INTEGRATED MODELING OF PHOTOVOLTAIC SYSTEM ROLE ON PROSUMER ENERGY DYNAMICS

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ABSTRACT

Towards resilient urban energy systems, prosumers play a crucial role in shaping sustainable energy practices. This study investigates how photovoltaic (PV) systems as the most common energy flexibility measure in context of prosumers can enhance self-sufficiency and contribute to a resilient energy future. This study introduces an integrated modeling approach to evaluate a simplified techno-enviro-economic assessment of photovoltaic (PV) system integration at different types of prosumers by residential buildings (both single and multifamily house), and industrial prosumers, each characterized by distinct load profiles. TRNSYS employed for electricity production modelling in different scenarios to ensure accuracy and reliability in capturing the dynamic interaction between energy consumption and production. Then model outcomes are used in an analytical assessment to find self-consumption efficiencies. This allows us to evaluate consumption levels and displays the ratio of direct solar energy consumption to total solar production over different seasons. In addition, the model quantifies the amount of electricity purchased from the grid to account for own consumption and helps evaluate electricity dependency It also examines excess electricity a is fed into the power grid, providing a detailed overview of the excess electricity to be generated and the feed conditions. Eventually, an environmental analysis is performed to estimate the total CO_2-equivalent savings from PV integration. The main expected result in this research includes but not limited to direct self-consumption, storage, and surplus productions; total savings and incomes; internal rate of return; payback time and total CO_2 mitigation for all different scenarios and studied cases. Additionally, the research outcomes in this study aid in enhancing energy resilience. These findings collectively emphasize the versatility and positive impact of PV systems in prosumers and contributing to a sustainable urban energy future.

1 INTRODUCTION

The transition towards sustainable and resilient energy systems is experiencing a notable shift due to the emergence of 'prosumers' entities engaged in both energy production and consumption. This shift is primarily driven by the availability of cost-effective renewable energy technologies, notably photovoltaic (PV) systems (Attoye, et al.,2020; Karalus, et al., 2023). Prosumers are key players in molding the trajectory of future energy systems. Their involvement leads to the dispersal of energy generation, which boosts grid resilience and energy security. Through producing their own energy, prosumers minimize their reliance on the grid, thus aiding in the decarbonization of the energy industry. Additionally, prosumers offer beneficial services to the energy system, such as microgeneration, demand reduction, load shifting, and energy storage (Huang, et al., 2019).

Globally and specifically including those countries with ambitious renewable energy objectives (e.g. Sweden), prosumers are emerging as key players in the energy transition. Across various households, the trend is towards increased self-sufficiency, with individuals and communities transforming into efficient 'prosumers', generating, and utilizing a significant share of their energy needs. This transformation is facilitated by the adoption of smart grid technologies, which enable households globally to transition from passive energy consumers to active contributors to the energy ecosystem (Huang, et al., 2019). Incorporation of PV systems into building structures, known as Building-

Integrated Photovoltaics (BIPV), is a crucial facet of this transformative process (Gholami et al., 2021). BIPV systems serve a dual purpose, functioning both as building materials and power generators, thus streamlining installation processes and enhancing architectural aesthetics. However, the integration of BIPV systems presents a multitude of challenges, including economic considerations, performance optimization, adherence to regulatory standards, and overcoming market limitations. Addressing these obstacles is essential to fully harnessing the potential benefits of BIPV technology (Wicki, L. et al., 2022). In the integration of prosumers into energy systems, numerous factors must be taken into account. These encompass the capability for microgeneration, the scope for demand reduction and load shifting, the accessibility of energy storage solutions, and the utilization of smart appliances and communication technologies. Additionally, the integration process should carefully consider the distinct load profiles characteristic of various prosumer categories, including residential buildings and industrial entities (Sommerfeldt N., 2019). Within the prosumer model, the self-consumption of energy produced by PV systems holds significant importance (Karalus et al., 2023; Gimeno et al., 2020). It enhances energy self-sufficiency and optimizes the utilization of locally generated electricity (Gimeno et al., 2020). Analyzing self-consumption is essential for assessing the financial viability of the investment. A higher level of self-consumption typically leads to greater savings on energy bills, as less electricity needs to be purchased from the grid. Additionally, the implementation of a battery storage system can further optimize self-consumption by storing excess energy generated during periods of high production for use during times of low production or high demand. This not only increases energy self-sufficiency but also maximizes the utilization of locally generated electricity, ultimately bolstering the economic benefits of the investment (Absalyamova, A., 2022). Sweden's solar energy market is growing fast, with an expected capacity of 2,178 MW by the end of the base year. Forecasts suggest a growth rate of over 23.3% in the coming years. Most of Sweden's solar energy comes from rooftops, but ground installations are also increasing. By the end of 2021, Sweden was set to have over 100,000 PV installations (Statista.com, 2023).
In terms of electricity use, homes and businesses in Sweden are the biggest consumers, using 72 TWh, followed by industries with 48 TWh, and transportation with 3 TWh. In 2020, Sweden's total energy supply was 508 TWh. Residential buildings, including both single-family homes and apartments, are a big part of Sweden's electricity use. By 2022, they were using over 43 thousand gigawatt hours of electricity (Swedish energy agency, 2023). In Sweden, electricity serves as a primary energy source for heating buildings, employing two main methods: water-based systems and direct electric heating systems. In water-based electric heating, an electric boiler or immersion heater warms the water, which is then circulated through a pipe network to heat radiators distributed throughout the building. Conversely, direct electric heating directly converts electricity into heat using air-to-air or air-to-water heat pumps within HVAC system, radiators or via coils embedded in the floor or ceiling. Notably, comfort underfloor heating, utilizing direct-acting electricity, is prevalent in newly constructed houses. For buildings not heated by electricity, alternative heating methods are employed, with district heating networks being a common choice in Sweden. These buildings' heating requirements underwent revisions in 2015, with adjustments tailored to the varying climatic conditions across different regions of Sweden (Niskanen, J. and Rohracher, H., 2022).

This study focuses on exploring the potential of solar power for various building types, including electrical and non-electrical residential buildings (both single and multifamily) and an commercial building. We aim to investigate how prosumers in these diverse settings can leverage solar panels to enhance their energy independence and contribute to the resilience of urban environments. By examining the energy usage and savings across different building types, we seek to demonstrate the feasibility and benefits of solar energy adoption on a smaller scale, tailored to specific building needs and characteristics.

2 METHODS

In this study, an integrated modeling approach was employed to assess the techno-enviro-economic implications of integrating PV systems across various building types. TRNSYS was utilized for electricity production modeling, ensuring accuracy in capturing the dynamic interaction between energy consumption and production. To streamline the modeling process, standardized load profiles for each building type and fixed PV system configurations were adopted.

Real-time data inputs from the year 2020 were utilized for model validation, while current prices were considered for cost analysis. The study encompasses five different cases: two single-family houses, one heated with a heat pump (air-to-air heat pump) and the other connected to a district heating network; two multifamily buildings, one with a heat pump and one solely connected to a district heating network; and one commercial building contains storing local, small manufacturing and workshop spaces and offices while heated by district heating network. All these buildings are located in Västerås, Sweden. Figure 1 illustrates all the buildings studied in this research.
The single-family house case studies utilized the same building construction model, while the heating source was alternated between a heat pump and a district heating source. This same approach was applied to the multifamily building models as well. As a result, three distinct building construction models were employed, each featuring two different heating sources for the residential building case studies. The total roof area for single-family, multifamily, and commercial building case studies are considered as 40 m^2, 300 m^2 and 3900 m^2.

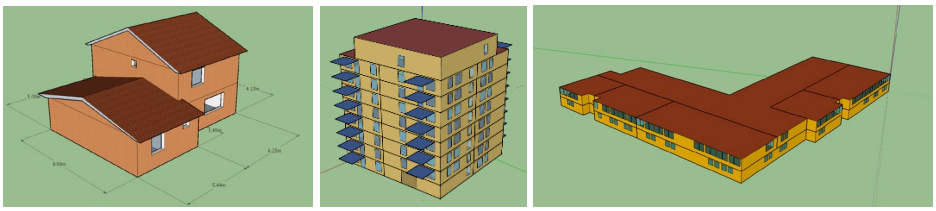

Figure 1: The building models demonstration-Single family building, multifamily building and commercial building examples

The cost analysis in this study incorporated the hourly electricity prices for the year 2023. The variation in electricity prices per month for Sweden is illustrated in the Figure 2. The electricity price is depicted in öre/kWh, with supposing 1120 öre equivalent to 1 euro. The climate zones in Sweden, denoted as SE1 to SE4, represent different geographical regions. Västerås, situated in SE3, served as the focal point for all cost analyses conducted in this study.

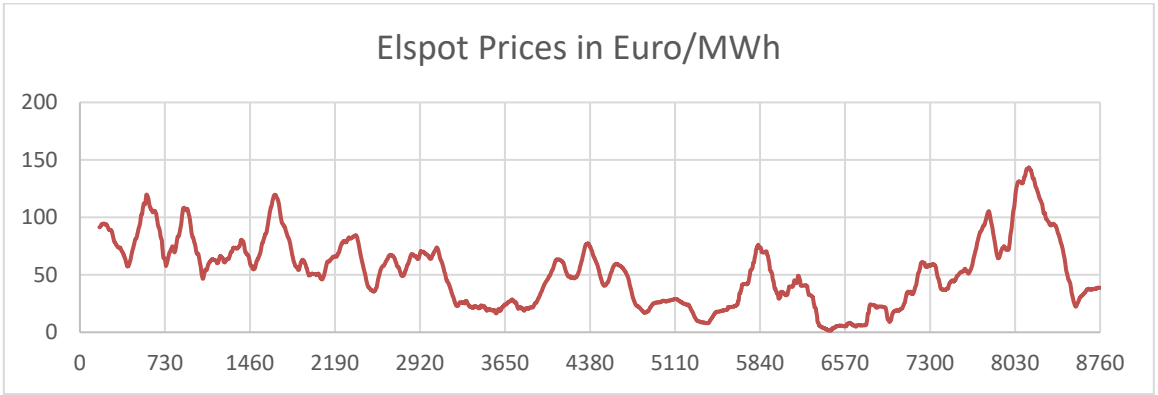

Figure 2: Electricity hourly price variation in SE3 (concerning the case study's climate Zone) in Sweden during 2023

The investment costs for photovoltaic (PV) systems were calculated based on the prevailing photovoltaic market conditions in Sweden. These costs, encompassing installation expenses, tax deductions, and VAT, are outlined in the Table 1 for various power sizing configurations.

Table 1: Photovoltaic cost per kW power production and total price including tax deductions, VAT and installation costs in Sweden in 2023 (Ref. https://hemsol.se/solceller/pris/)

Power on plant (kW)	**Price per kW (€)**	**Total price (incl. deduction, VAT and installation) (€)**
5	1,295	6,475
7	1,148	8,037
10	1,099	10,992
12	1,046	12,549
15	1,019	15,286
17	992	16,870
20	983	19,669
25	943	23,585
100	890	89,000
250	846	211,375
500	534	267,000

In this study, it has assumed that all electricity power production by photovoltaic systems will be directly used (direct self-consumption) to cover the whole electricity demand in the building then it will be saved and used later through battery storage, or it sells to grid. This was assessed by calculating direct self-consumption, degree of self-sufficiency, power outlet, over production and state of charge.
The term "direct self-consumption" refers to the solar energy produced and immediately used within the same organization without initial storage. This value is typically measured in kilowatt-hours (kWh). The self-sufficiency ratio, on the other hand, represents the ratio between self-consumed electricity and total electricity requirements, expressed as a percentage. While this value can be calculated on a daily, weekly, monthly, or yearly basis, the annual calculation is most commonly used. Power outlets denote the amount of electricity purchased from the grid, calculated as the difference between total electricity needs and self-consumption. Within this framework, power outlets are the portion of electricity procured from the grid after deducting all self-consumption (including direct usage and potentially stored electricity). This measurement is also expressed in kWh. Any surplus electricity generated that exceeds direct self-consumption or storage capacity is fed into the grid, referred to as overproduction and measured in kWh. State of charge, typically represented as a percentage, indicates the level of charge within a storage system.
The financial returns from selling electricity to the grid are closely linked to electricity rate structures. This interdependence is particularly complex in scenarios where customers have the freedom to select their electricity provider and seek the most favorable terms. For this study, it is assumed that all over production electricity is sold to Nord Pool AS, a prominent player in the European power market. The selling price of electricity comprises several components, including the hourly spot market price, grid compensation, electricity certificates, and tax deductions. When selling electricity to the grid, it is valued at the hourly spot price plus an additional 4.48 Euro/MWh for grid compensation. Furthermore, revenue can be earned from green certificates valued at 8.95 SEK/MWh. Since 2015, micro-producers of renewable electricity have been entitled to tax deductions for feed-in electricity, amounting to 53.7 Euro/MWh for each MWh of renewable electricity supplied to the grid annually. Hourly calculations were conducted to determine the total energy fed into the grid by each installation over the year and then multiplied by the respective electricity selling prices to estimate corresponding income; however, the results are shown monthly based.

Concerning environmental assessment, an equivalent CO2 emissions factor 36.02gCO2eq per kWh electricity production is considered and has been multiple to total amount of annual electricity saving in each case studies.

3 RESULTS AND DISCUSSION

The results expose the practical implications of integrating PV systems across various prosumer contexts, encompassing both residential and commercial buildings. Our analysis delves into critical factors such as self-consumption rates, reliance on grid electricity, and surplus energy generation, providing a comprehensive understanding of how PV systems contribute to sustainable energy practices. Notably, our findings underscore straightforward metrics such as direct energy utilization, storage capacity, and surplus energy generation across different scenarios.

In Figures 3a, 3b, and 3c, energy meters illustrate the energy dynamics from two perspectives: PV production and building electricity demand. The left-hand side graphs in these figures depict the annual energy performance of the studied prosumer cases, focusing on monthly direct self-consumption, electricity used for battery charging, and monthly surplus production. Conversely, the right-hand side graphs highlight the monthly electricity drawn from storage (batteries) and the amount of electricity required from the grid (indexed as power outlet in the figure). The results demonstrate that while the electricity demand in a single-family building heated by a district heating network is lower compared to one heated by heat pumps, the monthly surplus production is not significantly higher. However, monthly energy storage is higher in the former case. Furthermore, upon comparing the monthly grid-supplied electricity, the power outlet is substantially higher for the single-family house integrated with heat pumps. The results also show the overproduction for multifamily case studies is considerably higher than single-family case studies. Overproduction in multifamily building connected to the district heating network is started at February while for the single-family case study there was not possible to have overproduction until late March. Then during the summer while the cooling demand is usually supplied by fans and portable evaporative cooler or portable absorption chillers, the overproduction for heat pump integrated building became higher. However, the total annual power outlet (electricity demand from the grid) is considerably higher for the case study heated and cooled by heat pumps. Then in commercial building case study, due to higher capacity of power production, there is higher opportunity for self-consumption both directly and from the storge batteries in compared to other cases.

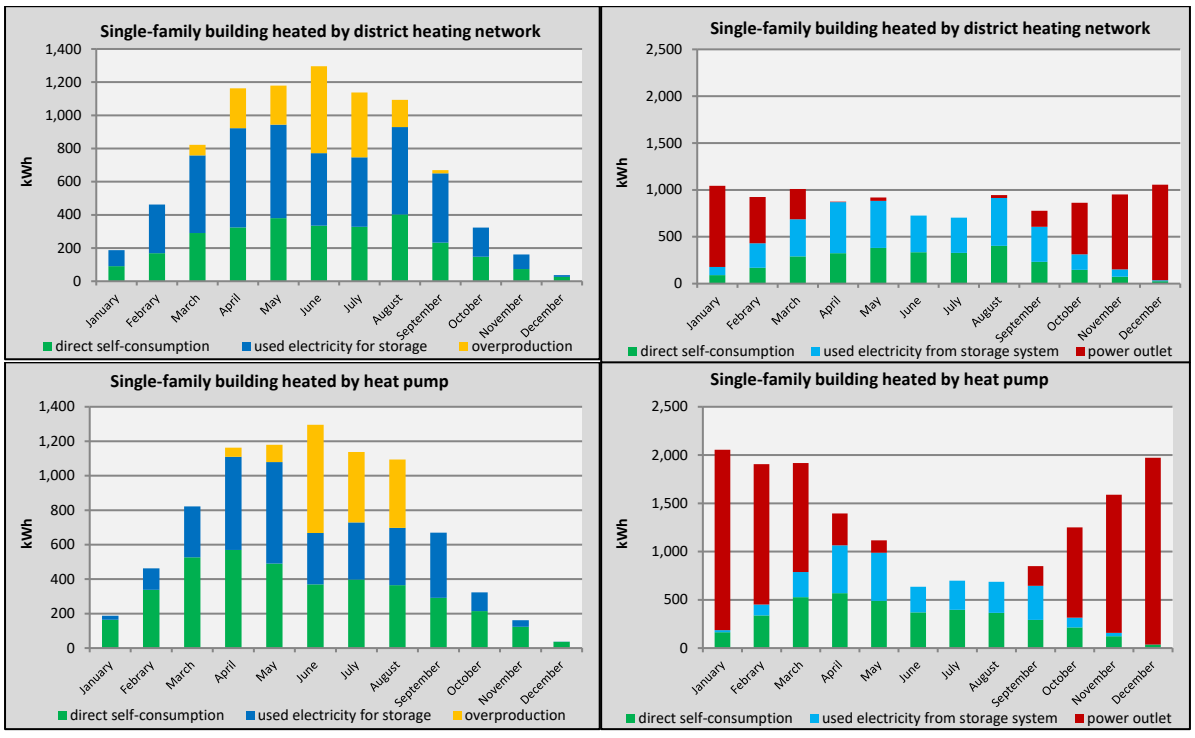

Figure 3a: Monthly based production and consumption perspectives in single family building case studies.

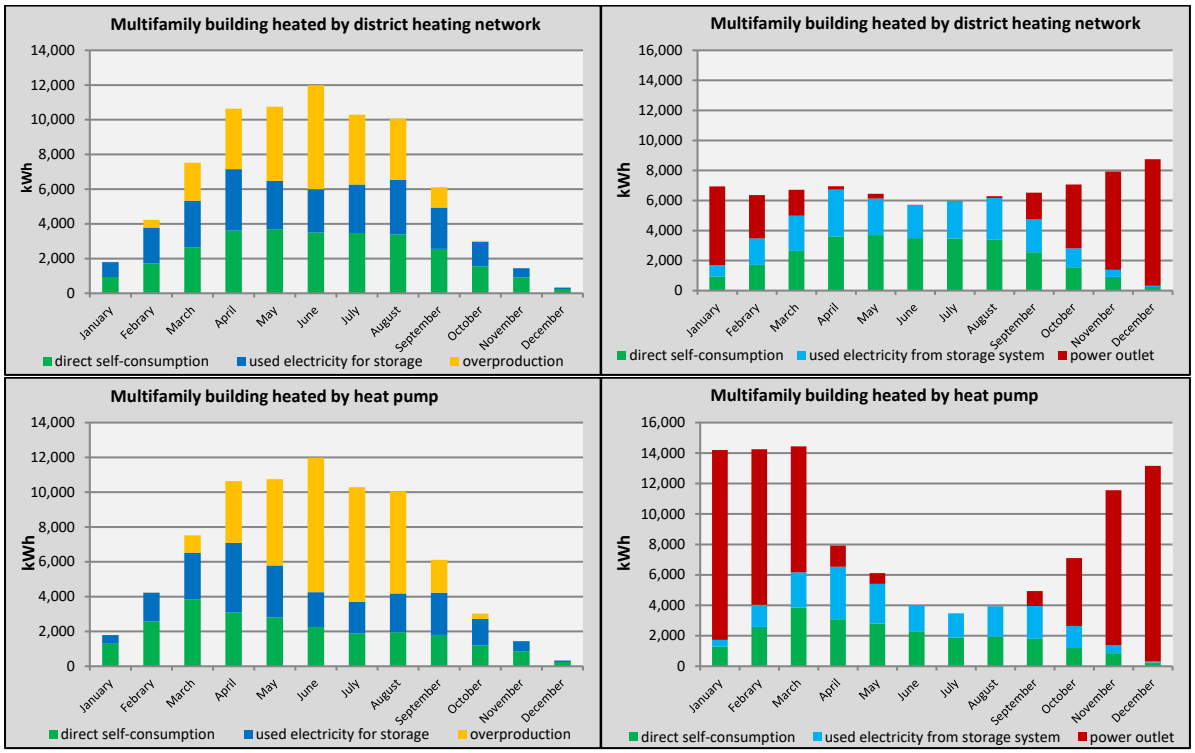

Figure 3b: Monthly based production and consumption perspectives in multifamily building case studies.

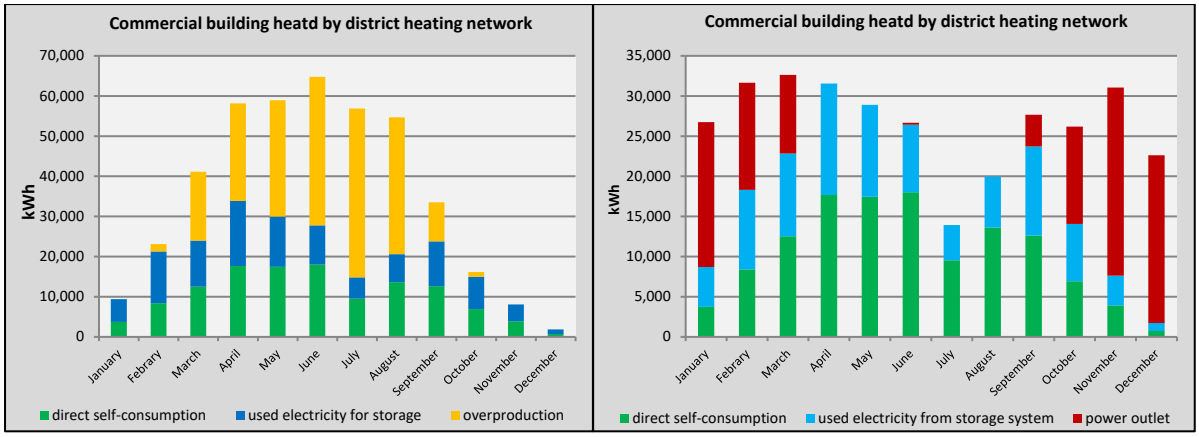

Figure 3c: Monthly based production and consumption perspectives in commercial building case studies.

Figure 4 demonstrate the aforementioned energy meters for a specific example week, ranging from April 18th to April 24th, during which there is ample solar radiation alongside significant heating demand. The weather conditions in Vasteras, where the case studies are conducted, are characterized by cold temperatures with a gentle breeze, featuring average highs of 10°C and lows of 1°C in April. In the single-family case studies, surplus energy is available on certain days for buildings connected to the district heating system. Conversely, for buildings integrated with heat pumps, some electricity must be sourced from the grid or the storage system as the direct electricity production from PV systems alone proves insufficient.

Concerning multifamily case studies, there is a notable surplus energy availability in the building heated by heat pumps. However, in the case of buildings connected to the district heating network, electricity demand surpasses that of the heat pump integrated scenarios. This discrepancy arises from the

phenomenon observed during spring, whereas outdoor temperatures rise, the supply temperature in the district heating network decreases. Consequently, it becomes common to resort to additional electric heating systems to compensate for the insufficient heat supply from the district heating network, particularly impacting multifamily buildings.

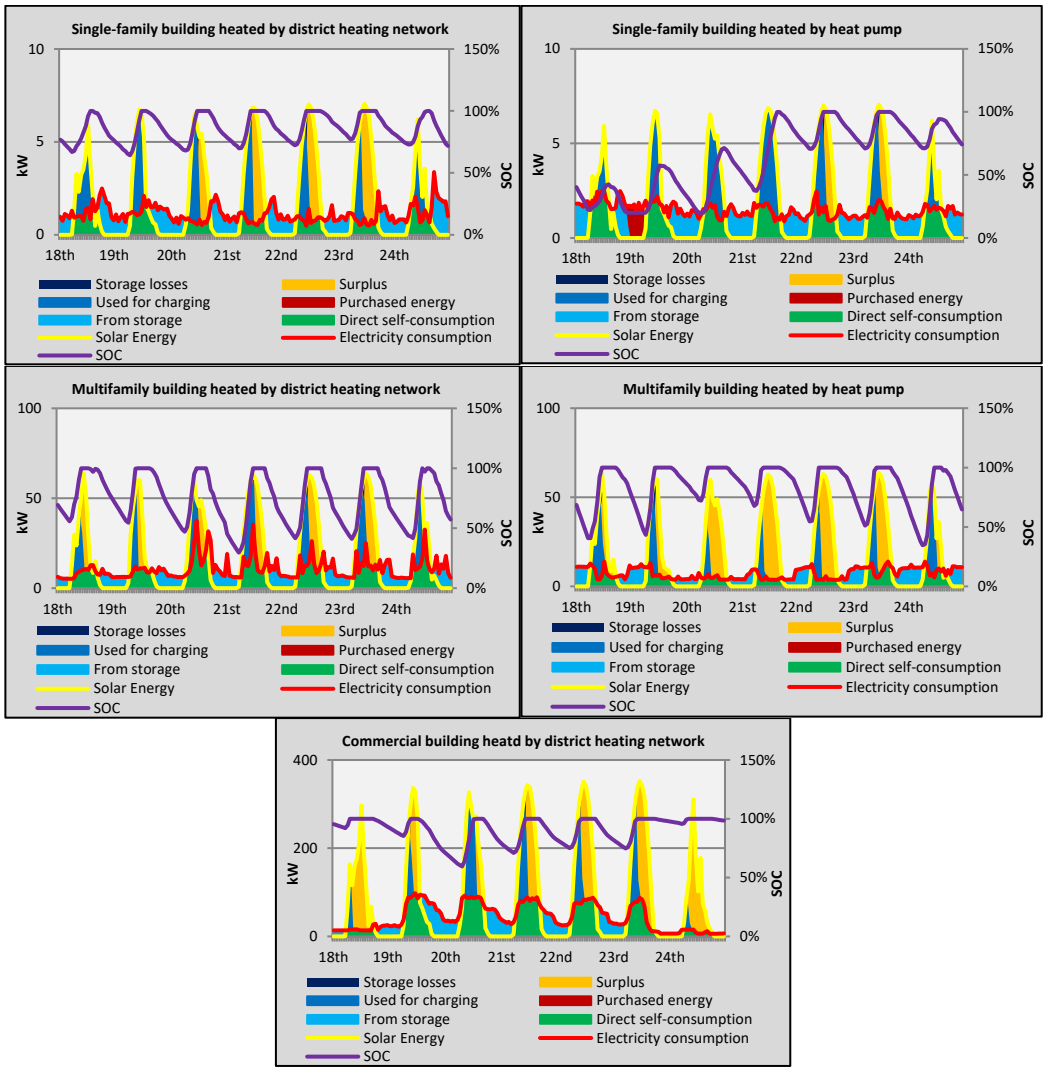

Figure 4: production and consumption perspectives in example week

The financial aspects has been also explored, including savings, income generation, and how quickly the investment pays off. Additionally, we quantify the environmental benefits, particularly in terms of reducing carbon emissions. The results are summarized in table 2. When comparing heat pump and district heating integrated buildings for single-family house case studies, it is evident that the payback period for SFH/HP configurations is substantially prolonged due to the significantly higher total power outlet. Notably, the impact of a higher ratio of electricity sold to the grid, rather than self-consumption, on the payback period was not explored in this research. Furthermore, in the comparison between multifamily buildings, the nature of the demand profile emerges as a crucial factor influencing financial outcomes. For instances where heat pumps are employed, there is a diminished benefit in terms of energy savings resulting from reduced energy purchases. However, there exists potential for increased electricity sales during summer months. Conversely, for multifamily buildings connected to

district heating, there exists greater potential for savings during colder months, while the opportunity for electricity sales to the grid diminishes during summer periods.
The lower total CO2 mitigation in case of MFH/HP in comparison to MFH/DH will be explained in similar way as there is less opportunity to save from reduce energy purchase in heat pump integrated building rather buildings heated by district heating network, however due to the low energy demand and storage capacity in single family house this is not considerable.

Table 2: enviro-economic benefit assessment for all case studies

		SFH/DH	SFH/HP	MFH/DH	MFH/HP	CB/DH
Financial aspects	Investment cost	11987.0	11987.0	53093.0	53093.0	313492.0
	Savings (from less purchased energy, fees and taxes)	365.0	194.0	2855.0	2698.0	12681.0
	Income from sales (tax free for private persons)	1680.0	1597.0	9585.0	9725.0	54034.0
	Total of savings and income	2045.0	1791.0	12440.0	12423.0	66715.0
	Internal rate of return	0.2	0.1	0.2	0.2	0.2
	Pay-back-time, year	5.9	6.7	4.3	4.3	4.7
Environmental benefit	Total CO2 mitigation (kg CO2)	234	240	1803	1570	15066

SFH: Single family house
MFH: Multifamily house
CB: Commercial building
DH: District heating
HP: Heat pump

4 CONCLUSIONS

The interplay between a building's characteristics and its heating system significantly influences energy dynamics and surplus generation. Notably, single-family buildings relying on district heating networks may show lower electricity demand, yet their surplus production isn't markedly higher compared to those utilizing heat pumps. Conversely, multifamily buildings connected to district heating networks may demonstrate earlier overproduction, indicating a potential advantage in surplus energy generation.
In addition to these factors, emerging prosumer support schemes exert a considerable influence on profitability. These initiatives can significantly impact the benefits received by prosumers, providing incentives or subsidies to encourage participation in renewable energy generation. However, the volatility introduced by the COVID-19 pandemic and global political crises has disrupted the power market, resulting in anomalies in demand and billing. Such fluctuations directly affect the profitability of prosumers, affecting their ability to maximize returns from energy generation activities.

Understanding the implications of surplus energy generation is paramount when assessing financial considerations. Notably, the payback period for single-family house configurations with heat pumps is notably extended due to higher total power outlet. This underscores the importance of factoring in system configurations during financial evaluations. Moreover, the nature of demand profiles plays a pivotal role in financial outcomes, with potential for increased electricity sales during summer months in certain scenarios.

Shifting our focus to commercial buildings, those equipped with higher power production capacity offer greater opportunities for self-consumption, both directly and from storage batteries. This presents a compelling case for larger-scale PV system integration in commercial settings to achieve energy autonomy.

Finally, the study underscores the environmental benefits of PV system integration, particularly in terms of reducing carbon emissions. Although specific figures are not provided in the abstract, the inference drawn is clear: PV systems contribute positively to environmental sustainability by reducing reliance on traditional energy sources. This alignment between financial profitability, energy autonomy, and environmental sustainability underscores the multifaceted advantages of PV system integration.

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