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Relief of the power grid through cost-effective hydrogen generation

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Abstract

Hydrogen generation sites convert electricity from renewable energy sources (RES) or the grid to satisfy targeted hydrogen production. The design and operation of hydrogen generation sites are conventionally treated as two separate silos. However, due to the intermittent and seasonal behaviour of renewable energy sources, the system design needs to facilitate cost-effective and flexible operation.
This work targets the optimal design of a hydrogen generation site producing 100 kg_{H2}/day. In contrast to the vast majority of the literature, dynamic boundary conditions with a 1-hour resolution are adopted to accurately account for the specificity of the considered case studies. A PEM electrolyzer powered by both a PV-battery couple and the grid is accounted for, and the deployment of the heat generated from the hydrogen conversion is considered. Different objective functions are associated with both the cost of the generated hydrogen and the flexibility services provided to the grid. The key aim to understand how the optimal design of the system varies depending on the targeted objective.
The results demonstrate significant variations in optimal sizes and performance metrics based on different optimization objectives. For cost minimization, the solution excludes battery components and maximizes PV usage, resulting in a value-adjusted levelized cost of hydrogen of 10.9 CHF/kg. Conversely, flexibility-focused optimizations favour larger electrolyzers and significant battery capacity. Multi-objective optimization targeting both cost and peak power minimization provides instead a balanced solution, significantly reducing the peak power metric by 40.5% compared to the cost minimization problem, while achieving lower costs than the peak power minimization problem.
Ultimately, this work highlights the critical interplay between design and operational aspects in hydrogen generation sites. It offers practical design guidelines for the optimal design and operation of hydrogen generation sites to both researcher and practitioner, as well as contributes to methodological advancements in optimizing such energy systems.

Introduction

In the context of energy systems, flexibility refers to the ability to adjust generation and consumption patterns in response to variability and uncertainty in demand and supply [1]. This capability is essential for maintaining grid stability, especially with the growing penetration of intermittent renewable energy sources (RES). In this regard, hydrogen is envisioned to play a critical role in future energy systems due to its ability to store energy and potential to decarbonize sectors considered hard to abate [2]. Hydrogen generation can significantly contribute to grid stability by absorbing excess electricity during periods of high RES availability and producing energy during low production periods, thereby balancing supply and demand. Traditionally, hydrogen generation sites the design and operation of hydrogen generation sites are treated as separate silos, with little consideration for their mutual influence. Conventional approaches often rely on approximated boundary conditions which fail to capture the variability of RES and grid conditions [3,4].
This work builds upon one of our previous study [5] and adopts a numerical tool targeting the simultaneous optimization of sizing and operation, namely a single-layer approach [6,7], of a hydrogen generation site. Unlike traditional methodologies, this study employs dynamic boundary conditions with a 1-hour resolution, accurately reflecting the intermittent nature of renewable energy sources. The system under consideration includes a PEM electrolyzer powered by both a PV-battery couple and the grid, incorporating the utilization of heat generated from hydrogen conversion. Further, by considering multiple objectives, such as the cost of generated hydrogen and the flexibility services provided to the grid, this work aims to understand how the optimal design varies depending on the targeted objectives.

1. Requirements for Grid Services - Technical & Market Conditions

This work adopts a mixed integer linear programming (MILP) model to concurrently optimize the sizing and operation of a hydrogen generation site. The full description of the adopted model is reported in [5]. The specific hydrogen generation site under consideration is depicted in Figure 1. A Proton Exchange Membrane (PEM) electrolyzer was considered, with size S_e, which was sourced by a PV-battery couple and by the grid. The size of the PV field, S_{PV}, indicates the peak of produced power, while the battery storage capacity is indicated with the symbol K_b. Waste heat recovery (WHR) solutions were also considered, with the recovered heat injected in a district heating networks (DHN) at 65 °C. Such temperature level was selected in agreement with the Empa campus in Dubendorf, Switzerland [8], and it is suitable for domestic hot water supply. It is worth nothing that, to inject heat into the high-temperature DHN, a heat pump is required, with the heat pump size referred to as S_{HP}.
The adopted optimization approach targets the objective functions described in section 2.1. It is important to note that, while Figure 1 depicts all the possible technology candidates considered in the work, the developed optimization model is allowed to select null size for each of these technologies. That is, the optimal design might not encompass all the components depicted in Figure 1, but rather a subset of these. The specific technical conditions for the considered energy systems are included in the constraints implemented. Specifically, the energy and mass balances need to be satisfied at each time step, *t*. Further, exclusivity constraints were imposed for the imported and exported electrical energy from the grid, as well as for the charging and discharging operation of the battery. A piecewise-affine (PWA) approximations for cost terms and for the PEM electrolyzer conversion efficiency was implemented. Finally, penalization terms were also

added to discourage on/off operation of the electrolyzer and to, therefore, ensure a long component's lifespan [9,10].
Concerning the considered market conditions, day-ahead prices for the electricity were considered for the electricity imports [11], while the export costs were calculated as per the import plus an additional cost for distribution and transmission costs. The revenues for exporting heat were calculated as a fraction of the electricity cost, in agreement to [12].

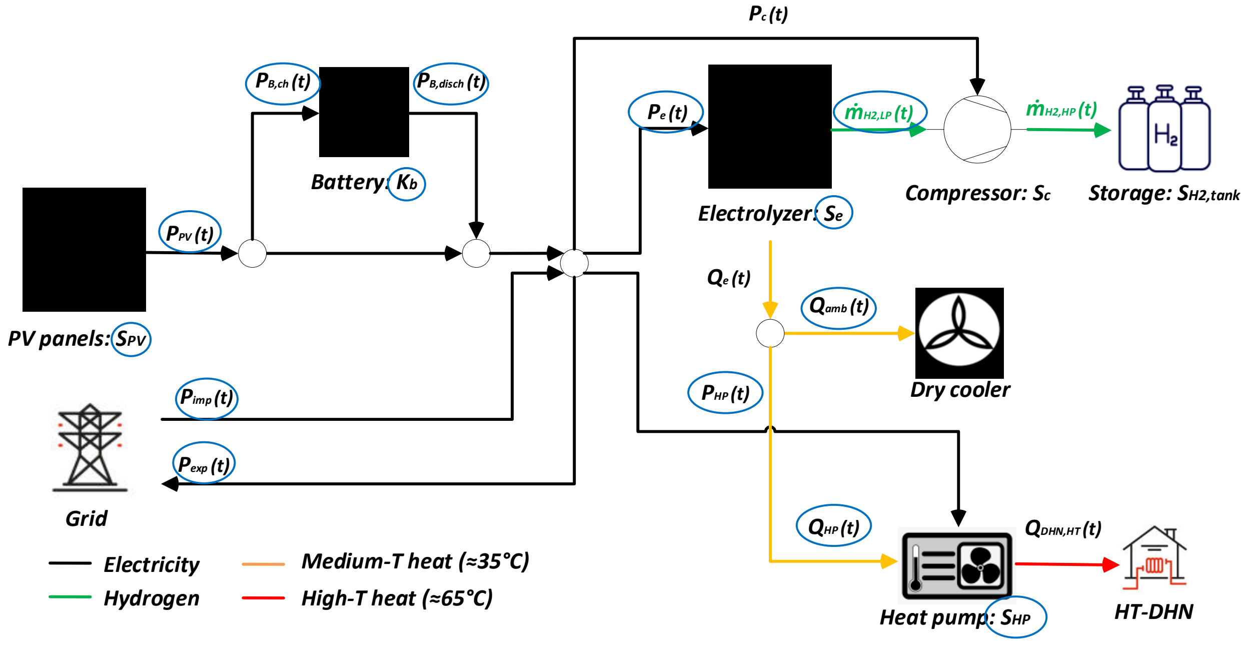


FIGURE 1 SCHEMATIC OF THE HYDROGEN GENERATION SITE UNDER INVESTIGATION. THE DECISION VARIABLES OF THE OPTIMIZATION PROBLEM ARE CIRCLED IN BLU.

1.1 Adopted input parameters

The adopted model requires techno-economic parameters to characterize the considered technology asset. Such techno-economic parameters consider the technology efficiency, unit price, lifetime, and maintenance cost [9,13]. Additionally, boundary conditions with a one-hour resolution and one-year horizon were imposed. Such boundary conditions refer to the considered heat price [12], an hydrogen demand of 100 kg/day [3], the solar irradiance [14], the ambient temperature, and the electricity cost [11]. No heat demand was considered, as the DHN is assumed to accept all the heat recovered from the site. As a case study, the year 2022 was considered and the site was assumed to be located in Dubendorf, Switzerland. Figure 2 reports the boundary conditions used for the analysis.

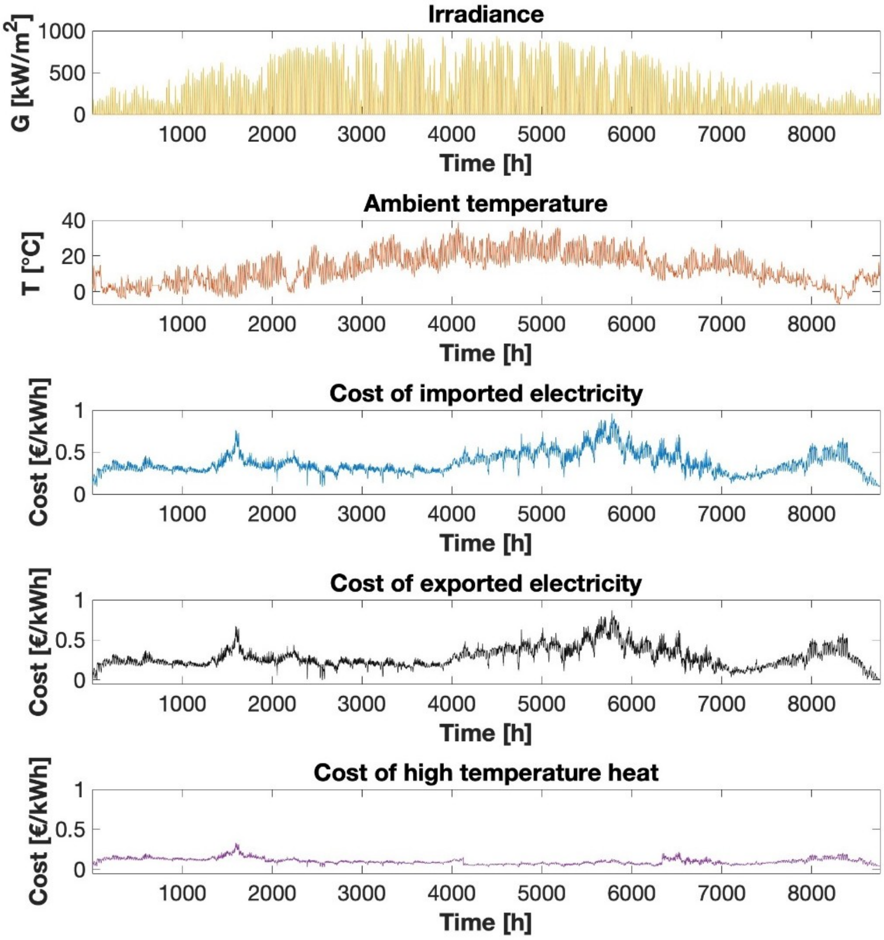


FIGURE 2 BOUNDARY CONDITIONS FOR THE CONSIDERED CASE STUDY IN DUBENDORF, SWITZERLAND, AND YEAR 2022.

2. Approach towards Flexibility

The optimization approach presented in section 1 was adopted to explore the impact of objective functions linked to hydrogen production cost and flexibility services on the optimal design. Conventionally, hydrogen generation sites are designed to minimize the value-adjusted levelised cost of hydrogen [3,15], VALCOH, defined as:

$$VALCOH = \frac{cost_{tot}}{m_{H2,year}} = \frac{cost_{inst,a} + cost_{op,year} + cost_{maint,a} + rev_{year}}{m_{H2,year}} \quad (1)$$

Where $cost_{inst,a}$ is the annualized investment cost linked to all the technologies selected by the optimizer, $cost_{op}$ is the operational cost linked to the purchased electricity over the year, $cost_{maint,a}$ is the annualized maintenance cost calculated as a percentage of the investment costs for each technology, while the term rev_{year} indicates the sum of the revenues over the year from the export of electricity and heat.

2.1. Flexibility metrics

This work considers three flexibility metrics among the most adopted ones in the literature [16], namely peak power, self-sufficiency, and flexibility factor. The definition of these metrics is provided in Table 1.

TABLE I. DEFINITION AND DESCRIPTION OF THE FLEXIBILITY METRICS CONSIDERED IN THIS WORK.

Flexibility metric	*Definition*	*Description*
Peak Power	$PP = max\ (P_{imp}(t))$	Peak power during the considered period of time (one year)
Self-sufficiency	$SS = 1 - \sum_{t=1}^{8760} \frac{P_{imp}(t)}{P_e(t) + P_c(t) + P_{HP}(t)}$	Indicator for the imported energy during high load hours versus during low load hours. The FF ranges between – 1 (energy imported only during high load hours) and 1 (energy imported only during low load hours).
Flexibility Factor	$FF = \frac{P_{imp,low\ load}(t) - P_{imp,high\ load}(t)}{P_{imp,low\ load}(t) + P_{imp,high\ load}(t)}$	Degree to which the on-site generation is sufficient to satisfy the energy needs of the site.

The low and high load times adopted in the definition of the flexibility factor were selected in agreement with typical energy tariffs from Swiss DSOs [17]: low load from 21.00 to 7.00, high load otherwise.

2.2. Objective functions

In agreement with the metrics introduced in Table I, four different objective functions were implemented:

- *Cost minimization: min* $(cost_{tot} + cost_{pen})$
  The minimization of the total costs associated with investment, operation and maintenance is targeted. Additionally, a penalization term was considered, in agreement with [9], to penalize undesirable operations of the electrolyzers.
- *Peak power minimization: min* $(P_{imp,max})$
  An additional scalar design variable, $P_{imp,max}$, was defined within the optimization problem which constraints the maximum value of the imported power over the year, $P_{imp}(t) \leq P_{imp,max}$.
- *Self-sufficiency maximization: min* $(\sum_{k=1}^{8760} P_{imp}(t))$
  Accounting for the self-sufficiency definition provided in Table 1 within the optimization problem would result in nonlinearities. Therefore, the implemented optimization problem only targets the minimization of the imported electricity from the grid to maximize the site's self-sufficiency. Please note that the proposed implementation does not consider the reduction of the site energy consumption as viable way to increase the SS metric.
- *Flexibility Factor minimization: min* $\sum_{k=1}^{8760}(P_{imp,\ lowhour}(t) - P_{imp,\ highhour}(t))$
  Directly considering the FF within the objective function of the optimization problem would cause nonlinearities. Therefore, only the numerator of the FF expression is minimized. Nonetheless, the identified optimal solution is the same as for the minimization of the FF term.

3. Key Results and Conclusion

Table II summarizes the key results for the single-objective optimization problems. The single objective optimization results reveal significant variations in optimal sizes and performance metrics depending on the targeted objective. For the cost minimization approach, battery solutions were excluded due to their high investment costs. Instead, the PV field size was maximized at 1500 kW, and a relatively large electrolyzer size of 397.1 kW was selected. This configuration allowed efficient use of daytime PV electricity and low-cost electricity imports.

In the peak power minimization scenario, the sizes of the PV field, battery, and electrolyzer were all maximized. This allows to reduce peak power by better exploiting the locally produced energy from PV and thus minimizing the amount of electricity required from the grid. Similarly, the self-sufficiency maximization scenario also selected maximum sizes for all key components. However, different operational strategies led to higher self-sufficiency (0.7) but also higher peak power (521.0 kW).

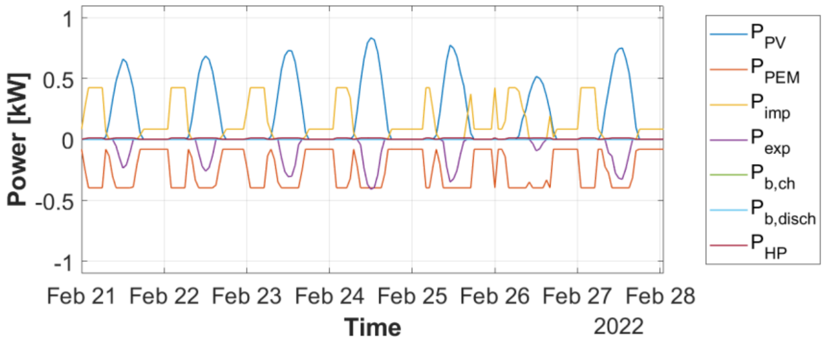
Finally, concerning the flexibility factor minimization problem, the optimal configuration included a 24 MWh battery and a 500 kW electrolyzer, but no PV field. This resulted in large imports during the night and low imports during the day to achieve the desired daily hydrogen production.

TABLE II. KEY RESULTS OF THE SINGLE-OBJECTIVE OPTIMIZATION.

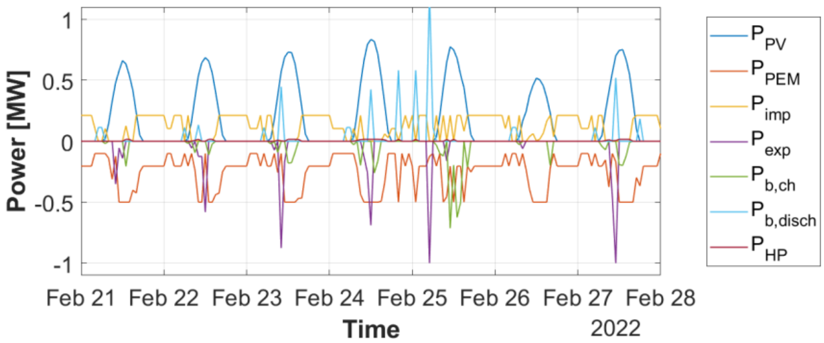
		Sizes				*Metrics*			
		C_b [MWh]	**S_e [kW]**	**S_PV [kW]**	**S_HP [kW_{el}]**	**VALCOH [CHF/kg]**	**PP [kW]**	**SS [-]**	**FF [-]**
Objective function	*VALCOH*	0.0	397.1	1500.0 (max)	12.2	10.9	426.0	0.5	0.4
	PP	24.0 (max)	500.0 (max)	1500.0 (max)	21.2 (max)	63.6	212.5	0.5	-0.1
	SS	24.0 (max)	500.0 (max)	1500.0 (max)	21.2 (max)	62.5	521.0	0.7	0.0
	FF	0.0	500.0 (max)	0.0	21.2 (max)	28.3	537.0	0.0	-1.0

The optimal operational trends are depicted in Figure 2 for a selected week in February. For the cost minimization problem, Figure 2 (a), electricity from the grid is only imported at night to exploit lower purchasing costs. During this period, the electrolyzer remains continuously operational to avoid penalization costs included in the objective function. In the peak power minimization scenario, Figure 2 (b), the amount of imported electricity is significantly reduced. The electrolyzer exhibits an on/off behavior, as no penalization costs were considered for this type of operation. This on/off operation is also affected by the minimum workload imposed (20%).

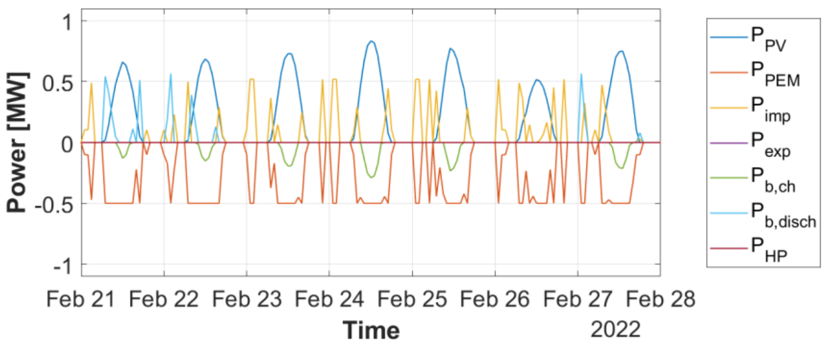
The operational trends for the self-sufficiency maximization problem, Figure 2(c), are similar to those for cost minimization. However, no electricity exports occur, and due to the larger size of the electrolyzer, more PV power is directly used to generate hydrogen during the day to meet the demand. Lastly, for the flexibility factor minimization problem, Figure 2(d), a straightforward trend is observed. Electricity is imported during the night (low load periods), while no imports occur during the day. To meet the hydrogen demand, battery storage is utilized to extend the operational hours of the electrolyzer.



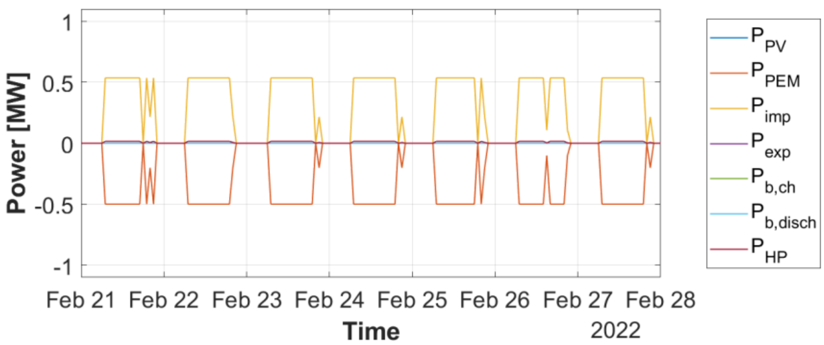
(a) Cost minimization



(b) Peak power minimization



(c) Self-sufficiency maximization



(d) Flexibility factor minimization

FIGURE 3 OPERATIONAL BEHAVIOURS FOR A SELECTED WEEK IN FEBRUARY FOR THE FOUR OPTIMIZATION PROBLEMS UNDER CONSIDERATION.

3.2. Multi-objective optimization

A multi-objective optimization approach was tested, considering both cost and peak power minimization problems with a 0.5 weight coefficient. The resulting metrics are depicted in Figure 4. A sharp decrease in both VALCOH and PP metrics is observed compared to the

single-objective optimization problems. Compared to the pure peak power minimization problem, the multi-objective optimization results in a VALCOH reduction of up to 81.4%. Similarly, the PP metric is reduced by 40.5% when compared to the cost minimization problem.
Regarding the selected technology sizes, a relatively large electrolyzer size of 357.2 kW is chosen, which is similar to the one selected for the cost minimization approach. Additionally, no battery component is selected, while the PV field size is maximized within the considered solution space. Overall, the selected sizes resemble those for the cost minimization approach. However, the peak power metric is significantly reduced by adopting operation strategies that target a smoother import of electricity throughout the year.

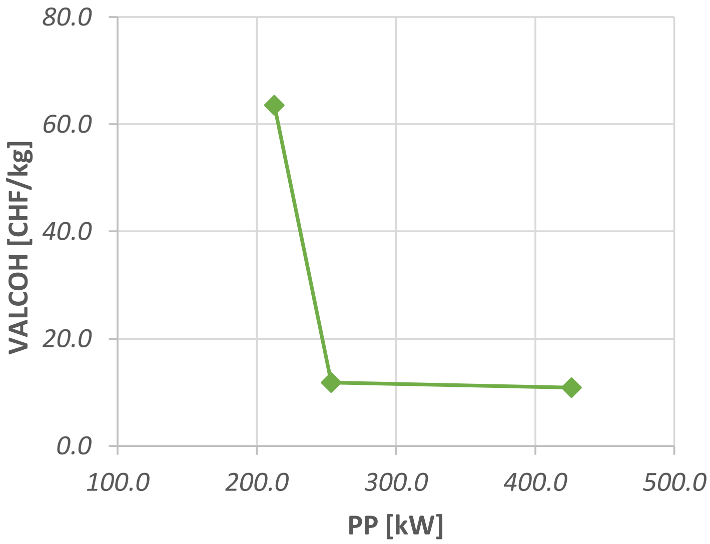


FIGURE 4 PARETO FRONT FOR THE VALUE-ADJUSTED LEVELISED COST OF HYDROGEN AND THE PEAK POWER.

3.2. Conclusion

Automation will change the way we operate systems and consequently also the way we design them. This study proposes a MILP optimization approach to concurrently optimize sizing and operation of a hydrogen generation site. Furthermore, given the increasing need for enhanced flexibility from energy systems, various optimization targets were considered. Together with the conventional cost minimization approach, flexibility-focused optimizations were studied. The key findings from the study are summarized as follows:

- *Concurrent optimization of sizing and operation*: the MILP optimization approach adopted in this work is proved beneficial to capture the specificity of a design case and is proved to embed flexibility metrics from the literature within the optimization framework. Overall, in the spirit of increase energy system automation, the adoption of design tools that considers the mutual influence of design and operational aspects is key;
- *Design differences by objective*: Designs targeting optimal flexibility differ significantly from the most cost-effective ones. For cost minimization, batteries are not selected, whereas for enhanced flexibility, batteries are always included. Higher flexibility is achieved with larger electrolyzer sizes. Local electricity production from renewable energy sources (RES) is always advantageous, except in designs targeting the maximal flexibility factor, where large imports during the night are beneficial;

- *Multi-Objective Optimization:* A multi-objective optimization approach, targeting both cost and peak power minimization, provides a balanced solution by significantly reducing the peak power metric compared to the cost minimization problem, and achieving lower costs compared to the peak power minimization problem. Although the cost is higher than the single-objective cost minimization, this approach effectively balances and reduces both metrics, resulting in a more robust overall design.

These conclusions highlight the impact of considering multiple objectives on the optimal design of hydrogen generation sites and the role of advanced optimization tools in developing effective and efficient energy systems. By understanding and leveraging these trade-offs, it is possible to design systems that better meet the diverse needs of modern energy grids.

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