Impact Analysis of Solar PV Integration and Heating System Retrofit: A District-Level Energy System Model

Ueli Schilt[1,2], Manuel Meyer[1], Sarah Schneeberger[1], and Philipp Schuetz[1]

[1] Competence Centre for Thermal Energy Storage, School of Engineering and Architecture, Lucerne University of Applied Sciences, Horw (Switzerland)

[2] School of Architecture, Civil and Environmental Engineering, École Polytechnique Fédérale de Lausanne (EPFL), Lausanne (Switzerland)

Abstract

The transition from fossil-based to renewable energy systems requires the integration of decentralized energy technologies such as solar photovoltaic (PV). Therefore, it is essential to evaluate multi-energy systems with different spatial and time resolutions. This study presents the first results of a multi-energy system model for the evaluation of district-level energy scenarios in Swiss communities. The model assesses both heat and electricity demand while estimating the potential for integrating decentralized renewables and retrofitting fossil heating systems with low-emission alternatives. Computations are carried out with an hourly resolution and timeframes of one year. The model was applied to a Swiss community, assessing solar PV integration and the effect of replacing fossil heating systems. It was shown that the replacement of fossil-based heating systems poses a significant potential for reducing carbon emissions. The impact of solar PV integration diminishes with increasing share of utilized potential due to a demand-supply mismatch and lack of storage and demand-side flexibility considerations.

Keywords: energy system model, solar PV integration, multi-energy system, decentralized energy, district-level

1. Introduction

The reduction of carbon-based emissions is becoming a growing priority amongst communities. By implementing renewable energy technologies and reducing the share of carbon-emitting infrastructure, progress can be made towards achieving net-zero targets. Orehounig et al. (2014) demonstrate the impact of renewable energy adoption by applying the energy hub approach to analyze the energy system of a Swiss village. The integration of solar photovoltaic (PV) energy systems also plays a key role in replacing carbon-based energy supply, as studied by Pero et al. (2019) in the framework of a multi-energy system of a smart district. Another case study where a model is applied to mixed residential and administrative buildings in Switzerland shows that implementation of solar energy using the energy hub approach is more efficient in contrast to just using standalone operation (Perera et al., 2017). In addition, the replacement of fossil-based heating systems such as oil and gas heaters can drastically reduce carbon emissions in the residential sector, as demonstrated by Wittenburg et al. (2023). To quantify the impact of these measures, a model can be deployed. Many studies of multi-energy system models for districts and communities exist in the literature, such as the one provided by (Heendeniya et al., 2020), focusing on nearly zero-energy districts.

In this study, we developed a district-level multi-energy system model to investigate how PV integration and fossil heating system replacement can contribute to the reduction of carbon-based energy consumption. While most models found in the literature are tailored to one specific district, the objective of this work is to create a model that is applicable to multiple communities. The model examines the impact of integrating solar PV and replacing heating systems on the supply of end-use energy (heat and electricity) for districts. Although model calculations are carried out using absolute values, the objective focuses on demonstrating trends, interrelations, and behavior of the energy demand and supply infrastructure of a community.

2. Methodology

The multi-energy system model discussed in this work represents a simplified description of the energy supply and demand scenario of a district-sized community. The model primarily focuses on Swiss communities, although it can be adapted for use in communities in other countries with just a few modifications. The model is implemented in Python programming language, computed with hourly resolution, and considers a one-year timeframe. A

10.18086/swc.2023.08.06 Available at http://proceedings.ises.org

representative schematic of the model is shown in Fig. 1. The modelling process consists of the following basic steps: (1) data collection for the specific community; (2) estimation of annual and hourly heat and electricity demands; (3) selection of technologies for energy supply, conversion, and storage; (4) parametrization of the model with available data for the specific district or community; (5) solving the energy balance equations for each time step (hour); (6) estimation of potential for additional implementation of renewable energy sources; and (7) application of scenarios with varying degrees of implementation of renewable energies and heating systems refurbishments. Output of the model is an hourly energy supply profile for electricity and heat divided by sources, and generation and conversion technologies, among others.

The model is parametrized using publicly available data containing information about the building stock and heating system types, ambient conditions, currently installed infrastructure, and potential for the implementation of additional energy-related technologies such as solar PV (Federal Statistical Office FSO, 2023). Data on ambient conditions such as temperature and solar irradiation is collected either from nearby weather stations or obtained from interpolated data (Lamprecht, 2023). Hourly weather data for a year is then generated using historic weather data from multiple years, which provides an average profile.

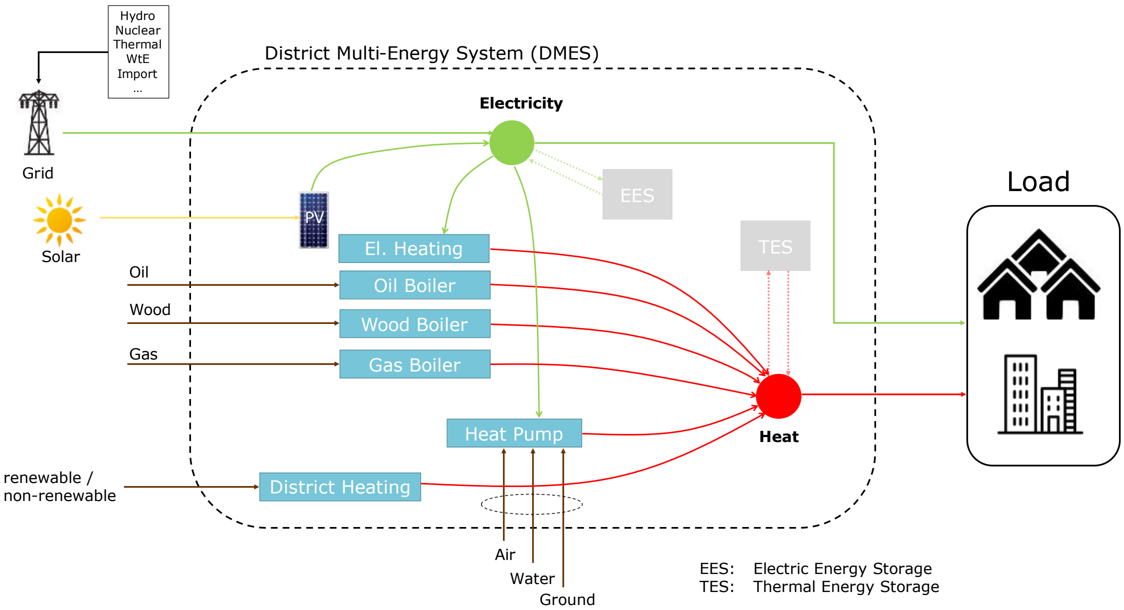

Fig. 1: Schematic of simplified multi-energy system model for districts and communities, including the heat and electricity sectors.

2.1 Electricity demand

In order to capture the intra-day operation, as well as the seasonal behaviour of the various technologies, an hourly electricity demand profile is used for the simulation. The hourly profile is modelled based on the annual electricity demand per community, using data provided by the communities themselves or by the respective utilities. If this data is not available, the annual demand is estimated using piecewise linear regression based on district properties such as the number of buildings, trained on the set of available consumption data from other communities. An hourly load profile is generated using recorded smart meter data across several years, scaling the profile to the respective annual demand. Such smart meter data is for example obtained from Huber et al. (2020). Currently, only residential load profiles are considered, which constitutes a strong simplification. However, in terms of solar PV integration it represents a conservative approach since industrial load profiles are generally more suitable for solar PV integration, as the demand is higher during daylight hours.

2.2 Heat demand

The heat demand in buildings is heavily dependent on ambient conditions and therefore on the time of day, as well as on the season of the year. An hourly demand profile is therefore required. The heat demand of the community is computed using a bottom-up approach: First, the heat demand is estimated for each individual building. Then it is aggregated to the heat demand of the whole community. The demand for an individual building is estimated based on the building properties (e.g. age and size of the building). Information about the building stock is available from the Federal Register of Buildings and Dwellings (Federal Statistical Office FSO, 2023). In combination with ambient temperature data, an hourly heat demand profile for the building is generated for the whole year.

2.3 Electricity supply

The electricity supply is divided into three main categories, namely locally generated PV; nationally generated electricity according to the Swiss electricity mix; and electricity imported from other countries (“cross-border”). Tab. 1 shows the breakdown of the electricity supply. The reason only solar PV was considered for local generation is that the focus of this study was on its integration in the local energy system. Electricity generated by other sources within the district (e.g. CHP) is considered to be shared within the national grid, meaning it is reflected in the national electricity mix. The composition of the nationally generated electricity by sources is based on fixed shares for each source, based on calculations for the year 2021 (Swiss Federal Office of Energy SFOE, 2023a). The share of cross-border imports varies by month, with higher imports in winter and less imports in summer but remains constant within a given month. A time-series of the monthly shares was created using statistical data for the years 2013 to 2022, provided by the SFOE (Swiss Federal Office of Energy SFOE, 2023a). A fixed fraction of the cross-border imported electricity was considered as renewable. Publicly available data on installed solar PV systems within the community provides information about estimated annual yields of the systems. PV yield simulations of individual buildings in various locations in Switzerland are then used to create hourly yield profiles. The profiles are scaled according to the annual yield values to generate an hourly yield profile for the community.

Tab. 1: Breakdown of electricity supply according to source.

Main category	Composition
Locally generated PV	Solar PV generated within the community.
Nationally generated electricity	Electricity generated within Switzerland according to Swiss electricity mix: • Hydro • Nuclear • Conventional CHP • Renewable CHP • Renewable other
Cross-border electricity import	Electricity imported from other countries.

2.4 Heat supply

The carbon-intensity of the heat supply heavily depends on the technologies used for supplying heat to the buildings. For example, supplying heat with an oil or gas boiler will generally have a much higher carbon-intensity as opposed to using other technologies. Therefore, in this model, the energy source used for heating is determined based on the deployed heating system type. It is a parameter that can be adjusted in the various scenarios. In the case of Switzerland, both the information of the heating system type and energy source for each building are available from the Federal Register of Buildings and Dwellings (Federal Statistical Office FSO, 2023). In the model, supplied heat is categorized into six sources: electricity, environment, biomass, fossil, district heating, and other. Tab. 2 shows the allocation of heating system type to heat source and the estimated share of renewable energy for each source.

Tab. 2: Heat sources based on installed heating systems.

Source	Heating system type	Share considered renewable
Electricity	Direct electric heating and electricity supplied to heat pumps	Depending on electricity mix.
Environment	Heat extracted from environment via heat pump (ground, water, air); assumption: fixed heat pump coefficient of performance of 3.	100%
Biomass	Wood burners (including pellets, cuts, and logs)	100%
Fossil	Oil and gas burners	0%
District Heating	Heat source not allocated	50%
Other	Where heating system unknown	50%

2.5 Scenarios

The available potential for additional renewables is identified based on available resources and infrastructure. In the case of solar PV potential, the assessment is based on available surfaces (roof and facades) and data provided by the SFOE (Swiss Federal Office of Energy SFOE, 2023b). Solar PV integration scenarios are generated by utilizing a selected percentage of the identified potential for additional renewables. Similarly, heating system retrofit scenarios are generated by replacing a selected percentage of fossil heating systems by heat pumps, which in turn increases the electricity demand due to increased heat pump capacity. Scenarios can be generated with various combinations of solar PV integration and heating system retrofit. The scenarios can then be compared among each other.

3. Results

The abovementioned energy-model has been applied to multiple municipalities in Switzerland. In this work, we present the results related to a suburban municipality located in the northern part of Switzerland which consists of approximately 6000 buildings and about 19,000 inhabitants. The following four scenarios were investigated (Tab. 3): base scenario (current state) with no additional PV integration or fossil heater replacement (Scenario 0); additional PV integration, no fossil heater replacement (Scenario 1); replacement of fossil heaters, no additional PV integration (Scenario 2); and PV integration and fossil heater replacement (Scenario 3).

Tab. 3: Evaluated scenarios for a Swiss community.

Scenario	Solar PV integration	Heating system retrofit
0	0%	0%
1	0 - 100%	0%
2	0%	0 - 100%
3	0 - 100%	0 - 100%

Fig. 2 to Fig. 4 shows the electricity supply to the community over one year for three selected scenarios, while the daily heat supply for the respective scenarios is shown in Fig. 5 and Fig. 6. While the calculation was done on an hourly basis, the graphs show daily aggregated values. For electricity, the values are split according to source of supply as described in Tab. 1. For heat, the values are split according to heating system type as described in Tab. 2. The annual values of some metrics that are impacted by the share of PV integration and the share of heating system retrofit are presented in Tab. 4, namely locally generated solar PV electricity, locally consumed solar PV energy (i.e. self-consumption), exported solar PV electricity, and cross-border imported electricity.

As a first “as is” scenario, the current state (Scenario 0) was investigated. The daily electricity supply to the community for this scenario is shown in Fig. 2: some electricity is generated locally by solar PV, relatively large shares come from hydro power and nuclear, while there is also a substantial amount of electricity imported from other countries. The share of cross-border imports is larger in winter than in summer. It must be mentioned that this study looks at the imported consumed electricity as opposed to the net imported electricity. Looking at the annual results in Tab. 4 it can be seen that almost all of the locally generated solar PV electricity is also consumed locally, and only a very small share (2 MWh) is exported. The respective daily heat supply for this scenario is presented in Fig. 5: a very large share of the heat demand is covered by oil and gas boilers, while smaller shares are served with heat pumps, district heating, and other technologies. Overall, it can be observed that the heat supply is still largely based on fossil energy sources.

In a “PV only” scenario (Scenario 1) 50% of the solar PV potential was utilized, while no heating system retrofit was considered. Therefore, the heat supply remains the same as in in the “as is” scenario (Fig. 5). The electricity supply, however, is different as can be seen in Fig. 3: the share of locally generated solar PV electricity has increased a lot. While some of the additionally generated solar PV electricity can be consumed (i.e. increased PV consumption), a large share of the generated solar PV electricity is exported due to a mismatch between supply and demand. This can also be seen in the annual values (Tab. 4, “PV only”): while the solar PV self-consumption increased from 6’222 MWh to 31’855 MWh, the solar PV export also increased (from 2 MWh to 30’458 MWh). More solar PV electricity is exported in summer than in winter due to increased generation and decreased overall demand. It can further be observed that the share of cross-border imports has decreased (from 48’186 MWh to 33’200 MWh), due to the increased PV consumption. As in the previous scenario, imports are larger in winter than in summer, but never zero.

In a "PV and heating" scenario, a PV integration rate of 50% and heating system retrofit rate of 50% was investigated (Scenario 3). In this case, the heat supply to the community has changed when compared to the two previous scenarios, as can be seen from the graph of daily heat supply in Fig. 6: while the overall heat demand remains the same, the share of heat supplied by heat pumps has increased, while the share of heat supplied by oil and gas boilers has decreased. The corresponding graph of daily electricity supply is presented in Fig. 4. It can be observed that a large share of the solar PV electricity is still being exported, which can also be seen from the annual values (Tab. 4, "PV and heating"): the solar PV self-consumption only slightly increased (from 31'855 MWh to 33'473 MWh), while the solar PV export slightly decreased (from 30'458 MWH to 28'840 MWh). Again, the reason for the large export is the mismatch between supply and demand. A large difference that can be observed when comparing to the "PV only" scenario is the increase in electricity imported from other countries (from 33'200 MWh to 52'917 MWh). The reason for this large increase of cross-border imports is the increased heat pump activity due to the 50% heating system retrofit.

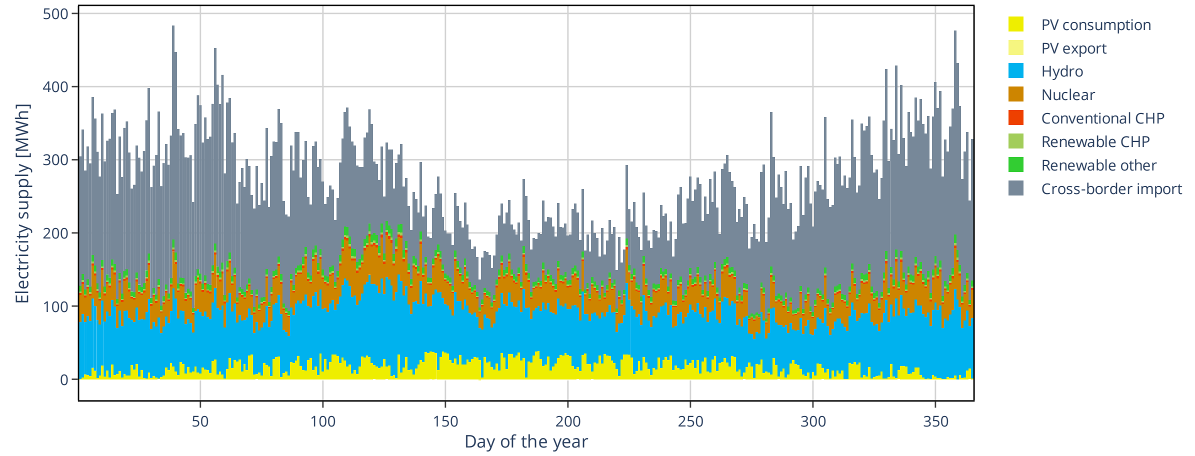

Fig. 2: Daily electricity supply aggregated by source based on hourly data for the "as is" scenario (Scenario 0, current state).

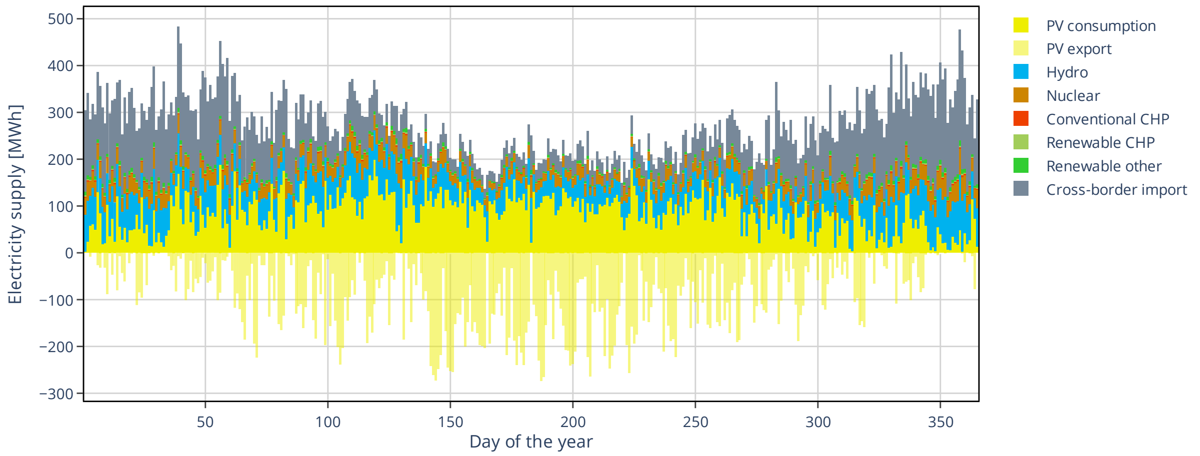

Fig. 3: Daily electricity supply aggregated by source based on hourly data for the "PV only" scenario (Scenario 1 with 50% solar PV integration and 0% heating system retrofit). A large share of the generated solar PV energy is exported due to a mismatch between supply and demand.

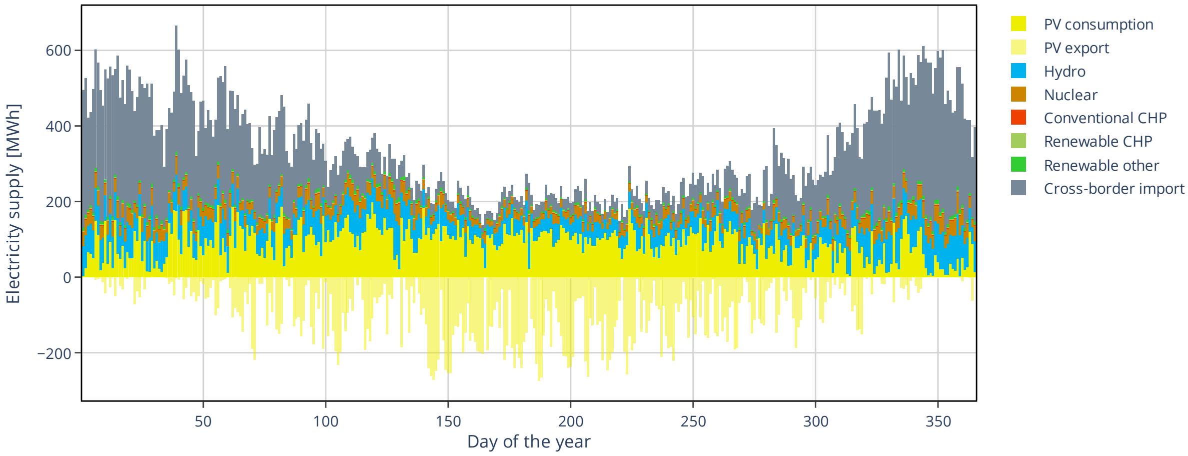

Fig. 4: Daily electricity supply aggregated by source based on hourly data for the “PV and heating” scenario (Scenario 3 with 50% solar PV integration and 50% heating system retrofit). The overall electricity demand has increased due to increased heat pump activity. Sill, a large share of the generated solar PV energy is exported due to a mismatch between supply and demand.

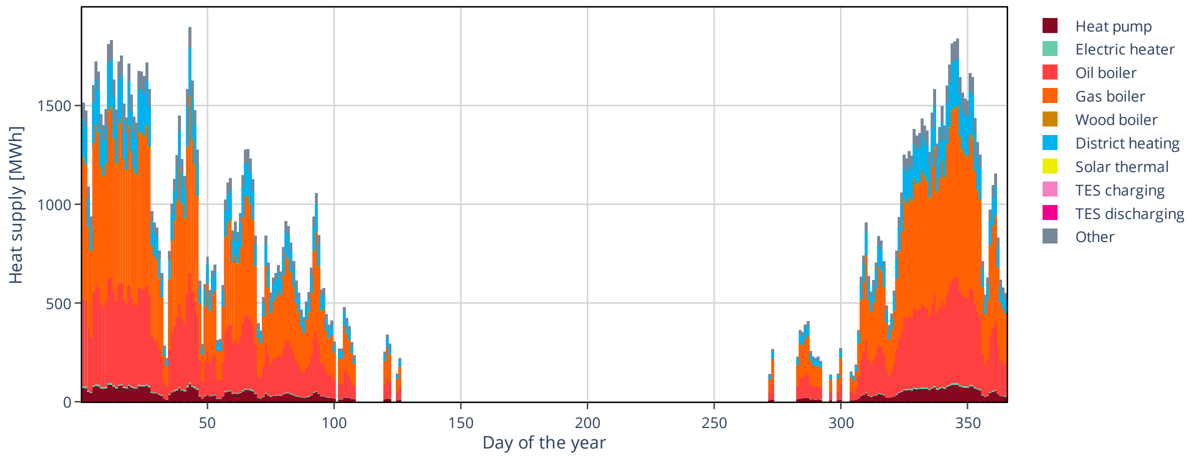

Fig. 5: Daily heat supply aggregated by heating system type based on hourly data for scenarios without heating system retrofit (current state). A large share of the heating demand is supplied by oil and gas boilers.

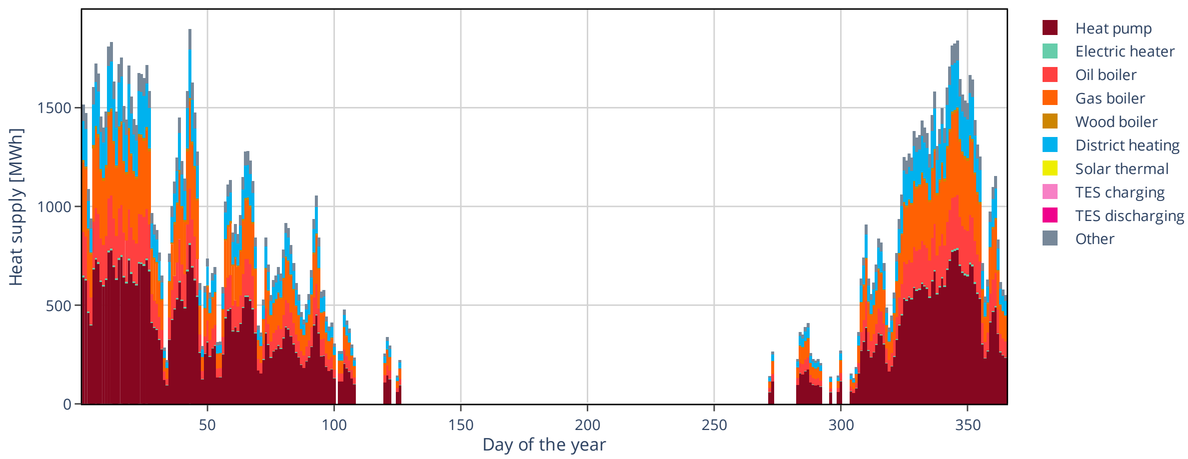

Fig. 6: Daily heat supply aggregated by heating system type based on hourly data for scenarios with a 50% heating system retrofit rate. While the total heating demand remains the same, the share of heating demand supplied by heat pumps has increased.

Tab. 4: Selected annual metrics of electricity supply for various scenarios.

Scenario	PV integration	Heating system retrofit	Annual solar PV generation [MWh]	Annual solar PV self-consumption [MWh]	Annual solar PV export [MWh]	Annual cross-border import [MWh]
“As is”	0%	0%	6’224	6’222	2	48’186
“PV only”	50%	0%	62’312	31’855	30’458	33’200
“PV and heating”	50%	50%	62’312	33’473	28’840	52’917

Fig. 7 shows the results of a parameter study for Scenarios 1 to 3 (see Tab. 3). Each study started with Scenario 0. For Scenario 1, the fraction of PV integration was varied from 0% to 100% (Fig. 7a). Here, it was observed that initial increases of PV integration resulted in notable increases in the share of renewable supply for both electricity and total energy. However, with higher PV integration, this effect diminishes, meaning that additional PV integration has very little effect on the overall share of renewable supply. This is due to the demand and supply mismatch: PV power is produced during hours of the day when demand is already met. For Scenario 2, the fraction of fossil heater replacement was varied from 0% to 100% (Fig. 7b). An increase in replacements results in an almost linear increase in share of renewable supply for both heat and total energy. For Scenario 3, the fraction of PV integration and fossil heater replacement was kept equal, varying from 0% to 100%. A cumulation of the effects from Scenario 1 and 2 can be observed, resulting in a slightly higher total share of renewable supply (Fig. 7c).

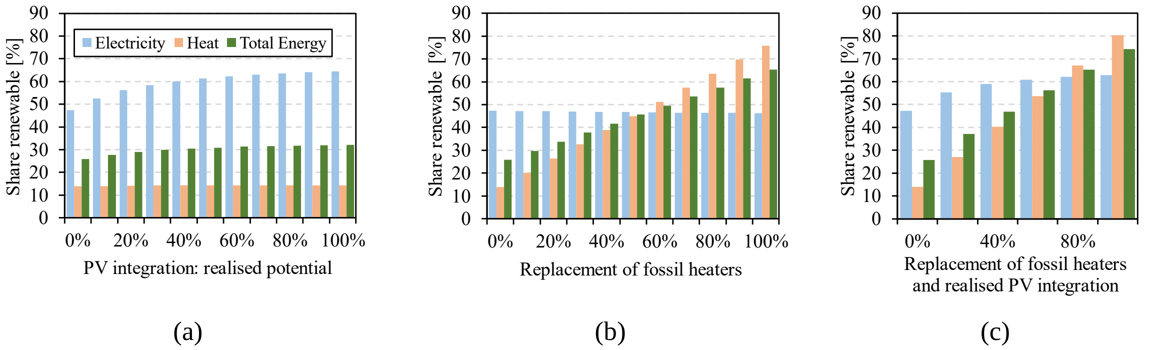

Fig. 7: Renewable share of supply for electricity, heat, and total energy for three scenarios: (a) PV integration, no fossil heater replacement, (b) fossil heater replacement, no PV integration, (c) equal shares of PV integration and fossil heater replacement.

4. Discussion and Conclusions

In this work, a model for the evaluation of energy supply scenarios of communities was introduced and the results of a simulation for a community in Switzerland were presented. The aim of the model is to show the impact of the various scenarios in regard to carbon-based emissions. Increasing the share of renewable energy supply decreases the carbon footprint of a community. The results presented above demonstrate that the replacement of fossil heating systems has a significant impact on the reduction of the overall non-renewable energy supply. This effect can be observed starting from small replacement rates up to a complete replacement of all fossil heaters (100%). For PV integration it is different: while PV integration increases the overall share of renewable supply initially, a 100% PV integration adds little benefit in this case. Even though high PV integration leads to a larger share of PV self-consumption, a large share of the generated solar PV electricity is also exported due to the mismatch between supply and demand. Increasing the share of heating system retrofit in this case increases the PV self-consumption, but only slightly, which is again due to the supply and demand mismatch. This mismatch is present because neither storage nor demand-side flexibility has been considered in the model and therefore excess PV power cannot be utilized. If storage or demand-side flexibility is introduced, this excess power could be shifted to another time on the load profile, where demand is high and renewable supply is low, e.g. during morning and evening hours when considering a daily profile. For example, with the introduction of thermal energy storage, excess PV power could be used to charge the storage via the heat pump. Later, this heat could be used when no PV power is available, reducing the need for cross-border imported electricity. A similar approach can be used for the implementation of demand flexibility: taking into account the thermal mass of the buildings, they could also act as a thermal storage, allowing to shift the heating activity to times of the day when excess solar PV is available. Various approaches to introduce storage and other means of flexibility in the energy system are also discussed in the literature (Connolly and Mathiesen, 2014;

Pleßmann et al., 2014; Solomon et al., 2014). In future work, the presented model can be extended to include storage and flexibility, allowing the investigation of additional scenarios. Further, the model can be coupled to an optimization framework, allowing for optimal control of the heat and electricity supply.

Overall, the results of this study show the benefits of heating system retrofit and PV integration in a community with regards to reducing carbon-based emissions stemming from energy generation. However, it is also shown that PV integration alone cannot generate the desired increase in renewable energy supply if not coupled with storage systems or demand-side flexibility considerations. It is therefore expected that the model presented above will be very useful in exploring this option when extended accordingly.

5. Acknowledgments

The research published in this report was carried out with the support of the Swiss Federal Office of Energy SFOE as part of the SWEET project EDGE. The authors bear sole responsibility for the conclusions and the results presented in this report.

6. References

Connolly, D., Mathiesen, B.V., 2014. A technical and economic analysis of one potential pathway to a 100% renewable energy system. Int. J. Sustain. Energy Plan. Manag. 7-28 Pages. https://doi.org/10.5278/IJSEPM.2014.1.2

Federal Statistical Office FSO, 2023. Federal Register of Buildings and Dwellings [WWW Document]. URL https://www.bfs.admin.ch/bfs/en/home/registers/federal-register-buildings-dwellings.html (accessed 10.8.23).

Heendeniya, C.B., Sumper, A., Eicker, U., 2020. The multi-energy system co-planning of nearly zero-energy districts – Status-quo and future research potential. Appl. Energy 267, 114953. https://doi.org/10.1016/j.apenergy.2020.114953

Huber, P., Ott, M., Friedli, M., Rumsch, A., Paice, A., 2020. Residential Power Traces for Five Houses: The iHomeLab RAPT Dataset. Data 5, 17. https://doi.org/10.3390/data5010017

Lamprecht, C.S., 2023. Meteostat Python [WWW Document]. URL https://github.com/meteostat/meteostat-python/tree/master (accessed 10.10.23).

Orehounig, K., Mavromatidis, G., Evins, R., Dorer, V., Carmeliet, J., 2014. Towards an energy sustainable community: An energy system analysis for a village in Switzerland. Energy Build. 84, 277–286. https://doi.org/10.1016/j.enbuild.2014.08.012

Perera, A.T.D., Mauree, D., Scartezzini, J.-L., 2017. The energy hub concept applied to a case study of mixed residential and administrative buildings in Switzerland. Energy Procedia 122, 181–186. https://doi.org/10.1016/j.egypro.2017.07.342

Pero, C.D., Leonforte, F., Lombardi, F., Stevanato, N., Barbieri, J., Aste, N., Huerto, H., Colombo, E., 2019. Modelling Of An Integrated Multi-Energy System For A Nearly Zero Energy Smart District, in: 2019 International Conference on Clean Electrical Power (ICCEP). Presented at the 2019 International Conference on Clean Electrical Power (ICCEP), IEEE, Otranto, Italy, pp. 246–252. https://doi.org/10.1109/ICCEP.2019.8890129

Pleßmann, G., Erdmann, M., Hlusiak, M., Breyer, C., 2014. Global Energy Storage Demand for a 100% Renewable Electricity Supply. Energy Procedia 46, 22–31. https://doi.org/10.1016/j.egypro.2014.01.154

Solomon, A.A., Kammen, D.M., Callaway, D., 2014. The role of large-scale energy storage design and dispatch in the power grid: A study of very high grid penetration of variable renewable resources. Appl. Energy 134, 75–89. https://doi.org/10.1016/j.apenergy.2014.07.095

Swiss Federal Office of Energy SFOE, 2023a. Electricity statistics [WWW Document]. URL https://www.bfe.admin.ch/bfe/en/home/supply/statistics-and-geodata/energy-statistics/electricity-statistics.html (accessed 10.8.23).

Swiss Federal Office of Energy SFOE, 2023b. Suitability of roofs for use of solar energy [WWW Document]. URL https://www.bfe.admin.ch/bfe/en/home/supply/statistics-and-geodata/geoinformation/geodata/solar-energy/suitability-of-roofs-for-use-of-solar-energy.html (accessed 10.8.23).

Wittenburg, R., Gierow, C., Pötke, R., Müller, K., Holtz, D., 2023. Transition of district heating from fossil to renewable energies – Pathways analysed by dynamic simulation. Renew. Energy Focus 45, 271–286. https://doi.org/10.1016/j.ref.2023.04.008