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Multi-Objective Optimization for a Grid-Connected Hydrogen Integrated Energy Community

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***Abstract*—Hydrogen is increasingly recognized for its role in enhancing the electrification of the built environment, particularly as a seasonal storage medium to balance the intermittent nature of renewable generation. Despite its potential, the high investment costs of hydrogen technologies make their integration challenging in current energy systems. This study addresses the gap in research concerning the impacts of hydrogen integration within energy communities, focusing on system performance and grid operations through different grid connection scenarios. We explore three grid connection capacities—unlimited, 24 kW, and 16 kW—using a case study from The Green Village. Our findings indicate that an unlimited grid connection poses a risk of grid congestion, whereas a restricted connection could result in unmet load demands. Our results suggest that aligning the grid connection capacity with the peak demand of the energy community effectively balances the need to reduce grid congestion while meeting energy requirements. This research highlights the need for strategic planning in the integration of hydrogen technologies within energy communities, advocating for a balance that supports both energy independence and grid stability.**

***Index Terms*—Energy community, Multi-objective optimization, Energy storage, Hydrogen, Grid congestion**

I. Introduction

ENERGY communities are increasingly recognized as vital components of the future energy infrastructure. Unlike the traditional energy system, which depends on large generation facilities linked to distant passive consumers, this approach centers on small hubs of consumption and production. This shift is propelled by the scaling up of renewable energy technologies such as photovoltaic (PV) and flexible storage solutions. These energy communities are defined not only by their technical properties like the technologies involved, but also by the involvement of the participants, who are being motivated by climate awareness and the willingness to become more self-sufficient with respect to the regional grid [1].

In energy communities, energy storage technologies play a vital role in effectively managing intermittent generation from renewable sources, and bridging the gap between energy generation and demand. Among the storage options, electrical energy storage systems, particularly batteries, gained significant attention for their ability to address short-term fluctuations in energy production swiftly. However, due to their inherent limitations in energy density, batteries are predominantly suited for short-term storage solutions [2]. Conversely, hydrogen is a compelling candidate for long-term energy storage with high energy density [3]. By integrating both short-term battery and long-term hydrogen energy storage, energy communities can ensure a reliable power supply. In addition, the integration of hydrogen in energy communities offers substantial improvements in self-sufficiency and utilization of local renewable generation [4]. The hydrogen energy community, therefore, emerges as an essential element in the transition towards a sustainable energy sector [5], [6].

The design of an energy community system is a complex task involving both technical and economic considerations. For instance, while the energy community system should be economically feasible for consumers, the demand should be met by the supply, either self-generated (including local storage), or taken from the grid [7], [8]. Additionally, energy communities may lead to congestion issues in the grid [1]. Therefore, sizing choices for the components in the energy community, such as short-term and long-term energy storage, PV panels, etc., significantly affect the energy community's techno-economic performance [9].

In order to address multiple of these aspects simultaneously, multi-objective optimization techniques becomes essential [10]. For example, [11] utilizes a multi-objective Genetic Algorithm to size off-grid solar home systems, highlighting the high investment costs due to oversizing in the absence of grid support. In contrast, grid-connected energy systems can save investment costs to a large extent, as indicated in [12] and [13].

Regarding long-term energy storage, the high cost of hydrogen system components represents a significant obstacle to their deployment in energy communities [14], [15]. Similar research also indicates that off-grid hydrogen-based energy communities are not economically feasible at this moment due to the high investment costs associated with the hydrogen components, such as hydrogen tanks and fuel cells [5], [6], [16]. However, there is not much research on grid-connected hydrogen energy communities and the optimal grid connection capacity that can enhance the community's techno-economic performance while minimizing its impact on the grid.

This paper aims to bridge this gap by employing a multi-objective optimization approach to assess the techno-economic performance of a grid-connected hydrogen energy community and its impact on the grid. For this purpose, we use a case study from an energy community in the Netherlands called The Green Village [17]. Furthermore, in order to study the grid congestion issues that might be caused by the energy community, we explore three grid connection capacity scenarios: unlimited, 24 kVA, and 16 kVA (kVA is denoted as kW thereafter).

The remainder of this paper is organized as follows: Section II describes the energy community system. Section III details the multi-objective optimization, constraints, and input data used in this study. Results are discussed in Section IV. Finally, Section V concludes the paper and provides future work recommendations.

II. System Description

Figure 1 schematically represents the architecture of the considered hydrogen-integrated energy community system. In this configuration, PV panels are the primary electricity generation sources, installed both on the roofs of the houses and on the ground in their surroundings. Due to the daily and seasonal variation of PV generation and load demand, the battery is used as short-term energy storage to match the daily imbalance, and hydrogen is used as long-term energy storage to address the seasonal imbalance. Hydrogen is mainly produced from surplus PV generation in summer via the electrolyzer, compressed, and then stored in the hydrogen tank. Electricity is produced again via the fuel cells where necessary.

The energy community system is also connected to the regional electricity grid, with which the system can exchange electricity bidirectionally. An energy management system is deployed in the energy community to optimize the energy flows among these components, guaranteeing efficient and reliable energy supply to the energy community. In the control and operation of this energy community system, we prioritize the use of self-generation, either direct electricity from PV and battery or indirect electricity via fuel cells. If the energy community system fails to meet demand, the remaining demand will be supplied by the grid. Conversely, excess electricity generation will be exported to the grid.

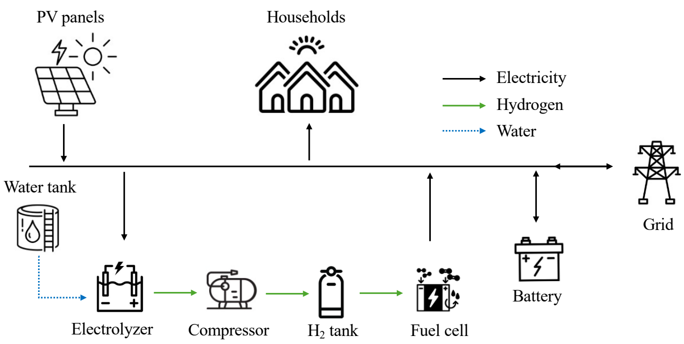

Fig. 1: An architecture of a hydrogen-integrated energy community system

A. PV panels

The hourly PV generation (P_{PV}^t) was determined by accounting for the solar irradiance and the orientation, and inclination of PV panels at The Green Village.

B. Battery

As mentioned before, the battery is used to address the daily imbalance: it charges when there is surplus PV generation and the battery is not full yet, and it discharges when there is insufficient PV generation and the battery is not empty yet. The charge (P_{cha}^t) and discharge (P_{dis}^t) processes of a battery are limited by its maximum and minimum energy capacity ($E_{\mathrm{bat}}^{\mathrm{max}}$and $E_{\mathrm{bat}}^{\mathrm{min}}$in kWh), maximum charge and discharge power ($P_{\mathrm{bat}}^{\mathrm{max}}$ in kW), and efficiency (η_{bat}), the energy state of the battery (E_{bat}^t in kWh) is determined by the following constraints:

$$E_{\mathrm{bat}}^t = E_{\mathrm{bat}}^{t-1} + \eta_{\mathrm{bat}} P_{\mathrm{cha}}^t \Delta t - (1/\eta_{\mathrm{bat}}) P_{\mathrm{dis}}^t \Delta t \quad (1a)$$

$$E_{\mathrm{bat}}^{\mathrm{min}} \leq E_{\mathrm{bat}}^t \leq E_{\mathrm{bat}}^{\mathrm{max}} \quad (1b)$$

$$0 \leq P_{\mathrm{cha}}^t \leq P_{\mathrm{bat}}^{\mathrm{max}} \quad (1c)$$

$$0 \leq P_{\mathrm{dis}}^t \leq P_{\mathrm{bat}}^{\mathrm{max}} \quad (1d)$$

C. Electrolyzers & compressors

The electrolyzer is set to operate during times of surplus PV generation, either when batteries reach full capacity, or their maximum charging power. According to manufacturer specifications, the electrolyzer is subject to ramping limitations and requires around 30 minutes to reach full operation status. In this work, it is assumed that the electrolyzer operates (P_{EL}^t in kW) at 80% of its nominal capacity ($P_{\mathrm{EL}}^{\mathrm{max}}$ in kW) at its first operation hour t_{EL}^1, and later operates at its full nominal capacity. Additionally, the electrolyzer must operate at a minimal power level of 60% of its nominal power. These operation conditions result in the following constraints for the electrolyzer:

$$P_{\mathrm{EL}}^{t_{\mathrm{EL}}^1} = 0.8 \cdot P_{\mathrm{EL}}^{\mathrm{max}} \quad (2a)$$

$$0.6 \cdot P_{\mathrm{EL}}^{\mathrm{max}} \leq P_{\mathrm{EL}}^t \leq P_{\mathrm{EL}}^{\mathrm{max}} \quad (2b)$$

The hydrogen produced by electrolyzers are pressurized via a compressor before it is stored in a hydrogen tank. The compressor's capacity must match the hydrogen production rate of the electrolyzer to ensure it can efficiently compress the hydrogen before being stored in a hydrogen tank.

D. Fuel Cells

Fuel cells are employed when PV generation is insufficient to meet load demand, and the battery either reaches its maximum discharging power limit, or is empty. Similar to the electrolyzer, the fuel cells operate at 50% of their nominal output power ($P_{\mathrm{FC}}^{\mathrm{max}}$ in kW) at their first operation hour (t_{FC}^1), and later on at a flexible power output [18]:

$$P_{\mathrm{FC}}^{t_{\mathrm{FC}}^1} = 0.5 \cdot P_{\mathrm{FC}}^{\mathrm{max}} \quad (3a)$$

$$0 \leq P_{\mathrm{FC}}^t \leq P_{\mathrm{FC}}^{\mathrm{max}} \quad (3b)$$

E. Hydrogen tank

The Hydrogen tank is used to store hydrogen generated by the electrolyzer and the fuel cells consume the stored hydrogen to produce electricity. This process is similar to the charging and discharging dynamics of a battery, with the distinction of storage and utilization of hydrogen instead of electricity. It is subject to specific constraints: the amount of hydrogen stored must remain between the hydrogen tank‘s minimum and maximum capacities ($H_{\mathrm{HT}}^{\min}$ and $H_{\mathrm{HT}}^{\max}$ in kg H_2). The hydrogen state of a hydrogen tank (H_{HT}^{t} in kg H_2) is determined by the following constraints:

$$H_{\mathrm{HT}}^{t} = H_{\mathrm{HT}}^{t-1} + \eta_{\mathrm{EL}} P_{\mathrm{EL}}^{t} \Delta t - (1/\eta_{\mathrm{FC}}) P_{\mathrm{FC}}^{t} \Delta t \quad (4a)$$

$$H_{\mathrm{HT}}^{\min} \leq H_{\mathrm{HT}}^{t} \leq H_{\mathrm{HT}}^{\max} \quad (4b)$$

where η_{EL} (kg·H_2/kWh) and η_{FC} (kWh/kg·H_2) are the electrolyzer and fuel cell efficiency, respectively.

F. Energy balance

An energy management strategy coordinates the components to operate within the constraints defined in equations (1) - (4), ensuring that the supply meets demand at all the times (for $t \in T$):

$$P_{\mathrm{PV}}^{t} + P_{\mathrm{dis}}^{t} + P_{\mathrm{FC}}^{t} + P_{\mathrm{im}}^{t} = P_{\mathrm{L}}^{t} + P_{\mathrm{cha}}^{t} + P_{\mathrm{EL}}^{t} + P_{\mathrm{ex}}^{t} \quad (5)$$

where P_{L}^{t} is the hourly load demand in the energy community. P_{im}^{t} and P_{ex}^{t} are the imported and exported power from/to the grid.

III. MULTI-OBJECTIVE PROBLEM FORMULATION

A. Objectives

The following three objectives are evaluated for the hydrogen-integrated energy community system, focusing on its techno-economic performance.

- **Annualized total cost:** Minimizing the total system cost is a natural objective for any energy system. In this paper, we optimize the annualized total costs (C_{A} in €), which includes capital expenditures (C_{CAP} in €), replacement costs (C_{REP} in €), operation and maintenance costs ($C_{\mathrm{O\&M}}$ in €), and costs for grid import ($C_{\mathrm{IMP}}^{\mathrm{grid}}$ in €) and revenues for grid export ($C_{\mathrm{EXP}}^{\mathrm{grid}}$ in €). The annualized total cost is calculated using the capital recovery factor (CRF), which depends on the interest rate (i= 5%) and the lifetime of the energy system (l = 25 years).

$$C_A = C_{\mathrm{CAP}} + C_{\mathrm{REP}} + C_{\mathrm{O\&M}} + C_{\mathrm{IMP}}^{\mathrm{grid}} - C_{\mathrm{EXP}}^{\mathrm{grid}} \quad (6a)$$

$$C_{\mathrm{CAP}} = \sum_{k=1}^{K} C_k \cdot N_k \cdot \mathrm{CRF} \quad (6b)$$

$$C_{\mathrm{REP}} = \left(\sum_{r=1}^{R} C_r \cdot N_r \cdot \frac{1}{(1+i)^{N_r \cdot l_r}} \right) \cdot \mathrm{CRF} \quad (6c)$$

$$\mathrm{CRF} = \frac{i(1+i)^l}{(1+i)^l - 1} \quad (6d)$$

$$C_{\mathrm{O\&M}} = \sum_{k=1}^{K} 0.2 \cdot C_k \cdot N_k \cdot \mathrm{CRF} \quad (6e)$$

where $K \in$ {PV, battery, electrolyzer, compressor, hydrogen tank, fuel cell}, $R \in$ {battery, electrolyzer, fuel cell}. C_k and C_r represent the capital and replacement capital cost of component k and r, respectively. N_k and N_r are the number of component k and replacement component r. l_r is the lifetime of replacement component r with $l_r \in \{12, 12, 8\}$. The annual O&M costs are considered to be 20% of its capital investment costs for each component.

- **Grid dependence ratio:** This objective is to minimize the system's dependence on the grid. By achieving this, the system would not only make the most out of its self-produced energy but can also relieve the grid under stressful conditions. The grid dependence ratio is calculated as follows:

$$\eta_{\mathrm{GD}} = \frac{\sum_t^T P_{\mathrm{im}}^t}{\sum_t^T (P_{\mathrm{im}}^t + P_{\mathrm{PV}}^t - P_{\mathrm{ex}}^t)} \quad (7)$$

- **Loss of load probability:** It evaluates the reliability of power supply from both the energy community system and the grid, accounting for potential constraints in grid connection capacity that could result in unmet load during peak demand hours. It is defined as the ratio of the total unmet load demand ($P_{\mathrm{L,unmet}}^{t}$ in kW) to the total load demand:

$$\eta_{\mathrm{LLP}} = \frac{\sum_t^T P_{\mathrm{L,unmet}}^t}{\sum_t^T P_{\mathrm{L}}^t} \quad (8)$$

B. Decision variables and constraints

The main scope of the optimization is to find the optimal sizes of the components in order to satisfy the requirements of the energy community, expressed in terms of constraints and described by the energy management strategy. Each solution vector is made of 6 components (decision variables): these are the number of PV panels, batteries, electrolyzer, compressors, and fuel cells to install, together with the total maximum capacity for hydrogen storage (expressed in kg). The allowed range for each component type is defined by the following constraint:

$$0 \leq N_k \leq N_k^{\max} \quad (9)$$

The constraints for each component, along with the energy balance, are specified in equations (1) - (5) and are directly embedded in the energy management strategy.

C. Input data

The input data used in this paper are solar generation, electricity demand of the energy community, electricity prices for energy exchange with the grid, and relevant cost data of each component. The hourly PV generation is calculated based on the irradiance data obtained through the Meteonorm software for the location of Delft for the year 2020. The hourly electricity demand is taken from the real data set from The Green Village from March 2021 to March 2022.

In this paper, we adopt a flat energy pricing for transactions between the energy community and the grid, where both the purchase and sale of electricity are conducted at uniform rates. The flat energy pricing is derived from the average household electricity price from 2012-2022 as reported by the Central Bureau of Statistics in the Netherlands [19], which is 0.33 €/kWh for electricity import from the grid. Furthermore, the export price for electricity fed back into the grid is set at 60% of the import price, resulting in a rate of 0.2 €/kWh.

The maximum capacity limits of each component are summarized in Table I. The quantity of PV panels is limited by the available areas in The Green Village, and is taken from the findings in [20], which is based on the approach described in [21]. Electrolyzer capacity aligns with the maximum PV generation, and fuel cell capacity corresponds to the peak demand. We set the upper limit of hydrogen tank capacity to be 780 kg and battery capacity to be 491.5 kWh (which is 32 modules). Lastly, the CAPEX and the relevant lifetime data of each component are obtained from The Green Village when they were purchased from manufacturers. O&M costs are assumed to 20% of the CAPEX.

TABLE I: Components capacities and limits

Component	Maximum capacity	Component capacity	CAPEX cost (€/piece)	Lifetime (years)
PV panels	87.6 kWp	365 Wp	260	25
Batteries	491.5 kWh	15.36 kWh	6000	12
Electrolyzers	114 kW	3 kW	9000	12
Fuel cells	34 kW	6.8 kW	20000	8
Hydrogen tank	780 kg	60 kg	200	25

IV. Results and Discussions

In this study, we develop three scenarios to investigate the impacts of different grid connection capacities on the performance of the energy community and its interactions with the grid. Each household was assumed to have average grid support of either 2 kW or 3 kW, leading to total grid connections of 16 kW and 24 kW (this also aligns with the community's peak demand), respectively. We also consider a scenario with an unlimited grid connection capacity. We use Genetic Algorithm, which is widely used to solve multi-objective optimization problems [22], as explained in Sections II and III. This results in a Pareto set with 102 equally optimal solutions. The Pareto optimal solutions for different grid connection scenarios are presented in Fig. 2.

Our findings show that a lower grid connection capacity (16 kW) is associated with an overall lower grid dependence (except in a few cases as indicated by the green circle in Fig. 2) compared to scenarios with a higher capacity (24 kW and an unlimited) connection. Furthermore, the Pareto optimal solutions for the 24 kW and unlimited connection scenarios are similar. This outcome is primarily attributed to the fact that the energy community's peak demand is approximately 24 kW. Consequently, both the 24 kW and unlimited grid connections are able to meet the load demands, even when there is no energy supply from the energy community itself.

The plot in Fig. 2 includes three vertical lines (green, purple, and blue colored) that separate solutions incorporating hydrogen components (to the right of the line + the green circle) and those without (to the left), where only PV and battery configurations appear. The latter solution sets show lower costs but higher grid dependency, indicating their inadequacy in

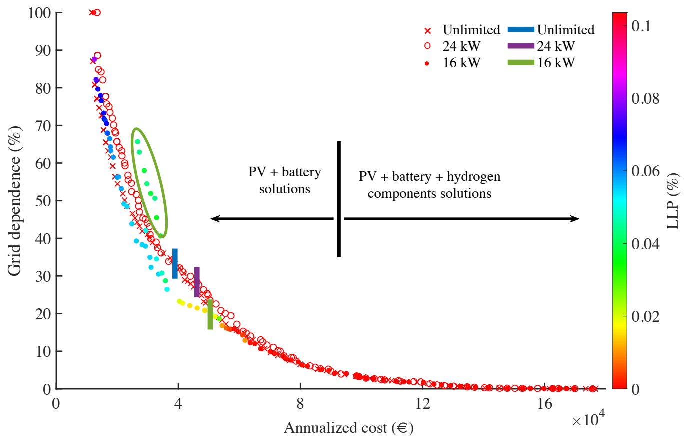

Fig. 2: Pareto optimal solutions for the multi-objective optimization problem (Unlimited: no grid connection limitation; 24 (16) kW: max import and export power from/to grid is 24 (16) kW). Solutions to the left of the vertical lines indicate system configurations only with PV and batteries. Solutions to the right of the vertical lines and the green circles indicate system configurations with hydrogen components.

achieving self-sufficiency. In contrast, hydrogen-based systems show potential for self-sufficiency, but at higher costs that currently limit their economic viability. To facilitate the broader adoption of hydrogen systems within sustainable energy communities, it is essential to focus on reducing costs through technological innovations and the implementation of supportive policies. These efforts are vital to integrate hydrogen effectively into future energy solutions and realize its full potential in supporting the development of self-sufficient communities.

Furthermore, we analyze the performance of solutions that include hydrogen components under various grid connection scenarios. We focus on solutions from each grid scenario where hydrogen components are integrated at a relatively low cost; we select solutions where the annualized cost is approximately equal to €5 $\times 10^4$. Table II provides details of these solutions. This table indicates that the 16 kW grid connection scenario has the lowest level of grid dependence, which can be explained by the limited grid connection capacity. However, this also results in 6 hours in a year where the load demand is not met out of the total 8760 hours.

In addition, Table II also shows that the unlimited grid connection scenario has a maximum export power of 74 kW, posing a high risk of grid congestion. We also analyze the hours in a year when the energy community exports electricity to the grid exceeding 24 kW, resulting in 440 hours, which is likely to affect grid stability. In contrast, the 24 kW and 16 kW scenarios control their power exports more effectively, thus preventing grid congestion during peak demand periods. On the other hand, the 16 kW scenario is unable to fully meet load demands at all times, with 6 hours of unmet demand annually.

The results indicate that at comparable costs, the ideal scenario in terms of grid connection capacity for the energy community depends on their preferences. The 16 kW scenario has the lowest grid dependence ratio, yet it causes unmet load demand. On the other hand, the unlimited capacity

TABLE II: System performance indicators for solutions including hydrogen components from three scenarios (unlimited connection, 24 kW, 16 kW)

	Annualized cost (€)	**Grid dependence ratio (%)**	**LLP (%)**	**Load unmet hours**	**Max import power (kW)**	**Max export power (kW)**	**Total import energy (kWh)**	**Total export energy (kWh)**
Unlimited connection	5.05×10^4	21.32	0	0	17	74	9.7×10^3	3.0×10^4
24 kW	5.04×10^4	23.58	0	0	24	24	1.3×10^4	3.0×10^4
16 kW	5.05×10^4	19.76	0.04	6	16	16	1.2×10^4	2.4×10^4

connection scenario has low grid dependency and zero unmet load. However, the unlimited capacity connection is not favored by the grid due to the high export power, which has a high risk of causing grid congestion. Nevertheless, the 24 kW scenario not only mitigates grid congestion, but also still satisfies the load demand.

V. Conclusions

This paper studied the role of seasonal hydrogen storage in supporting self-sufficiency within grid-connected energy communities, focusing on the technical and economic impacts through a multi-objective optimization framework. We analyzed three scenarios based on different grid connection capacities: unlimited, 24 kW, and 16 kW. Our findings indicate that while hydrogen technologies, such as electrolyzers, fuel cells, and storage tanks, lead to higher levels of self-sufficiency, they come with substantial investment costs. In scenarios with hydrogen components, an unlimited grid connection poses a great congestion issue caused by feed-in power from surplus PV generation. Conversely, a restricted grid connection of 16 kW poses risks of failing to meet load demands at all times. Our results suggest that aligning the grid connection capacity with the peak demand of the energy community effectively balances the need to reduce grid congestion while meeting energy requirements. This strategy not only improves the community's operational efficiency but also supports investment decisions in grid connection capacity in planning.

In conclusion, the integration of hydrogen as a seasonal storage solution is important in improving the self-sufficiency of energy communities within the built environment and, at the same time, supports efficient grid operations at a proper grid connection capacity. Future work can consider the energy community's preferences regarding the three objectives, by applying multi-criteria decision-making techniques, to identify the most suitable solutions, thus guiding more informed and effective energy planning decisions.

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