TOWARDS NET ZERO PATHWAYS FOR BUILDING STOCK PORTFOLIOS BASED ON KEY PERFORMANCE INDICATORS

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ABSTRACT

In alignment with the Paris Agreement, Switzerland aims to reach net zero emissions by 2050. According to the recent Climate and Innovation Act, Swiss federal agencies must decarbonize their building portfolios to reach net-zero emissions already by 2040, in advance of the national net-zero targets. In support of these efforts, in this study, we develop an approach to analyze potential decarbonization pathways for a large building portfolio (approx. 1000 buildings) owned by a federal agency. First, the impact of different envelope retrofits on demand reduction is evaluated on the building level using CESAR-P simulation software based on EnergyPlus, together with the corresponding costs and embodied emissions. Trade-offs between cost- and emission-optimal solutions are evaluated via multi-objective optimization using the MANGOret model for each building, with the corresponding combinations of building envelope retrofit, heating system replacement, and PV system integration over a time horizon of 15 years. The Pareto optimal solutions at the building level are aggregated to the portfolio level and compared to the point closest to the origin (i.e. zero costs and zero emissions) for each building. The solutions at this point comprise the zero scenario. Additionally, trade-offs between key performance indicators (KPIs) measuring cost-effectiveness of emission reduction, demand and emission intensity, as well as renewable energy generation are assessed. We show that the most favorable cost-effectiveness of emission reduction with respect to the cost-optimal point are achieved with the zero scenario. At the two extremes, cost-optimal solutions rely mainly on heating system replacement and PV system installations to reduce the emission intensity of the portfolio, while emission-optimal solutions include a high share of envelope retrofits to reduce useful heating demand, in addition to energy supply solutions. Additional KPIs can be used by decision-makers to prioritize retrofit interventions across the portfolio, enabling a side-by-side comparison of potential decarbonization pathways.

1 INTRODUCTION

The building sector holds a significant share of CO_2 emissions, making decarbonization efforts crucial in achieving net zero emissions by 2050. Among the EU countries, the building sector accounts for around 40% of energy consumed and about one third of greenhouse gas (GHG) emissions, with approximately 80% for heating, cooling, and hot water needs (European Environment Agency, 2023; Eurostat, 2023). The Energy Performance of Buildings Directive (EPBD) is designed to increase renovation rates, especially targeting the worst performing buildings (European Commission, 2024). Despite the public sector representing a small portion of the overall building stock, the decarbonization of public and publicly-owned buildings can serve as a model, highlighting specific measures and effective implementation strategies that can be adopted by the private sector.

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Aligned with the recast of the EU Energy Efficiency Directive (EED), specifically Article 5 and 6, public bodies are now mandated to integrate precise energy efficiency measures into their long-term planning tools. Meeting a 3% annual renovation rate target is required, with some flexibility to achieve this goal through varying levels of renovation intensity, changes in occupant behavior, and/or improved building management, all aimed at achieving equivalent savings. The decision of which buildings to renovate towards nearly-zero or zero-emission standards is left to the discretion of public bodies, with considerations including cost-effectiveness, technical feasibility, and life cycle carbon emissions (Directive 2023/1791, 2023). Similarly, the Climate and Innovation Act in Switzerland (UVEK, 2023) has spurred comparable requirements for the public sector.

A primary challenge for public bodies lies in planning the subsequent series of retrofits that are both cost-efficient and impactful in emissions reduction. Limited availability and reliability of data often pose the initial obstacle in establishing a baseline and exploring potential retrofit pathways. Building upon previous research on portfolio decarbonization (Petkov, Lerbinger, et al., 2023), this paper seeks to examine potential retrofit pathways using building-level energy demand and retrofit modeling as inputs to a multi-objective optimization framework. Potential decarbonization scenarios are evaluated at the portfolio level using a set of key performance indicators (KPIs) encompassing heating demand intensity, carbon emission intensity, and renewable energy generation.

2 METHODOLOGY

In this study, we evaluate a large portfolio of federal buildings distributed across Switzerland. Managed by a Swiss government agency, these buildings vary widely in type, construction period, and heating technologies. The primary goals of this analysis is to outline potential decarbonization options—combination of building envelope retrofit, heating system replacement, and local renewable energy generation—that minimize total emissions (operational and embodied) in a cost-effective way.

To achieve these goals, we employ a two-step approach. First, we conduct a detailed analysis at the building level to identify Pareto optimal solutions for each building. These solutions are then aggregated and analyzed at the portfolio level to determine the most effective strategies for cost and emission reductions across the entire portfolio.

The following sections detail the data inputs, the models, and the methods at both the building and portfolio levels.

2.1 Data

The data utilized in this study was primarily sourced from public databases (summarized in Table 1 below), which were supplemented by more recent data from the Swiss federal agency. Notably, public sources often contained inaccuracies regarding replacement of heating technologies, which were updated for this study. The building portfolio comprises both public and publicly-owned buildings. To perform the analysis, the minimum building-level information required are the building type and age, and 2.5D building geometry (building footprint and building height).

Table 1: Data Sources and Attributes

Name	Attribute	Source
Swiss Federal Register of Buildings and Housing (GWR)	Building type, Building age, Heating technology	Swiss Federal Office of Statistics
OpenStreetMap	Building footprint	OSM contributors
swissBUILDINGS3D2.0	Building height	Swisstopo
CH2018	Climate regions	MeteoSwiss

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2.2 Building energy demand modeling and the optimization framework

To assess building energy demands and the impact of various building envelope retrofit interventions on demand reduction, as well as associated costs and emissions, we employed the CESAR-P model that uses EnergyPlus for urban energy demand simulations (Orehounig et al., 2022). Weather files are chosen according to building location, building envelope properties (i.e., U-values, window-to-wall ratio, air infiltration rate) according to building age, and indoor schedules and setpoints (e.g., activity, occupancy, temperature) according to building type. The available options in each category are represented in Figure 1. The building information is then coupled to the corresponding building geometry, and then each building is simulated. In case of retrofit, the building geometry is used to calculate the areas of insulation materials and window surfaces, and their corresponding costs and embodied emissions. These results served as inputs to an adapted building energy optimization framework, the MANGOret model, which seeks long-term building retrofit strategies that minimize the strategy's total cost and/or emissions. The strategies resulting from MANGOret combine demand-side interventions, such as envelope retrofit measures, and supply-side interventions, such as heating technology replacement and the installation of renewables (Petkov, Mavromatidis, et al., 2022). The analysis incorporates full emissions (embodied, operational, and salvage) and costs (capital, operational, and salvage) over the simulation horizon of 15 years. The key input and assumptions are summarised in the Appendix, including costs and carbon intensity of energy carriers (in Table 2), as well as capital costs and embodied carbon of heating technologies (in Table 3) and of renewable energy and storage (4).

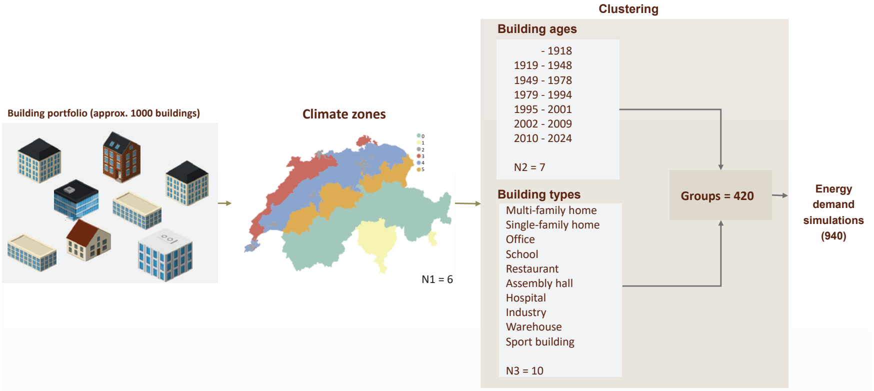

Figure 1: Grouping of buildings for energy demand simulations in CESAR-P

For each building results along seven scenarios / cases are obtained:

- Reference scenario (ref): corresponds to keeping the existing heating technology type with replacement at the end of life
- Pareto points (P0 to P4): the point on the Pareto front from cost optimal (P0) to the emission optimal (P4)
- Retrofit scenario (retro): a window-wall retrofit is forced to be implemented at Year 1

2.3 Portfolio level analysis

At the portfolio level we additionally define the zero scenario, which aggregates the Pareto points from each building that are closest to the origin (i.e., zero costs and zero emissions). This scenario serves as a benchmark for evaluating the cost-effectiveness of emission reduction strategies across the entire

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portfolio. By identifying these optimal points, we can assess the potential for achieving significant cost and emission reductions in a systematic and efficient manner.

2.4 Key performance indicators for evaluating decarbonization pathways

For the evaluation of portfolio decarbonization measures, we carefully selected key performance indicators encompassing cost-effectiveness, building envelope efficiency, emission intensity, and renewable energy supply. These indicators included metrics such as cost-effectiveness of emission reduction (CHF/kgCO$_2$), specific annual energy demand (kWh$_{th}$/m^2), specific annual energy import [kWh/m^2] specific annual emission intensity (kgCO$_2$/m^2), and share of renewable energy (%). Through these methodologies, we aimed to comprehensively assess the impacts of various interventions on both decarbonization efforts and economic viability within the context of building retrofits.

3 RESULTS AND DISCUSSION

Figure 2 summarizes the building-level results for the full portfolio across each scenario, including the Zero scenario, where optimal points are systematically selected for each building separately based on their proximity to the origin (as described in Sec. 2.3).

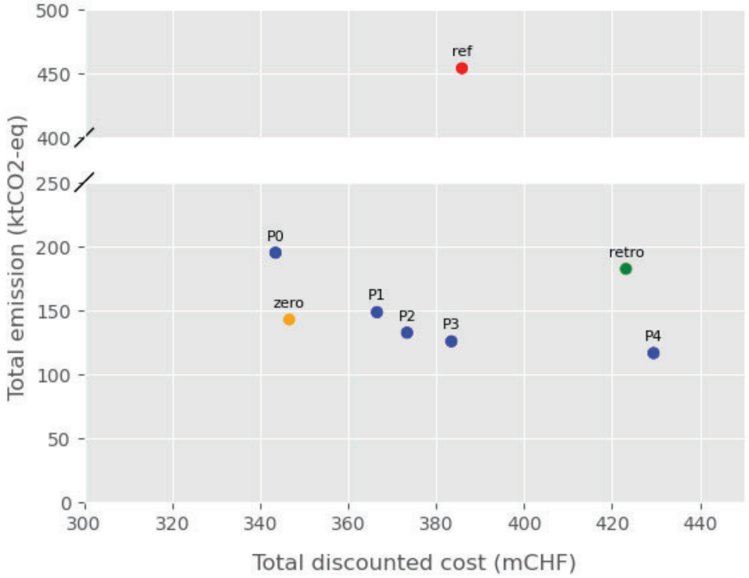

Figure 2: The total discounted cost and total emission of each scenario at portfolio level

Figure 3 summarizes the implementation of heating technologies, PV, and building envelope retrofit at each stage for the seven scenarios. In the cost optimal scenario (P0), ASHP is the major heating technology to be installed in the first stage and Year 10-12, when existing heating systems reach the end of their lifecycle. PV systems are mainly installed in the middle of the horizon (Year 7-9) or later. This is due to the assumed reduction of PV cost (-60%) and the increased price of electricity (+15%) with respect to Year 1-3. In the emission optimal scenario (P4), biomass boilers are the most commonly selected heating technology. Additionally, full PV potential is installed in the first stage (Year 1-3) to maximize emission reduction over the simulation period. Deep building envelope retrofit (window-wall and window-wall-roof) is chosen for about half of the energy reference area in the portfolio.

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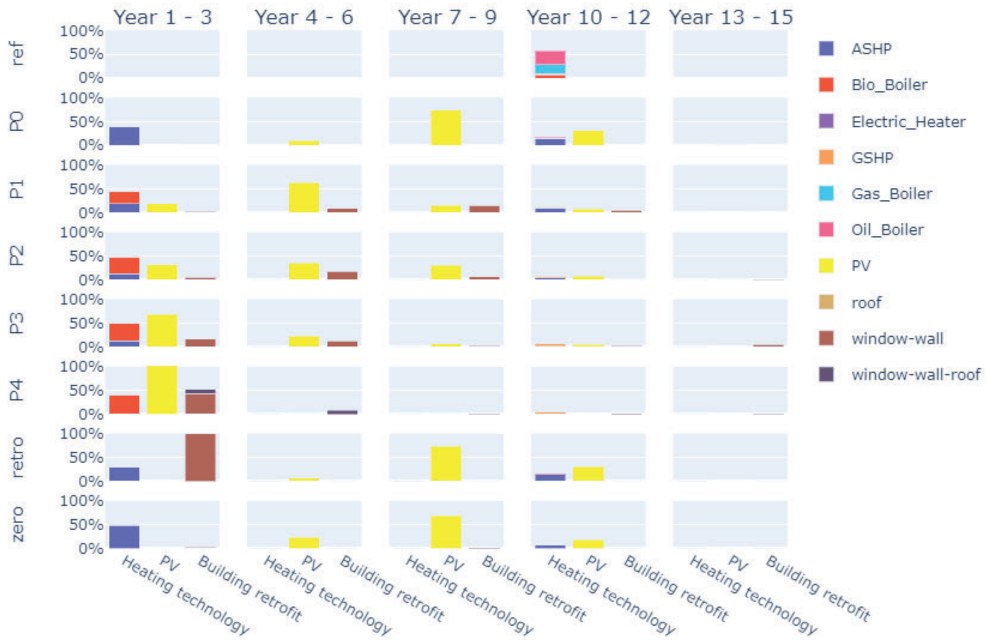

Figure 3: Implementation of heating technologies, PV, and the building envelope retrofit, at each stage across the scenarios. They are represented as a percentage of their respective maximum heating and PV capacity potential and total energy reference area available for building envelope retrofit

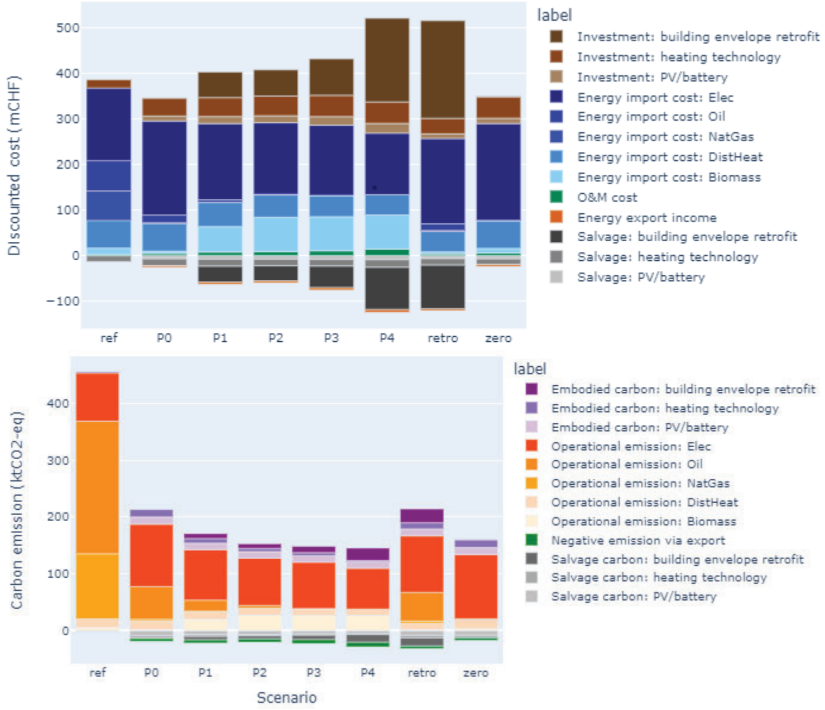

Figure 4: The breakdown of total cost and emission of the building portfolio over 15 years

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Figure 4 shows the breakdown of the total cost and the total emission of the portfolio over 15 years. With the increase of the implantation of building envelope retrofits and low-carbon technologies, the investment can increase from 19m CHF in the reference scenario to 52m CHF in the minimum cost scenario and 260m CHF in the minimum emission scenario, which accounts for more than half of the total cost when salvage value is not considered. Increased embodied carbon of building envelope retrofits and building energy technologies is accompanied by reduced total emissions. However, the fraction of embodied carbon is less than 25% over the examined portfolio, where building envelope retrofits are applied to half of the energy reference area.

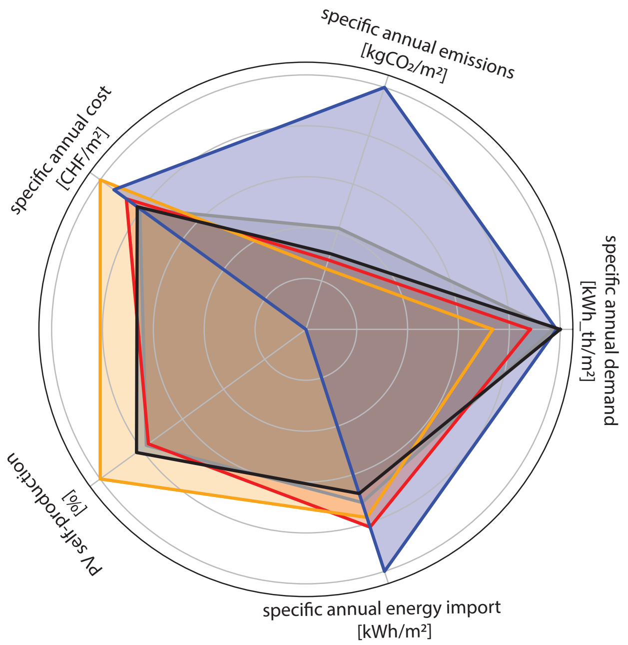

Figure 5: Summary of KPIs for the reference (blue), cost-optimal (grey), midway (red), emission-optimal (orange), and zero (black) solutions at the portfolio level, including specific annual heating demand, specific annual emissions, specific annual cost, and self-production.

Figure 5 below provides a summary of the KPIs for the cost and emission-optimal solutions, in addition to the reference and zero scenarios. While both cost and emission optimal cases lead to a significant decrease in specific annual emissions, cost optimal solutions do so with negligible changes to specific annual demand while increasing self-production of PV generated electricity. Additional emission savings are achieved through increased envelope efficiency at the cost of lower renewable energy generation from PV, while keeping the specific annual costs of similar magnitude to the reference case.

Based on the evaluated KPIs, the decarbonization pathways can be evaluated beyond the total costs and emissions, leading to different choices of retrofit interventions (heating technologies, PV generation, and building envelope retrofits).

4 CONCLUSIONS

This study provides a comprehensive framework for analyzing potential decarbonization pathways for a large building portfolio, which necessitates an efficient and systematic approach for selection of Pareto-optimal solutions at the building level. Beyond the simple aggregation of building-level solutions from the cost- to emission-optimal, we introduced the zero scenario, where a point closest to the origin

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(i.e. zero costs and zero emissions) is chosen for each building individually. A set of key performance indicators enabled the comparison of specific costs, demands, and emissions, as well as renewable energy integration across potential decarbonization strategies. Based on the study results, we have identified the following key takeaways:

- **Cost-Optimal Solutions**: The most cost-effective solutions primarily involve replacing heating systems and installing photovoltaic (PV) systems. These measures significantly reduce the emission intensity of the portfolio, while keeping the costs low.
- **Zero Solutions**: Compared to cost-optimal solutions, zero solutions prioritize the early replacement of fossil-fuel-based systems and the installation of PV systems, focusing on immediate emission reductions.
- **Emission-Optimal Solutions:** Strategies optimized for emission reductions emphasize reducing useful heat demand through building envelope retrofits, along with a transition to low-carbon heating systems.

The proposed approach provides a valuable framework for decision-makers planning the next set of retrofits. However, a notable limitation of the current analysis is that costs are concentrated at the start of the time horizon. This does not account for the budgetary and personnel constraints faced by portfolio owners. Future work will explore these constraints in more detail to better prioritize retrofits and develop a more feasible implementation plan.

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APPENDIX

Table 2: Cost and carbon intensity of energy carriers

Energy carrier	**Carbon intensity** kgCO2-eq/kWh	**Cost in reference year** CHF/kWh (Year 1)	**Future changes** %/year
Electricity	0.125	0.225	+1.5
Natural gas	0.23	0.146	+2.0
Heating oil	0.324	0.101	+2.0
Wood chip	0.011	0.041	+1.5
Pellet	0.028	0.089	+1.5
District heating	0.037	0.108	+1.5

Table 3: Costs and embodied carbon of heating technologies

Technology	**Lifetime [Year]**	**Capex fixed (Year 1; 10) [CHF]**	**Capex (Year 1; 10) [CHF/kW]**	**Opex [% of Capex/year]**	**Embodied carbon [kgCO2-eq/kW]**
Air-source heat pump	20	49635; 38927	610; 478	0.8%	363.75
Ground-source heat pump	20	49130; 35885	2450; 1788	0.8%	272.5
Gas boiler	25	23785; 23785	175; 175	2.4%	51.2
Electric heater	25	19028; 19028	70; 70	1.6%	-
Oil boiler	25	26164; 26164	193; 193	2.3%	51.2
Biomass boiler	25	55885; 55885	320; 320	2.1%	51.2

Table 4: Costs and embodied carbon of renewable energy and energy storage

Technology	**Energy conversion efficiency**	**Lifetime [Year]**	**Capex (Year 1; Year 10) [CHF/kW]**	**Opex [% of Capex/year]**	**Embodied carbon [kgCO2-eq/kW]**
Solar PV rooftop	20%	30	500; 196	1.7%	254
Solar PV facade	20%	30	630; 247	1.7%	254
Electric battery	90% (round-trip efficiency)	20	367; 310 (CHF/kWh)	2.0%	157

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