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An approach for sizing a PV–battery–electrolyzer–fuel cell energy system: A case study at a field lab

Na Li [a,*], Zofia Lukszo [a], John Schmitz [b]

[a] Faculty of Technology, Policy and Management, Delft University of Technology, Jaffalaan 5, 2628 BX Delft, The Netherlands
[b] The Green Village, Van den Broekweg 4, 2628 CR Delft, The Netherlands

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ABSTRACT

Hydrogen is becoming increasingly popular as a clean, secure, and affordable energy source for the future. This study develops an approach for designing a PV–battery–electrolyzer–fuel cell energy system that utilizes hydrogen as a long-term storage medium and battery as a short-term storage medium. The system is designed to supply load demand primarily through direct electricity generation in the summer, and indirect electricity generation through hydrogen in the winter. The sizing of system components is based on the direct electricity and indirect hydrogen demand, with a key input parameter being the load sizing factor, which determines the extent to which hydrogen is used to meet seasonal imbalance. Technical and financial indicators are used to assess the performance of the designed system. Simulation results indicate that the energy system can effectively balance the seasonal variation of renewable generation and load demand with the use of hydrogen. Additionally, guidelines for achieving self-sufficiency and system sustainability for providing enough power in the following years are provided to determine the appropriate component size. The sensitivity analysis indicates that the energy system can achieve self-sufficiency and system sustainability with a proper load sizing factor from a technical perspective. From an economic perspective, the levelized cost of energy is relatively high because of the high costs of hydrogen-related components at this moment. However, it has great economic potential for future self-sufficient energy systems with the maturity of hydrogen technologies.

1. Introduction

With the changing landscape of energy systems towards 100% renewable energy, the transition shift from a centralized energy system to multiple decentralized energy systems is not only a necessity but also a strategically imperative [1,2]. A decentralized energy system is an energy system with distributed energy resources (DERs) where energy generation is close to energy consumption [3]. The current centralized energy system can operate well without energy storage, as traditional power plants are predictable and can be dispatched as needed. However, decentralized energy systems rely on variable renewable energy sources (RESs), such as wind and photovoltaic (PV) generation [4]. These RESs generation is variable and non-dispatchable, which depends on the weather conditions. Energy storage is a necessity to match supply and demand continuously. On a daily basis, an average load demand profile is low during the daytime and high in the evening hours. PV generation can meet the load demand during the day, and surplus generation can be stored in battery energy storage to supply load demand in the evening hours. Besides the daily imbalance, there is also a seasonal imbalance: PV generation is higher in summer than in winter, whereas load demand in certain high-latitude cold regions is higher in winter than in summer. It requires a high capacity of renewable generation and battery energy storage to provide a highly reliable energy supply, leading to high capital costs and a high excess generation that cannot be stored or used. In addition, batteries are not suitable for storing energy for long periods of time due to technical constraints as well as economic considerations. Therefore, an energy system with renewable generation and battery energy storage is not yet a feasible solution to meet this seasonal imbalance. Hydrogen, however, is highly scalable for long-term energy storage [5,6]. It is considered an important energy carrier for long-term energy storage to make up the seasonal variation of renewable generation [7,8]. Surplus PV generation in summer times can be used to produce hydrogen and store it in a hydrogen storage tank. The stored hydrogen can produce electricity through fuel cells to supply load demand in winter times. In this study, the integration of hydrogen into a small-scale decentralized energy system without transmission networks is considered where generation is close to consumption, such as in a household or an energy community.

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[*] Corresponding author.
E-mail address: n.l.li@outlook.com (N. Li).

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Nomenclature

Abbreviations

DERs	Distributed energy resources
RESs	Renewable energy sources
PV	Photovoltaic
LLP	Loss of load probability
CAPEX	Capital expenditures
OPEX	Operational expenditures
LCOE	Levelized cost of energy

Symbols

$t1$	Hour in summer time $t1 \in \{1,2,\dots,ts\}$ [hour]
$t2$	Hour in winter time $t2 \in \{1,2,\dots,tw\}$ [hour]
P_{summer}	Hourly load demand in summer times at $t1 \in \{1,2,\dots,ts\}$ [kW]
E_{summer}	Total energy consumption in summer times [kWh]
P_{winter}	Hourly load demand in winter times at $t2 \in \{1,2,\dots,tw\}$ [kW]
E_{winter}	Total energy consumption in winter times [kWh]
SF_L	Load sizing factor [–]
$E_{winter}^{H_2}$	Load demand in winter times that is supplied by hydrogen [kWh]
E_{summer}^{PV}	PV generation required for supplying load demand in summer times [kWh]
E_{winter}^{PV-Ele}	PV generation required for supplying part of load demand in winter times [kWh]
$E_{winter}^{PV-H_2}$	PV generation required for producing hydrogen [kWh]
SF_{PV}	Sizing factor for PV generation [–]
η_{EL}	Production rate of the electrolyzer [kg/kWh]
η_{FC}	Production rate of the fuel cell [kWh/kg]
E^{PV}	Total required annual PV generation [kWh]
E_{year}^{PV-kW}	Annual PV generation per kW [kWh/kW]
Cap_{PV}	PV capacity [kW]
E_{ave}^{D}	Average daily load demand in the year [kWh]
SF_{bat}	Sizing factor for battery [–]
DOD_{max}	Maximum depth of discharge of the battery [–]
Cap_{Bat}	Battery capacity [kWh]
P_{year}^{peak}	Peak demand in the year [kW]
Cap^{FC}	Fuel cell power rating [kW]
Cap_{H_2}	Hydrogen storage tank capacity [kg]
ESH_{ave}^{D}	Average equivalent sun hours [hour]
Day_{summer}	Summer days [day]
Cap_{EL}	Electrolyzer power rating [kW]
Cap_{com}	Compressor capacity [kg/hour]
R_{dump}	Dumped energy ratio [%]
E_{dump}	Annual dumped energy [kWh]
E_{year}^{load}	Annual load demand [kWh]
E_{failed}	Load demand cannot be met by the energy system [kWh]
η_{LLP}	Loss of load probability [%]
E_{used}^{PV}	PV generation used by the energy system [kWh]
η_{PV}	PV utilization efficiency [%]
Y	System lifetime [year]
r	Discount rate [%]
C_y	CAPEX in year y [€]
M_y	OPEX in year y [€]
E_y^{PV}	PV electricity yield in year y [kWh]
$E_{end}^{H_2}$	The end energy state of the hydrogen storage tank [kg]
$E_{start}^{H_2}$	The requirement for hydrogen at the beginning of the year [kg]

Hydrogen is currently gaining significant attention around the world with the ambition to provide a clean, secure, and affordable energy future [9,10]. The European Union (EU) has set ambitious goals to produce 1 million tonnes of green hydrogen by 2024 in the first phase, and 10 million tonnes by 2030 [11]. To achieve this goal, the European Commission's hydrogen strategy aims to install at least 40 GW of renewable hydrogen electrolyzer capacity within the EU by 2030, to help decarbonize the European economy [12]. Today, hydrogen is primarily used for industrial applications, such as oil refining and ammonia production, where it is mostly derived from fossil fuels. However, it is becoming increasingly important for its application in the built environment [13,14]. For instance, it can be used as an alternative to natural gas for producing heat or generating green electrical energy [15,16]. Green hydrogen, which is produced from renewable sources, is an alternative energy carrier to replace traditional energy fuels [17,18]. It produces only water, electricity, and heat when hydrogen is used in a fuel cell. Therefore, green hydrogen has a great potential to help the built environment achieve zero carbon emissions [19,20].

Previous studies have commonly referred to PV–battery–electrolyzer–fuel cell energy systems as PV–fuel cell hybrid energy systems [21,22]. Among them, most of the studies focus on off-grid/autonomous/stand-alone applications [23,24], system control and energy management strategies [25,26], and optimal system sizing with techno-economic analysis by using the HOMER simulation tool [27,28]. For example, in the study of [29], a hybrid energy system consisting of PV, electrolyzer, and fuel cells is designed to meet both electricity and heat demand for a greenhouse. The PV power capacity is sized based on a worst-case scenario considering the lowest solar irradiation and the highest load demand. The electrolyzer is sized based on the daily hydrogen demand of the fuel cell. However, this study lacks a rational and systematic approach for sizing each component in the hybrid energy system. Similarly, a techno-economic analysis of a hybrid energy system with PV, battery, and fuel cells is conducted in the study of [8]. The results show that a hybrid system with PV, battery, and hydrogen fuel cells has the potential to achieve self-sufficiency and balance the seasonal variations in PV generation. The study in [30] compares optimal sizing and economic analysis of a stand-alone PV–battery energy system with and without hydrogen production. The system components' sizing is optimized based on two evaluation criteria: fulfilling the predefined loss of power supply and minimizing the levelized cost of energy (LCOE). The study concludes that LCOE is higher for a system with hydrogen production compared to the one without hydrogen production. Similar studies about the comparison between energy systems with and without hydrogen production are presented in [31,32]. In addition, the study in [22] explores the selection of renewable energy systems from a multi-criteria perspective. The results indicate that a hybrid PV–wind–battery–fuel cell energy system is the most desirable and feasible energy system if multiple criteria (economic, technical, and environmental

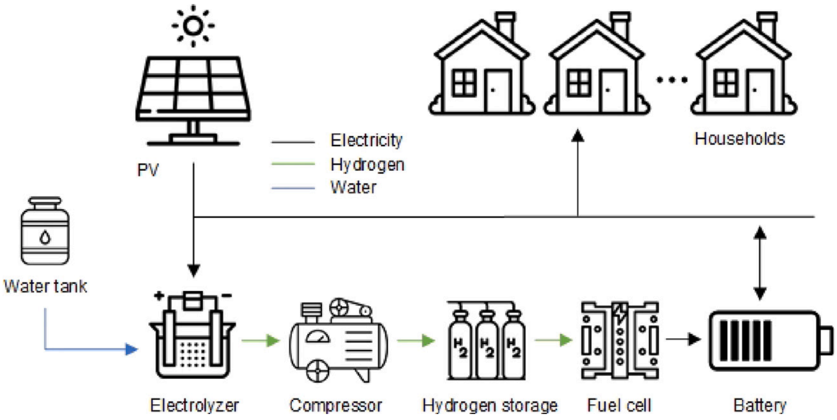

Fig. 1. A typical off-grid PV–battery–electrolyzer–fuel cell energy system.

criteria) are taken into account [22]. Overall, these studies suggest that the inclusion of hydrogen in PV–battery energy systems can help achieve self-sufficiency.

Most studies in this field focus on optimal system sizing, developing control, and energy management strategies. However, these studies do not provide a systematic approach for sizing the system components. This is crucial to have a comprehensive analysis of the energy system's working flow, and for making economic feasibility considerations as well. A common problem these studies do not consider is the long-term system sustainability of the designed energy system. The optimal sizing results may work for the current simulation year, but may not be the optimal sizing for other years, since an energy system should be reliable over a number of years considering variable weather and demand patterns. In addition, the control strategy and optimization objectives often focus on satisfying load demand and minimizing system costs to make the energy system self-sufficient. They neglect the role of hydrogen as a powerful long-term energy storage medium in the energy system. To fully utilize the potential of hydrogen in the energy system, its role should be redefined and emphasized. Furthermore, a systematic and theoretical analysis of each component is essential for designing a PV–battery energy system with hydrogen production.

In this study, a straightforward approach is proposed for component sizing in PV–battery–electrolyzer–fuel cell energy systems systematically instead of using optimization methods. The strategy that hydrogen is considered the long-term energy storage medium is adopted in the sizing approach from the perspective of system sustainability. The proposed approach adopts a load sizing factor as the key input parameter, it determines the extent to which the load demand in winter times is supplied by hydrogen to meet the seasonal imbalance. In addition, a rule for selecting a proper load sizing factor to achieve the defined objectives, such as self-sufficiency, system sustainability, or lowering energy costs, is proposed. The sizing approach is easy to implement in practical applications. The main contributions made by this study are as follows:

(1) The strategy that hydrogen is the long-term energy storage medium to balance the seasonal variation of renewable generation and load demand and a battery is the short-term energy storage medium to balance the daily variation of renewable generation and load demand is investigated.

(2) An approach for sizing a PV–battery–electrolyzer–fuel cell energy system is proposed in this research. The approach is generic and straightforward for practical engineering applications.

(3) A field lab case study is conducted to simulate the PV–battery–electrolyzer–fuel cell energy system in a real-life scenario.

(4) The performance of the designed energy system is evaluated in terms of various techno-economic indicators.

The remainder of this study is organized as follows: Section 2 describes the architecture of the PV–battery–electrolyzer–fuel cell energy system. Section 3 presents the approach for sizing the energy system with a detailed explanation for each component. Technical and financial indicators are proposed in Section 4 for system performance analysis. Section 5 provides the necessary input data and assumptions to conduct the energy system simulation. Section 6 presents the overall system performance analysis with a discussion. Finally, a conclusion as well as future work recommendations, are given in Section 7.

2. The PV–battery–electrolyzer–fuel cell energy system architecture

PV generation and load profiles are seasonal in nature that they show an opposite trend in different seasons. One attractive option would be the use of hydrogen as the energy storage medium to make up for this seasonal difference to make the energy system to be self-sufficient and independent from the grid. A typical off-grid PV–battery–electrolyzer–fuel cell energy system is depicted in Fig. 1. The end-users could be one household or a local community, where the generation is close to consumption. In this study, the aim is to design a system for an energy community consisting of several buildings.

Considering the fact that it takes several seconds or minutes for the fuel cell to ramp up to its full power [33], an energy management strategy is proposed that the battery is frequently charged by the fuel cell when PV generation is less than the load demand to ensure the state of charge of the battery is always above 40%. By doing so, it provides enough time for the fuel cell to ramp up its power. Therefore, hydrogen can also be used as the emergency energy supply when the short-term storage battery cannot provide sufficient energy. The battery will be charged when PV generation is higher than load demand and the upper charging limit is not met yet, and discharged when PV generation is lower than the load demand and the lower limit is not met yet. When the upper limit is met, the surplus PV generation will be delivered to the electrolyzer to produce hydrogen and store it in the hydrogen storage tank. When the lower limit is met (in this study, when the state of charge of the battery is 40%), the fuel cell will start to produce electricity to supply the load demand until hydrogen runs out. The electrolyzer mainly operates in summer times to produce hydrogen for winter use, while the fuel cell mainly operates in winter times to produce electricity for supplying load demand.

3. The approach for designing a PV–battery–electrolyzer–fuel cell energy system

In this section, an approach for designing a PV–battery–electrolyzer–fuel cell energy system is presented by illustrating components sizing one by one. The key points of the sizing approach are depicted in Fig. 2. It is essential to look at the load profile first since the components are required to fulfill load demand at each instant.

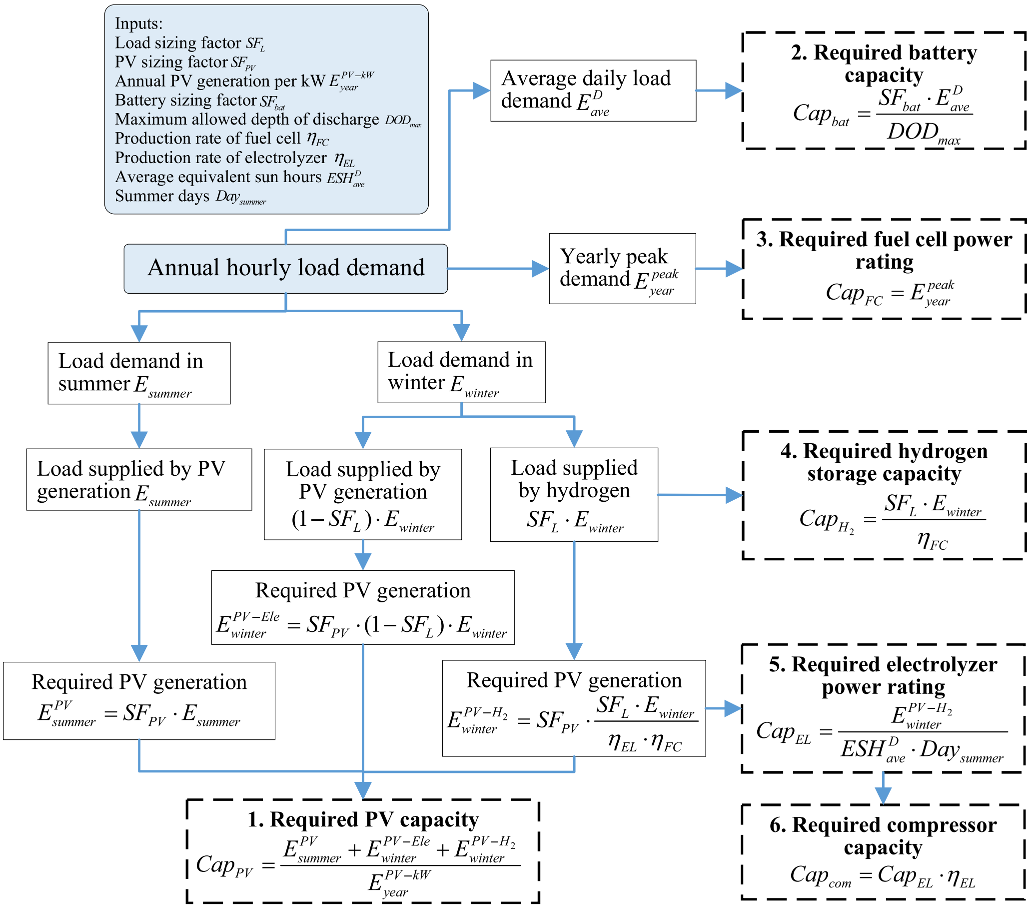

Fig. 2. The flow diagram depicting the basic steps of the proposed sizing approach.

3.1. *Load profile*

Load profile not only has a daily pattern where peaks happen in the morning and night hours, but also has a seasonal pattern with increased electricity consumption in winter times. PV generation has an opposite pattern compared to the load profile. In summer times, PV generation is high during the day, and it is easy to satisfy load demand at night hours with a battery. However, PV generation is so low in winter times that there is not enough energy stored in the battery to satisfy load demand at night hours, especially on days with significantly low PV generation. In the energy system architecture, hydrogen is adopted as the long-term storage medium, which is primarily used to provide electricity in winter times. Therefore, it is essential to clearly distinguish the load demand between summer and winter times.

The total load demand in summer and winter times are given by:

$$E_{summer} = \int_{1}^{ts} P_{summer}(t1)\, dt1 \qquad t1 \in \{1, 2, \dots, ts\} \tag{1}$$

$$E_{winter} = \int_{1}^{tw} P_{winter}(t2)\, dt2 \qquad t2 \in \{1, 2, \dots, tw\} \tag{2}$$

where $t1$ (hours) and $t2$ (hours) are summer and winter hours, respectively. $P_{summer}(t1)$ (kW) is the hourly load demand at summer times, and $P_{winter}(t2)$ (kW) is the hourly load demand at winter times. E_{summer} (kWh) and E_{winter} (kWh) are total load demand in summer and winter times.

3.2. *PV generation*

PV generation is used to supply load demand either directly or via the battery or in the form of hydrogen. In summer times, PV generation is high enough to supply load demand directly or via the battery. In contrast, in winter times, PV generation is relatively low compared to summer times, making it difficult to meet the load demand requirement. In this research, an innovative idea is proposed that load demand in winter times is divided into two parts. The first part is supplied by PV generation directly or via battery storage, and the second part is supplied by hydrogen when PV generation is not possible and the state of charge of the battery is below 40%. The hydrogen is produced from PV generation via the electrolyzer in summer times. In this design, a key parameter of the load sizing factor is adopted to represent the ratio by which the load demand in winter times is supplied by hydrogen.

$$SF_L = \frac{E_{winter}^{H_2}}{E_{winter}} \tag{3}$$

where $E_{winter}^{H_2}$ (kWh) is the load demand in winter times that is supplied by hydrogen. SF_L is the load sizing factor, its range is between 0 and 1. It also determines the capability of achieving self-sufficiency in the designed energy system.

The PV sizing follows the approach in [34] that annual PV generation equals annual load demand. The required PV generation for producing hydrogen is determined by both the efficiency of the electrolyzer and the fuel cell. The required PV generation for each phase is as follows:

$$E_{summer}^{PV} = SF_{PV} \cdot E_{summer} \tag{4}$$

$$E_{winter}^{PV-Ele} = SF_{PV} \cdot (1 - SF_L) \cdot E_{winter} \tag{5}$$

$$E_{winter}^{PV-H_2} = SF_{PV} \cdot \frac{SF_L \cdot E_{winter}}{\eta_{EL} \cdot \eta_{FC}} \tag{6}$$

where SF_{PV} is the sizing factor for PV generation, which is usually assumed to be 1.1 [34]. It is used to account for the balance of system efficiency incorporating cable losses, inverters, and other system losses [34]. E_{summer}^{PV} (kWh) is the required PV generation for supplying load demand in summer times. E_{winter}^{PV-Ele} (kWh) is the required PV generation for supplying load demand in winter times directly or via the battery. $E_{winter}^{PV-H_2}$ (kWh) is the required PV generation for producing hydrogen for winter use. η_{EL} (kg/kWh) and η_{FC} (kWh/kg) are the efficiencies of the electrolyzer and the fuel cell, respectively.

The total required annual PV generation and the required PV capacity are:

$$E^{PV} = E_{summer}^{PV} + E_{winter}^{PV-Ele} + E_{winter}^{PV-H_2} \tag{7}$$

$$Cap_{PV} = \frac{E^{PV}}{E_{year}^{PV-kW}} \tag{8}$$

where E^{PV} (kWh) is the total required annual PV generation. E_{year}^{PV-kW} (kWh/kW) is the annual PV generation for per kW installed. Cap_{PV} (kW) is the required PV capacity.

3.3. Battery

In this energy system, a battery is used as short-term storage to provide energy supply at night or during periods of limited sunlight. According to [34], the battery size is determined by the days of autonomy of the energy system, which is further affected by the location of the energy system. In this approach, it is defined that the battery has the capability to meet the average daily load demand, which is calculated as follows:

$$Cap_{bat} = \frac{SF_{bat} \cdot E_{ave}^{D}}{DOD_{max}} \tag{9}$$

where E_{ave}^{D} (kWh) is the average daily load demand in the year. SF_{bat} is the sizing factor for the battery, which is similar to the sizing factor for PV modules already defined in Eq. (7). DOD_{max} is the maximum allowed depth of discharge of the battery. Cap_{Bat} (kWh) is the required battery capacity.

3.4. Fuel cells

A fuel cell is an electrochemical cell that converts hydrogen and oxygen into electricity through a redox reaction. It should be noted that a significant amount of heat, which is around 45%–60% of the energy content of hydrogen, is produced in the redox reaction process [35,36]. This heat can be recovered and has potential usage in applications such as space heating and domestic hot water supply [37,38]. Fuel cells operate continuously as long as hydrogen is supplied. The fuel cell should produce sufficient electricity to supply the load, even on the worst weather day when there is no PV generation or the state of charge of battery is less than 40%. In this design, the power rating of the fuel cell is set as the peak demand in the year in order to make sure load demand is fully satisfied:

$$Cap_{FC} = P_{year}^{peak} \tag{10}$$

where Cap_{FC} (kW) is the required fuel cell power rating, and P_{year}^{peak} (kW) is the peak demand in the year.

3.5. Hydrogen storage tank

Hydrogen storage is used to store the hydrogen generated by the electrolyzer and compressed by the compressor. The hydrogen storage capacity is determined by the load demand in winter times and the fuel cell efficiency since the hydrogen storage should be large enough to store the hydrogen cumulatively generated in summer times and provide enough electricity during winter times. Therefore, the hydrogen required for generating enough electricity for usage in winter times is also the capacity of the hydrogen storage tank:

$$Cap_{H_2} = \frac{SF_L \cdot E_{winter}}{\eta_{FC}} \tag{11}$$

where Cap_{H_2} (kg) is the hydrogen storage tank capacity, which is also the amount of hydrogen needed to provide for the fuel cell to provide enough electricity in winter times.

3.6. Electrolyzer

The electrolyzer mainly operates in summer times to produce hydrogen when there is sufficient PV generation. PV generation in summer times is very high that it requires a high capacity of electrolyzer to produce hydrogen. However, it is not necessary to convert all the surplus PV generation to hydrogen, as it would result in a high investment cost. The requirement is that the electrolyzer can produce enough hydrogen required in the system. In this design, the average number of daily sun hours (equivalent sun hours) is used for the operating hours of PV panels. Considering the fact that the electrolyzer mainly operates on summer days, the required power rating of the electrolyzer is calculated as follows:

$$Cap_{EL} = \frac{E_{winter}^{PV-H_2}}{ESH_{ave}^{D} \cdot Day_{summer}} \tag{12}$$

where Cap_{EL} (kW) is the required power rating of the electrolyzer, ESH_{ave}^{D} (hour/day) is the average number of equivalent sun hours, Day_{summer} (day) is the summer days. The equivalent sun hours are determined by the solar irradiation data of the location.

3.7. Compressor

Hydrogen has a very low volumetric energy density both as a gas and a liquid because it has the lowest atomic weight. Hydrogen must be made more energy-dense to be useful for storage or transportation. A hydrogen compressor is a device that increases the pressure of hydrogen to compress the hydrogen and reduce its volume. In the designed energy system, the hydrogen generated from the electrolyzer is delivered to a compressor and then stored in a hydrogen storage tank. The capacity of a compressor is determined by the amount of hydrogen generated by the electrolyzer. It should be capable of compressing the amount of hydrogen delivered by the electrolyzer.

$$Cap_{com} = Cap_{EL} \cdot \eta_{EL} \tag{13}$$

where Cap_{com} (kg/hour) is the required capacity for the compressor. It indicates that the compressor should have the capability to compress the amount of Cap_{com} hydrogen per hour.

4. Indicators for system performance assessment and system sizing determination

Once the energy system design is complete, it is essential to evaluate its performance. From a technical perspective, it is essential to validate the system design to see if the selected capacity meets the energy balance of the energy system. From an economic perspective, the costs for hydrogen-related components, such as electrolyzers, compressors, hydrogen storage, and fuel cells, are relatively high. It is also vital to conduct an economic analysis to see if the energy system is economically feasible. Several technical and economic indicators are adopted to assess the performance of the designed energy system. In addition, the rule for system sizing determination is also presented to achieve the defined objectives.

4.1. Technical indicators

4.1.1. Dumped energy and dumped energy ratio

Dumped energy is the energy produced by the energy system that is neither used for load demand nor stored in the battery or delivered to the electrolyzer to produce hydrogen. In order to make it easy to compare, dumped energy ratio is introduced. It is the ratio between the total energy dumped of the energy system in a year and the total annual load demand [39]:

$$R_{dump} = \frac{E_{dump}}{E_{year}^{load}} \cdot 100\% \tag{14}$$

where E_{dump} (kWh) is the annual dumped energy, E_{year}^{load} (kWh) is the annual load demand, R_{dump} (%) is the dumped energy ratio.

4.1.2. Loss of load probability

Loss of load probability (LLP) is defined as the ratio between the load demand that cannot be met by the energy system in a year divided by the total annual load demand [34].

$$\eta_{LLP} = \frac{E_{failed}}{E_{year}^{load}} \cdot 100\% \tag{15}$$

where η_{LLP} (%) is the LLP of the energy system. E_{failed} (kWh) is the load demand that cannot be met by the energy system. The lower the LLP is, the more stable and reliable the energy system is.

4.1.3. PV utilization efficiency

The PV utilization efficiency is used to present how much PV generation is used in the energy system, either in the form of electricity or hydrogen. It is defined as the PV generation used in the energy system divided by the total PV generation:

$$\eta_{PV} = \frac{E_{used}^{PV}}{E^{PV}} \cdot 100\% \tag{16}$$

where η_{PV} (%) is the PV utilization efficiency, E_{used}^{PV} (kWh) is PV generation used by the energy system to supply load demand directly, store in a battery, or produce hydrogen via the electrolyzer.

4.2. Economic indicator: levelized cost of energy

Cash flow over the lifetime of the system is calculated after determining the energy system size and incorporating the costs of each component. This results in lifetime capital expenditures (CAPEX) and operational expenditures (OPEX). Another economic indicator of levelized cost of energy (LCOE) is adopted to assess the economic feasibility of the designed energy system. To calculate this, a depreciation of money is taken into account for CAPEX and OPEX cost, which is then divided by the annual PV electricity yield.

$$LCOE = \frac{\sum_{y=0}^{Y} \frac{C_y + M_y}{(1+r)^y}}{\sum_{y=0}^{Y} \frac{E_y^{PV}}{(1+r)^y}} \tag{17}$$

where Y (years) is the lifetime of the energy system. r (%) is the discount rate, which is used to discount future costs and translate them into the present value. C_y (€) is CAPEX in year y, and M_y (€) is OPEX in year y. E_y^{PV} (kWh) is the PV electricity yield in year y. In addition, some components, such as the battery and fuel cell, have a shorter lifetime than other components. It is required to take the new investment cost in the year for replacement. By that time, the capital cost of that specific component may reduce a lot, which needs to be taken into account in the calculation.

4.3. The rule for system sizing determination

The load sizing factor is an essential factor in the system design as it significantly affects component sizing and system performance. The energy system can achieve various objectives under different load sizing factors, such as self-sufficiency, minimizing system cost, or minimizing or limiting the dumped energy ratio to a certain range in order to not waste PV generation. Therefore, it is important to select an appropriate value for the load sizing factor to achieve the defined objectives. These indicators can be translated into the constraints for selecting a proper load sizing factor.

In this study, the aim is to design an autonomous energy system with hydrogen as the long-term energy storage medium and battery as the short-term energy storage medium. Therefore, the most important indicator for this design is to make sure the LLP is always equal to 0. In addition, considering the fact that PV generation is lower in winter times (the beginning and the end of the year) when load demand is higher compared to summer timers, it is important to ensure that there is enough hydrogen stored by the end of the year to supply load demand at the beginning of the next year for system sustainability consideration. Therefore, the end state of the hydrogen tank (which is denoted as $E_{end}^{H_2}$ (kg)) is also a constraint for selecting the load sizing factor. In this system design, it is assumed that the hydrogen left in the tank by the end of the year should be able to supply load demand for the hours at the beginning of the year (which is considered the winter times). The electricity demand at the beginning of the year is converted into the hydrogen requirement (which is denoted as $E_{start}^{H_2}$ (kg)). The third indicator to look at is the LCOE, as it is the most essential economic factor affecting the implementation of the energy system. The three indicators are translated into the following constraints:

$$LLP = 0 \tag{18}$$

$$E_{end}^{H_2} - E_{start}^{H_2} \geq 0 \tag{19}$$

$$\min \quad LCOE \tag{20}$$

The load sizing factor is selected in a hierarchical manner, using a one-by-one constraint satisfaction approach to ensure that all constraints are met.

5. Input data & assumptions

The proposed approach is implemented to design a self-sufficient PV–battery–electrolyzer–fuel cell energy system to meet the load demand of the buildings at a field lab - The Green Village. The Green Village is located on the TU Delft campus with an area of 9600 m^2. It is a field lab for sustainable innovation in the built environment. The current energy system at The Green Village is designed with electricity, heat, and hydrogen grid. It comprises of four family houses, four student one-bedroom apartments, and one office building. Among them, the four family houses are equipped with electricity and hydrogen grid. In addition, a hydrogen boiler (central heating system) is installed in one of the family houses. The four student apartments are fully electrified. In this section, the relevant input data are presented for this case study.

5.1. Input data

5.2. Hourly energy demand

The case study makes use of the hourly load consumption data available from The Green Village buildings: the four student apartments and three family houses in the year 2020.

5.3. Hourly PV power generation

The hourly PV generation data is obtained from the open data platform Renewables.ninja [43–45] in the year 2020, which corresponds to the load demand year.

Table 1
The techno-economic parameters of each component in the energy system.

Component	CAPEX	OPEX % of CAPEX (€/year)	Lifetime (Years)	Other parameters	Source
PV	240 €/kW	0.5	25	–	[40,41]
Battery	500 €/kWh	1	12	Minimal state of charge: 0.20 Maximal state of charge: 0.95	The Green Village
Electrolyzer	3750 €/kW	1	12	Production rate: 500 NL/hour Nominal power consumption for Nm3 of hydrogen produced: 4.8 kW/Nm3	The Green Village
Compressor	300 €[kg H2/day]	1	25	Throughput: 2 kg/day Power consumption: 0.7 kW	[42]
Hydrogen tank	200 €/kg	1	25	The costs for hydrogen tubing, valves, and connectors are around 12000 €	The Green Village
Fuel cell	3044 €/kW	1	8	Rated power 6.8 kW Maximal hydrogen consumption: 77Nl/min at full power The cost for the surrounding environment is 6000 €	The Green Village

5.4. Techno-economic parameters

The techno-economic parameters for each component in the system are summarized in Table 1. They include CAPEX, OPEX, lifetime, and other essential data. The capital costs of the battery, electrolyzer, hydrogen tank and fuel cells are obtained from The Green Village when purchasing the components from the manufacturer. The capital cost data of PV and compressor are not known yet. Hence, some assumptions are made according to the most recent cost data provided by the manufacturer. In addition, the OPEX costs are not available from the manufacturers, some assumptions are also made about them.

5.5. Other relevant input data

In this study, the load demand and PV generation data are based on the Netherlands. It is necessary to take the weather condition into account to make the following relevant assumptions. Load demand is usually classified between summer and winter. Spring and fall are commonly included as transition periods as load demand decreases from spring to summer and increases from fall to winter. In this research, it is assumed that the summer days are from 1 March to 30 October, and winter days are from 1 January to 29 February and 1 November to 31 December. In total, there are 142 winter days and 224 summer days in 2020. The second assumption is that the initial state of the hydrogen storage tank is filled with 50% of its capacity. The third assumption is the average number of equivalent sun hours. The average number of daily sun hours is 3.1 h for the optimal tilt at Delft, the Netherlands [34]. However, the sun hours in summer times are much longer than in winter times. In addition, the electrolyzer is mainly used in summer times. In this research, an average number of 6 sun hours per day is assumed as the equivalent sun hours for the case study.

6. Results analysis and discussions

6.1. Simulation results: overall system performance

Based on the system design and input data, a one-year simulation for the energy community at The Green Village is conducted. The required capacity for each component in the designed energy system is calculated based on the approach proposed in Section 3. In this part, the load sizing factor is set to one with the assumption that all the load demand in winter times is fully supplied by hydrogen. The overall load demand throughout the year is 4.29×10^4 kWh. And the required PV generation over the year is 1.05×10^5 kWh, which is approximately 2.5 times higher than the load demand. The PV generation is much higher than the load demand because of the low efficiencies of the electrolyzer (producing hydrogen from surplus PV generation) and the fuel cell (producing electricity by using hydrogen). The operational state of the fuel cell and the electrolyzer over the year when the load sizing factor is one are presented in Fig. 3(a) and (b), respectively. As expected, the fuel cell mainly operates in winter times to produce electricity by using the hydrogen stored in summer. While the electrolyzer mainly operates in summer times to produce hydrogen by using the surplus PV generation. The energy state of the hydrogen storage tank throughout the year when the load sizing factor is one is summarized in Fig. 3(c). At the beginning and end of the year (winter times), hydrogen storage decreases as the hydrogen is used to produce electricity via the fuel cell to supply the load demand (corresponding to the operational state of the fuel cell). When summer comes, PV generation increases, and surplus PV generation is used to produce hydrogen via the electrolyzer (corresponding to the operational state of the electrolyzer). Then, hydrogen storage starts to increase until it reaches its maximum capacity (which is 1040 kg when the load sizing factor is one). It should be noted that the energy system is oversized when the load sizing factor is one. This will be further analyzed in the following section.

Fig. 4 presents the profiles of load demand, PV generation, the energy state of the battery, and the energy state of the hydrogen storage tank on a summer day when the load sizing factor is one. During the daytime, PV generation is high and surplus generation is first used to charge the battery until it is full (as shown in the blue line). After that, the remaining PV generation is used to produce hydrogen as hydrogen in the hydrogen storage tank is increasing (as shown in the orange-red line). During evening hours, since there is no PV generation, and the battery has enough energy to supply load demand as its state of charge decreases, the electrolyzer stops producing hydrogen.

Similarly, the profiles of load demand, PV generation, the energy state of the battery, and the energy state of the hydrogen storage tank on a winter day when the load sizing factor is one are depicted in Fig. 5. PV generation is only sufficient to meet load demand for 11–13 h. For the remaining hours during the day, PV generation is so low that the battery is firstly used to supply load demand. The battery is frequently charged by the fuel cell as shown in the blue line, to ensure its state of charge is always larger than 40%. Fuel cells start to operate to produce electricity for charging the battery and supplying load demand as the hydrogen in the hydrogen storage tank decreases (as shown in the orange-red line). The simulation results verify the control strategy proposed in this research that hydrogen is mainly produced in summer times for winter energy supply and battery for daily energy supply.

6.2. Sensitivity analysis: the impact of load sizing factor on system design

In the energy system, the load sizing factor is the main factor affecting the component sizing and overall performance of the PV–battery–electrolyzer–fuel cell energy system. In the simulation results, the techno-economic performance of the designed energy system is

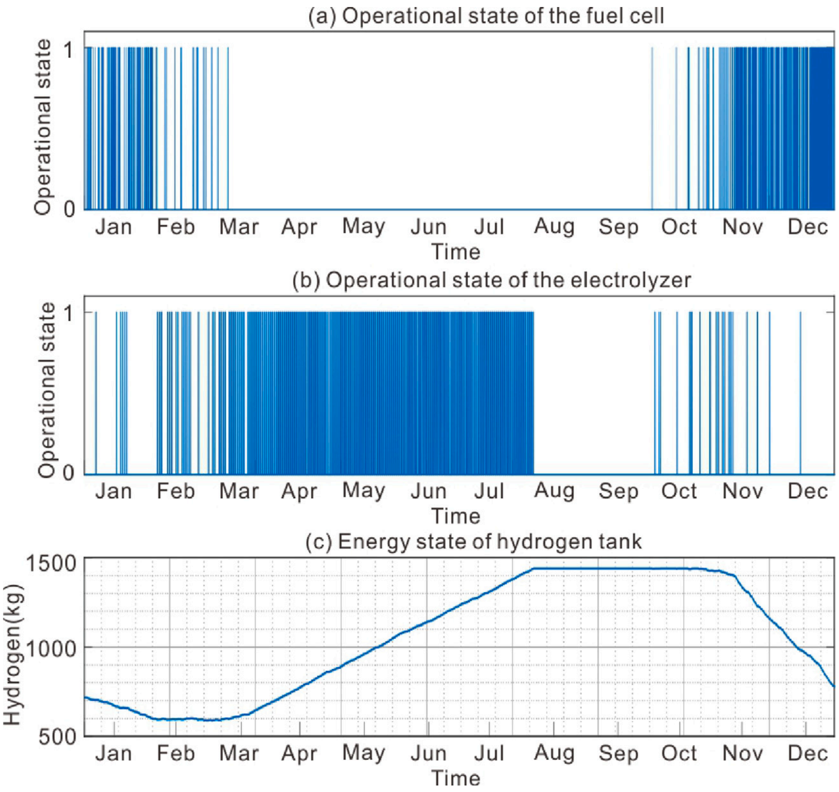

Fig. 3. (a) Operational state of the fuel cell throughout the year (1: on; 0: off);(b) Operational state of the electrolyzer (1: on; 0: off); (c) Energy state of hydrogen storage tank (kg) throughout the year when the load sizing factor is one.

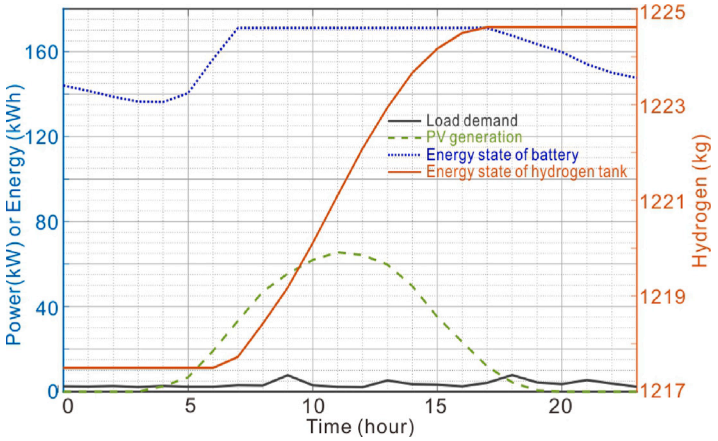

Fig. 4. Load demand [kW], PV generation [kW], energy state of battery [kWh], and energy state of hydrogen storage tank [kg] on a summer day when the load sizing factor is one.

investigated under various load sizing factors in terms of the indicators proposed in Section 4. The results of LLP (green line), dumped energy ratio (black line), PV utilization efficiency (blue line), and the end state of the hydrogen tank (red line) in a year under various load sizing factors are shown in Fig. 6. These results will be explained one by one in this section.

LLP decreases as the load sizing factor increases, reaching zero when the load demand is fully met. The breakpoint occurs at a load sizing factor of 0.6. The dumped energy ratio is the largest when there are no hydrogen-related components (electrolyzer, compressor, hydrogen storage tank, and fuel cells) in the energy system (load sizing factor is 0). The load demand is solely supplied by PV generation and battery. In this study, the battery is designed to satisfy daily load demand, resulting in a large amount of surplus PV generation being dumped. Gradually, with the introduction of hydrogen-related components in the system (with the increase of load sizing factor), surplus PV generation is used to produce hydrogen when the battery is full, and the dumped energy ratio starts to decrease. However, a breakpoint occurs (for dumped energy ratio) when the load sizing factor increases, as a larger load sizing factor results in a greater portion of load demand in winter times being supplied by hydrogen. In turn, it requires higher PV generation and leads to more surplus generation.

When it comes to PV utilization efficiency (as shown in the blue line), it indicates the utilization of PV generation either in the form of electricity or hydrogen. When the load sizing factor is small, the load demand is mainly supplied by PV generation directly or by the battery, resulting in high dumped energy (as shown in the black line) and low PV utilization efficiency. As the load sizing factor increases,

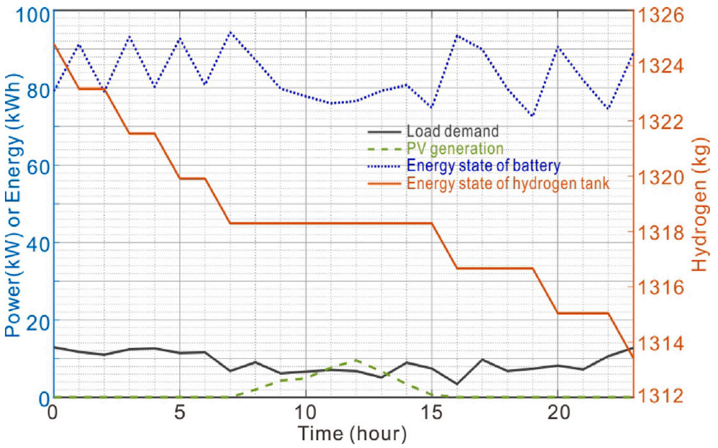

Fig. 5. Load demand [kW], PV generation [kW], energy state of battery [kWh], and energy state of hydrogen storage tank [kg] on a winter day when the load sizing factor is one.

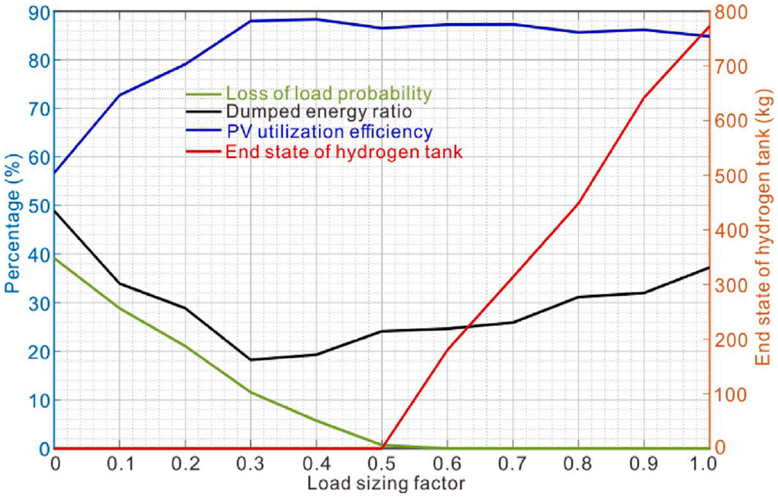

Fig. 6. Loss of load probability [%], PV utilization efficiency [%], dumped energy ratio [%] and the end state of hydrogen storage tank [kg] in a year under various load sizing factors.

PV utilization efficiency also increases. PV generation is used in the form of electricity directly and in the form of hydrogen indirectly by the energy system. As the load sizing factor becomes higher, the hydrogen storage tank capacity increases as well. A large amount of hydrogen is produced by the surplus PV generation. The PV utilization efficiency is more or less the same, with a slightly decreasing trend. It indicates that the energy system is oversized. Based on this, it is also necessary to look at the end state of the hydrogen storage tank to see how much hydrogen is left in the tank by the end of the year (as shown in the red line). When the load sizing factor is small, all of the hydrogen is used in winter times, leaving no hydrogen in the tank by the end of the year. As the load sizing factor increases, the amount of hydrogen left in the tank also increases. Considering system sustainability, it is essential that there is enough hydrogen left in the tank by the end of the year for use at the beginning of the next year. However, it is not necessary to oversize the hydrogen storage size, as it leads to high system costs.

The cost of each component and LCOE of the energy system are also calculated under various load sizing factors according to the input data in Section 5.4. The results are summarized in Fig. 7. It is clear that the total system cost and LCOE increase with the increase of the load sizing factor. The most influencing factors are the costs of the hydrogen storage tank, electrolyzer, and battery. Battery costs are fixed for each load sizing factor because the battery is used for daily energy supply, and its size is based on the average daily load demand. The costs of the hydrogen storage tank and electrolyzer increase with the increase of load sizing factor since the requirement for hydrogen also increases with the increase of load sizing factor. Overall, the load sizing factor has a significant impact on the performance of the energy system in terms of both technical and financial indicators. The selection of the load sizing factor depends on the objectives of the system design.

6.3. Determination of the load sizing for achieving self-sufficiency and system sustainability

Based on the system performance and analysis presented in previous parts, the load sizing factor is determined to achieve self-sufficiency and system sustainability for the energy system based on the rules proposed in Section 4.3. These objectives are classified one by one based on a hierarchical approach. The first two priorities are the constraints defined in Eqs. (18)–(19). It is assumed that the first 1000 h are winter times. The third layer aims to minimize LCOE based on the first two layers.

According to the simulation results presented in Section 6.2, a load sizing factor of 0.7 is selected. Once the load sizing factor is determined, the size for each component is also determined. At this point, LLP is 0, and the end state of the hydrogen storage tank is 313 kg, which exceeds the minimum requirement of 278 kg to meet the load demand at the beginning of the year. The PV generation over the year is 8.75×10^4 kWh, which is around 2 times higher than the load demand. The LCOE is 0.482 €/kWh, which is slightly higher than the current energy

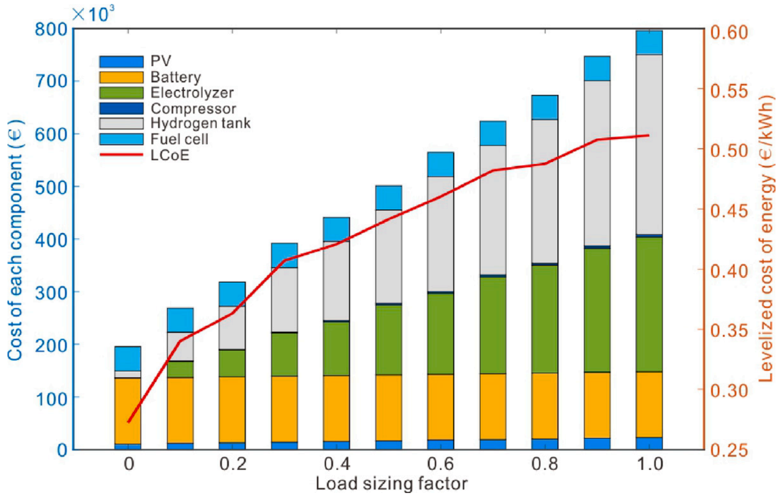

Fig. 7. The cost of each component and levelized cost of energy of the energy system under various load sizing factors.

price of 0.4156 €/kWh (as of June 2022, including environmental and energy taxes) [46]. LCOE is relatively high because of the high costs associated with hydrogen-related components. The LCOE calculated in this study is specific for the assumed solar irradiance, latitude, and behavior of local power consumers in a high-latitude cold region. Low-latitude hot regions may present lower power demand in winter and a proportionally lower LCOE due to the reduced need for hydrogen during winter.

6.4. Discussions

System design approach

In this study, an approach is developed to size the components of a PV–battery–electrolyzer–fuel cell energy system, which is very practical for real-life applications. The components' sizes are selected based on the performance analysis of the energy system in terms of technical and financial indicators and are achieved by a one-by-one objective satisfaction rule. Self-sufficiency is the first priority of the system design, system sustainability is the second objective, and minimizing LCOE is the third objective. An appropriate load sizing factor is determined by satisfying the objectives in a sequential manner. The technical performance of the energy system is the focus of the objective over its financial performance, which leads to a high LCOE making it not affordable for the end-users at this moment. However, it is possible to make the energy system partially autonomous by connecting it to the grid, thus making the energy system economically feasible. Therefore, the objectives of the system design are adjustable depending on the specific circumstances.

This study assumed that the load demand in winter is higher than in summer. In low-latitude hot regions, the load demand in summer is usually higher than in winter, leading to a reduced need for high-capacity hydrogen generation, storage, and fuel cell system. Also, high-latitude cold regions such as the Netherlands are subject to snow coverage over PV modules for several days in winter. Severe snow coverage reduces PV power generation from 90% to 100% [47]. Assuming a severe snow coverage on PV modules, the hydrogen storage and fuel cell capacity should support 100% winter power peak demand during the snow melting and sliding period. Assuming 14 days of snow in the Netherlands, a larger hydrogen storage tank capacity would be required to meet load demand and achieve self-sufficiency, which would further increase the total system cost. Future studies may explore the possibility of utilizing an external power supply from the utility grid to address this power supply gap during winter snow periods to reduce system costs. Overall, the sizing approach can be applied to any electricity-hydrogen system with different objectives with minor modifications.

System design strategy

In this study, the strategy of having hydrogen as the long-term energy storage medium and battery as the short-term energy storage is investigated as a solution to the problem of seasonal variation in PV generation. Surplus PV generation in summer times is used to produce hydrogen. Hydrogen is mainly used to supply load demand in winter times. The design strategy effectively achieves the objectives of self-sufficiency and system sustainability. In addition, hydrogen helps in an emergent situation to supply load demand, for instance, there is no sun for a few days in summer times.

There could be also other interesting system design strategies, such as using the battery as the main energy storage and hydrogen as the supplement energy storage medium. Under this strategy, surplus PV generation can be directly used to charge the battery, thus improving PV utilization and system efficiency. This would result in a larger battery capacity and a smaller size of the hydrogen storage tank. It is essential to calculate the supplementary hydrogen required by the energy system to size the hydrogen-related components. Since the costs of the hydrogen tank and electrolyzer are the most influencing cost factors under the system design strategy in this study. It would be interesting to compare the two system design strategies to see which one is more economically feasible.

System configurations

In this study, only electricity usage is considered, and hydrogen is used for producing electricity again when PV generation is insufficient, or the state of charge of the battery is below 40%. The process of producing hydrogen from electricity and using hydrogen to produce electricity reduces the overall system efficiency. In addition, heat demand, which dominates the energy demand in the residential sector, is not considered. Hydrogen can be used directly by a hydrogen boiler to produce heat is an option that could be further explored. Therefore, different energy system configurations with multi-energy carriers and multiple components could be taken into account for further improvement. The component sizing approach developed in this study still applies to different system configurations with hydrogen with minor modifications. Another important aspect that is not addressed in this research is the utilization of the heat generated during fuel cell operation for electricity production. The energy system can be configured to satisfy multiple energy demands (both electricity and heat) by incorporating multiple energy generations. It is necessary to compute the heat produced in the process of producing electricity with fuel cells. In addition, it is also essential to take heat storage into account in the system configuration due to the mismatch between heat generation and consumption.

Concluding remarks

In this study, a systematic sizing approach for designing a PV–battery–electrolyzer–fuel cell energy system is proposed with the goal of achieving self-sufficiency and system sustainability. A straightforward approach without optimization is adopted in order to size these components one by one and show their working principles according to the design strategy. The approach provides results that are appropriate and valid for system sizing with the defined objectives of the energy system. The approach is generic in that it can be used to size energy systems with similar design strategies. An additional remark is about the system simulation. In this study, the system simulation starts at the beginning of the year when hydrogen is required to supply load demand. Therefore, an assumption is made that the initial state of the hydrogen storage tank is filled with 50% of its capacity to satisfy load demand at the beginning of the year. Another option is that the simulation can start at the beginning of summer when surplus PV generation is high and hydrogen production starts and stores in the hydrogen storage tank cumulatively. However, regardless of the starting point, the requirement for the size of the hydrogen storage tank remains the same for both options in order to satisfy load demand in winter times.

From a practical application perspective, this type of system can be used in remote or off-grid locations where access to the grid is limited. In addition, this type of energy system has the potential to create new business models in the production and distribution of renewable energy, as well as in the system design. Furthermore, hydrogen generation and storage in energy systems can provide flexibility to the grid. This can ease the burden on the grid if the flexibility is utilized effectively, for instance, by supplying extra power during peak hours, particularly in winter times. This can prevent the need for unnecessary capacity expansion and investments in the electric grid.

Incorporating hydrogen in the existing PV–battery system can help meet policy targets related to energy security, emission reduction, and environmental protection. It can also help to increase the penetration of renewable energy and reduce dependence on fossil fuels. Overall, this study contributes to the sizing of self-sufficient energy systems with hydrogen as the long-term energy storage medium. It contributes to the deployment of green hydrogen in the energy system and thus achieves the carbon-neutral mission in the coming years.

7. Conclusions and future work

7.1. Conclusions

In this research, a straightforward and systematic approach is proposed for sizing a PV–battery–electrolyzer–fuel cell energy system for applications in a decentralized energy system where generation is close to consumption. The strategy of utilizing hydrogen as a long-term energy storage medium to balance the seasonal variations and battery as a short-term storage medium to balance the daily variations of renewable generation and load demand is investigated. The simulation results indicate that by incorporating hydrogen as a long-term energy storage medium, the energy system can provide a highly reliable energy supply, especially in winter times when renewable generation is limited. The load sizing factor is a flexible and key input parameter in the system design to achieve different objectives, such as self-sufficiency and system sustainability. The techno-economic analysis indicates that the energy cost of such a self-sufficient energy system is still high compared to the current energy price, thus making it financially challenging for local communities to afford it. From a technical perspective, the integration of hydrogen into the existing PV battery system can definitely increase the reliability and security of the energy supply. However, as technology advances, the costs associated with hydrogen storage tanks and electrolyzers are expected to decrease, thereby increasing the affordability of this type of energy system. In addition, the efficiencies of electrolyzers and fuel cells will also improve at the same time, which will also increase the system's overall efficiency. Overall, such energy systems have a wide range of applications in rural areas where transmission and distribution networks are difficult to access. The designed PV–battery–electrolyzer–fuel cell energy system has zero carbon emissions during operation. It contributes to achieving the decarbonization goal in the energy transition.

7.2. Future work

The aim of this study is to design a self-sufficient PV–battery–electrolyzer–fuel cell energy system with hydrogen as the long-term energy storage medium, which has potential applications in rural areas. The primary focus of this study is to analyze the technical performance to achieve self-sufficiency and system sustainability. However, there is also future work that could significantly improve the economic feasibility of the energy system. For instance, a hydrogen storage tank is the main cost driver of the energy system. It is possible to investigate other options for hydrogen storage, such as in chemical form or underground hydrogen storage [48,49], to reduce the total system cost. Furthermore, fuel cells produce both heat and electricity. However, in this study, only electricity generation is taken into account. In future work, it is worth investigating the use of heat to meet the heat demand of the end-users to help them save heat costs as well.

CRediT authorship contribution statement

Na Li: Conceptualization, Methodology, Investigation, Writing – original draft, Writing – review & editing, Visualization. **Zofia Lukszo:** Supervision, Writing – review & editing. **John Schmitz:** Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.rser.2023.113308.

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