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Hydrogen-based electricity storage optimization on buildings by coupling thermal and photovoltaic electricity production towards carbon neutrality

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Abstract. Self-sufficiency (SS) of buildings with low greenhouse gas (GHG) emissions can be obtained using photovoltaics (PV). To maximize self-consumption - minimizing the import of grid electricity - PV can be coupled with a hydrogen storage system converting the electricity to hydrogen by electrolysis during the summer season, when the on-site production is higher, and using it during the winter season with fuel cells. This article deals with the sizing constraints of solar hydrogen systems at building-scale. The future building for the Smart Living Lab (SLL) in Fribourg (Switzerland) has been taken as case study. It has four stories and a mixed usage (Office-building and Research facilities), with a multi-oriented PV installation in order to produce enough electricity to achieve at least 50% of self-sufficiency. Using the PV production, this study aims to optimise the sizing of a hydrogen storage system allowing to reach the required self-sufficiency ratio. Finally, a comparison of the global efficiency of the system for three different demand-side scenarios.

Keywords. building energy analysis, solar hydrogen storage, cell fuel, battery storage system

1. Introduction

Photovoltaics is one of the easiest and cheapest ways to produce renewable electricity from solar energy. Over the last 20 years, the number of PV installations has increased exponentially [1], and the trend is expected to continue over the coming years, if carbon neutrality is to be reached by 2050 [2]. Despite the growing popularity of solar panels, the main problem with PV installations remains unchanged: solar energy is only available during a short period of time throughout the day. The main challenge of an increasing number of solar installations will therefore be to store the overproduction when the sun is shining so that it can be reused when needed. Such systems already exist, they are mainly composed of Li-ion battery packs, but they present high embodied impact [3] and short lifetime [4]. Depending on the building demand, a reasonably small battery pack can store enough energy for a daily demand in summer. However, during the winter time, energy production is not high enough to compensate for the demand [5,6]. This article focuses on the sizing and efficiency evaluation of a seasonal hydrogen (H_2)

system as an electricity storage for the overproduction of the PV installation. The H_2 system is coupled with the thermal demand of the building in order to take advantage of the wasted thermal energy produced by the hydrogen-electricity conversion process [7]. The proposed system converts electricity to H_2 by electrolysis mainly during the summer season and then the accumulated H_2 can be used during winter in the building. To analyse the global efficiency of the H_2 storage system, a combining workflow using Polysun software [8] and an in-house coding in the MS Excel environment was designed to simulate the way the energy is stored. The main input data used to launch the analysis are:

- Hourly time-step electricity PV production and consumption [kWh]
- Capacity of the hydrogen storage [kWh PCI] *PCI: Gross Calorific Power*
- Fuel-cell and electrolyser technical specification (power and efficiency)
- Size of the Li-ion battery [kWh]

Using this information, the SS ratio of the building is calculated. From a preliminary study conducted, we observed that to reach 100% of SS, the amount of H_2 that needs to be stored is enormous and the global efficiency of the H_2 storage system reaches only about 30%. This is why this article focuses on the way to recover this residual heat and use it in the building. Therefore, by combining electricity and thermal demand, the global efficiency of the H_2 system should be improved. In order to address this issue, this article uses a real case study currently under development, the new mixed building (offices and laboratories) for the Smart Living Lab [9] to be built in Fribourg, Switzerland. The building will have a PV installation with a classic Li-ion battery storage system, but as the purpose of this building is to be a research infrastructure for experiments in real conditions, the building will provide the necessary space for testing new energy storage systems. In this context, the present article studies the possibility of integrating an additional electricity storage system based on H_2 that can be consumed in the form of electricity through a fuel cell.

2. Methodology

The methodology has three main phases: 1) The energy modelling and analysis of the building in order to estimate hourly electricity and thermal demand. Energy simulations were conducted using the DesignBuilder software [10] with EnergyPlus simulation engine [11]. The PV production has been calculated with the help of the Polysun software [8]. 2) The addition of the hydrogen-based storage system to the building. The sizing method takes into account: the electrolyser, the H_2 storage, Li-ion batteries, and the fuel cell. The proposed concept considers that the daily self-consumption is provided using a small standard Li-ion battery pack, and the seasonal self-consumption is obtained by the solar H_2 storage system. To increase the efficiency of the system, the potential thermal couplings have been considered with heat-recovery systems. 3) The sizing optimization process. Simulations have been carried out to maximise the SS.

2.1. Phase 1 - Energy modelling and analysis of the building

The building project for the SLL in Fribourg will have about 5,000 m² of floor area, spread over four floors and a basement. It is a mixed-use building, with office and laboratory-type research areas with an Energy Reference Area (ERA) of 3,859 m². The entire building will be used as a research infrastructure to carry out projects under real conditions. In terms of technical systems, the building is equipped with a double-flow mechanical ventilation system with heat recovery, the air handling unit (AHU) is connected to the district heating/cooling of the neighbourhood by means of two coils. In the interior spaces a series of radiant panels on the ceiling and a series of clay composite panels contribute to the thermal inertia of the building. The latter counterbalances the low inertia of the building's construction, except for the stairwells and the basement, which are made of reinforced concrete in a light wooden structure. Due to the very limited consumption of domestic hot water (DHW), and in order to have the maximum possible flexibility, the DHW is generated using decentralised electric heaters installed at the consumption end points. This flexibility will facilitate the evolution of the building and its installations and will allow the implementation of the researchers' experiments. During the design phase of the project, an advanced study was conducted in order to use the best-oriented and productive PV surfaces

on the building envelope. The project will have a multi-oriented installation of 135 kWp (976 kWh/kWp). Figure 1 shows the building energy model built with DesignBuilder [10].

By integrating the experimental component of the building, various energy demand-side scenarios will be calculated: **Scenario 1**: Sizing of the system taking into account only the DHW demand and coupling it with the hydrogen system. The heating demand comes from the district heating. **Scenario 2**: Additional thermal demands have been added to the basic project, consisting of heating and DHW due to the construction of an experimental apartment on the 4th floor, as well as the thermal demand for tempering the entire basement, as it will be used quite frequently by the researchers. Sizing of the system to meet only the additional thermal needs. **Scenario 3**: Assuming the hypothesis that the building could not be connected to the district heating and needs to produce its own heating/cooling energy by a hypothetical local geothermal heat-pump. Thus, in this case, the H_2 system can contribute to the overall thermal demand (heating and DHW) of the building through the waste energy due to the production of H_2 and its use by the fuel cell. Figure 2 and 3 show the monthly thermal demand, the electricity needs and the on-site electricity production of the building used in Scenario 1. Figure 4 shows the additional thermal demand to be used in scenario 2.
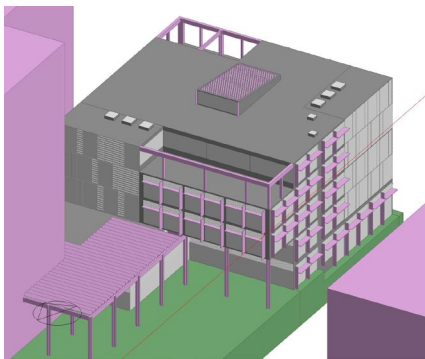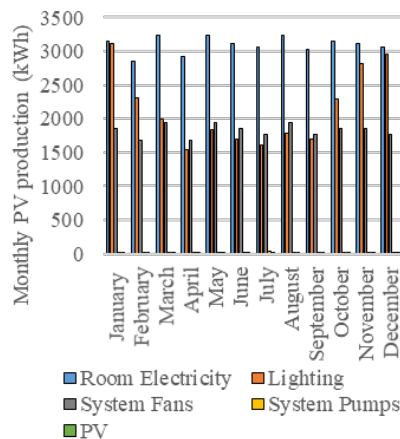

Figure 1. Building energy model.

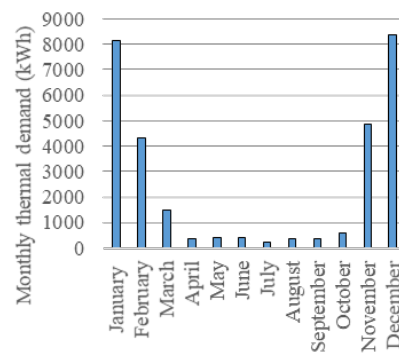**Figure 2.** Heating demand.
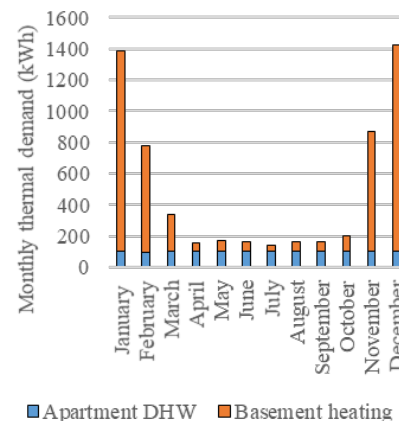

Figure 3. Monthly electricity demand.

Figure 4. Additional thermal demand.

2.2. Phase 2 - Implementation of a hydrogen-based storage system

The implementation of this system consists of an electrolyser, a fuel cell and hydrogen tanks. The DHW and heating demands depend on the chosen scenario presented above. The electrolyser, battery pack and PV installation are also implemented in the Polysun software (Figure 5). The totality of the thermal demand (DHW and heating) is produced by the fuel cell. The fuel cell uses H_2 to produce heat and electricity. The electricity is either used for building, stored in the battery or injected into the grid. The heat generated is stored in a water tank. The hot water is then used in the ceiling heating panels or to produce DHW. Unfortunately, Polysun does not include H_2 tanks nor electrolysers, and is also limited in the way the fuel cell is used, which means that it is only possible to use it (and manage it) on the basis

of a heating demand. This implies that the electricity is the result of a thermally demand-controlled process, without the generation of electricity by the fuel cell being controlled/regulated according to the electricity demand of the building.
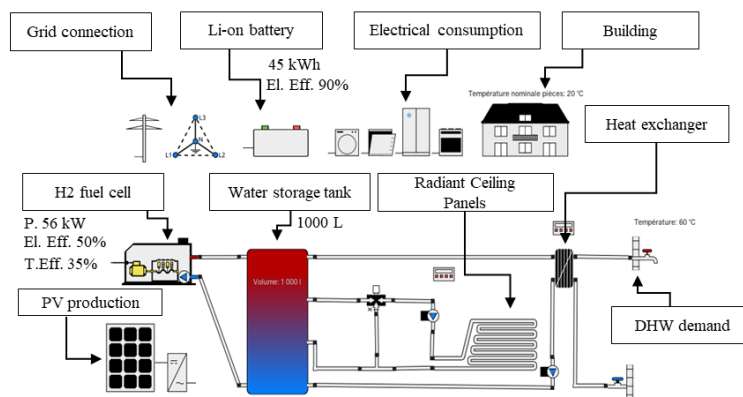

Figure 5. Polysun implementation schema including the main features assumed for the different components.

2.3. Phase 3 - Sizing and optimisation process

The three scenarios mentioned in the methodology have been calculated following the same workflow (Figure 5). For each scenario, the input data has been modified at the level of the thermal demand of the building, and thus the "recoverable" energy capacity of the hydrogen system. However, as explained above, by using only Polysun it is not possible to simulate a full H_2 storage system. Therefore, a workflow (Figure 6) has been developed to come up with a solution that allows to compute a hydrogen storage system.
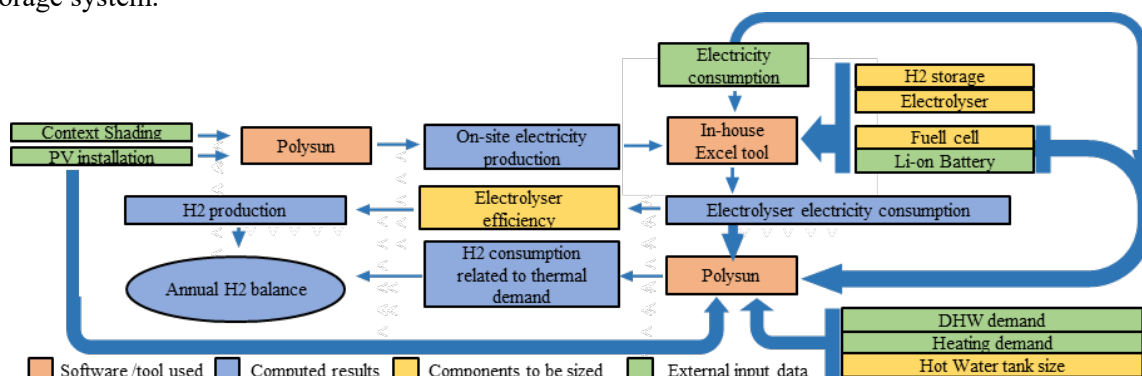

Figure 6. Workflow with the different software / tools used.

The computation process takes place in the following four phases: 1) Hourly on-site electricity production is calculated using Polysun and based on the PV installation and shading curve of the surroundings. 2) This electricity production is then imported to the Excel written program (see section 1) along with the electrical demand of the building, the H_2 storage sizing and electrolyser, fuel cell and battery pack characteristics. The program then simulates a H_2 production, storage and usage cycle over a year. From this simulation, the electrolyser electrical consumption is exported along with the amount of H_2 produced throughout the year (H_2 production). 3) All the data is transferred back to Polysun to simulate, by using the electrolyser as a consumption component (as a standard electrical consumption profile), the annual consumption profile of the fuel cell (H_2 consumption related to thermal demand). 4) Using the H_2 production obtained with the Excel tool and the H_2 consumption obtained with Polysun, it is possible to compute an annual balance of the level of hydrogen in the tanks during the year. This method is used to size the installation for the three different scenarios in an iterative way.

3. Results

This section presents the sizing (H_2 storage tanks) and analysis of the three demand-side scenarios. For the sizing, it is important to make sure that the level of H_2 in the tanks at the beginning of the year equals the level at the end of that same year. This means that the amount of H_2 produced by the electrolyser compensates for the amount consumed by the fuel cell and that the H_2 tanks are correctly sized. H_2 is stored in individual 50 L cylinders at 300 bars. Table 1 presents the DHW and heating demands taken into account for the three demand-side scenarios, as a basis for the H_2 storage sizing. The electrolyser and the fuel cell efficiencies and max electrical power are what can be found on the market [7]. The water tank is big enough so it can admit extra energy from the fuel cell.

Table 1. The three demand-side scenarios.

Scenario	DHW demand		Heating demand	
1	Standard demand	1.8 MWh/yr	-	-
2	Additional demand, experimental apartment, 4th floor	1.2 MWh/yr	Additional demand, technical areas in basement	4.7 MWh/yr
3	Standard demand	1.8 MWh/yr	Standard demand	29.9 MWh/yr

Scenario 1: This scenario only covers the DHW demand of the SLL. This demand is only about 1800 kWh/yr which means it could easily be covered with the thermal energy released by the fuel cell. Using the same workflow (Figure 6) and the hypothesis made earlier (Figure 5), the H_2 tanks need a capacity of 2000 kWh which represents a volume of 2.8 m^3 or 57 individual gas cylinders. The graphic in Figure 7 shows the amount of H_2 stored throughout the year. The H_2 level is at its lowest during the winter when the PV production is not sufficient to produce hydrogen. During the summer, however, the tanks are full and the energy used by the fuel cell is quickly compensated by the electrolyser which fills up the tanks using solar power.
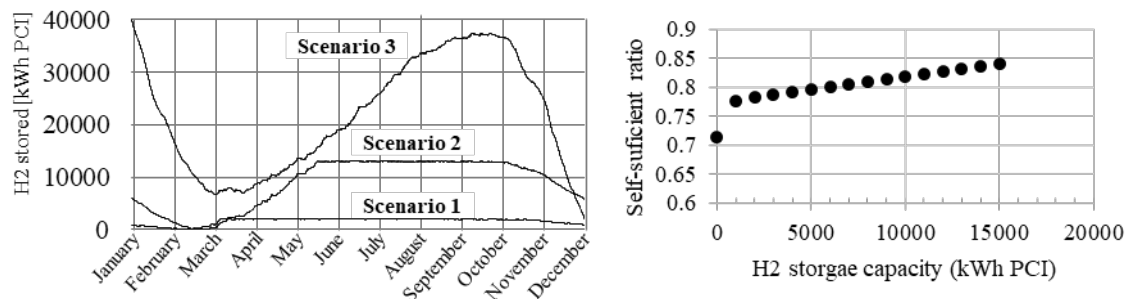

Figure 7. H_2 storage level throughout the year and SS ratio depending on the H_2 storage capacity. *PCI: Gross Calorific Power.*

Scenario 2: The total demand for this scenario (apartment on 4th floor and basement) is 1,250 kWh for the DHW and 4,716 kWh for the heating. The curve for scenario 2 (Figure 7) looks very much like the one from scenario 1 except the storage size is about 6.5 times bigger. This means a storage capacity of 18.57 m^3 (300 bars). If this amount of H_2 was stored in individual 50 L cylinders, a surface of 22 m^2 would be needed.

Scenario 3: In this last scenario, a simulation is made for the entire heating and DHW demand of the building (additional demands from scenario 2 excluded). The curve for scenario 3 (Figure 7) shows the same trend as the first two scenarios but in this case, the demand is much higher than the production. This means that the maximum amount of H_2 produced with the solar panels is not enough to cover the heating demand. In this case after a year, the level of H_2 in the tanks would be 38,000 kWh PCI lower than it originally was. Such storage would also require about 57 m^3 of H_2, which stored in individual tanks would require 70 m^2 of space. For these two reasons this scenario is not retained.

Electrical efficiency for scenarios 1 and 2: Using the custom MS Excel tool, it was possible to compute the SS ratio of the building. Without any H_2 system, the current SS is 71.4%. In scenarios 1 and 2, the SS is improved to 78.3% and 83.1% respectively. The right chart in Figure 7 shows the correlation between the amount of H_2 stored and the SS ratio. This graphic shows a large increase in the SS ratio; with the implementation of a small hydrogen storage system, the SS evolves in a linear manner. No simulation was made for more than 15,000 kWh, as this amount of H_2 would take too much space in the building and wouldn't be cost-effective. In view of these results, scenario 2 appears to be the most profitable configuration regarding the SS ratio and the thermal recovery.

4. Conclusion

By using the thermal energy released by the fuel cell, the overall efficiency of the system (electricity to hydrogen to electricity and heat) is improved from 29% (without heat recovery) to 43%. This clearly shows the true potential of cogeneration units. By using different programs (in-house Excel tool and Polysun software) it was possible to simulate the full-cycle of a H_2 production, storage and cogeneration system. However, this method has shown some limitations. First, the operating management of the fuel cell used the thermal demand instead of the electricity demand. As it was not possible to include electrolysers on the main schema (Figure 5), it was not possible to include heat recovery from this process, otherwise it could be an efficient way to produce DHW during the summer season. By addressing these issues, these optimizations could help improve the overall efficiency even more.

To pursue this project, the next step will be to code the entire schema in Excel to simulate the complete H_2 process, allowing to have full control over the regulation of the system. Optimization will then be based on when to use the fuel cell depending the thermal or electricity demand. This will allow to size all the elements (max power, size, number of units). A sizing method based on costs and GHG emissions will be included to find the most suitable system, in turn leading to finding the most relevant elements (fuel cell, electrolyser, H_2 storage) available on the market.

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