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Flexibility implications of optimal PV design: building vs. community scale

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Abstract. The Swiss Energy Strategy 2050 aims for a significant increase in renewable energy generation, with photovoltaic (PV) energy having the largest share. Such development challenges the balance between electricity supply and demand, which can be partly mitigated through optimized PV integration together with energy storage systems. This study investigates the optimal placement of rooftop and façade PV for a small energy community considering investment and operational costs, embodied and operational emissions, and financial and environmental benefits of excess on-site electricity production, as well as batteries and different heating system options. Additionally, a methodology is developed to quantify energy flexibility needs at both the building and community scale. A case study neighborhood, comprising three single-family and two multi-family homes is optimized across different scenarios. Results show that when individual self-consumption is considered, installing an air-to-water heat pump system with a heating buffer tank allows for smaller PV systems with better grid interaction conditions. When collective self-consumption is considered, an overall reduction in PV system size is observed, contributing to reduced energy flexibility needs by effectively lowering peak feed-in power and improving the match between on-site PV production and demand.

Keywords: Collective self-consumption, Energy community, Energy flexibility, Multi-objective optimization, Photovoltaics

1. Introduction

Swiss Energy Strategy 2050 [1] involves a significant expansion in renewable energy capacity, where photovoltaic (PV) production is expected to cover 40% of the annual electricity production in 2050. With higher shares of PV integration, the grid faces an increasing challenge of matching electricity supply and demand. This, in turn, increases energy flexibility requirements [2]. Existing studies show that the optimal PV installation decisions (i.e., capacity and placement) for one single building lead to a reduction in *operational* cost and greenhouse gas emissions [3]. Additionally, there is a trend towards optimizing PV installation for collective self-consumption, i.e., within private self-consumption communities [4]. Moreover, PV installation combined with batteries and inter-building energy exchange within an energy community can significantly increase the self-consumption of the community [5]. However, these studies do not assess and compare building and community-level optimization impact on energy flexibility needs, while considering different energy flexibility options. This study investigates the optimal placement of rooftop and façade PV for a small energy community considering investment and operational costs, embodied and operational emissions, and financial and environmental benefits of excess on-site electricity production, as well as different energy storage options. We present a methodology to quantify energy flexibility needs at both building and energy community scales. **The results compare energy flexibility needs of the case study community for building- and**

community-level optimization. Different flexibility options are considered across four scenarios. The remainder of this paper is organized as follows. The methodological framework is described in Section 2 and a case study is presented in Section 3. Section 4 summarizes the results followed by conclusions in Section 5.

2. Methodology

The overall process flow is summarized in Figure 1, which includes modeling and multi-objective optimization. DesignBuilder was used to model building construction and energy systems, and the baseline models were further modified in EnergyPlus to apply loads and hourly schedules in accordance with SIA 2024 [6], as described in Subsection 2.1. Subsection 2.2 introduces optimization parameters and objectives defined using jEPlus [7] and jEPlus+EA [8]. Assessment indicators are explained in Subsection 2.3.

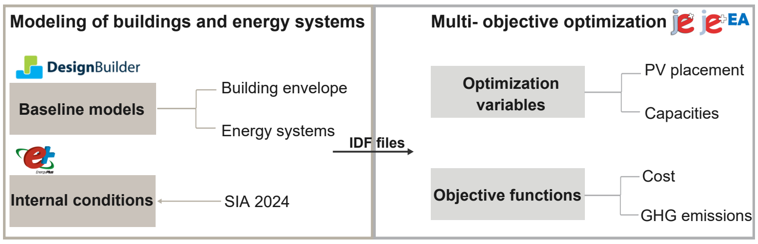


Figure 1. Process flow of building modeling and multi-objective optimization.

2.1. Modeling of buildings and energy systems

The database of CESAR-P [9] was taken as input for building constructions based on the construction year. In the baseline models, PV panels for rooftops and eastern, western, and southern façades were modeled. The weather profiles of the year 2018 were obtained from Meteoswiss [10] and used for both simulating hourly heating demand and on-site PV production. Different heating systems were considered to supply space heating demand, while domestic hot water demand was assumed to be supplied exogenously. Specifically, both air-to-air heat pump systems and air-to-water heat pump systems with a heating buffer tank and floor heating systems were modeled with a rule-based controller, following the heating setpoint schedule derived from CESAR-P. Additionally, battery systems were modeled to store excess on-site PV generation.

Both individual and collective self-consumption were modeled. Electricity exchange occurred directly between each building and the grid for the individual case. The excess on-site production was either stored in batteries or fed back to the grid. For the collective case, a virtual sink was considered for the energy community to share the excess production within this neighborhood. This neighborhood was assumed to have one meter for billing from the perspective of the energy supplier. In this case, the aggregated demand and generation profiles of the entire neighborhood were considered in the optimization. Both scenarios were simulated for one year with a time step of 1 hour.

2.2. Multi-objective optimization

The economic and environmental assessments were performed using the non-dominated sorting genetic algorithm (NSGA-II). The model was executed to optimize the placement (i.e., tilt and azimuth angles) of rooftop and façade PV panels and the sizing of PV and battery systems, in order to find a trade-off between the objective of minimizing the total annual cost and the objective of minimizing the total annual greenhouse gas emissions.

Several variables were defined in jEPlus to represent the sizing, tilt, and azimuth angles of rooftop and façade PV panels and the capacity of battery systems. The azimuth angle of PV panels installed on rooftops was set to range from 90° to 270° with a step size of 5°, and the tilt angle ranges from 0° to 45° with the same step size. To prevent self-shading between each row of rooftop PV panels, the spacing between each row was calculated as a function of the tilt angle.

The sizing of PV panels ranged from 0 to cover the maximum available areas with a step size of one standard PV module. The capacity of each battery system was set to vary from 0 kWh to 100 kWh with a step size of 1 kWh.

The first optimization objective was to minimize the annualized total cost, taking into account the annual capital investment of rooftop and façade PV panels [11] and battery systems [12], the annual operational cost due to electricity imported from the grid [13], and annual revenue from the feed-in of excess on-site production [14]. The second objective was to minimize the annualized total greenhouse gas (GHG) emissions, considering the annual embodied emissions of rooftop and façade solar panels [15] and battery systems [16], the annual operational emissions due to the electricity imported from the grid, and annual offset emissions of exporting the excess on-site production back to the grid. Dynamic GHG intensities of consumed electricity from Swissgrid of the year 2018 at an hourly resolution were obtained from reference [17]. Constraints were formulated to represent the energy balance and the technical characteristics of the energy systems.

2.3. Grid interaction indicators

The subsection presents quantification methods for assessing energy flexibility needs. Quantitative energy flexibility indicators were used to describe grid interaction conditions focused on the hourly net load profile (Eq. 1). Positive values represent electricity imports and negative values indicate excess production being fed back to the grid. The capacity factor (Eq. 2) sums up the absolute value of the net load over a year, and a higher value indicates a larger amount of energy exchanged with the grid. Load variability [18] is calculated as the change in net load between time steps (Eq. 3), with higher values indicating greater challenges for grid operators.

$$P_{net,t}=P_{demand,t}-P_{production,t}+P_{battery,t} \tag{1}$$

$$\text{capacity factor} = \sum_{t=t_1}^{t=t_2} |P_{net,t}| \cdot \Delta t \tag{2}$$

$$\text{load variability} = \sqrt{\frac{\sum_{t=t_1}^{t=t_2} (P_{net,t+1}-P_{net,t})^2}{t_2-t_1+1}} \tag{3}$$

3. Case Study

A case study neighborhood consisting of three single-family houses (SFH) and two multi-family houses (MFH) in Zurich of Switzerland was selected to showcase the proposed methodology. Relatively new buildings (SFH3 and MFH2) were modeled with heat pump systems to fulfill the heating demand, while the old ones (SFH1, SFH2, and MFH1) were assumed to use natural gas boilers for heating. As described in Table 1, four scenarios are considered, where each scenario considers optimizing for both individual and collective self-consumption.

Table 1. Scenario description

	Heat pump	**Thermal storage**	**PV**	**Battery**
Scenario 1	air-to-air		✓	
Scenario 2	air-to-water	✓	✓	
Scenario 3	air-to-air		✓	✓
Scenario 4	air-to-water	✓	✓	✓

4. Results and discussion

This section presents the optimization results of the four scenarios, for both individually and collectively optimized approaches. Results for scenarios 3 and 4 indicate that there is no installation of batteries and that the optimized PV installation decisions in these scenarios are identical to scenarios 1 and 2, respectively. Therefore, only the results for scenarios 1 and 2 are presented in the rest of the paper.

Figure 2 shows the total capacity of rooftop and façade PV systems for the whole neighborhood. At the CO_2 optimal point on the Pareto curve where the costs are the highest, when collective self-consumption is considered, an overall reduction in PV system size (25% - 37%) is observed, which is due to the exchange of excess on-site PV production within the neighborhood. The difference between scenario 1 and scenario 2 is most evident in the individually optimized case. When optimized individually, in scenario 2, the space heating load is shifted to non-peak hours during the day for SFH3 and MFH2, which allows for smaller rooftop PV systems to be installed.

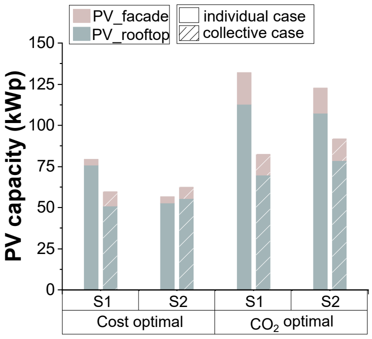
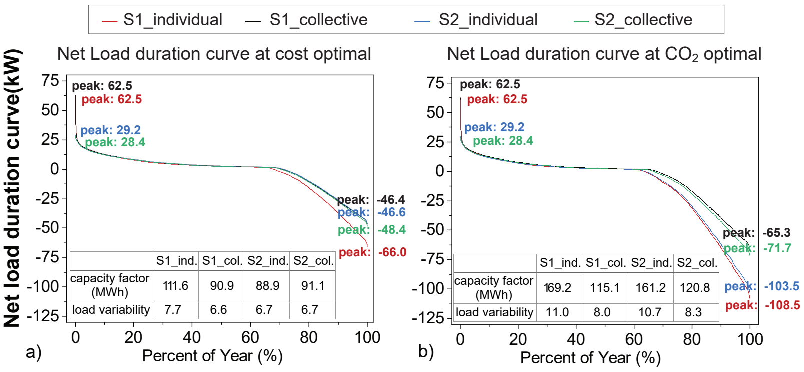


Figure 2. Total capacity of installed rooftop and façade PV systems.



a)

	S1_ind.	S1_col.	S2_ind.	S2_col.
capacity factor (MWh)	111.6	90.9	88.9	91.1
load variability	7.7	6.6	6.7	6.7

b)

	S1_ind.	S1_col.	S2_ind.	S2_col.
capacity factor (MWh)	169.2	115.1	161.2	120.8
load variability	11.0	8.0	10.7	8.3

Figure 3. Net load duration curve of the neighborhood at: a) cost-optimal point on the Pareto curve and b) CO_2-optimal point on the Pareto curve.

Figure 3 shows the net load duration curve of the neighborhood for both individual and collective self-consumption. At both cost and CO_2 optimal points, four curves overlap for over 60% of the year with different values of peak net demand power and peak net feed-in power. Collective self-consumption mainly contributes to reducing peak net feed-in power (30% - 41% reduction) with smaller PV systems installed for scenarios 1 and 2, indicating a better grid interaction condition that lowers the need for an infrastructure upgrade. The installation of air-to-water heat pump systems with heating buffer tanks shifts the heating demand to non-peak hours, thus significantly reducing the peak demand. This can be quantified by the overall reduction in capacity factor (5% - 20%) and load variability (3% - 13%).

Figure 4 presents the total electricity exchange of the neighborhood for scenarios 1 and 2. The impacts of collective self-consumption and thermal storage systems can be observed; collective self-consumption leads to a smaller amount of feed-in energy, while thermal storage systems effectively reduce the peak net import power of the neighborhood. Moreover, the contribution of each building within this energy community is different. *MFH2*, with the largest rooftop and the highest electricity demand, is always a net electricity exporter, whereas the roles of the rest switch between being net importers and net exporters of energy depending on the size of PV systems installed.

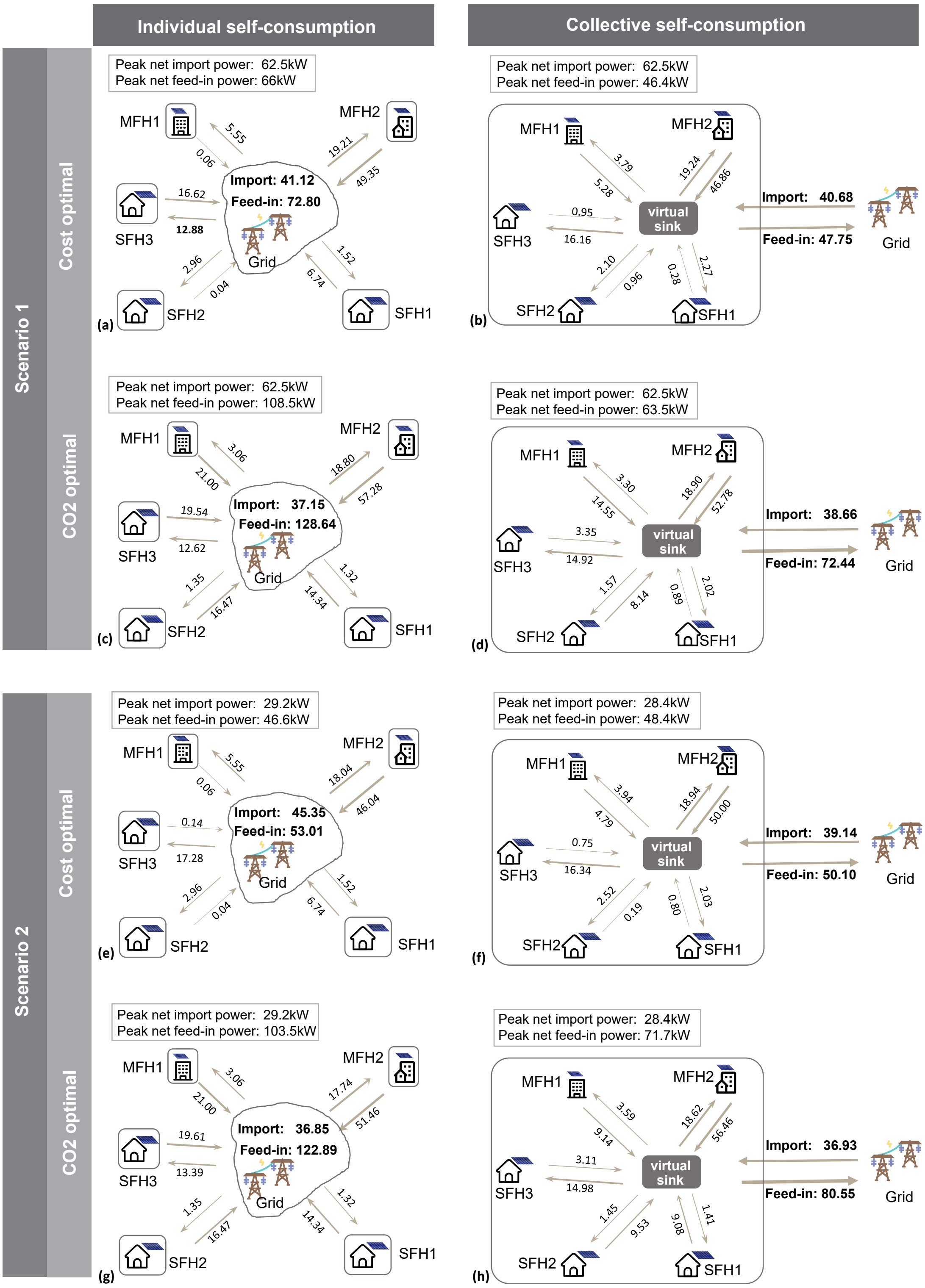


Figure 4. Electricity flow among individual buildings, the aggregated neighborhood, and the electrical power distribution network for both individual and collective optimization for scenarios 1 and 2 at both the cost and emission optimal points. Peak net power is shown with kW; annual energy in MWh is shown without units for conciseness.

5. Conclusion

This paper presented a methodology for evaluating the optimal PV installation decisions considering multiple indicators and influencing factors. Specifically, economic and environmental indicators, the impacts of individual and collective self-consumption, and the quantification of required energy flexibility are considered in four scenarios using an optimization-based approach. A case study neighborhood, comprising three single-family and two multi-family homes, is used to demonstrate the approach. When individual self-consumption is considered, inclusion of thermal storage systems results in better grid exchange profiles with an overall reduction in capacity factor (5% - 20% reduction) and load variability (3% - 13% reduction). Furthermore, collective self-consumption leads to an overall reduction in PV system size (25% - 37%), contributing to reduced energy flexibility needs by effectively lowering peak feed-in power (30% - 41% reduction). Future work will investigate the impacts of different policies related to excess PV generation (i.e., environmental and economic benefits of surplus generation being fed into the grid) on installation decisions. Additionally, we will extend this study to consider optimization during the operation phase (e.g., demand-side management) and to assess its potential for addressing energy flexibility needs at different timescales.

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