant power to the load for almost two days before the theoretical DSG (or any other external power source) is deployed to meet the load demand. Respectively, when the RES failure occurs during April, where the load peaks are almost half in comparison to January, the hybrid system manages to sustain the power supply for five days before the hydrogen storage is low enough to stop the fuel cell operation.



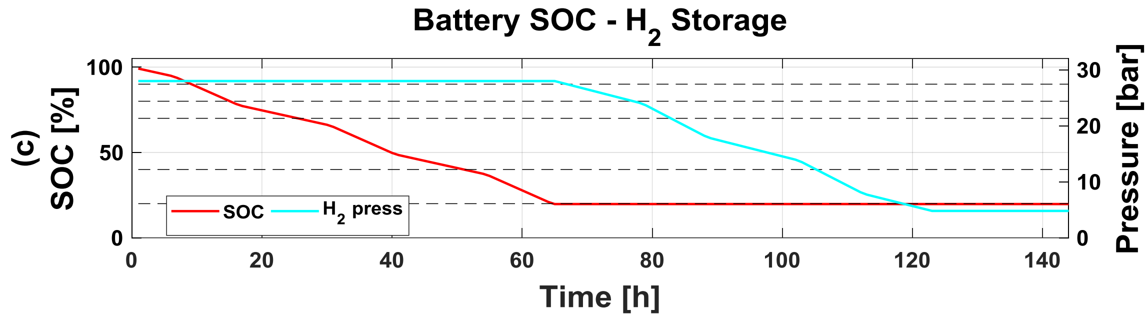


Figure 16 . (a) Available RES, load and surplus-deficit, (b) Power distribution, (c) Battery SOC and hydrogen storage level. Month April.

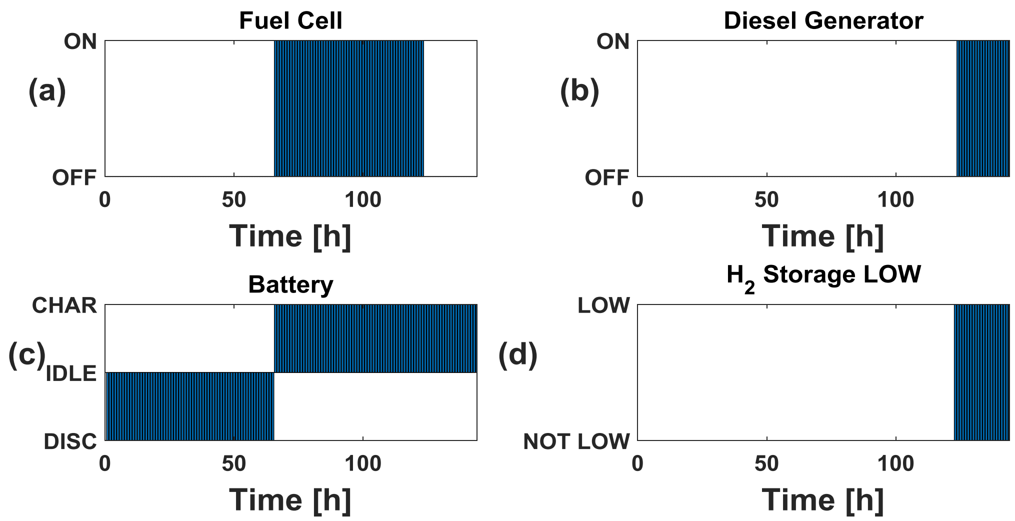


Figure 17. Hourly state (ON/OFF) of the FC (a), the DSG (b), hourly state (Char/Idle/Disc) of BAT (c), hourly state (Low/Not low) of HT (d). Month April.

According to the design specifications of the hybrid P2P system, its role as a back-up system is justified as seen in the results in the above figures. The station will definitely sustain the agro-food unit's energy demand for 2 days before an external source is needed to take over.

4.2.3 DEMO 3 (Ambornetti)

The integration of a biomass generator and the use of a battery that is not large enough to cover the load independently, require a different approach in the formulation of the control strategy. The proposed EMS prioritizes the supply of energy coming from BIO with the use of the fuel cell and diesel generator coming next depending on the H_2 availability. The battery is able to cover some loads for short periods but only when it is charged above 70%. The results produced by the FSM simulation are shown in the figures below.

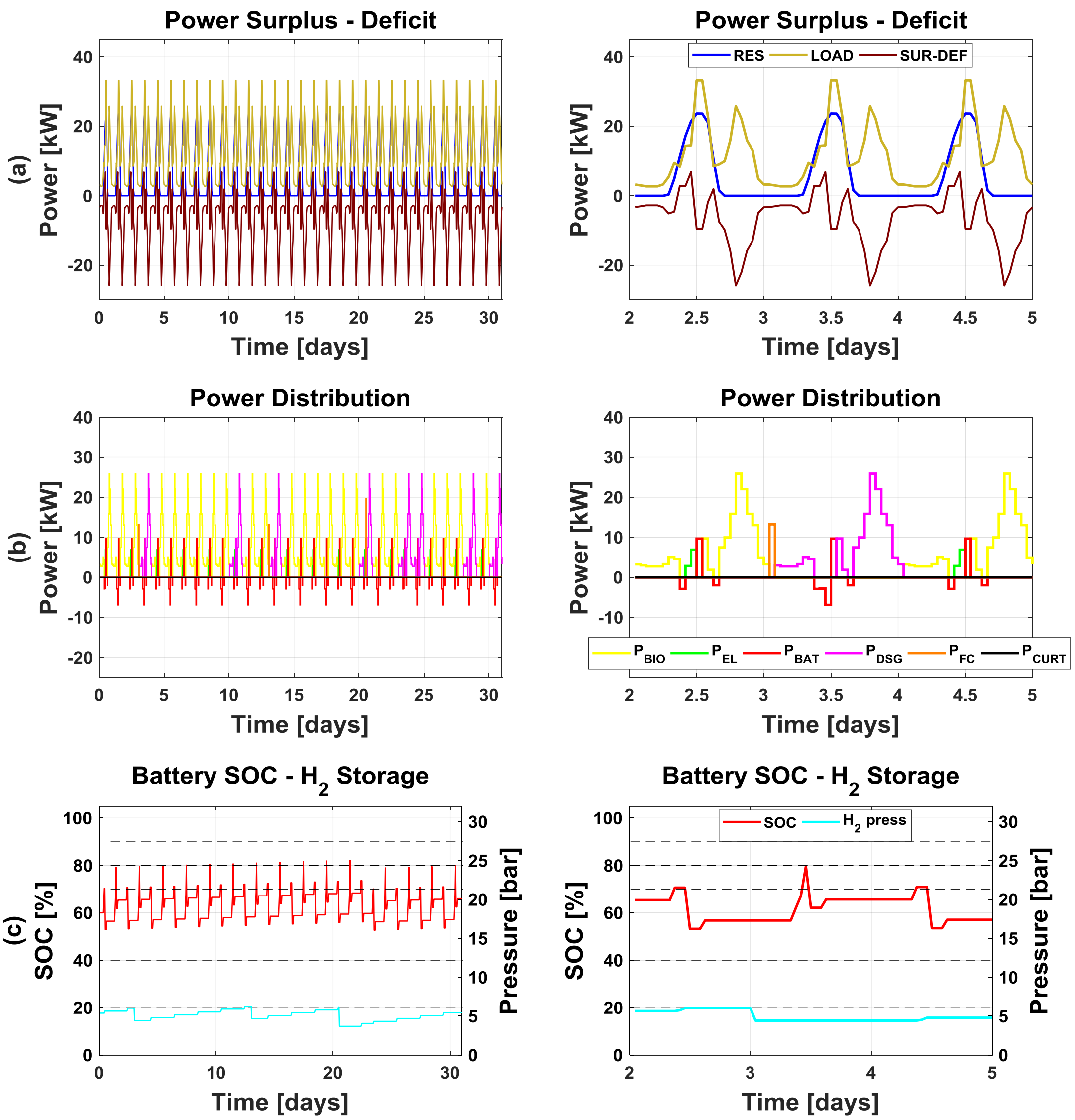


Figure 18. (a) Available RES, load and surplus-deficit, (b) Power distribution, (c) Battery SOC and hydrogen storage level. (left) Whole January and (right) 3 days in January.

Figure 18a shows the RES availability in January. As it is seen, there is an almost constant deficit of power during the whole month with only small peaks of surplus appearing during the day. The RES in this diagram accounts only for the PV installation.

The hourly distribution of power among the subsystems is presented in Figure 18b. The right side displays three days of operation in the first week of January. The first and last day of the three include BIO as an energy source because it is available on these days. The second day BIO is non-existent. When BIO is unavailable, the fuel cell is responsible for the load satisfaction but it is limited by the hydrogen supply. When hydrogen is also unavailable, which is the usual case for a winter month like

January, then a theoretical diesel generator acts as an external source of power to satisfy the load demand.

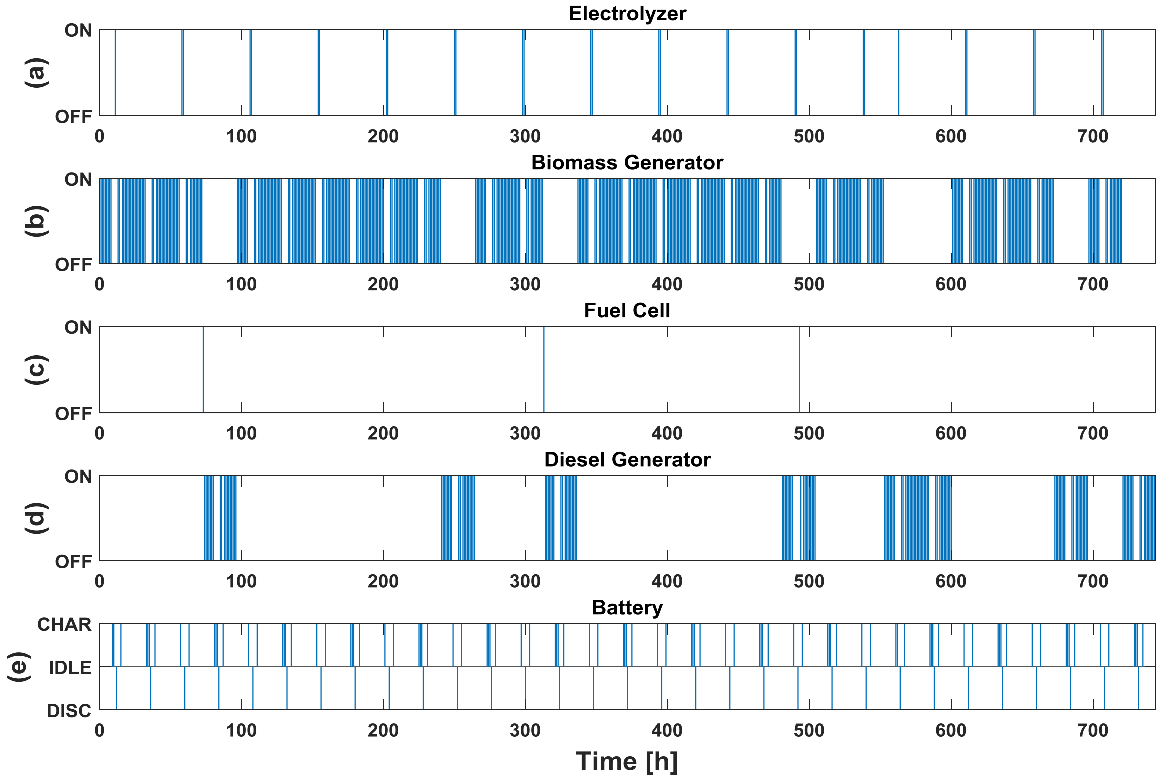


Figure 19. Hourly state (ON/OFF) of the EL (a), the BIO (b), the FC (c), the DSG (d), hourly state (Char/Idle/Disc) of BAT (e). Whole January.

As mentioned before in the control strategies overview, the biomass generator is characterized by a yearly availability of 80% for the purpose of this simulation. In Figure 20b, this availability is shown throughout the month. When there is the possibility to exploit energy from biomass then no other source is necessary to cover the load since no peak load demand is greater than 50kW (max power of the BIO generator). In the opposite case, the fuel cell seems to not have enough available hydrogen to operate continuously during a deficit of power, with the DSG being employed to fill in. This means that either a larger hydrogen storage is required or an installation of additional PV panels in order to have enough RES supply to keep the energy storage at high levels throughout the year. Moreover, the small contribution of the battery is apparent from Figure 20 c, where it is seen that 83% of the time the battery is idle. The deployment of more battery stacks should also be considered, since it can minimize the intervention of the external source of power (DSG).

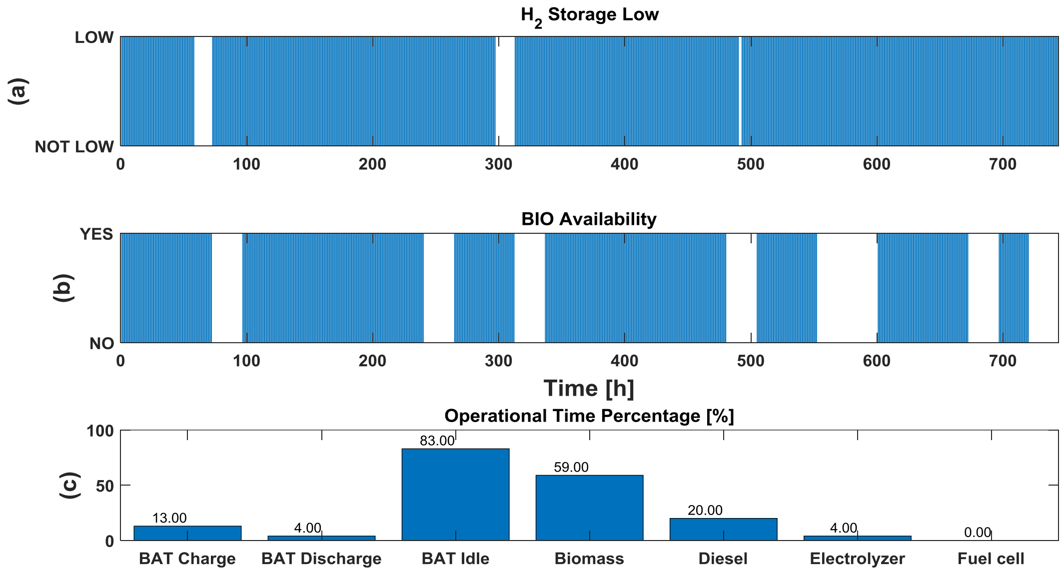


Figure 20. Hourly state (Low/Not low) of HT (a), hourly biomass availability (b), operational time percentage for each subsystem (c). Whole January.

By analogy to the case of DEMO 1 these results offer a base case for the future development of the control strategies and the energy management.

4.2.4 DEMO 4 (Froan/Rye)

For the Rye station (Froan data not yet available) the results refer to one month (October). This month is characterized by a high variability in the RES production. Despite the variability though, the RES is high enough to keep the hydrogen storage full. The control strategy employed is identical to that employed at the Ginostra station. The initial conditions of the system, since October is right after a period where there is reduced deficit, display a storage level for the hydrogen and battery at high values (28bar H_2, 80% SOC). The results produced by the FSM simulation are shown in the figures below. In Figure 21, in particular, the results refer to the whole month (left side) and to three consecutive days of the month (right side).

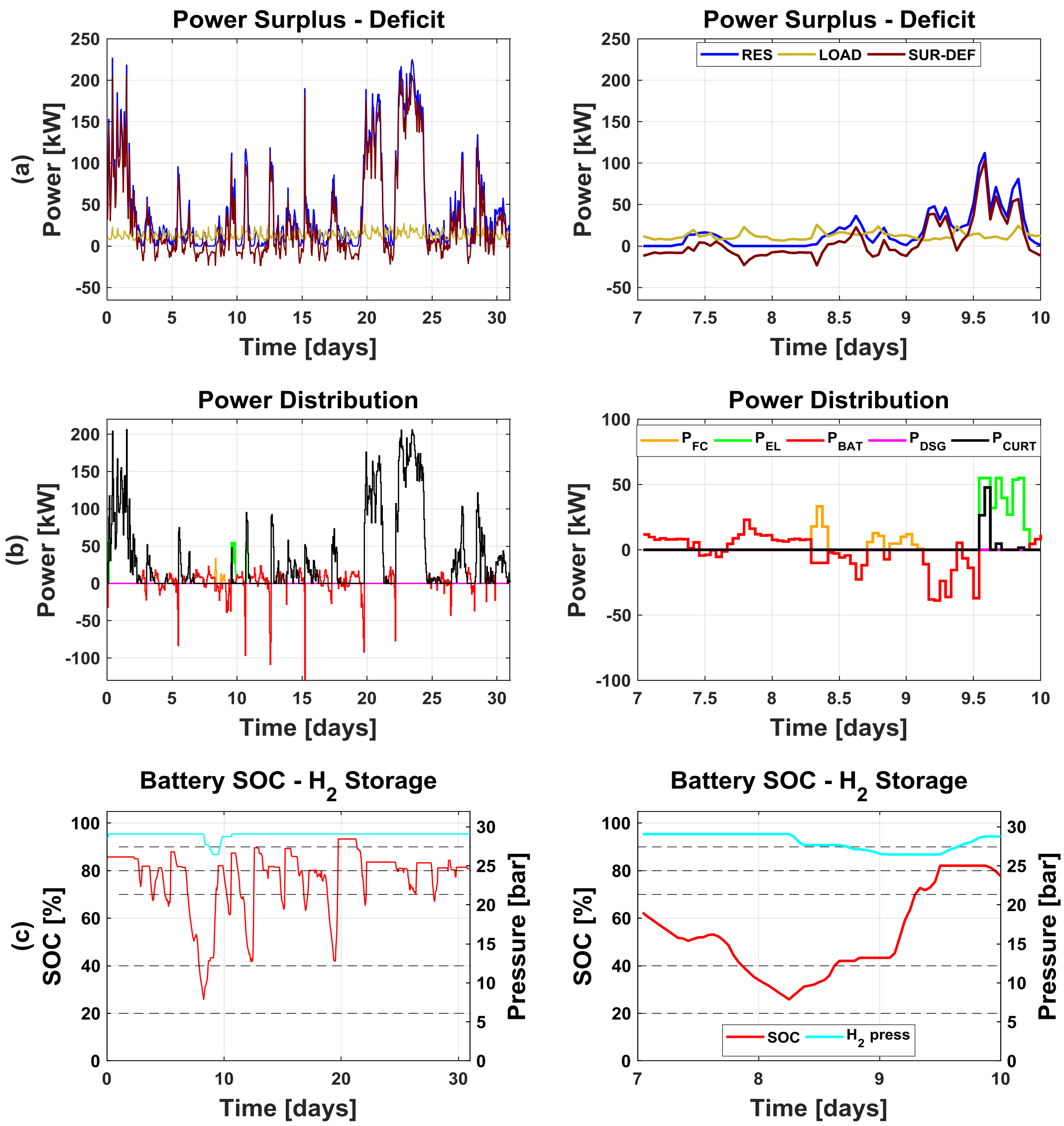


Figure 21. (a) Available RES, load and surplus-deficit, (b) Power distribution, (c) Battery SOC and hydrogen storage level. (left) Whole October and (right) 3 days in October.

The hourly distribution of power among the subsystems is displayed in Figure 21b. The same behaviour of the subsystems as in Ginostra is presented here, with the fuel cell taking on the load but also being responsible to charge the battery up to a point where it is not in the hysteresis zone (20-40%). Again, when there is a shortage of hydrogen in the tank then the DSG will operate instead of the FC. As displayed in Figure 21c, the battery is the main module that meets the load duty, sitting idle only when it is charged above 80% and allowing the EL to produce H_2 by exploiting the RES surplus. The power being curtailed in Figure 21b is a result of the RES surplus being greater than the maximum modulation range limit of the EL (55 kW).

The hourly operation of each module is shown in the next figure.

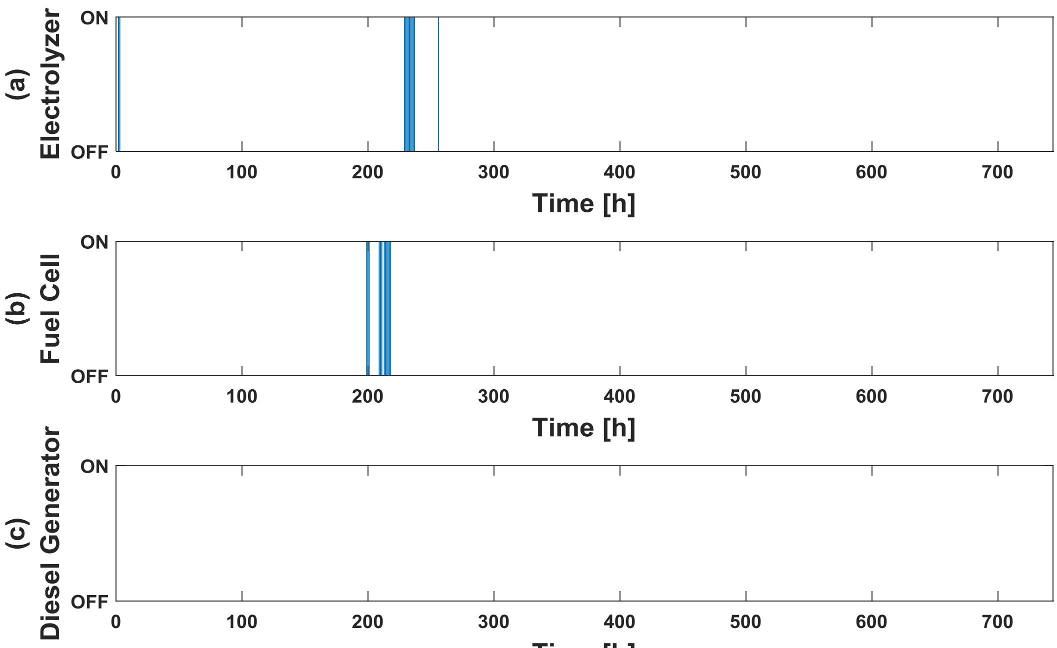


Figure 22. Hourly state (ON/OFF) of the EL (a), the FC (b) and the DSG (c)

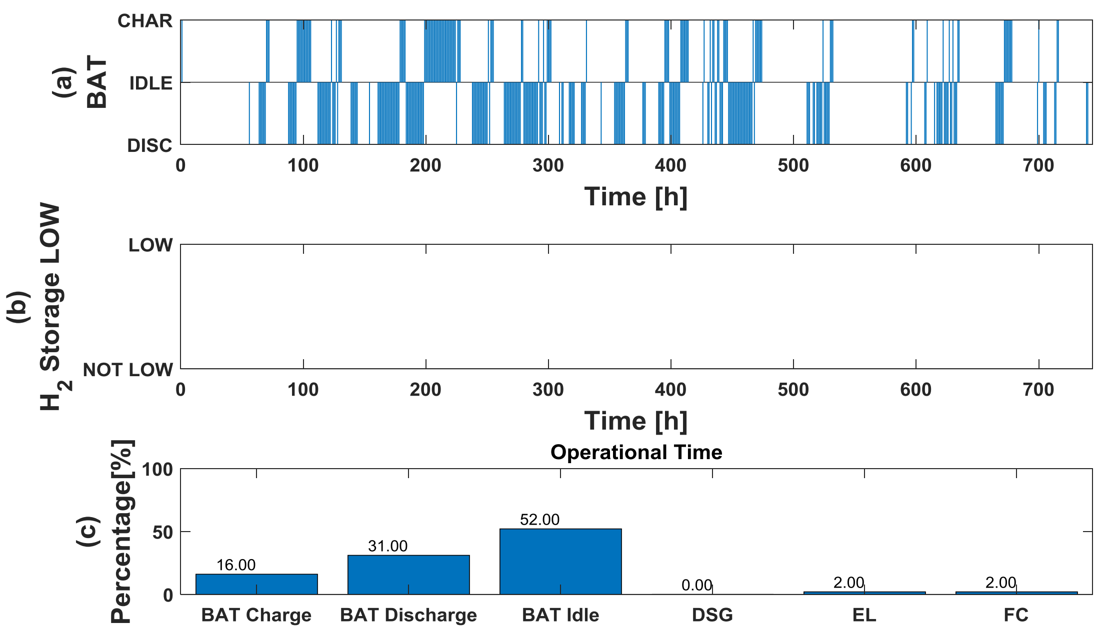


Figure 23 Hourly state (Char/Idle/Disc) of BAT (a), hourly state (Low/Not low) of HT (b), operational time(c)

When considering the yearly operation, the use of a diesel generator is limited to the months where longer deficits of power are presented, mainly in December. By reverse analogy, the hydrogen production from the electrolyzer is favoured all year except the winter months (see results for other months in the Appendix). The results produced by this strategy are showing that the intermittency of the wind turbine, although it is adding high peaks that end up being curtailed and long plateaus that are not enough to fill the storage and cover the load, necessitates the use of external sources only in December and January. Accordingly, as in the other three DEMOs, these results offer a base case scenario for the further development of the strategies employed for this DEMO.

5 Comparative Analysis of DEMOs Behaviour – KPIs

Isolated micro grids, due to their complexity and multi-disciplinary character (involving a stack of technologies), can be very difficult to assess their overall performance. Because of this a metric is required. In this section, a set of key performance indicators (KPIs) is defined for the rating of each demo site. This tool allows us to evaluate and compare possible control strategies.

5.1 Definition of KPIs

The KPIs can be characterized as an analysis tool that enables us to assess the effects of each technology under potential scenarios. The information that this tool offers us is useful for the evaluation of each DEMO, allowing us to make the most appropriate decisions for its operation based on the performance indicators. In the present analysis, the key performance indicators that were developed are ratios of the cumulative energy of each subsystem in kWh over the course of a year. The produced values were converted to percentages (%) in order to present a more definitive aspect of the performance of each demo site. Below there is a list of the proposed KPIs.

- Converted RES surplus to electricity, [%]
- Converted RES surplus to hydrogen, [%]
- Converted RES surplus to curtailed power, [%]
- Satisfied demand by FC, [%]
- Satisfied demand by Diesel Generator, [%]
- Satisfied demand by Battery, [%]
- Satisfied demand by RES, [%]
- Satisfied demand by BIO, [%]
- Battery health preservation by Diesel Generator, [%]
- Battery health preservation by FC, [%]
- Diesel Generator for Battery health preservation, [%]
- FC for battery health preservation, [%]
- Satisfied demand by DSG for Battery health, [%]

A description for every KPI is presented in Table 18.

	KPI	Ratio	Description
1.	Converted Surplus Energy to Electricity	$\left[\frac{\text{BAT energy (char)}}{\text{RES surplus}}\right]$	The percentage of the RES surplus energy that is converted to electricity and stored in the battery
2.	Converted Surplus Energy to Hydrogen	$\left[\frac{H_2 \text{ produced}}{\text{RES surplus}}\right]$	The percentage of the RES surplus energy that is converted to hydrogen and stored in the high pressure tank
3.	Curtailed Energy versus RES Surplus	$\left[\frac{\text{RES curtailed}}{\text{RES surplus}}\right]$	The percentage of the RES surplus energy which ended up being curtailed
4.	Satisfied Demand by Fuel Cell	$\left[\frac{\text{FC energy}}{\text{Total Load}}\right]$	The percentage of power demand that is satisfied by the fuel cell operation
5.	Satisfied Demand by Diesel Generator	$\left[\frac{\text{DSG energy}}{\text{Total Load}}\right]$	The percentage of power demand that is satisfied by the diesel generator operation
6.	Satisfied Demand by Battery	$\left[\frac{\text{BAT energy (disc)}}{\text{Total Load}}\right]$	The percentage of power demand that is satisfied by the battery discharge
7.	Satisfied Demand by Biomass	$\left[\frac{\text{BIO energy}}{\text{Total Load}}\right]$	The percentage of power demand that is satisfied by the biomass CHP generator
8.	Satisfied Demand by RES	$\left[\frac{\text{Load} - \text{Deficit}}{\text{Total Load}}\right]$	The percentage of power demand that is satisfied directly by the RES supply
9.	Battery Health Preservation by Diesel Generator	$\left[\frac{\text{DSG energy to BAT}}{\text{BAT energy (char)}}\right]$	The percentage of battery charging energy that was delivered by the diesel generator cell in order to keep the SOC in the predefined areas
10.	Battery Health Preservation by Fuel Cell	$\left[\frac{\text{FC energy to BAT}}{\text{BAT energy (char)}}\right]$	The percentage of battery charging energy that was delivered by the fuel cell in order to keep the SOC in the predefined areas
11.	Diesel Generator for Battery Health Preservation	$\left[\frac{\text{DSG energy to BAT}}{\text{DSG total energy}}\right]$	The percentage of the total diesel generator energy that was spent in order to keep the SOC in the predefined areas
12.	Fuel Cell for Battery Health Preservation	$\left[\frac{\text{FC energy to BAT}}{\text{FC total energy}}\right]$	The percentage of the total fuel cell energy that was spent in order to keep the SOC in the predefined areas
13.	Satisfied Demand by Diesel Generator for Battery Health	$\left[\frac{\text{DSG energy to BAT}}{\text{Total Load}}\right]$	Fuel losses for battery health as a percentage of the annual load

Table 18. Definitions of the proposed KPIs.

Overall there are three main targets that need to be assessed by the KPIs:

- The assessment of the distribution of the available RES surplus energy. The first three KPIs (1-3) are applied to fulfil this target.
- The assessment of the part that each subsystem has in the satisfaction of the load demand is evaluated through KPIs (4-8).
- The last five KPIs (9-13) fulfil the target of preserving the battery, which is essential when the SOC drops below the minimum point. At that point, regardless the RES availability, the fuel cell or the external source must dedicate part of their power to charge the battery.

The aforementioned KPIs are applied to the 3 DEMOs of the project (Ginostra, Ambornetti and Froan/Rye). The demo site of Agkistro is not part of the evaluation as the proposed systems are only activated in case of a failure of the main hydroelectric plant or during maintenance periods of the plant.

5.2 Evaluation of KPIs

The evaluation is performed on a yearly basis and relies on the data that were delivered by the involved partners. The previous analysis at Chapter 4 was related to a monthly-based operation, whereas the KPIs analysis is performed on a yearly basis. In Table 19, a comparison between the KPIs of each DEMO is presented.

		DEMO 1 (Ginostra)	**DEMO 3 (Ambornetti)**	**DEMO 4 (Froan/Rye)**
	KPIs	**Value [%]**	**Value [%]**	**Value [%]**
1.	Converted Surplus Energy to Electricity	38.5	12.4	14.0
2.	Converted Surplus Energy to Hydrogen	9	61.2	17.2
3.	Curtailed Energy versus RES Surplus	52.5	26.4	68.8
4.	Satisfied Demand by Fuel Cell	4.6	6.4	4.4
5.	Satisfied Demand by Diesel Generator	4.4	4.3	0.6
6.	Satisfied Demand by Battery	43.2	3.2	25.5

7.	Satisfied Demand by RES	47.8	55.9	69.5
8.	Satisfied Demand by Biomass	-	30.2	-
9.	Battery Health Preservation by Diesel Generator	2.2	0	1.6
10.	Battery Health Preservation by Fuel Cell	2.3	0	13.3
11.	Diesel Generator for Battery Health Preservation	40.1	0	42.0
12.	Fuel Cell for Battery Health Preservation	37.1	0	44.0
13.	Satisfied Demand by DSG for Battery Health	0.9	0	0.5

Table 19. KPIs values for every DEMO.

Following the presentation of the KPIs values, a detailed analysis of each DEMO through the KPI scope is conducted.

Demo 1: Ginostra

The available annual energy coming from RES is roughly 273 MWh, whereas the annual load demand is around 171 MWh, as seen in Table 4. KPIs 1 to 3 are intended to capture the conversion of the surplus RES energy that is available. Excess energy is either stored or curtailed. In the Ginostra site, 38,5% of the RES surplus is stored in the battery. The utilisation of the battery is favoured against hydrogen usage, thus the big difference in the converted surplus to hydrogen percentage. However, KPI number 3 shows that over 50% of the available surplus is being curtailed by the system. This is a result of the small hydrogen tank in comparison to the excess energy that is available through spring and summer (Figure 3) but also because of the maximum modulation range of the EL resulting in curtailing power over 50kW (Figure 11b). A larger hydrogen storage should help with minimizing the energy being curtailed.

The satisfaction of the load demand is mainly met by the RES (47,8%) and the battery (43,2%). When there is not enough electricity stored then the fuel cell takes on the satisfaction of the load (4,6%). Through the months December and January the lack of RES production plus the lack of stored energy (H_2) is resulting to the need of the intervention of the diesel generator (4,4%). The minimization of the need or even the exclusion of the back-up DSG can be achieved with a bigger hydrogen tank as stated above.

The battery health preservation has been included to the KPI analysis and it is presented by KPIs 9 to 13. KPIs 9 and 10 have as a reference the energy that ended up in the battery during the charging phase. A percentage of this energy was delivered either by FC (2,3%) or by DSG (2,2%). This amount of energy, compared to the total load duty of both modules is about 40% of their load (KPIs 11-12). The hydrogen expense is not of concern because it originated from a renewable source. On the contrary, the diesel fuel consumption which is about 1% in comparison to the annual load (KPI 13) is a variable that requires further investigation on how it can be minimized.

Demo 3: Ambornetti

The available annual energy coming from RES, specifically from PV, is roughly 87 MWh, whereas the annual load demand is around 97 MWh, as seen in Table 11. The exploitation of a CHP biomass generator (50 kW) with an assumed 80% availability throughout the year, integrates the power production of the system. In the Ambornetti site, only 12,4% of the RES surplus is stored in the battery due to the small size of it. Moreover, not as much power is being curtailed (26,4%) of the total RES surplus as in the other two DEMOs. The utilisation of the battery in this site is kept at a minimum (KPI 6: 3,2%), due to its ability to only cover the load for two or three hours when a deficit occurs. However, KPIs number 7 and 8 show that almost 86% of the total load demand is satisfied by renewable sources (PV+BIO).

The diesel generator operates only when the biomass CHP in not available. The size of the hydrogen tank allows the fuel cell to be operating through a whole day of no biomass only in a period when it is full (Figure 42b). If BIO is not in working condition in a time of low hydrogen capacity (Figure 39b) then hydrogen runs out quickly and the intervention of an external source (DSG) is imperative. To this end, the addition of more hydrogen storage in parallel with the addition of more PV panels can result to the minimization or even the curtailment of the use of a DSG instead of the FC.

Finally, the control strategy employed for this DEMO is formulated in a way that the battery is never allowed to reach the minimum state of charge. Thus, KPIs 9-13 are zero because no preservation is required.

Demo 4: Froan/Rye

The available annual energy coming from RES (PV and Wind) is almost 285 MWh, whereas the annual load demand is around 127 MWh, as seen in Table 15. Figures 6 and 7 display a huge difference between the monthly load and RES production. This difference is quantified by a number of KPIs in Table 19. In particular, RES surplus to curtailment shows that almost 70 % of the 203 MWh of excess energy is not used.

The satisfaction of the load demand is mainly met by the RES (69,5%) and the battery (25,5%). The percentage of FC contribution to the load is 4,4% and the DSG contribution is only 0,6%. When considering the fact that all year long the energy coming from RES is greater that the load demand (Figures 6 and 7), in addition to the fact that the DSG operates nonetheless, a larger hydrogen storage to fully cut off the use of fossil fuels deems necessary.

Similar to the Ginostra site, the battery health preservation has been included to the KPI analysis and it is presented by KPIs 9 to 13. The resulting values differ only to the percentage of dedicated fuel cell power to preserve the battery (KPI 10: 13,3%).

Conclusions

The previous tasks of WP2 have focused on the specification of use cases, the definition of the economic and regulatory framework, as well as the technical specifications of the four technological demonstrators. The main objective of Task 2.4 was to propose different control cases for the four demonstrators.

The work performed in this deliverable followed a use case-driven approach, starting with the presentation of the use cases for each DEMO. Following the use cases, the definition of the energy management framework was performed. The basis, upon which the EMS was formulated, was a Finite State Machine in conjunction with a propositional-based reasoning. The control cases for every DEMO were developed in accordance to the respective use case. For the Ginostra and Froan/Rye sites the nominal operation was explored with the aim of preserving the battery life and the health of the electrolyzer and fuel cell. The case of Ambornetti incorporated the availability of the biomass CHP into the nominal operation of the plant. Finally, the Agkistro site was only tested under the extreme conditions of a hydro plant failure or maintenance.

The simulation results relied on data regarding the RES production and load demand for each DEMO that were delivered by the involved partners. The operation of the three (excluding the Agkistro case) stations was explored using the aforementioned EMS with the FSM through the results of the monthly operation of each one. The distribution of power between the different subsystems and their response was displayed through these results.

In order to evaluate and compare the proposed control strategies a set of key performance indicators (KPIs) was defined. This analysis tool enabled us to assess the effects of each technology under potential scenarios and indicate possible issues for the operation of the DEMOs. The values of the KPIs set a base case for the future development of the control strategies.

From the point of view of the work to be carried out in the future by the several WPs, the specification of application scenarios, use cases and procedures are significant results from this task that will be used as input to subsequent activities of the project. In general, the results included in this document are expected to be utilized in the next steps of the project.

References

[1] R. M. Hierons, “Checking states and transitions of a set of communicating finite state machines,” *Microprocess. Microsyst.*, vol. 24, no. 9, pp. 443–452, Feb. 2001.

[2] C. Manson - Whitton, "Gasification in the UK – How to seize the opportunities" [PowerPoint Presentation], BRISK Open Workshop / TOTeM 40, Delft University of Technology, the Netherlands,2015.[Online].Available:http://briskeu.com/resources/TOTeM%20Presentations/04_Gasification%20in%20the%20UK%20-%20how%20to%20seize%20the%20opportunities%20-%20C.%20Manson-Whitton.pdf. [Accessed December. 10, 2018].

[3] C. Ziogou, D. Ipsakis, P. Seferlis, S. Bezergianni, S. Papadopoulou and S. Voutetakis, "Performance Assessment and Efficiency of a Renewable Hydrogen Production Station Based on a Supervisory Control Methodology", *Chemical Engineering Transactions*, vol. 35, pp. 163-168, 2013.

[4] C. Ziogou, D. Ipsakis, P. Seferlis, S. Bezergianni, S. Papadopoulou and S. Voutetakis, "A Novel and Flexible Energy Management Strategy with Application in a Hydrolytic Solar Hydrogen Autonomous System", *Chemical Engineering Transactions*, vol. 29, no., pp. 1189-1194, 2012.

[5] C. Ziogou, D. Ipsakis, P. Seferlis, S. Bezergianni, S. Papadopoulou and S. Voutetakis, "Optimal production of renewable hydrogen based on an efficient energy management strategy", *Energy*, vol. 55, pp. 58-67, 2013.

[6] C. Ziogou, D. Ipsakis, C. Elmasides, F. Stergiopoulos, S. Papadopoulou, P. Seferlis and S. Voutetakis, "Automation infrastructure and operation control strategy in a stand-alone power system based on renewable energy sources", *Journal of Power Sources*, vol. 196, no. 22, pp. 9488-9499, 2011.

[7] E. Personal, J. Guerrero, A. Garcia, M. Peña and C. Leon, "Key performance indicators: A useful tool to assess Smart Grid goals", *Energy*, vol. 76, pp. 976-988, 2014.

[8] S. Voutetakis, P. Seferlis, F. Stergiopoulos, S. Papadopoulou, A. Papadopoulos, D. Ipsakis, C. Ziogou and C. Elmasides, "System Integration", in *Design, Optimization and Control of Stand-Alone Power Systems using Renewable Energy Sources and Hydrogen Production*, Ed. United States of America: Nova Science Publisher, 2011.

[9] W. Harder, "Key Performance Indicators for Smart Grids", Master of Science, University of Twente, 2017.

6 Appendix

The results are referring to the months of each season for each DEMO that were not shown in Chapter 4.

6.1 DEMO 1: Ginostra

For this demo site we found January to be the most critical month of operation to show. The results for January, which is an indicative month for winter, are shown in pages 23-25. Here below are the results for the indicative months (i.e. April, July, October) of the rest of the seasons (i.e. spring, summer, autumn).

6.1.1 April

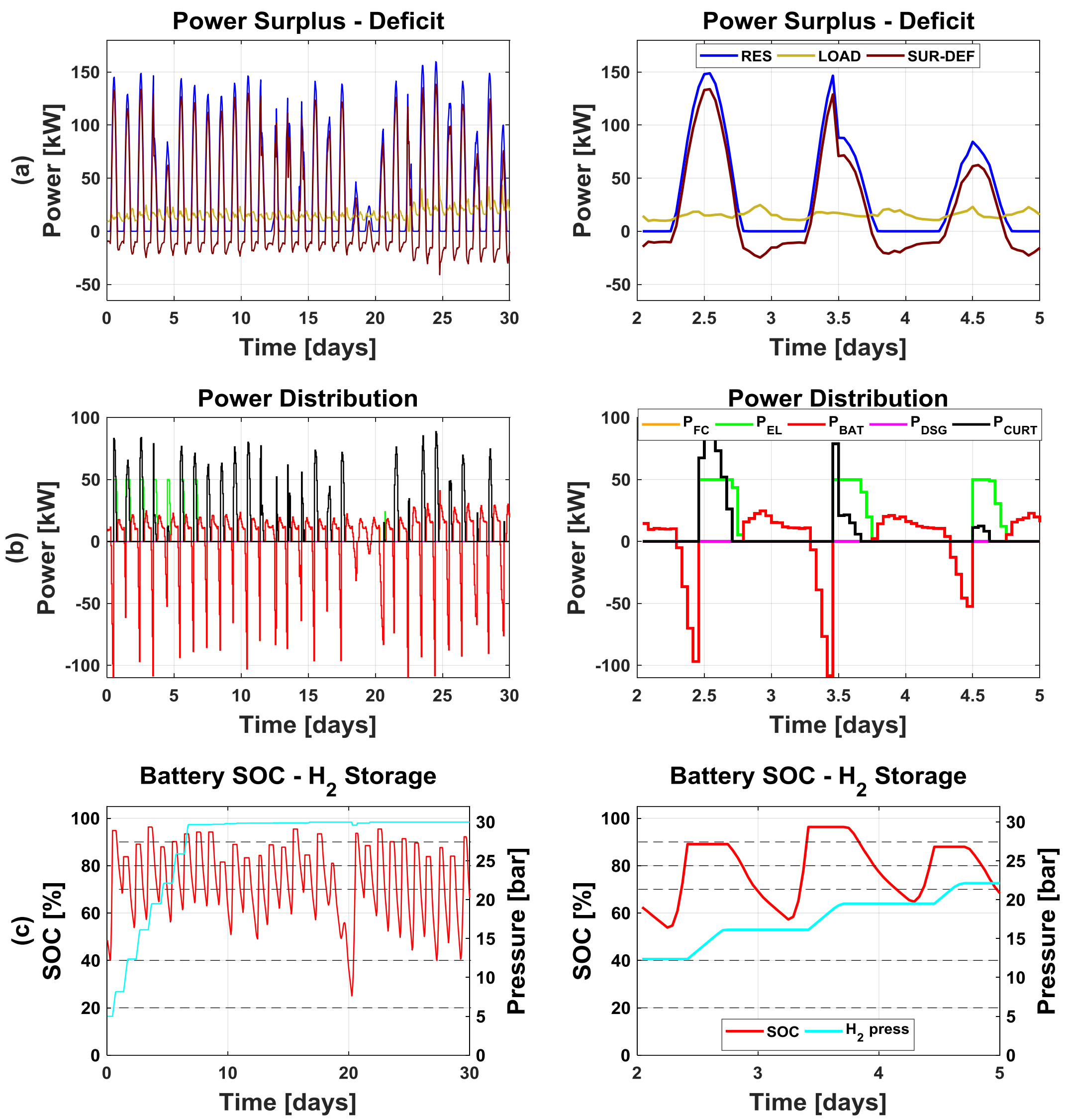


Figure 24. (a) Available RES, load and surplus-deficit, (b) Power distribution, (c) Battery SOC and hydrogen storage level. (left) Whole month and (right) 3 days of the month.

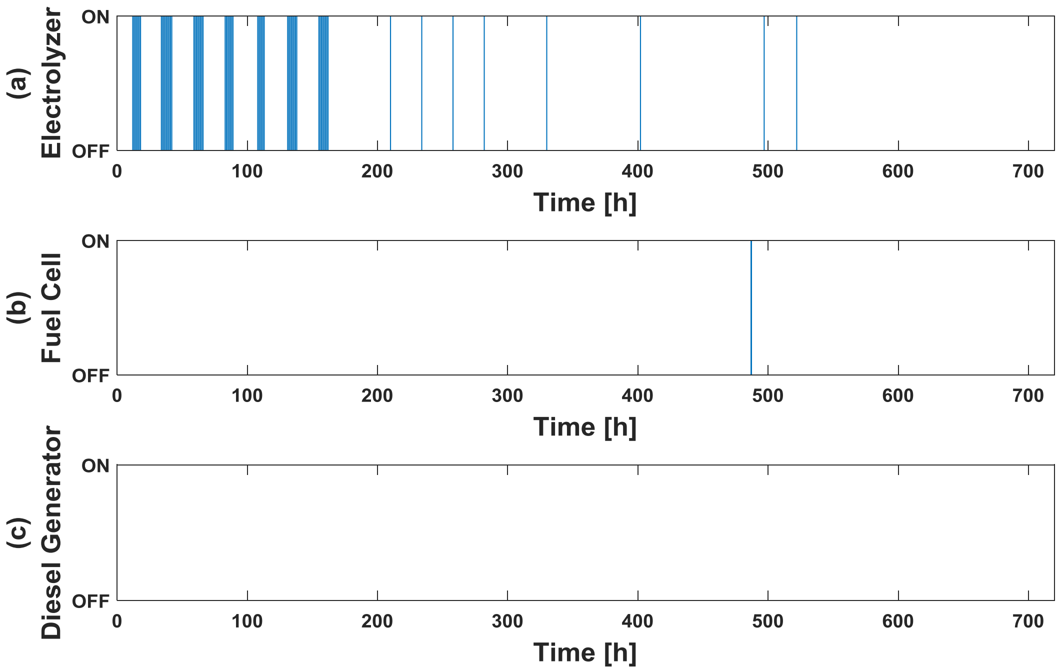


Figure 25. Hourly state (ON/OFF) of the EL (a), the FC (b) and the DSG (c)

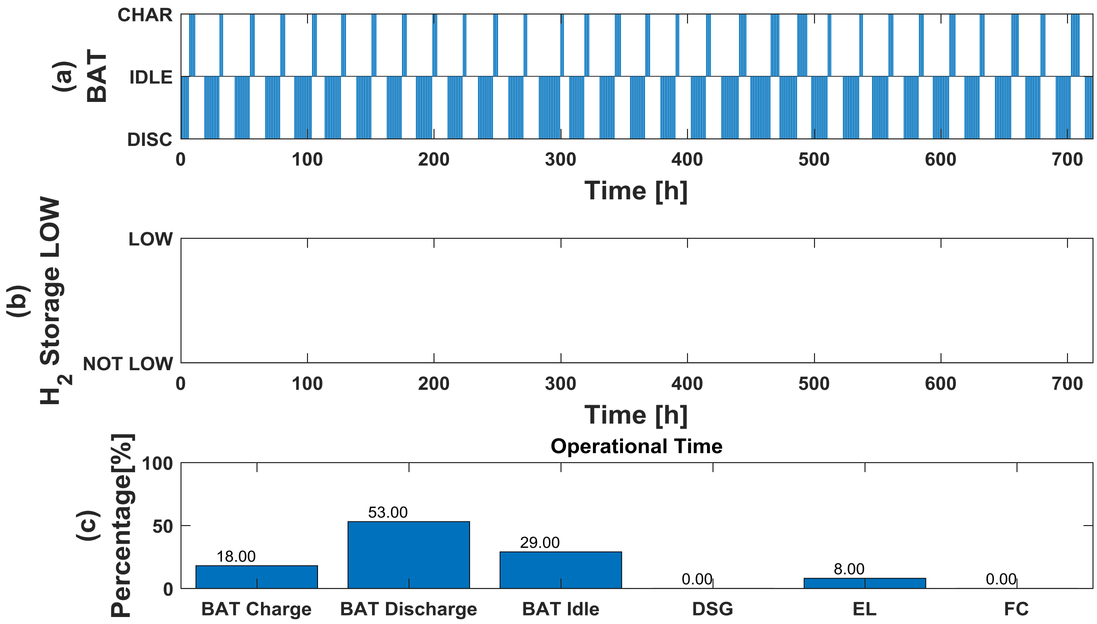


Figure 26. Hourly state(Char/Idle/Disc) of BAT (a), hourly state(Low/Not low) of HT (b), operational time percentage for each subsystem(c)

6.1.2 July

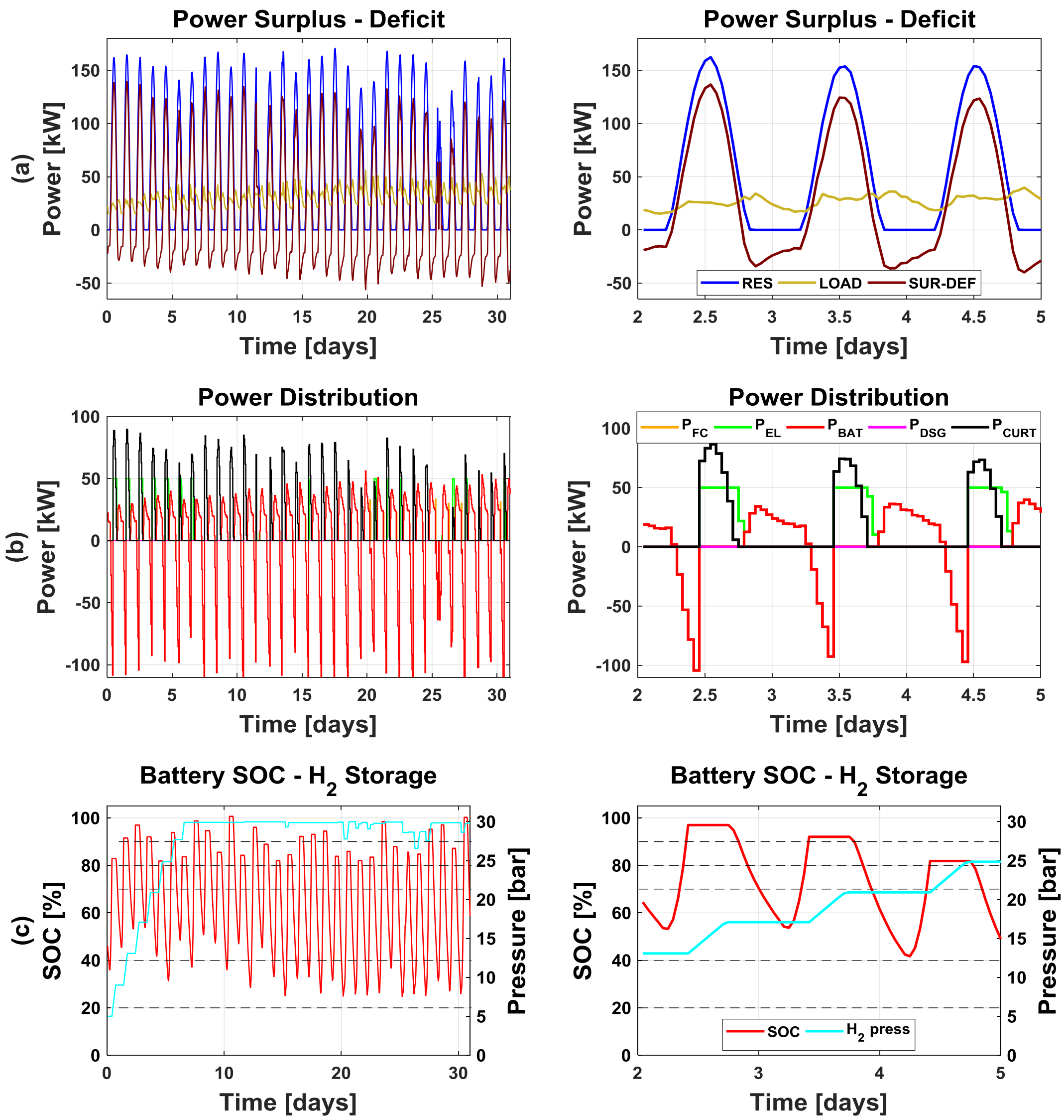


Figure 27. (a) Available RES, load and surplus-deficit, (b) Power distribution, (c) Battery SOC and hydrogen storage level. (left) Whole month and (right) 3 days of the month.

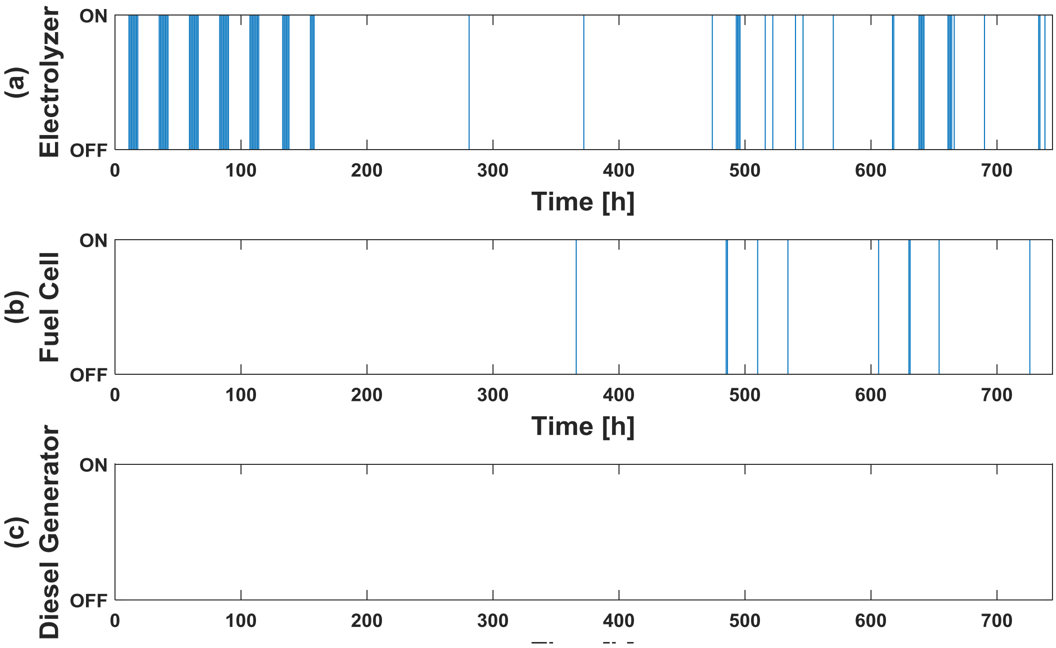


Figure 28. Hourly state (ON/OFF) of the EL (a), the FC (b) and the DSG (c)

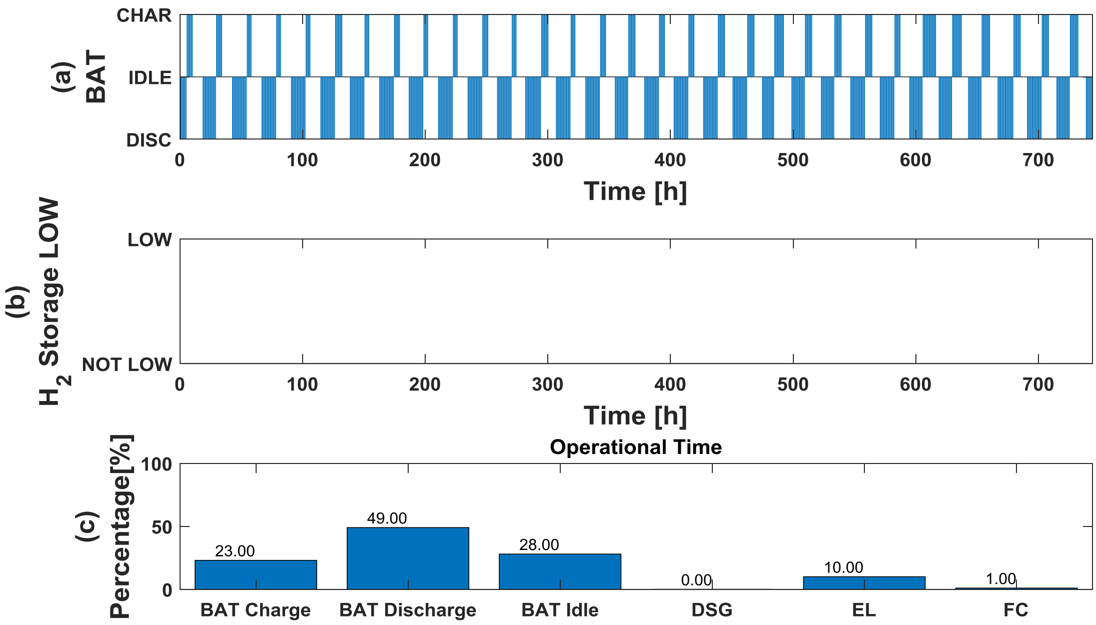


Figure 29. Hourly state(Char/Idle/Disc) of BAT (a), hourly state(Low/Not low) of HT (b), operational time percentage for each subsystem(c)

6.1.3 October

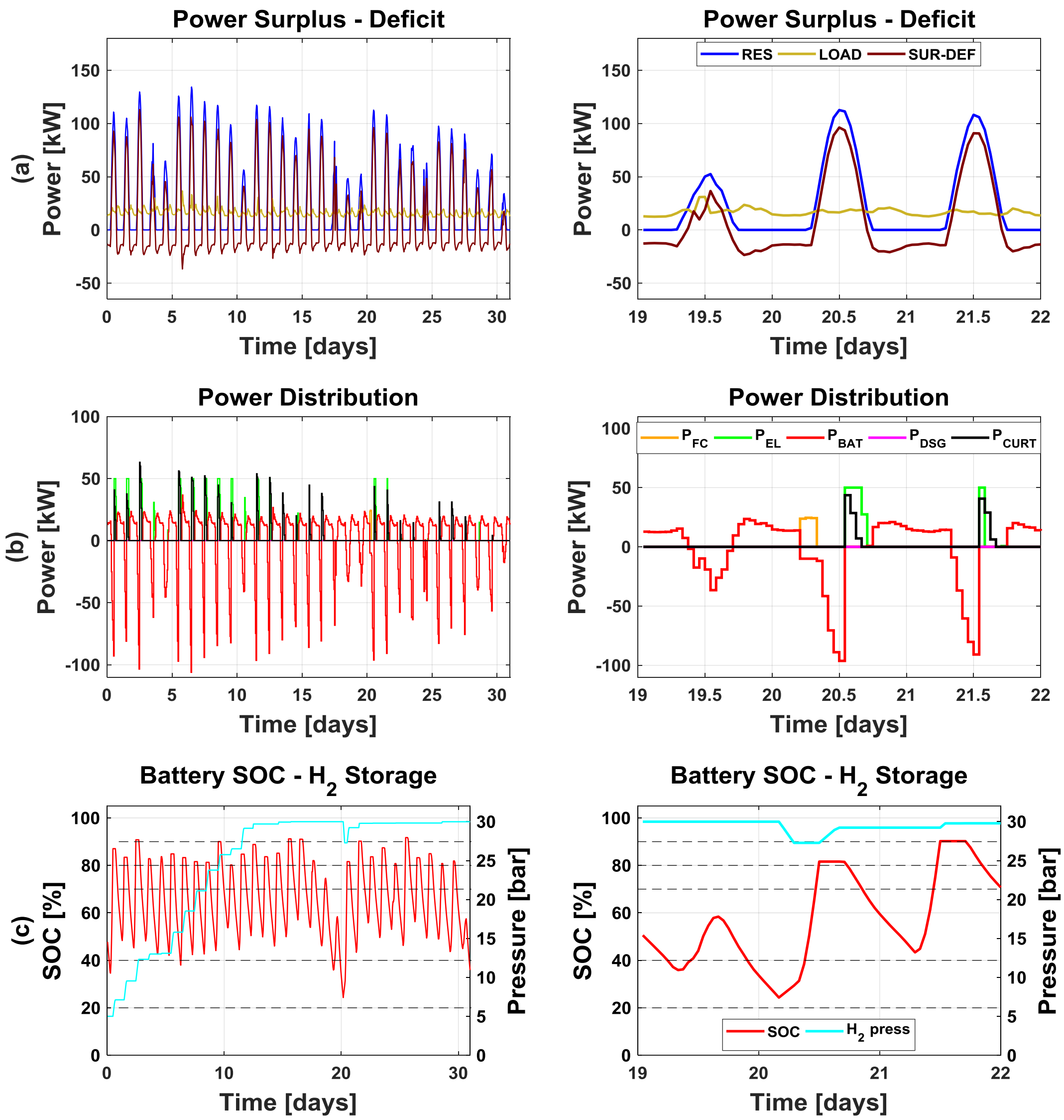


Figure 30. (a) Available RES, load and surplus-deficit, (b) Power distribution, (c) Battery SOC and hydrogen storage level. (left) Whole month and (right) 3 days of the month.

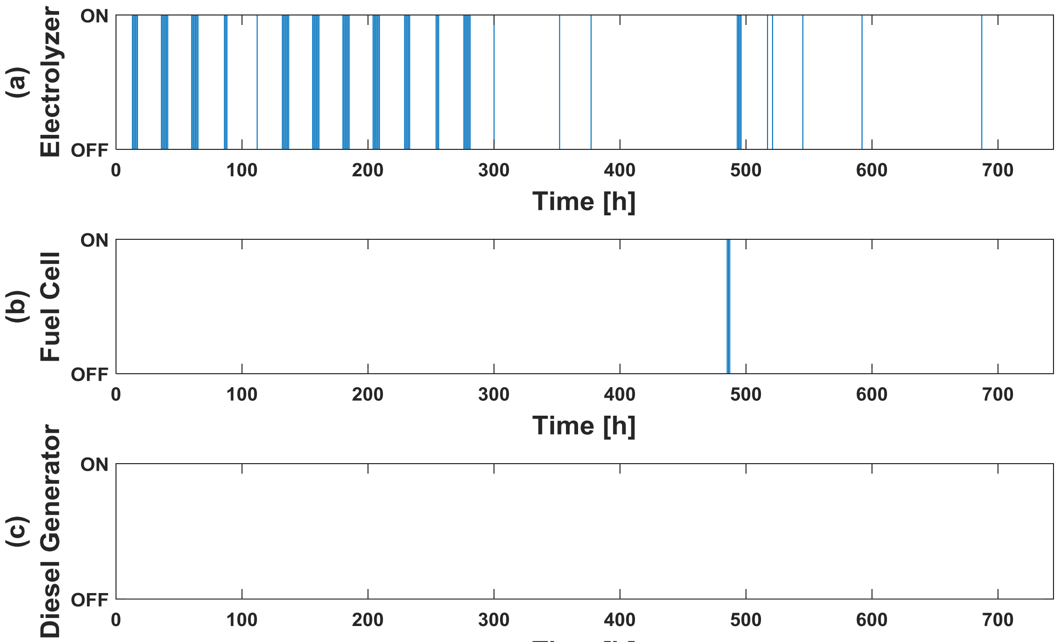


Figure 31. Hourly state (ON/OFF) of the EL (a), the FC (b) and the DSG (c)

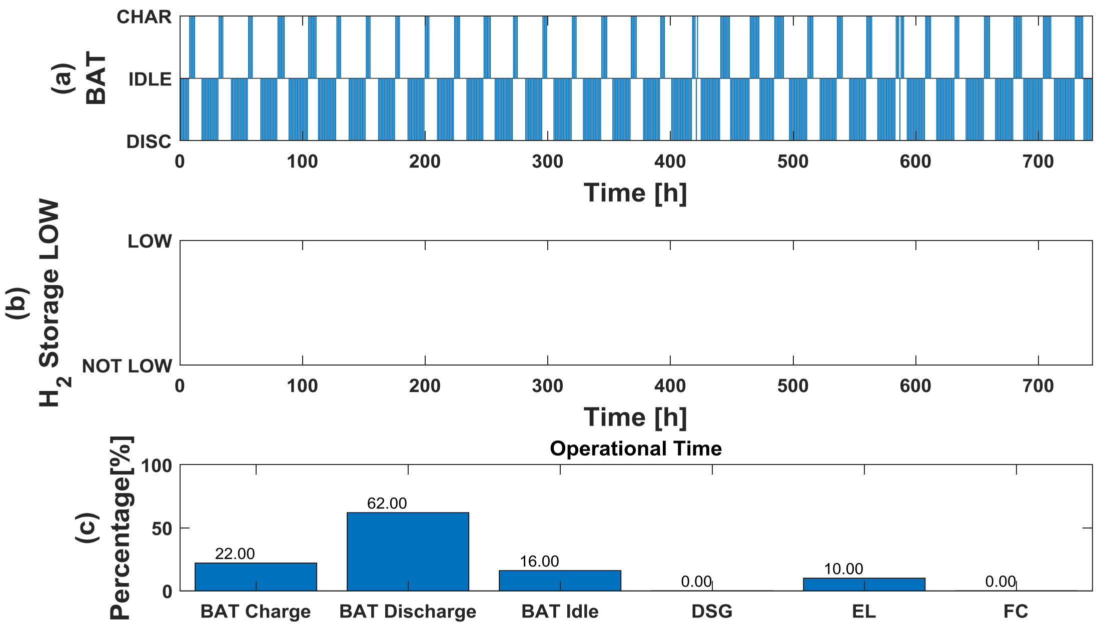


Figure 32. Hourly state(Char/Idle/Disc) of BAT (a), hourly state(Low/Not low) of HT (b), operational time percentage for each subsystem(c)

6.2 DEMO 3: Ambornetti

For this demo site we found January to be the most critical month of operation to show. The results for January, which is an indicative month for winter, are shown in pages 29-31. Here below are the results for the indicative months (i.e. April, July, October) of the rest of the seasons (i.e. spring, summer, autumn).

6.2.1 April

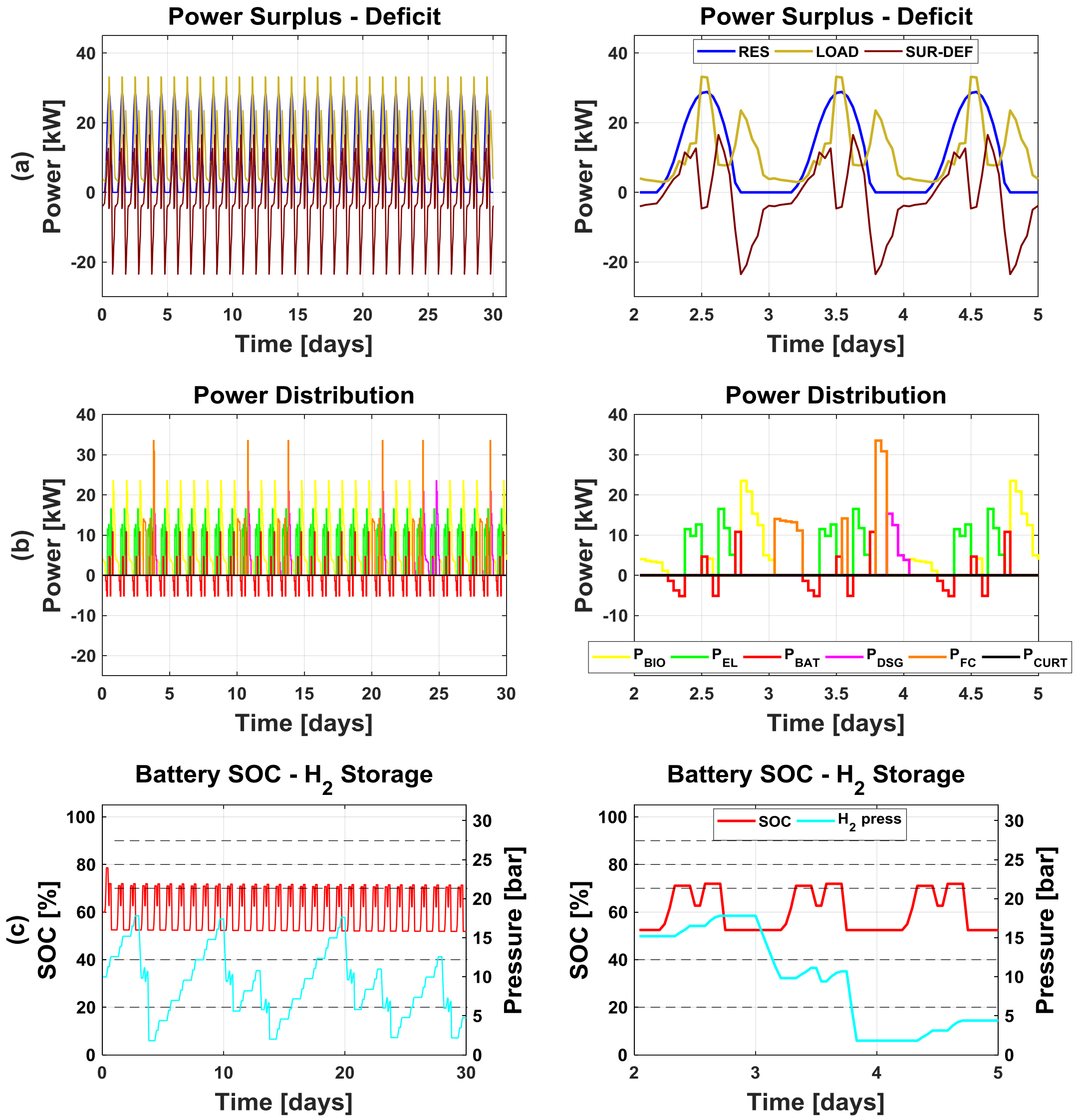


Figure 33. (a) Available RES, load and surplus-deficit, (b) Power distribution, (c) Battery SOC and hydrogen storage level. (left) Whole month and (right) 3 days of the month.

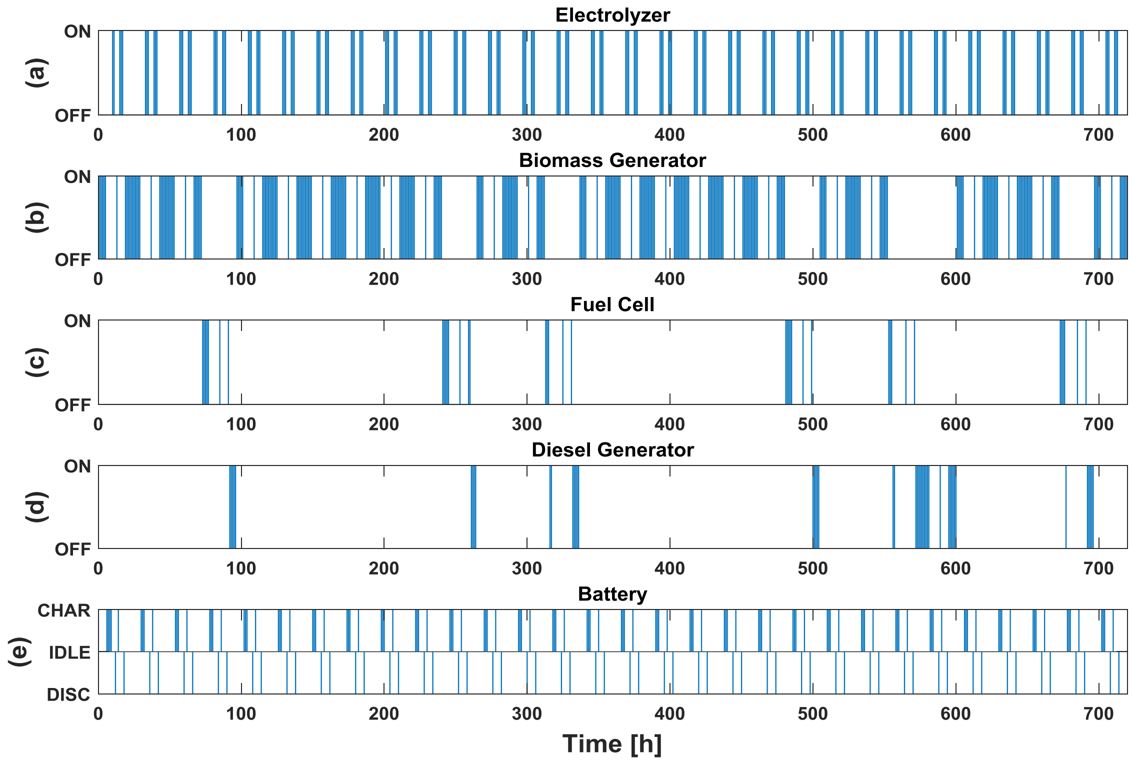


Figure 34. Hourly state (ON/OFF) of the EL (a), the BIO (b), the FC (c), the DSG (d), hourly state(Char/Idle/Disc) of BAT (e). Whole month.

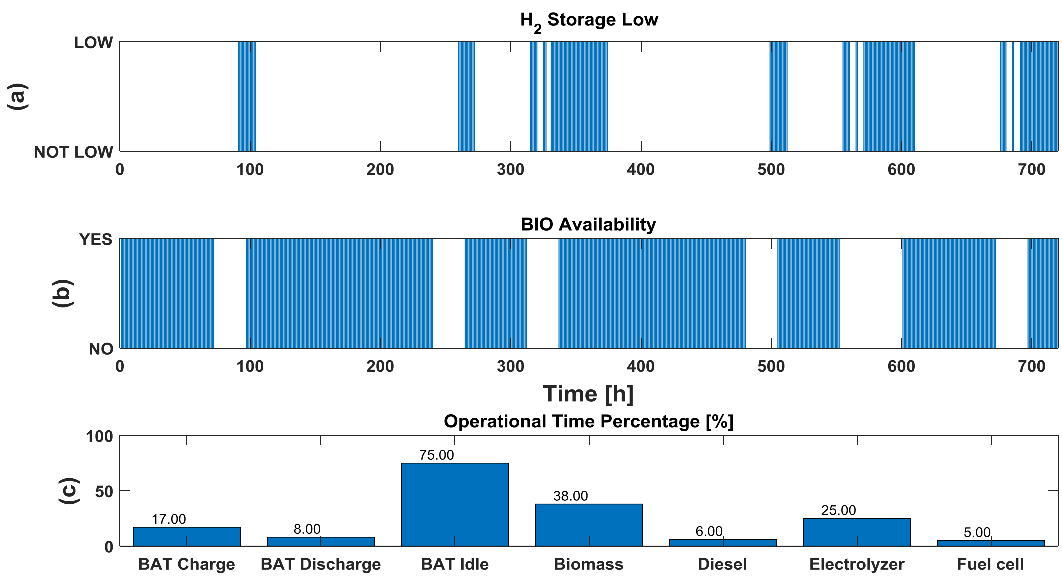


Figure 35. Hourly state (Low/Not low) of HT (a), hourly biomass availability (b), operational time percentage for each subsystem (c). Whole month.

6.2.2 July

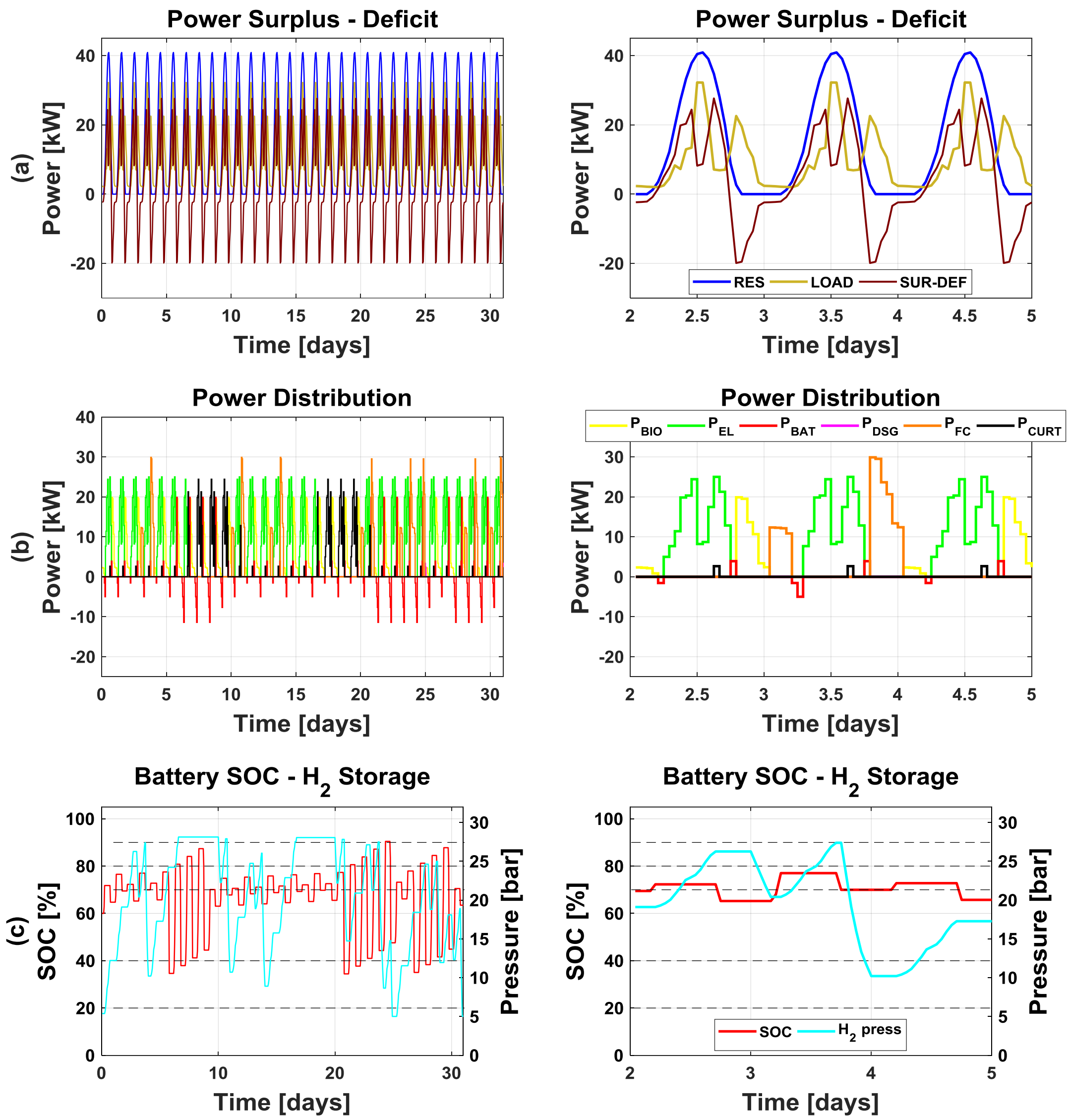


Figure 36. (a) Available RES, load and surplus-deficit, (b) Power distribution, (c) Battery SOC and hydrogen storage level. (left) Whole month and (right) 3 days of the month.

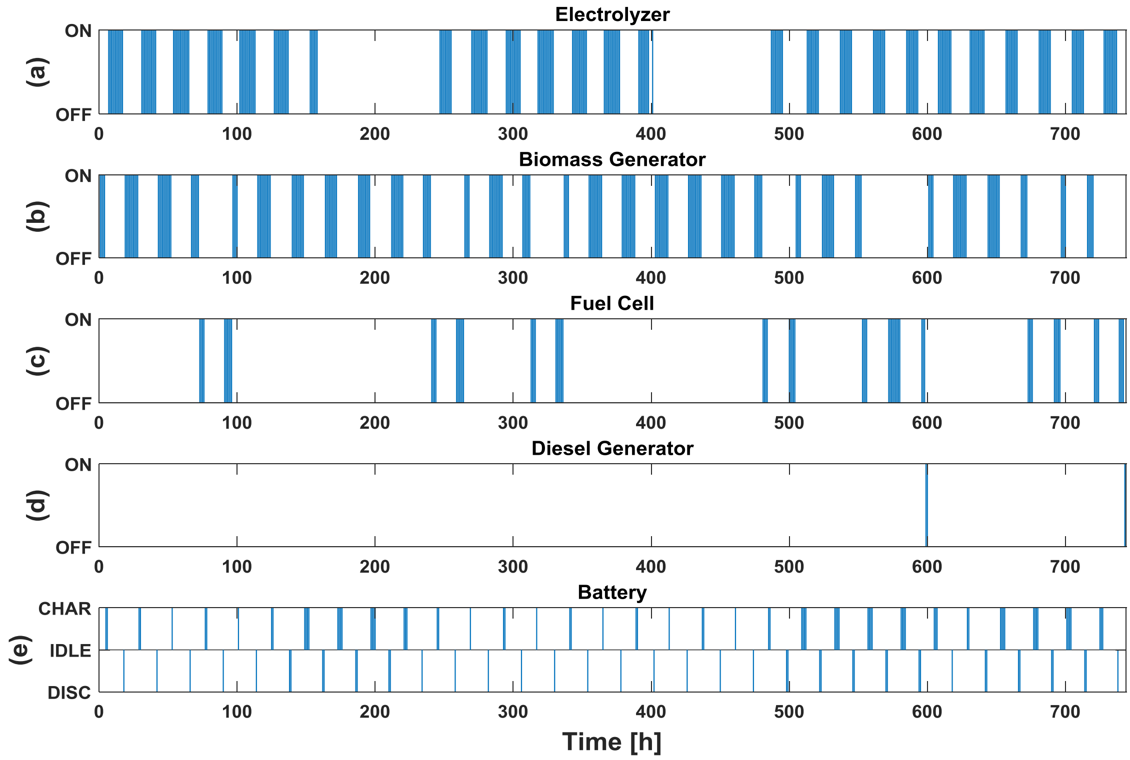


Figure 37. Hourly state (ON/OFF) of the EL (a), the BIO (b), the FC (c), the DSG (d), hourly state(Char/Idle/Disc) of BAT (e). Whole month.

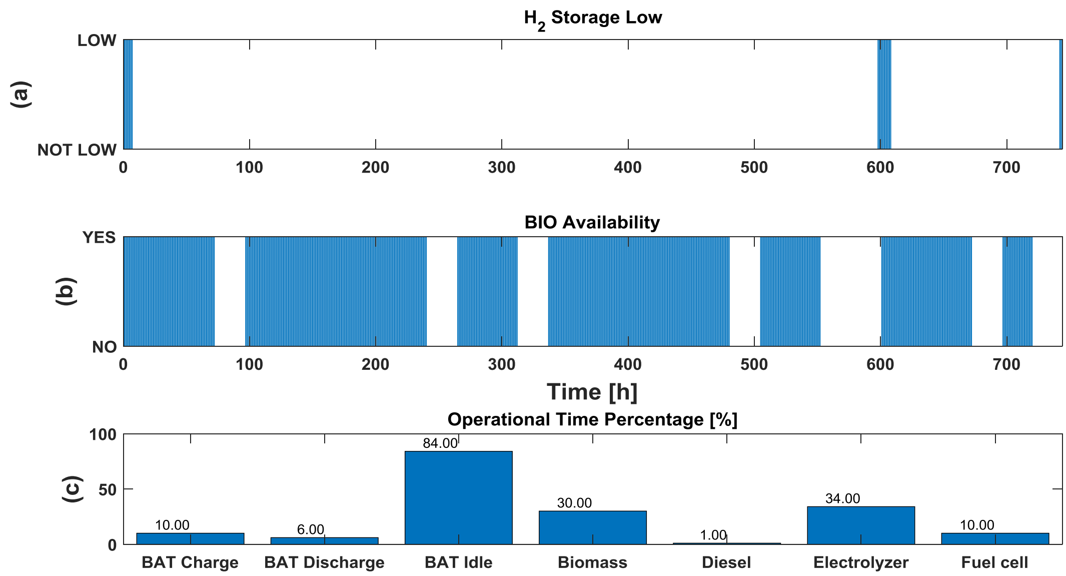


Figure 38. Hourly state (Low/Not low) of HT (a), hourly biomass availability (b), operational time percentage for each subsystem (c). Whole month.

6.2.3 October

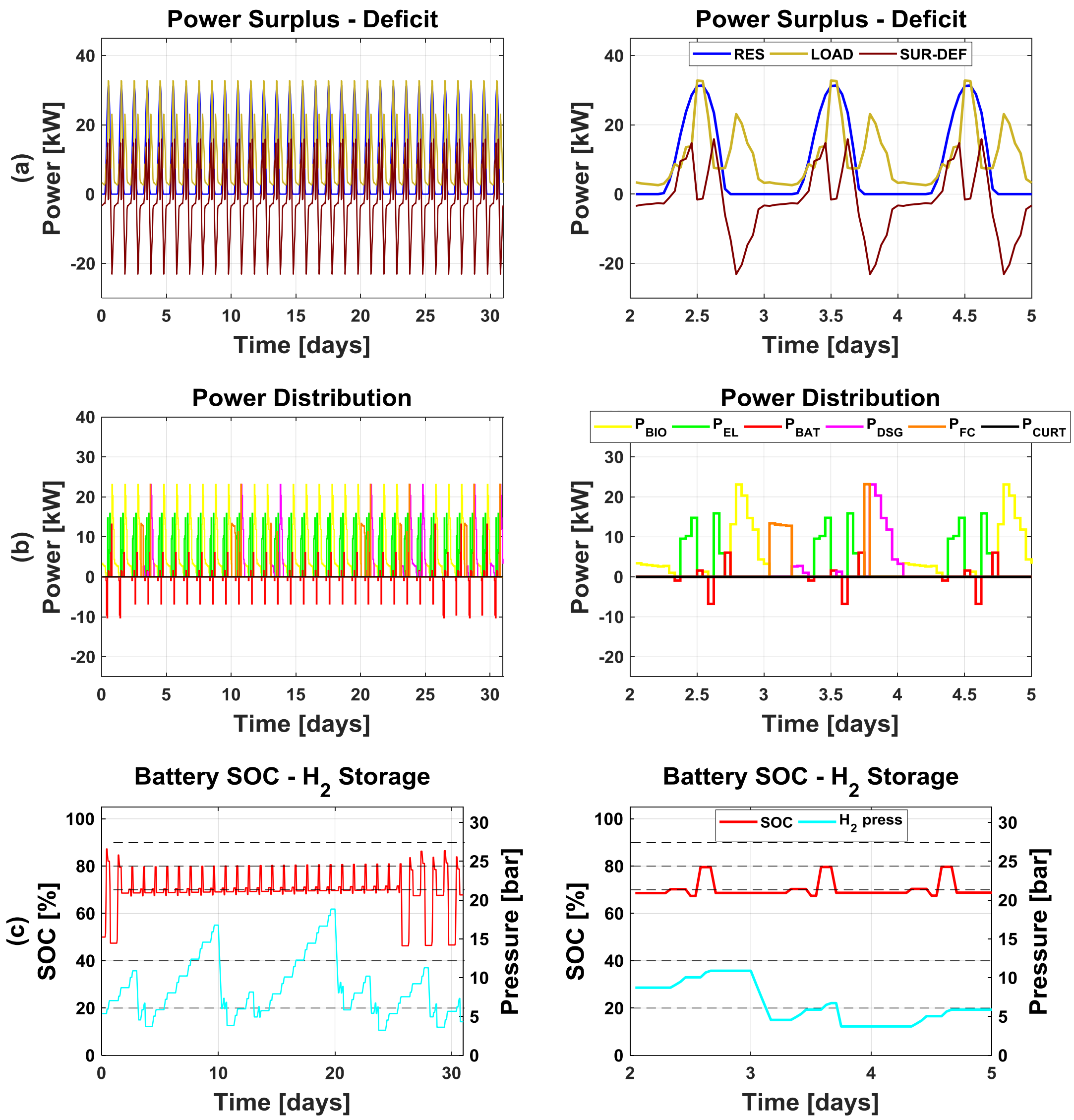


Figure 39. (a) Available RES, load and surplus-deficit, (b) Power distribution, (c) Battery SOC and hydrogen storage level. (left) Whole month and (right) 3 days of the month.

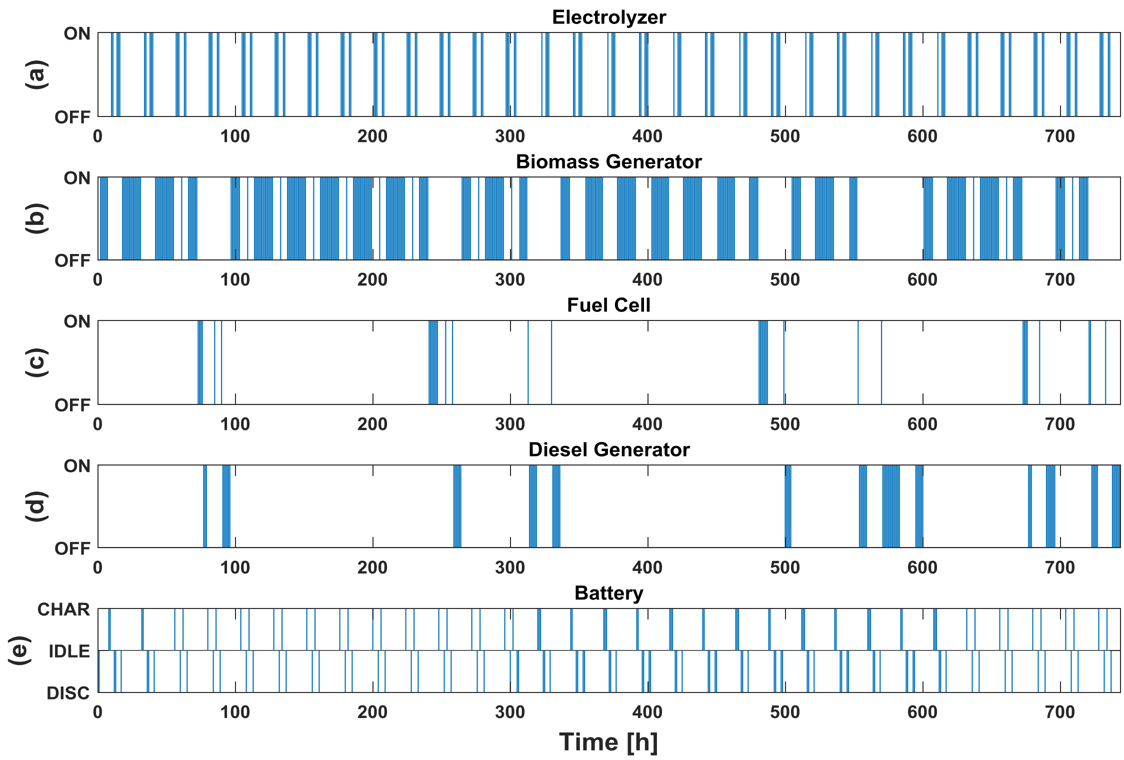


Figure 40. Hourly state (ON/OFF) of the EL (a), the BIO (b), the FC (c), the DSG (d), hourly state(Char/Idle/Disc) of BAT (e). Whole month.

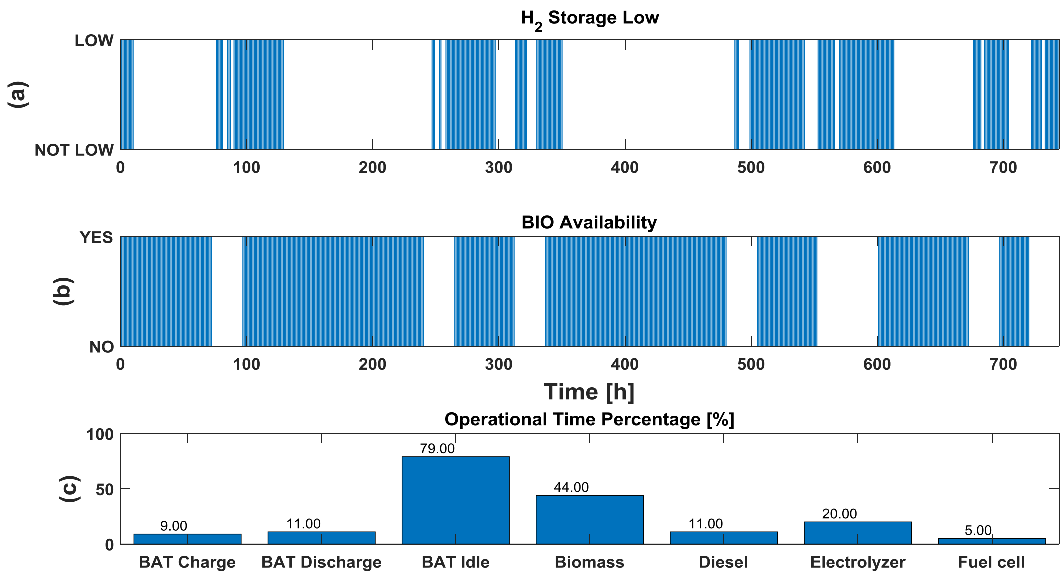


Figure 41. Hourly state (Low/Not low) of HT (a), hourly biomass availability (b), operational time percentage for each subsystem (c). Whole month.

6.3 DEMO 4: Froan/Rye

For this demo site we found October to be the most critical month of operation to show. The results for October, which is an indicative month for autumn, are shown in pages 32-33. Here below are the results for the indicative months (i.e. January, April, July) of the rest of the seasons (i.e. winter, spring, summer).

6.3.1 January

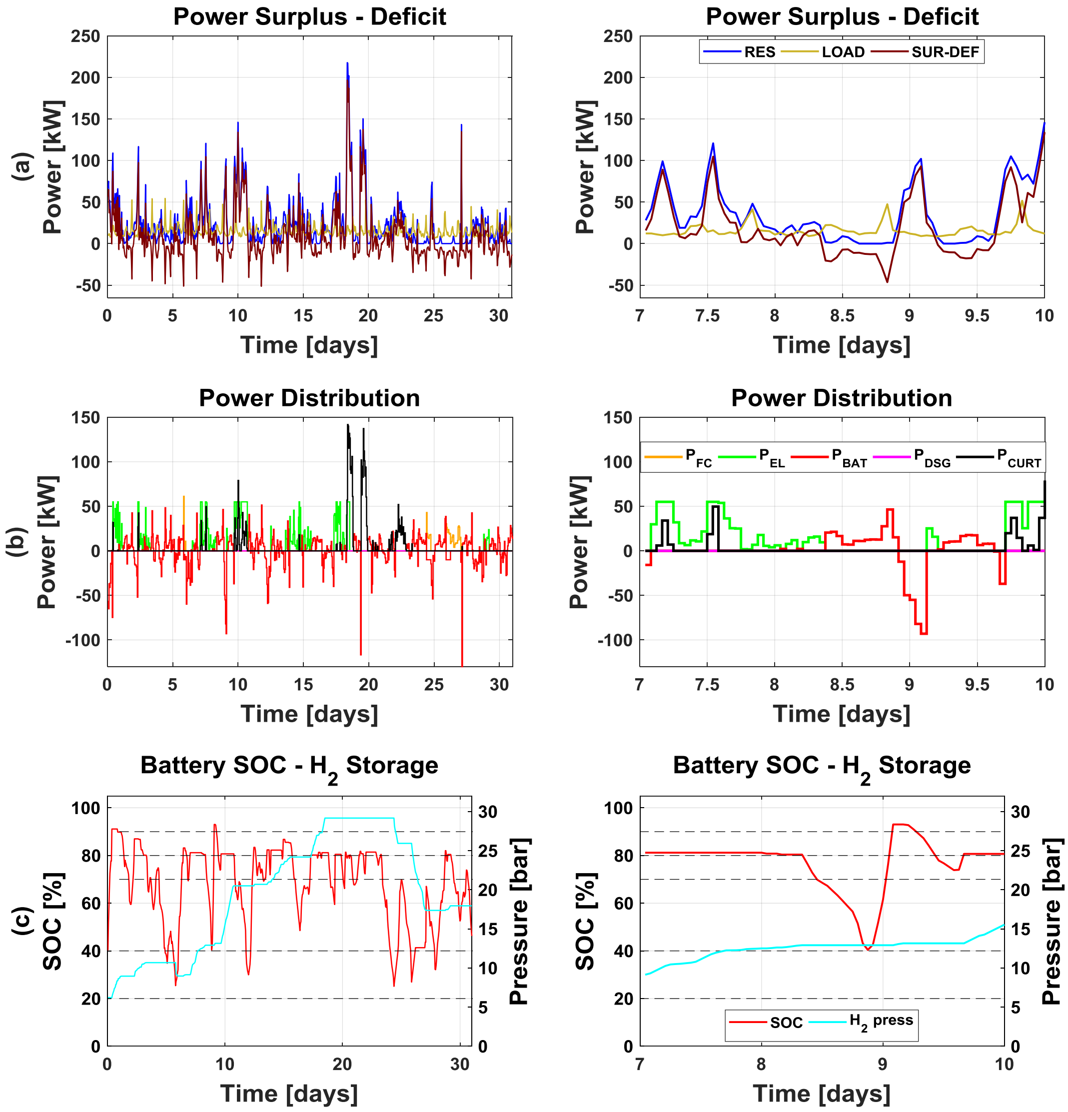


Figure 42. (a) Available RES, load and surplus-deficit, (b) Power distribution, (c) Battery SOC and hydrogen storage level. (left) Whole month and (right) 3 days of the month.

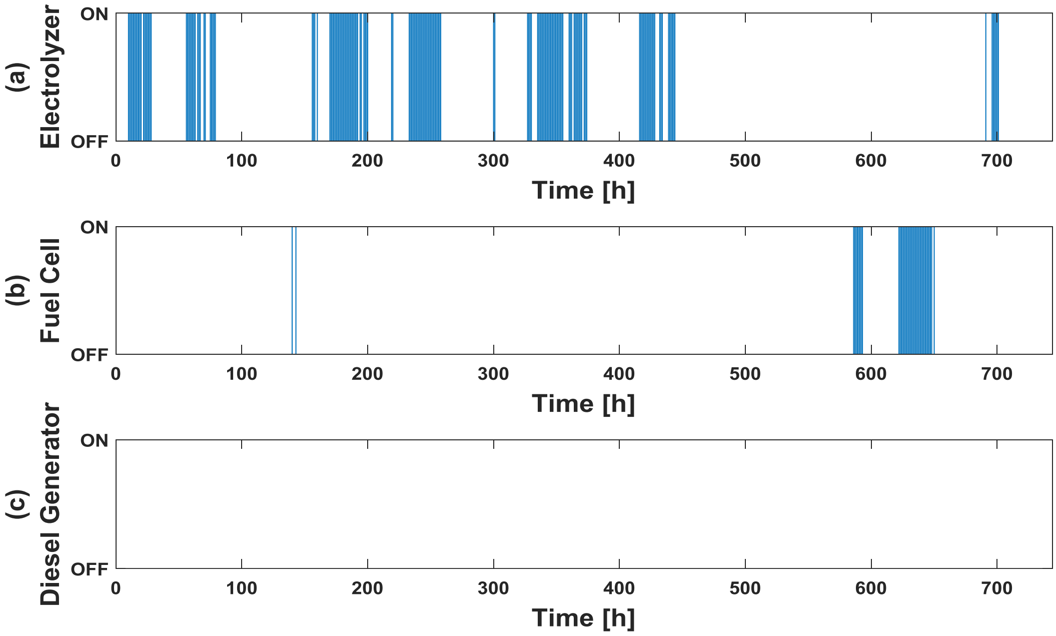


Figure 43. Hourly state (ON/OFF) of the EL (a), the FC (b) and the DSG (c)

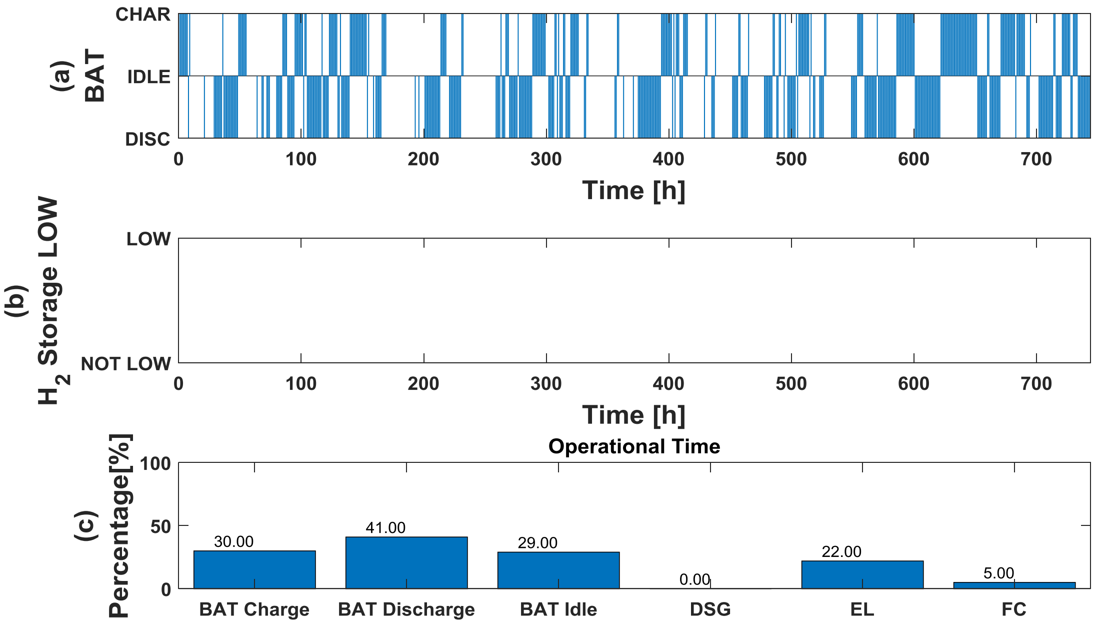


Figure 44. Hourly state(Char/Idle/Disc) of BAT (a), hourly state(Low/Not low) of HT (b), operational time percentage for each subsystem(c)

6.3.2 April

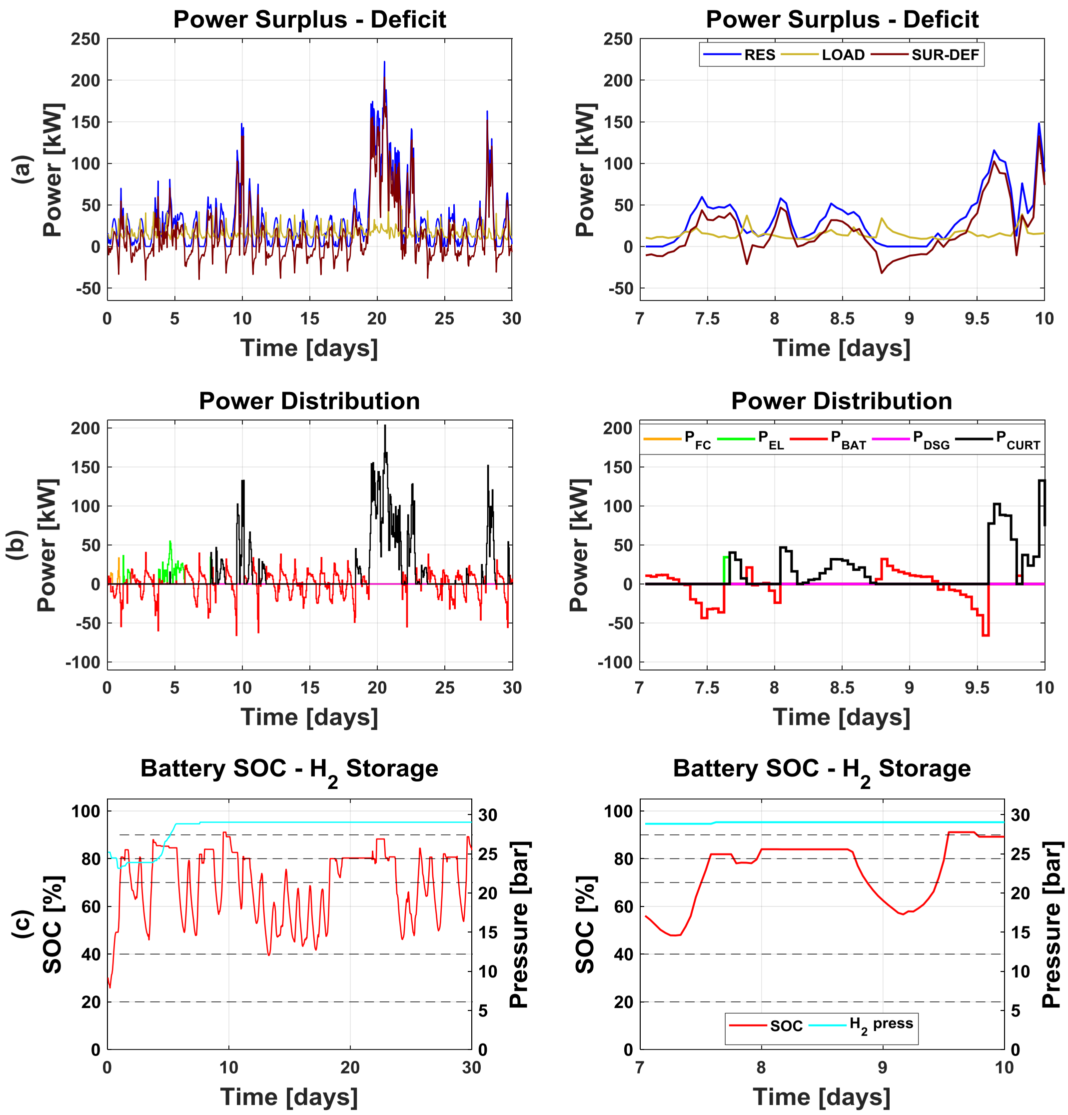


Figure 45. (a) Available RES, load and surplus-deficit, (b) Power distribution, (c) Battery SOC and hydrogen storage level. (left) Whole month and (right) 3 days of the month.

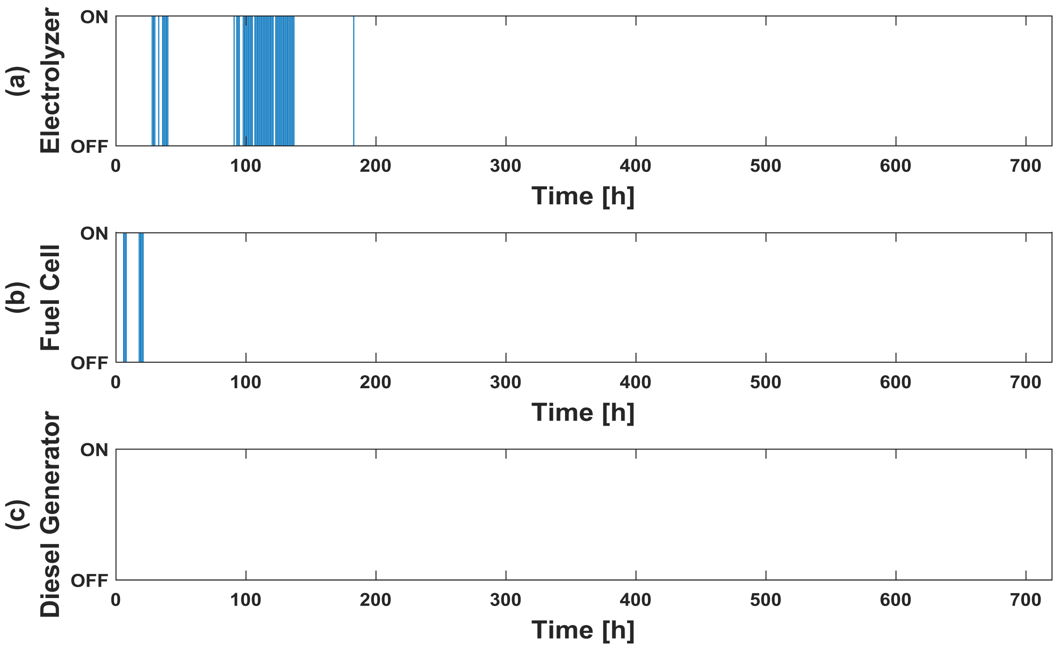


Figure 46. Hourly state (ON/OFF) of the EL (a), the FC (b) and the DSG (c)

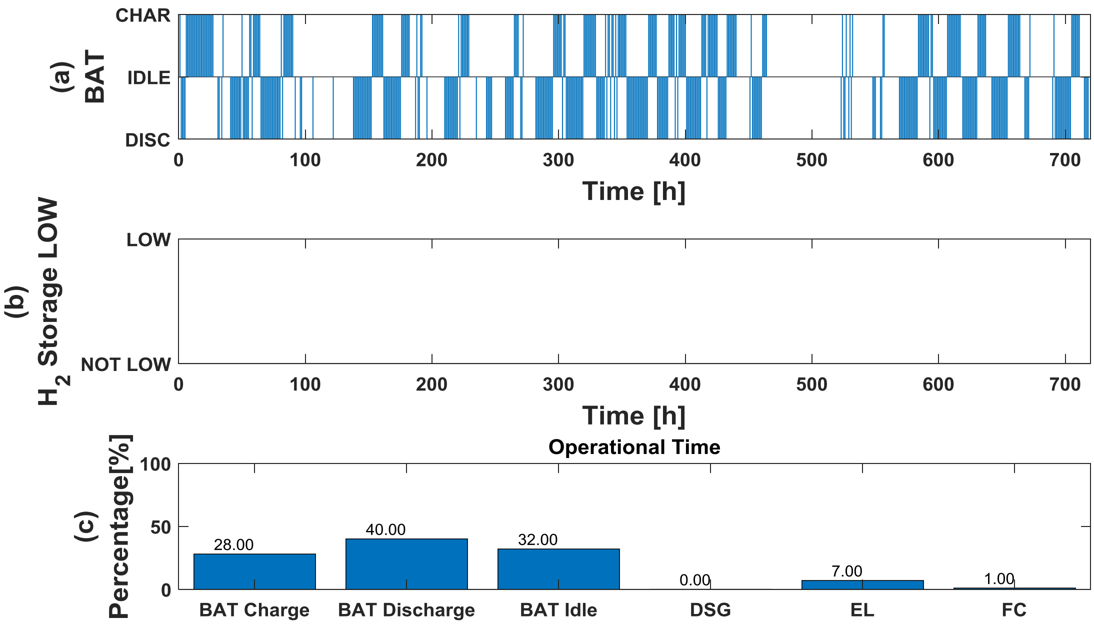


Figure 47. Hourly state(Char/Idle/Disc) of BAT (a), hourly state(Low/Not low) of HT (b), operational time percentage for each subsystem(c)

6.3.3 July

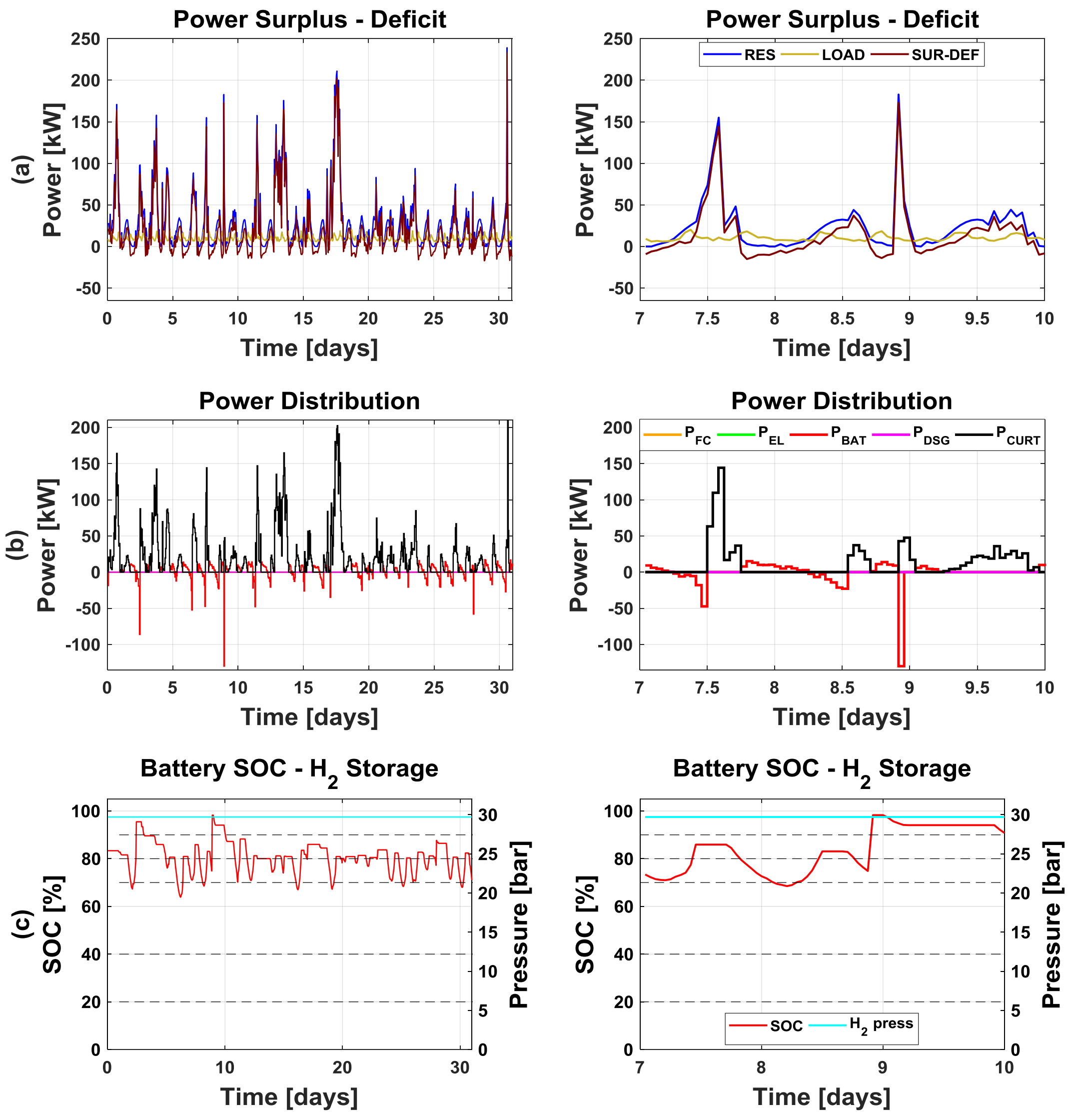


Figure 48. (a) Available RES, load and surplus-deficit, (b) Power distribution, (c) Battery SOC and hydrogen storage level. (left) Whole month and (right) 3 days of the month.

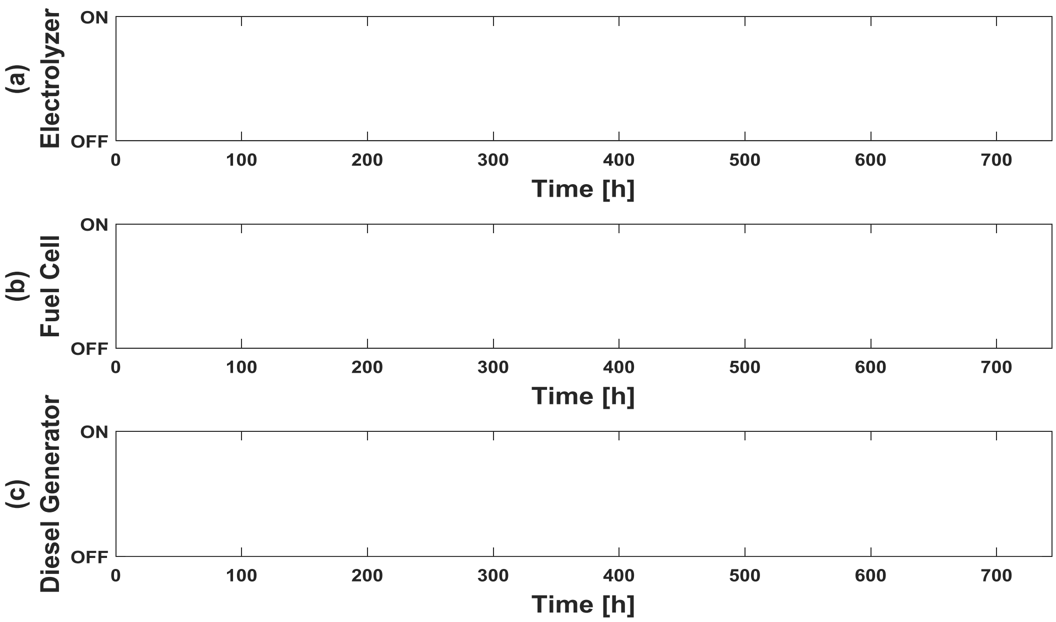


Figure 49. Hourly state (ON/OFF) of the EL (a), the FC (b) and the DSG (c)

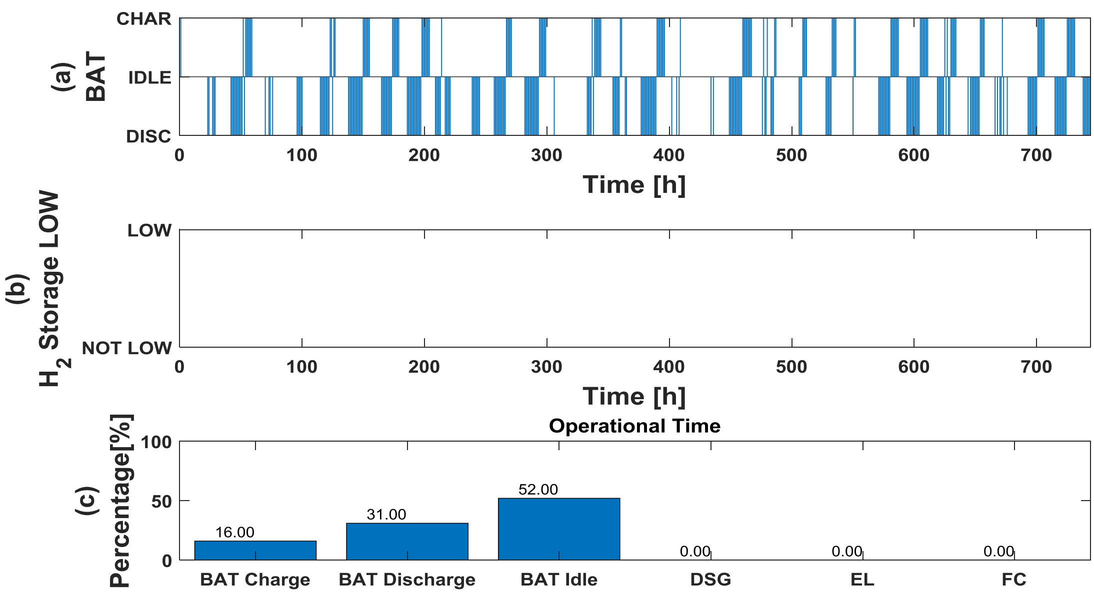


Figure 50. Hourly state(Char/Idle/Disc) of BAT (a), hourly state(Low/Not low) of HT (b), operational time percentage for each subsystem(c)