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Future-proofing positive energy districts: climate change impacts on energy demand and supply in Jättesten, Gothenburg

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Abstract. Positive Energy Districts (PEDs) are based on the EU directive on energy transition pathways, promoting energy-resilient communities. PEDs produce more energy than they consume via renewable energy sources, energy efficiency, energy flexibility, and decarbonised mobility. Current research on PEDs focuses on technology deployment, literature studies, legislation, and implementation frameworks but lacks consideration of climate change impacts. PED strategies use Typical Meteorological Year (TMY) datasets, which omit unusual events like heat waves. PED planning requires climate data reflecting Future Climate Scenarios (FCS), especially in heating-dominated regions facing new cooling demands. This study investigates the impact of FCS on candidate residential buildings currently under consideration for PED transformation. The case study examines the Jättesten neighbourhood in Gothenburg, Sweden. Jättesten is a residential district undergoing renovations. This study uses FCS for 2080 under four Shared Socioeconomic Pathways (SSP). The research aims to investigate the impact of climate change on PEDs under FCS. The methodology employs simulation-based energy modelling that integrates renovation measures and renewable energy systems. The results reveal a mild increase in seasonal cooling energy demand, partly offset by a substantial decrease in heating energy demand and variations in PV production. These insights highlight the need to include additional considerations for renovation planning for PEDs in Sweden and other heating-dominated regions.

1. Introduction

Positive Energy Districts (PEDs) are defined within the SETPLAN [1] as a “district with annual net-zero energy import and net zero CO_2 emission working towards an annual local surplus production of renewable energy.” [2]. PEDs have emerged as a potential solution to enhance energy resilience by achieving an annual positive energy balance and net zero CO2 emission. Researchers exploring methods for transforming existing neighborhoods into PEDs typically focus on strategies to reduce heating demand through renovation measures [2], [3], [4] and integrating renewable energy systems capable of producing surplus energy for external sharing [2], [5].

However, these approaches often overlook Future Climate Scenarios (FCS), focusing merely on adaptive resilience. *Adaptive resilience* refers to how a system responds during a crisis and typically involves creative solutions lacking a long-term focus on capacity building [6]. On the other hand, *inherent resilience* refers to decisions and everyday practices undertaken in the present that shape and strengthen the ability to withstand disruptions in the long term [7]. It is important to consider inherent resilience when making decisions to avoid solving current issues at the expense of future energy stability.

Studies indicate significant anticipated a reduction in solar energy production [8] and shifts in energy demand patterns, with heating needs expected to decline and cooling requirements projected to rise sharply, particularly in northern European climates such as Sweden [9]. By prioritizing current heating demand reductions without accounting for future cooling loads, proposed renovation packages (RPs) will indeed reduce heating demand today, but they may inadvertently lead to increased cooling energy demand, affecting overall energy resilience. However, it is unclear what the magnitude of the change is.

Consequently, this gap highlights a pressing need to integrate FCS into PED planning. Comprehensive renovation strategies should simultaneously address current and future energy demands, ensuring inherent energy resilience under evolving climate conditions.

This study aims to investigate the impact of climate change on PEDs under FCS, using four Shared Socioeconomic Pathways (SSP) climate scenarios with increasing severity of temperature rise. Additionally, this paper aims to highlight how today's renovation decisions can affect the energy performance of buildings in the future. However, this study does not assess the economic feasibility of RPs, nor does it consider life cycle perspectives on global warming potentials.

2. Methods and materials

This research examines one of the multifamily residential buildings within the Jättesten neighborhood in Gothenburg, Sweden. It analyses the current and projected future energy performance. Four scenarios are explored: a baseline scenario (BL), where no renovations are performed, and three scenarios incorporating various RPs. Further, renewable energy production and performance of PV is calculated for the FCS.

The study site, Jättesten, is a mixed-use neighborhood in northwest Gothenburg, Sweden. The area comprises 22 residential buildings, two mixed-use buildings, one school, and one preschool. The residential and mixed-use buildings were constructed during the late 1950s and early 1960s, featuring typical mid-20th-century architectural styles with basements and three floors above ground. Given their age, these buildings generally exhibit lower energy efficiency and require significant renovations to improve their performance. Jättesten is a district representative of a typical ageing residential building stock of Gothenburg, which is under consideration for renovation in the near future.

The baseline energy model reflects the existing conditions in the Jättesten neighbourhood, see ***Figure 1***. using detailed 3D geometries and a construction set representative of the local building stock. Heating systems were modelled with a theoretical district heating network, using a 21 °C temperature setpoint in line with Swedish building codes. The model was calibrated with a heating demand error below 5%. Air infiltration was set at 0.00045 $m^3/s \cdot m^2$, based on blower door tests. Vegetation and surrounding buildings were included to account for shading, using point cloud data from Lantmäteriet [10].

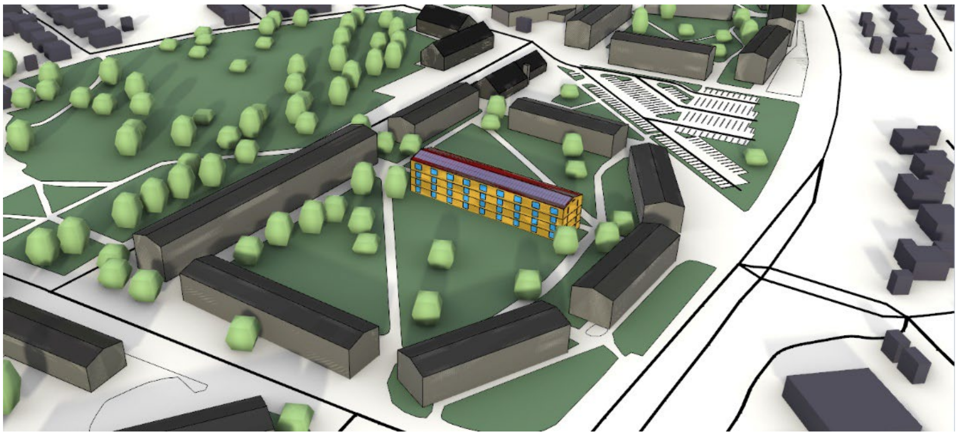

Figure 1. The baseline energy model set up in Rhino and Grasshopper with the context buildings & trees

The FCS data was generated using the Future Weather Generator tool [11], employing climate projections from the EC-Earth3 General Circulation Model (GCM), currently employed by the Swedish

Meteorological and Hydrological Institute (SMHI) [12]; it is part of the Coupled Model Intercomparison Project phase 6 (CMIP6), contributing to the 6th IPCC Assessment Report. FCS modelled for the year 2080 (representative of the 2066–2095 period), considering four standardized SSPs, see Table 1.

Table 1. SSP emission pathways with stabilized temperature increase.

FCS	Emission pathway	Temperature increase
SSP1-2.6	Emissions are cut severely, reaching net zero after 2050	1.8 °C
SSP2-4.5	Emissions will not reach net zero by 2100	2.7 °C
SSP3-7.0	Global CO_2 emissions will roughly double from current levels by 2100	3.6 °C
SSP5-8.5	Current CO_2 emissions levels will roughly double by 2050	4.4 °C

The modelling framework follows several interconnected steps. It begins by establishing a baseline scenario that represents the current state of an existing residential building, calibrated to less than 1% error. Using Rhinoceros 3D and Grasshopper, parametric models for PV roof system and building envelope construction sets were developed. Honeybee plugin is used to perform energy performance analyses through the EnergyPlus simulation engine. System Advisor Model (SAM) models hourly renewable energy production through PVWatts version 8. Finally, the results are integrated and visualized using Python see ***Figure 2***.

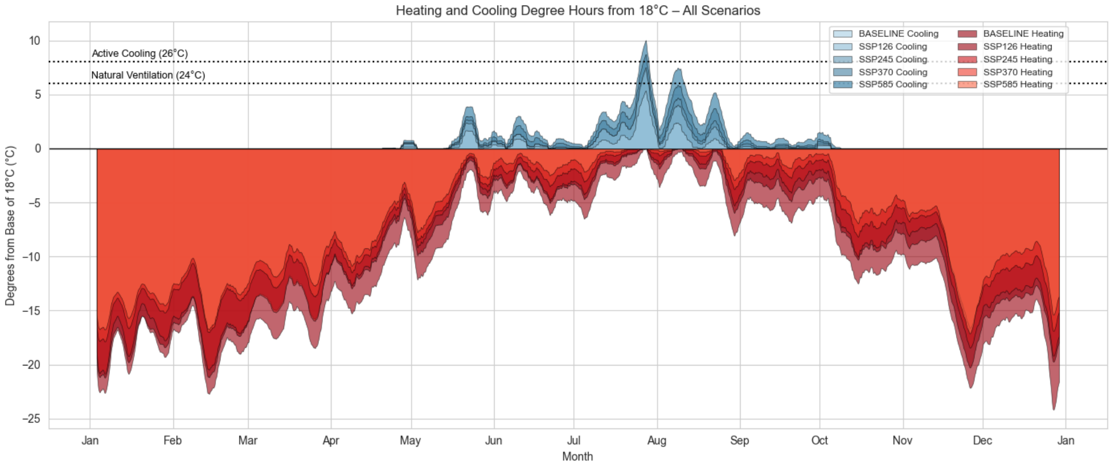

Figure 2. Annual heating degree hours and cooling degree hours for FCS around an 18°C [13], [14]baseline. The natural ventilation setpoint for the simulation model is at 24°C, and the active cooling trigger is at 26°C [15].

Energy demand modelling utilizes comprehensive schedules reflecting building use, including residential units, corridors, and laundry rooms. Occupancy schedules, internal gains from appliances and occupants, and usage profiles of shared facilities such as laundry rooms were integrated into the energy demand simulations. As for the construction set, there is baseline (BL) scenario that represents the current construction set. RP2 and RP3 are representing medium and deep renovation strategies adopted from the Tabula building typologies web tool [16], while RP1 lies in between BL and RP2 see Table 2.

Table 2. Renovation packages including envelope U-values per construction element and infiltration rates.

	U-values (W/m²K)				Infiltration rate (m^3/s)
RP	Wall	Roof	Floor	Window	Exterior surface area
BL	1.6	2.2	1.2	2.4	0.00045
RP1	0.58	0.36	0.32	2.22	0.00030
RP2	0.29	0.12	0.24	0.90	0.00030
RP3	0.09	0.06	0.24	0.76	0.00020

3. Results

3.1 Change in heating and cooling demand

Under current climate scenario and existing building construction (BL_existing), the baseline heating demand is 140.75 kWh/m^2, representative of a large proportion of the Swedish residential building stock. RP1 reduces the heating load to 76.41 kWh/m^2 (-45.7%). Medium renovation (RP2) further reduces the heating demand to 62.60 kWh/m^2 (-55.6%), while the deep renovation (RP3) naturally achieves the lowest heating demand of 45.03 kWh/m^2 (-68%).

As the severity of the future climate pathways increases, the absolute heating demand decreases resulting from warmer winters. Under SSP585, the baseline heating demand drops to 80.32 kWh/m^2 (-42.9%) with no renovation interventions. The maximum reduction in heating demand is seen in applying RP3 under SSP585, achieving 00.69 kwh/m^2 (-71.7%).

The results show an increase in cooling demand with climate warming in the future. The current climate conditions at the baseline construction result in a cooling demand of 3.04 kWh/m^2. This cooling demand while low, currently remains unmet in the Swedish multifamily residential building stock and is experienced today as short overheating periods. In the future however, these cooling demands rise to 20.02 kWh/m^2 under SSP585- (+559%).

Renovation has limited impact on cooling demand across different RPs and the FCS. Except for RP1, which results in a marginal increase in cooling demand under mild heating scenarios (SSP126), RP2 and RP3 show reductions from 20.02 to 18.09 kWh/m^2 (-9.6%).

Table 3. Result of scenario analysis across renovation packages and FCS with respective Heating (H) in kWh/m^{2}and Cooling (C) demands in kWh/m^2.

	Existing		ssp126		ssp245		ssp370		ssp585	
Scenario	H	C	H	C	H	C	H	C	H	C
Baseline	140.8	3.0	114.0	6.4	107.3	7.5	87.9	12.4	80.3	20.0
RP1	76.4	3.0	58.0	11.1	55.9	10.8	51.9	14.8	45.5	19.2
RP2	62.6	3.1	50.7	6.4	47.3	7.3	37.0	11.7	33.3	18.0
RP3	45.0	3.3	36.2	6.6	33.7	7.6	25.5	11.9	22.7	18.1

3.2 Electricity production

The analysis of PV output under different SSPs shows that projected climate change has a modest but nuanced impact on PV production in Jättesten. Compared to the existing baseline scenario, the monthly PV output varies by +1% to -25% depending on the season and scenario.

In winter months (December–February), all scenarios show a consistent decrease in PV production, with reductions of up to 25%, driven by increased cloud cover and reduced solar irradiance. In contrast, the summer months (May-August) show modest gains, with SSP126 and SSP245 with increases in PV output of +1%.

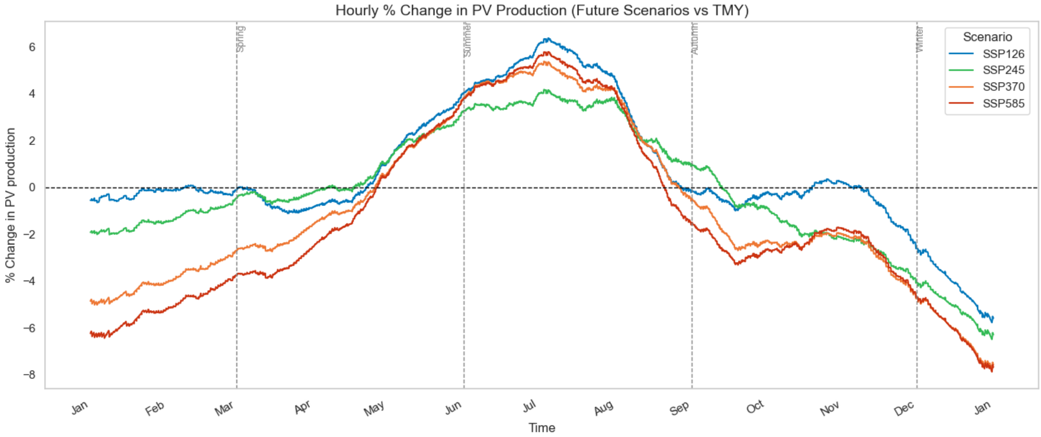

Figure 3. Hourly percent change in PV production- FCS vs existing weather data

The hourly analysis shown in ***Figure 3*** indicates that daily PV output is not uniformly affected. Instead, FCS enhances peak production in summer but amplifies reductions in winter and shoulder months. The percentage change in hourly PV output fluctuates throughout the year in the range of –8% to +8%. Annual changes to PV productions across the four SSPs are limited to ±3%. Hence PED simulations were only run for existing baseline weather data to provide an indicative result. Utilizing 100% of roof top with PV and a 9.8 kWh battery system, key PED performance indicators show that the building will be self-sufficient 54.25% of the time, see Table 4.

Table 4. Key PED performance indicators under baseline existing weather data.

PED indicator	Value
PV capacity	44.53 kWp
Battery capacity	9.80 kWh
Annual PV generation	34,280 kWh
Self-sufficiency ratio (fraction of total load demand supplied by local generation)	54.25 %
Grid dependency ratio (fraction of total load covered by grid import)	45.75 %
Self-Consumption Ratio (fraction of total PV generation consumed locally)	43.81 %

4. Discussion

The study set out to understand how today's renovation decisions can affect the energy performance of buildings in Sweden under future climate scenarios. The results confirm that the deep renovation strategies (RP3) have a high impact on decreasing heating demand regardless of the FCS, as seen in **Table 3**. The energy savings in the warmest projected future scenario (SSP585) show the long-term value of investing in improving the building envelope; reduced thermal transmittance and air tightness.

While deep renovation strategies (RP3) substantially reduce heating demand—up to 71.7% under SSP5-8.5—their effectiveness in mitigating future cooling demand is limited. For example, under SSP5-8.5, cooling demand only decreases by 9.6%, from 20.02 kWh/m² to 18.09 kWh/m², despite significant envelope upgrades. This outcome reflects a challenge in heating-dominated climates transitioning to mixed or cooling-dominated profiles: improved insulation and airtightness reduce winter losses but can trap internal and solar heat gains during warmer months, increasing risk of overheating and cooling demand. This highlights a critical blind spot in current renovation strategies focused solely on envelope performance. Passive cooling measures—such as external shading systems, low-emissivity glazing, and smart natural ventilation—must be integrated early in renovation planning, similar findings have been shown by [17]. Without these additions, building upgrades risk becoming maladaptive, solving historical heating inefficiencies while introducing future cooling challenges. Building codes should incentivize or even require adaptive measures addressing both heating and cooling performance. Integrating passive cooling measures [17], night-time ventilation flushing, solar gain control, and adaptive comfort models will be critical to ensure PEDs remain resilient, efficient, and comfortable in a warming climate.

The ventilation control strategy plays a vital role, as demonstrated in the cooling and heating degree hours, as seen in ***Figure 2***. In Gothenburg, where peak summer temperatures remain moderate even in extreme warming scenarios, ventilation strategies can limit mechanical cooling demands. However, as nighttime temperatures get warmer in the future, smart ventilation control logic may be required. The results underscore the role of cooling resilience in Swedish multifamily residential buildings.

Future climate scenarios impact renewable energy supply [17] — particularly PV performance — requiring examination and long-term planning. This study shows that climate change does not significantly diminish PV viability in Sweden. Instead, seasonal shifts in production may create new energy flexibility challenges and opportunities. PV production slightly increases in summer due to elevated solar irradiance and longer clear-sky periods, especially in scenarios with strong mitigation efforts (e.g., SSP126). However, winter output decreases across all SSPs, reinforcing the seasonality challenge of PV electricity generation in high-latitude countries. These trends support a need for seasonal balancing through storage, demand-side flexibility, or hybrid systems. Temperature-related PV efficiency losses in warmer climates, remain minimal in Sweden. Even under SSP585, temperatures stay below critical thresholds; thus, temperature-induced efficiency losses are negligible. Some studies report up to a 10% long-term decline in PV system output [8], but this include panel degradation, and system ageing over time — not climate. The results suggest that climate-induced losses are unlikely to account for more than 5% of long-term PV reduction, making system quality and maintenance more decisive.

The case study building represents a significant portion of the Swedish building stock identified for renovation in the near future. By highlighting the impacts of FCS on renovation and PV strategies, this research helps property owners make informed decisions and embed resilience in existing buildings.

This study has several limitations. First, it focuses on a one multifamily building in Jättesten, which may not capture the full variability of building types, orientations, and user behaviors across the district. Second, modeling assumes static occupancy patterns and internal gains, which may evolve under FCS as occupant behavior adapts to increased cooling needs. Third, the PED simulations were limited to baseline weather due to limited projected variation.

Future studies should analyse multiple buildings and orientations, incorporate behaviour modelling, life cycle assessment, and economic evaluations of RPs. Exploring adaptive technologies integration; dynamic shading, hybrid cooling systems, and real-time energy management under different climate scenarios would further support robust PED planning in warmer climate.

5. Conclusion

This study demonstrates the strong potential of RPs to reduce heating demand in Swedish multifamily residential buildings by over 70%, even under warmer climate scenarios. However, cooling demand is projected to increase six times -SSP585, and envelope upgrades alone provide limited reduction in cooling demands. While deep renovation achieves modest cooling reductions, the need for cooling will continue to rise in FCS. At present, building owners are transitioning towards building renovation strategies to prepare for climate change impacts. Hence, it is crucial to include shading, low emissivity solutions, smart ventilation and active cooling measures in renovation plans to avoid unforeseen cooling demand increase in the future.

The FCS has a relatively small direct impact on PV energy production in Gothenburg. While winter reductions of up to -25% are expected, summer output may slightly increase, especially under scenarios with stabilized climate conditions. These fluctuations indicate PV systems remain a resilient component of the future energy mix in Sweden. However, seasonality of production and limited winter generation underline the need for integrated energy planning, combining PV with storage, load shifting and complementary renewables. Moreover, System degradation and aging may outweigh climate impacts in future PV performance. Designers, policymakers, and energy planners should consider these insights to guide investment in solar infrastructure that is climate-resilient, performance-optimized, and strategically supported by grid flexibility and thermal demand management.

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Credit author statement

Sara Abouebeid: Conceptualization, Methodology, Software, Validation, Formal Analysis, Investigation, Visualization, Writing. Elena Malakhatha: Review & Editing, Supervision. Holger Wallbaum: Funding acquisition. Liane Thuvander: Funding acquisition, Resources, Review & Editing.

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