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Evaluating the need for energy storage to enhance autonomy of neighborhoods

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Abstract

Energy storage is generally considered as a means to bridge a period between when/where energy is available and when/where it is in demand. Storage plays an important role by providing flexibility to energy systems, increasing the potential to accommodate variable renewables generation and improving management of electricity networks. However, currently it remains unclear when and under which conditions energy storage can be profitably operated at a district level. The present study aims to quantify the level of integration of solar energy and storage in the Junction district of Geneva. A simulation tool is developed to investigate the techno-economical and environmental assessment under different scenarios. For a given investment over 20 years, the model calculates the levelized cost of electricity (LCOE), the autonomy level as well as the CO2 emissions. Given the assumptions of the model, four scenarios are analysed based on the combination of solar PV, storage, solar thermal and heat pump to find out an economically optimal configuration in terms of system size. A comparison with the Homer software is performed to test the robustness of the solar PV and battery model. The economic profitability of solar PV and battery system is in very good agreement with Homer and the autonomy level is validated by using a simulation tool created by SI-REN (Services Industriels des Energies Renouvelables de Lausanne). However, combining solar PV with battery system doesn't bring additional autonomy to the model for Geneva study case. Under the assumptions of the model, to foster investments in solar PV and battery installations, falling investments costs seem necessary for the future. A reduction gap between buying and selling price in grid for solar panel is recommended to increase solar installations. A validated simulation tool has been developed in this work and provide a reliable based that will be extended in the future to include the thermal demand and production. The availability of thermal storage at a large scale as well as the production over a district should further increase the autonomy of the district.

Keywords: Battery Storage, Electricity Price, Solar Energy, Solar Photovoltaic Power, Techno-Economic Model, Thermal energy storage

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1. Introduction

Renewable energy technologies are expected to play a major role in societal challenges (such as climate change, resource depletion and abandon of nuclear energy by 2050) in Switzerland [1] and with the development of decentralized energy systems [2]. Among the many options available, solar photovoltaic (PV) power has been found to have a particularly large physical potential for electricity generation [3]. PV systems are attractive because of the simplicity of the installations and the fact that PV systems are scalable and can be integrated directly into the unit [4].

While solar energy system captures sunlight, and turns it into power for use during sunlight hours; it is unable to provide power without direct and constant sunlight [5]. Consequently, there are often gaps between consumption and the supply of the plants. An effective means for reducing the mismatches between demand and supply as well as heating demand and supply by energy sources are storage technologies [5]. Energy storage have different aims as bridging seasonal differences and imbalances, levelling daily load cycle, peak shaving and improving grid stability, power quality and reliability of supply [6]. Unfortunately, adding storage technologies to solar PV increase the overall investment cost. It also currently remains unclear when PV and storage investments will become economically interesting in a large-scale application as studies focused mostly at individual building scale. It is however necessary to analyse the economic and ecological assessment of the combination of different energy storage strategies at large scale.

A simulation tool is thus developed and validated with several input parameters to analyse the economic and environmental aspect of the integration of several energy conversion units. The objective of this work is to furthermore to evaluate the integration of solar energy and storage on a specific cluster of buildings in the Junction district of Geneva with the aim of finding an optimal configuration in terms of system size. We will give an overview of the techno-economical model implemented and then devise multiple scenarios that will be studied with a combination of different SPV integration and energy storage size. Finally we describe the validation and the results obtained and discuss the future extension of the model to include the thermal demand and production.

2. Models

The approach chosen for the current study aims to consider the energy and cash flows for 8760 time steps in one year and over 20 years. In the next subsections, the mathematical models and the inputs required for the model (energy demand, CO_2 emissions, cost for each technology) will be explained.

2.1. Techno-economical models

Three criterions are used to evaluate the energy systems. The **Autonomy level** is defined as the share of electricity generated by the PV system that is directly consumed by the consumers. It is assumed that whenever electricity demand during the day met the electricity generation of the PV system, the consumers consumes its own electricity [5]. The ratio between electricity that is directly self-consumed and the total electricity demand defines the autonomy level (self-consumption ratio). In the model, self-consumption is calculated for each time step (hourly here) over one year. The autonomy level is calculated using:

$$Autonomy\ Level = \frac{Self\ Consumption}{\sum_{Total\ Demand}} \tag{1}$$

The **Levelized Cost of Electricity** (LCOE) is the net present value of the unit cost of electricity of the lifetime of a generating asset. It is a first order economic assessment of the cost competitiveness of an electricity generating system that incorporates all costs over its lifetime [7]. The LCOE concept determines the total costs that occur during the lifetime of a technology divided by the total energy demand and accounts for the differences in lifetimes across technologies [8]. LCOE may vary strongly from one technology to another depending on the application. With Eq. 2, an application with very high energy demand is likely to have a lower LCOE than an application with a little energy demand. LCOE will provide us with a useful metric to compare different costs of various technologies over the years.

$$LCOE = \frac{-NPV}{20 \times \sum_{Total\ Demand}} \tag{2}$$

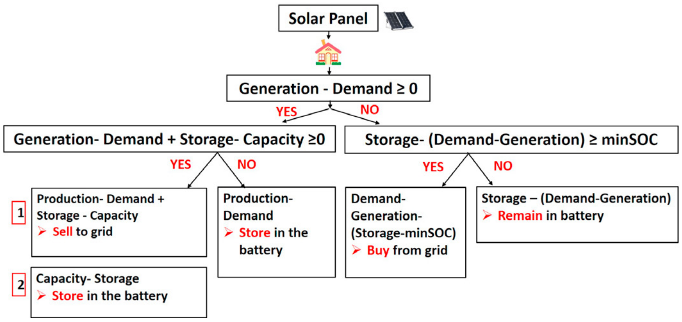

Fig. 1. General logic of the battery operations strategy

The NPV can be calculated as follows: For a given investment over year *y*, the net present value (NPV) is the profitability of an undertaking that is calculated by subtracting the present values of cash outflows (including initial cost) from the present values of cash inflows over the 20 years lifetime of the PV system [9]. Cash outflows comprise the investment costs, the operations and maintenance expenses as well as the price of electricity bought from grid. Cash inflows comprise the price of excess electricity that is neither self-consumed nor stored, and is sold to grid. In this model, the NPV is calculated with negative numbers to analyse the situation from the point of view of the user. NPV calculation for a given technology is given with Eq. 3.

$$NPV(Year1) = E_s - E_b - IC \qquad NPV(Year2 - 20) = E_s - E_b - OM \tag{3}$$

where E_s is Energy sold to grid; E_b is Energy bought from grid [kWh]; IC is Installation cost of the technology - tax incentives and OM is Operations and maintenance cost of the technology. We calculate the specific **CO_2 emissions** based on the lifetime of the technology used. More details on the CO_2 emissions from the each of the devices considered in the current study will be given in section 3.2.

$$CO_2 = \frac{mCO2 \times \sum_{Qg}}{\sum_{Total\ Demand}} \tag{4}$$

where mCO_2 is CO_2 emissions of the specific technology in [kg/kWh]; Qg is Generation of the specific technology in [kWh] and the total demand is in [kWh].

2.2. *Storage size and strategy*

The storage capacity is determined by choosing an average day on the whole year and by integrating the area under the average generation curve. This calculation will be further used to calculate the storage capacity of the battery in section 4.1. Figure 1 explains the operating strategy of the storage in a battery. If the generation is higher than the demand, the excess electricity can be stored in the battery. If the battery capacity is reached, the excess electricity can be sold to the grid. On the contrary, if the demand is higher than the generation, two options are available: buy from the grid or use the available stored electricity in the battery. The minimum state of charge is an important parameter which reflects the battery performance. It is defined as a threshold that shows the available capacity remaining in the battery. The energy stored in the battery can only be used if the minimum state of charge is not reached.

3. Case study

3.1. *Junction District in Geneva*

A neighbourhood containing approximately 800 buildings in the Jonction district in Geneva, Switzerland is considered for this study. In a previous study, the electricity demand, heating demand as well as the solar production of each building were simulated using CitySim [10] for every hour (8760 time steps) over one year. K-means algorithm, based on the Euclidean distance, was besides used to cluster the time series data of each building in order to identify the possible strategies of implementing a district heating network. For the purpose of this study we will hence focus only on one of these clusters.

Table 1. Economic input parameters for PV system

Solar Panel	Unit	Value	Sources
Cost	[CHF/kW]	1350	[12]
Lifetime	[years]	20	[8]
Operations and Maintenance cost	[CHF]	1.5% of PV system cost per year	[13]
CO_2 emissions	[kg/kWh]	0.044	[6]

Table 2. Economic input parameters and characteristics for battery technologies

Battery Technologies	Unit	Lead-Acid Battery	Lithium-Ion Battery	Sources
Cost	[CHF/kW]	163	440	[14]
Operations and Maintenance cost	[CHF]	22	19	[13]
CO_2 emissions	[kg/kWh]	15	70	[6]
Lifetime	[years]	7	15	[6]
Efficiency	[%]	81	92	[6]
Minimum state of charge	[%]	30	20	[6]

3.2. Scenarios

The Swiss franc (CHF) is chosen as the currency since the study case is located in Switzerland. Based on a market data analysis, the average price of electricity bought over the network in Geneva in 2016 is 20.6 cts/kWh [11] and the average selling price is 10.9 cts/kWh [11]. The price of electricity in Geneva has decreased by 7% compared to 2000 prices but has increased by 2% per year [11] over the past two years. In our model, we will however assume that the electricity and the selling price increase every year by 2%. The CO_2 emissions of the grid in Geneva that we take into consideration in this model are 0.003 kg/kWh. Two different scenarios are simulated based on the level of integration of the solar PV panels (30%, 60% and 90% of the maximum roof coverage) and the size of the batteries (30%, 60%, 90% of the maximum calculated storage). Table1 gives the input parameters used for the SPV scenario and Table2 for the batteries.

Two type of storage technology are compared in this study: lead-acid battery and lithium ion battery but we will only show the results for the lead-acid. For the year 20, we added the additional sewage cost of the battery (1/3 of the battery price after 20 years). We assumed that the battery price decreases each year by 7.6%.

4. Results and Discussions

4.1. Characterisation of the system

The PV electricity production in kWh is obtained by using the available irradiation in hourly resolution for a specific cluster in the Junction District of Geneva. To reflect inefficiencies in the PV system, such as inversion losses, the solar PV generation is multiplied with a performance ratio of 15%. The capacity of solar PV panel is determined based on the peak generation of the cluster. The maximum solar PV capacity is 2'441 kW. Based on a research in Geneva university (Base de Donnes Climatiques - Systmes nergtiques - UNIGE 2011) the maximum global irradiance in Junction District is 1.094 kWh/mm^2. The maximum irradiation is equal to 16'279 kWh and this lead to a maximum roof area of 14'880 m^2. As expected the demand for such a district, is usually higher than to the electricity produced but during summer, when the generation is higher than the demand, the excess electricity can be stored in a battery. The capacity of storage is determined as the integral below a curve representing the average production of the whole system (not shown here). This calculation leads to a battery capacity of 7582.9 kWh.

4.2. Model validation

We validate our model with two different independent tools, HOMER (for the LCOE) and BARTPower / BARTHome (for the autonomy level), to test the validity and robustness of the solutions. When the results are compared with

Table 3. Results for scenarios 1 (Solar PV) and 2 (Solar PV and battery)

Solar Panel	Capacity [kW]	LCOE [CHF/ kWh]	Autonomy Level	CO_2 emissions [kg/kW]
30%	733	0.238	6%	0.005
60%	1465	0.227	11%	0.008
90%	2198	0.217	16%	0.010
Solar Panel	Lead-Acid Battery	LCOE [CHF/ kWh]	Autonomy Level	CO_2 emissions [kg/kW]
90%	30%	0.222	17%	0.018
90%	60%	0.228	17%	0.025
90%	90%	0.234	17%	0.032

HOMER, we obtain the same result for the LCOE with solar PV as well as for the batteries under the two following conditions: (1) HOMER software uses a normalized value for generic flat plate PV for Geneva and has a total production of 1873735 kWh/yr which is 1.13 times higher than our total generation. (2) The inflation rate is considered as 1% in HOMER (2% in our model). If we change our total production and the inflation rate to 1%. We then compared the results with the simulation tools called "BARTpower" and "BARTHome" made by Services Industriels des Energies Rnouvelables de Lausanne (SI-REN) for a 30% roof coverage with solar PV. The same value is obtained for the autonomy level (self-consumption ratio) which is 6%.

As we validated our model, we use different integration scenarios to evaluate the one that will provide with the more competitive LCOE will also increasing the autonomy level and decrease the CO_2 emissions.

4.2.1. Solar PV panels

As expected, the autonomy level as well as the CO_2 emissions increase with the percentage of solar panel that we installed. Autonomy level up to 16% can be reached by using 90% solar panels. The optimal scenarios are those that minimize the LCOE value to be competitive with the grid price of 0.206 CHF/kWh. As can be seen, 90% scenario is the most optimal case regarding the LCOE value (see Table 3). The capacity of solar PV corresponding to 90% scenario is 2.2 MW. The second most optimal scenario is 60% of solar PV corresponding to 1.46 MW. As can be expected with the high demand of the district, when more solar PV is installed, a higher percentage of the demand is satisfied and the district become more autonomous.

The findings presented demonstrate that solar PV can be competitive with the grid in a district level. As the demand of the district is high an autonomy level up to 16% can only be reached by installing 90% of solar PV. A decrease in electricity price and a concurrent increase in the selling price lead to a higher economic viability of the PV system. For instance, a reduction of price gap (buying and selling) in grid for solar panel is recommended to increase solar installations. A decrease in the solar PV price allows decreasing the LCOE by 1%. Given that the market prices fluctuate significantly over the years, future scenarios are difficult to predict. Finally, PV system is competitive with grid price of 0.206 with an LCOE of 0.217 (90% scenario) but its remain higher.

4.2.2. Solar Panels and batteries

Table 3, displays the optimal storage situation with lead acid batteries. The best case is, as expected, the one with 90% solar PV with 30% of lead acid battery with the lowest LCOE and the highest autonomy level. The second most optimal case is 90% solar PV with 60% of battery. The lowest LCOE that we obtain with a lead acid battery is 0.222 and with a lithium ion battery is 0.225. As can be seen the autonomy level isnt affected by the size and the battery type, even if the battery percentage is 90%, the autonomy level is identical to a 30% scenario. At a first glance, the results seem intuitive, when the solar PV and battery size become important, the CO_2 emissions are higher. The scenario with 30% of solar PV and 30% of battery can be compared to the best scenario (90% solar PV and 30% battery). When solar PV size is larger (90%), the scenario becomes more advantageous (LCOE decrease) because the consumers tend to sell a higher share of the electricity on the market. Investments in storage remain still not profitable because when the storage size increase, correspondingly the LCOE level increase in each scenario. Overall,for lithium-ion battery, as the price is higher than lead acid battery, the LCOE is higher. Investments in storage are even not profitable compared to the grid price under the assumptions of the model. The lithium battery is more performant in the long term than lead acid and the profitability of storage can rise over time with the falling investment costs.

5. Conclusions and perspectives

The current study aims to present a decision-making support tool for researchers by reviewing costs and environmental impacts of solar PV, battery technologies. Building upon a review of previous studies on the clustering methods applicable to a neighbourhood in Geneva, in this paper we devise a simulation tool easy to use that investigates the techno-economic assessment under different scenarios. For a given investment over 20 years, the model calculates the LCOE value, the autonomy level as well as the CO_2 emissions for each scenario. Different scenarios analyse the economic profitability for solar PV and battery. The solar PV and battery model is validated by using HOMER software and the simulation tool created by SI-REN. However, we find that, a decrease in electricity price and a concurrent increase in the selling price can increase the demand on solar PV and battery installation. For instance, if the demand on solar PV and battery installation increase, the prices of solar and battery installations will decrease and this will be profitable for the PV and battery model. A reduction gap between buying and selling price in grid for solar panel is recommended to increase solar installations. The electricity sector and market can allow shaping the future of solar PV installation and storage. We conclude that, under the assumptions of our model, to foster investments in solar PV and battery installations, the falling investments costs seems necessary for the future. In addition, integration of batteries into PV systems can help to reduce cost but will become a major challenge for the near future. Finally, in a future work, the model can be improved by changing the input parameters and the initial assumptions. In addition, the heating demand can also be integrated in the model in order to extend our investigation into both thermal and electrical energy simultaneously by adding solar thermal panel or heat pumps. Quantifying the level of integration of those other renewable energy scenarios can allow to get a more accurate and global model.

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