OPTIMIZED DESIGN AND SCHEDULING OF A HYDROGEN-BASED MICRO-GRID: TOWARDS FULL INTEGRATION OF RENEWABLE SOURCES

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ABSTRACT

Production of energy from renewable energy sources (RES) is pivotal for the reduction of the greenhouse emissions and to address the growing world energy demand. However, the intermittent availability of RES causes a fluctuating energy generation. Sustainable energy storage systems (ESSs) coupled with RES play the important roles of mitigating fluctuations, improving the reliability, and increasing the share of energy due to the RES unpredictable and intermittent nature. Moreover, among all the different energy storage systems, hydrogen is recently receiving attention as carbon-free energy carrier. In this study, the optimized scheduling and design of a real micro-grid that includes hydrogen as energy storage media is proposed. The micro-grid is located in a research center in Sardinia (Italy), and it supplies the energy demand of the office buildings using batteries and hydrogen as energy storage systems. The RES is composed of a PV panel plant coupled with batteries, while the hydrogen production technology and storage system are respectively one PEM electrolyzer and four gas storage tanks. The hydrogen-based energy production modules include two types of fuel cells: a SOFC and a PEM. A Mixed-Linear Integer Programming (MILP) model has been developed with the objective to minimize the overall cost of the grid assuming a planning horizon of one year and considering one-hour time discretization. Two different scenarios have been analyzed: on-grid and off-grid applications. In the first scenario, the micro-grid operates at its current state, with the power distribution grid operating as backup when the PV panels and the storage systems are not able to fully meet the end-user demand. The optimal scheduling is obtained by fixing the size of the processes and the storage components to the existent values. Similarly, the off-grid scenario is evaluated starting from the same model developed for the first case. However, in this scenario, the optimization involves not only the scheduling, but also the size of the components that are optimized to operate the micro-grid independent from the public grid. The results show that, in the first scenario, the on-grid solution relies for the 37% on the electric power from the grid. Moreover, the design and scheduling optimization for the second scenario demonstrates that to enable the off-grid operation of the micro-grid, a significant increase of the hydrogen storage capacity is required from 4.4 kg to 632 kg. The design optimization of the micro-grid also allows to increase the contribution of the hydrogen as a seasonal energy storage system to meet the demand using the fuel cell from the 4% in the first scenario to 14% in the second.

1 INTRODUCTION

The energy production from renewable energy sources is increasing, reaching a global installed capacity of 3064 GW in 2021 (Van *et al.*, 2023). However, the unpredictable behavior of RESs is a significant limitation to the increase of renewable energy penetration. Therefore, to address these issues, energy storage systems (ESSs) are considered a viable and efficient solution. The existing EESs can be classified based on the size and on the discharge time. Usually for small and medium-scale power systems short-term ESSs are preferred, such as batteries, capacitors, and supercapacitors, while large-scale power systems require long-term ESSs, such as pumped hydroelectric energy storage (PHES) and mechanical storage, as compressed air energy storage (CAES). Hydrogen can be

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also used as large-scale ESS, but it comes with challenges such as the energy management system, while achieving other technical and economic objectives. Table 1, adapted from Mitali *et al.* (2022), reports the power range, the discharge time and the energy density of the main energy storage systems.

Table 1: Properties of different EESs (Mitali *et al.,* 2022)

ESS	Power range (MW)	Discharge time	Energy Density (Wh/kg)
PHES	10-5000	1-24 h	0.5-1.5
CAES	3-300	1-24 h	30-60
Hydrogen	0.1-50	Secs-24 h	600-1200
Li-ion	0-0.1	Mins-hours	100-200
Capacitor	0-0.05	Millisecs-1 h	0.05-5
Supercapacitor	0-0.3	Millisecs-1 h	1.5-2.5

With the increasing of deployment of small-scale decentralized RES plants, micro-grids (MGs) are becoming more important since they allow to increase the reliability of RES plants and reducing CO_2 emissions (Pang *et al.*, 2024). A MG is a local energy grid network composed of a RES power plant and ESSs able to provide electrical and/or thermal energy to an end-user. The power systems are usually represented by small-scale RES plants, while the ESSs make the MGs more reliable and contribute to mitigate the fluctuations of RES energy production (Vera *et al.,* 2019). The MG has its own control capability and can be connected to the public grid or operate in a stand-alone/island mode. In the MG, batteries are mostly used as the main ESS due to their flexibility, mature technology level and low costs. But lately, the growing interest in hydrogen has led to considering this technology as an alternative and carbon free fuel to substitute the traditional energy sources, providing long-term, seasonal energy storage and higher capacity.

Several approaches in the literature have been used to investigate the integration of hydrogen as ESS in standalone micro-grids, applying optimization methods to define the design and scheduling of the MGs. Marocco *et al.* (2021) applied a Mixed-Linear Integer Programming (MILP) approach to obtain the optimal design of a standalone community using batteries and hydrogen as ESS. The methodology has been applied to a real case study of an island in Italy to decrease the amount of CO_2 produced using traditional energy plants. The MILP approach to the problem has been considered more performing than a metaheuristic method, making the MG reliable and cost competitive. Ancona *et al.* (2023) optimized the design and scheduling of a battery-hydrogen MG. The model has been developed and applied to a case study of the ENEA research center with the aim of maximizing the use of energy from RES. The studied MG is composed of PV panels, batteries, and thermal storage systems. The integration of hydrogen has been studied to maximize the usage of RES production considering a seasonal energy storage strategy. Diaz *et al.* (2023) developed an MILP model to study the feasibility of hydrogen as ESS applied to MGs. Eight investment optimization scenarios have been analyzed with reference to two distinct reference cases. Different technologies have been considered for the generation of both hydrogen and power. The total annual cost of the MG was assumed as objective function, also considering the purchasing of electricity and natural gas for the different scenarios. Wouters *et al.* (2015) studied the integration of hydrogen in a MG in a South Australian case study. An MILP model has been applied to identify the optimal design of the system. In this case, the MG also includes a thermal and an electrical energy storge, and it is connected to the public grid. The objective is to minimize the total annualized cost of the system to meet its yearly energy demand. Different scenarios with different technology have been analyzed. The model led to consistent results when up scaled. Sanchez *et al.* (2022) applied an MILP approach to study a network that includes three RESs (solar, wind and biomass) coupled with four ESSs (batteries, hydrogen, methane, and ammonia) considering the different regions of Spain. The analysis has been conducted under two points of view: the economic and the social aspects. The seasonal energy storage systems have resulted to be effective to meet the energy demand of the regions.

In this framework, firstly this paper investigates the scheduling of an existing MG with a hybrid batteries-hydrogen storage system and connected with the grid. Then, it identifies the optimal design and scheduling of the MG to enable an off-grid scenario, applying an MILP model in both cases. In

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the literature, MILP models have been effectively applied to design the hydrogen units, especially in off-grid scenarios. However, this work also applies the model to an existing MG in order to optimize the scheduling considering the installed units and using real data. Finally, the second scenario allows to evaluate the possible changes of the installed units to make the MG independent from the public grid. The MG, currently not yet fully operating, used as a case study is located in the research center of "Sardegna Ricerche" in Italy and it has been developed with the aim to supply energy to the facility and to study the implementation of hydrogen technologies coupled with RES in a small-scale set-up.
This work focuses on two steps:

- the optimization of the scheduling of the existing MG when the units' sizes are fixed to the actual ones and the MG is connected to the electric grid;
- the optimization of the design and scheduling of the MG to operate as a stand-alone configuration.

These two approaches are then compared in terms of required costs of operation, of the percentage of energy demand covered by the various energy production systems and use of the hydrogen storage. In this work, Section 2 describes the MG architecture detailing the present sizing of the components, Section 3 describes the MILP model and the optimization approach, Section 4 discusses the results and Section 5 concludes the paper.

2 MICRO-GRID ARCHITECTURE

In the MG of the "Sardegna Ricerche" facility, the loads are represented by the electric energy requirement of the facility (end-user) and the installed units are represented in the scheme in Figure 1. The energy is generated by a PV plant with a power of 44 kW_p covering an area of 280 m^2. For the energy storage, batteries and hydrogen are included. The batteries are lithium-ion type, with a total capacity of 46 kWh and a total nominal power of 23 kW. The hydrogen section is composed of a PEM electrolyzer, a hydrogen storage system and two fuel cells. The PEM electrolyzer has a nominal power of 8.3 kW and produces hydrogen at a rate of 1 Nm^3/h. The hydrogen is stored in of four stainless steel tanks with a total capacity of 4400 L and with a storage pressure of 13 bar. The first fuel cell is a PEM with a nominal power of 5 kW and a hydrogen consumption of 5.4 g/min. The other fuel cell is a Solid Oxide (SO) with a nominal power of 9 kW.

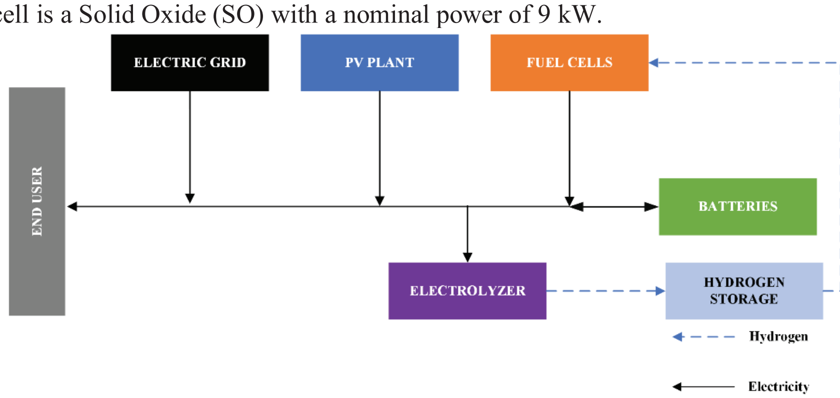

Figure 1: Micro-grid architecture.

3 MATERIALS AND METHODS

An MILP model has been developed with the objective to minimize the overall cost of the MG with a scheduling horizon of one year and a one-hour time discretization.

3.1 Micro-grid structure

The MG has been modelled following the Resource-Task representation (Castro *et al.*, 2004 and Zhang *et al.*, 2019). In the scheme of the MG in Figure 2, two types of nodes can be identified: the process and the resource nodes. The processes transform the input resources in output resources and each process is connected to each other through an energy or material flow.

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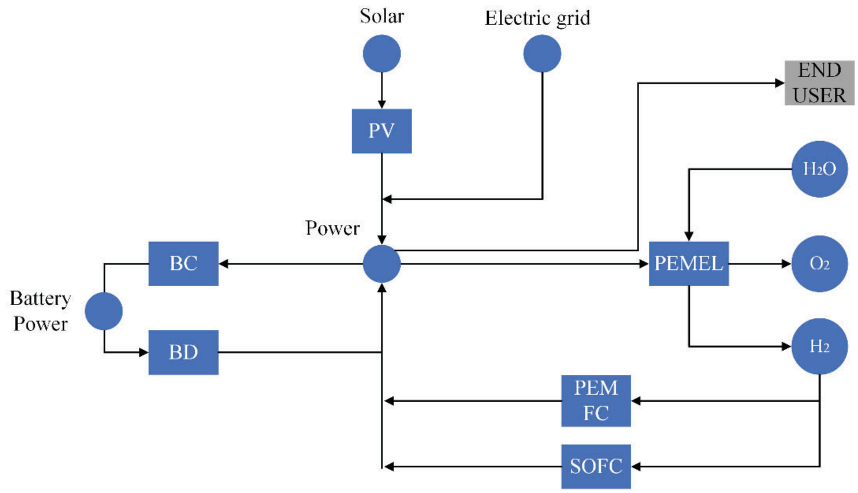

Figure 2: Process-resource network of the MG.

The resources are represented by solar, water, hydrogen, power, battery power and are divided in storable (hydrogen and battery power) and non-storable. The processes are PV panels, battery charge and discharge, PEM electrolyzer, PEM fuel cell and SOFC. The main processes of the MG and the relative input and output resources are shown in Table 2.

Table 2: Input and output resources for each process.

Name	Process	Input resources	Output resources
PV	Photovoltaics	Solar	Power
BC	Battery Charge	Power	Battery power
BD	Battery Discharge	Battery Power	Power
PEMEL	Electrolysis	Power, Water	Hydrogen, Oxygen
PEMFC	PEM fuel cell energy production	Hydrogen	Power
SOFC	SO fuel cell energy production	Hydrogen	Power

As mentioned in the introduction, the MILP model is considered effective for optimizing the design and scheduling of MGs. The model is based on the one developed by Sánchez *et al.* (2022) and it is constructed on a multiscale time representation where the planning horizon of one year has been divided in 12 time periods, each representing a month of the year. This division allows to account for both the different weather conditions that affect the PV energy production and the different energy demand profiles based on the month and the day of the week. The PV panels energy production was simulated using the SAM (System Model Advisor) model with data from 2019 from NREL (National Renewable Energy Laboratory) database, since real data from the facility were not available. The model was developed in Julia, using Gurobi as optimizer.

3.2 MILP model

In the following, the objective function and the constraints of the MILP model are described through the most significant equations used in the model. All the variables in the equations are specified in the nomenclature.

3.2.1 Objective function: the objective function, represented in Equation (1) is composed of the overall operating costs.

$$OC = \sum_{i}\sum_{m\in M_i}\sum_{h}\sum_{t} J_{imht} + \sum_{i}\sigma_i(\delta_i x_i + \gamma_i C_i) + \sum_{j\in \hat{S}}(\alpha_j \bar{x}_j + \beta_j \bar{C}_j) + \sum_{i}\sum_{j}\sum_{h}\sum_{t}\xi_j \rho_{ij} P_{iht} + \sum_{h}\sum_{t}\psi_{EG} B_{EG,ht} \quad (1)$$

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The first term refers to the operating costs not related to the capital cost (such as utilities and materials cost). The second term includes the operating costs of the processes related to the capital cost or maintenance. The third term includes to the annualized capital cost of the storage facilities. The fourth term is related to the Operation and Maintenance (O&M) costs of the storage facilities based on the amount of resource to store. Finally, the last term is linked to the cost of the energy from the electric grid and it is implemented only in the first scenario model. The capital cost of processes and storage facilities was linearized. The modeling parameters are based on literature values and on the builder information available for the installed units of the real MG. The values of the parameters of the linearized capital costs for each process and storable resource are specified in Table 3. The parameter ρ refers to the performance of each process and the values of the parameter for each process respect to the corresponding resource are reported in Table 4.

Table 3: Parameters values assumptions for each process and storable resource.

Process	σ_i	δ_i $[M€]$	γ_i $[\frac{M€}{area} or \frac{M€}{kW}]$
PV	0.0611	0.0001	1.6e-4
BC and BD	0	0	0
PEMEL	0.1183	0.0365	0.0011
PEMFC	0.2	0.0947	1.95e-3
SOFC	0.1	0.1	0.012
Resource	α_j $[M€]$	β_j $[\frac{M€}{kJ} or \frac{M€}{kg}]$	$\xi_j [\frac{M€}{kJ} or \frac{M€}{kg}]$
Battery Power	0	0.0711	83.3e-9
H_2	0.0001	500	0

Table 4: $\boldsymbol{\rho}$ parameter values for each process and the corresponding resources

Process	**Resource**	$\rho_{i,j}[\frac{kW}{kW} or \frac{kg}{kJ}]$	**Process**	**Resource**	$\rho_{i,j}[\frac{kW}{kW} or \frac{kg}{kJ}]$
PV	Solar	-1	PEM	Water	-4.48e-5
PV	Power	1	PEM	H_2	2.811e-6
BC	Power	-1	PEMFC	Power	1
BC	Battery Power	0.97	PEMFC	H_2	-1.8e-5
BD	Power	1	SOFC	Power	1
BD	Battery Power	-1.15	SOFC	H_2	-1.7e-5
PEMEL	Power	-1			

The processes can work in four different operation modes (off, startup, on, shutdown) with a minimum stay time based on the technology. In particular, for the SOFC the minimum stay time is equal to 2 hours for the startup and shutdown modes and of 4 hours for the on mode. For each of the 8760 yearly hours, the model determines: a) the operation mode, b) the material and energy flows in the network, c) the amount of input resources required by each process, and d) the quantity of resources stored.

Three categories of constraints were implemented: network design constraints, resource balance constraints and continuity constraints.

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3.2.2 Network design constraints: this category of constraints refers to the upper and lower bounds of the capacity of processes, the storage systems and the input resources. This type of constraints allows:

- To limit the capacity of the i_{th} process in Equation (2) to C_i^{max} and of the j_{th} resource in Equation (3) to $\bar{C}_j^{max}$. However, in the first scenario the capacities are fixed to the installed ones.

$$C_i \leq C_i^{max} x_i \quad \forall i \tag{2}$$
$$\bar{C}_j \leq \bar{C}_j^{max} \bar{x}_j \quad \forall j \tag{3}$$

- To restrict the upper bound of the storage level of the j_{th} storable resource between 0 and $\bar{C}_j$:

$$\bar{Q}_{jht} \leq \bar{C}_j \quad \forall j \in \hat{S}, h, t \in \bar{T}_h \tag{4}$$
$$\bar{Q}_{jht} = 0 \quad \forall j \notin \hat{S}, h, t \in \bar{T}_h \tag{5}$$

- To limit the consumption of raw materials to a set value $B_{jht}^{\max}$.

$$B_{jht} \leq B_{jht}^{\max} \quad \forall j \in \hat{B}, h, t \in \bar{T}_h \tag{6}$$

3.2.3 Resource balance constraints: this category of constraints refers to the mass balance of the different resources. The equation (8) describes how the stored resource $\bar{Q}_{jht}$ varies depending on the amount of consumed or discharged resources at each time, while the production of a certain resource is limited by each process capacity.

$$\bar{Q}_{jht} = \bar{Q}_{jht-1} + B_{jht} - S_{jht} + \sum_i \rho_{ij} P_{iht} \quad \forall j, h, t \in \bar{T}_h \tag{8}$$

3.2.4 Continuity constraints: this category of constraints forces the mode of operation to be the same in the transition between one month to the following one.

$$y_{imh,0} = y_{imh,|\overline{T_h}|} \quad \forall i, m \in M_i, h \tag{9}$$
$$y_{imh,|\overline{T_h}|} = y_{im,h+1,0} \; \forall i, m \in M_i, h \in H \setminus |H| \tag{10}$$

4 RESULTS AND DISCUSSION

4.1 Results Scenario 1

In the first scenario, the capacities of the processes and of the storage units is based on the current ones installed in the real MG.

Table 5 details the fixed capacities of the processes, while Table 6 specifies the fixed capacities of the storage facilities.

Table 5: Installed capacity for each process.

Process	Capacity	Process	Capacity
PV	44 kW	PEMEL	8.3 kW
BC	23 kW	PEMFC	5 kW
BD	23 kW	SOFC	9 kW

Table 6: Installed capacity for each storage unit.

Resource	Capacity
Hydrogen	4.4 kg
Battery Power	46 kWh

The data of the power demand were provided by the research center and are related to the time period from September 2022 to August 2023. The energy cost is the average price of electric energy in Italy, set equal to 160 €/MWh. Figure 3 and Figure 4 summarize the results of the scheduling of the Scenario 1 for two cases: a summer week (August) and a winter week (January) respectively.

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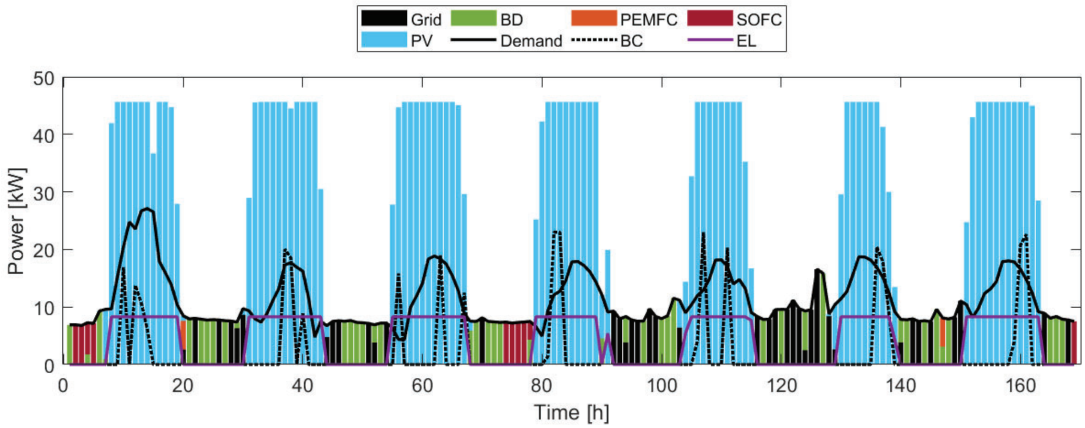

Figure 3: Scheduling results for Scenario 1 of one week of August with the power output and requirement of each technology.

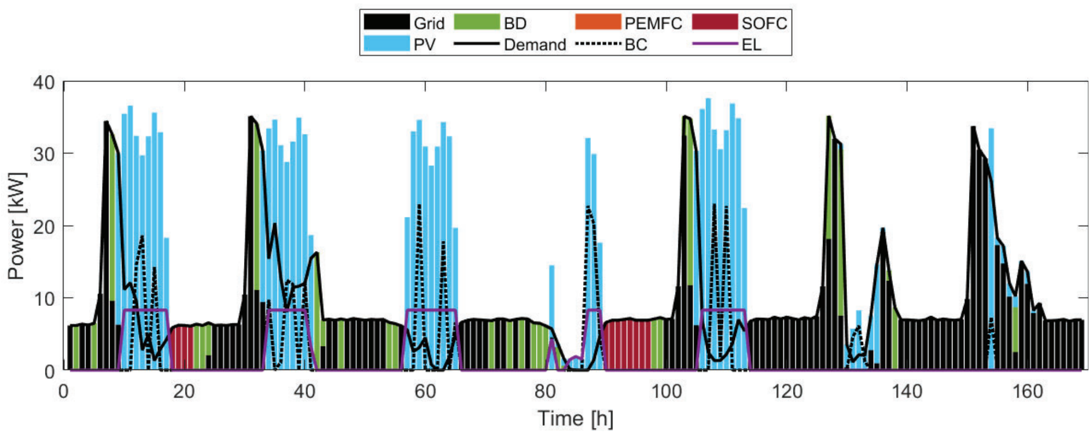

Figure 4: Scheduling results for Scenario 1 of one week of January with the power output and requirement of each technology.

The black line represents the power demand of the facility, while the black dashed line represents the charge of the battery and the purple line the power requirements from the electrolyzer. During the day, when power from the PV plant is available, the demand is met using solar resource. The residual energy is stored in batteries or converted into hydrogen through the PEM electrolyzer. During the night, the demand is met by the batteries (operating in discharge phase) and by the fuel cells. However, when the demand is not satisfied by the MG, the required energy is bought from the grid.

Comparing the two months, it appears that during the winter months the MG heavily relies on the grid. Figure 5 shows the hydrogen storage level inside the tanks during the whole year. In this case, hydrogen is constantly stored and used as fuel during the year and does not show the typical seasonal storage behavior. Since in this scenario only the scheduling was optimized, the capacity of the hydrogen storage tanks currently installed in the real MG is not enough to allow a seasonal storage.

The overall operative cost considering the optimal scheduling is equal to 51.4 k€/year, with a unit cost of 603 €/MWh.

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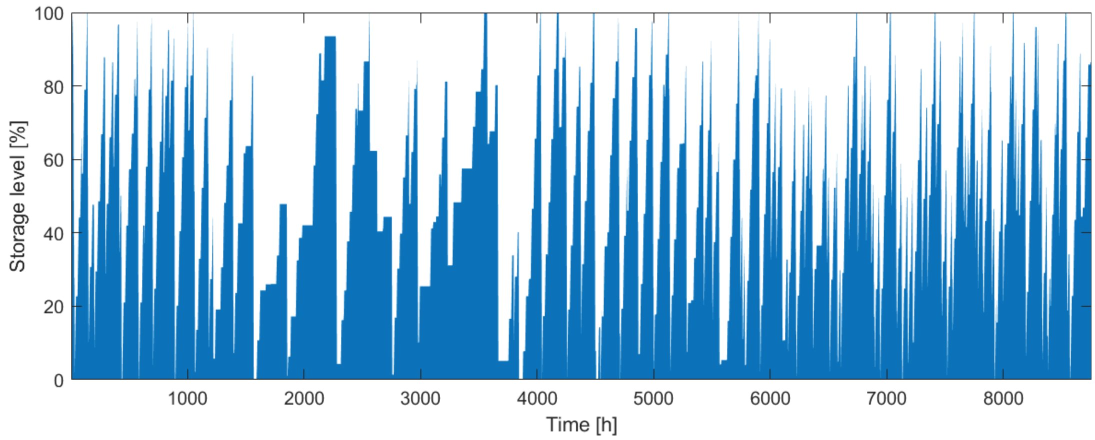

Figure 5: Hydrogen storage level of the tanks during the year for Scenario 1 (from September to August).

4.2 Results Scenario 2

In this scenario the optimization involves the design of the MG in order to avoid buying energy from the public grid, allowing the system to operate in standalone configuration. Table 7 shows the optimal value of the capacities of the processes, while Table 8 shows the capacities of the storage units.

Table 7: Capacity of the processes for the Scenario 2

Process	Capacity	Process	Capacity
PV	57 kW	PEMEL	39.1 kW
BC	45.7 kW	PEMFC	0 kW
BD	45.7 kW	SOFC	12.2 kW

Table 8: Capacity of the storage facilities for the Scenario 2

Resource	Capacity
Hydrogen	632 kg
Battery Power	230 kWh

The results show that the hydrogen storage should significantly increase to allow the off-grid operation. In particular, a notably increase from 4.4 kg to 632 kg is expected. Moreover, the standalone configuration requires a PV with the capacity set equal 57 kW_p, the 30% more respect to the current state, the size of the PEMEL would be almost five times bigger and the size of the batteries would double. The PEMFC results to be zero, since being a less cost-efficient technology compared to the SOFC. Figure 6 and Figure 7 shows the results of the optimization of two weeks of the year: a summer month and a winter month, the same weeks shown in Figure 3 and Figure 4.

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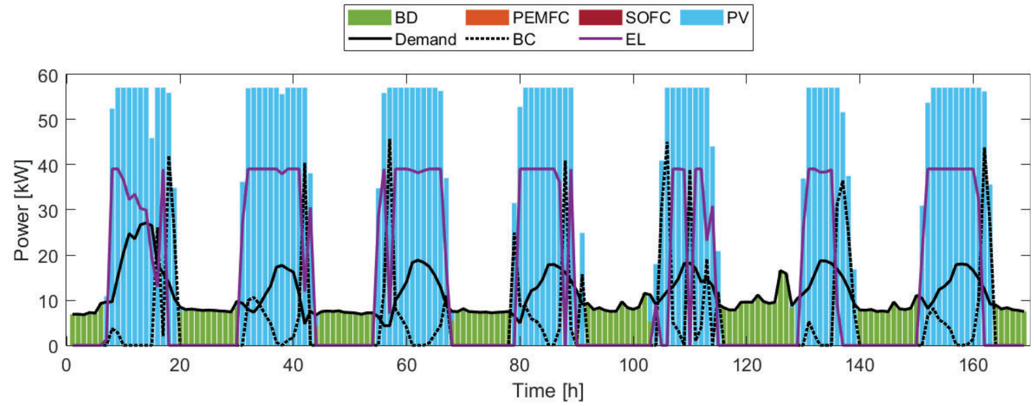

Figure 6: Scheduling results for Scenario 2 of one week of August with the power output and requirement of each technology.

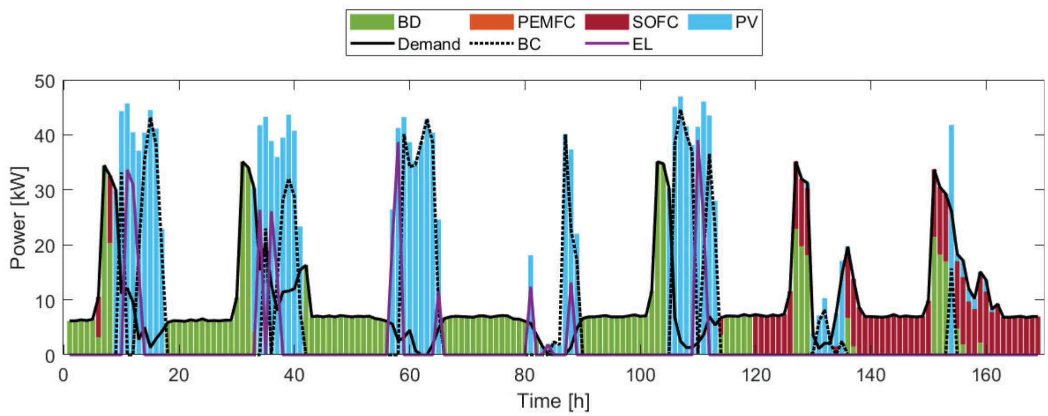

Figure 7: Scheduling results for Scenario 2 of one week of January with the power output and requirement of each technology.

During the summer, the demand can be satisfied mainly by the PV power production (in blue) and the batteries (in green), while the excess energy from the PV panels can be used to charge the batteries (black dashed lines) and to activate the electrolyzer (in purple). On the other hand, during the winter months, the hydrogen stored during the summer fuels the SOFC (in red) contributes to provide energy to the end-user.

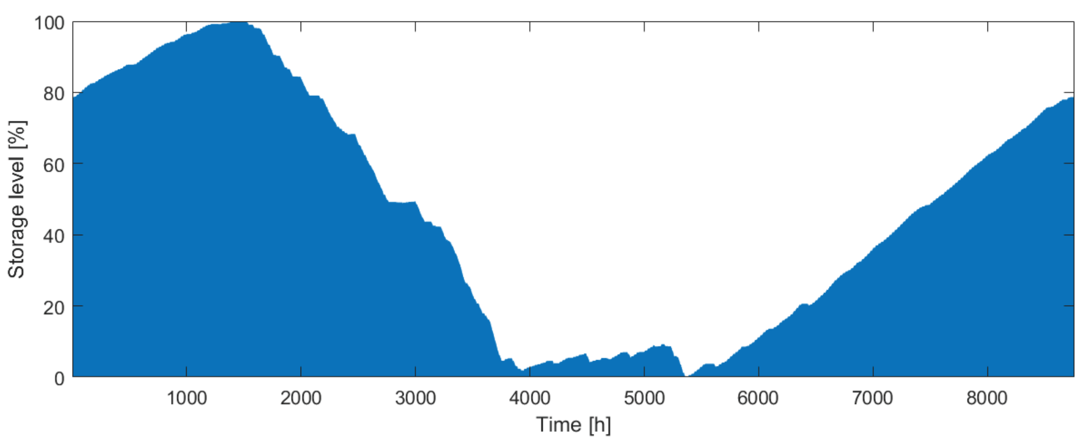

Figure 8: Hydrogen storage level during the year for scenario 2 (from September to August).

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Figure 8 shows the seasonal behavior of hydrogen as storage system. In fact, it is produced and stored during the summer months when the energy demand can be covered by PV panels and batteries alone. Comparing this graph with the one in Figure 5 it is possible to highlight how appropriate sizing of the hydrogen storage impacts on the optimal use of this ESS. In this scenario, the operating cost for implementing the standalone configuration of the MG is equal to 58.6 k€/year with a unit cost of 688 €/MWh. Figure 9 shows the distribution of the capital cost of the MG for the two scenarios. In the first scenario the capital cost is equal to 378 k€ and from Figure 9 is possible to notice that the fuel cells constitute the mayor portion to the cost, with 50% for the SOFC and 25% for the PEMFC. In the second scenario, the capital cost resulted in 700k€, nearly the double of the first scenario. In this case the main contributors to the capital cost are the hydrogen storage system (40%) and the SOFC (33%).

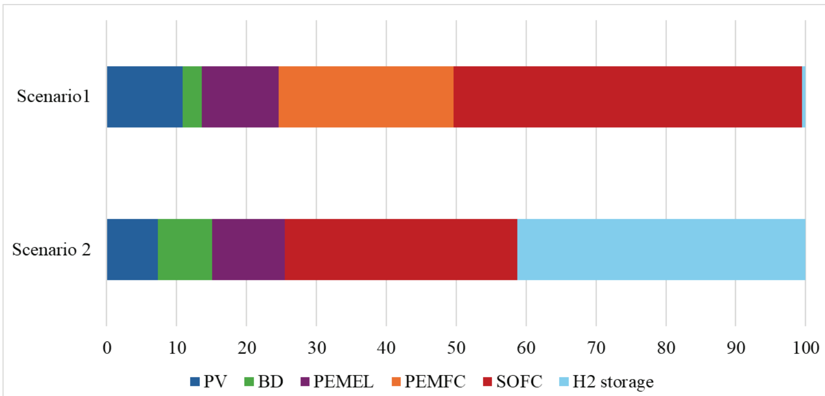

Figure 9: Percentage distribution of capital cost among the different technologies for each scenario.

Figure 10 shows how each power source covers the energy demand of the end-user in the two scenarios. The PV power plant covers around the 42% of the demand in both cases, while the batteries percentage goes from 16% to 43% in the second scenario. In the second scenario, the PEMFC is not required, while the SOFC contribution increases from 5% to 14%. In the first scenario, the grid covers the 37% of the demand.

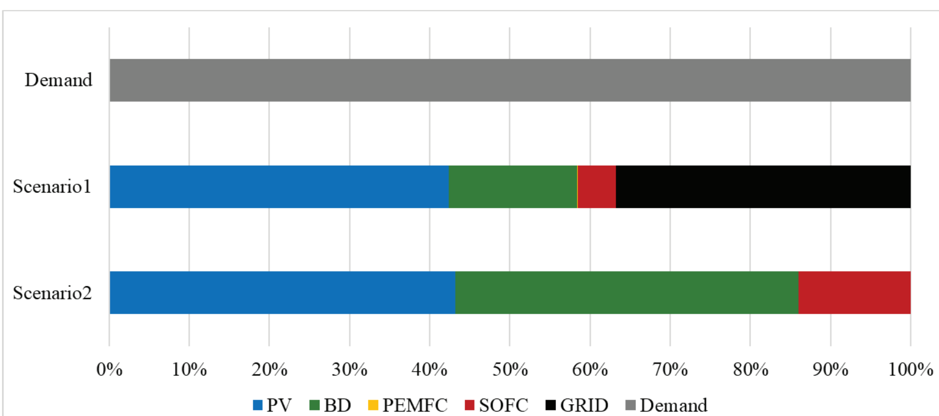

Figure 10: Percentage of the energy demand covered by each power source for each scenario.

The results presented are subject to the influence of the techno-economic assumptions such as the cost of electricity and of the units, and the technological advancement especially of hydrogen units. Additionally, the uncertainties like the load profile and energy production from RES can influence the outcomes. Therefore, future research should be extended in areas such as optimization under uncertainty to handle these characteristics of renewable sources and be able to build a new and more resilient power system.

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5 CONCLUSIONS

This paper proposes the optimized scheduling and design of a real MG located in Sardinia, Italy. The MG consists of a PV power plant as RES, and it is integrated with a batteries-hydrogen hybrid storage system to meet the energy demand of the facility. Utilizing an MILP model, the operating costs of the MG are minimized over a one-year horizon, exploring both on-grid and off-grid scenarios. While the on-grid setup relies on the public grid for backup, transitioning to off-grid operation requires substantial hydrogen storage capacity increases. In the on-grid scenario, the MG relies for the 37% on the public grid, while the off-grid scenario highlights the potential of hydrogen as seasonal energy storage. However, the increase of the hydrogen storage facility capacity in the off-grid scenario is significant compared to the current sizing, suggesting that this is a key factor for optimizing the MG. In conclusion, hydrogen-based energy storage systems can contribute substantially to the MG reliability and to achieve a standalone configuration. Future research may explore further refinements in scheduling algorithms and component designs to optimize micro-grid performance and enhance energy autonomy while seeking to refine the sizing of hydrogen storage systems for off-grid applications.

NOMENCLATURE

B	amount of consumed resource
$\hat{B}$	set of raw resources
C	process capacity
$\bar{C}$	storage facility capacity
H	number of seasons of the scheduling horizon
J	operative cost not related to the capital cost
M	set of modes
P	amount of resource produced or consumed
$\bar{Q}$	amount of stored resource
S	amount of discharged resource (out of the network)
$\hat{S}$	set of resources that can be stored
$\bar{T}_h$	set of time periods of one hours for the season h
x	binary variable indicating if a process is selected
$\bar{x}$	binary variable indicating if a resource that can be stored is selected
y	binary variable indicating if a mode of a process is selected
α	fixed capital cost coefficient for storage facilities
β	annualized unit capital cost coefficient for storage facilities
γ	unit capital cost coefficient
δ	fixed capital cost coefficient
ξ	O&M cost for storage
ρ	conversion factor between resource and the reference resource of process to calculate the amount of resource produced or consumed by each process
σ	conversion coefficient between capital and operative costs
ψ	cost of raw materials to buy outside the MG

Subscript

EG	electric grid	j	resources
h	month	m	operation mode
i	processes	t	hour

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