First solar hydrogen storage in a private building in western Switzerland: building energy analysis and schematic design

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Abstract. Self-sufficiency of buildings with carbon emission reduction can be obtained thanks to the introduction of Photovoltaics systems coupled with Hydrogen seasonal storage. To be self-sufficient over the year, the electricity converted to hydrogen by electrolysis during the sunny season can be re-used with the help of fuel cells during the winter season. This article is dealing with the dimensioning methodology of a solar PV hydrogen-electrochemical system for self-sufficient buildings. We introduce the case study of the first private building in western Switzerland that will be equipped with solar hydrogen storage. Calculation results of the dimensioning of the PV system with storage will be presented. The life cycle assessment and the calculations of the environmental indicators GWP and CED will be introduced.

1. Introduction
Buildings have a great potential to produce their own electricity thanks to photovoltaics and available areas on roofs and facades. In this article, we introduce the case study of the first private building that will be equipped with PV panels on roof and facades coupled with solar hydrogen storage in western Switzerland. Harvesting energy produced by PV systems and optimizing energy self-consumption in buildings will have significant perspectives of reduction of carbon emission of buildings. With sufficient installed power and reduced consumption, buildings can have positive energy [1].

Renewable energies such as wind and PV require an electrical storage because of their daily intermittence and the variable amount of produced energy over the seasons. The Hydrogen solution is suitable for the seasonal storage with a high storage capacity (> 100 kWh). It must be coupled with electrochemical batteries such as Lead, Lithium NMC, Iron phosphate, Lead crystal batteries …. The battery can deliver enough instantaneous power in kW for the consumers and allow to smoothen the intermittence of renewable energy. To be self-sufficient over the year, the electricity converted to hydrogen by electrolysis during the sunny season can be re-used with the help of fuel cells during the winter season. Self-sufficiency of the building as well as a carbon emission reduction could be obtained depending on the local grid carbon contents [2][3].

This concrete project demonstrates the potential of deployment of solar hydrogen in the building market from single family homes to multi-storey buildings. At the time this article has been written, the project is in the development design phase, and the PV systems and hydrogen will be purchased Q4 2019. The article will focus on the dimensioning methodology of the schematic design phase.

2 Schematic design
2.1 Project description
The aim of the project is to maximize the self-sufficiency of an architectural building with an energy reference area 1200 m2. In this project, we have also a swimming pool that will be used over the whole
year and which must be only heated by renewables, which is mandatory in Switzerland. This will be achieved by installing solar PV on roof and facades, electrochemical batteries and solar hydrogen system coupled with the geothermal heat pump. The building heat needs are 50'695 kWh thermal (Lesosai [4] calculations) and the swimming pool heating needs 49'514 kWh thermal (Polysun [4] calculations). Solar thermal 11.8 m² will be used to cover a minimum of 30% of DHW needs 16'528 kWh thermal. The yearly consumption of electrical appliances is about 60'000 kWh.

2.2 Schematic design
For a Solar Hydrogen project, the schematic design phase is critical and the objectives of the installation must be well defined from the beginning of the project. In this phase, the global energy analysis of the building is performed by taking into account the planned consumption of the building as well as the potential of self-production on roofs and facades. The pre-dimensioning of the PV and storage systems must be done at the early phase of the schematic design phase, because the building’s systems can have a significant impact on the architectural project. All constrains on the building must be known, such as the choice of aesthetic PV panels installed on the roof and facades with variable panel efficiency depending on the technology, or the space available to install the building systems in the building itself. After the calculations steps, the suggestion of reliable technologies available on the market can be made, and subsequent needs for infrastructures and security are studied. Final iterations allow then to make the final choice of the technologies, and the project can move in the development design phase.

3 Calculation method to dimension electrical energy storage
3.1 Yearly and monthly energy calculations
The global energy analysis is the first step to dimension the solar Hydrogen system. Yearly and monthly energy balances of the building with production - consumption – storage are calculated. The yearly and monthly energy balance will determine the overall storage potential and relevance before performing hourly simulations with more accurate models and software. At this step, some design iterations can be made: redesign the building energy concept, reduce building and swimming pool consumptions, increase available PV surfaces, and choosing technologies with higher efficiencies. Assuming an average coefficient of performance COP of the heat pump of 4.5, the electrical consumption corresponding to the building needs as well as the heating of the swimming pool can be calculated. The values of consumptions and PV production are given in table 1. As a first main result of these preliminary calculations, it can be concluded that the PV production can only cover the building needs or the swimming pool needs, with a yearly positive balance of 7'769 kWh and 8'032 kWh respectively. The values of the electrical balance over the year indicate that electrical energy can be stored during the sunny season and can be retrieved back for the cold season.

3.2 Dynamic hourly simulations of the building
After monthly energy calculations, the dynamic simulations can be performed with the different options of building systems. In this project, dynamic simulations have been performed with the help of Polysun Software [4], see physical model in figure 1. The building systems, the building as well as the swimming pool, are modelled in the same Polysun model. The building systems include the geothermal heat pump, domestic hot water, appliances as well as the PV system on roof and facades. Building heat needs are an input of the model. The electrical and domestic water needs are modeled in Polysun by taking consumption profiles. Electrical mobility can be introduced in the model as an additional consumer. The overall electrical consumption depends on building characteristics and building systems as well as on the program usage and activities of the owner quantified by consumption profiles. The result output of the dynamic simulations is the hourly electrical PV production on roof and facades, consumption of the building, consumption of the swimming pool, the consumption for domestic hot water and electrical appliances. The software Polysun also take into account all the losses of the systems. The hourly data
files can be then exported, and it is possible to extract separate components data such as heat pump energy use for the swimming pool or heat pump energy use for the building itself.

Table 1. PV Production on roof and facades, electrical consumption of heating building, heating swimming pool, electrical appliances, calculated monthly electrical balances between production and consumption.

| Month   | kWh Building heating (COP 4.5) | Domestic hot water (COP 4.5) | Appliances and various | Swimming pool | PV on roof | PV on facade | Balance building | Balance swimming pool |
|---------|-------------------------------|-----------------------------|------------------------|---------------|------------|-------------|-------------------|-----------------------|
| January | 2'947                         | 306                         | 5'000                  | 644           | 233        | 289         | -2'495            | -192                  |
| February| 1'992                         | 306                         | 5'000                  | 755           | 292        | 344         | -1'159            | 78                    |
| March   | 919                           | 306                         | 5'000                  | 730           | 294        | 346         | 782               | 1'012                 |
| April   | 309                           | 306                         | 5'000                  | 1'892         | 1'238      | 806         | 1'735             | 152                   |
| May     | 7                             | 306                         | 5'000                  | 1'458         | 1'583      | 954         | 2'530             | 1'079                 |
| June    | 0                             | 306                         | 5'000                  | 1'411         | 1'663      | 995         | 2'658             | 1'247                 |
| July    | 0                             | 306                         | 5'000                  | 267           | 1'737      | 1'028       | 2'765             | 2'498                 |
| August  | 0                             | 306                         | 5'000                  | 669           | 1'473      | 939         | 2'412             | 1'743                 |
| September | 397                      | 306                        | 5'000                  | 1'200         | 1'015      | 738         | 1'746             | 553                   |
| October | 1'955                        | 306                        | 5'000                  | 538           | 565        | 476         | 644               | 503                   |
| November | 2'734                      | 306                        | 5'000                  | 758           | 168        | 155         | -2'411            | -535                  |
| Year    | 11'266                       | 3'672                      | 60'000                 | 11'003        | 11'338     | 7'697       | 7'769             | 8'032                  |

3.3 Calculation of hydrogen and battery storage capacities

Python programs have been developed by Tecphy to interface the Polysun hourly simulations with customized Hydrogen system and algorithm simulations. These programs allow the dimensioning of system’s power in kW, PV, charger-inverters, electrochemical batteries, electrolyser and fuel cell, as well as the electrical storage capacity in kWh.

The Hydrogen system is a hybrid system comprising an electrochemical battery absorbing fast changes and the hydrogen storage feeding fuel cells to manage longer run energy needs. The daily self-consumption is obtained with the help of the battery storage, and the seasonal self-consumption is provided by the solar Hydrogen storage. For the simulations, a round trip efficiency of 90% and 35% has been taken for the battery and the hydrogen system respectively.

Results of simulations are illustrated in the graphics in figures 2 and 3. The hourly simulations of the electrical flux between PV, consumers, electrochemical and hydrogen storage and the public grid are computed. In figures 2 and 3, graphics from top to bottom in kWh units correspond to: 1) state of charge of the battery 2) State of charge of the hydrogen storage 3) import and export to the building grid. The electrical flux will also depend on algorithms of energy management in the building. Both state of charge of the battery and of the hydrogen are expressed in kWh. A conversion factor of 15 kWh per kg of Hydrogen can be used to calculate the Hydrogen quantity in kg that must be stored.

From the simulations, the number of storage cycles and grid import/export as a function of storage capacities, installed powers and storage strategies can be deduced. Optimum powers and capacities which minimize grid import with a minimum investment cost for the owner can be obtained with these hourly simulations.
Figure 1. Building system simulations with PV production on roof and facades. Building energy analysis is performed with the help of Polysun software and add-in modules.

Figure 2. Hourly simulations of condition #1 table 2, Hydrogen storage system coupled with PV producer and swimming pool consumer: state of charge electro-chemical battery, Hydrogen storage level, Grid import and export powers.

Figure 3. Hourly simulations of condition #7 table 2, Hydrogen storage system coupled with PV producer and swimming pool consumer: state of charge electro-chemical battery, Hydrogen storage level, Grid import and export powers.
4 Final results
The objective of the project has been focused on the self-sufficiency of the Swimming pool which is therefore the only considered consumer. To reach this target, a low consumption swimming pool has been designed. To limit the heat loss in the cold season, the pool is also covered and isolated. During the hot season, from day 90 to 273, the pool is covered between 10h and 20h. The temperature setting of the pool is 25°C over the whole year. The final electrical consumption over the year is 11’003 kWh. Various options have been tested in the simulations from the conditions #1 to #9:
- Various PV technologies and installed power to meet aesthetic criteria
- With and without PV on façade
- Various battery and hydrogen capacities

The final results are presented in table 2. To reach the self-sufficiency, the grid import value should be zero. The results show that the PV installation on the façade is mandatory with some flexibilities on the choice of installed power and technologies with yearly productions ranging from 15’472 kWh to 17’697 kWh. Best options are #1 and #4. The options no façade #5 - #9 with only 10’514 kWh PV energy production are not self-sufficient. Simulations show that the reduced PV production without façade cannot be compensated by extra storage capacities. The smoothening of PV production is mostly performed by the battery, which has a better round trip efficiency. The numerous cycles of the battery are clearly shown in top graphics in figure 2 and 3. In this very particular application of swimming pool heating, the number of cycles of the hydrogen storage is very low, with less than 2 cycles and the storage capacity is quite big, between 500 kWh and 1000 kWh. This is explained by the fact that we only need to convert hydrogen to electricity from November to April. At the beginning of the spring around day 90 in April, the coverage of the swimming pool is opened but the ambient temperature is still cold. This explains the usage of hydrogen to heat the swimming at this transitory season from cold to hot. This is clearly shown in middle graphic of hydrogen storage in figure 2 and 3.

Table 2. Simulation of self-sufficiency with variable PV production and storage capacities

| #condition | PV on facade | PV production (kWh) | Battery capacity (kWh) | Hydrogen capacity (kWh) | Number of battery cycles | Number of Hydrogen cycles | Grid import (kWh) | Grid export (kWh) | Maximum reached H2 level (kWh) |
|------------|--------------|---------------------|------------------------|-------------------------|--------------------------|------------------------|-----------------|-----------------|--------------------------|
| #1         | yes          | 17’697              | 41                     | 500                     | 88.3                     | 1.5                    | 0               | 6’213           | 500                      |
| #2         | yes          | 15’734              | 500                    | 86.8                    | 1.8                      | -23                    | 4’020           | 500              |                          |
| #3         | yes          | 15’472              | 41                     | 86.6                    | 1.8                      | -37                    | 3’749           | 500              |                          |
| #4         | yes          | 15’472              | 41                     | 86.2                    | 0.9                      | 0                      | 3’646           | 1’000            |                          |
| #5         | no           | 10’514              | 41                     | 500                     | 74.3                     | 1.5                    | -1’314          | 420             | 500                      |
| #6         | no           | 10’514              | 41                     | 74.3                    | 0.9                      | -1’167                 | 0               | 610             |                          |
| #7         | no           | 10’514              | 57                     | 54.8                    | 0.9                      | -1’113                 | 0               | 610             |                          |
| #8         | no           | 10’514              | 200                    | 17.8                    | 0                        | -1’541                 | 1’969           | 0               |                          |
| #9         | no           | 10’514              | 300                    | 12.5                    | 0                        | -1’341                 | 1’747           | 0               |                          |

5 Economic viability and environmental impact assessment
Thanks to the hourly simulations, it is possible to pre-dimension the system and choose the technologies for the hydrogen system with the correct storage capacity and power. Moreover, unlike the PV systems with a typical expected lifetime of 30 years, the lifetimes of the components of a hydrogen system such as electrolyser and fuel cell are variables and are highly dependent on the chosen technologies. Therefore the calculation of the components cycles will allow to optimize the CAPEX cost as well as the operating and maintenance costs, while fulfilling the project objectives in terms of building self-sufficiency and minimized embodied energy. It must be noted that Hydrogen system price is highly variable with used technologies and suppliers. For a system comprising an electrolyser 0.25-1 Nm³/h, a battery of capacity 25-41 kWh, a fuel cell 1.5-3.5 kW, and a hydrogen storage capacity 500-1000 kWh, the price ranges between 100’000 CHF and 350’000 CHF (2018). The global project cost of the project must also take
into account not only the system itself but also the additional costs of consultancies in engineering and security, building infrastructure with storage rooms and fire protections measures.

A methodology to calculate the environmental indicators Gas Warming Potential (GWP) and Cumulative Energy Demand (CED) will be applied for the project [2][3]. At first, embodied energies for the chosen technologies must be calculated, they are generally expressed per installed capacity kWh (storage) and per installed power kWp, and they are scaled to the final system size. Calculations will include the PV system [5] with battery storage [6][7] as well as the hydrogen storage system [8]. Then, hourly simulations will calculate the power flux and resulting transfers of self-consumed energy in the storage components. Considering the lifetime of the components and the number of forecast cycles, embodied energy will be calculated and the replacement of components should be considered over the entire assessment period. Finally, the indicators GWP and CED will be finally expressed per kWh of self-consumed energy.

6 Conclusions and perspectives

Thanks to an integrated design with multi-oriented façades and flat roof, the potential of available surface for PV production has been maximized for the building with a yearly production up to 17'697 kWh on roof and facades. This energy can cover the yearly heating needs of the swimming pool 11'000 kWh electrical, which are close to the building needs of 11'266 kWh electrical. With the PV system coupled with hydrogen storage, 100% self-consumption and 100% self-sufficiency of the swimming pool is expected. The optimum capacity of the electrical storage has been calculated with 40 kWh battery capacity and 500 kWh solar hydrogen storage capacity. With the presented approach and methodology, a 100% self-sufficient building could be easily designed. To achieve self-sufficiency objectives and propose effective cost solutions, hourly simulations of the complete building’s systems with renewables and storage are mandatory. This first installation in western Switzerland will open the road of solar hydrogen systems for private building owners which until now was reserved to the industrial market.

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