A parametric tool to evaluate the environmental and economic feasibility of decentralized energy systems.

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Abstract

A simulation tool is developed to make a comprehensive techno-economic and environmental assessment of a case study under different scenarios. Different capacity of solar and storage technologies are considered. The model calculates the levelized cost of electricity, the autonomy level and the CO_2 emissions. We demonstrate that the economic profitability of solar 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. We show that combining solar PV with battery system doesn't bring additional autonomy to the model for Geneva considering the present market prices for batteries and seasonal changes in solar energy potential. The validated tool is then extended to include the thermal demand and generation by adding heat pumps and solar thermal. The availability of thermal storage at a large scale and the generation over a neighbourhood are shown to increase the autonomy of the neighbourhood. Finally, multiple scenarios are also run by changing the input parameters to perform a sensitivity analysis of these parameters on the performance of the model. Under the assumptions of the model, to foster investments in solar PV and battery installations, falling investments costs seem necessary for the future.

Keywords: , Battery storage, Electricity price, Solar photovoltaic, Solar energy, Techno-Economic assessment, Thermal energy storage

1. Introduction

The extensive use of fossil fuels as primary source of energy is the major source of greenhouse gas emissions and is hence responsible for the current climate change [32]. Furthermore, the world population living in urban areas has since 2010, reached 50% and this figure is expected to rise to 75% in 2050 [55]. It is thus urgent to address both these critical issues by decreasing our

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carbon based energy and providing secure and sustainable sources of energy for the ever growing urban areas. Renewable energy technologies are expected to play a major role in Switzerland to face such societal challenges such as climate change, resource depletion and the abandonment of nuclear energy by 2050 as mentionned by the law [45].

Decentralized energy systems combining different renewable energy technologies are becoming more popular to establish a more sustainable and autonomous neighbourhoods [6, 21, 30, 31, 39]. Among the energy technologies available solar photovoltaics (SPV) is becoming promising, with the rapid improvement in energy efficiency and price reduction [49, 10]. Energy systems based on solar energy technologies are attractive because of the simplicity of the installations. Moreover, PV systems, for example, are scalable for applications ranging from watts to megawatts [54]. By 2050, it would be possible to meet around 20 percent of the current level of electricity demand in Switzerland through the use of photovoltaic systems only [44].

However, the stochastic nature of the resources is the main limitation to the installations of renewable energy systems [28]. Consequently, there are often gaps between consumption and the supply of the plants. Energy storage are one means to balance the fluctuations in the demand and generation [35],[25],[24]. Furthermore, solar and battery technologies are often installed at individual building scale while it could be interesting to look at such installation at neighbourhood scale. This will clearly improve the potential of integration of SPV/thermal panels and to be part of an integrated energy system.

A complete review of computational tools to analyse the integration of renewable energy systems was performed by Connolly et al., [14]. Previous studies highlighted the role of energy storage with renewable electricity generation [16] and the operation conditions of batteries in PV applications [33]. Other studies examined the economic viability of storage [28] and the use cases for stationary battery technologies [36] but it is necessary to analyze the economic and ecological cost of the combination of different energy storage strategies [22, 29]. Nonetheless, integrating storage technologies into solar PV systems increase the overall investment cost. It currently remains unclear when PV and storage investments will become economically interesting in a large-scale application. However, this requires a detailed techno-economic and environmental assessment considering the lifetime operation of the energy system. Energy interactions within the system, cash flow and environmental impact at both design and operation stages should be considered at the neighbourhood scale. The detailed assessment at neighbourhood scale have hardly been addressed to this extent [40, 50] and often require extensive sources of data and are not easy to use. Additionally, methods that have been developed in the past have a coarse temporal resolution which do not allow them to capture the dynamic of the generation and consumption. This makes it very difficult for the assessment and analysis of decentralized energy systems.

The capture and efficient utilization of renewable energy in today's energy markets requires multiscale integration of several factors, including matching of the resource and demands that would encourage the use of renewable energy

[54]. A simulation tool has hence been developed to analyze the economic and environmental aspect of the integration of several energy conversion units. The objective of this work is to setup and validate a robust, but easy to use, simulation tool and to evaluate the integration of solar energy and storage on a specific cluster of buildings in the Junction district of Geneva. The major aim of this study is to find the best configuration in terms of system size. Therefore, we will first estimate the cost of solar PV panel, batteries, solar thermal and heat pumps. Then we will define an accurate techno-economical cost model for the Geneva study case. Multiple scenarios will be studied with a combination of different energy storage size by changing the input parameters and initial assumptions to perform a sensitivity analysis and further analyze the future scenarios.

The remainder of this paper is structured as follows: Section 2 gives an overview of the techno-economical models, the general operating strategy of storage in a battery and the storage sizing methods. Section 3 explains the case study followed by the model results, the limitations and their environmental implications in Section 4. The paper concludes in Section 5 with some discussions and suggestions for future research.

Nomenclature

D_t	Hourly demand
E_{b}	Energy bought from grid
E_{s}	Energy sold to grid
eCO_2	CO_2 total emissions from specific technology [kg/kWh]
G_t	Hourly generation
IC	Installation cost of the technology - tax incentives
mCO_2	CO_2 unitary emissions of a specific technology in [kg/kW]
OM	Operations and maintenance cost of the technology
Q_c	Capacity of the specific technology in [kW]
Q_p	Generation of the specific technology in [kWh]
COP	Coefficient of Performance
LCOE	Levelized cost of energy [CHF/kWh]
LEA	Lead-Acid battery
LI-ion	Lithium-Ion battery
MSC	Minimum state of charge

NPV Net present value [CHF]

O&M Operation and maintenance cost

SI-REN Services Industriels des Energies Renouvelables de Lausanne

SPV Solar Photovoltaics

ST Solar Thermal

2. Methodology

We present here a comprehensive methodological approach used to integrate technical, economical and environmental aspects in the assessment of the energy system. The approach chosen for the current study aims at considering the energy and cash flows for 8760 time steps in one year and over 20 years. The inputs required for the model (energy demand, CO_2 emissions, cost for each technology) will be explained in the next subsections. Please see nomenclature for variables definition in the next sections.

2.1. Techno-economical models

2.1.1. Autonomy level calculation

The autonomy level is defined as the share of generation by the solar system that is directly used by the consumers and is calculated by simulating the electricity flows of the system over the year at an hourly resolution. It is thus assumed that whenever demand during the day meets the generation or available energy from the storage, the energy is consumed directly [28]. The ratio between electricity that is directly self-consumed and the total electricity demand defines the autonomy level and gives an indicator of the dependence on the grid. It is calculated with the Equation 1 :

$$Autonomy\ Level = \frac{\sum_{t=0}^{8760} (D_t - E_{b_t})}{\sum_{t=0}^{8760} D_t} \tag{1}$$

2.1.2. Levelized Cost of Energy (LCOE) Calculation

Levelized Cost of Energy (LCOE) is the net present value of the unit cost of electricity over the lifetime of a generating asset. It's 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 [11] . The LCOE calculation is based on the following formula:

$$LCOE = -\frac{\sum\limits_{y=1}^{y=20} NPV}{20 \times \sum\limits_{t=0}^{8760} D_t} \tag{2}$$

The NPV can be calculated as follows: for a given investment over y years, 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 of lifetime of the system [17]. Cash outflows takes into account the investment costs, the operations and maintenance expenses as well as the price of electricity bought from grid while cash inflows includes the price of excess electricity that is neither self-consumed nor stored, and is sold to grid. The NPV also include the replacement cost of technologies that would become obsolete within the duration of 20 years. In this model, the NPV is calculated with negative numbers to analyze the situation from the point of view of the user. NPV calculation for a given system is given with Equation 3.

$$\begin{aligned} NPV(y_1) &= E_s - E_b - IC \\ NPV(y_{2-20}) &= E_s - E_b - OM \end{aligned} \tag{3}$$

More importantly, the LCOE may vary strongly from one technology to another depending on the application. Note that from Eq. 2, an application with very high energy demand is likely to have a lower LCOE than an application with little energy demand. The LCOE gives with a useful metric to compare different costs of various technologies over the years and is here always computed as connected to the grid/network and is not calculated for a stand alone system (e.g. demand completely satisfied with only PV). More details on the calculation of the LCOE for different technologies will be given in Section 3.3.

2.1.3. CO_2 emissions

We calculate the specific CO_2 emissions based on the lifetime of the technology used.

$$eCO_2 = \frac{mCO2 \times \sum Q_c}{\sum\limits_{t=0}^{8760} D_t} \tag{4}$$

More details on the CO_2 emissions from each of the devices considered in the current study will be given in Section 3.3.

2.2. Dispatch algorithm

The operating strategy for storage in the energy system is shown in Figure 1. 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 defined as a threshold such that the energy stored in the battery cannot be used.

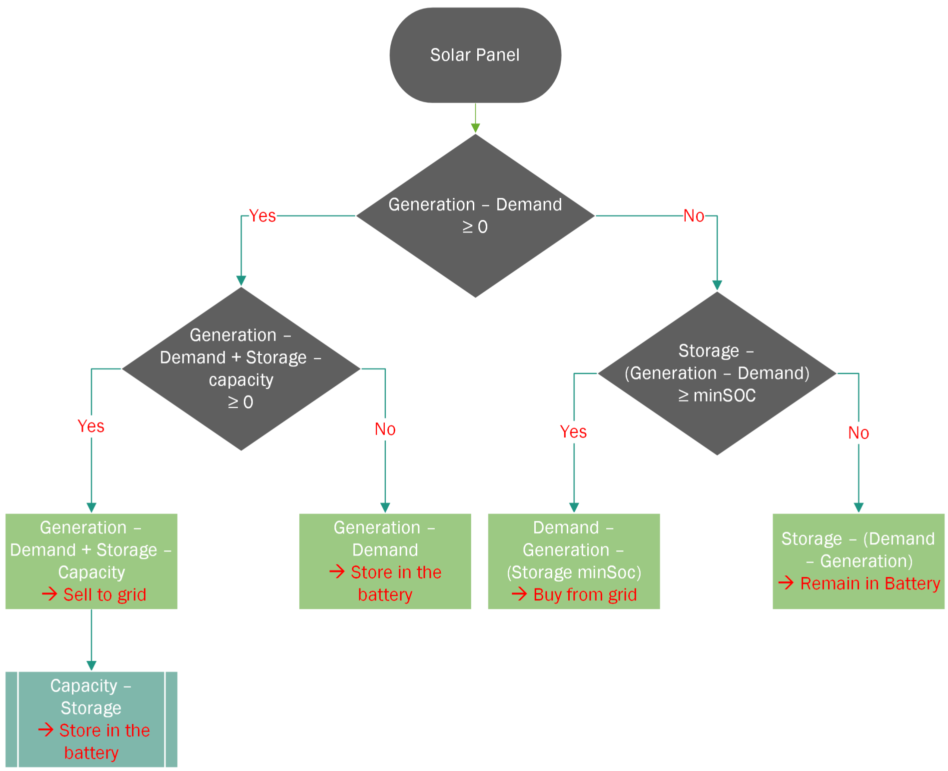

Figure 1: Strategy for the battery operations

2.3. Sizing of the storage

Currently, the sizing of the storage is usually done with respect to the demand. The advantage of using such a methodology is the optimization of the size of the batteries based on the demand. However, the drawback to this, is that the energy produced is not often consumed locally and hence the full potential of the generation of the system is not used [38, 23]. In order to address this, we propose here to determine the size of the storage by using an average day, representative of a typical day over the whole year and by integrating the area under the generation curve. This methodology will be further used to calculate the storage capacity of the battery and also the water tank capacity in Section 4.1.

2.3.1. Energy generation and demand

The PV electricity generation in kWh is obtained by using the available irradiation (obtained from the CitySim software) in hourly resolution for a specific cluster in the Junction District of Geneva. In a different study, we used the CitySim software to evaluate a more accurate generation from installed PV on top of individual buildings. Since this is outside the scope of this paper as we are working at the neighbourhood level, we only consider inefficiencies in the PV system, such as inversion losses, to calculate the solar PV generation and hence the irradiation is multiplied with a solar cell efficiency of 15%. The maximum capacity of solar PV installed is finally determined based on the peak generation of the cluster. The maximum hourly irradiation over the year in Junction District is 1.094 kWh/m^2 [5]. The maximum irradiation extracted from our data is equal to 16,279 kWh and this allows to determine a maximum roof area calculated in the Equation 5.

$$RoofArea = \frac{16,279}{1.094} = 14,880\ m^2 \tag{5}$$

Figure 2a illustrates the electricity generation and demand over a year. As can be expected the demand is higher compared to the electricity generated. Figure 3a illustrates the generation divided by the demand during different seasons. Clearly during the summer time, when the generation is higher than the demand, the excess energy can be stored. However it can be seen that when working with a time resolution of an hour, there are significant other periods during the year where the generation is higher than the demand.

The solar thermal generation 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 thermal grid, the solar thermal generation is multiplied with an efficiency of 80%. Figure 2b illustrates the generation and heating demand over a year. The mismatch between generation and heating demand can be stored in a boiler to be used when it is required. If the boiler capacity is reached, the excess energy produced during summer can be sold to the "grid". The efficiency of the boiler is set to 93%.

3. Case study

3.1. Junction District in Geneva

A neighbourhood containing approximately 800 buildings in the Junction district in Geneva, Switzerland is considered for this study. In a previous study, the electricity demand, the heating demand as well as the solar generation of each building were simulated using CitySim [43] for every hour (8,760 time steps) over one typical year [12] using the Meteonorm dataset [42]. The annual net electricity consumption variation of the district is modeled in the Figure 4(a).

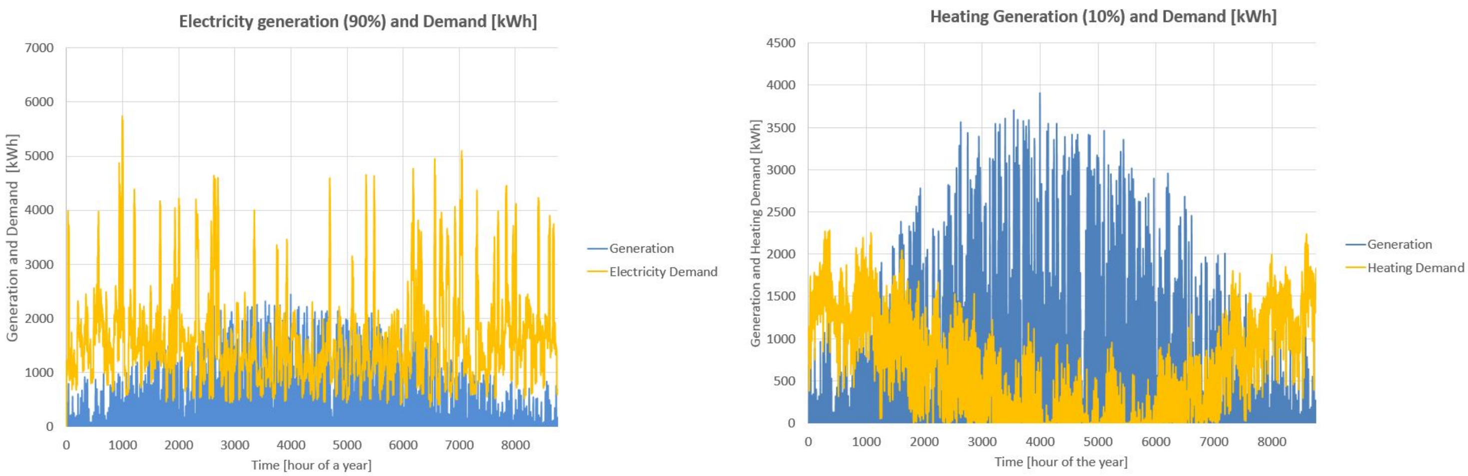

Figure 2: (a) PV electricity generation (Example with a solar PV capacity of 2197.7 kWp) and electricity demand over a year; (b) Solar thermal generation and heating demand over a year (Example with a solar thermal capacity of 1302.34 kWp)

Depending on the location, some buildings have a higher electricity demand than other buildings. K-means algorithm, based on the Euclidean distance, was 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 the current study, we will focus only on one of these clusters to determine the optimal energy system for one of the clusters (see Figure 4(b) for the green cluster with Nk=10.) Indeed, a similar analysis can be made by including all the other clusters to take into account the whole district, but this is beyond the scope of the study.

3.2. General assumptions

Since, we are modelling the Junction district of Geneva, we choose Swiss franc (CHF) as the currency (note that 1CHF is currently 1$). Naturally, all the houses are connected to the grid to cover the demand not supplied by the local resources. Based on a data analysis of consumer prices, the average price of electricity bought over the network in Geneva in 2016 is 20.6 cts/kWh [48] and the average selling price is 10.9 cts/kWh [48]. The price of electricity in Geneva has decreased by 7% compared to 2000 prices but has increased by 2% per year over the past two years [48]. In our model, we will however assume the general consensus that the electricity and the selling price increase every year by 2%. The average price of natural gas bought over the network in Geneva in 2016 is 6.3 cts/kWh [48]. We will also assume that the natural gas buying and selling price increase by 2% each year. The CO_2 emissions of the electrical grid in Switzerland are 0.155 kg/kWh. The CO_2 emissions of the electrical grid in Switzerland is determined based on hourly values of the electricity taken on the network during a specific day[2]. The CO_2 emissions of the electrical and

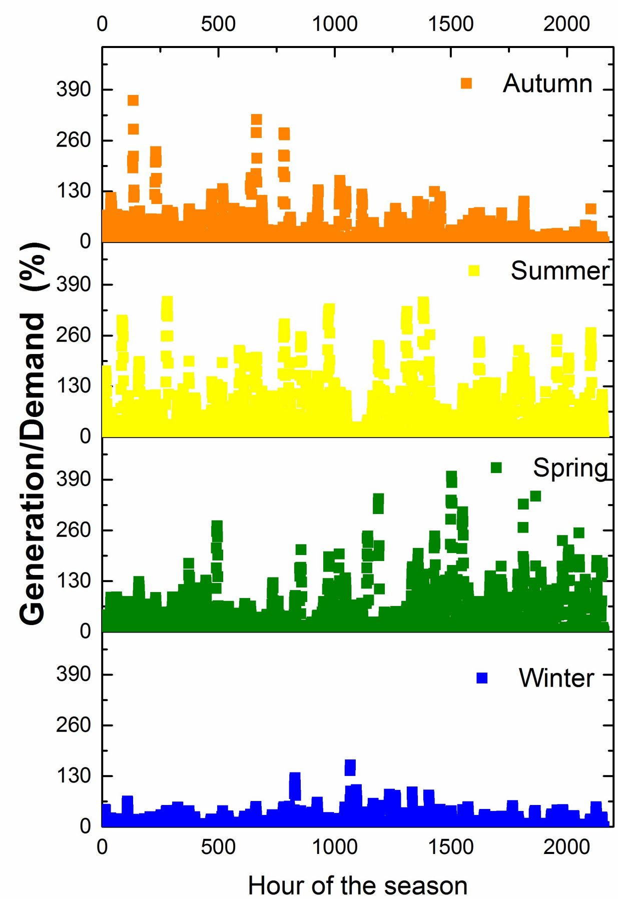

Figure 3: Solar PV generation (90% Scenario with a capacity of solar PV of 2,197.7 kWp) divided by the electric demand for different seasons

natural gas grid in Switzerland are 0.160 kg/kWh by considering that in 2015 the energetic mix in Geneva is composed by 5% of natural gas [47].

3.3. Energy system configuration scenarios

Different technologies are considered for the energy system: solar PV, solar thermal, storage technologies (lead-acid or lithium ion batteries) and also assisting energy technologies such as boilers and heat pumps. A combination of different components have been tested with multiple scenarios by changing their maximum installed capacity. In the next section, a detailed description of the four different scenarios are presented based on the input parameters that have

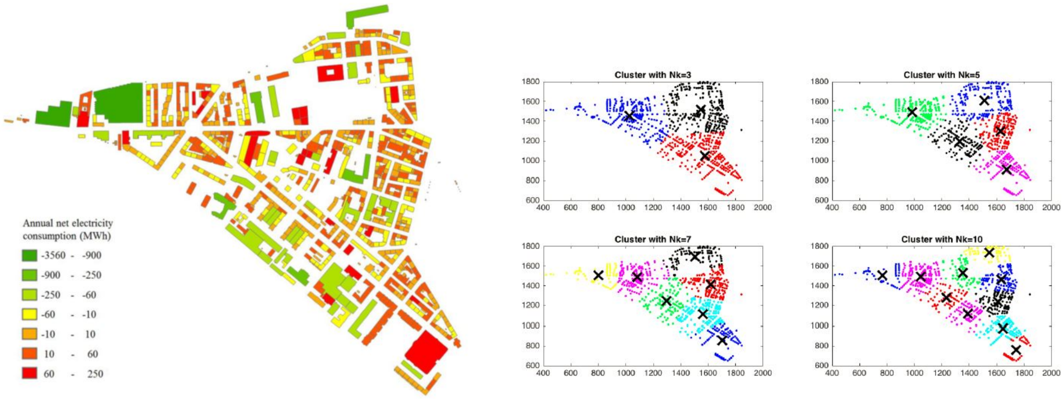

Figure 4: (a) Annual net electricity consumption in the Junction district in Geneva [27]; (b) Plot of the cluster in Geneva [27]

been entered in the model. An example scenario tree including all the combinations that we considered for solar PV and battery is described in Figure 5 (Scenario 3 and 4 not presented in the scenario tree).

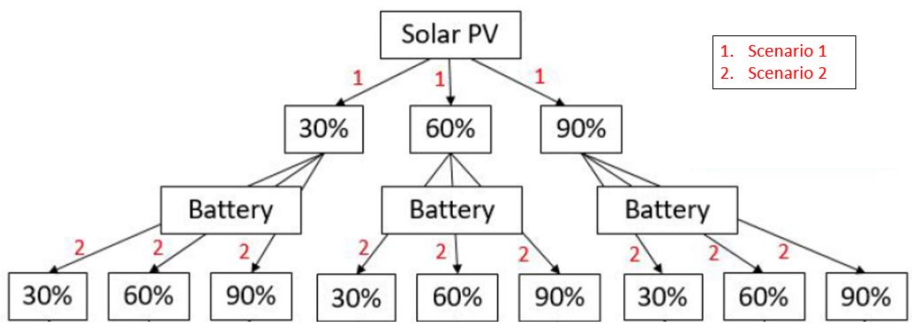

Figure 5: An example scenario tree including all the combinations that we considered for solar PV and battery (values at the top is for the first scenario and values below is for the second scenario including solar PV and battery)

3.3.1. Scenario 1 :Solar Panels

In the first scenario, 30%, 60% and 90% of the maximum capacity of solar panel will be considered. The input parameters for large scale PV system are summarized in the Table 1. The LCOE of PV by itself is calculated by taking into account all the cost during the lifetime of the technology such as the given investment, the O&M cost, the discount rates. The cost per kWh of solar PV is given in the Table 1. The entire PV system life cycle (transport, operation, electric installation, construction and production phase) is considered to calculate

Table 1: Economic input parameters for Solar PV

Solar Panel	Unit	Value	Sources
Cost	[CHF/kW]	1,350	[15]
Lifetime	[years]	20	[11]
O&M cost	[CHF]	1.5% of SP cost per year	[41]
CO_2 emissions	[kg/kWh]	0.03	[9] [46]
Electrical grid CO_2 emissions over a year without PV	[kg/kWh]	0.155	[2]
Electrical and natural gas grid CO_2 emissions over a year without PV	[kg/kWh]	0.160	[2]

Table 2: Economic input parameters for batteries

LEA Battery	Unit	Value	Sources
Cost	[CHF/kWh]	163	[4]
O&M cost	[CHF]	22	[41]
CO_2 emissions	[kg/kWh]	15	[26]
Lifetime	[years]	7	[26]
Efficiency	[%]	81	[26]
MSC	[%]	30	[26]
Energy density	[Wh/L]	100	[26]
LI-ion Battery	Unit	Value	Sources
Cost	[CHF/kWh]	440	[4]
O&M cost	[CHF]	19	[41]
CO_2 emissions	[kg/kWh]	70	[26]
Lifetime	[years]	15	[26]
Efficiency	[%]	92	[26]
MSC	[%]	20	[26]
Energy density	[Wh/L]	250	[26]

the CO_2 emissions for solar panels. Previous studies [20, 34] showed that the entire CO_2 emissions for PV system is 702.5 kg/kWp. The CO_2 emissions can be multiplied with the capacity for a given scenario according to the Equation (6) over a lifetime of 20 years. The formula given in Section 2.1.3 can be applied to find the CO_2 emissions of the PV system by multipliying 0.03 kg/kWh with the solar generation and by dividing it with the total hourly electricity demand.

$$eCO_2 = \frac{mCO2 \times \sum Q_c}{20 \times \sum Q_p} = 0.03 \frac{kg}{kWh} \tag{6}$$

3.3.2. Scenario 2 :Solar Panels and batteries

The second scenario combines different percentage of solar panels (30%, 60%, 90%) and batteries (30%, 60%, 90%). Two types of storage technology are

Table 3: Economic input parameters for thermal demand

Heat Pump	Unit	Value	Sources
Cost [VITOCAL 300-G]	[CHF/kW]	1,326.54	[56]
Lifetime	[years]	15	[3]
CO_2 emissions	[kg/kWh]	0.04	[57]
Solar Thermal grid	Unit	Value	Sources
Cost [Vitosol 200-F]	[CHF/m2]	432.6	[56]
Lifetime	[years]	20	[52]
OM	[CHF]	0.58 % of IC	[53]
CO_2 emissions	[kg/m^2]	0.040	[37]
Natural gas boiler	Unit	Value	Sources
Cost [Vitocell 100-L]	[CHF/m^3]	4,564.5	[56]
Lifetime	[years]	15	[1]
CO_2 emissions	[kg/m^3]	0.225	[13]

compared in this study: lead-acid battery and lithium ion battery. The input parameters for large scale batteries are described in the Table 1. The LCOE of PV and battery system by itself is calculated by taking into account all the cost during the lifetime of those technologies such as the given investment, the O&M cost for solar PV and batteries and their discount rates. For the year 20, we added the salvage value of a used battery (1/3 of the battery price after 20 years). We assumed that the battery price decreases each year by 7.6%. The energy efficiency reflects the losses during charging and discharging periods. The characteristics of these two types of battery are summarized in the Table 2 [8]. Note that we have not accounted for battery inverters in these scenarios.

3.3.3. Scenario 3 :Solar Panels and heat pumps

The third scenario combines different percentage of solar panels (30%, 60%, and 90%) as in the second scenario but in this case the electricity demand of the heat pump is added to satisfy the heating demand. We assume that the heat pump has a constant COP of 3.2, although the efficiency of heat pumps are subject to climatic conditions. The hourly heating demand is divided by the COP and is added to the current electricity demand. The LCOE of solar PV and heat pump by itself is calculated by taking into account all the cost during the lifetime of those technologies (investment, the O&M cost, the discount rates).

3.3.4. Scenario 4 :Solar Panels, heat pump and solar thermal

The fourth scenario combines different percentage of solar panels (30%, 50%, 70%), solar thermal panels (70%, 50%, 30%) that corresponds to the remaining available roof area and also heat pumps. In this scenario, the aim is to satisfy both the heating demand and the electricity demand. The input parameters for solar thermal panels and boilers are described in Table 3. Figure 6 shows the operations scheme of thermal storage.The heating demand that is not totally satisfied by using solar thermal panel is satisfied by using heat pumps.

The whole demand is then satisfied by using solar thermal panels, heat pump and solar PV. We assume here that a district heating network is installed (as proposed in the current construction plan of the district) and that excess heat produced in the district can be sold to the grid (6.3 cts/kWh).

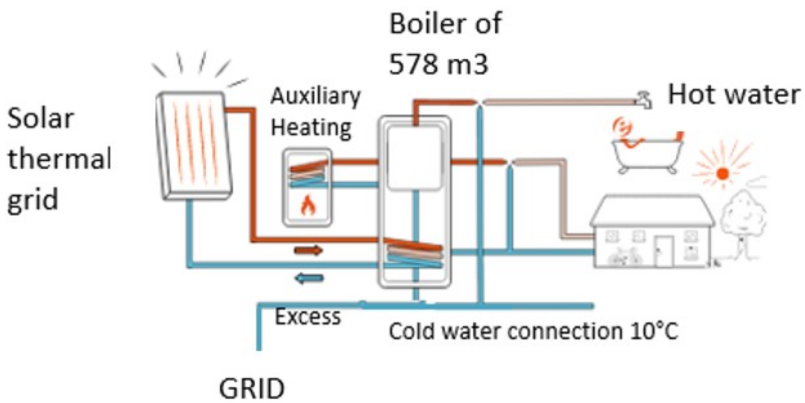

Figure 6: General operation scheme of thermal storage adapted from (Swissolar 2017)

4. Results and Discussions

4.1. Characterization of the system

The capacity of storage is determined based on the Figure 7 as the integral below the bold blue line (which is the average generation of the system). This calculation leads to a battery capacity of 7,582.9 kWh. As mentionned previously, the capacity of storage is only based on the average generation in order to maximize the use of the solar potential.

The capacity of boiler is determined based on the Figure 7. The calculation leads to the boiler capacity of 40,442 kWh. Using,

$$Q = mc_p\Delta\theta \tag{7}$$

The mass of water can be found with using c_p=4.2 kJ/kg/K, $\Delta\theta$=60 K (considering an application with water at 70 K) and Q= 145,591,200 kJ, which leads to a boiler of capacity of 578,000 kg or 578 m^3.

The maximum storage capacity for each technology are presented in the Table 4.

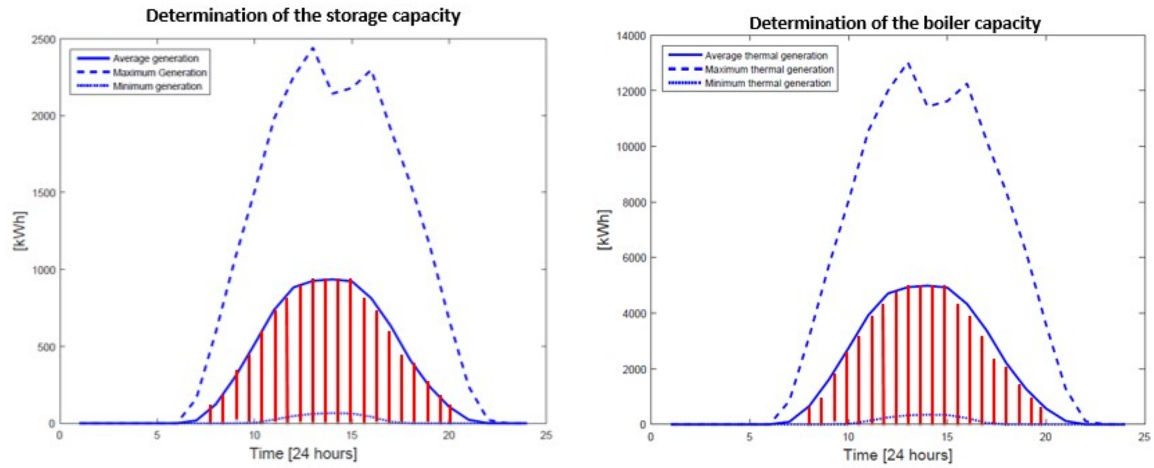

Figure 7: (a) Determination of the electrical storage capacity from the energy generation of the system (maximum, minimum and average); (b) Determination of the boiler capacity from the energy generation of the system (maximum, minimum and average)

Table 4: Energy technologies and the maximum capacity for each technology

Technology	Capacity
Solar PV panel	2,441 kW
Battery	7,582.9 kWh
Solar thermal panel	13,023.41 kW
Boilers	578 m^3
Heat Pump	4,070 kW

4.2. Model validation

In this section, the model validation with the PV system and battery is done. A comparison is made between the two first scenarios by only considering the electricity demand. The best scenarios are those that have the lowest LCOE value to be competitive with the grid price. In addition, we also try to choose the scenario that maximize the autonomy level and minimize the CO_2 emissions to have an energy system that is more autonomous and sustainable.

4.2.1. Solar PV panels

As expected, the autonomy level increase with the percentage of solar panel that we installed. An autonomy level up to 16% can be reached by using 90% solar panels. As can be seen, the CO_2 emissions is notably decreased (0.138 kg/kWh) with 90% solar PV in the roof compared to the CO_2 emissions of the electrical grid in Switzerland (0.155 kg/kWh). If we focus only on the economic competitiveness of the system, the best scenarios are those that minimize the LCOE value to be competitive with the grid price of 0.206 CHF/kWh. Nevertheless, it can be seen that the 90% scenario with a capacity of 2.2 MW still has

Table 5: Results for solar PV (scenario 1)

SP	LCOE [CHF/ kWh]	Autonomy Level	CO_2 emissions [kg/kWh]
30%	0.238	6%	0.148
60%	0.227	11%	0.143
90%	0.217	16%	0.138

a higher LCOE value (see Table 5). In addition, by considering the investment cost as well as the O&M cost of solar PV, we have obtained the LCOE of solar PV as a stand alone system. Figure 8 gives an example of the net present value calculation for solar PV over 20 years.

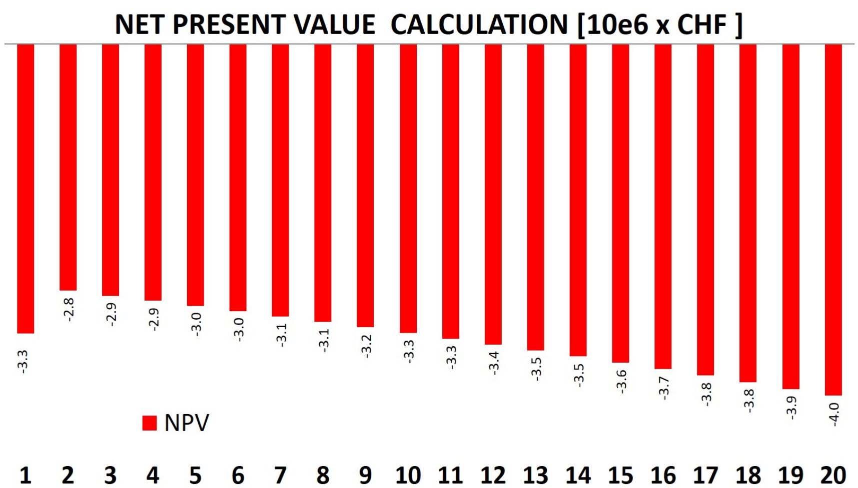

Figure 8: Net present value calculation for solar PV over 20 years

We validate our model with HOMER for the LCOE and with SI-REN for the autonomy level to test the robustness of the solutions obtained for solar PV panel. After a comparison of results with HOMER software, we obtain the same result 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 generation of 1,873,735 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 generation and the inflation rate to 1%, we obtain the same value for LCOE. We also compared the results with the simulation tool called "BARTpower" made by Services Industriels des Energies Rénouvelables de Lausanne (SI-REN). The results for 30% of solar panel are presented in Figure 9. We obtain the same value for the autonomy level which is 6% for 30% of solar PV.

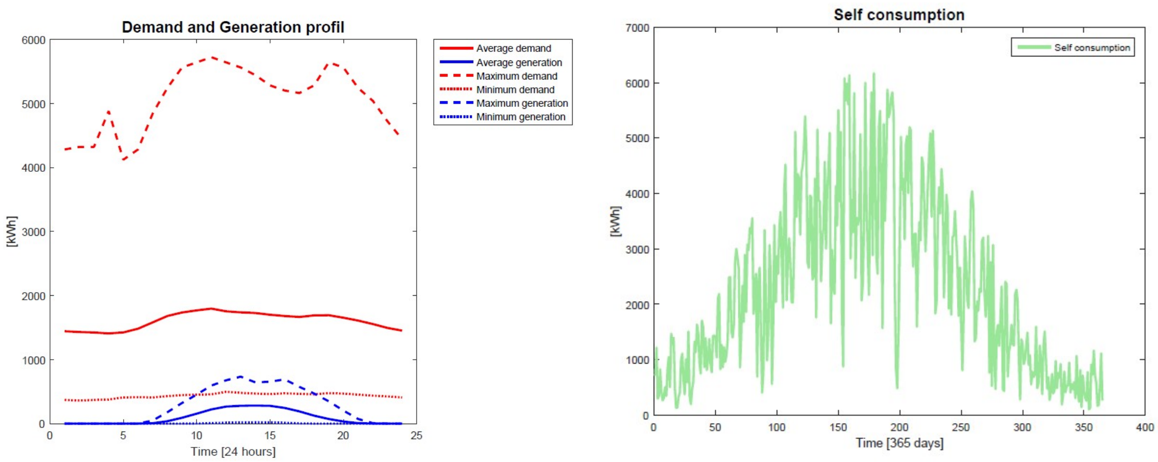

Figure 9: (a) Electric demand and solar PV generation profile for a typical day with a maximum, minimum, average demand and generation; (b) Autonomy level (Self-consumption) over a year for 30% scenario

4.2.2. Solar Panels and batteries

For this scenarios, our findings show that battery technology doesn't bring additional autonomy level for the considered electricity generation of our study case. Battery technologies are still expensive and add considerable additional cost to the PV system. For instance, the lowest LCOE that we obtain with a lead acid battery is 0.222 and with a lithium ion battery is 0.225 with 90% of solar PV and 30% of battery. The main drivers behind this variation of LCOE are the difference in investment cost between those two technologies. It seems that the integration of battery technology is still not profitable economically for large scale installation. A lower battery size of 30% is more adapted to reduce the LCOE. Moreover, a decrease in battery cost can allow a lower LCOE and can lead to a high economic viability of storage. In addition, by considering the investment cost as well as the O&M cost of battery, we have obtained the LCOE of battery as a stand alone system.

In a second step, we compared the results for solar PV and batteries with the simulation tool called "BARThome" made by SIREN. Similar values are obtained for the autonomy level. Note however that in "BARTHome", it is also possible to define the orientation of the solar PV panels.

4.3. Extension of the model with thermal demand

In the following section, the validated simulation tool is extended to include the thermal demand as well as the electricity demand. A comparison is made between the third and fourth scenario by considering the electricity demand as well as the thermal demand.

Table 6: Results for scenario 3 with solar panels and heat pump

SP	LCOE [CHF/ kWh]	Autonomy Level	CO_2 emissions [kg/kWh]
30%	0.264	5%	0.150
60%	0.243	10%	0.145
90%	0.224	14%	0.141

Table 7: Results for Solar Panels, heat pump and solar thermal

SP	ST	LCOE [CHF/ kWh]	Autonomy Level	CO_2 emissions [kg/kWh]
30%	70%	0.236	6%	0.150
60%	40%	0.230	11%	0.144
90%	10%	0.222	14%	0.141

4.3.1. Solar Panels and heat pump

Battery technologies are not used in this section because the previous findings demonstrate that batteries are not well adapted in a large scale application. Table 6 shows that the lowest LCOE that we obtained is 0.224 with 90% of solar PV. The heating demand as well as the electricity demand is satisfied in this scenario. The CO_2 emissions are again relatively lower than the grid since the system is now providing at least 14% of the demand as can be noted from the autonomy level figures. A higher autonomy level can be reached if the hours of operation of the heat pump would be in better correspondance with the production from the PV. This could be achieved for example by using real-time pricing to encourage use of locally produced energy during peak time hours.

4.3.2. Solar Panels, heat pump and solar thermal

The combination of 90% of solar panel and 10% of solar thermal with heat pumps gives an LCOE value of 0.222 with an autonomy level up to 14%. The autonomy level isn't maximized by adding solar thermal panel compared to the previous scenario with only solar PV and heat pump but the obtained LCOE values are much lower. Solar thermal allows to get an economically more advantageous possibility compared to the case where we only have heat pumps and solar PV. This system is an attractive process to generate both heating and electrical energy simultaneously by using solar thermal, heat pumps and solar PV panels. It offsets 0.01 CO_2 emissions per kWh with 90% solar PV and 10% solar thermal that is slightly higher than the Scenario 3 (see Table 7).

4.4. Cost sensitivity analysis and future scenarios

Finally, we present a sensitivity analysis by varying the input parameters. We extend our analysis to show the LCOE changes when varying the most critical input parameters that are covered by Scenario 1 and Scenario 2 with lithium ion battery. To analyze how the Scenarios 1 and 2 respond to a change of parameters first, we have varied the grid price and the selling price by -10%, -20%, +10% and +20%. As can be seen from Figure 10, the model is very

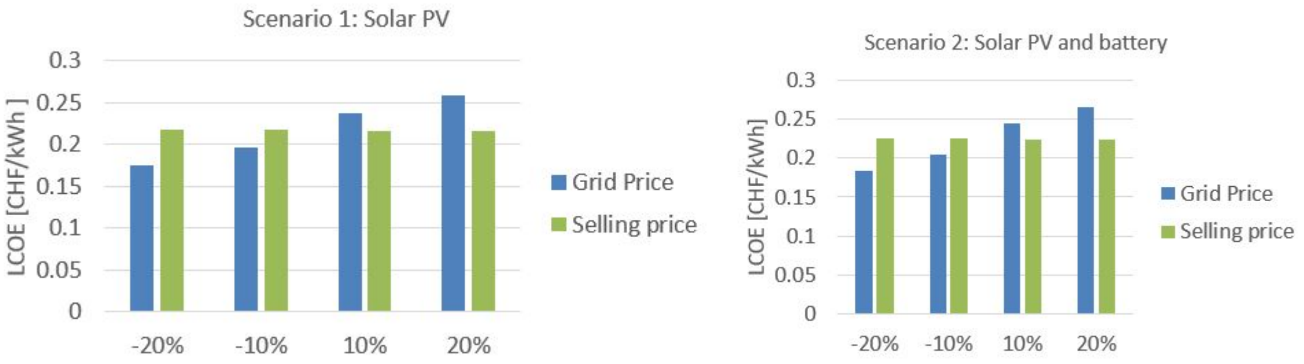

Figure 10: (a) Scenario 1 by changing the grid price and selling price; (b) Scenario 2 by changing the grid price and selling price.

sensitive to the variation of the grid price. A lower LCOE value is obtained by decreasing the grid price up to 20% and increasing the selling price up to 20%.

Current trends in Switzerland assume a decrease in electricity prices for 2017 and a concurrent increase in the selling prices that can lead to a high economic profitability for solar PV and battery scenarios.

The model is sensitive to changes in the assumption of future battery and solar PV cost decrease. The future scenarios were conceived by reducing the solar PV and battery investment costs. The cost for solar PV and battery is expected to decrease by 10% in 2020 and by 20% in 2025 respectively, according to [18]. If this is applied, then the following can be noted:

1. A decrease of 1% is observed between 2016 and 2025 in the LCOE value of the first scenario by only changing the solar PV price.
2. A decrease of 1% is observed between 2016 and 2025 in the LCOE value of the second scenario by only changing the battery price.
3. By changing the solar PV price as well as the battery price, the LCOE value decrease by 2% between 2016 and 2025.
   It becomes obvious that of all input parameters, the grid price, the battery and solar PV investment cost reduction have the greatest effect on the model.

The LCOE value fluctuates by the change of the solar PV and battery price (Figure 11). However, the obtained values for solar PV and battery are still not under the grid price that is 0.206. To be under the grid price, the LCOE value should decrease by 9% between 2016 and 2025.

4.5. Implications on the environment

Besides economic considerations, the adoption of PV, battery and solar thermal technologies depends on environmental factors. Solar PV system generates relatively low CO_2 emissions but the increase of battery diffusion in the markets raise the environmental pollution significantly. Lead acid batteries contain

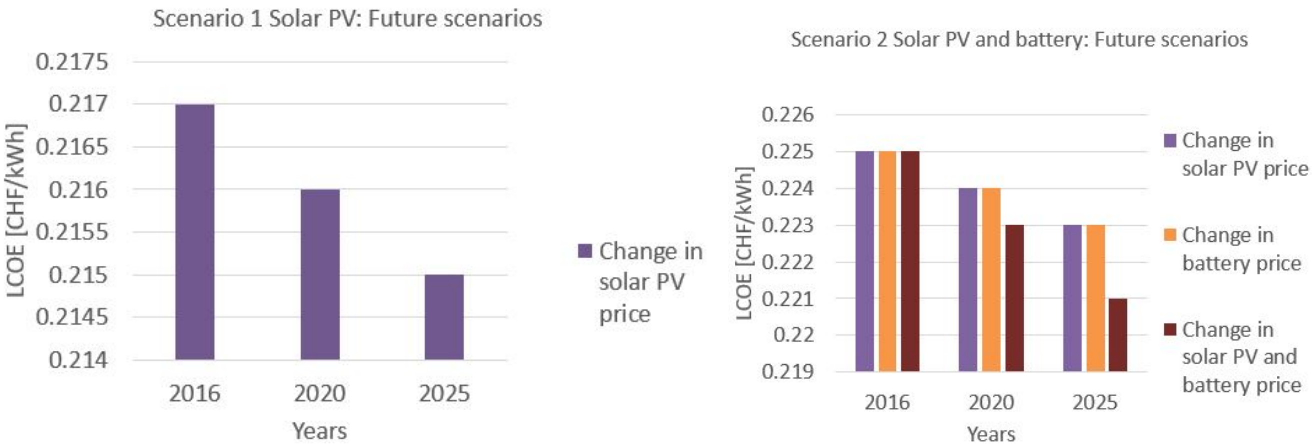

Figure 11: (a) LCOE in the "breakthrough" scenario 1 in 2020 with a decrease in the investment cost of solar PV by 10% and with a decrease by 20% in 2025; (b) LCOE in the "breakthrough" scenario 2 in 2020 and 2025 with a decrease by 10% and 20% respectively in the investment cost of solar PV and battery price.

sulfuric acid and are toxic and generate carbon emissions. These environmental impacts can be reduced by recycling the lead acid. The batteries can be charged many times, but after numerous uses, lead acid plates deteriorate and the battery loses its efficiency. Lithium-ion batteries contain among others, useful metals as cooper and aluminum as well as transition metals. Recycling processes for lithium batteries are also needed to enable a sustainable life cycle of these technologies. In Switzerland, nearly 70% of the commercial batteries are recycled in 2012 [19]. The total CO_2 emissions using 0% of solar PV and heat pump gives 0.003 kg/kWh. Combining 90% solar PV, 10% solar thermal with a heat pump give a total CO_2 emissions of 0.141 kg/kWh that is relatively lower than the case without the use of those technologies that is 0.160 kg/kWh.

The limitation of the thermal storage is the large water tanks because they have problems with corrosion and fouling. Instead of large water tanks, packages of gravel, rock, or massive parts of buildings can be more adequate to store thermal energy. Or storing heat in geothermal ground source or subsurface aquifer can be another solution to store properly thermal energy [26]. Although heat pumps system generates low carbon emission, combining solar PV and heat pump is not critical regarding the environmental impacts according to our findings but can be used as a means to completely satisfy demand.

4.6. 2000-watt society

In a future scenario, the heating demand can be decreased to achieve the 2000-watt society. The vision of a "2000-Watt Society" was developed at the Swiss Federal Institute of Technology (ETH) in Zürich. It is a model for energy policy which demonstrates how it is possible to consume only as much energy as worldwide energy reserves permit. It is possible when every person in every

Table 8: Results for solar PV (scenario 1) in a 2000-watt society

SP	LCOE [CHF/ kWh]	Autonomy Level	CO_2 emissions [kg/kWh]
30%	0.207	20%	0.134
60%	0.177	29%	0.129
90%	0.151	34%	0.129

Table 9: Results for solar PV and lead-acid battery in a 2000-watt society

SP	LEA	LCOE [CHF/ kWh]	Autonomy Level	CO_2 emissions [kg/kW]
90%	30%	0.164	44%	0.143
90%	60%	0.180	50%	0.161
90%	90%	0.200	52%	0.186

society limits their energy consumption to a maximum of 2000 watts [51] in 2050.The 2000-watt society's idea is to divide electrical and heating needs by four.So if the electrical demand is divided by four in a future scenario in 2050, an autonomy level of 34% can be reached by adding 90% solar PV in the roof with a relatively low LCOE value and CO_2 emissions of 0.151 CHF/kWh and 0.129 kg/kWh respectively (Figure 8). In addition, the findings show that battery technology (lead-acid battery or lithium-ion battery) can bring additional autonomy level for the considered electricity generation of our study case if we considered 2000-watt society's case as can be seen in the Table 9. An autonomy level up to 52% can be reached by adding a 90% lead-acid battery with 90% solar PV. The CO_2 emissions stay relatively high but the LCOE of 0.200 CHF/kWh is also competitive with the grid price (0.206 CHF/kWh).

Finally, to satisfy both thermal and electrical energy, the demand are reduced by four in a future scenario. By adding solar panel (90%), heat pump and solar thermal panel (10%), an autonomy level of 16% can be achieved with an LCOE value of 0.218 CHF/kWh and low CO_2 emissions (0.153 kg/kWh). After extending the model with thermal and electrical energy for a future scenario, the findings show that adding solar PV (90%) with 10% solar thermal and heat pump allow to achieve significantly low CO_2 emissions and a competitive LCOE value.

5. Conclusions and perspectives

The current study aims to present a decision-making support tool for urban planners, energy system designer and researchers by reviewing costs and envi-

Table 10: Results for Solar Panels, heat pump and solar thermal in a 2000-watt society

SP	ST	LCOE [CHF/ kWh]	Autonomy Level	CO_2 emissions [kg/kWh]
30%	70%	0.224	6%	0.167
60%	40%	0.221	11%	0.178
90%	10%	0.218	16%	0.191

ronmental impacts of solar PV, battery technologies, solar thermal panels and heat pumps. In this paper we devise a practical parametric simulation tool, that can be used at an early design stage, to investigate the techno-economic assessment at an hourly time step throughout a typical year.

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 analyze the economic profitability for solar PV, battery, solar thermal and heat pump. The solar PV and battery model is validated by using HOMER software and the simulation tool created by SI-REN. After validating the model for the electricity generation, in a second step, we extend our investigation with both thermal and electrical energy simultaneously by adding solar thermal panel and heat pumps.

In winter, a high autonomy level is more difficult to reach, whereas in summer the solar thermal and solar PV often produce excess heat and electricity. Although it could be expected in the future for thermal and electrical storage to bridge the gap between seasonal differences and imbalances, we have shown here for this case study that the addition of the storage did not bring significantly more autonomy to the system as most of the production is immediately consumed and only a small portion of the energy from the PV are stored in the battery (9%). According to our findings, combining solar PV with battery can lead to a high LCOE value because battery technologies are still expensive and are still not advantageous in a neighbourhood level.

A few factors can help the integration of solar PV. A reduction in the price gap between buying and selling price would increase the penetration of such systems. Moreover, a decrease in the solar PV price allows a decrease of the LCOE by 1%. Current trends in Switzerland, assume a decrease by 4% in PV installation cost in 2017 that can lead to a lower LCOE of 0.216 instead of 0.217. 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 it remains higher.

After extending the model both with thermal and electrical energy, we find that combining solar PV , solar thermal and heat pumps is economically more advantageous than the combination of only solar PV and heat pumps. Combining 90% solar PV panel, 10% solar thermal with heat pumps gives the best and lowest LCOE value to satisfy both the thermal and electrical demand. This combination allows reducing significantly the CO_2 emissions. This scenario is the best possible one from an ecological and economical point of view. By combining solar panels and solar thermal collectors together with a large volume storage tank, we can manage to heat and to produce electricity at the same time much more autonomously. Although the efficiency does not exceed 14%, solar PV can be used to produce hot water with an acceptable energy conversion efficiency in combination with heat pumps. The self-consumption of solar electricity can be maximized by adding a heat pump for heating but the operations hours of the heat pump with the sunshine must be regulated.

However, we find that, a decrease in electricity price and a concurrent increase in the selling price can increase the demand of solar PV and battery installation. The energy 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, a decrease in the costs of investments 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.

There were several limitations regarding the generation using PV systems, in this study. The orientation and the technology of solar PV panel are not considered in the model. This work can be improved by adding the orientation of panels or by working with a specific efficiency for different photovoltaics technologies or taking values from well known softwares such as CitySim or PVSyst. Although we have only considered a constant COP for the heat pumps, the modeling framework can be slightly modified to account for changing effiiencies in the future. On another hand, the limitation of solar PV and storage system is that we restricted the choice of battery technologies to two different types of battery. Another work could be done by considering other battery types for example flow batteries (vanadium-based). In addition, we consider an average electricity price in Geneva, different electricity price can be applied to the model. Electricity price tends to be higher during the day and lower during the night, two different prices or real time pricing as well as real time emissions, can be considered to improve the model. Some hours in the day are known as "peak hours" because electricity needs are high. By striving to use electricity, when possible, during off-peak hours, the peaks in electricity demand can be reduced. Nowadays, people alter their consumption depending on the prices, that is why it can be important to enhance the model. Storage can also have an implication on the economic value because two different prices can be applied: a price for buying electricity at night and reselling it to the grid at day times when electricity prices are higher. Our work has indeed shows that it is possible to use locally generated energy as a means for peak shaving and delay the beginning of the heating season.

This study showed that to achieve the vision of a "2000-Watt Society", a high autonomy level and low LCOE value can be obtained by using only solar PV panel. In addition, in this case, the integration of battery technologies with solar PV is interesting. An autonomy level up to 52% can be obtained with 90% solar PV and 90% battery to satisfy the electrical demand. In addition, if the model is extended in the future by taking into consideration both thermal and electrical energy, adding 90% solar PV with 10% solar thermal and heat pump is also advantageous. This combination permit in the future to achieve a low LCOE value and significantly low CO_2 emissions. Finally, in a future work, the model can be improved by changing the input parameters and the initial assumptions. This work can be extended by analyzing the economic and environmental assessment combining technologies such as hydro power, bio mass, geothermal energy that can be applicable to the Junction district of Geneva. Quantifying the level of integration of those other renewable energy scenarios can allow to get a more accurate and global model.

Acknowledgements

This research has been financed by the CTI (Commission for Technology and Innovation) within the SCCER Future Energy Efficient Buildings and Districts, FEEB&D, (CTI.2014.0119).

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