Sustainable energy supply for self-sufficient buildings with seasonal energy storages – parametric study

Andrii Zakovorotnyi
Lucerne University of Applied Sciences and Arts, Switzerland
andrii.zakovorotnyi@hslu.ch

Abstract. To reduce greenhouse gas emissions, the efficiency of energy supply systems must be increased, for example, using renewable energy sources. Since the generation of renewable energy can depend on weather conditions and other parameters, the use of short- or long-term energy storage enables an increase in the covered building energy demand. Due to the large number of available technologies for renewable energy generation and storage, it is possible to combine these systems into different energy supply concepts. By optimizing and comparing the designed concepts, the most suitable one can be determined with respect to the current and future investments. A comprehensive comparison of energy supply concepts must include both economic and energy evaluation criteria. This study focuses on parametric numerical simulations to identify economically feasible and sustainable energy supply concepts for a practical case of new residential buildings. The results show that electrical storage and on-site power generation can provide the greatest benefits. In contrast, large thermal storage systems are not economically viable.

1. Background and aim of the research
Solar photovoltaic (PV) systems and solar thermal collectors utilize solar energy and are important renewable energy systems for power and heat generation. According to [1], PV systems are the fastest growing renewable energy technology in the world with an annual increase of 20% in installed capacity. Heat pumps can be used to convert the electrical energy generated by PV systems into heating and cooling energy. Solar systems are weather dependent and electrical or thermal storage can improve the energy supply.

With a given initial investment and limited space, energy supply components can be selected and sized differently.

In the study on multi-objective optimization of a solar energy supply concept [2], a following methodological optimization approach is proposed:

1. Experimental study, where geo-solar system is investigated, in order to estimate their energetic characteristics (output power, efficiency, energy losses). The experimental results are further used in numerical study.
2. Numerical study, where a complete numerical model of a chosen renewable energy system with demand side (for example, building) is created and simulated for chosen period. The simulation results are further used in life cycle cost analysis.
3. Life cycle cost analysis, where the annual operation costs and savings, as also greenhouse gas emissions, are calculated.
However, in [2] only four designs of energy supply concept were studied - two designs of solar collectors and two designs of water storage tank. The life cycle cost analysis was done only for one combination of parameters.

The research [3] provides a comparison of the following energy supply concepts: (1) PV-system with lithium-ion battery and district heating and cooling, (2) PV-system with lithium-ion battery and heat pump, (3) PV-system with solar thermal collector and district heating and cooling.

The best scenario is optimized, considering the initial and operational costs to be minimized simultaneously. The results of the study [3] are shown in Table 1. As it can be seen, the scenario 2 (with a heat pump) has much lower annual energy costs, largest initial costs and an average payback period in comparison with other scenarios. But the key parameters that led to the system selection are not clear and should be further investigated.

**Table 1 - Comparison of annual economic indicators of each scenario simulated in [3]:**

| Scenario | Initial costs ($) | Operating and maintenance costs ($) | Annual energy costs ($) | Reduced energy costs ($) | Payback period (Years) |
|----------|-------------------|-----------------------------------|-------------------------|-------------------------|------------------------|
| 1        | 634’800           | 31’740                            | 32’631                  | 63’860                  | 9.9                    |
| 2        | 740’879           | 37’043                            | 5’400                   | 91’092                  | 8.1                    |
| 3        | 457’792           | 22’890                            | 27’400                  | 69’095                  | 6.6                    |

The research project [4] considers the optimization of energy supply of the city Chur (Switzerland) using numerical simulations. The optimal solution is situated on the presented pareto fronts (Fig. 1). However, it is unclear how the input parameters for the simulations are chosen, whether the same optimal solution can be achieved with different technologies and how high the optimal investments are.

**Figure 1 – Results of the study [4]:** Pareto fronts of the energy supply of the city Chur (Switzerland) for the years 2018, 2035, 2050: the optimal solution lies on the colored pareto fronts, grey points are simulated designs, which are not optimal. Optimal investments are, however, not identified

1.1. Focus of the present research

The focus of the present research is on use of solar energy in residential buildings. The research has two objectives:

1. to elaborate a methodology to determine the optimal energy supply concept considering predefined investments, usage, location and space.
2. identify the economically optimal energy concept for residential buildings with renewable energy sources.
2. Methodology

2.1. Evaluation criteria
To select the most appropriate energy supply system, each design being considered should be evaluated against certain criteria. Since all new and retrofitted buildings still have energy demand – electricity, space heating, heating of domestic hot water (DHW) – an energy supply system is necessary. Therefore, a reference scenario is chosen as the basis for further relative evaluation. Since equipment efficiency degrades over time, a fixed time interval \{years\} can also be considered in evaluation.

Based on comparison with a selected reference scenario, the following main evaluation criteria are proposed for a given time interval:

- **Investment profit** \{CHF\} as a difference between saved costs due to energy savings (compared to the reference case) and life-cycle costs (compared to the reference case).
- **Emission gain** \{kg CO2-eq.\} as a difference between saved emissions due to energy savings (compared to the reference case) and savings during the life-cycle (compared to the reference case).

2.2. Numerical simulations and setup of parametric study
The estimation of annual performance of energy supply systems can be investigated by using numerical simulations analog to [2, 3, 4]. For the numerical simulations in the current study, a stand-alone web-application is used. This web-application is available at https://builergy.ch and allows to run an annual simulation with an hourly timestep for different configurations of energy supply systems (Table 2). The simulation estimates the investment profit and emission gain.

**Table 2 – Types of components available in simulation web-application** https://builergy.ch

| Category          | Type                          | Description                                                                 |
|-------------------|-------------------------------|-----------------------------------------------------------------------------|
| Energy consumer   | Space heating demand          | Annual profile is set on hourly basis                                        |
|                   | DHW heating demand            |                                                                             |
|                   | Electricity demand            |                                                                             |
| Energy supply     | PV-system                     | Application carries out calculations for the whole year with an hourly timestep and considers the sun position, angles of inclination and heat losses of panels. |
|                   | Solar thermal collectors      |                                                                             |
|                   | Electrical power grid         | Input / Output power can be limited                                          |
|                   | Conventional heating device   | Output power can be limited                                                 |
|                   | Heat pumps (HP)               | COP and power of HPs for space heating, DHW heating, charging and discharging of thermal storage |
| Energy storage    | Electrical Storage “El. Stor.” | Total capacity, maximal input/output power, charging / discharging efficiency can be considered. (chemical battery) |
|                   | (water tank with insulation)  | 5-nodes dynamic thermal model with temperature stratification and heat losses |

The algorithm is based on governing equations described in [5], Chapter “On-Site Generation, Power Conversion, and Storage”:

- electricity production of PV-system is modelled according to “20.3.1 Simple Model”
- thermal solar collector – according to “18.4.1 Flat-Plate Solar Collectors”
- electrical storage – according to “20.2.8 Electrical Storage – Simple Energy Balance Model”
- heat pump – according to “15.2.11 Single-Speed Electric Heat Pump DX Air Heating Coil”
- thermal storage – according to “19.3.3 Stratified Water Thermal Tank”

For a parametric study, numerous simulations scenarios with different input parameters must be simulated. The distribution of input parameters in given range can be various: uniform, normal, random. It is proposed to perform a sensitivity analysis to identify the distribution of input parameters.
3. Case Study – two apartment buildings in Zürich, Switzerland

3.1. Case Definition

A practical design example of two new multi-family buildings is studied to determine the preferred energy supply design [6]. The reference case includes a PV-system, two air-to-water heat pumps covering the DHW and space heating demand. Further parameters are:

- energy reference area: 4250 m²
- electricity demand: 19.8 kWh/(m²·a)
- DHW heating demand: 20.5 kWh/(m²·a)
- space heating demand: 26.8 kWh/(m²·a)
- area of PV-system: 60 m² roof, 1600 m² facade (317 kWp, 211 MWh per year)
- Investment limit – 10⁵ CHF
- Costs for electrical storage – 900 CHF/kWh
- Costs for thermal storage – 1200 CHF/m³
- Swiss grid emissions – 0.102 kg CO₂-eq./kWh
- El. tariff – 0.12(buy)/0.07(sell) CHF/kWh
- Th. Stor. embedded energy – 175 kg CO₂-eq./m³
- El. Stor. embedded energy – 120 kg CO₂-eq./kWh

Using the proposed methodology, the capacity of electrical storage (li-ion battery) and the volume of the thermal storage (steel water tank with thermal insulation) shown on Fig. 2 must be optimized.

![Figure 2 – Scheme of the investigated energy supply concept for two apartment buildings [6]: electricity and heating demand is covered by a PV-system, power grid and air-to-water heat pumps. Overproduction of the PV-system is stored in electrical and heat storages (using heat pump) or is sold to the power grid.](image)

4. Results of sensitivity analysis and parametric study

In order to investigate the wide range of possible solutions of energy supply, the capacity of the electrical storage was varied in a range from 1 to 210 kWh, while the volume of thermal storage was varied in a range from 0.1 to 210 m³. The results of sensitivity analysis are shown on Fig. 3 and state that the self-sufficiency is largely influenced by the capacity of electrical storage can. The volume of thermal storage above 8 m³ has a negligible impact on self-sufficiency.

![Figure 3 – Results of sensitivity analysis for two parameters of energy supply concepts: capacity of electrical storage (left), volume of thermal storage (right): self-sufficiency of energy supply is more sensitive to the capacity of electrical storage rather than to the volume of thermal storage.](image)
Fig. 4 shows the results of parametric study – savings of emissions during 30 years of operation, gained over the embedded energy, for different energy supply scenarios. The results are relative to the reference case (energy supply scenario without thermal and electrical storages). As it can be seen, the highest possible accumulated saving of emissions with a predefined investment limit of 100’000 CHF is around 200 t CO₂-eq. (appr. 7 t CO₂-eq. per year). This value corresponds to the scenario, where the capacity of the electrical storage equals to 110 kWh and the volume of thermal storage lies between 4 m³ and 8 m³ (Fig. 4 – Cluster 2 and Cluster 5).

The evaluation of an economically optimal investment is shown in Fig 5. The economically optimal scenario lies in Cluster 1 and includes 2 kWh Li-ion battery and 4 m³ steel water tank. The investments above 100’000 CHF are for the considered time frame (30 years) not economically feasible.

In comparison to [3, 4], economically optimal solution for the time frame of 30 years is determined and it requires the initial investment below 10⁴ CHF, which is only 10 % of investment limit. The energetically optimal solution by 10⁵ CHF investment has lower positive investment profit (see Fig. 5).

**Figure 4** – Saved emissions, which can be gained over the embedded energy after 30 years of equipment operation, in comparison with the reference case (without thermal and electrical storages). According to pareto front, emission profit increases with the investment below 170’000 CHF and then decreases, since the rise of annual savings is slower than rise of embedded energy of storage systems.

**Figure 5** – Amount of saved costs, which can be gained over the returned initial investments after 30 years of equipment operation, in comparison with the reference case (without electrical and thermal storages): small storage systems require less initial investment, however, bring relatively substantial annual energy savings.
5. Discussion
The results of the numerical study show that investments required for economically optimal energy supply are different from investments required for the most sustainable option. However, an intermediate solution between these two options can be chosen.

Investigating different time intervals can change the optimized design. Considering longer time intervals increase the similarity of solutions between the economically and energetically optimal energy supply designs.

In this case, the definition of the realistic time frame of equipment operation is essential.

Consideration of long-time interval also implies the consideration of climate change, change of energy demand of the buildings, change of greenhouse gas emissions of power generation and prices for electricity and other energy carriers. Such forecast is a focus of the future research.

6. Conclusions
- Renewable energy sources and energy storages give an opportunity for new and retrofitted buildings to further reduce their greenhouse gas emissions.
- Optimization of energy supply concept is a multi-dimensional task, which needs a comprehensive evaluation methodology to make sustainable energy supply systems economically feasible.
- Numerical simulations of energy supply systems offer the possibility of estimating annual energy parameters that can be used to assess cost and greenhouse gas emissions savings. The presented methodology demonstrates how to find the economically optimal and most sustainable energy supply designs for residential buildings.
- The energy supply system with the highest investment profit is different from the energy supply system with the highest emission gain.
- Forecasting of future building energy demand, prices for energy carriers and greenhouse gas emissions of power generation can increase the accuracy of the optimization results.

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