CHEMICAL ENGINEERING TRANSACTIONS

VOL. 114, 2024

A publication of AIDIC

The Italian Association of Chemical Engineering
Online at www.cetjournal.it

Guest Editors: Petar S. Varbanov, Min Zeng, Yee Van Fan, Xuechao Wang

ISBN 979-12-81206-12-0; **ISSN** 2283-9216

DOI: 10.3303/CET24114151

Hydrogen System Design Methodology for Autonomous Houses in Central-East Europe

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As part of the energy transition, the building sector must be revolutionized to reach the goal of carbon neutrality since it is responsible for 3 Gt of CO_2 emission worldwide every year. Energy storage capacities, which could help in the spread of renewables – are still at a very low level. Hydrogen is considered a solution for seasonal hydrogen storage, but only a few examples exist still worldwide to showcase the technology. The residential sector is more underrepresented in this manner. Therefore, the number of good practices should be higher to give examples to architects and engineers. In this paper, a design methodology is presented, which can help to identify and size the system components for autonomous (i.e., grid-independent) homes. An opportunity is given to estimate the cost of the whole complex electrical system. As the heat loss factor of buildings and the energy use of residents can be determined as part of the energy label certification, the sizing of the renewable energy equipment is an iterative process. For that, more grade system losses have to be taken into consideration. The result of this study is a numerical formula that gives the needed component properties. This offers stakeholders and real estate developers an easy tool to predesign their systems in the early stages of development.

1. Introduction

According to the EU Hydrogen Strategy (2020), hydrogen will have to be such a key energy carrier by 2030 as natural gas is nowadays. For this aid, a supply chain has to be made available while the gas network stays in some places and works in parallel. The Green Deal 2022 agrees that 45 % of the EU's energy supply should be produced from renewables by 2030. That goal is only reachable if renewable energy can be stored as well, preferably also in the form of hydrogen. Hydrogen is considered one of the promising alternative energy carriers due to its high energy density, zero carbon emissions during use, and its potential to be produced from renewable energy sources.
The development process of alternative energy applications, especially hydrogen technologies, has been further accelerated by supply uncertainties and rising prices of fossil fuels as a consequence of the Russian war in Ukraine. Even the domestic use of hydrogen comes into focus of several innovations (Stewart et al., 2009) since meeting the needs of the residential energy demand through alternative solutions is already not only a political requirement but an increasing social expectation as well.
In the following, the three most relevant options for hydrogen usage for domestic houses are presented:

1. Mixing hydrogen into natural gas and using the old network without any further investment or
2. Connecting to a new hydrogen infrastructure or bottled supply chain or
3. Generating the hydrogen locally on-site, storing it, and converting it back to electricity and heat (autonomous solution).

Referring to the first option, trials have already been made to mix hydrogen into natural gas (Erdener et al., 2023). The question lies in the reliability of the old natural gas infrastructure for hydrogen. Considering the different material qualities and physical properties of hydrogen, the infrastructure must meet a higher safety level. Instead, the construction of a new, hydrogen-specific infrastructure is recommended. This second option requires significant investment, considering the high costs of building a completely new hydrogen infrastructure or the implementation of bottled solutions. The environmental conditions also have to fulfill the requirements of

Paper Received: 9 July 2024; Revised: 23 October 2024; Accepted: 10 December 2024
Please cite this article as: Háber I.E., Cserta E., Meszaros V., 2024, Hydrogen System Design Methodology for Autonomous Houses in Central-East Europe, Chemical Engineering Transactions, 114, 901-906 DOI:10.3303/CET24114151

the safety regulations. This implies a limited execution at a few localities only. At the current maturity of the technology and lack of supply chain capacity, the manufacturing of a grid-independent, autonomous energy system for domestic use of hydrogen (Option 3 above) appears to be the most realistic solution in an effort to proceed towards a circular economy and carbon neutrality. Local generation and storage of hydrogen is already accessible with components that are available on the market, and even integrated solutions exist in limited size/quantities.

2. State-of-the-art

Since hydrogen became a central piece of the decarbonization puzzle, an increasing number of research articles deal with the exploitation of hydrogen energy storage systems in the building sector with the aim of achieving sustainability. The concept of hydrogen-based renewable energy systems (Gil Mena et al., 2024) is accepted as a promising solution to address the long-term energy requirements of buildings' microgrid systems (Sarwar et al., 2024). The key role of hydrogen in addressing the intermittency of renewable energy generation and enhancing the resilience and sustainability of Net Zero Energy Building (NZEB) systems (Sun, 2024).

To find the optimum design of the NZEBs (Abdolmaleki and Berard, 2023), the first step is to prepare the energy demand and energy efficiency analysis (Zhoua and Zhou, 2022) for the design phase (Vatandaş et al., 2024). All system optimizations are designed to meet energy demands without interruptions while minimizing costs (Gil Mena et al., 2024).

The novel aspect of the analyses was to utilize hydrogen as the energy storage technology in a power-to-hydrogen-to-power design (Bellos et al., 2023). Solar PV energy systems were the major power producers that met the load demand. An electrolyzer utilized the PV's excess power to produce hydrogen and store it in a hydrogen tank. Fuel cells (FCs) were implemented to meet the load demand during non-PV-generation hours. After feeding the electrolyzer, the excess energy from the PV could be exported to the grid. If there was no additional incentive for energy exported to the grid through a net metering policy, the system was rather designed to utilize the maximum energy produced by the solar PV system (Urs et al., 2023).

Although a major part of the model analysis research is interested in managing properly renewable electricity production and avoiding the use of grid electricity (Bellos et al., 2023), for systems connected to the grid, Gil Mena et al. (2024)'s findings indicate that selling surplus energy can be economically competitive and enhance the efficiency of grid-connected self-consumption systems in Spain (Gil Mena et al., 2024). For the simulations, the TRNSYS (Guo et al., 2022) used in different research works (Abdolmaleki and Berard, 2023) or the HOMMER (Urs et al., 2023) software were applied generally, but other (Aguacil et al., 2022) system-dedicated programs that fit the parameters of the analysis (number of sunny hours a day/month/year, energy demand, storage tank capacity, etc.) can be applied as well. The integration of different energy systems was investigated additionally (Olympios et al., 2024). These multiple energy interactions (e.g., renewable-to-vehicle, vehicle-to-building (V2B), grid-to-building (G2B), etc.) were deployed to enhance renewable penetration, self-consumption, and mitigate grid dependence (Zhoua and Zhou, 2022).

The literature analysis indicates that the hydrogen-based energy storage system effectively addresses the seasonal energy mismatch, improves the energy self-sufficiency rate of NZEBs (Wu and Zhong, 2023), and provides long-term and seasonal energy storage and can be beneficial to supply the load demand in solar radiation missing intervals of the year (Abdolmaleki and Berard, 2023). At the same time, the development of effective and efficient hydrogen storage technologies is a critical barrier to the widespread use of hydrogen as an energy carrier. Although there are already some good examples (The Green Village, 2023) demonstrating that hydrogen can be safely stored for domestic buildings as well, they are still not widely known, and their technical applications are unique.

In this paper, the design methodology of a hydrogen storage method and its suitability for a specific autonomous (i.e., grid-independent) building is discussed. The hydrogen-related storage facilities are scalable. Therefore, the hereby presented formula can be applicable in further cases as well, so for smaller family houses with an average of 5-6 kW of hydrogen production capacity (and its conversion back to electricity), private/domestic houses with larger energy need up to MW scale.

3. Hydrogen storage system at home

For local hydrogen generation and usage, a NZEB-type domestic house needs renewable excess energy to be converted and stored in the form of hydrogen. In the present work, solar energy is utilized as excess energy generated by a photovoltaic (PV) system. In relation to the EU, solar panels produce far more energy in the summer than in the winter due to the sun's trajectory and weather conditions. Because of their seasonally intermittent operation, the connection of hydrogen conversion and storage systems to the PV systems can be an ideal combination. In this complex energy supply method, the role of the solar PV system is to produce renewable energy that can be converted to hydrogen and, in this form, stored for later sunless weather periods. A PV system can be sized in such a way that it generates enough energy during the sunny season for the whole year, even without taking advantage of the losses of hydrogen conversion. There are three common types of PV systems used in domestic applications in Hungary:

- Net metering (annual saldo) is a type in which production is handled on a yearly basis, but contracts of this kind are constantly being phased out since it puts the responsibility to store the energy on the distribution system operator (DSO).
- Periodic billing can be made on monthly, weekly or even hourly based. In this case, the end-user sells the excess energy in the summer to DSO and buys it "back" in wintertime if the billing is monthly or weekly based. If hourly based, even in the evenings, buying electricity is needed. This system is characterized by the fact that the buying price is higher than the selling price.
- Based on the experiences, the hybrid PV inverter-based system can handle a battery pack that can be used in daily storage. (For seasonal storage, it would need too much raw material in the form of lithium, which cannot be provided in general.)

The seasonal storage of the produced excess solar energy can be solved by hydrogen (or pumped hydro, or some mechanical, etc.) storage systems. In this way, even the need for a service provider can be eliminated since not only can electricity be provided, but the heating demand can also meet it. For this reason, the PV system needs to be oversized to be able to handle technology losses.

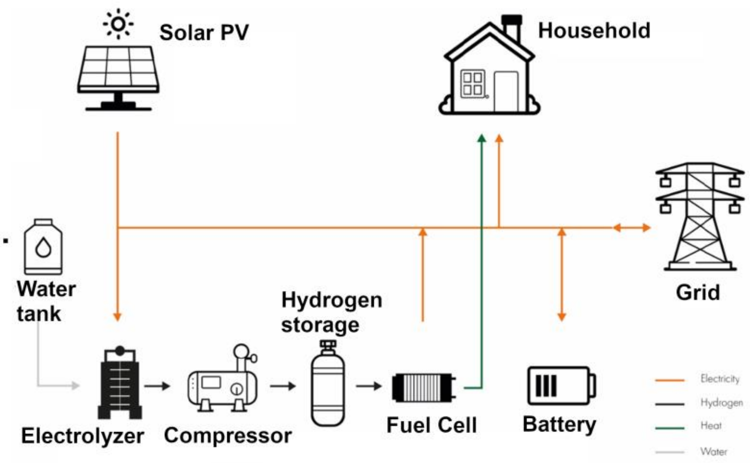

Figure 1: System components of a household's hydrogen-based storage system

In Figure 1, a proposed domestic hydrogen-based storage system is demonstrated that contains the following components:

- A solar PV system to produce everyday energy plus the excess energy, even enough to be stored for wintertime.
- An electrolyzer with a water supply to produce hydrogen.
- A compressor to pressurize the gas into containers.
- A fuel cell (FC) to convert hydrogen directly back to electricity and provide heat energy for the heat demand of the house.
- A battery to serve the peaks as the fuel cell needs time to scale up its production.

The realization of a house with a grid-independent, autonomous energy supply, as detailed above, is not yet a common case. Despite the fact that all the necessary instruments are available on the market, its complexity and safety challenges make it difficult to design and build the outlined energy system. In order to facilitate planning, it is first of all worth performing energy calculations for the correct sizing of the individual components.

4. Case study of the hydrogen-supported NZEB house

The Renergy HyFlats building complex is a completely autonomous family house running on hydrogen to be planned for Pecs/Hungary. The house was originally planned to meet the NZEB characteristics by using PV, heat pump, and even passive ventilation. After joining a funding process, the building's plan was converted to operate by hydrogen. This means that the PV system produces surplus energy in the summer, which will be stored in hydrogen for the wintertime.

4.1 Adjustment of the hydrogen-based energy system

The basic construction plan contained a Building-Integrated PV (BIPV) system that functions as a climate facade – ventilated automatically by opening vents in the summer and collecting sun rays on colder sunny days. Similarly, a venturi effect-based wind deflector and a passive ventilation system (a vertical channel) were designed in the middle of the building.

The H_2 is produced by electrolyzers on site and stored in mid-pressure containers, then converted back to electricity with FC stacks. The fuel cells' excess heat is also collected (combined heat and power FC). That makes it possible to operate the FCs with high efficiency and use them for air heating and hot water production.

- PV panel: First, the size of the heating and PV system is determined to match the size of the building. The optimal operation of a PV system is achievable if its capacity is adjusted to the total energy demand of the building. That means that the missing amount of solar energy (in wintertime) has to be completed with the energy production of the stored hydrogen that was previously produced in the solar energy-rich seasons. At that point, the efficiency of the hydrogen production and the fuel cell applications are considered (these are around 80-85 %). Their working schedule is optimized to increase the efficiency of the planned PV system. This is an iterative task, and it finally defines the number of kilograms of hydrogen that have to be stored on a yearly basis. Based on this amount of hydrogen, a suitable storage method can be chosen. BIPV facade, the roof-mounted, and the ground-mounted PV system have a peak performance of 90 kW.
- Water tank: To produce hydrogen gas, cleaned tap water is needed (= 9 times the weight of the hydrogen; that is around 1 m^3/y for a family house) that can be provided by reversed osmosis membrane filters.
- Electrolyser: In the second step, an electrolyzer splits the water up, and the hydrogen is compressed into the tank. The electrolyzer system has to be adjusted to the technical parameters and energy demand of the planned building, as well. The size of the electrolyzer is calibrated to the highest amount of PV production excess per hour in the solar energy-rich seasons.
- Fuel cell: In the same way, the size of the fuel cell system is determined by the difference between the lowest PV production in wintertime and the highest estimated energy demand in electricity as in heating.

5. Method for the estimation of the domestic hydrogen-based energy supply

In this chapter, the estimation of the size of the hydrogen system’s setup is presented. It can be an enormous time-saving in the design process since only the dynamic simulation part of such a design requires an average of one month of preparation time. In this approach, the data of those publications are considered (Carnieletto et al. 2019) that discuss how the monthly distribution of heating and cooling demand (Kurevija et al. 2016) differs from climate to climate (Ashere Handbook, 2015). According to the Köppen-Geiger Climate Classification, the larger part of Central-East Europe is categorized as a humid continental climate with warm summer (DfB zone). The economic estimation of such an investment can also be executed based on this procedure. The performance of this kind of energy demand calculation is especially recommended for nonprofessional stakeholders because the costs of the investment can be precisely predicted by adjusting the approximate energy supply system size and defining the referring energy production.

5.1 The principle of estimating the PV panel size

By means of a simplified model, the entire energy process for the hydrogen-based energy storage system can be specified. Based on the obtained results, the dimensions of the system’s units can also be prepared. To define the parameters of the PV panel, it is necessary to know the house's annual summarized energy needs, including the losses that come from the properties, as well as the energy consumption of the house and the characteristics of its users. This is the amount of energy that the PV panel must produce as a minimum if you want to create a house with a truly autonomous energy supply. However, since this energy consumption is only an approximate value, the PV panel must be oversized.

The total house annual energy demand (E_{SUM}) is evaluated according to Eq.1. The heating energy is the one that is most important to cover with the storage system. In addition, the yearly domestic electricity need (E_{DOM}), the number of electric cars (N_{ECAR}) and the yearly cooling demand ($E_{COOLING}$) have to be considered as well.

$$E_{SUM} = E_{PED} \cdot A_{HOUSE} + E_{DOM} + N_{ECAR} \cdot C_{CAR} \cdot N_{CH-MONTH} \cdot 12 + E_{COOLING} \quad (1)$$

By definition, the domestic primary energy demand (E_{PED}) is the energy that has not undergone any conversion or transformation before using it in the buildings (The Green Village, 2023). Practically, the E_{PED} is determined using the basic building mass. The most relevant energy consumption is the yearly heating demand (E_{HY}), which is to be covered with the stored hydrogen. The physical properties of the building define the values of E_{DOM}, as well. E_{DOM} can be determined based on Eurostat (European Commission, 2012), which highlights the average electricity consumption per capita per year in divisions of the European countries. In order to monitor and predict more accurately the extent of the harmful impact on the environment (ecological footprint) and reduce it, there is a technical expectation to determine the monthly (E_M) or even daily (E_D)/weekly (E_W)/hourly (E_H) energy demand. The orientation and size of the PV panels are taken into consideration when figuring out the yearly and monthly/weekly/hourly energy production.

$$E_{SUM} > E_{PED} \quad (2)$$

Consequently, the yearly PV energy production (E_{PVY}) has to be higher than E_{SUM} (Eq.2), which was defined in Eq.1. If calculated as a monthly average, there is a deficit in the PV energy production in the winter months. Generally, PV energy covers the energy demand in the spring and autumn, while there will be significant PV excess energy production in the summer. On a daily basis, a supplement load is necessary from the hydrogen storage in winter and sometimes in the evening and nighttime. The PV system size is to cover the yearly consumption on an annual balance where the summertime surplus is converted into hydrogen for seasonal storage. The conversion and storage losses are considered by defining the dimensions of the PV system size.

6. Results and discussion

In the present model, the parameters of a household are as follows:

- A_{HOUSE} = 100 m^2,
- E_{PEDY} = 30.000 kWh,
- 4 monthly charging of two electric cars of 60 kWh battery

where A is the net surface of the household. The referring calculation matrix is shown in Table 1. The size of the PV energy system has a minimal E_{PVY} value of 83 kWp. Based on the PV size, the component capacities of the electrolyzer and the fuel cell have to be given.

Table 1: Average energy values for the sizing of the PV system and the H_2-storage system

Energy components (kWh)	Jan-Feb	Mar-Apr	May-Aug	Sept	Oct	Nov-Dec	Yearly
Yearly energy consumption sum	1,795	1,397.5	1,407.5	1,285	1,420	1,690	18,100
Initial PV system production	1,036.53	2,122.83	2,573.1	2,059.2	1,728	949.5	22,297.32
System balance without H_2 system	-1,516.94	725.33	1,165.6	774.2	308	740.5	4197.32
Maximal H_2 generation	-	544	872.2	580.65	231	-	5,396.445
Extra energy need through conversion loss	1,084	-	-	-	-	1057.857	4,282.771

Electrolyzer: There are different approaches for the electrolyzer sizing. Losses can be avoided if the sizing is based on bigger surplus energy production than $E_{STORAGE}$, but the high range scalability is a "must" in this case. The other possibility is to grant a range of losses with smaller sizes and more favorable costs.

Fuel cell: The fuel cell is shaped to the required size, summarizing the power need and the heat demand of the household. The biggest consumers in the household are the car chargers with 7.5 kW (see IEC 61851-1 standard), the cooking equipment, etc. Finally, at around 10 to 15 kW peak power, CHP FC is generally eligible to serve the consumers for an average 100 m^2 one-family house. The components of the detailed calculation and the corresponding (partial) results are published in Table 1. The results highlight that for every 100 m^2 netto-house space with 30 kWh/m^2, a specific heat loss is supposed to store around 60 kg (~1,900 kWh) of hydrogen gas. Since 1 kg of hydrogen requires 11,1 m^3 of storage space. Therefore, it is necessary to compress the produced hydrogen for small-scale stationary applications to save space.

7. Conclusion

The suitability of different hydrogen storage options for stationary applications depends on various factors, such as safety, cost, and efficiency. Building design for autonomous houses with hydrogen-based storage requires several steps, including defining the concept and dimension of the final system. In this paper, a design methodology is proposed for the implementation of hydrogen storage in NZEB, and the suitability of this technology for autonomous (i.e. grid, independent) buildings is discussed. Since the hydrogen-related store equipment is scalable, the hereby presented approach can be applicable so for smaller family houses with an average of 5-6 kW of hydrogen production capacity (and its back conversion to electricity), as for private/domestic houses with larger energy need up to MW scale.

Nomenclature

E_{PED} – primary energy demand, kWh/m^2.a
A_{HOUSE} – net surface area of the house, m^2
E_{DOM} – yearly domestic electricity demand, kWh/m^2.a
N_{ECAR} – number of the charging cars (e-cars)
$N_{CH\text{-}MONTH}$ – expected number of charging cycles per month
C_{CAR} – battery capacity of one electric car, kWh
N_{MONTH} – 12 is the number of months
$E_{COOLING}$ – yearly cooling demand, kWh/m^2.a

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