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BUILDING-INTEGRATED PHOTOVOLTAICS (BIPV) COMBINED WITH HYDROGEN-BASED ELECTRICITY STORAGE SYSTEM AT BUILDING-SCALE TOWARDS CARBON NEUTRALITY

Sergi Aguacil[a,*], Yvan Morier[b], Philippe Couty[b,c],
Jean-Philippe Bacher[b]

[a] *Ecole Polytechnique Fédérale de Lausanne (EPFL), Building2050 group, Fribourg, Switzerland*
[b] *University of Applied Science of Western Switzerland (HEIA-FR, HES-SO), Energy Institute, Fribourg, Switzerland*
[c] *TECPHY Sàrl, Renens (VD), Switzerland*
[*] corresponding author: sergi.aguacil@epfl.ch

Abstract. Electricity storage technologies in buildings are evolving, mainly to reduce their environmental impact and to improve self-sufficiency of buildings that produce their own energy through Building-Integrated Photovoltaics (BIPV) installations. To maximize self-consumption – minimizing the import of grid electricity – photovoltaic (PV) systems 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 employing it during the winter season with fuel cells. This study focuses on the sizing constraints of solar hydrogen systems at building-scale using an innovative research-centre that will be built in Fribourg (Switzerland). It presents four stories and a mix-usage (office spaces and research facilities areas) and multi-oriented PV installation in order to produce enough electricity to achieve at least 50 % of electricity self-sufficiency ratio. Using the PV production, this study aims to optimise the sizing of a hydrogen storage system allowing to reach the required self-sufficiency ratio with the lowest environmental impact possible. Ultimately, the global energy and financial efficiency of the system will be analysed.

Keywords: Building-integrated photovoltaics, building energy analysis, solar hydrogen storage, fuel cell, battery storage system.

1. Introduction

Photovoltaic offers an easy and affordable manner to produce sustainable electricity using solar power. Over the last decade, the number of solar panels installation in Switzerland has been multiplied by five [1] and the overall electricity efficiency of these panels has kept increasing. Solar energy will play a big role in the path to reach carbon neutrality by 2050. However, one issue remains unchanged, solar energy is only available during a short period of time during the day and in most countries, the production varies greatly throughout the year. This means that great self-sufficiency (SS) ratios (Equation (1)) can be achieved during the day and summer but energy needs to be stored in order to be reused during the night or winter when the production isn't sufficient.

$$SS_{ratio} = \frac{PV\ production\ used\ onsite}{Total\ electrical\ consumption} \tag{1}$$

Daily storage is usually achieved by using battery packs, however, they have a large carbon footprint [2]. Nowadays, In most PV installations, very little storage is integrated allowing the building to be self-sufficient for 4 to 6 hours [3, 4]. This paper focuses on the use of seasonal hydrogen (H_2) storage at building-scale. In the summer, excess of production can be used to produce H_2 by electrolysis of water and can then be stored in individual tanks. In the winter, when the electrical demand is higher than the on-site production, the H_2 can be used in a fuel cell to produce electricity. This process also releases heat which can be recovered for heating or domestic hot water (DHW) converting the fuel cell in a co-generation unit. To simulate the H_2 cycle over the year, a MS Excel tool has been developed in order to simulate the way the energy is stored and reused. The program allows for two types of storage, a Li-ion battery pack and a hydrogen storage system. In order to run a simulation, the program requires the following main input data:

- Hourly time-step electricity PV production and electrical and thermal demand [kWh].
- H_2 storage specification (power and efficiency of the fuel cell and electrolyser, storage capacity).
- Battery pack specification (Capacity and efficiency).
- Thermal storage specification (Hot water tank volume, tank's insulation, storage temperature).
- Additional data on components (life cycle, cost, greenhouse gases (GHG) emission).

Using this information, the program simulates the energy storage during a year and can display output values such as SS ratio, amount of electrical energy imported and exported from or to the grid, amount of thermal energy stored, the overall efficiency of the H_2 cycle or the amount of GHG emitted. In a first scenario, the sizing of a H_2 storage system allowing to reach 100 % SS was computed. This showed that to achieve such a goal, the amount of H_2 stored had to be enormous, around 75 days of autonomy and 1.4 tons of H_2. In this paper, the goal is to reach an SS ratio of 80 %. Moreover, without using heat recovery on the fuel cell, the overall efficiency of the H_2 storage system only reached about 30 %. In a further study [5], the focus was placed on heat recovery on the fuel cell. This time, parts of the simulation were made using Polysun software [6]. Heat recovery allowed the system to reach 43 % overall efficiency; however, limitations were quickly encountered. Using the Polysun software, we had very little control of the fuel cell as the program would only consider the thermal demand to switch it on. This is why this article focuses on the writing of an In-house Excel tool that allows the user to control every energy flux (electrical and thermal). The global efficiency of the system can be optimized by controlling the electrolyser and the fuel cell in the most efficient way using different control modes that are presented in this paper. An effective sizing of the H_2 storage system is then possible and outputs values are available to analyse the project. In order to run the simulation, this paper uses the Smart Living Lab (SLL) [7] as a real case study. The building will already be equipped with energy storage in the form of Li-ion batteries but will provide enough space for further research, in our case, a H_2 storage system with a co-generation fuel cell allowing to produce heat and electricity for the building.

2. Methodology

The methodology encompasses three phases:

(1.) Hourly energy demand and production are estimated using the energy modelling and analysis of the building. The thermal and electrical demands are computed using DesignBuilder [8] with EnergyPlus simulation engine [9]. The PV production is calculated using the Polysun software [6]. These data will be used in the further phases in the form of hourly time-step value.

(2.) The implementation of a hydrogen-based storage system. In order to simulate the addition of a H_2 storage system a dedicated program was written using a combination of MS Excel and VBA coding. This program includes a Li-ion battery pack mainly for daily energy demand and a H_2 system for seasonal storage. Heat recovery on the fuel cell, hot water storage, and heat distribution are also included in the computation.

(3.) The sizing and optimization process. The sizing process is made with the help of Design Explorer [10]. The optimization process then consists of tweaking the program in order to obtain different improved results such as greatest SS ratio, lowest GHG emission or highest overall efficiency for the H_2 system.

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

The future SLL building in Fribourg will be constituted of 4 four floors and a basement for a total surface of about 5 000 m^2 of floor area. It will serve as a hybrid-use building, with offices and laboratory-type research area covering an Energy Reference Area of 3 859 m^2. The complete structure will be utilized as a research platform for conducting studies in real-world settings. The building is fitted with a double-flow mechanical ventilation system with heat recovery, and heat is provided via the air handling unit (AHU) connected to the neighbourhood's district heating/cooling system using two heat exchangers. A number of radiant panels on the ceiling and a series of clay composite panels in the interior areas add to the building's thermal inertia. The latter counterbalances the building's low inertia as, except for the stairwells and basement, which are built of reinforced concrete the rest of the building is made in a light timber frame. Domestic hot water (DHW) is created utilizing decentralized electric heaters installed at the consumption end points due to the low consumption of DHW and the need for maximum flexibility.

This adaptability will help the structure and its installations evolve, as well as enabling the researchers' tests to be carried out. An extensive research was done during the project's design phase in order to employ the best-oriented and productive PV surfaces on the building exterior. The SLL building will have a multi-oriented installation of 135 kWp (976 kWh/kWp). Figure 1 shows the solar energy model built with Rhino [11] and DIVA for Grasshopper [12].

2.2. Phase 2 – Design of a hydrogen-based storage system

The H_2 storage system is composed of an electrolyser, storage tanks and a fuel cell. On the electrical side, the H_2 storage system works just like a battery pack, it allows to store electrical energy from the PV panels in the form of hydrogen and reuse when needed. On the thermal side, heat can be recovered from the fuel cell and stored in a hot water tank before being redistributed to the heating system. In parallel to the fuel cell, a small heat pump can cover the additional thermal needs when no hydrogen is available. On the far left of Figure 2, an air-water heat exchanger is needed in the case where the fuel cell is working but no thermal demand is present. As it is presented in Figure 2, in our case study, the main heating of the building is provided by the district heating, heat recovery from the fuel cell will be used for additional demand that consists of the heating of the basement.

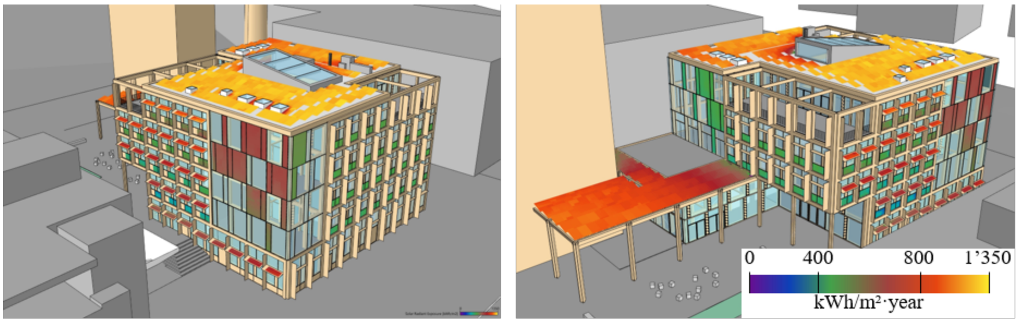

Figure 1. Cumulative annual irradiation of BIPV installation.

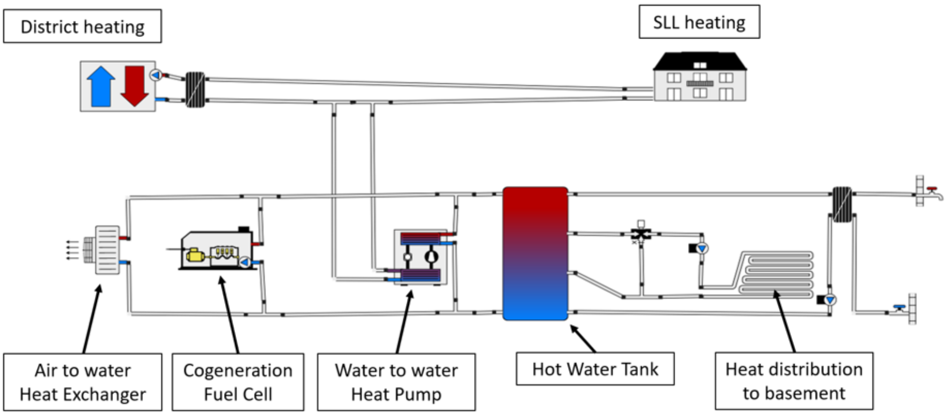

Figure 2. Schematic design of the fuel cell in the heating system.

The choice here was made to recover heat only on the fuel cell (not on the electrolyser) as it's mainly used in the wintertime when the thermal demand is much higher. The simulation program integrates the following algorithm of energy management: each hour of the year is treated individually, when the PV production is higher than the demand, energy can be stored in the battery, used to create hydrogen or injected into the grid. When the demand is more important than the production electricity can be withdrawn from the battery or from the H_2 storage system otherwise it can be imported from the grid. The program lets the user choose all the specifications regarding the H_2 storage system, the battery pack and heat recovery on the fuel cell. The program then runs a simulation over a one-year period and presents the following output values that can be used to analyse the results.

2.3. Phase 3 – Sizing and optimisation process

In this phase, the sizing of the hydrogen storage system is made for the SLL. To run the simulations, the PV production, electrical consumption and thermal demand for the heating of the basement are added. Two parameters can be tweaked in order to modify the simulations. Firstly, the components that will be implemented in the building. For example, the volume of the H_2 tanks, the capacity of the battery pack, the volume of the hot water tank or the electrical/thermal efficiency of the fuel cell. Secondly, the way in which the system is controlled (control mode). That is, in our case, the way in which the fuel cell and electrolyser are activated. To size the system, the base mode has been used, meaning that the electrolyser will be turned on when the production is higher than the demand and the battery pack is fully charged. The fuel cell is turned on when the consumption is higher than the demand and the battery pack is empty. In a second step, using the same system other modes will be tested.

Four modes were developed specifically to achieve different goals:

- Maximum self-sufficiency ratio.
- Lowest injection/withdrawal peaks into and from the grid.
- Lowest GHG emissions.
- Maximum overall efficiency of the H_2 storage system.

In order to run multiple simulations, a VBA code has been added to the program. It offers the opportunity to automatically test multiple scenarios by varying the input values and writing the output values in a `.csv` file. The data will then be analysed with the help of Design Explorer [10]. It is then possible to choose the best inputs to obtain the targeted results. In our case study, four inputs were chosen to be sized. The four components and the values chosen are as

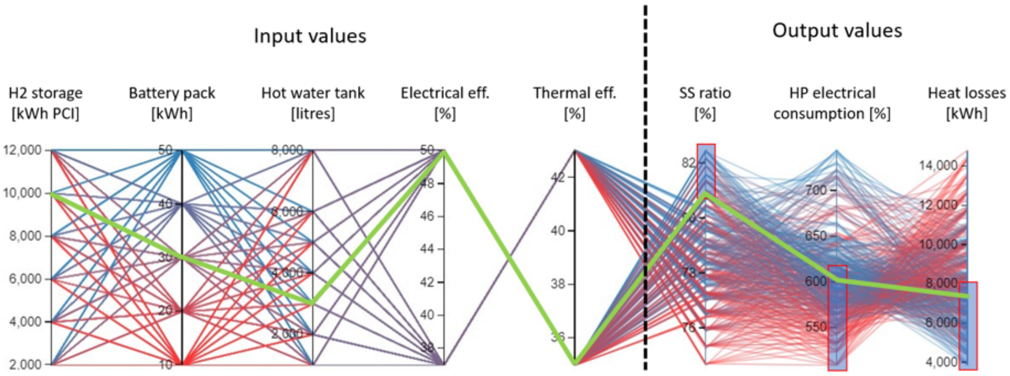

Figure 3. Sized system from Design Explorer.

follow:

- Capacity of the H_2 storage system (2 000, 4 000, 6 000, 8 000, 10 000, 12 000 [kWh PCI]).
- Capacity of the battery pack (10, 20, 30, 40, 50 [kWh]).
- Volume of the hot water tank (1 000, 2 000, 3 000, 4 000, 5 000, 6 000, 8 000 [litres]).
- Efficiencies of the fuel cell:
  (1.) electrical 50 %, thermal 35 %;
  (2.) electrical 37 % thermal 43 %.

By combining these inputs together, 420 scenarios are computed. To compare all the scenarios, we will look at three output values: the SS ratio, the amount of energy consumed by the additional heat pump and the overall thermal losses of the system. Figure 3 shows the 420 solutions presented in Design Explorer. On the horizontal axis are the 5 input values and 3 outputs. On the vertical axis are the chosen values for the input and the obtained values for the outputs. The blue areas show all the solutions that allow to maximize the SS ratio and lower the heat losses and amount of energy used by the additional heat pump. Finally, the green line shows the chosen solution that takes into account the limitations on the outputs and selects the smallest H_2 storage, battery pack and hot water tank possible.

3. Results

In this section the main results are presented.

3.1. Optimized sizing of the hydrogen storage system

The sizing of the hydrogen storage system was made according to Phase 3 of the methodology. Using this process, the following values were found:

- Hydrogen storage system: 10 000 kWh PCI (Gross Calorific Power).
- Li-ion Battery: 30 kWh.
- Hot water tank: 3 000 litres.
- Fuel cell: 50 % electrical efficiency and 35 % thermal efficiency.

A 10 000 kWh PCI storage capacity corresponds to 14.3 cubic meters of hydrogen stored at 300 bars or about 300 kg. The Li-ion battery was sized to be as small as possible, prioritizing H_2 storage. It's worth mentioning that if the building had to reach the same SS ratio without H_2 storage, the Li-ion battery would need to be 17 times larger. The hot water tank also serves as an energy storage device. The bigger the tank, the more energy from the fuel cell it can store but as the tank gets bigger, the heat losses increase too. In our case, 3 000 litres appeared to be the ideal size. In this paper, two different fuel cells were considered, one with higher electrical efficiency and the other one with higher thermal efficiency. As it can be seen in Figure 3 the only suitable fuel cell to achieve the goals fixed in the previous section is the one with the higher electrical efficiency (50 % electrical efficiency). For all further analysis this sized system will be used.

3.2. Output values from the program

In this section, the sized system will be used to present different results. All the following solutions use the same system but the control mode used will vary. The control mode is the way in which hydrogen production/consumption is managed. In the previous section, the base mode was used, meaning that the electrolyser and fuel cell are activated whenever it's possible. This mode allows for the highest SS ratio but also means that the H_2 storage is completely empty during a few months in the winter and entirely full during around two months in the summer (Figure 4).

The maximum SS ratio mode is the one that has been used so far and in our previous researches. The goal for other control configurations is to focus not only on the SS ratio but to show the other advantages of a H_2 storage system. The second control mode aims to reduce production and consumption peaks (injection and withdrawal into the grid). One of the main issues with PV panels is the peak production happening around midday when the sun's intensity is at its highest. The energy that cannot be used or stored is to be injected into the grid. This could soon

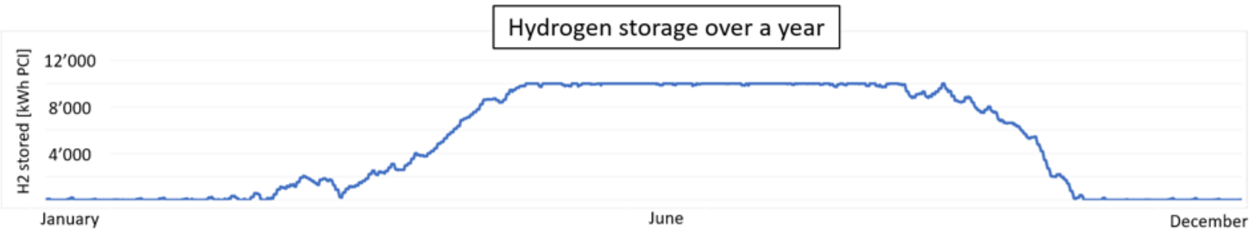

Figure 4. Amount of H_2 stored over a one-year period time using the max SS ratio mode.

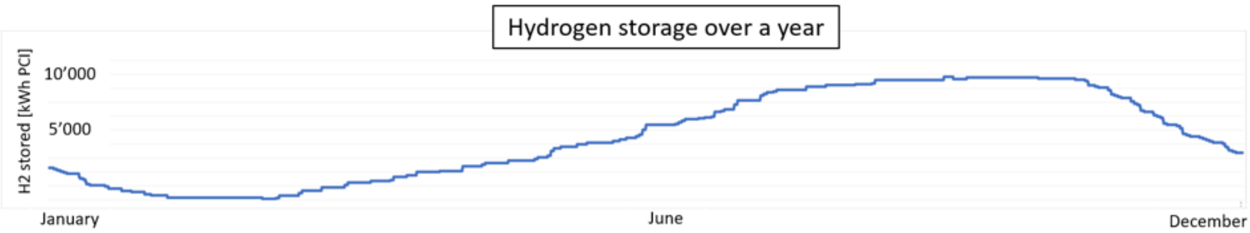

Figure 5. Amount of H_2 stored over a one-year period time using the peaks limitation mode.

become a problem as more and more PV systems are installed and the grid would have to withstand a huge amount of energy over a short period of time. In this case, the H_2 storage system limits the injection peaks by turning on the electrolyser only when the production exceeds a certain value. By comparing Figures 4 and 5 we can see how the curve gets much smoother and the H_2 storage tanks are almost never empty or full.

The lowest GHG emission mode uses an hourly step-time data file containing the CO_2eq emissions factors for the Swiss electricity mix over one year [13]. Using this data, the H_2 program can choose when to buy/sell electricity to the grid according to its carbon content. By withdrawing electricity from the grid only when the carbon content is low, the GHG emissions of the building related to electricity import can be kept at their lowest. The last mode aims to maximize the overall efficiency of the H_2 system. The efficiency of the H_2 storage system can be computed using Equation (2).

$$\eta_{global} = \eta_{Electrolyser} \cdot \frac{Q_{Hydrogen}}{Q_{Thermal} + Q_{Electrical}} \quad (2)$$

Equation (2) clearly shows that to maximize efficiency, both thermal and electrical energy needs to be used. The aim of this mode is to make sure the fuel cell is turned on only when there is both a thermal and electrical demand. To do so, the program will look at the temperature of the hot water tank and the electricity consumption of the building. If the temperature is not maxed out and there is an electricity demand, then the fuel cell will be activated. The results obtained with these different modes can be seen in Table 1.

4. Discussion

In a previous study [5], a similar system was modelled without heat recovery, the overall efficiency of the hydrogen cycle back then was around 30 %. This value can be computed using Equation (1) with $Q_{Thermal}$ equalling zero. By recovering heat on the fuel cell, the efficiency can be increased by 65 % percent to reach 49.5 %. This clearly shows that to take full advantage of a hydrogen storage system, thermal recovery must be integrated. Looking at the SS ratio, the sized H_2 storage system allows to gain around 12 % reaching 80.7 %. However, it has been shown in previous computations that to further increase this ratio the amount of hydrogen needed is impossible to store. It would then become necessary to look at other factors such as the cost and carbon footprint required to build a space dedicated to the H_2 storage tanks.

Regarding the GHG emissions, the chosen sized H_2 storage system can help reach the same emissions but can't improve this value. This is due to two factors. First, the GHG emissions related to the implementation of an Electrolyser, Storage tanks and Fuel cell are still relatively high as these components are not very common. Secondly, to the fact that in our computation, when electricity is exported from the building into the grid, the GHG emissions of the PV panels and the grid carbon content are compared. As the carbon content of the electricity from the PV system is always lower than the grid's, for every kWh exported a negative value is added to the GHG emission balance.

When electricity is stored and reused, the model does not take advantage of this benefit. If we were to compute GHG emission balance without this deduction, the H_2 storage system would always have a better carbon footprint. This H_2 storage system also allows to reduce both injection and consumption peaks. With the dedicated mode, the injection peaks drop from 143 to 99 kW and consumptions from 51.2

Mode	**SS ratio** [%]	**GHG emissions** [kg CO_2eq]	**Overall efficiency** [%]	**Max withdrawal** [kW]	**Max injection** [kW]
Max SS ratio	80.7	9671	34	47.5	140
Peaks limitation	72.5	6764	48.5	39	99
Max efficiency	77	8071	49.5	45.3	140
GHG limitation	73.6	5658	41	47.5	142.8
No H_2 storage	69	5586	0	51.2	142.8

TABLE 1. Results from the different program modes.

to 39 kW preventing overloads on the network. This could also be very beneficial to a neighbourhood like blueFactory [14] in Fribourg, where the SLL will be built, as it would be possible to store or distribute energy from/to all the buildings in the area.

It should be remembered that all these results are obtained using different control modes and that just one wouldn't be able to reach all of these values at once. The financial aspect of this H_2 storage system still needs be evaluate in further details. It's is still complicated to estimate prices regarding the components of an H_2 storage system. Moreover, with today's electricity prices in Switzerland [15] the building would basically have no electrical cost as the amount of energy sold to the grid is much higher than what's consumed. The constant evolution of electricity prices and the feed-in tariffs should be also taken into account.

Further research will be necessary to evaluate every aspect of an H_2 storage system. Financial facets still need be analysed in details to evaluate in which context this installation would be profitable. The H_2 program could be optimized by selecting the best mode for every case or by writing other modes allowing to furthermore improve system operation. The H_2 storage system could be used not only for the building but in harmony with the grid allowing, when needed, to store energy peaks or to provide great amount of energy. New ideas could also be implemented in this project with the potential of hydrogen vehicle. A quick calculation shows that the SLL would have the potential to produce enough H_2 for cars to travel about 150 000 km each year.

5. CONCLUSIONS

This paper demonstrates the many interesting aspects of integrating a hydrogen-based electricity storage system at building-scale. This case study shows the potential of H_2 storage and the various benefits that it could have. The use of thermal energy released by the fuel cell is necessary to greatly improve the overall efficiency of the H_2 cycle. To pursue this project, the MS Excel written code will be improved and optimized, further analysis will be conducted to evaluate the financial aspects in more details and new opportunity for the use of H_2 will be implemented. The challenges regarding energy storage will become more and more common and this paper clearly demonstrate that H_2 will have a role to play in the future of renewable energy.

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