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An adaptive power management tool for sizing a PV-battery-hydrogen off-grid electrical energy system

Loris Pace^{1,*}, Ayyoub Zouaghi¹, Matthieu Beley¹, Naoufel Haddour¹

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Abstract

Off-grid electrical energy systems based on renewable energy sources (RESs) have become increasingly popular for their ability to generate low-carbon electricity in remote areas without access to traditional power grids. These systems rely on the effective management of RESs and storage solutions. Designing and sizing these systems can be a complex task, requiring careful consideration of various parameters such as energy demand, solar irradiance, storage capacity of batteries and State of Charge, power management of fuel cells, and hydrogen production and storage. This study presents an adaptive power management tool that facilitates the sizing of energy equipment for standalone low-carbon microgrids. The proposed simulation tool, implemented in Matlab/Simulink, is based on mathematical models for each energy unit and incorporates a specific power management strategy to determine the optimal size of each component in the system. The effectiveness of the tool is illustrated through a case study involving a PV-battery-hydrogen energy system designed to supply electricity to a standalone district. Results show that the developed tool can be a valuable aid for system designers and planners for creating sustainable and reliable off-grid electrical energy systems, as well as for educational and learning activities.

Keywords: solar panels, green hydrogen, fuel cell, battery storage, optimal sizing, standalone microgrid

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1. Introduction

Within the context of climate change, depletion of natural resources and energy crisis, low-carbon emitting off-grid electrical energy systems, and smart autonomous microgrids have become increasingly popular in recent years [1–3]. The development of such systems is enabled by the continuous improvement in the exploitation of renewable energy sources (RESs), such as solar or wind energy, and advancements in the power system efficiency [4]. Although RESs show high capability in resolving actual environmental issues related to fossil energy exploitation, their intermittency requires efficient storage systems to ensure a steady supply of electricity. Previous work has shown that hybrid storage systems based on batteries and green hydrogen systems are the most efficient solutions to satisfy short- and long-term electrical load requirements [5].

In autonomous low-carbon energy microgrids, the management of combined energy sources and storage systems led to a more complex design of the installed equipment. Batiyah et al. [6] present a Model Predictive Control (MPC) scheme based on mathematical models which is able to manage disturbances and storage systems in a standalone microgrid. The studied system includes photovoltaic (PV) panels, wind turbines (WT), and battery storage. In the study by Cecilia et al. [7], the same MPC method is applied to a power system that includes a hybrid

battery and hydrogen storage. However, these articles do not cope with the sizing of different energy equipment and consequently no optimization procedures are applied. Several optimization algorithms are compared for the sizing of a PV-battery-hydrogen microgrid in the study by Diab et al. [8]. Nevertheless, the proposed sizing methodology is mostly driven by costs and the obtained results strongly depend on these economic constraints [9]. Similar approaches are used in the notorious existing software such as HOMER Pro [10] or H2RES [11] to design such energy systems in regard to techno-economic aspects [5, 12–14]. However, there are no real guidelines for the user to set the optimal size of the energy equipment during simulations and no obvious indications are given about the energy management process in these software solutions.

To the best of the authors' knowledge, there is still a lack of methodology, independent of economic constraints and easily adaptable, to provide the optimal size of the energy equipment in the case of standalone microgrids comprising RESs and hybrid battery-hydrogen storage systems. In this context, this study aims to present an adaptive power management tool that achieves this goal. The main contributions of this work are based on an innovative power management strategy using state machine principles and an iterative sizing optimization of the

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energy equipment from a power study conducted hour by hour, on a yearly basis. Moreover, proven mathematical models [3, 9] and a detailed specification extraction methodology are used to represent the energy units (sources and storage systems). Furthermore, since users have full access to each part of the system, the presented tool can be easily modified to integrate other energy units, as well as costs or environmental constraints. In this work, the proposed sizing tool is developed in Matlab/Simulink. It is applied to a fictive off-grid district, named New Era thereafter, that is supplied by 100% of green electricity through a PV-battery-hydrogen power system.

The study is structured as follows. First, the Section 2 is divided into five sub-sections. The standalone New Era district, to which the developed simulation tool is applied, is presented in Section 2.1. An overview of the studied PV-battery-hydrogen energy system is also provided in this part. Section 2.2 presents the hourly electrical consumption profiles considered over a year of operation. Subsequently, Section 2.3 details the proposed models for the different energy units considered in this work. The power management strategy used to satisfy the electrical load at each time step is presented in Section 2.4, while Section 2.5 describes the proposed sizing methodology to get the optimal values of the equipment capacities in order to ensure a whole year operation of the power system. The Section 3 highlights the obtained simulation results for the specific case study. Finally, a discussion about the performance of the proposed sizing tool is engaged, and the prospects are identified for future work.

2. Materials and methods

2.1. System overview

The power management tool proposed in this work is designed in Matlab/Simulink in order to supply electrical energy to a standalone green-energy district. The only source of energy comes from a photovoltaic (PV) unit composed of several PV panels. The rated power of the PV group and the number of panels must be determined. The electrical energy is stored in two distinct ways:

- Short-time storage by using a battery unit composed of multiple battery cells. The number of cells and the rated power of the battery group must be determined.
- Long-time storage by converting excess electricity into hydrogen. The unit consists of an electrolyzer group, a fuel cell group, and a hydrogen tank. The parameters to be sized include the rated power of the electrolyzer and fuel cell group, as well as the required mass of hydrogen to be stored. The hydrogen is considered to be stored in gaseous form.

To size the studied electrical energy system, the power flows must be known during a complete year of operation depending on the PV production, the battery group State of Charge (SoC), and the stored quantity of hydrogen. Therefore, a power management strategy based on a state machine principle is proposed in this work. **Figure 1** provides an overview of the energy system implemented in Matlab/Simulink.

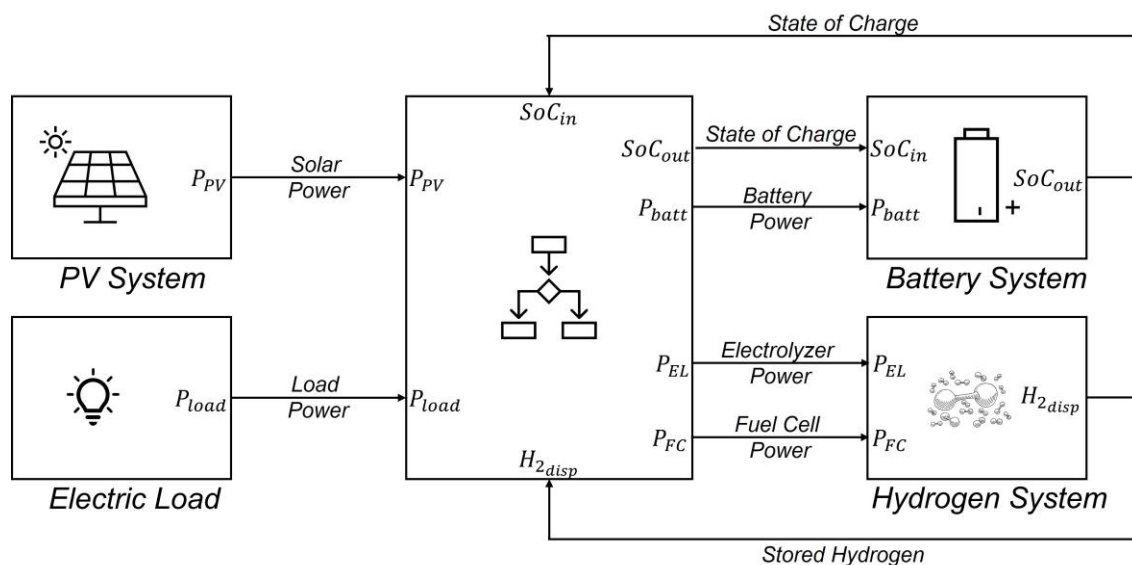


Figure 1 • Synopsis of the implemented energy system.

The fictive New Era district is considered to be located in the city of Ecully, France. It is composed of several buildings:

- A residence including 40 apartments
- An office center including 20 offices
- Three different stores: a grocery, a bakery, and a pharmacy
- An Electric Vehicle (EV) service station comprising four charging points and an office

Additionally, two parking areas are available for the residents and some areas are left available and could be used to install some parts of the energy system such as storage units. **Figure 2** shows an overview of the studied New Era district. Vacant lands

are also available around the district and could be used to place photovoltaic panels.

2.2. Electrical consumption profiles

The electrical consumption profiles of New Era are built by stocktaking all the electrical equipment, identifying their electrical power and determining their operation time as shown in **Table 1**. These data have been collected from the French Agency of Environment and Management of Energy (ADEME) [15] and the energy consultant Hello Watt [16], in order to give the most realistic characteristics to this fictive case study. Some assumptions are made to simplify the profiles:

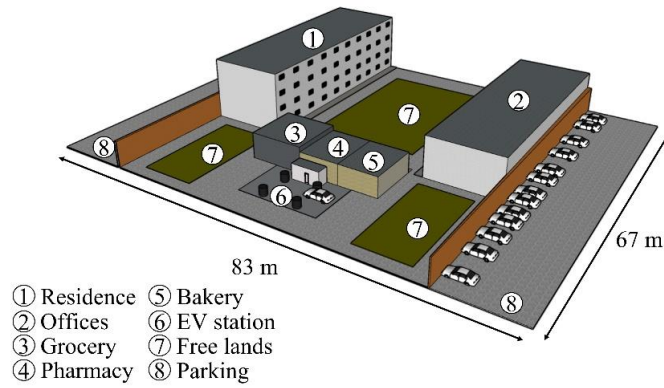


Figure 2 • 3D model of the New Era district.

Table 1 • Electrical equipment power and operation time

Equipment	Quantity	Power (kW)	Operation time
Office computer	20	0.2 p.u.	8 AM–6 PM
Wi-Fi Box	43	0.025 p.u.	Midnight–11 PM
Laptop charger	40	0.1 p.u.	7 PM–8 PM
Lighting	3,840 m ²	0.0025/m ²	6 AM–8 AM 7 PM–Midnight
TV	40	0.1 p.u.	8 PM–Midnight
Oven	40	2 p.u.	6 PM–7 PM
Industrial oven	2	2.5 p.u.	5 AM–8 AM
Induction plate	40	2.5 p.u.	6 PM–7 PM
Fridge	40	0.03 p.u.	Midnight–11 PM
Vacuum cleaner	40	0.4 p.u.	5 PM–6 PM
Dishwasher	40	1.5 p.u.	Midnight–1 AM
Washing machine	40	2.5 p.u.	1 AM–2 AM
Clothes dryer	40	2.5 p.u.	2 AM–3 AM
EV charger	4	7 p.u.	7 AM–8 PM

- Two seasons are considered: summer (Apr–Sept) and winter (Oct–Mar)
- People are assumed to be at work during the day (8AM–6PM) and at the apartment during the night (7PM–7AM)
- Only LED lighting is considered
- Dishwashers, washing machines, and clothe dryers are assumed to operate during the night to level off the electrical consumption profiles
- 4 EVs are charged every hour during the day (7AM–8PM)

Figure 3a reveals the electrical consumption profiles of each building. It can be observed that the major part of the electrical power consumption takes place early in the morning and at the evening for the residence, while the electricity is mainly consumed during the day by the office and the service station. Figure 3b illustrates the total consumption profiles of New Era during winter and summer seasons. A slight difference between the winter and summer profiles originates from light usage during the day, mainly at the office. It should be noted that the heating system is not considered in this work.

From Figure 3b, the maximum demand of electricity per day, $P_{load_{max}}$, is found to be equal to 168 kW. This value will be used for the initialization of the proposed system sizing strategy presented in Section 2.5.

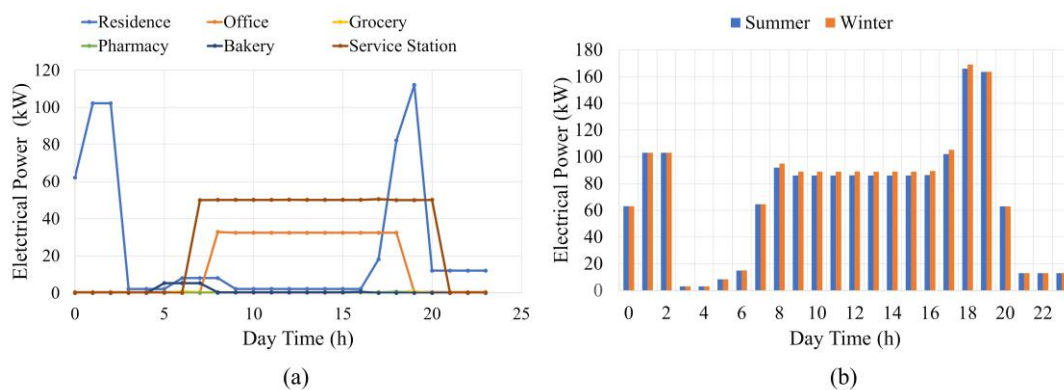


Figure 3 • Electrical consumption profiles (a) by building and (b) total consumption of the district during winter and summer.

2.3. Energy units modeling

This section aims to present in detail the implemented models for the considered energy units which include the PV panels group, the battery unit, and hydrogen storage. As this work focuses on

the development of the power management tool and the sizing strategy, the models proposed here are simplified and several physical phenomena that could impact the power conversion are neglected. For each energy unit, the limitations of the presented models and some leads to overcome these limitations are given.

2.3.1. Photovoltaic unit

The PV unit, comprising all the solar panels, aims to evaluate the produced power, P_{PV} , at every simulation time step, which is considered equal to one hour in this work. This parameter can be adjusted regarding the energy consumption profiles.

The proposed model is inspired from the study by Zahboune et al. [9] but the energy variables are converted in power variables, considering then that the power remains constant during one time step. Thus, the input data of the model are solar irradiance, G (W/m^2), given every hour of the day for each season. The solar

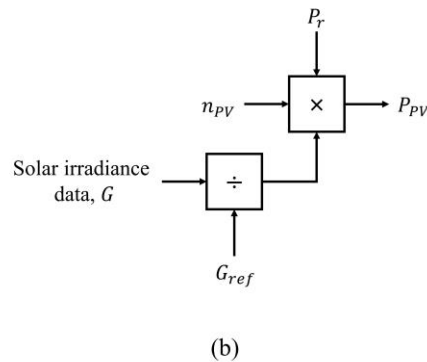
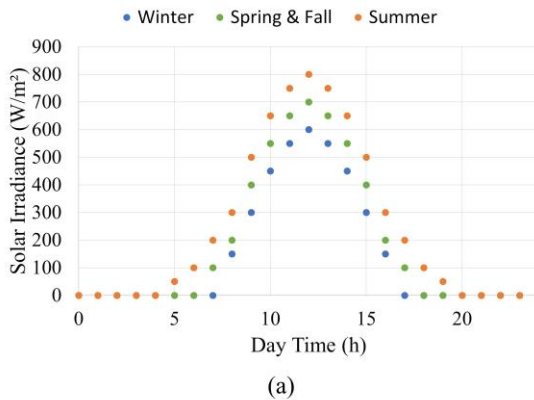


Figure 4 • PV unit (a) solar irradiance data for each season and (b) block diagram.

$$P_{PV} = n_{PV} P_r \frac{G}{G_{ref}} \quad (1)$$

where P_r is the rated power of one solar panel at an irradiance of G_{ref} and n_{PV} is the number of solar panels considered. In this case study, the selected solar panels are RSP200D from Renogy ©. The rated power at $G_{ref} = 1000 W/m^2$ is $P_r = 200 Wc$. The photovoltaic conversion efficiency is found to be 18.1%. The surface area of the PV panel is $1.1 m^2$.

The presented PV unit model assumes an electrical power production that only depends on solar irradiance data and the number of panels considered. It does not take into account several factors that could impact the produced power such as PV panel orientation, shadow, temperature, or aging effects. Also, the probable use of power electronics systems such as Maximum Power Point Tracking (MPPT) converters and their associated efficiency are not considered here. However, the implementation of this model in the Matlab/Simulink software only requires a few operator blocks and the user can easily modify the PV unit to improve the model accuracy by considering some physical parameters and possibly its own characterization data.

2.3.2. Battery unit

The battery unit aims to evaluate the SoC of the battery group at every simulation time step based on the SoC at the previous time step and the present supplied/demanded electrical power. The battery group is composed of n_{cell} battery cells, where n_{cell} is a parameter to optimize, which allow one to level off the SoC variation by limiting the cell current.

For this case study, the selected solar battery cell is the GEL Ultimatron JDG12-100 12 V 100 Ah [18]. The recommended charging current is 10 A with a limit at 25 A. Here, we propose a

irradiance data used in this work are obtained from Global Solar Atlas [17] and are presented in Figure 4a. In one day, the solar irradiance increases to reach its higher value at mid-day, then it decreases. It must be noted that the four seasons are considered, whereas the same solar irradiance has been considered for spring and fall for simplification.

Knowing that the reference solar irradiance, G_{ref} , given in datasheet for solar panels is $1,000 W/m^2$, the electrical power generated by the PV group, P_{PV} , is given by equation 1. The block diagram of the PV unit is given in Figure 4b.

methodology to build the battery unit model based on the technical documentation of the chosen cell [18]. Although the presented model lays on the same approach proposed by Zahboune et al. [9], it is not based on energy variables but depends mainly on SoC and the power supplied or demanded to the battery group. In the proposed battery unit model, all battery cells are considered to be connected in parallel, meaning that the voltage of battery group is considered equal to the voltage of one cell, V_{cell} , being around 12 V.

According to Ultimatron JDG12-100 [18], the battery cell voltage, V_{cell} , is given as a function of the SoC following the expression in equation 2.

$$V_{cell} = V_o + k_1 SoC \quad (2)$$

where $V_o = 12 V$ is the battery cell voltage at $SoC = 0\%$ and $k_1 = 1 V$. In the formulae SoC is between 0 and 1 without unit.

Once the battery voltage is known, the battery cell current I_{cell} can be obtained from the battery unit power, P_B , using equation 3. This current is either positive when the battery cell is charging ($P_B > 0$), or negative when the battery cell is discharging ($P_B < 0$).

$$I_{cell} = \frac{P_B}{n_{cell} V_{cell}} \quad (3)$$

Figure 5 gives the SoC variation, ΔSoC , according to the charging current per cell. This curve is obtained from data available in the technical documentation [18]. For simplicity, it is considered that the SoC variation is symmetrical in charging and discharging modes. Therefore, the hysteresis phenomena in the battery are not taken into account in this work.

From **Figure 5**, the relation between ΔSoC and I_{cell} can be expressed as equation 4.

$$\Delta\text{SoC} = \text{sign}(I_{\text{cell}})k_2 I_{\text{cell}}^2 + k_3 I_{\text{cell}} \quad (4)$$

where $k_2 = 8.10^{-5} \text{ A}^{-2}$ and $k_3 = 0.01 \text{ A}^{-1}$.

According to equations 2–4, the block diagram of the battery unit is given in **Figure 6**.

As previously mentioned, the design of the proposed model is fully based on the battery cell specifications. However, it presents some simplifications and some factors are neglected. Apart from the hysteresis phenomenon, the temperature and aging effects, for example, are not considered here. Similar to the PV unit model, power electronics systems, such as the Battery Management System (BMS), and their associated efficiency are not taken into account. Nevertheless, the user can easily modify the battery unit model to improve its accuracy by considering some physical parameters and possibly its own characterization data.

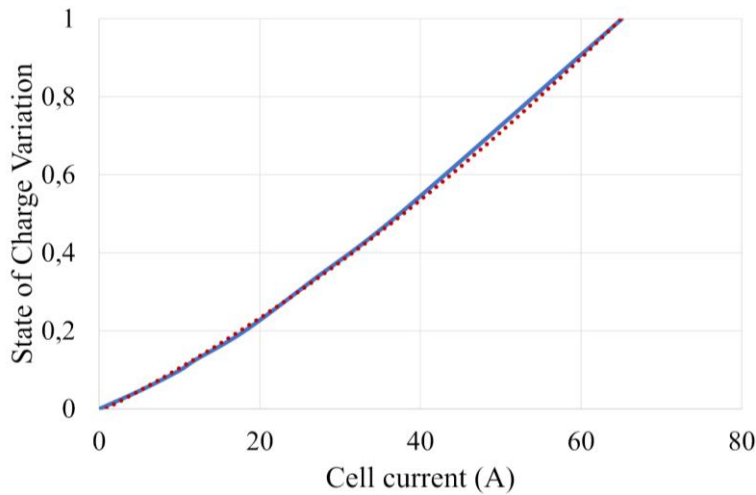


Figure 5 • State of charge variation vs. cell current: extracted data (the blue line); polynomial model (red dots).

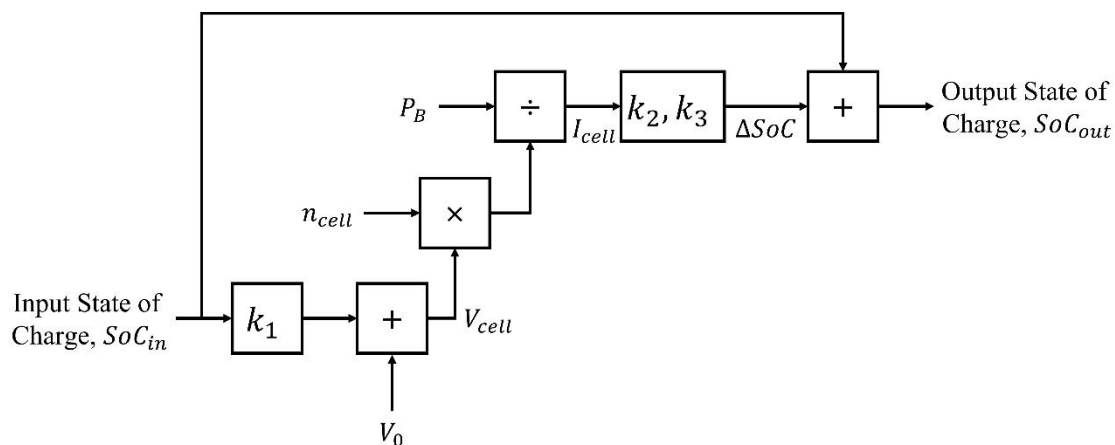


Figure 6 • Proposed block diagram for the battery unit.

2.3.3. Hydrogen storage unit

The proposed hydrogen storage (HS) unit model uses the same approach as those presented in Chamandoust et al. [3], as it aims to evaluate the quantity of stored hydrogen in grams, m_{H_2} , at every simulation time step. The hydrogen mass available is evaluated based on the stored quantity at the previous time step, the electrical power supplied to the electrolyzer group P_{EL} , and the electrical power demanded by the fuel cells group P_{FC} . In the proposed sizing strategy detailed in Section 2.5, the stored quantity of hydrogen given by the HS unit model will be used as the main optimization criteria.

According to the Gibbs relation [19], 30 g of H_2 corresponds to an electrical power of 1 kW during one hour (one time step). Based on this value, the conversion factor $k_4 = 30 \text{ g/kW}$ is considered. The mass of hydrogen produced by the electrolyzer

group, $m_{\text{H}_2\text{prod}}$, is obtained using equation 5. By the same principle, the mass of hydrogen consumed by the fuel cell group, $m_{\text{H}_2\text{cons}}$, is given by equation 6.

$$m_{\text{H}_2\text{prod}} = \eta_{\text{EL}} k_4 P_{\text{EL}} \quad (5)$$

$$m_{\text{H}_2\text{cons}} = \frac{k_4 P_{\text{FC}}}{\eta_{\text{FC}}} \quad (6)$$

where η_{EL} is the efficiency of the electrolyzer group and η_{FC} is the efficiency of the fuel cell group. In this work, these efficiency values are taken from El-Emam and Özcan [20] and Felseghi et al. [21] considering the Proton Exchange Membrane (PEM) electrolyzer and fuel cell groups.

The block diagram of the HS unit is given in **Figure 7**. In the model, the power generated by the electrolyzer group, P_{EL} , is considered positive and the power demanded by the fuel cell group, P_{FC} , is considered negative.

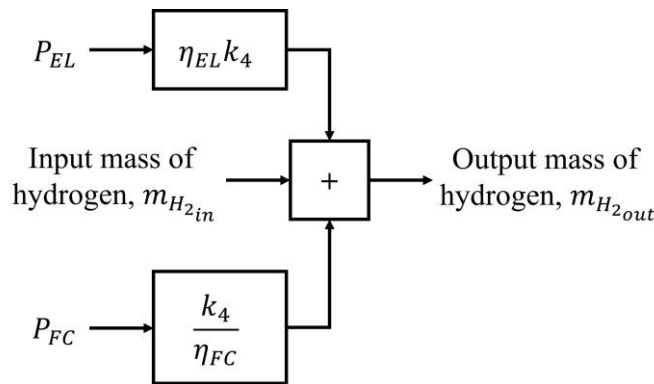


Figure 7 • Hydrogen storage unit block diagram.

2.4. Power management unit

This subsection presents the proposed power management strategy in order to optimize the sizing of the different energy equipment. First, the basic principle of the method is exposed. Then, different ways to implement the Power Management Unit (PMU) in the Matlab/Simulink software are given.

2.4.1. Methodology

The PMU aims to evaluate at every time step the difference of electrical power, ΔP , between the power produced by the PV unit, P_{PV} , and the power demanded by the district, P_{load} , as given by equation 7.

$$\Delta P = P_{PV} - P_{load} \tag{7}$$

Then, depending on the sign of ΔP (i.e. an excess or deficit of electrical energy) and the SoC returned by the battery unit model, the power difference ΔP is sent either to the battery, or to the electrolyzer or to the fuel cell group. This strategy is implemented using a state machine as summarized in **Table 2**. In the case of electrical energy deficit ($\Delta P < 0$), it is preferable to use the battery group (due to higher electrical energy conversion efficiency) if the SoC is sufficient, here, $SoC > 0.2$ (State 1 or State 2); otherwise the fuel cell group will be used (State 0). In the case of an excess of PV production ($\Delta P > 0$), it is chosen to preferably charge the

The presented HS unit model, inspired by Chamandoust et al. [3], does not take into account some factors that could impact HS capabilities such as temperature or pressure effects for example. Nevertheless, similar to the other energy unit models, the user can straightforwardly modify the HS unit model to improve its accuracy by considering some physical parameters and possibly its own characterization data.

battery group if the SoC is not at its maximal value, here, $SoC < 0.9$ (State 1 or State 2); otherwise the electricity will be used to produce hydrogen using the electrolyzer group (State 3). It should be noted that there are two impossible combinations, highlighted in red in **Table 2**, that would lead to $SoC > 0.9$ but $SoC < 0.2$. Depending on the resulting state value (0, 1, 2 or 3), ΔP is either attributed to the battery group, to the electrolyzer group, or to the fuel cell group as illustrated in **Figure 8** which gives the block diagram of the proposed PMU.

Table 2 • Proposed management strategy using a state machine

$\Delta P > 0$	$SoC > 0.2$	$SoC > 0.9$	State (sum)	$\Delta P =$
0	0	0	0	P_{FC}
0	1	0	1	P_B
0	1	1	2	P_B
1	0	0	1	P_B
1	0	1	NA	NA
1	1	0	2	P_B
1	1	1	3	P_{EL}

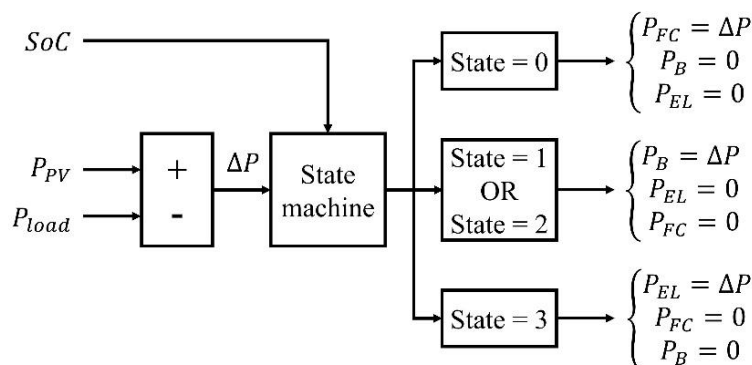


Figure 8 • Proposed PMU block diagram.

2.4.2. Matlab/Simulink implementation

There are many possible ways to implement the previously described PMU in the Matlab/Simulink software. Here, three different possibilities, tested by the authors, will be presented and will give the same results. The first implementation, presented in **Figure 9**, is based on the diagram presented in **Figure 8**. The state machine is carried out using “Switch” blocks that commute between 0 and 1 states according to defined

switch conditions. Then, a “Matlab Function” block which includes Matlab code is performed to specify the actions according to the state value (see **Figure 8**). This solution is robust and is almost instantaneous to simulate. However, this method requires the user to be familiar with the Matlab code. Another drawback is that the modification of the power management strategy will require the user to modify at least the Matlab code and potentially all the block architectures.

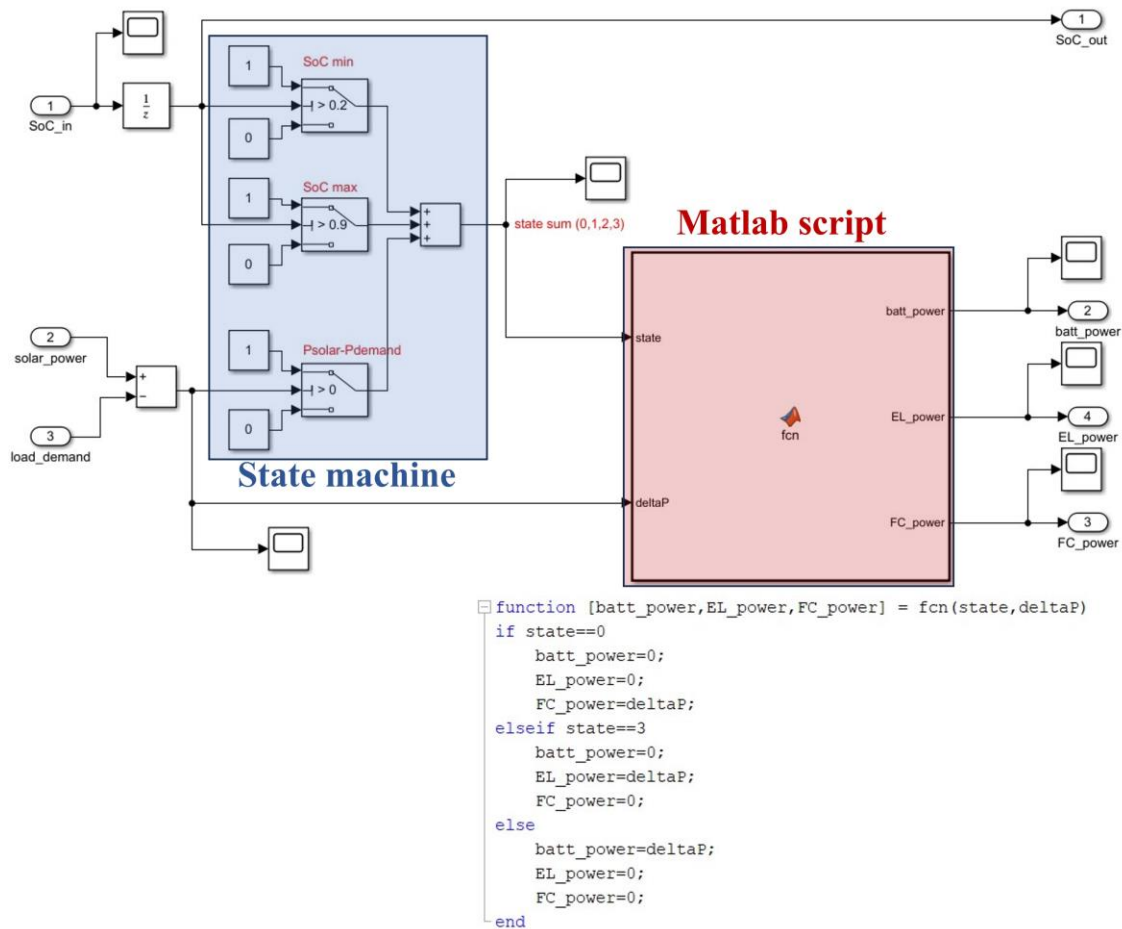


Figure 9 • PMU implementation in Matlab/Simulink using switches and Matlab code.

A second proposed implementation of the PMU is by using a “Truth Table” block. This can be done by a direct implementation of **Table 2** as shown in **Figure 10**. The “Condition Table” will return actions defined in the “Action Table” according to the state value. In comparison with the previous solution, this method does not require the user to have specific knowledge in Matlab code. As the previously proposed implementation, the simulation time is not increased by this method.

Finally, the PMU can be implemented using the “Stateflow” toolbox as shown in **Figure 11** using a “Chart” block. This solution gives a graphic view of the different states and transitions as well as an easily adaptive simulation block to the user. Furthermore, when increasing the studied system complexity, the state flow methodology will become the most convenient implementation. Another advantage in the software is that the user is able to observe the switching between states while running the simulation, which could be useful for debugging. However, the simulation time is notably lengthened in most cases which constitutes a major drawback in the case of the implementation of the optimal sizing method that is presented in the next subsection.

2.5. System sizing methodology

In this subsection, an iterative process to optimize the size of the energy equipment is suggested. In contrast to existing software solutions such as HOMER Pro or H2RES which are mainly driven by economics, the proposed sizing method is only driven by energy requirements. This could be an attractive methodology especially in the case of standalone microgrids. The sizing results obtained with the proposed strategy are presented in the Section 3. It should be noted that the following optimization strategy is not unique and shall be compared in terms of performance to a set of other solutions in future work.

The sizing of the studied PV-battery-hydrogen system depends on three parameters that must be optimized:

- The number of PV panels, n_{PV}
- The number of battery cells, n_{cell}
- The maximal quantity of hydrogen to store, $m_{H_2_{max}}$

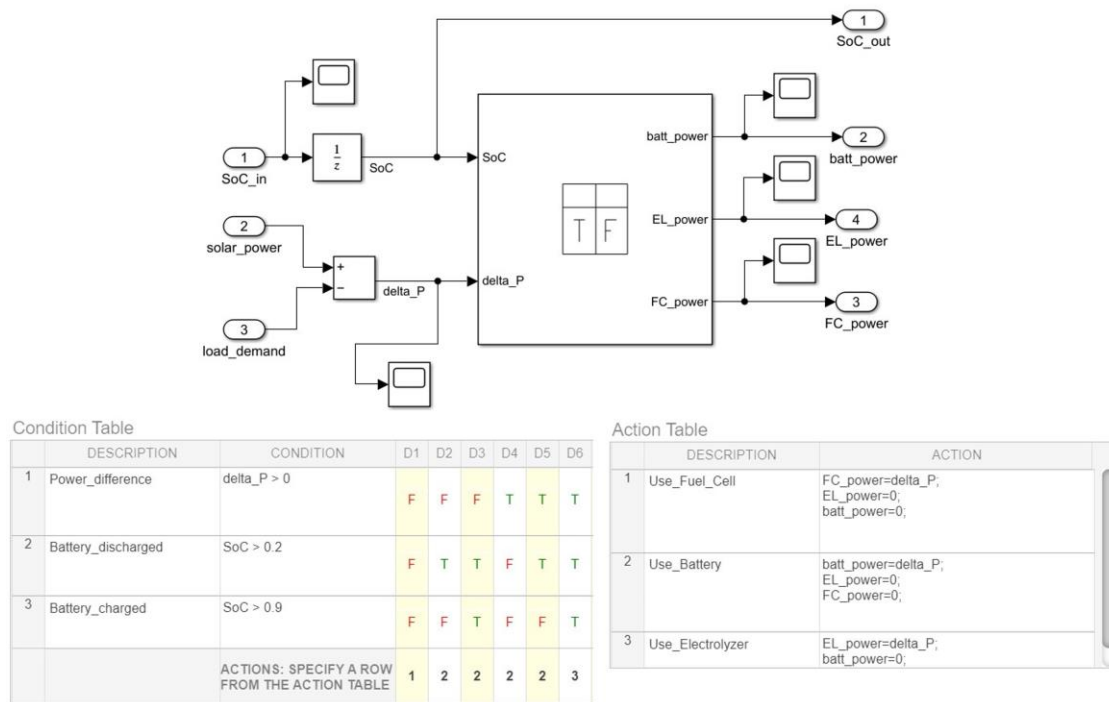


Figure 10 • PMU implementation in Matlab/Simulink using a truth table.

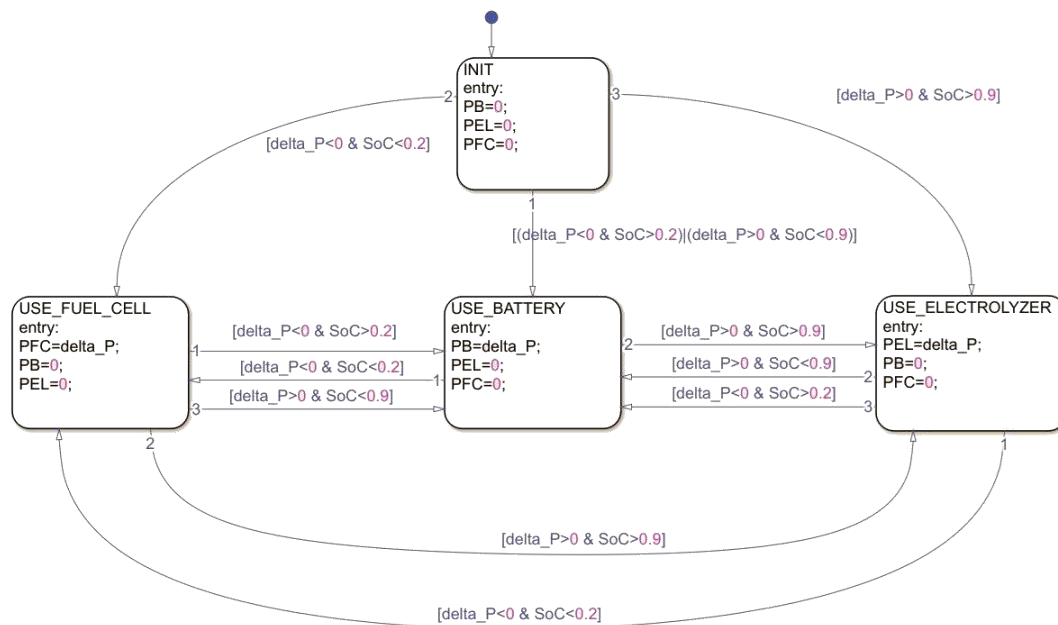


Figure 11 • PMU implementation in Matlab/Simulink using state flow with PB: the battery unit power, PEL: the electrolyzer group power, and PFC: the fuel cell group power.

The iterative process starts by setting an initial value for n_{PV} according to the maximal load demand $P_{load_{max}}$ determined previously. Then, the n_{cell} value is calculated according to the maximal PV production, $P_{PV_{max}}$, to ensure that the maximal admissible cell current $I_{cell_{max}}$ is not exceeded. The simulation is launched and the algorithm is completed to compare the stored hydrogen quantity at the beginning of the year ($m_{H_2}(0)$) and at

the end of the year ($m_{H_2}(8,760)$), leading to a mass of hydrogen variation coefficient, Δ as given by equation 8.

$$\Delta m_{H_2} = m_{H_2}(8,760) - m_{H_2}(0) \quad (8)$$

If $\Delta m_{H_2} = 0$, then the energy system is optimized. Else, n_{PV} is either increased or decreased and the algorithm process is repeated. The stopping criterion ($\Delta m_{H_2} = 0$) can be adapted to the user needs in terms of remaining hydrogen mass at the end of the year. Figure 12 shows a schematic representation of the

proposed sizing method. In **Figure 12**, G_{max} corresponds to the ratio of the maximal solar irradiance in W/m^2 obtained during the year and the reference value of $1,000 W/m^2$.

3. Results

The simulations are conducted over one year starting by the winter season. It has been verified by authors that there is no impact on the sizing results if the user starts the simulation by another season than winter. However, careful consideration must be taken with regard to initial values. If the simulation starts with the winter season, because of low global irradiance, an important initial stored mass of hydrogen is needed for correct operation of the power system. Thus, in this work, the initial values listed below are set:

- Initial SoC: 0.5
- Initial stored mass of hydrogen: 1,200 kg

The sizing methodology presented in **Figure 12** is then applied. The convergence of the proposed iterative process is highlighted in **Figure 13** which gives the mass of hydrogen difference between the beginning and end of one year, Δm_{H_2} , according to the number of PV panels, n_{PV} . The optimal number of PV panels, leading to $\Delta m_{H_2} = 0$, is 2,095 for the studied system. Moreover, it has been observed that the initial value of n_{PV} (1,050) is quite far from the optimal value (2,095) for this case study which suggests that future work shall focus on this initial value formulae to improve the convergence time of the algorithm.

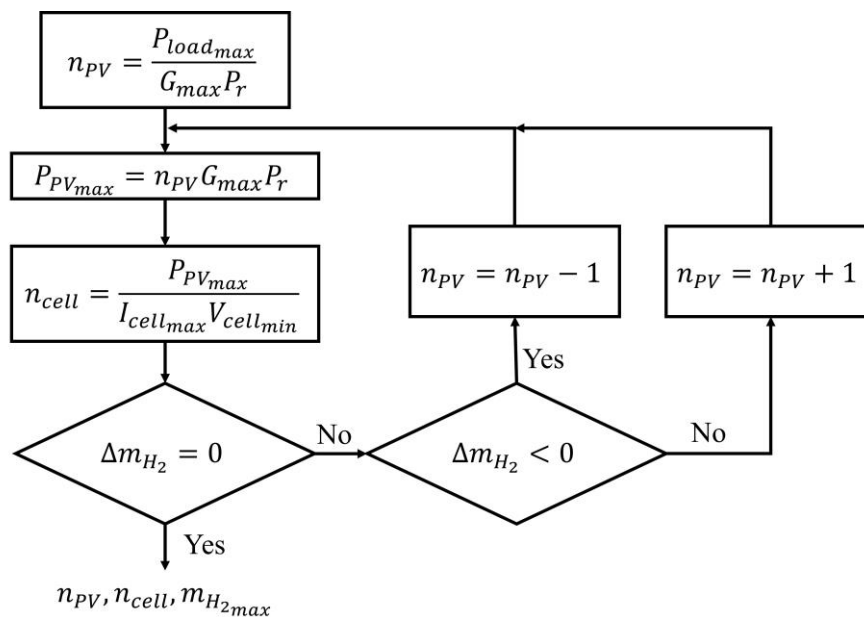


Figure 12 • Schematic representation of the proposed system sizing strategy.

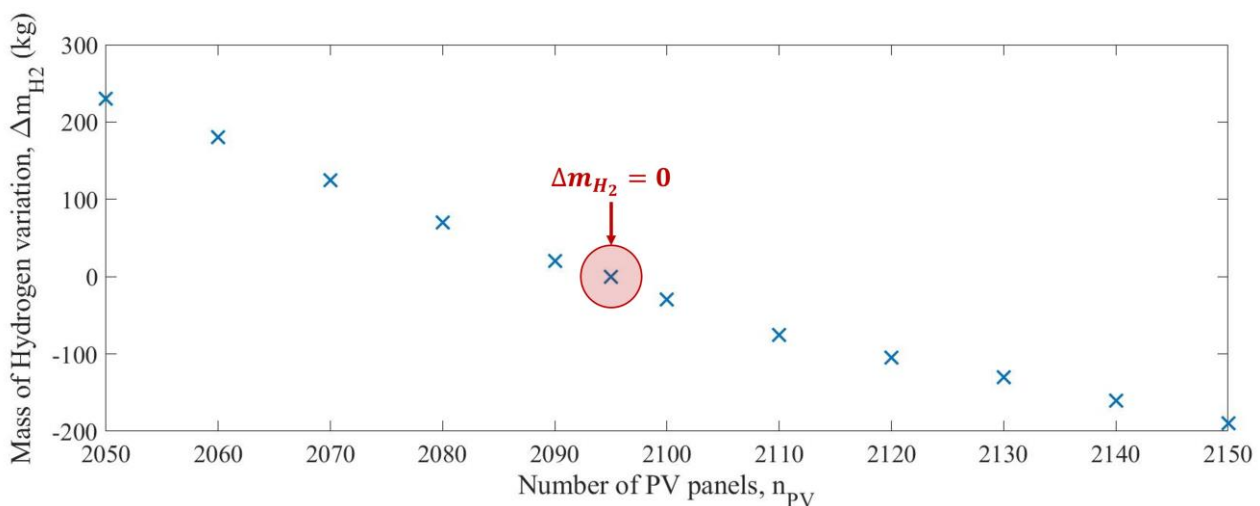


Figure 13 • Convergence of the sizing method for the case study.

Figure 14 shows the yearly evolution of the amount of stored hydrogen. From **Figure 14**, it can be seen that the stored hydrogen quantity quickly decreases in winter because of the high energy required for the storage, and therefore a high hydrogen consumption by the fuel cells. In contrast, the stored hydrogen quantity quickly increases during summer since the PV

production is important and the battery group is well charged. In spring and fall, the stock of hydrogen still increases but with a clearly lower slope, which suggests that the balance between produced and demanded electricity is more effective during these seasons. These results are reasonable and expected in the case of a standalone microgrid supplied by solar panels.

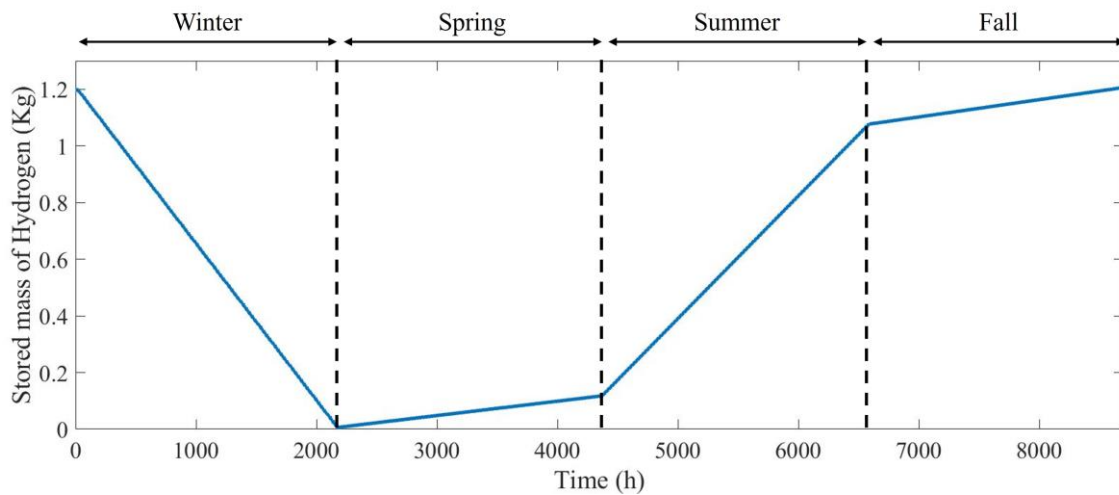


Figure 14 • Simulated stored mass of hydrogen over one year after optimization.

Figure 15 gives the yearly evolution of the power of the battery group, the current of a single battery cell, the power of the electrolyzer group, and the power of the fuel cell group. **Figure 16** shows the electrical power evolution over a day in each energy unit for the winter and summer seasons. These results are obtained for a maximal PV unit power $P_{PV_{max}}$ of 335 kW.

The power profiles depend on the season, as highlighted in **Figures 15** and **16**. As expected, there is no power in the electrolyzer group in winter because of the lack of PV production. At the same season, the fuel cell power is high. A contrasting behavior can be observed in summer where the electrolyzer group power is high and the fuel cell group power is low. As shown in **Figure 16**, the daily electrical power in the battery group has positive and negative values, meaning that the battery group is charging and discharging every day during the year. As shown in **Figure 15b**, it should also be verified that the battery cell current, I_{cell} , does not exceed the maximal specified charging or discharging current of 25 A. **Table 3** summarizes the

main results using the proposed sizing which are the rated power of the PV unit, $P_{PV_{max}}$, the size of the hydrogen tank, $m_{H_2_{max}}$, the rated power of the battery unit, $P_{B_{max}}$, the rated power of the electrolyzer group, $P_{EL_{max}}$, the rated power of the fuel cell group, $P_{FC_{max}}$, the number of PV panels, n_{PV} , and the number of battery cells, n_{cell} . The total area occupied by the solar panels is estimated to be 2,305 m².

Table 3 • Main simulation results

$P_{PV_{max}}$ (kW)	$m_{H_2_{max}}$ (kg)	$P_{B_{max}}$ (kW)	$P_{EL_{max}}$ (kW)	$P_{FC_{max}}$ (kW)	n_{PV}	n_{cell}
335	1,200	250	230	110	2,095	1,085

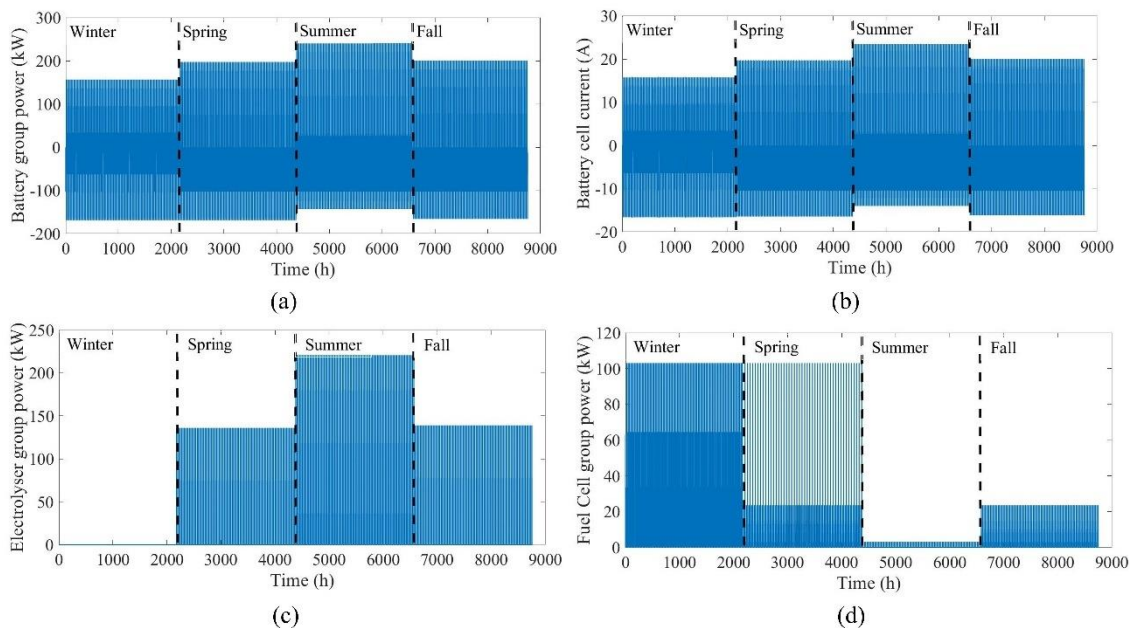


Figure 15 • Simulation results over one year: (a) battery group power, (b) single battery cell current, (c) electrolyzer group power, and (d) fuel cell group power.

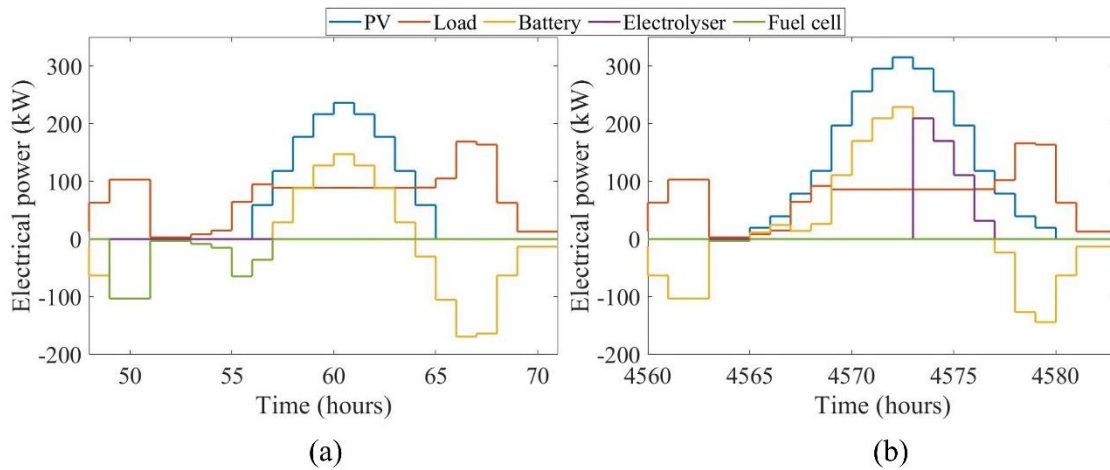


Figure 16 • Daily simulated power profiles (a) in winter and (b) in summer.

4. Conclusion

This work has presented the development of a helpful fully accessible and customizable power system sizing tool for standalone hydrogen-based microgrids which is not directly driven by costs. Thus, the user can obtain optimal initial values for equipment capacities in its application before performing techno-economic analysis.

A straightforward state machine has been proposed to drive the power flows at every hour of the year depending on load demand, PV production, battery group SoC, and hydrogen availability. Then, an optimal sizing strategy is proposed and implemented to set the PV and battery storage capacities in order to have the same amount of stored hydrogen at the beginning and the end of every year. Consequently, the sizing method only relies on a proper energy management. The tool has been applied to a case study, consisting of a PV-battery-hydrogen power system, to demonstrate its effectiveness. It provides a deep view in the power exchange in the system hour by hour on a yearly basis, which could be of great help for energy designers. Moreover, the obtained results conform to the expectations for a standalone microgrid supplied by solar panels.

Furthermore, the proposed simulation tool presents various advantages:

- **Comfortable implementation:** the tool is based on mathematical models. In this work, it has been implemented in the Matlab/Simulink software but other simulation environments can be used.
- **Easy model improvement:** the energy unit models presented in this study can be straightforwardly improved to better fit the user needs. For example, the temperature and pressure conditions or aging could be taken into account. The efficiency of the associated power electronics could be considered and added.
- **Adaptability (flexibility):** The power management and sizing strategy can be applied to other power architectures. For example, WT could have been integrated to the case study based on the model presented in the study by Zahboune et al. [9]. Moreover, the tool could be used to size a hybrid H₂-battery storage system for e-mobility applications. In this specific last case, no energy source would be considered.

It should be noted that the management of thermal loads have not been taken into account in this work. Indeed, various low-carbon heating solutions could be considered such as electric heaters, heat pump, hydrogen boiler, etc. The proposed power sizing tool can also be of great help to determine the best solution for a specific application. This study will be a part of future work. Future work shall also focus on the implementation of economic constraints and its influence on the power system sizing. Adding other energy sources such as wind power should be considered as well. Finally, the integration of environmental criteria and life cycle analysis with the sizing strategy should be considered.

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Author contributions

All authors contributed equally to this research work. L. Pace (LP), A. Zouaghi (AZ), and M. Beley (MB) work in the field of electrical engineering while N. Haddour is specialized in electrochemistry. Conceptualization and methodology: LP, AZ, MB, and NH. Simulation results: LP. Formal analysis and validation: LP, AZ, MB, and NH. Project administration: LP. Writing-original draft preparation: LP.

Conflict of interest

The authors declare no conflict of interest.

Data availability statement

Data supporting these findings are available within the article or upon request.

Institutional review board statement

Not applicable.

Informed consent statement

Not applicable.

Sample availability

The author(s) declare that no physical samples were used in the study.

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References

1. Siddaiah R, Saini RP. A review on planning, configurations, modeling and optimization techniques of hybrid renewable energy systems for off grid applications. *Renew Sust Energ Rev.* 2016;58:376–96.
2. Mbungu NT, et al. Control and estimation techniques applied to smart microgrids: a review. *Renew Sust Energ Rev.* 2023;179:113251.
3. Chamandoust H, Hashemi A, Bahramara S. Energy management of a smart autonomous electrical grid with a hydrogen storage system. *Int J Hydrog Energy.* 2021;46(34):17608–26.
4. Karamov DN, Ilyushin PV, Suslov KV. Electrification of rural remote areas using renewable energy sources: literature review. *Energies.* 2022;15(16):5881.
5. Dawood F, Shafiullah G, Anda M. Stand-alone microgrid with 100% renewable energy: a case study with hybrid solar PV-battery-hydrogen. *Sustainability.* 2020;12(5):2047.
6. Batiyah S, Sharma R, Abdelwahed S, Zohrabi N. An MPC-based power management of standalone DC microgrid with energy storage. *Int J Electr Power Energy Syst.* 2020;120:105949.
7. Cecilia A, Carroquino J, Roda V, Costa-Castelló R, Barreras F. Optimal energy management in a standalone microgrid, with photovoltaic generation, short-term storage, and hydrogen production. *Energies.* 2020;20;13(6):1454.
8. Diab AAZ, El-Rifaie AM, Zaky MM, Tolba MA. Optimal sizing of stand-alone microgrids based on recent metaheuristic algorithms. *Mathematics.* 2022;10(1):140.
9. Zahboune H, et al. Optimal hybrid renewable energy design in autonomous system using Modified Electric System Cascade Analysis and Homer software. *Energy Convers Manag.* 2016;126:909–22.
10. HOMER Pro microgrid software [Internet]. Colorado, USA: UL Solutions; [cited 2023 Aug 8]. Available from: <https://www.homerenergy.com/products/pro/index.html>
11. H2RES - Energy System Modelling Software [Internet]. Zagreb, Croatia: Faculty of Mechanical Engineering and Naval Architecture; [cited 2023 Aug 8]. Available from: <https://h2res.org/>
12. Khalil L, et al. Optimization and designing of hybrid power system using HOMER pro. *Mater Today: Proc.* 2021;47:S110–5.
13. Kalamaras E, et al. Techno-economic assessment of a hybrid off-grid DC system for combined heat and power generation in remote islands. *Energy Procedia.* 2019;158:6315–20.
14. Krajačić G, Duić N, Carvalho M da G. H2RES, Energy planning tool for island energy systems – the case of the Island of Mljet☆. *Int J Hydrog Energy.* 2009;34(16):7015–26.
15. ADEME - Agir pour la Transition [Internet]. [cited 2023 Aug 9]. Available from: <https://agirpourlatransition.ademe.fr/>
16. Hello Watt [Internet]; [cited 2023 Aug 9]. Available from: <https://www.hellowatt.fr/>
17. Global Solar Atlas [Internet]. [cited 2023 Apr 19]. Available from: <https://globalsolaratlas.info/map>
18. Ultimatron JDG12-100 [Internet]. [cited 2023 Apr 19]. Available from: https://www.batteries44.com/index.php?controller=attachment&id_attachment=222
19. Khotseng L. Fuel cell thermodynamics. In: Vizureanu P, editor. *Thermodynamics and energy engineering* [Internet]. IntechOpen; 2020 [cited 2023 Apr 19]. Available from: <https://www.intechopen.com/books/thermodynamics-and-energy-engineering/fuel-cell-thermodynamics>
20. El-Emam RS, Özcan H. Comprehensive review on the techno-economics of sustainable large-scale clean hydrogen production. *J Clean Prod.* 2019;220:593–609.
21. Felseghi RA, Carcadea E, Raboaca MS, Trufin CN, Filote C. Hydrogen fuel cell technology for the sustainable future of stationary applications. *Energies.* 2019;12(23):4593.