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Distributed Urban Energy Systems (Urban Form, Energy and Technology, Urban Hub)

Feasibility of renewable hydrogen based energy supply for a district

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Abstract

Renewable generation technologies (e.g. photovoltaic panels (PV)) are often installed in buildings and districts with an aim to decrease their carbon emissions and consumption of non-renewable energy. However, due to a mismatch between supply and demand at an hourly but also on a seasonal timescale; a large amount of electricity is exported to the grid rather than used to offset local demand. A solution to this is local storage of electricity for subsequent self-consumption. This could additionally provide districts with new business opportunities, financial stability, flexibility and reliability.

In this paper the feasibility of hydrogen based electricity storage for a district is evaluated. The district energy system (DES) includes PV and hybrid photovoltaic panels (PVT). The proposed storage system consists of production of hydrogen using the renewable electricity generated within the district, hydrogen storage, and subsequent use in a fuel cell. Combination of battery storage along with hydrogen conversion and storage is also evaluated. A multi-energy optimization approach is used to model the DES. Results of the model are optimal battery capacity, electrolyzer capacity, hydrogen storage capacity, fuel cell capacity and energy flows through the system. The model is also used to compare different system design configurations. The results of this analysis show that both battery capacity and conversion of electricity to hydrogen enable the district to decrease its carbon emissions by approximately 22% when compared to the reference case with no energy storage.

Keywords: power-to-gas; fuel-cells; hydrogen storage; multi-energy optimization; renewable hydrogen production

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1. Introduction

Renewable or distributed energy generation such as rooftop solar panels are commonly installed in districts or communities. Interest in distributed generation can be attributed to five major factors: developments in generation technologies, constraints on the construction of new transmission lines, increased customer demand for highly reliable electricity, the electricity market liberalization, and concerns about climate change [1,2]. In most cases renewable generation capacity in districts is not designed to cover total electricity demand, and the districts do not intend to operate as stand-alone systems. Rather, renewable generation capacity is often installed with an aim to reduce non-renewable energy consumption or to reduce peak power demand of the district. Since renewable generation (PV) has hourly and seasonal variation (in European countries), time resolved energy balances show there is excess electricity produced during summer months while demand is higher during winter months. The intermittency and seasonal variability of this electricity production is usually balanced by the electricity grid.

However, accommodating an increasing amount of electricity generation from renewable sources will require new approaches to extending and operating the grid. Local storage of energy where it is produced would not only avoid issues with overloading the grid; but also enable districts and communities to use locally generated electricity. This would additionally provide them with new business opportunities such as arbitrage (buying and selling of electricity in order to take advantage of time-dependent prices), provision of ancillary services to the grid, and provision of energy for mobility (hydrogen and electric vehicles).

The aim of this research work is to evaluate if hydrogen production, storage and use in a fuel cell is a feasible, long term storage solution for a district. A case study is used as a basis for this evaluation; however the results could be translated to other similar districts. The selected case study is a newly built district situated in Risch Rotkreuz, Switzerland, with low energy commercial and residential buildings. PV and PVT panels installed on rooftops supply part of the electricity demand of the district and also feed heat into a low temperature network (LTN) which is connected to a borehole field. The installed capacity of PV and PVT panels is 800 kWp and a summary of the heating and electricity demand of the district is described in [3]. Use of thermal storage in the district has been assessed in [3], and the focus of this paper is on electricity storage. A secondary aim of this research is to compare different system configurations when considering installation of both short term (hourly or daily), and long term (seasonal) electricity storage.

In section 2 the different system configurations are described. A brief description of the model and the assumptions are also included in section 2. In section 3 the results of the optimization model and a comparison of the different system configurations are presented. Discussions and conclusions are presented in section 4 and 5.

2. System description

In the case study considered, the electricity demand of the district (sum of electricity demand of heat pumps, network pumps and other DES equipment) is met primarily with on-site PV generation. A mixed integer linear programming (MILP) model of the DES (energy hub model) is developed and the electricity demand of a full year with hourly time-steps is used as an input to the model. The objective of carbon minimization is used to derive optimal capacities for the specified DES system components. The results are used to compare the following system configurations:

Reference case: No battery, no electrolyser
1a: Battery and electrolyzer in series (battery discharge only used to stabilize operation of electrolyzer)
1b: Battery and electrolyzer in series (with battery also discharging for direct consumption)
2: Battery and electrolyzer in parallel
3: Electrolyser, hydrogen storage and fuel cell (no battery)
4: Battery storage only (no hydrogen production)

In figure 1, a representation of the model with configurations *1a*, *1b* and *2* is presented. Configuration *1b* includes the grey arrow, where the battery is also discharged to directly meet electricity consumption. The blue line in figure 1 represents hydrogen (energy), the black lines represent electricity flows and the red line represents heat.
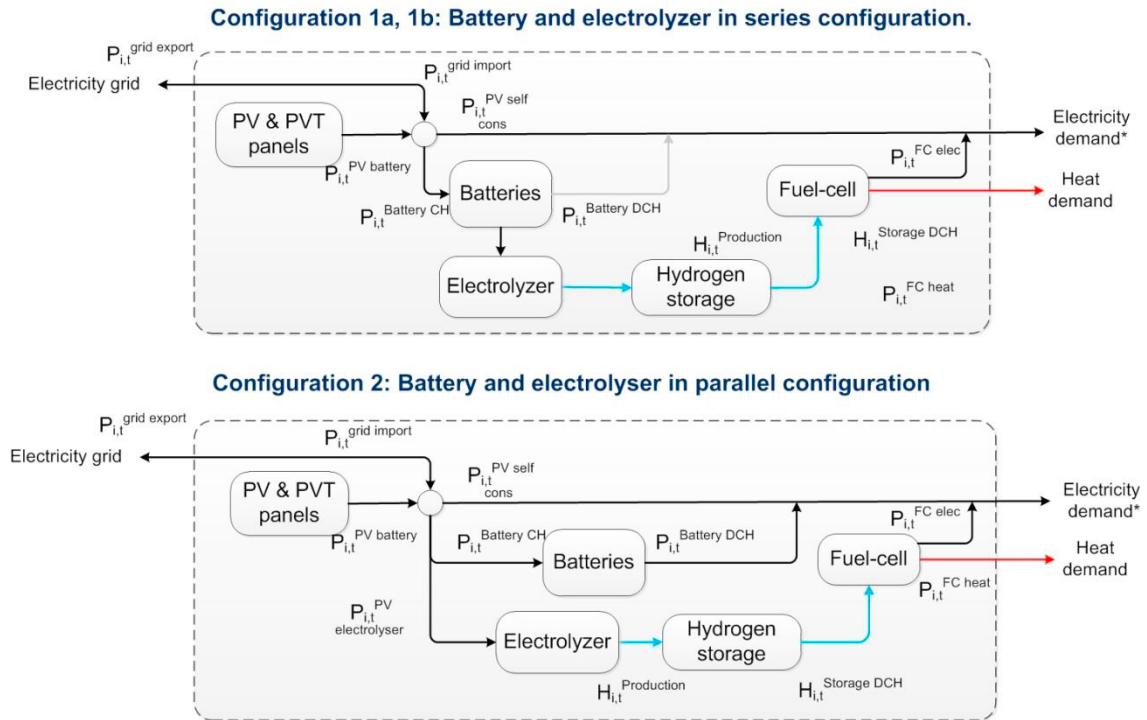
Fig. 1. Description of system configurations which are evaluated

Installation of energy storage in DES does not automatically reduce emissions or energy consumption: Fares and Weber [4] find that while a typical battery system can reduce peak power demand and peak power injections, battery storage inefficiencies increase annual energy consumption by 324–591 kWh per household on average. Thus the operation strategy of the battery management system has a large impact on battery energy consumption. Since the stakeholders of the district have the aim of reducing carbon emissions, the optimization model was set up such that both hourly and seasonal storage can only be charged with excess electricity produced by the on-site PV and PVT panels. Some assumptions related to operating strategy and system characteristics are listed below:

- Electricity discharged from battery or electricity production of the fuel cell is only used to meet demands of the district (and is not exported to the grid).
- Only PV generation which cannot be used directly on-site (or stored) at the same time-step is exported to the grid.
- Operation of the battery or of fuel-cell for arbitrage is not considered.
- No constraints on the amount of heat generated by the FC which is fed into the LTN.
- Initial state of charge (SOC) at the first time-step is equal to the SOC at the last time-step for both types of storage. Initial SOC of the hydrogen storage is zero.
- The maximum number of shut-downs per year of the fuel cell is set to 60 (switching frequency constraint described in [5]).
- Electrolyzer efficiency is fixed at 50% with a part-load constraint of 30%.
- Charging and discharging efficiency of the hydrogen storage is 99% and maximum charging and discharging rate (kW) are set to 30% of storage capacity (kWh).
- The charge and discharge efficiency of the battery system is 90% and maximum charging and discharging rate (kW) are set to 80% of its storage capacity (kWh). The minimum state of charge of the battery system is 20% of its storage capacity (kWh). The battery system has a standing loss of 1%.
- The fuel cell has a fixed electrical efficiency of 50% and thermal efficiency of 35%

Conversion from direct current (DC) to alternating current (AC), or compression of hydrogen are not considered in this analysis. The charging and discharging losses of the storage systems are assumed to take into account losses arising from these conversions.

3. Results

The optimal capacities of the battery, electrolyzer, hydrogen storage and fuel cell for the different system configurations are presented in table 1. For cost optimization (assuming current electricity prices), the optimal solutions do not include any hydrogen or battery storage capacity.

System configurations *1b* and *2* which include both battery and hydrogen storage have the lowest emissions (table 1). The optimal capacity of battery storage is highly dependent on the system configuration and ranges from 300 kWh to 1100 kWh. The optimal capacity of the electrolyzer ranges from 200 kW to 400 kW. Optimal hydrogen storage capacity ranges from 1300 kg to 1800 kg and optimal fuel cell capacity ranges from 14 kW to 17 kW.

Table 1. Optimization results (carbon minimization) for capacity of the system components*

System configuration	Battery capacity (kWh)	Electrolyzer capacity (kW)	Hydrogen storage capacity* (kWh)/(kg)	Fuel cell capacity (kW)*	Carbon emissions (tonnes CO_2)
1a. Series configuration	310	200	45085/1353	17	606
1b. Series configuration (modification for battery)	1093	203	61750/1854	17	506
2. Parallel configuration	819	405	59472/1786	14	520
3. Electrolyser, hydrogen storage and fuel cell	0	308	46581/1399	15	596
4. Battery storage only	819	0	0	0	552
5. No storage	0	0	0	0	646

Figure 2 (left panel) shows the percentage electricity imported from the grid as a percentage of the annual electricity demand for the different configurations. These results directly relate to carbon emissions produced by DES operation which are calculated using the carbon factor of the swiss grid and the amount electricity imported from the grid. The results show that even with installation of storage, the district would need to import approximately 58% of its annual electricity demand. In figure 2 (right panel), the percentage of self-consumption of electricity from PV and PVT is presented in the right panel. For system configuration *2* (battery and electrolyzer in parallel), almost all of the on-site produced electricity can be used within the district. The combination of both hourly and seasonal storage thus increases self-consumption from 38% (no storage) to 99% (system configuration 2).

An analysis of the dispatch of electricity from the battery storage, PV, grid or fuel cell to meet demand provides further insight on why the optimal capacities differ for different configurations. The dispatch of electricity for configurations *1b* and *2* is presented in figure 3a and 3b respectively. In configuration *1b*, the battery system is used for hourly or daily storage (light blue bars in figure 3a) while the hydrogen conversion, storage and fuel cell system provide seasonal storage. Hydrogen is mainly produced during summer months and used in the fuel cell during winter months (purple bars in figure 3a).

In configuration *2* (figure 3b), both the battery and hydrogen production and storage are used for storage of electricity for a few hours or days. The produced hydrogen is used in the fuel cell which operates both in the summer months once a sufficient amount of hydrogen is produced, as well as during winter months (purple bars in figure 3b). Thus, the battery capacity is smaller in configuration *2*, while the electrolyzer capacity is larger.
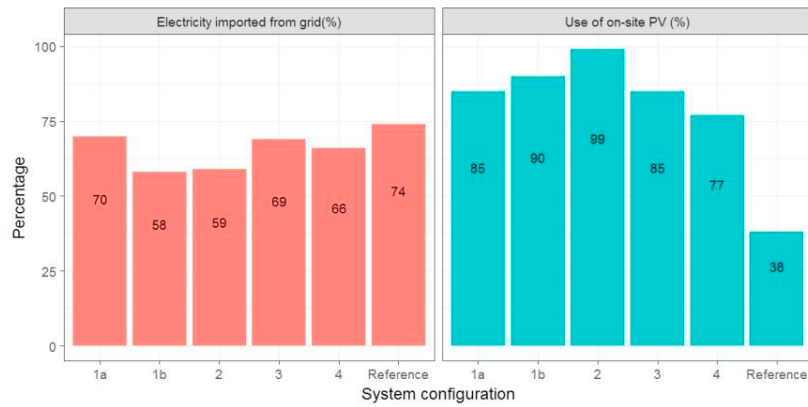
Fig. 2. Comparison of electricity imported from the grid and self-consumption of PV/PVT production for the different system configurations
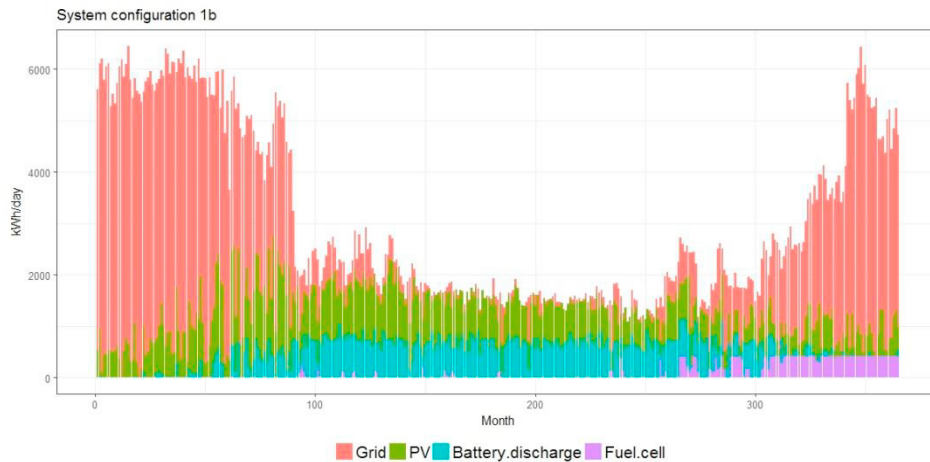

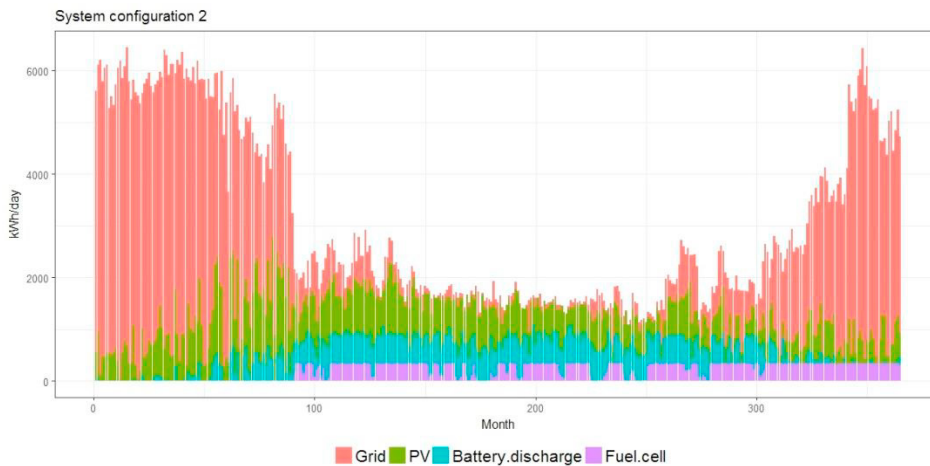Fig. 3a. Dispatch of electricity to meet demand for configuration 1b

Fig. 3b. Dispatch of electricity to meet demand for configuration 2

4. Discussion

The results show that a combination of short term and long term storage enables the district to utilize close to 100% of on-site generated electricity. The results presented in table 1 do not consider the use of hydrogen for mobility, nor the use of the battery system for electric mobility. Rather, the presented optimal capacities are used to store excess electricity produced by the PV and PVT panels. The produced hydrogen is then used in the fuel cell which is operated mainly to meet peak demand. Other use cases which consider arbitration or mobility might require larger storage capacity.

Figures 3a and 3b show that the fuel cell is mainly operated during winter months and periods with peak demand. Thus the storage systems improve reliability of not only of the DES, but also the electricity grid. In addition, storage eliminates feed-in of excess electricity from PV and PVT panels to the grid during summer. While the optimal solution does not show continuous operation of the fuel cell throughout the year, the system once installed could be used as backup generation capacity. Therefore the proposed storage system provides several benefits to both the DES and the grid.

5. Conclusion

The results presented in this paper show that battery storage and/or hydrogen storage are technically feasible solutions for energy storage. The optimal result with lowest carbon emissions (during operation) is a system configuration which includes both types of storage in parallel (figure 1, system configuration 2). The results show that carbon emissions of the district can be further reduced by 22% when compared to the reference case without any storage. In addition, the storage systems would enhance grid and system reliability and also decrease operational cost (by reducing electricity purchased from the grid).

Due to the large choice of possible storage solutions and system configurations for DES, careful assessment is required to select suitable system designs based on the stakeholder requirements and use cases. This research work will add to a review on energy storage solutions for different types of DES and different use cases. The results presented in this paper will also be used to inform and aid decision making in selection of relevant storage solutions for the district considered in this analysis.

Acknowledgements

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