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Addressing Voltage Sag Contributions from an Optimally Sized Industrial Hybrid Power System in the Netherlands

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Abstract—Industry plays a significant role in the energy transition due to its share of energy consumption. More complex energy systems are proposed to accelerate the energy transition, including coupling renewable energy sources and energy storage to supply part of the industrial loads locally. In this work, we used a multi-objective genetic algorithm to optimally size an industrial hybrid power system comprising a PV system, a battery energy storage system, and a diesel generator to minimise energy costs and overall equivalent CO₂ emissions. The results suggest that the system does not require high power and capacity components to minimise the energy cost and equivalent CO₂ emissions, highlighting the importance of the EMS strategy. In our case scenario, the optimal HPS reduced the emission cost by 46.7 % and the energy cost by 8.7 %. For the EMS, we proposed a rolling horizon average approach, which defines a setpoint for the power exchanged with the grid to minimise its change rate in time. The EMS dispatched the power to minimise the sudden changes in the demand from the network, with a power allocation priority order of PV, BESS, and generator. We also evaluated the effect of adding the optimally sized hybrid power system into a CIGRE medium-voltage distribution network, using a real industrial load profile for each node. The hybrid power system improved the voltage sag on the hybrid power energy system node and its neighbouring nodes.

Index Terms—Energy Management System, Genetic Algorithms, Hybrid Power System, Mosaik, Voltage Sag

I. INTRODUCTION

The Dutch industry plays a significant role in the nation's energy consumption, accounting for around 46 % of the total electric energy usage by 2021 [1]. As a result, the sector is responsible for a third of the total CO₂ emissions in the Netherlands [2]. This heavy reliance on conventional energy sources raises environmental concerns and highlights the need for sustainable energy solutions. Transitioning to a more sustainable energy system mitigates climate change,

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reduces greenhouse gas emissions, and ensures long-term energy security. To address these challenges, the concept of hybrid power systems (HPS) has emerged as a promising solution [3]. HPS combine different energy sources, including Renewable Energy Sources (RES), Energy Storage Systems (ESS), and supplementary generation capabilities, to achieve a more balanced and efficient energy supply. If the HPS consider other demands, such as thermal, it can be defined as a multi-carrier energy system. By integrating these diverse components, HPS can optimise energy generation, enhance grid stability, and reduce costs and environmental impact.

Optimal sizing of HPS components is critical to designing an efficient and cost-effective system. The capacity of each component (e.g., PV system, diesel generator, microturbine, wind turbine, and ESS) must be carefully determined to ensure optimal performance, considering factors such as energy demand, resource availability, grid capacity, and economic viability. With the changing landscape of emission regulations, this sizing can become more difficult for fossil-fuel-based components, as emission penalties can be applied. Traditional approaches to sizing energy components often overlook the interconnected nature of the energy infrastructure. Individual sizing decisions are made without considering the potential impact on the overall energy system and voltage stability within an industrial bus system. Consequently, there is a need for a comprehensive multi-objective framework that incorporates cost, CO₂ emissions, and voltage stability considerations to guide the sizing process of HPS components for industrial applications.

To evaluate the state-of-the-art, we evaluated 70 papers on the sizing of multi-energy systems, considering the optimization method and objective. A summary is shown in Tables I and II, respectively. The columns show the different categories found per table, the second last column provides the number of references found using the indicated categories, and the last provides some representative references. In the last row, we

TABLE I: Common optimisation methods used in literature.

GA	PSO	HOMER	MILP	Other	Refs.	Examples
X					22	[5]–[7]
X	X				4	[8]
X	X		X		2	[9]
X	X	X			3	[10]
X		X			1	[11]
	X				6	[12], [13]
		X			3	[14], [15]
			X		6	[16], [17]
				X	23	[18]–[20]
32	15	7	9	23	Total	

TABLE II: Common objective functions used in literature.

Cost	Emission	Other	Refs.	Examples
X			49	[10], [13], [15]–[17], [20]
X	X		15	[7], [9], [21]
X		X	1	[14]
	X		1	[6]
		X	4	[19]
66	16	6	Total	

provided the number of references that used each category. Note that some papers fit into different categories; therefore, the sum of the last row will not coincide with the sum of the references column. The full details can be found in [4]. The literature review shows that genetic algorithms are the preferred sizing technique, and most works focus on cost as the optimization objective.

As we evaluated an industrial system, we narrowed the literature review even more to evaluate the work done in this sector. The research in [21] focused on the sizing aspect of industrial loads with cost and emissions as objective functions. The scope of [22] includes an emission analysis after the sizing is performed instead of including it in the objective functions. In [12], a particle swarm optimisation was used to maximise energy and power autonomies while minimising capital cost and payback period. The software HOMER was used by [14] to minimise energy costs and equivalent emissions. In [17], mixed integer linear programming minimises the net energy lifetime cost. Genetic algorithms were used in [21] to size the components of an HPS using cost as the optimisation objective.

The contributions of this paper are:

- an EMS strategy aimed to minimise the rate of change of power exchanged with the grid in time, based on a rolling horizon average, for an industrial hybrid power system comprised of a PV system, a BESS and a diesel generator,
- an optimal sizing of such industrial hybrid power system using a multi-objective genetic algorithm which minimised the energy cost and the CO₂ emissions, and
- evaluating the effect of the optimally sized hybrid power system on the voltage of a CIGRE MV distribution network.

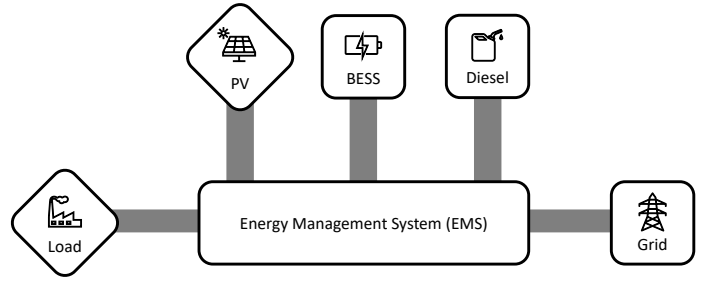


Fig. 1: Hybrid power system studied.

II. MODELLING AND EMS FRAMEWORK

The sizing for the HPS components will depend on the system's operation. This way, we used the simulation framework Mosaik to couple models for the PV, diesel generator and BESS with the electric loads, as shown in Fig. 1. We used PVGIS to generate a scalable PV profile. For the diesel generator, we used datasheet information to correlate the fuel consumption as a function of the power output percentage (25 %, 50 %, 75 % and 100 % of the generator's nominal power) for generators up to 3.6 MVA [23]. This way, we obtain an expression for the accumulated fuel consumption O_{D-L} as a function of the power output $P(t)$ given by

$$O_{D-L}(t) = \begin{cases} O_{D-L}(t-1) + 0.0513P(t) + 1.562, & \forall P(t) > 0 \\ O_{D-L}(t-1), & \forall P(t) = 0 \end{cases}, \quad (1)$$

with an RMSE of 2.43. The energy in the BESS E was modelled as

$$E(t) = \begin{cases} E(t-1) + \left[\frac{P(t)}{\eta_{\text{discharge}}} - \sigma_{\text{self}} \right] \Delta t & \forall P(t) > 0 \\ E(t-1) + \left[P(t)\eta_{\text{charge}} - \sigma_{\text{self}} \right] \Delta t & \forall P(t) < 0 \end{cases}, \quad (2)$$

where $P(t)$ is the BESS power, η the charging and discharging efficiency as corresponds, and σ is the self-discharge rate. Finally, for the electric load, we used data from [24], which contains a dataset of industrial load profiles sampled every 15 min. We randomly selected load profiles for the HPS and the other CIGRE medium-voltage distribution network nodes.

We assumed that industrial sites perform power factor compensation for the EMS power scheduling if necessary, but the grid point connection has a fixed power factor of 0.85 [25]. The PV, BESS, and diesel generators are all assumed to be able to work at that power factor [26]. Their power scheduling will be according to the apparent power of the load profile, and the reactive power will be computed to ensure the power factor. The EMS used to control the power dispatch of the studied HPS is centred on a rolling average, where the aim is to reduce the change in time of the power exchanged with the grid (dP/dt). A detail on the EMS strategy is depicted as a flowchart in Fig. 2, and an illustration of its steps is shown in Fig. 3. The steps of the EMS depicted in the flowchart are segmented below:

- 1) A rolling average (RA) is created between the load and PV profiles (see Fig. 3a).

- 2) Upper (RA_{upper}) and lower bounds (RA_{lower}) are set around the RA, which can be a fixed interval (static) or proportional to the rolling horizon (dynamic) (see Fig. 3b).
- 3) The grid usage is set as close as possible to the load profile within the RA bounds and its capacity limit (see Fig. 3c).
- 4) The PV is used to supply as much power as possible to the load and grid outside the rolling average bounds (see Fig. 3d).
- 5) The BESS system supplies or extracts power between the current power combination and the load profile. During the night, the BESS will discharge at a constant power (see Fig. 3e).
- 6) The diesel generator is used to supply power where the current power combination (shortage after Grid, PV, and BESS) is still below the load profile within its rated power limit. The diesel generator model has a lower threshold and will thus not turn on for small power demands (30% of diesel generator rating) (see Fig. 3f).
- 7) The PV power is reevaluated to minimise curtailment with the grid usage staying within the rolling average bounds (see Fig. 3g).
- 8) If the power combination is not satisfactory to supply the load demand (shortage after Grid, PV, BESS, and Diesel), the grid is allowed to exit the RA bound to supply the load (see Fig. 3h).

III. OPTIMAL SIZING

Four sets of parameters for the EMS will be examined for the sizing, as shown in Table III. We used the non-dominated sorting genetic algorithm II (NSGA-II) as a proven method in the literature to determine the best size combination [27]. The parameters used were a population of 395 individuals, 99 offspring individuals, 15 generations, a crossover rate of 0.9 and a mutation rate of 0.01. The objective functions for the optimization consider the energy cost and the equivalent CO₂ emissions associated with the HPS. This will create a Pareto front from which an optimal solution with the shortest Euclidean distance to (0,0) (a solution with no costs nor emissions) is chosen, normalized to the point (1, 1), associated with the energy cost and emissions of the system without the HPS. Each component (PV, BESS, and diesel generator) will be evaluated for the objective function based on their LCOE or LCOS; the grid connection will be evaluated based on yearly energy cost (we assume the grid connection has already been installed). Additionally, we included a penalty for energy not supplied (ENS) to ensure the solutions always supply the load. This way, the energy cost F_C is given by

$$F_C = C_{Grid} + C_{PV} + C_{BESS} + C_{Diesel} + ENS(1 + 10ENS), \quad (3)$$

where the cost is a function of the power of the component P_i and its respective levelized cost (c_i)

$$C_i = P_i c_i \Delta t. \quad (4)$$

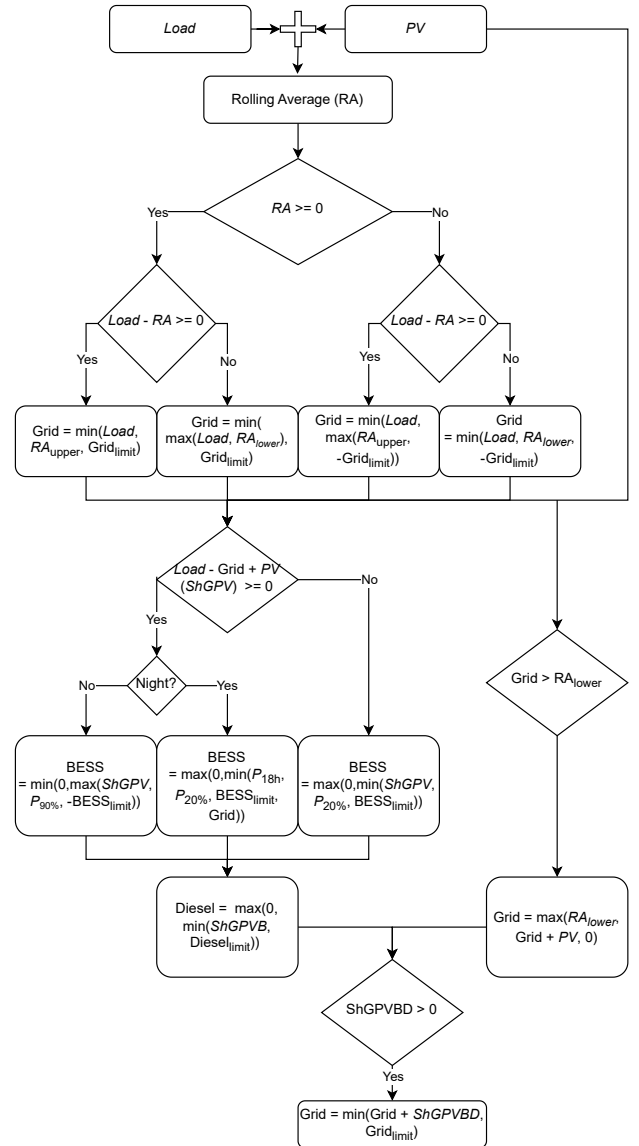


Fig. 2: Energy management system flowchart used for the proposed HPS.

Note that we do not consider any reward for injecting energy into the grid to ensure that the optimization focuses on balancing the load instead of making revenue by selling energy. Similarly, the equivalent emissions objective function evaluates the environmental performance of the HPS configuration, considering the equivalent direct and indirect CO₂ emissions resulting from grid usage and the generator's fuel consumption. This way, the emissions cost is given by

$$F_E = E_{Grid} + E_{Diesel} + ENS(1 + 10ENS), \quad (5)$$

where the emissions are a function of the power of the component P_i and its respective carbon intensity (CI_i)

$$C_i = P_i CI_i \Delta t. \quad (6)$$

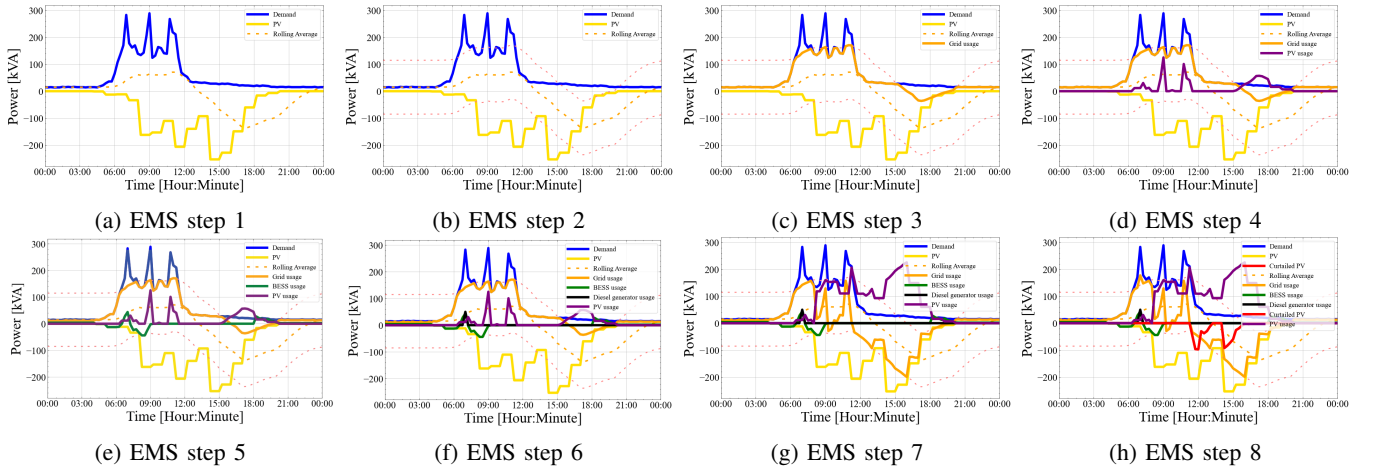


Fig. 3: Explanation of the EMS with a 6 hour rolling average and a static bound of 25%.

TABLE III: Four EMS scenarios that will be sized

Scenario	Rolling average [hours]	Bound	Percentage bound
1	12	Static	100%
2	12	Dynamic	100%
3	6	Static	50%
4	6	Dynamic	50%

Both functions are then normalized with respect of the cost and emissions to the system without including the HPS.

We used ten times the maximum load peak (3910 kVA) as the cap for the PV size and considered available commercial sizes for the diesel generator (3 600 kVA [23]) and the BESS (24 000 kVA [28]) to determine their maximum value. With these parameters, the sizing optimization problem is

$$\min F(m)(x_{\text{Grid}}, x_{\text{PV}}, x_{\text{Diesel}}, x_{\text{BESS}}), \quad m = F_C, F_E \quad (7)$$

with

$$\begin{aligned} 50 \leq x_{\text{Grid}} \leq 2000, & \quad x_{\text{Grid}} \in \mathbb{N} & | & \quad x_{\text{Grid}} = 25g, \quad g \in \mathbb{N} \\ 0 \leq x_{\text{PV}} \leq 3910, & \quad x_{\text{PV}} \in \mathbb{N} & | & \quad x_{\text{PV}} = 100i, \quad i \in \mathbb{N} \\ 0 \leq x_{\text{Diesel}} \leq 3600, & \quad x_{\text{Diesel}} \in \mathbb{N} & | & \quad x_{\text{Diesel}} = 100j, \quad j \in \mathbb{N} \\ 0 \leq x_{\text{BESS}} \leq 24000, & \quad x_{\text{BESS}} \in \mathbb{N} & | & \quad x_{\text{BESS}} = 200k, \quad k \in \mathbb{N} \end{aligned}$$

This minimisation equation takes the previously mentioned constraints and displays them in a universal language. The objective functions are cost and CO₂, calculated by running a year-long power profile with a combination (within certain limits) of variables: grid, PV, diesel, and BESS. This minimisation is done until 15 generations of solutions are reached.

After the NSGA-II optimisation for each scenario, we obtained the Pareto front to evaluate the possible non-dominated solutions (see Fig. 4), choosing the one with the shortest Euclidean distance to the origin for each scenario. Table IV presents the solutions obtained for each scenario. Then, we compared the objective functions between scenarios to determine the optimal trade-off between the EMS configuration and the HPS sizing. The four scenarios have comparable grid and generator values. In contrast, the PV power and the BESS capacity change considerably. We determined that the

optimal solution would be Scenario 2 based on the Euclidean distance to the origin. Although it has the second-highest equivalent emission cost (reducing 46.7 % compared to the base case without the HPS), the overall system achieves the lowest energy cost (reducing 8.7 % compared to the base case without the HPS) with less capacity than the scenarios with lower emission costs. Note that the benefit in CO₂ emissions arises from the lower usage of the grid than the case without the HPS. Therefore, one can consider a direct correlation between reduced energy purchased from the grid and the reduction in CO₂ emissions. Nevertheless, using the diesel generator would increase the CO₂ emissions, explaining the reasoning behind the EMS strategy generator usage and the resulting smaller capacity and lower participation frequency in the power dispatch compared with the other assets in the HPS.

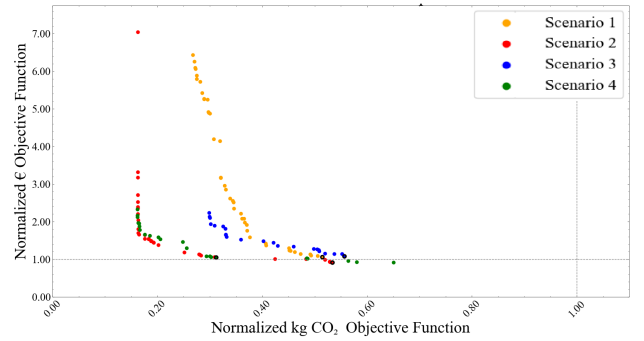


Fig. 4: Pareto fronts created for scenarios 1, 2, 3, and 4 described in Table III

IV. IMPACT ON THE GRID

For industrial applications, the IEEE recommends performing a balanced steady-state load flow analysis [29]. To this end, we used PandaPower [30] to simulate a 14-node medium-voltage CIGRE distribution system. The load profiles from

TABLE IV: Optimal HPS configurations for the four EMS scenarios described in Table III

Scenario	1	2	3	4
€ objective function	1.055	0.913	1.080	1.045
CO ₂ objective function	0.514	0.533	0.556	0.312
Euclidean distance to (0,0)	1.174	1.058	1.214	1.090
Sized grid capacity [kVA]	375	325	425	300
Sized PV capacity [kWp]	800	500	600	1400
Sized diesel generator [kVA]	100	100	0	100
Sized BESS [kWh]	1000	1200	200	2600

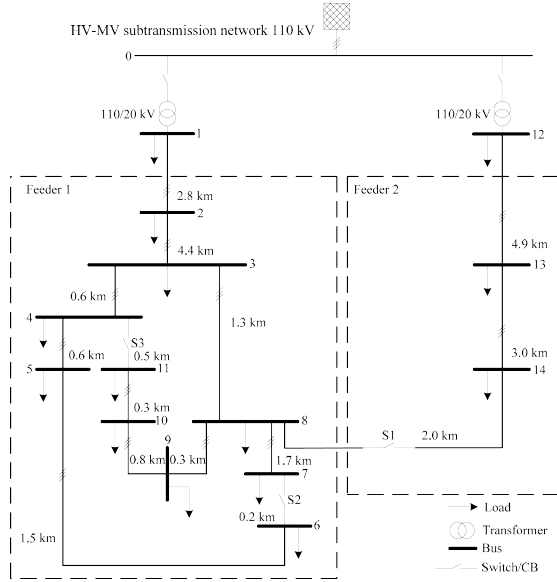


Fig. 5: 14-node CIGRE MV Distribution network.

[24] associated with each node were chosen randomly, as shown in Table V.

TABLE V: Load profile assignment to the busses in the CIGRE MV distribution network

Bus	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Profile	3	20	17	7	8	5	14	9	12	18	1	2	16	10

To assess the changes in voltage behaviour due to the introduction of the HPS in the network, the voltages of buses 10, 9, and 8 (and the lines connected to them) are examined separately as direct neighbours of bus 11. A large load in node 8, as shown in Fig. 6, creates a sag in voltage. Introducing the optimally sized components at bus 11 demonstrates, albeit minor, a positive effect in combating this voltage sag, as shown in Fig. 7. Thanks to the rolling average EMS, the new load profile avoids sudden power changes. Thus, the new grid-usage profile, consequent to the optimally sized HPS components and the EMS, at bus 11 results in a decreased voltage sag. This is because the HPS demands, in general, less power from the distribution network. The only periods where including the HPS does not improve the voltage sag is between 4:30-5:00 and 12:00 - 14:00; however, Fig. 6 shows that, in those periods, the voltage barely changes. Thus, the voltage sag caused is neglectable.

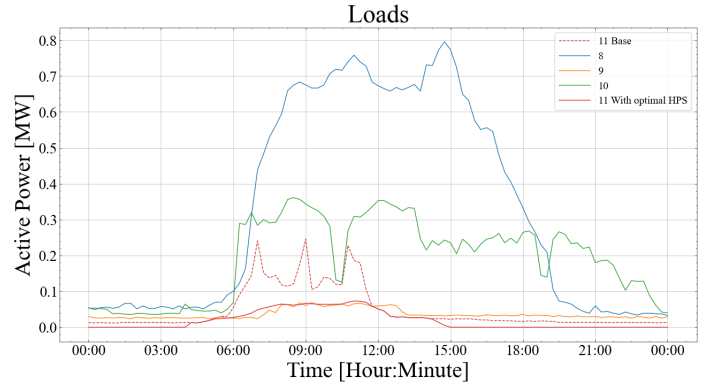


Fig. 6: Loads for bus 8, 9, 10, and 11, with and without HPS (01 October).

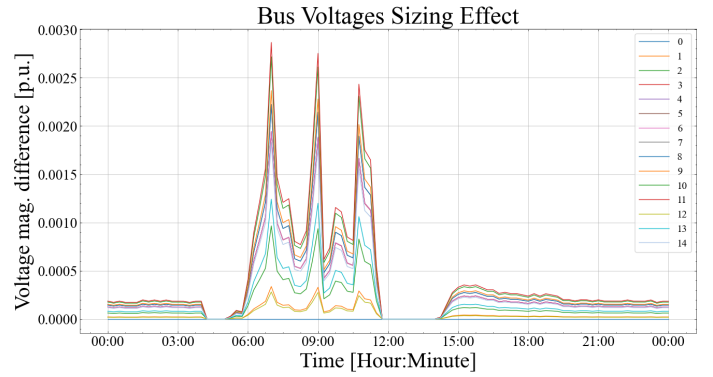


Fig. 7: Bus voltage deviation after sizing (01 October).

V. CONCLUSIONS

In this work, we optimally sized a hybrid power system for an industrial load comprised of a PV system, a diesel generator, and a battery energy storage system. We used a multi-objective minimisation considering energy cost and equivalent CO₂ emissions, achieving a reduction of 46.7 % and 8.7 %, respectively, compared to the case without the HPS. The results suggest that the system does not necessarily require the highest power and capacity components; thus, the EMS is critical. We proposed a rolling average control for the power exchanged with the grid to avoid sudden power changes. For this EMS strategy, longer rolling averages improve the performance of the EMS. After this sizing, the CIGRE MV Distribution system voltage was analysed through a balanced load flow study for two cases: with and without including the optimally sized HPS in node 11. The resulting analysis showed that the optimally sized system positively affected the voltage sag thanks to the rolling average EMS strategy, which avoided sudden power changes due to the addition of the HPS. This lead to a reduction of over 60 % of the peak power demand, improving the overall voltage magnitude up to 0.3 %, despite neighbouring loads having higher power demands. Also, the EMS avoided injecting power back to the grid, which often worsens the power congestion in the network.

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