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PACE REFITS

Policies for accelerating renewable and efficient building & district retrofits

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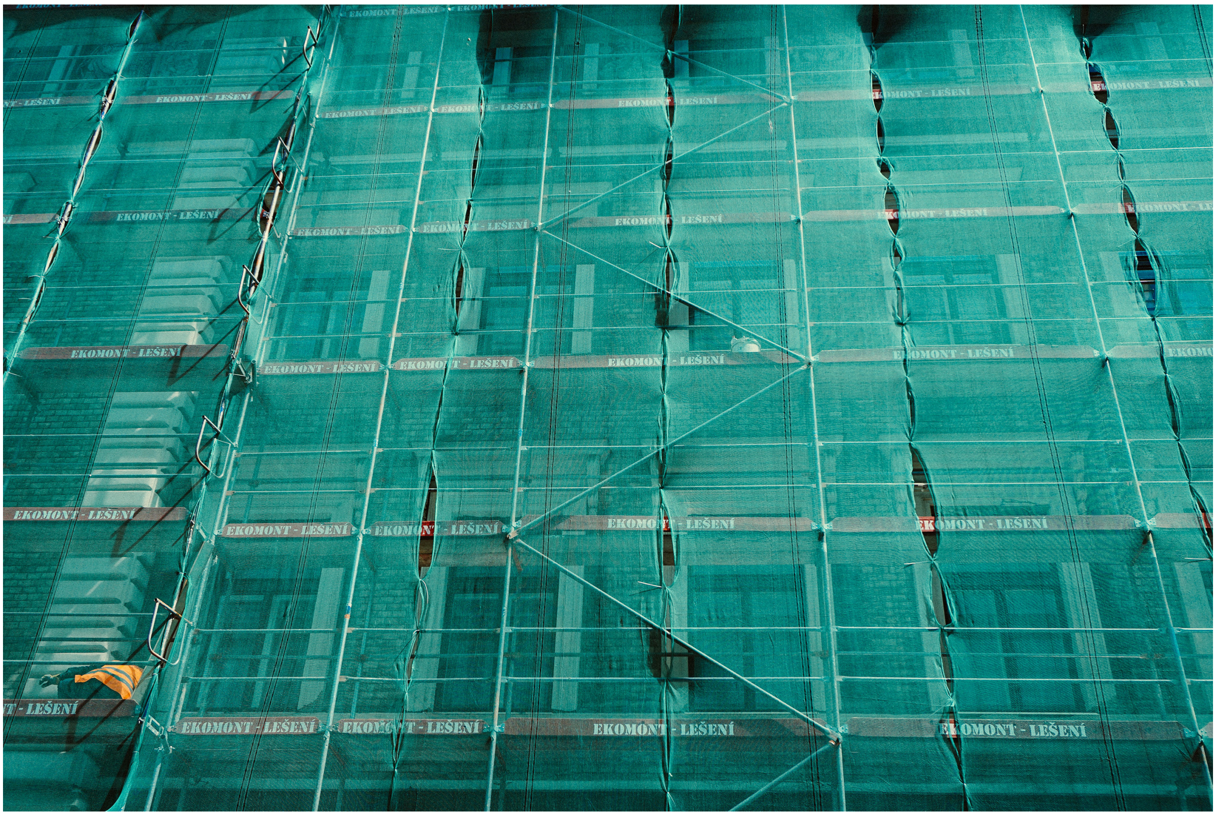

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Zusammenfassung

Der Energiebedarf und die CO_2-Emissionen aus dem Gebäudebereich können mit zeitgemässen erneuerbaren und energie-effizienten Gebäudetechnologien, sowohl auf der Gebäude- wie auch auf der Arealebene, drastisch reduziert werden. Im Neubaubereich sind diese Technologien bereits weit verbreitet, während bei Renovierungen eher konventionelle Technologien eingesetzt werden. Mit dem Fokus auf Grossinvestoren, untersucht dieses Projekt deren Motivation und Hinderungsgründe, sowie welche regulatorische Rahmenbedingung deren Investitionen in erneuerbare und energie-effiziente Renovierungen unterstützen würden. Das Projekt wendete einen Mixed-Methoden Ansatz an, in welchem qualitative Methoden wie Interviews und Workshops mit quantitativen Energie System Modellierungsansätzen kombiniert werden.

Mittels einer Interviewkampagne wurden Entscheidungsverhalten, Motivation und Hinderungsgründe von Grossinvestoren für energetische Sanierungen untersucht, um das Zusammenspiel zwischen dem Sanierungsverhalten und Politikmassnahmen zu evaluieren. Weiter wurde in einem Politik-Szenarien-Workshop die Rolle und Entwicklung von Regulationen, finanziellen Anreizen und Normen im Entscheidungsprozess von Grossinvestoren analysiert. Dabei wurden drei unterschiedliche Zukunft Szenarien, zusammengesetzt aus einer Vielzahl von direkten und indirekten Politikinstrumenten, entwickelt und quantifiziert. Aufbauend auf diesen qualitativen Ergebnissen bezüglich des Entscheidungsverhaltung von Grossinvestoren wurde ein multi-stage Optimierungsframework (MANGO: Multi-stAge eNerGy Optimization) entwickelt. Mango erlaubt die Optimierung von Emissionen und Kosten von multi-energie Systemen über einen langen Zeithorizont (e.g. 30 Jahre) und dient als Basis um den Einfluss von techno-ökonomischen und regulatorischen Rahmenbedingungen auf Sanierungen auf der Gebäude- und Arealebene zu untersuchen. MANGO wurde erweitert damit sanierungs-spezifische Aspekte adressiert werden können (MANGOret). Nachdem wir detaillierte Portfoliodaten eines Grossinvestors akquirieren konnten, wurde MANGOret nun zu einer skalierbaren Real-Options Methode weiterentwickelt. Weiter wurde die Methode auf eine reale Fallstudie angewandt, um Sanierungsaspekte auf der Areal Ebene zu untersuchen.

Das vorliegende Projekt liefert folgende Hauptresultate: Erstens, in den Interviews, wurde ein geringer Einfluss von direkten Energiepolitikinstrumenten gefunden, während die Wichtigkeit von «indirekten» nicht-energie bezogenen Regulationen im Bereich Mietrecht, Städteplanung und des sozialen Wohnungsbaus herausgestrichen wurde. Die Untersuchungen zeigten, dass direkte und indirekte Politikinstruments an verschiedenen Punkten im Entscheidungsprozess gegenläufige Wirkung haben können und daher nur in einem gut integrierten Policymix effektiv die Diffusion von energetischen Sanierungen beschleunigen können. Zweitens, die Anwendung der quantitativen Modelle bestätigte, dass emissions-minimierende Lösungen immer noch teuer sind, mehrheitlich getrieben durch die hohen Investitionskosten der Sanierung der Gebäudehülle. Auf der Portfolio-Ebene zeigen unsere Resultate, dass das Reduzieren der Lebenszyklusemissionen bis 2050 von dem Kosten-minimum zum Emissions-minimum CO_2-Emissionen um 47% reduziert aber Kosten um 45% erhöht. Trotzdem können mit minimalen Zusatzkosten (<1%) schon eine starke Reduktion (e.g. >11%) der Emission im Vergleich zu den kosten-optimalen Lösungen erreicht werden auf der Gebäude- und Portfolio-Ebene. Drittens, zeigen die Simulationen der Politik-Szenarien die Wichtigkeit einer Transformation hinzu Netto-null orientierten Politikmassnahmen im Vergleich zu einem Business-as-usual Szenario (i.e. Weiterführung der bisherigen regulatorischen Massnahmen) für die Dekarbonisierung des Gebäudebestands. Darüber hinaus zeigt sich auch die Dringlichkeit der Massnahmen. Das ambitioniertere Netto-Null 2040 Szenario – mit früheren aber auch strikteren Regulationen – führte zu deutlich stärkeren Emissionsreduktionen als ein moderateres – an die EnergieStrategie 2050 angelehntes – Netto-Null 2050 Politik-Szenario. Viertens, für Grossinvestoren erwies sich die Art der Implementierung der Politikmassnamen als mindestens ebenso wichtig wie der Instrumentenmix selbst. Eine «Flotten» (i.e. Regulationen auf der Portfolioebene) Implementation der Politik-Szenarien zeigte sich als eine attraktivere Lösungen um Gebäudeportfolios kosteneffizient zu dekarbonisieren als die heute gültigen Regulationen auf der Gebäudeebene. Falls kombiniert mit einem maximalen Emissionsgrenzwert, präsentiert ein solche Portfolio-Umsetzung von Politikmassnamen eine wertvolle Alternative zur effektiven Dekarbonisierung

von Immobilienportfolios von Grossinvestoren. Schliesslich, zeigen die Anwendung auf der Areal-Ebene das Zusammenspiel von Sanierungen auf der Gebäude-Ebene mit dem Design des Energiesystems auf der Areal Ebene, aber auch dessen Abhängigkeit von Infrastrukturentscheidungen wie Erweiterung von Fernwärmenetzen oder Dekarbonisierung derjenigen.

Summary

Energy demand and CO_2 emissions from buildings can be drastically reduced with state-of-the-art renewable and energy-efficient technologies on the building and district scales. For new buildings, these technologies have been implemented widely, however for retrofits they are far from standard. Focusing on large-scale investors (LSIs), this project analyses their motivation and barriers, and which regulatory conditions support their investment in renewable and energy-efficient retrofitting technologies. We applied a mixed-method approach combining qualitative methods such as expert interviews and policy scenario development with quantitative energy system modelling approaches.

To evaluate the interplay between LSIs' retrofit decision making and policies we interviewed 32 key stakeholders about LSIs' decision-making processes, motivations, and barriers in executing building-level retrofits in order to better understand their interplay with the overarching retrofitting policy mix. Further, we conducted a policy scenario workshop to explore the role of regulations, polices, and norms for their influence on the LSI decarbonization strategies and developed and validated three distinct scenarios using a policy toolkit including regulatory, market-based, as well as financial incentives and fiscal instruments.

Building on the qualitative findings relating to real estate decision-making, we have developed a multi-stage optimization framework called MANGO (Multi-stAge eNerGy Optimization), focusing on the design and operation of minimum cost and emissions multi-energy systems over long-term horizons (e.g. 30 years). MANGO acts as the foundational basis to further study the impacts of techno-economic and policy considerations on retrofits at both building and district scales. We extended MANGO to have specific considerations for retrofits (MANGOret). After securing a key data exchange of several real estate portfolios with an LSI industry partner, MANGOret has been adapted to become a scalable real options method to consider uncertainties for any Swiss real estate portfolio. In addition, the method was applied to an urban district system to study retrofit considerations for district scale energy systems.

The project led to the following key results: First, out of the interviews, we observe the limited impact of direct energy policy instruments on retrofitting decisions, highlighting the importance of non-energy – indirect – policy instruments affecting LSIs retrofit investment decisions primarily relating to affordability, tenant security, and urban planning. Our findings suggest that direct and indirect instruments potentially interfere at various leverage points in LSIs' value-driven retrofitting decisions, necessitating an integrated policy mix to encourage broader market penetration of deep retrofits. Second, the application of the quantitative methods, confirmed that minimal emission solutions are still costly largely driven by high costs for building envelop retrofits. On a portfolio level our results demonstrate that decreasing life-cycle CO_2 to 2050 from the *minimum-cost* to the *minimum-emissions* portfolio strategy fosters a 47% CO_2 reduction but comes with a 45% increase in total cost. However, considerable emission reductions (e.g. >11%) are possible for negligible additional costs (<1%) compared to a cost minimizing retrofitting strategy on a building and portfolio level. Third, the simulation of the policy scenarios demonstrated the necessity of a shift towards net-zero oriented policies compared to a business-as-usual scenario (i.e. extrapolation of the existing regulatory mix), for real-estate decarbonization. Furthermore, the timing of the polices is critical, the more ambitious scenario with a Net-Zero 2040 goal – with earlier and more stringent regulations – shows much larger reductions than a more moderate Net-Zero 2050 scenario – oriented on the national Energy Strategy 2050. Forth, for large-scale investors, the implementation of the policy mix is as critical as the regulatory mix itself. A "fleet" level (i.e. regulations on a portfolio level) implementation of the policy scenarios presents more attractive solutions for achieving low-CO_2 cost-effectively that the current building level regulations, but also allows for higher emitting cost-minimizing solution. If combined with an upper emission threshold however, this presents a valuable new regulatory approach for effectively decarbonizing large real estate portfolios. Lastly, the application to the urban district demonstrates the interrelation of individual building retrofits and the urban energy system design, but also its dependance on infrastructure decisions such as district-heating extensions or decarbonization through carbon capture and storage.

Résumé

La consommation énergétique et les émissions de CO_2 du secteur du bâtiment peuvent être considérablement réduites en utilisant de nouvelles technologies renouvelables et plus efficaces, au niveau du bâtiment ou du quartier. Pour les bâtiments neufs, ces technologies sont déjà implémentées à grande échelle. En revanche, elles sont encore rarement utilisées dans la rénovation des bâtiments existants. Ce projet se concentre sur les grands investisseurs immobiliers (GIIs) : nous analysons leurs motivations et les régulations qui favoriseraient des investissements de leur part dans les énergies renouvelables ou les rénovations pour améliorer l'efficacité énergétique des bâtiments existants. Nous avons utilisé une combinaison de méthodes qualitatives, comme des entretiens avec des experts et le développement de scénarios politiques, et de méthodes quantitatives, comme la modélisation du système énergétique.

Pour évaluer les interactions entre les décisions de rénovations des GIIs et les scénarios politiques, et pour mieux comprendre leurs prises de décisions, nous avons fait passer 32 entretiens à différents acteurs du domaine. Dans chaque entretien nous leurs avons demandés leurs motivations et les barrières rencontrées lors de l'exécution d'une rénovation, pour comprendre comment ils interagissent avec l'ensemble des politiques. Nous avons animé un atelier sur le sujet des scénarios politiques pour étudier l'influence de la régulation, les politiques et les normes sur la stratégie de décarbonisation des GIIs. De plus, nous avons développé et validé trois scénarios distincts en utilisant une boite à outils politique comprenant des mesures réglementaires, fondées sur le marché, et fiscales.

En s'appuyant sur ces résultats qualitatifs, nous avons développé un environnement d'optimisation, MANGO (Multi-stAge eNerGy Optimization). MANGO peut concevoir la composition et l'opération d'un système énergétique optimisé en termes de coût et d'émissions de CO2, sur une période de 30+ années. MANGO est un outil puissant pour l'étude d'impacts techno-économiques et politiques sur la rénovation de bâtiments et de quartiers. Nous avons développé une nouvelle version pour ces questions en particulier : MANGOret. Après avoir obtenu des données importantes sur quelques portefeuilles immobiliers d'un partenaire GII, nous avons adapté MANGOret pour l'application sur n'importe quel portefeuille immobilier Suisse. Cette méthode prend en considération les doutes et paramètres particuliers d'un tel portefeuille et produit plusieurs options de rénovation réalisables. De plus, nous avons adapté MANGOret pour étudier la rénovation du système énergétique d'un quartier urbain.

Ce projet a produit les principaux résultats suivants. Premièrement, nous avons observé durant les entretiens que les politiques énergétiques sur la prise de décisions de la rénovation ont un impact limité, ce qui souligne l'importance des politiques non-énergétiques (indirectes) mais pertinentes pour les GIIs telles que l'accessibilité, la sécurité des locataires, et l'aménagement urbain. Nos résultats suggèrent que les politiques directes et indirectes sont potentiellement en conflit sur quelques éléments décisifs sur la prise de décision des GIIs, et qu'il faut un ensemble de politiques mieux intégré pour soutenir une meilleure pénétration du marché de profondes rénovations énergétiques. Deuxièmement, nous avons confirmé par l'application des méthodes quantitatives que les solutions optimales en termes de coût sont fortement influencées par le prix haut d'une « rénovation de l'enveloppe » d'un bâtiment. Au niveau du portefeuille, nos résultats montrent que la stratégie *cout-minimum* donne une augmentation des émissions de CO2 en cycle de vie d'ici 2050 de 47% comparé à la stratégie *émissions-minimum* mais avec une réduction de coût de 45%. Des réductions d'émissions importantes (e.g. >11%) sont quand-même possible à coût négligeable (<1%), comparé à la stratégie cout-minimum pour le portefeuille ou pour le bâtiment. Troisièmement, la simulation de scénarios politiques nous a montré la nécessité de se déplacer vers des politiques net-zero, comparé au statu quo (i.e. continuation de l'ensemble des politiques existantes), pour atteindre la décarbonisation de l'immobilier. En outre, le programme de ces nouvelles politiques est crucial. Le scénario le plus ambitieux, où net-zero est atteint en 2040 (avec des régulations plus tôt et fortes) donne une réduction des émissions totales beaucoup plus grande que le scénario où net-zero est atteint en 2050. Quatrièmement, pour les GIIs, l'implémentation de l'ensemble des politiques est aussi importante que les politiques elles même. Il est beaucoup plus facile pour les GIIs de réduire les émissions à un coût faible si les politiques sont ciblées au niveau du portefeuille et

non au niveau d'un bâtiment, mais cela engendre une solution coût-minimum avec de plus grandes émissions de CO2. En revanche, si l'ensemble des politiques au niveau du portefeuille sont combinées avec un plafond d'émissions, cela représente une stratégie politique de très grande valeur pour la décarbonisation des grands portefeuilles immobiliers. Finalement, l'application de nos analyses à un quartier urbain montre que la rénovation des bâtiments individuels est liée à la configuration du système énergétique local, et dépend, par exemple, de la présence d'un système de chauffage urbain ou la décision de poursuivre la capture et le stockage de carbone.

Take-home messages

- The limited impact of direct energy policies on retrofitting decisions of large-scale investors highlights the importance of a more integrated policy mix considering objectives beyond building stock decarbonization.
- A portfolio level implementation of policies – if combined with an emission cap – can lead to more cost-effective real estate decarbonization pathways than previous approaches focused on the individual building level.
- On a district level, optimal retrofitting strategies not only depend on individual building conditions but also on infrastructure decisions such as district-heating extensions or decarbonization through carbon capture and storage.
- While minimal emission solutions are still costly, drastic emission reductions are possible for negligible additional costs, compared to a cost minimizing retrofitting strategy on a building and portfolio level.
- The multi-stage optimization methods developed in this project help large-scale real estate investors to navigate the vast retrofitting option-space, while still considering the high contextuality of individual buildings requiring tailored retrofitting strategies.

Contents

Abbreviations

BEC – Building Energy Code

DRES – District-level Renewable Energy Systems

D-MES – Decentralized Multi-Energy System

EPC – Energy Performance Certificate

EE – Energy Efficiency

LSI – Large-Scale Investor

MILP – Mixed-Integer Linear Program

RE – Renewable Energy

RO – Real Options

WP – Work Package

1. Introduction

1.1 Background information

The context of this project is to reduce emissions in the building sector which as of 2017 accounted for 44% of final energy use and approximately 30% of energy-related CO_2 emissions in Switzerland (FOEN, 2020; Infras; Prognos; TEP; BFE, 2017). In order to properly contextualize the project, this introduction remains largely unchanged from the previous project report.

Building sector emissions could be drastically reduced with state-of-the-art renewable and energy-efficient technologies on the building-level (Ürge-Vorsatz et al., n.d.), and on the district-level with district renewable energy systems (DRES) (Grosspietsch et al., 2018). For new buildings and districts, these have already been widely implemented in progressive countries (e.g. EU, CH, California): Building energy codes (BECs) are moving towards net-zero energy buildings (Schwarz et al., 2019) and DRES are demonstrating their potential on the neighborhood to city scales (von Wirth et al., 2017). For existing building retrofits, the most impactful energy efficiency (EE) measures are generally categorized as interventions relating to insulating the façade, floors, and/or roof along with improving windows and lighting. Managing buildings' electricity and heating production relates to self-producing renewable energy (RE) (e.g. solar PV) and/or converting to electrified heating sources (e.g. heat pumps), bio-based boilers, or connecting to district heating networks if available.

However, in the existing building stock, the implementation of state-of-the-art EE and RE solutions – which prevail for new developments – are far from standard due to the uniqueness of each building. Significant efforts are required from investors and building contractors to determine profitable technical, economic, and organizational arrangements for retrofitting (Kontokosta, 2016; Schneider, 2017). This is demonstrated by the fact that in Europe, annually on average less than 1% of the building stock is retrofitted (Schneider, 2017), 2-3 times less than called for by various European nations' energy strategies (European Commission - Joint Research Centre, 2019; SFOE, 2018). Further, 90% of the European building stock was built before 1990, and almost 75% of it is 'energy inefficient' according to current building standards (European Commission - Joint Research Centre, 2019). Due to the long lifespan of buildings, existing buildings will still constitute a major part of the European building stock of the coming decades (Sandberg et al., 2016). This puts at risk the net zero CO_2 emissions goals set out by governments to 2050 (FOEN, 2019), which involves limiting global warming to well below 2°C from pre-industrial levels (IPCC, 2018). Thus, retrofitting existing buildings is vital to achieve significant energy and emissions savings, and will play a key role in the clean energy transition.

The slow transformation towards a sustainable building stock has in the past been linked to three main areas of barriers. First, economics; high up-front investment costs of renewable and energy-efficient retrofitting technologies, their rapid technological learnings, and split-incentives in their implementation, together with the already long lifetimes of sub-par technologies, decrease the possibility for 'deep' (i.e. highly energy efficient and renewable) retrofits (Ürge-Vorsatz et al., n.d.). Second, district-level complexities; promising DRES solutions are considerably harder to install in-stock compared to greenfield developments due to multiple ownerships, regulatory barriers, and path-dependency to already installed technologies (von Wirth et al., 2017). Third, stakeholder heterogeneity; both the characteristics and ownership of the building stock are fragmented, meaning the techno-economic and regulatory conditions which could drive retrofitting for various owner classes for the building stock as a whole have not been identified (Gabrielli & Ruggeri, 2019).

Previous research on retrofitting decision-making, motivations, and barriers largely focused on new residential buildings and private homeowners, e.g. (Hecher et al., 2017). However, for Large-Scale (i.e. commercial and public) Investors (LSIs), the political, regulatory and socio-economic conditions which increase retrofit implementation 'speed' and 'depth', and enable in-stock district solutions, are less well understood (Christensen et al., 2018; Kontokosta, 2016). Therefore, this project specifically focuses on

LSIs due to their large share of ownership and annual building investments in the European building stock. For residential buildings which constitute ~75% of the European (including Swiss) building stock, tenant rates vary from over 60% (e.g. Switzerland), to 47% (e.g. Germany), to under 10% in former communist countries (European Institute of Innovation & Technology, 2017; Eurostat, 2020). While data availability is limited to determine the exact ownership structure of the European building stock from 'rented' residential and commercial buildings, for the Swiss case, institutional and public investors (LSIs) own approximately 20% of rented total building value (Meier, 2015).[1] Overall, it can be assumed that a significant portion of European buildings rented to residential or commercial tenants are owned by LSIs. Further, for the example of Switzerland, of the CHF 51b invested in buildings in 2020, LSIs constituted the largest share investments (19% public and 57% commercial), with approximately one third of investments going into existing buildings and two thirds into new construction (BfS, 2020). This shows, that LSIs will contribute a massive potential to retrofit the existing building stock, although it is less clear how to accelerate the speed and depth of their retrofits to meet national energy and climate targets.

On the building-level, LSIs face the problem of how to allocate retrofitting activities across their broad building portfolios over long-term investment horizons due to uncertainty about the real estate markets, tenants, intervention costs, along with regulatory and political developments (Menassa, 2011). As their retrofit project scope often includes multiple self-owned buildings in close proximity, they are also key players in initiating and investing in DRES. On the district-level, multi-stakeholder ownership, necessary cross-institutional support, and public acceptance present additional challenges (Häkkinen et al., 2019). Furthermore, the optimal technical configuration and viability of in-stock DRES largely depend on how well individual buildings are retrofitted (Murray et al., 2018) which adds another layer of uncertainty in DRES design. Consequently, support measures for individual building retrofitting should align with those for district solutions.

Policy instruments relevant to retrofitting such as BECs, labels / certificates, financial regulations / incentives along with zoning, tenant, and climate laws, and their combinations (i.e. policy mixes) are disparate across sectors and countries. There is generally an observed trade-off between retrofit speed and depth between regulations. For example, France holds one of the strictest European retrofitting obligations through the mandate of the retrofit of all private residences consuming more than 330 kWh/m^2/year (lowest EPC levels – F and G) by 2025, while further blocking the sale of social housing above this threshold (Schwarz et al., 2019). Although the retrofit obligation has sped up retrofits to this level of depth, many view this as a lost opportunity due to technology lock-in to a 'low' level of EE without any RE installation. Aside from retrofitting obligations, European BECs for retrofitting generally contain prescriptive requirements (e.g. U-value for envelope efficiency) set at lower thresholds than for new construction. Nonetheless, specific technology choice can be triggered in different ways through various incentive schemes at the component- or retrofit depth-level, tenant laws allowing for the pass-on of investments to the rent, minimum RE production requirements, or climate regulations such as CO_2 taxes. Other BECs for retrofits, such as parts of Switzerland and Denmark, focus on banning the replacement of older heating technologies (e.g. electric resistance, oil) upon retrofit initiation if approved options such as gas networks or district heating are available (Schwarz et al., 2019).

Overall, a gap in literature exists in elaborating and 'unpacking' the retrofit investment decision, motivations, and barriers throughout the decision-making processes of LSIs / building owners. As regulation is continuously evolving with generally increased stringency and becoming more holistic in prescribed metrics, there is potential to adapt processes at the building- and district-levels to account for policy and techno-economic developments over time.

[1] This does not consider the ownership of the category 'firms and others', which could increase the LSIs proportion due to owner-occupied buildings.

1.2 Purpose of the project

The purpose of this project was to understand under which conditions large-scale investors increase investments in building-level retrofitting and involve themselves in in-stock DRES developments.

We therefore addressed the following three research questions (linking to each WP) leading to our objective in the following:

(1) What is the interplay of LSIs' retrofit decision-making with policy mixes in accelerating deep retrofits?

(2) How can different economic assessment methods facilitate LSIs' assessment of building-level retrofitting across their portfolio under regulatory, technical, and economic uncertainty?

(3) For which technical configurations, district characteristics, and regulatory conditions do in-stock DRES solutions become economically viable?

This report synthesizes the findings as recommendations towards investor strategies and policy mixes which accelerates investments in building-level retrofitting and in-stock DRES developments by LSIs.

Further, this project constitute the majority of the PhD thesis of Evan Petkov at the Group for Sustainability and Technology at ETH Zurich, supervised by Dr. Christof Knoeri and Prof. Dr. Volker Hoffmann along with input from Dr. George Mavromatidis. It is supported by colleagues at the Empa Urban Energy Systems Laboratory (UESL).

1.3 Objectives

The objective of this project was to holistically answer the three mentioned research questions while further:

(1) Gaining resonance with LSIs to aid in the development of decarbonization strategies and retrofit decision-making processes for their portfolios.

(2) Evaluating recommended policies for addressing both retrofit 'speed' and 'depth' at the building- and district-scales.

The steps to achieve these objectives are outlined in detail in the further sections.

2. Procedures and methodology

Work Package 1

WP1 aimed at answering the first research question: What is the interplay of LSIs' retrofit decision-making with policy mixes in accelerating deep retrofits? Consequently, the goal of this WP was two-fold: (i) to analyze and uncover the decision-making processes, motivations, and barriers of LSIs in executing building-level retrofits and in developing in-stock DRES, and (ii) better understand their interplay with the overarching retrofitting policy mix beyond solely energy policy.

We choose a mixed methods approach - using literature review, semi-structured interviews, policy scenario development, and a stakeholder workshop - to address the research question from multiple perspectives. In the following, we briefly present the methods for each subsection.

Literature review: We first conducted an extensive and structured literature review using the Scopus database to shed light on the existing research relevant to LSI decision-making processes, motivations, and barriers for retrofitting. We reviewed 116 scientific articles on retrofitting decisions in general, out of which 26 focused on LSIs or real-estate in particular. The focus was on compiling these aspects for LSIs' energy retrofitting decisions, along with correlations between those drivers and barriers, differences among different LSI types, and policy recommendations to increase retrofit rates (speed and/or depth). These findings helped direct the semi-structured interviews and framing of the WP.

Semi-structured interviews: We used semi-structured interviews as the core methodology in this study. Qualitative interviews provided in-depth narratives within each LSI type and explored relevant actors' views on strategic orientations, decision-making processes, and individual role priorities, along with the most meaningful policy mixes which would influence retrofitting for LSIs. We rely on a sample of 32 semi-structured interviews based mainly on "deep dives" into the four cases of real estate LSIs. Within each LSI, we interviewed four to six people at all hierarchical levels of real estate teams to gain an in-depth understanding of their processes and role priorities, such as portfolio, asset, and construction management — along with strategic decisions relating to ESG. This was supplemented by interviews with property managers, real estate consultants, and retrofit developers, along with heads of relevant associations and federal / cantonal policymakers. The interview campaign was completed in November 2020. Each interview lasted about an hour (±10 min.) and was audio recorded (for both in-person and phone interviews) to enable full transcription for scientific accuracy and ethics. A full description of the methodological procedure can be found in Publication Nr. 1 (Petkov et al., 2021).

Policy scenario development and stakeholder workshop: Building on the structured literature review and semi-structured interviews, we developed future policy scenarios relevant to retrofitting which LSIs could use in their multi-year planning in order to quantify the impact of policy uncertainty. We first develop these future policy scenarios internally based on historical trends of relevant regulations, real estate market aspects, and incentives, and then validate and quantify them in a stakeholder workshop. Due to the importance of industry collaboration for PACE REFITS, the decision was taken to hold this workshop alongside the project Board meeting which was held at ETH Zurich (with some members joining on Zoom) on September 30th, 2020. The three policy scenarios where developed in four steps: First, distinct 2050 emissions goals are set in order to develop scenarios using dual forecasting and backcasting approaches to provide a reference basis for future scenarios (Kishita et al., 2016). Second, once the intermediate and the 2050 GHG emission goals for the three scenarios are defined, specific policy measures and a policy toolkit are developed for each scenario. Third, the long-term context parameters and future trends of the real estate market development, interest rates, component and energy prices are assumed based on probability distributions. The fourth and last step involves the verification of internal consistency and the alignment with the historical narratives. A full description of the methodological procedure can be found in Publication Nr. 5.

Work Package 2

WP2 targeted the second research question of this project: How can different economic assessment methods facilitate LSIs' assessment of building-level retrofitting across their portfolio under regulatory, technical, and economic uncertainty? This required first the development of the methodology and second the testing and implementation with a real-world application. We approached this through the following two steps: First, we developed a dynamic, long-term or multi-stage, and scalable "real options" retrofit planning method to substitute LSIs' static multi-year planning for optimal portfolio decarbonization strategies under uncertainty. Second, we tested various policy scenarios (developed in WP1) to determine recommended policy pathways for cost-effective decarbonization of the existing building stock.

Development of long-term retrofitting planning method: The goal was to build a scalable real options method for optimal planning strategies for Swiss real estate portfolios which would be able to demonstrate the uncertain regulatory trade-offs between optimal retrofit speed and depth in decarbonization pathways. The project team has conceptualized the models for PACE REFITS in a modular way. The base model (MANGO – developed and described in WP3) acts as the 'engine' of the multi-stage optimization framework and served as a basis for the building and portfolio level optimization in WP2 along with for district level optimization in WP3 (Mavromatidis & Petkov, 2021).

Advancing the MANGO model, in WP2 we developed the MANGOret (MANGO - retrofitting) optimization framework and model to provide a methodology relevant for the long-term planning of existing buildings' D-MES and envelope retrofits (Petkov et al., 2022). While reducing the spatial scope of MANGO to individual units (buildings), the methodological scope of MANGOret increases the technological complexity by introducing more D-MES technologies along with adding the thermal energy efficiency capability. Further, the comprehensive data framework addresses critical modeling trade-offs of model scalability and the contextual individual building data.

The MANGOret framework is depicted in the Figure 1 workflow. The preliminary steps 1–4 relate to retrieving and processing the necessary building input data. In Step 1 (Input data from the building owner), we gather a small set of relevant data which is necessary to conduct both steps 2 and 3. In Step 2 (Existing component condition degradation), we determine a range of years for when various components must first be retrofitted ('necessity intervals') via the Schroeder component condition degradation method. In Step 3 (Address to archetype matching), we develop an archetypal energy demand database to retrieve the relevant retrofitting packages' energy demands and statistical building data from government databases for any building address. In this database, all buildings contained within the building registry are assigned an archetype with simulated energy demand profiles for different retrofitting packages and climate scenarios. Since we take a multi-year perspective for the holistic building DRES and envelope retrofit investment strategy, we utilize typical days to reduce computational complexity. In Step 4 (Clustering time-series parameters), we conduct a peak and typical days k-medoids clustering of the time-series parameters (solar irradiation and energy demands). Combined with the techno-economic database, these automated data retrieval and processing steps form the necessary input data for the MANGOret optimization model. Represented in the right side of Figure 1, the MANGOret model conducts a multi-stage and multi-objective optimization (cost vs. CO_2), and further DCF valuation based on rental income, to output a long-term asset retrofitting strategy. A full description of all methodological steps and the mathematical model is provided in Petkov et al. (2022).

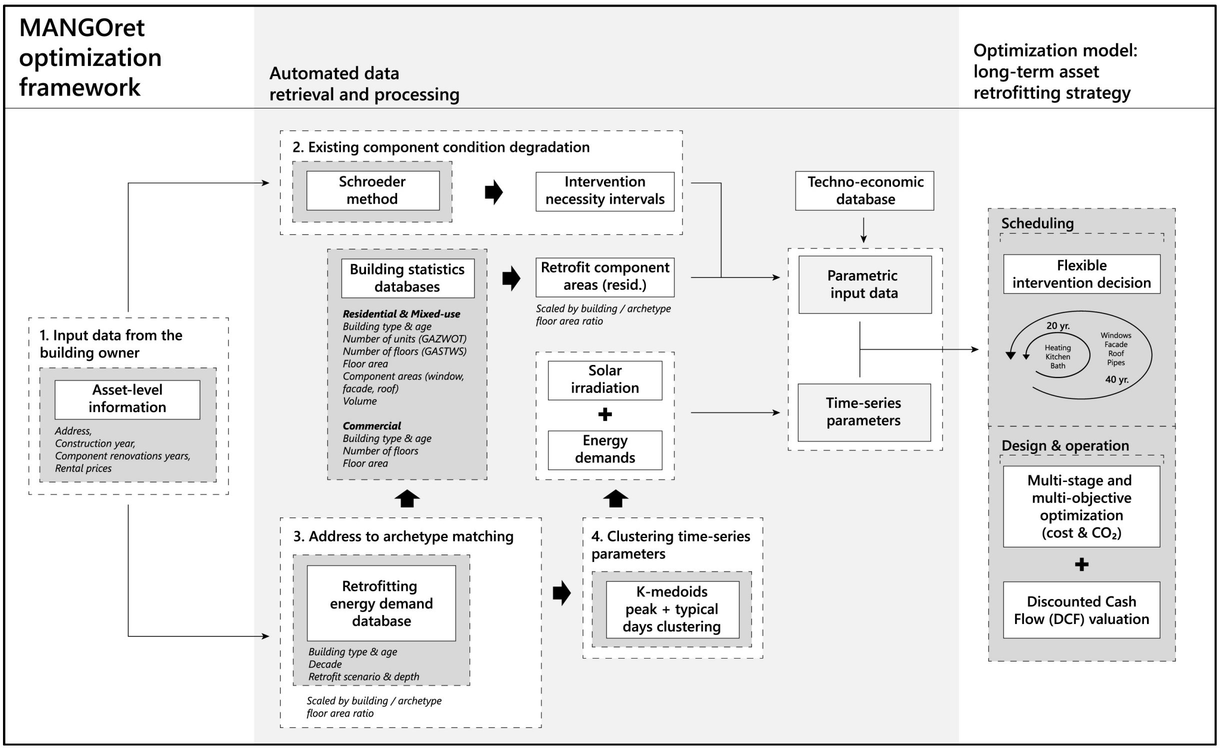

Figure 1: MANGOret optimization framework considering three sections — Input data from the building owner (step 1), Automated data retrieval and processing (steps 2–4), which supply the necessary time-series and parametric input data to the MANGOret optimization model.

Testing and implementation on real-world portfolios: To test the framework on a portfolio level we extended the. MANGOret model with a newly developed portfolio-level optimization model to generate long-term budgeting and decarbonization strategies from the individual asset plans. Full details of the portfolio extensions are provided in Publication Nr. 5 of this project (Petkov et al., 2023).

As this relies heavily on partner data contribution, we have completed the data exchange with our main LSI project partner. This data involves a detailed set of building-level information for 500+ large buildings in Switzerland, including energy data, component lifetime, real estate data, etc. Table 1 shows an overview over the basic date of the three portfolios. This data was partnered with additional internally-gathered data regarding techno-economic parameters such as costs, efficiencies, and lifetimes, along with context parameters (electricity / gas prices, carbon intensity factors, etc.).

Table 1: Basic data on the three portfolio case studies. Usage is reported in weighted floor area from GRESB categories. Other building usage comprises Manufacturing, Lodging & Leisure, Medical Office, and Restaurant & Bar. To assure anonymity, values are rounded.

Portfolio	Value (bEUR)	Assets	Bldgs.	Average build yr.	Floor area (m²)	Usage				
						MFH	Office	Retail	Hotel	Other
1	3.00	175	400	1970	800,000	80%	10%	5%	2%	3%
2	2.25	75	115	1971	500,000	25%	35%	30%	5%	5%
3	2.50	50	100	2011	700,000	40%	35%	15%	5%	5%
Total	**7.75**	**300**	**615**	**1984**	**2,000,000**	**55%**	**25%**	**15%**	**3%**	**2%**

Work Package 3

WP3 targeted the third research question of the project focusing on the district level: For which technical configurations, district characteristics, and regulatory conditions do in-stock DRES solutions become economically viable?

The methodological development for WP3 was done parallel with WP2, as the same multi-stage and multi-objective model 'engine' was used at both the building- and district-scales, although with slight variations. In the following, we briefly outline methodological procedure of the base model MANGO presented in Publication Nr.3 (Mavromatidis & Petkov, 2021). Its' application and extension to an urban district case study is presented in Publication Nr.3 (Lerbinger et al., 2023).

MANGO (Multi-stAge eNerGy Optimization) methodology: The MANGO (Multi-stAge eNerGy Optimization) model, a novel approach to deal with the multi-stage design and operation of several district-scale DRES (Mavromatidis & Petkov, 2021). Here, a deterministic Mixed-Integer Linear Programming (MILP) optimization is formulated to address the methodological and knowledge gaps relating to the interaction of various units in a system network over a long-term horizon to highlight the value of dynamic multi-stage DRES modeling. The MANGO suite of models are (and will continue to be) developed in-house at the ETH Zurich Group for Sustainability and Technology for the purpose of studying decision-making problems at different scales. Figure 2 shows the potential technical configurations in terms of energy conversion and storage technologies.

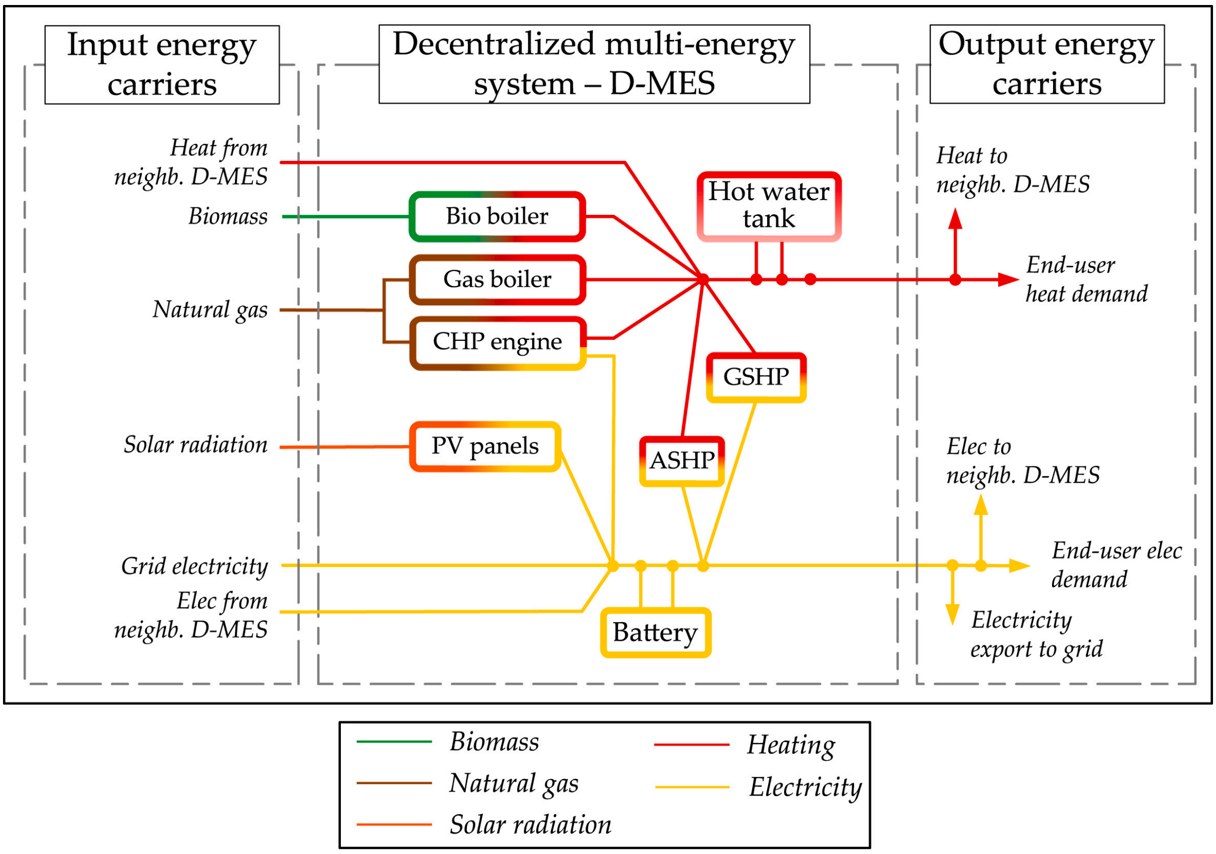

Figure 2: Superstructure representation of candidate energy conversion and storage technologies for the composition of a DRES (Source: Mavromatidis & Petkov (2021)).

3. Results and Discussion

Work Package 1

The results of WP1 are summaries based on **Publication Nr.1 of this project *"The interplay of policy and energy retrofit decision-making for real estate decarbonization"*** (Petkov et al., 2021).

This article focuses on the case of Large-Scale Investors (LSIs) who account for a significant share of ownership and investments in the built environment, specifically real estate. Recent social, economic, and regulatory pressures are pushing these institutional building owners to adapt traditional approaches of investment management for existing buildings. Considering LSIs' crucial leverage in decarbonizing real estate, this article ventures to (i) uncover LSIs' firm-level retrofit decision-making processes to (ii) better understand their interplay with the overarching retrofitting policy mix. An institutional perspective is adopted to investigate how LSIs' internal strategies and retrofit decision-making processes support or hinder decarbonization. This is accomplished through a semi-structured interview campaign (n=32), broken down into (i) 18 stakeholders from four different LSI cases with granularity towards different roles in the retrofit decision-making process, along with (ii) 14 supporting stakeholders such as policymakers and other industry players.

First, the findings outline three phases of real estate decarbonization to reach Net-Zero CO_2 emissions (Figure 3). The first two phases were observed by interviewees in the 2010s. Phase 1, "Niche ESG implementation", is characterized by (i) Environmental, Social, and Governance (ESG) reporting for selected portfolios, (ii) flagship niche labeled assets, and (iii) the possible creation of ESG-focused portfolios for 'clear product differentiation'. The recently observed step-change driven by sociopolitical pressure and real estate market forces have recently led towards the next phase in the second half of the decade. Phase 2, "Institutionalizing decarbonization", is characterized by (i) an institutionalization of ESG reporting built on energy and CO_2 data transparency, (ii) the creation of label-oriented guidelines to steer retrofit decision-making, and (iii) an increased firm-level focus on decarbonization trickling down to all portfolios. Interviews affirmed that inconsistencies in real estate decision-making processes and policy in phase 2 must be ironed out to decarbonize a significant proportion of real estate. As such, interviewees envisioned phase 3, "Mainstream net-zero CO_2 requirement", to transform retrofit decision-making with decarbonization criteria incorporated in order to achieve long-term Net-Zero CO_2 goals. This phase would prospectively be marked by (i) minimum standards for ESG and CO_2 performance, (ii) earlier-than-planned retrofits, and (iii) considerations for energy embodied in materials as part of the CO_2 footprint.

Second, the interviews uncovered the 'black-box' of real estate firm-level decision-making processes, As a starting point, the traditional retrofit decision-making process is generalized for the four main budgetary decision points in real estate portfolios, with granularity towards individual roles. Findings show that the retrofitting strategy for each asset is highly contextual and value-driven, depending on the maximum possible attainable value (at the market rent), the potential value increase through retrofitting, and the profit margin. Importantly, real estate teams focus on maximizing (or preserving) building value and smoothing portfolio budgets, explicitly contradicting academic studies utilizing payback periods or economic returns of energy retrofits as the sole economic decision-making metrics. Further, the main managerial decision relating to the environmental footprint of existing buildings lies in the Multi-Year Planning (MYP) processes of asset and portfolio managers, typically non-technical roles with regards to energy. Overall, there is significant potential to align institutional CO_2 goals and LSI retrofit decision-making processes in three ways: (i) integrating MYP with extended time horizons beyond five years to align with long-term CO_2 goals and building component lifetimes (30+ years), (ii) benchmarking CO_2 metrics for assets to consider 'transferring' costs between assets based on an internal CO_2 tax at the portfolio-level, and (iii) establishing adequate deep retrofitting KPIs (energy or CO_2) at role-levels.

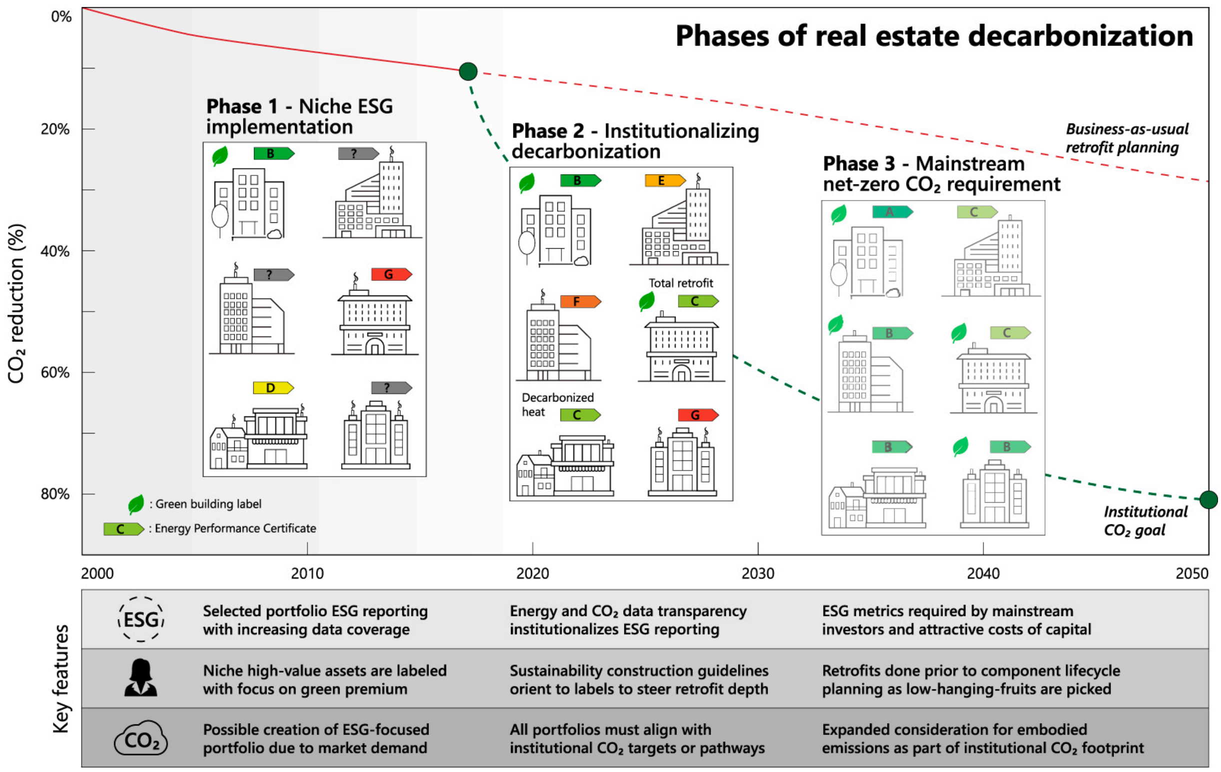

Figure 3: Conceptual schematic depiction of the three phases of real estate decarbonization (Source: Petkov et al. (2021)). Each phase is typified by three generalized key features in the categories of ESG considerations, management strategies, and CO2 topics. Here an example portfolio is shown on its decarbonization pathway with a goal of reducing operational CO2 emissions by 80% by 2050, taken from an actual LSI strategy. Each phase is represented by a portfolio snapshot, depicting the evolution of each building's color-coded EPC rating (corresponding to energy and CO2 performance) through retrofits, along with the scope for green building labels.

As a key conceptual connection to the following quantitative articles in this project, the processes and relevant quantitative tools for infrastructural MYP are a key mechanism for the decarbonization of the built environment. However, they were deemed currently unsuitable for its adequate consideration on the three main aspects: considering (i) technological complexity (ii) over a long-term time horizon and at (iii) various spatial scales.

Third, results unveil the interplay of how policies from the energy domain, and beyond, influence retrofitting decisions. Paradoxically, direct (energy and emissions-focused) instruments have only a limited impact on the retrofitting decision of LSIs itself. Building energy codes are deemed indecisive for altering retrofitting options due to LSIs' affinity towards green building labels, and financial incentives a 'nice to have' due to their minimal influence on budgeting. Findings show that instruments tied to CO_2 benchmarks have the most influence, such as CO_2 taxes and high-level taxonomies on portfolio budgeting with reduced interest rates (e.g. GRESB). Most interviewees expressed strong aversion to more restrictive types of direct instruments such as technology mandates and retrofitting obligations. In contrast to direct policy instruments, indirect (not energy and emissions-focused) instruments from other domains crucially impact retrofits. Primarily, policies in the domains of affordability, tenant security, and urban planning influence real estate valuations which are critical to MYP and the environmental footprint of retrofits. Findings point to a dilemma for how to regulate real estate markets in light of various policy objectives which could potentially be conflicting. Considering this, interviewees called for policy instruments from various domains to be aligned in order to meet societal and corporate CO_2 goals.

Finally, through combining both the firm-level and policy perspectives, the article provides an initial attempt towards a pathway for an integrated policy mix to encourage broader market penetration of deep retrofits while accounting for all policy objectives. Particular importance relates to the consideration of the cross-impacts of policy silos and conflicting social goals when envisioning the decarbonization the existing building stock. Without consideration of the broader objectives in the policy mix, relevant decision-makers such as LSIs would potentially not have favorable regulatory or market conditions for decarbonization. The impact of a low and high coherence policy mix scenarios on the LSI value-driven retrofit decision-making process is conceptually demonstrated. Here, significant potential lies in policy instruments which can address multiple objectives such as affordability and retrofitting depth. As an innovative example, a portion of tenants' rents in a building property could be subsidized to assure affordability upon the owner achieving a green building label with a retrofit, with an assured market rate of return. Paired with a CO_2 tax, such an instrument would directly target the MYP process, allowing LSIs to effectively budget for deep retrofits.

Work Package 2

The PACE REFITS project quantitative WPs 2 and 3 utilize a novel multi-stage optimization model as the core methodology. We have developed and published the base model 'engine' in *Applied Energy* in early 2021 titled "*MANGO - A novel optimization model for the long-term, multi-stage planning of decentralized multi-energy systems*" (Mavromatidis & Petkov, 2021) which is summarized under WP3. In WP2 we extended this base model and developed it further into a novel optimization framework and model for the long-term investment planning of existing building DRES and envelope retrofits termed MANGOret. In the following we summarize the results of WP2 based on the Publication 2 and 5 of this project, while the latter focuses on the portfolio aspect the former describes and demonstrates the methodological approach.

Summarized results from **Publication Nr. 2** ***"MANGOret: An optimization framework for the long-term investment planning of building multi-energy system and envelope retrofits"*** of this project (Petkov et al., 2022).

This article builds upon the MANGO model developed in WP3 to introduce MANGOret, a novel optimization framework and model for the long-term investment planning of existing building D-MES and envelope retrofits. MANGOret bridges the methodological gaps between energy system optimization and real estate management to present a scalable framework to optimize all cost categories – both energy and non-energy – while considering rental revenues and building value. While harnessing MANGO's strategic value of investment flexibility to optimally phase investments across the multi-objective cost and CO_2 decision-space, MANGOret overcomes a key limitation of the previous articles to comprehensively capture the technoeconomic energy efficiency investment decision simultaneously with D-MES design and operation. Due to the significant increases the technical complexity on both sides of the energy balance – demand and supply – MANGOret only considers one building unit at a time (no system-scale interactions) although with scalability to multiple building portfolios. MANGOret's increased techno-economic decision-space presents an exponential increase of computational effort. To simplify the optimization problem, temporal granularity is decreased while maintaining a long-term horizon through the bundling of several years into periods in order to approximate operating patterns.

By bridging the domains of energy optimization and real estate management, MANGOret is able to comprehensively answer the techno-economic what, where, when, and how questions relevant for both energy developers and building owners. From the energy perspective, by capturing the interdependent trade-offs between demand- and supply-side measures for a number of technologies, MANGOret is able to optimally schedule their investments over the long-term horizon to truly value future options to defer, expand, or extend the life of each technology (what and when). Schedules are constrained by the degradation of existing technology conditions over their lifetime utilizing the Schroeder method (Christen et al., 2016). This is particularly relevant for mismatched component life-cycles which naturally stagger retrofit interventions, presenting an optimal retrofit scheduling problem of a particular component or whether to conduct a deep retrofit which could benefit from reduced project fixed costs such as scaffolding. Further, the model more holistically captures the emission-reduction decision-space by considering both operational and embodied CO_2 emissions for all D-MES and envelope retrofitting technologies.

From the real estate management perspective, the framework aims to digitize the MYP process of institutional real estate investors, previously highlighted in Article I, to choose from various multi-objective investment strategies on a cost, CO_2, and building value basis (how). This primarily relates to the impact on rental revenues upon investing in value-added technologies or components in a building retrofit, with further consideration of how the building value is affected by cost vs. CO_2 trade-offs. Energy focused retrofitting investment methodologies which do not consider the rental revenue-side of investments could potentially miss strategic trade-offs. Further, the framework addresses the difficult trade-offs of building contextuality and model scalability. This is particularly relevant for LSIs who must develop significant numbers of building-level retrofitting strategies in MYP processes. The model is supported by series of automated data retrieval and processing steps to consider each contextual building project (where). Importantly, the framework consists of an archetypal energy demand database connected to various government building statistics databases to reference the energy demands of various retrofitting packages which include combinations of insulation and window interventions, along with buildings' contextual information. We demonstrate the value of the MANGOret framework for the case of four buildings taken from an LSI portfolio in Switzerland across various building types, sizes, and real estate markets. Exemplary "Building 3", discussed in the following illustrative results, is a multi-family house block-style residential property in Zurich city.

Our results demonstrate relevance for energy developers and building owners relating to the long-term design, operation, and investment scheduling of existing buildings. Aligning with previous studies, our results show that higher investment costs are necessary to achieve low-CO_2 DRES and envelope retrofits relative to minimum cost strategies. For the example of Building 3, the minimum emission solution is able to decrease both operational and embodied emissions by 42% with a 21% increase in total cost relative to the cost-optimal solution. Nevertheless, we show that these tradeoffs do not necessarily have to be weighed at the extremes (i.e. minimum costs or minimum emissions) of the Pareto front, instead presenting 'minimal regret' solutions in the Pareto front which reduce CO_2 at negligible cost increase, such as Pareto point 3. Relative to the cost-optimal point, Pareto point 3 achieves 11% lower emissions with a negligible increase in cost (<1%). This demonstrates, that relatively inexpensive additional emission savings are possible, if LSIs do not minimize-costs but aim such a "minimal regret" solution. However, the results also show the trade-off of decreasing building value with low-CO_2 retrofits largely due to high investment costs outweighing rental revenue increases. Here, the minimum emissions solution demonstrates an approximately 3% decrease in value relative to the minimum cost solution and the minimal regret solution.

Figure 4 presents the building investment cost composition and nominal rental income per floor area for each period for the minimum emissions (top-left) and Pareto point 3 (top-right) strategies for the exemplary Building 3. This figure simultaneously depicts the answers for the when and what questions of optimal retrofitting investment strategies relating to various investment categories, along with the investment cost and revenue sides of the optimal investment strategy over the long-term horizon. The increased investment costs in low-CO_2 retrofitting strategies are primarily due to larger capital expenditure (CAPEX) investments towards deeper & 'greener' envelope retrofits, driven by lower embodied emission technology choices. Nonenergy miscellaneous technologies such as kitchens, bathrooms, and pipes also present an important part of retrofitting budgets. Energy supply systems contribute to a small part of budget.

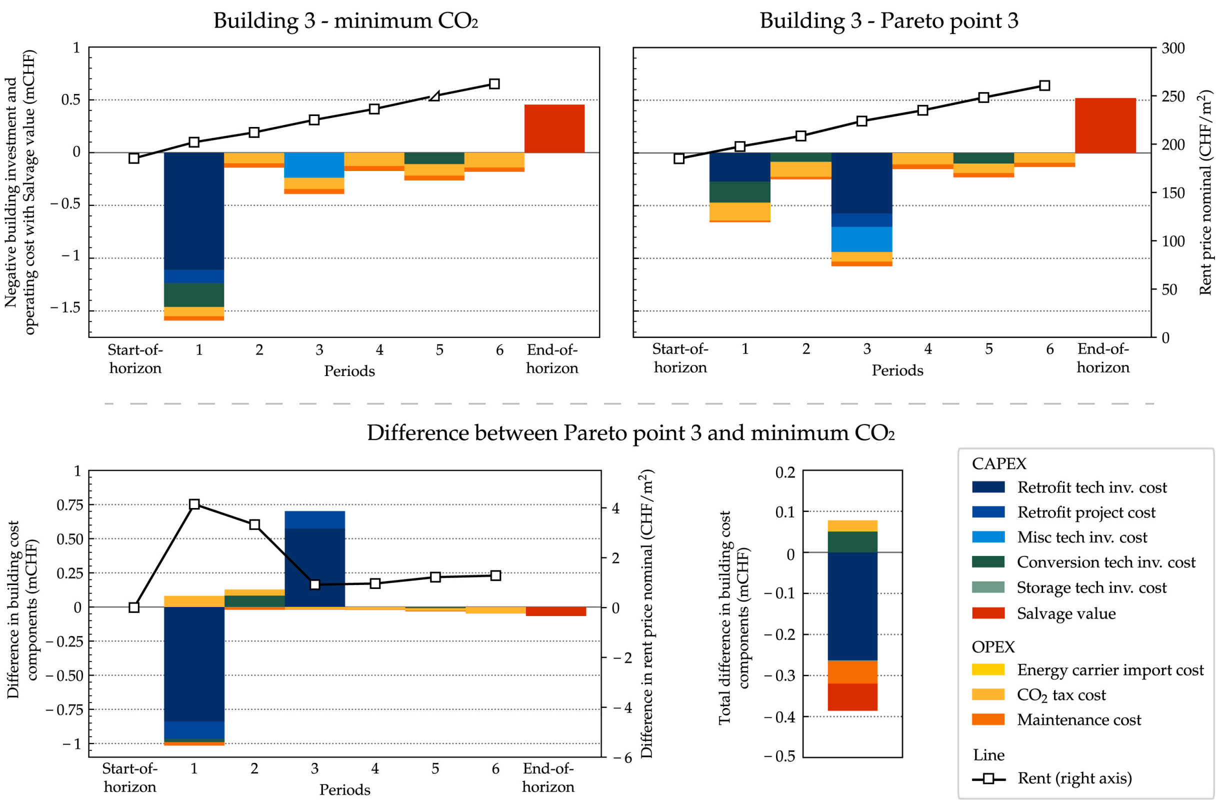

Figure 4: Compositions of investment cost categories per period represented as negative values, with revenues from salvage as positive, for the minimum emissions (top-left) and Pareto point 3 (top-right) for Building 3 (Source: Petkov et al. (2022)). The 30-year is composed of six, 5-year periods. On the right axis, we present the nominal rent per floor area in each period as the positive revenue stream. The bottom of the figure presents the period-by-period difference in investment cost compositions (bottom-left) between Pareto point 3 and the minimum emissions point, along with the total difference over the 30-year horizon (bottom-right).

Relating to scheduling, achieving low-CO2 retrofits is largely due to conducting deeper retrofits at earlier investment stages, e.g. period 1, subsequently reducing the required investments in conversion technologies due to lower energy demands. In Pareto point 3, along with the minimal cost solution, the optimal solution is to wait ‘as long as possible’ until the components must be retrofitted due to the condition-based necessity constraints, equivalent to the ‘real-world’ minimum cost approach of retrofitting at component end-of-life. For the example of Building 3, the component condition degradation methodology dictates that windows must be retrofitted in period 1 while facade and roof must be retrofitted latest in period 3. On the bottom of Figure 4, the difference between the per period cost components of the minimum emissions and Pareto point 3 (bottom-left) along with the total cost difference over the 30-year horizon (bottom-right) is shown. Here, it is clearly presented that the deeper, earlier retrofits required to achieve minimum emissions subsequently benefit from reduced costs for conversion technologies and energy carrier imports, albeit with the former outweighing the latter greatly. This highlights the importance of considering the interdependencies of the demand- and supply-sides of the energy balance in buildings’ retrofitting schedules over the long-term horizon.

While all presented cost and value results are discounted, nevertheless the nominal difference between earlier (minimum CO_2) and later retrofits (minimum cost) is smaller than that of the discounted difference, implicating the prominence of the risk-adjusted discount rate of real estate assets. Regarding rental revenues, Building 3 demonstrates a linear increase of rents due to the market parameters in a dynamic real estate market. The influence of value-added investments can be seen in the difference graph of Figure 4 (bottom-left) with positive differences denoting the higher value-added investments of the minimum emissions point, particularly when the deep retrofit is conducted period 1. The total nominal rent is slightly higher in the minimum emissions point but nevertheless the increased investment costs outweigh the discounted rents, and thus the building value decreases. Further granularity for the cost categories is also provided, with relevant results showing the influence of technological embodied emissions on optimal retrofitting strategies.

The three main contributions relate to MANGOret's:

(i) scalable, data-driven framework to optimize investments – both energy and non-energy – for any existing building,

(ii) long-term retrofitting design solutions, operating strategies, and investment schedules which simultaneously consider the demand- and supply-sides of the retrofit along with both embodied and operational emissions, and

(iii) inclusion of important budgeting elements relevant for building owners' multi-year retrofit investment planning such as rental revenues and building value.

First, the contextual nature of existing buildings make retrofit investment planning arduous and time-consuming. To aid in the planning process especially for large numbers of buildings, the model relies on a framework encompassing a series of automated data retrieval and processing steps. Importantly, the framework consists of an archetypal energy demand database connected to various building statistics databases to reference the retrofitting packages' energy demands and buildings' contextual information. Second, from the energy perspective, the model generates long-term investment strategies considering energy and non-energy technology design, operation, and scheduling. The model is able to consider the interdependent investment and scheduling trade-offs between demand- and supply-side measures for a number of technologies. Further, embodied emissions of all technologies relevant for building sector decarbonization are considered. By considering a 30-year horizon 0 to 2050 for all aspects within the framework, MANGOret is able to harness the strategic value of investment flexibility to optimally phase investments across the multi-objective cost and CO_2 decision space. Third, from the real estate management perspective, the model includes a key novelty relevant for building owners' MYP processes relating to the possible building rental income post-retrofit, formulated from value-added investment regulations. This provides important insights to the additional trade-offs of building value with the traditional cost vs. CO_2 multi-objective optimization. Overall, we show the value of optimal MYP by considering all relevant technologies' cost and emissions contributions over a long-term horizon for a case study of four buildings in Switzerland.

Aligning with previous studies, our results show that higher investment costs are necessary to achieve low-CO_2 retrofits relative to minimum cost strategies. Nevertheless, we show that these trade-offs do not necessarily have to be weighed at the extremes of the Pareto, instead presenting 'minimal regret' solutions in the Pareto front which reduce CO_2 at negligible cost increases. We provide relevant insights for real estate owners by demonstrating the trade-off of decreasing building value with low-CO_2 retrofits largely due to high investment costs outweighing rental revenue increases. While all presented cost and value results in this paper are discounted, the nominal difference between earlier (minimum CO_2) and later retrofits (minimum cost) is smaller than that of the discounted difference. As suggested in previous research, this puts the prominence of the risk-adjusted discount rate into the frame (Copiello et al., 2017).

The increased investment costs in low-CO_2 retrofitting strategies is primarily due to larger CAPEX investments towards deeper & 'greener' envelope retrofits, driven by lower embodied emission technology choices. Non-energy miscellaneous technologies also present an important part of retrofitting budgets. Relating to scheduling, achieving low-CO_2 retrofits is largely due to conducting deeper retrofits at earlier investment stages, subsequently reducing the required investments in conversion technologies due to lower energy demands. Our results demonstrate that optimal emission reductions in buildings necessitate subsequent reductions in energy consumption due to their direct correlation. These results directly contradict studies which argue that decarbonizing supply-side solutions should be prioritized to the expense of EE solutions due to their high costs (Patt et al., 2019).

This presents a strategic change for owners to retrofit building envelopes before their end-of-life. Here, we highlight the importance of incorporating embodied emissions in D-MES and envelope optimization studies as they encompass the majority of total emissions. This is particularly important for RE technologies such as solar PV which present a large fraction of embodied emissions in our results. Nevertheless, our results reaffirm the present-day attractiveness of grid-connected buildings powered by solar PV and heat pumps, corresponding to a significant portion of solutions.

Future studies should seek to relate multiple asset-level optimal retrofitting strategies together at a portfolio-level relevant for MYP, or otherwise at the district-level if many adjacent buildings relevant for energy planning. Considering portfolios, owners would potentially choose different optimal strategies (Pareto points) between the decision-space of various assets (Pareto front) subject to desired CAPEX budgets, value targets, and/or CO_2 constraints. Further, the influence of various techno-economic and contextual uncertainties, along with policy scenarios, over the long-term horizon could strongly influence results. Efforts to include policy aspects within an optimization modeling framework could give further insights to practitioners and policymakers, with major hurdles being the consideration of building contextuality versus model scalability (Strachan et al., 2016; Wouters et al., 2017; Zhu et al., 2022). While this would potentially be computationally expensive to run in such a complex model, it would nevertheless present interesting results for building sector decarbonization. Related to advancing embodied emissions considerations, future studies could integrate material- and technology-level life-cycle analysis data into the considered set of technologies.

Summarized results from **Publication Nr. 5** ***"Decarbonizing real estate portfolios considering optimal retrofit investment and policy conditions to 2050"*** of this project (Petkov et al., 2023).

This article addresses the outlined research aspects above by combining the state-of-the-art building optimization model framework relevant for comprehensive existing building retrofitting investment MANGOret (Petkov et al., 2022), with a newly developed portfolio-level optimization model to generate long-term budgeting and decarbonization strategies from the individual asset plans. Doing so we address the important portfolio level for LSIs, but also incorporate uncertainty in relation to climate change, techno-economic developments, and regulatory changes. Specifically, we incorporate a dynamic dataset from 2020-2050 including (i) climatic Relative Concentration Pathways (RCPs) impacts on retrofitting energy demands, (ii) developments of all techno-economic model parameters, and (iii) building sector policy scenarios. Bringing together the qualitative insights about the interplay of real-estate retrofit decision making and policy impact from WP1 (Petkov et al., 2021) with the optimization framework for the long-term investment planning for real estate MANGOret (Petkov et al., 2022) allows to assess the impact of different policies on investment strategies and building decarbonization pathways

To better establish the energy modeling—policy interface, we develop two sets of policy conditions: (i) scenarios and (ii) implementation approaches. The three policy scenarios consider the long-term evolutions of over ten different policy instruments relevant for European buildings from the energy, climate, and real estate domains, along with national energy scenarios. As different policy regimes can influence investment strategies, we used the prominent rationale used in scenario development methods to create two extreme scenarios - Business-as-usual (BAU) and Net-Zero 2040 (NZ-40) - and a "middle path" which is the current goal of Net-Zero 2050 (NZ-50).

The implementation approaches pertain to how policies toward decarbonization are enforced in the building fleet. Here, we take inspiration from automotive fleet CO_2 regulations to differentiate two policy implementation approaches for performance-based policies - thermal energy efficiency, CO_2 performance, renewable heating, and on-site electricity production requirements - at the "fleet-level" vs. the building-level. For example, automobile manufacturers are regulated at both (i) standard for individual vehicle types (e.g. cars, vans, trucks) and (ii) fleet-wide average requirements such as Europe's 2020 goal of 95 gCO_2/km45–47. In the real estate context, this would mean enforcing performance metrics for (i) each building in an asset vs. (ii) a weighted average value for the entire portfolio. Taken together, we first optimize retrofitting strategies for each asset on a multi-objective basis from minimum-cost to minimum-CO_2 considering the three policy scenarios. Next, we optimize portfolio plans based on the optimal asset strategies considering the two policy implementation approaches.

Our results demonstrate the influence of policy conditions on the cost to CO_2 optimal portfolio strategies is shown in Figure 5. The option ranges, termed Pareto fronts, have strategic points which represent 30-year performance. Due to the attractive cost-effective emissions reductions from Min-cost towards the left in the Pareto, in the following we term the 4th strategy (middle) as the Baseline. As reducing emissions becomes more expensive, we colloquially term the 5th point as the Min-regret strategy, the 6th point as the Feasible low-CO_2 strategy, followed by the Min-CO2 strategy. Comparing the extreme strategies (Min-cost BAU vs. Min-CO2 NZ-40, both fleet-level), total costs without considering incentives increase 45% (with incentives, 25%) with subsequent lifecycle emissions reductions of 47%. In other words, the modeled scenario futures present a large option-space with cost and CO_2 implications for owners' investment strategies. This affirms importance of reliability and clarity of future policy developments to aid investment decision-making.

Towards more stringent policy scenarios (i.e. NZ-50 1nd NZ-40), the Pareto fronts get tighter both from a cost and CO_2 perspective. However, the option-space is far more reduced by the policy implementation approaches than the scenarios. Within each policy scenario, the building-level policy implementation Paretos (gray) are always sub-optimal in relationship to the fleet-level (colors): for similar levels of emissions in the Feasible low-CO2 NZ-40 strategy, the fleet-level approach reduces costs by EUR 48m (8%). However, the fleet-level implementation lower-cost solutions come at the extremes with higher emissions. For the policy-maker this means that in general, a fleet-level (i.e. portfolio) approach presents more attractive solutions for achieving low-CO_2 cost-effectively but might have to be combined with a maximum emission threshold on a portfolio level to constrain LSIs from cost minimal high emission solution. Such an approach shows promise for innovating beyond performance requirements regulated solely at the building-level, as currently done in all Building Energy Code (BEC) regimes globally and in Europe.

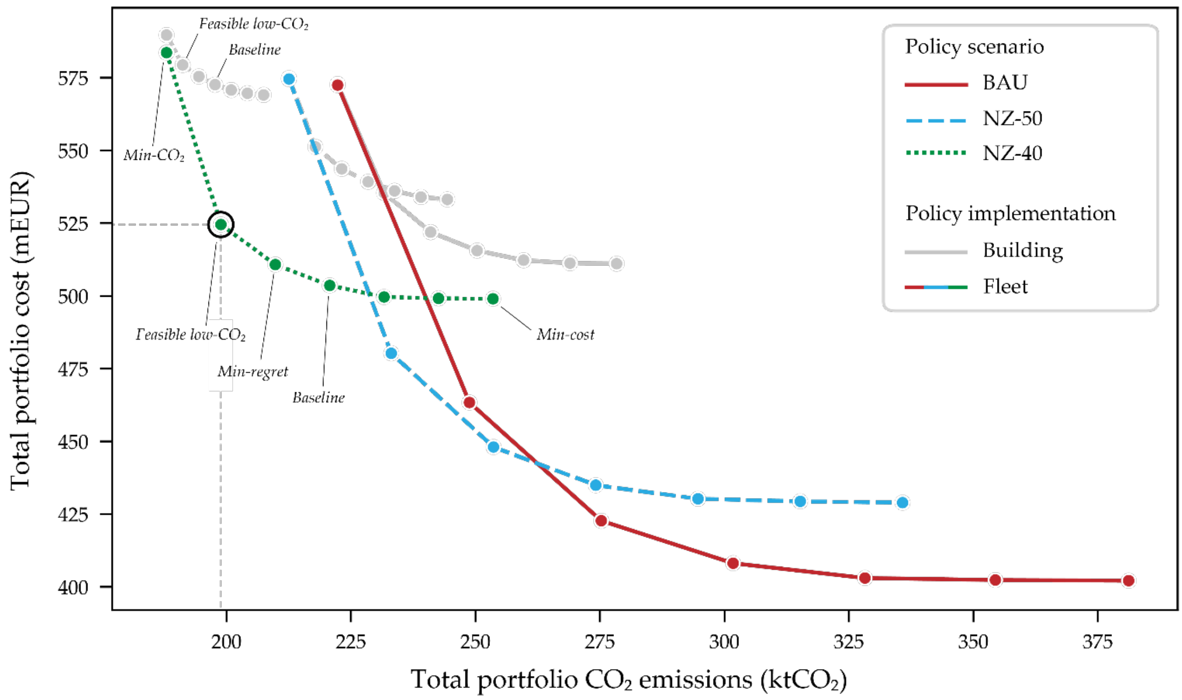

Figure 5: Optimal portfolio strategies under policy conditions. Pareto fronts for the total aggregated portfolio 30-year costs and CO_2 emission with RCP 4.5. The Paretos are varied across policy conditions: three policy scenarios under different performance-based policy implementation approaches: building-level (gray) vs. fleet-level (colors).

Decarbonized real estate portfolios requires a significant number of deep retrofits earlier-than-planned, comprising complete re-insulation of building envelopes coupled with RE-based heating systems. Significant CAPEX into retrofits in the near-term could create capital liquidity and workforce adequacy issues, such as the burgeoning "green" buildings and construction workforce supported in the upcoming European Renovation Wave. Owners used to smoothing CAPEX over the years could try to sell (brown-spin) or redevelop assets which are flagged as stranded. This could potentially further grow the carbon bubble in the building sector, necessitating both owner and policymaker urgency.

Due to their distinctive starting conditions and existing systems, building assets have varied energy and CO_2 reduction potentials, and therefore costs. Scaling bottom-up asset strategies to portfolio plans, assets lie in a distribution from hard-to-decarbonize to low-hanging-fruit. In this light, we explore a policy innovation to regulate portfolio CO_2-performance as a building fleet, similar to the automotive industry. Moving away from a "one-size-fits-all" approach for performance-based policies on EE and CO_2 benchmarks could reduce transition costs 8% with equal emissions. While a fleet perspective means that dirty assets still remain, it could prove important to give owners flexibility to manage the high-cost transition in time to 2050.

Our main conclusion is that a portfolio policy implementation presents an valid approach for a cost-effective decarbonization of existing buildings, as each unique building presents different retrofitting potential and performance metrics. Even in the *feasible low-CO_2* strategy, not all building assets are able to reach regulatory energy and CO_2 performance benchmarks, such as 80 kWh/m²·a and 10 kgCO_2/m²·a for European existing buildings by 2030. While these assets would be flagged as *stranded* on a CO_2-basis in the portfolio strategy, nevertheless they could still be highly valuable and profitable. Further, the assets' contextual situation - building use, construction quality, etc. - could mean that there is no cost-effective way to reduce energy and CO_2. While these carbon-outliers could flag a potential sale to improve the owners' portfolio performance, this would not solve the problem of reducing the buildings' emissions. If the real estate owner is able to decarbonize the portfolio far below the benchmark by leveraging the optimal reduction potential of each asset, that would be a more cost-effective approach then mandating every building reach the benchmark.

Work Package 3

The district level results of WP3 are outlined and discussed based on the Publication Nr. 3 presenting the base model of the project (Mavromatidis & Petkov, 2021) and Publication Nr. 4 applying the model to a real-world case study of an urban district (Lerbinger et al., 2023).

Summarized results from **Publication Nr. 3 *"MANGO: A novel optimization model for the long-term, multi-stage planning of decentralized multi-energy systems"* of this project** (Mavromatidis & Petkov, 2021).

This article presents MANGO (Multi-stAge eNerGy Optimization), a novel optimization model that incorporates a multi-year planning horizon, along with flexible, multi-stage investment strategies for the effective, long-term design and operation of DRES. By considering the dynamic techno-economic and contextual landscape surrounding system-scale DRES over a long-term horizon, MANGO harnesses the strategic value of investment flexibility and can optimally phase DRES investments. The model considers the most relevant dynamic aspects, such as year-to-year variations in energy demands, changing energy carrier and technology prices, technical improvements, and equipment degradation. Through adopting this technology-focused modeling approach, all investments in energy conversion and storage technologies are tracked separately, thus their capacities are not aggregated. This allows the model to dispatch each installed technology individually taking into account their different performance characteristics, such as performance degradation or technological improvements, during the project lifetime. Further, MANGO extends the state-of-the-art optimal multi-stage DRES design with capability to optimize multi-location D-MES configurations through network interconnections and by treating end-of-horizon effects for more accurate design decisions. The model is formulated as a deterministic MILP.

A stylized case study, inspired from of an actual urban district composed of 3 sites in Zurich, Switzerland (Meuer et al., 2021), is utilized to develop a six-stage energy design plan with MANGO along a 30-year project horizon. The district is composed of one existing (site A) and two new neighborhoods (site B & site C), which are assumed to be developed in different construction phases. One candidate DRES is considered per site and six different scenarios are examined regarding building retrofitting and DRES interconnections, although the retrofitting investment decision is not explicitly formulated in the model. With its long-term perspective, MANGO can offer decision-making insights that closely match the dynamic class of real-world energy system design projects led by energy developers through providing strategic-, economic-, and technical-level insights.

Our results show that DRES design plans in all optimization settings and scenarios benefit from the multi-stage investment strategy, with technologies installed in all investment stages to echo the developments in the urban district benefiting from reduced future technology costs. Regarding specifically the examined scenarios, results show that allowing DRES interconnections to achieve a system-level perspective leads to better economic and environmental performance, for instance, 2% lower costs and 10% lower emissions on average for the cost-optimal designs across all scenarios. On the other hand, while retrofitting increases total costs significantly, it allows for lower CO_2 emission levels to be reached. For instance, the lowest possible emission level for the system without building retrofits is approximately equal to 3,500 tCO_2 while under the ‘100% retrofit scenario’ the minimum achievable emissions are reduced by 25% to approximately 2,700 tCO_2.

Figure 6 details the most relevant information relevant to MANGO’s ability to provide strategic-, economic-, and technical-level insights. Figure 6a-d and f-i depict the evolution of the installed conversion technology capacities at each site, in four scenarios, and for the cost- and CO_2-optimal Pareto points respectively. The scenarios represent the four possible combinations between the two interconnection scenarios and the ‘No retrofit’ and ‘100% retrofit’ scenarios. It must be noted that to aid the readability of these figures, the available capacities of the same technology type in each year are aggregated before plotting.

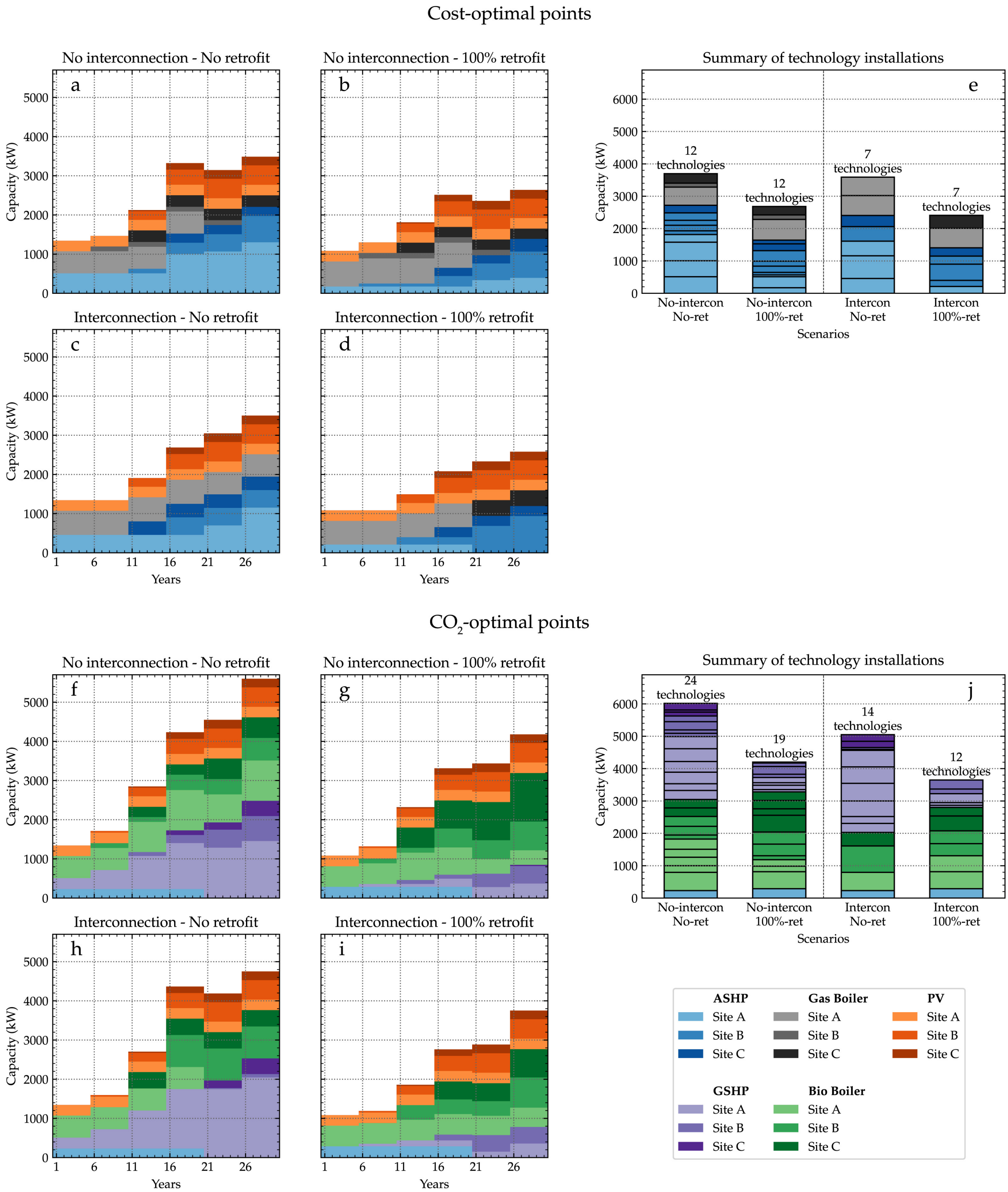

Figure 6: (a-d, f-i) Evolution of installed capacities of energy conversion technologies at each site during the 30-year planning period for four interconnection–retrofit scenarios and the cost-optimal (a-d) and CO2-optimal (f-i) Pareto points. (e,j) Summary of total, aggregated installed capacities of conversion technologies for four scenarios over the cost-optimal (e) and CO2-optimal (j) Pareto points.

Figure 6e and j summarize the technological complexity for the cost- and CO_2-optimal Pareto points respectively, with solar PV installations excluded since the total installed capacity is always maximized and equal across all scenarios. Beginning with the cost-optimal results, the overall impact of the four retrofitting and interconnection scenarios do not have a significant impact in terms of system selection, with most cost-effective designs including combinations of natural gas boilers, ASHPs and solar PV, while designs with the lowest CO_2 emissions transition to biomass boilers, Ground-Source Heat Pumps (GSHPs) and solar PV configurations. Nevertheless, retrofits affect the total capacities of the technologies installed, while interconnections allow for technology sharing, and reduce the system complexity by decreasing number of technologies installed. The reduction in the total installed technology capacity due to retrofitting is equal to -28% and -33% when interconnections are not and are considered, respectively. Under both interconnection scenarios, the reduction in installed capacity is mostly reflected on the ASHPs, while the natural gas boiler capacity remains relatively unaffected. A similar influence of retrofitting to the overall reduction of installed capacity is seen in the CO_2-optimal points, overall reductions equal to -30% and -28% when interconnections are not and are considered, respectively, which is, in turn, translated to lower total GSHP and higher total biomass boiler capacities.

Interconnections have only a small influence in the total installed capacity and in both retrofit scenarios. Here, interconnections also: (i) reduce technological installation complexity of the energy system, (ii) smooth capacity investments, (iii) albeit with more complex operating patterns for the whole system. Reduced technological complexity is demonstrated by the smaller number of larger thermal energy generation technology installations, such as ASHPs, reducing the total number of installed technologies, in both cost optimal cases, from 12 to 7, with a similar pattern shown for the CO_2-optimal cases.

Overall, MANGO can facilitate strategic decision-making by creating multiple design alternatives that highlight trade-offs on a multi-objective cost vs. CO_2 basis. Additionally, with its detailed breakdown of costs per year and per expenditure type, such as capital and operating costs, it can inform and drive decisions at the economic-level. Finally, MANGO generates valuable insights that can assist decisions at the technical engineering levels regarding the design of multiple D-MES in terms of technology selection, sizing, and siting, as well as information on the optimal operating patterns of each system.

In practice, MANGO more closely matches the needs of energy developers in their adoption of DRES technologies. Developers are recommended to re-run the model every few years when better information is available regarding best possible estimates of the model's dynamic parameters. Given that uncertainty grows larger the further the prediction horizon lies, one can have more confidence in their short-term predictions and, hence, the short-term investment decisions of the model that need to be implemented first.

Summarized results from **Publication 4 *"Optimal decarbonization strategies for existing districts considering energy systems and retrofits"*** of this project (Lerbinger et al., 2023).

Within this article, MANGO is further adapted to include the building-level retrofitting aspects from WP2 (MANGOret) and applied to a real-world urban district to answer research question 3: For which technical configurations, district characteristics, and regulatory conditions do in-stock DRES solutions become economically viable? In the urban context, district heating networks (DHN) are a promising way of doing the latter especially with carbon capture and storage (CCS) on the horizon. However, investment decisions for both - energy supply and demand reduction - measures must take into account individual buildings as part of district-scale considerations.

In this study, an extension of the MANGO (Mavromatidis & Petkov, 2021) and MANGOret (Petkov et al., 2022) models was used to determine optimal decarbonization strategies for existing districts over a long-term horizon. The model is characterized by the following aspects: it considers building-level investments in retrofits and energy systems, including the expansion of an existing DHN, along with consideration of CCS for the DHN central plant, in order to reach a low-emission DH supply. It incorporates a long-term horizon with multiple investment stages, allowing to represent economic and technological developments, as well as a multi-objective perspective, capturing the trade-offs between total system costs and emissions. Overall, the model and analysis in this study presents a contribution to the growing field of optimization models examining the trade-offs between energy system and retrofitting investments at the district-level with a building resolution. It can offer energy system planners and developers first insights into technological choices and scheduling of interventions over a long-term horizon.

In this work, the extended model is applied to two existing neighborhood case studies representing two different typologies: a dense inner-city neighborhood (Quader) consisting mostly of large mixed-use and retail buildings with high heating demands, along with a typical residential neighborhood (Neubruch), composed mostly of single- and multi-family homes. The results show, that in the inner-city district, DH reduces both total system costs, and in combination with a low-emission DH supply ensured by the installation of CCS technology, also emissions. On the other hand, in the residential neighborhood, decentralized heating systems offer the best cost versus emission tradeoffs. When buildings utilize decentralized heating systems, the importance of earlier retrofits increases. This allows for the installation of renewable and energy-efficient energy systems with smaller capacity and reduces the energy system and import costs (Figure 7).

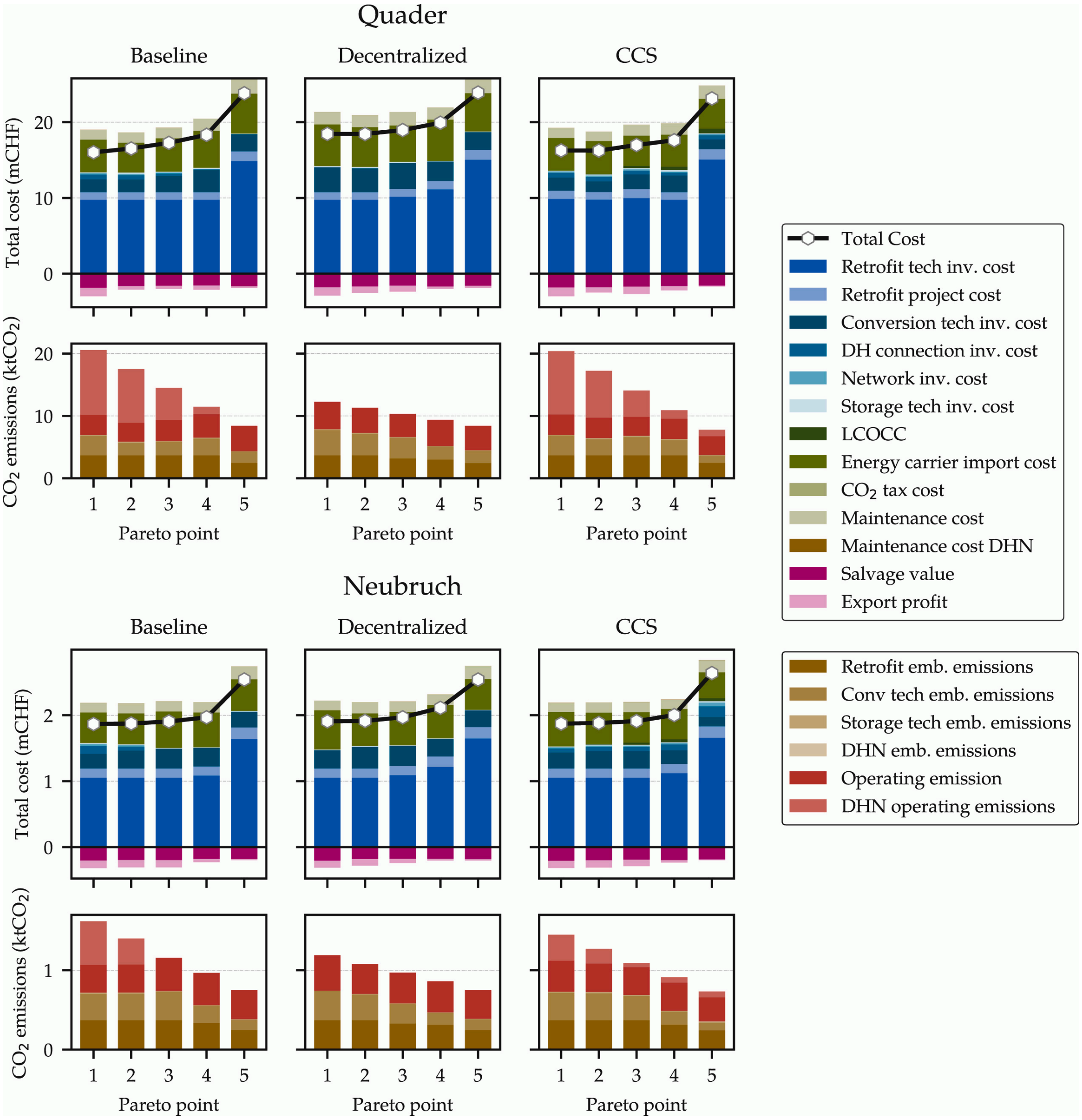

Figure 7: Pareto fronts detailing the composition of total system cost and emissions for the three scenarios of the Quader (top) and Neubruch (bottom) cases.

Retrofitting accounts for the largest share of the total system cost, even when the cheapest retrofitting technology options are chosen and retrofits are postponed to the end of the 'necessity interval'. In order to achieve a low-emission district, it is necessary to advance the retrofitting interventions to an earlier time, along with choosing technology options with less embodied emissions, albeit with higher costs. Examining the interplay of energy system and retrofitting investments, the results demonstrate that supply-side interventions have the greater potential to reduce emissions with a moderate increase in costs. In comparison, advancing the retrofitting intervention and switching to the cleaner technology option, yields fewer emission reductions at a higher cost.

Further research should focus on how the optimal decarbonization strategies for different district topologies are affected by various policy measures, along with future uncertainties pertaining to techno-economic parameters (e.g. technological learning rates, energy prices, etc.). As retrofitting contributes the largest share to the total system cost, it presents a suitable case for incentivizing policy instruments especially due to the large burden on building owners. Further, incentives for decentralized heating systems and DHN interconnections for buildings could be of interest.

Finally, further research could explore the cost distribution perspective. Currently, an energy system planning perspective is taken with overall system costs being optimized. However, costs are unequally distributed between the DHN operator, the building owners, and the tenants. Further analysis should be conducted on what distributional effects the different scenarios and Pareto points imply for the three stakeholders and how a fair cost distribution can be achieved. Including this cost distribution perspective will add additional value to the model as it helps to determine politically feasible solutions based on costs versus emissions trade-offs at the district-level.

4. Conclusions

In the following we briefly outline the key contribution of this project to the scientific literature it's implications for practitioners and policy makers.

Contribution to scientific literature

This project contributes to the energy science literature within the domain of the low-CO_2 built environment. Major contributions pertain to methodological and analytical advances in the techno-economic modeling of two cases – thermal Energy Efficiency (EE) with building envelope retrofits on the building level and Decentralized Renewable Energy Systems (DRES) on the district level – considering the comprehensive technological, spatial, and temporal scopes relevant for decarbonization.

In WP1 this project uncovered the 'black box' of firm-level technological adoption decision-making processes for the case of existing building retrofits encompassing EE, Renewable Energy (RE), and complementary technologies. The project adopts an institutional perspective to investigate how large-scale investors must transform their processes towards decarbonization, and further, how the processes interplay with the overarching retrofitting policy mix. As the sole qualitative article in this mixed-methods albeit heavily quantitative project, it provides the key problem statement of the limitations and needs of building investors in considering the complexities of modern-day energy technology adoption. Within their Multi-Year Planning (MYP) processes, investors must be able to techno-economically assess multi-technology interactions at various spatial scales over the long-term to determine optimal decarbonization conditions for their infrastructures. Understanding the qualitative managerial decision-making processes in any sector is particularly relevant for motivating quantitative modeling formulations. Further, this is the first comprehensive consideration of the influence of the overarching retrofitting policy mix on retrofit decision-making processes. For policymakers, this is a key insight to the importance of an integrated policy mix which considers the cross-impacts of policy instruments from various domains.

In WP 2 & 3 novel MILP optimization model formulations have been developed to consider multi-technology interactions at various levels of complexity with long-term temporal scopes and multi-stage investments. Consecutively increasing in spatial complexity: Publications 2 & 5 consider individual units (buildings and portfolios) while Publications 3 & 4 take system-scale (district) perspectives with interconnections between units. These articles present the core methodological contributions of this project to assess the optimal techno-economic conditions for building and district decarbonization. Expanding the optimization model decision-space in technological, spatial, and temporal aspects allows for significantly more attractive cost and CO_2 emission solutions, moving towards a 'global optimum'. Of particular value is the temporal scope, allowing the model to determine when to schedule interdependent technology investments. Increased technological scope includes expanding traditional Energy Supply (ES) side DDESS modeling to include the Energy Demand (ED) side with thermal EE building envelope retrofits, along with many other tangential aspects relevant for real estate managers and energy developers. For example, the cost and CO_2 emission trade-offs can be assessed for when to build a smaller RE-integrated heating systems relative to a forthcoming thermal retrofit. Expanding spatial scope to include system-scale District Heating Network (DHN) modeling is relevant for considering the expansion of existing network infrastructure. Allowing interconnections between buildings in a DHN generally reduces system cost and technological complexity through infrastructure 'sharing'.

Implications for practitioners and policy makers

Current decision-making processes and investment practices, especially for large-scale investors, are rarely able to determine the optimal decision, never mind capture the entire decision-space of innovative technologies over relevant spatial and temporal scales. Aside from the required energy technology adoption, a major hurdle to overcome is practitioners' and policymakers' adoption of the state-of-the-art optimization model technologies, within and outside of this project. Generally, decision-making processes in infrastructure-related domains pressured by decarbonization must be transformed to consider different approaches in managing their investments. Especially relevant for decision-making is the consideration of long time horizons to address intertemporal tensions. While there is definitely room for improvement, the quantitative optimization techniques developed in this project offer a significant potential to give decision-makers necessary insights for optimal adoption of low-CO_2 technologies.

For practitioners to fully realize the potential of low-CO_2 technology and infrastructure investments, a significant amount of work needs to be done to develop profitable business models for the adoption of technologies, but also to overcome the hurdles in the conventional decision-making processes. Practitioners and policymakers should be prepared for not just a transformation of traditional decision-making processes, but also of traditional business models in both the energy and building sectors.

The power of optimization models gives policymakers a clear perspective as to the 'best' investments practitioners could make, thereby providing conditions in which to set the right policies. The question therefore reveals itself – what would the optimal policies be considering optimal technological adoption? In this case, the policymaker would want to reduce policy costs while minimizing the practitioners' system costs while maximizing emissions savings.

As demonstrated in this project, neither individual policy instruments nor policy domains can be considered in a vacuum in the context of infrastructure decision-making. Here, mixed-methods approaches can be powerful to develop policy scenarios for a particular case to then be fed into an optimization model. For the real estate case, tenant security and affordability policies strongly influence investors' adoption of deep low-CO_2 retrofits. This projects explores and demonstrates, that a portfolio level implementation of policies – if combined with a emission cap – can lead to more cost-effective real estate decarbonization pathways than the previous building/asset level regulations. However, such an approach would necessitate to move away from the previous approach of regulating all buildings equally, allowing large scale real estate owners to keep their stranded assets but raising questions about non-discrimination of single building owners.

The different matter of perspectives are also important to consider, that of the actors who are represented in optimization models – what is optimal for whom? This actor perspective is particularly important to assure fair cost and emission accounting for those in the low-CO_2 built environment sociotechnical system: system operators, building owners, tenants, etc. However, this is not considered in this project. Policymakers should consider the equity perspective between actors to understand the distributions within a single Pareto point in the 'system' view. This does not just relate to costs but also emissions since they could be 'leaked' between actors.

Lastly, a critical connecting implication for both practitioners and policymakers relates to data management in techno-economic decision-making models. This is especially relevant for the large assumptions made with long time horizons, such as values for electricity grid CO_2 intensity, costs and learning curves of early stage technologies, etc. Whenever model outputs are compared and critiqued, so should their inputs. It is the responsibility of researchers, practitioners, and policymakers to have synchronized data platforms with good agreement between the relevant sources.

5. Outlook and Implementation

The results and ongoing discussion within and beyond the PACE REFITS project have led to several developments for further research and practical implementation of the results. In the following we briefly address these in turn.

Further research: The development of the MANGO suite models at the chair of Sustainability and Technology at ETH Zurich, which started within this research project, let to two further PhD projects. One addressing design and long-term development for grid connected storage applications, and the other extending the model to include endogenous policy decision variables into the techno-economic energy system optimization. Beyond these ongoing projects further aspects are explored like for example the dependance of the results on different emission accounting methods in several MSc theses.

Practical implementation: Throughout the PACE REFITS project we received a lot of interest for collaboration from industry partners and stakeholders. While developing and testing the long-term investment planning method for real estate portfolios that interest intensified. We have been approached by several Swiss LSIs and real estate consulting companies to further develop the methodology and transfer it to an industry application. Motivated by these interests, the ETH spin-off company OPTIML has been founded (optiml.ch) in November 2022. In the few weeks leading up to the spin-off, OPTIML already attracted first investors to ensure the company's' first product launch in late 2023. Based on the models and methods developed in this project, the spin-off company develops software-as-a-service products which help real estate owners to make smarter investment decisions to decarbonize their building portfolios.

6. National and international cooperation

Research collaboration with the Empa UESL was developed for WPs 2 and 3. In addition, we have ongoing discussion about the project and related topics with other research groups from ETH, Empa, PSI, UniGE, and EPFL, which led to further project collaborations and research proposals.

Industry collaboration was very strong with our main LSI project partner, with regular data and content exchange. In addition, we also developed a strong relationship with further companies in the real estate industry many of which have become project Board members though our interview campaign. We continue the discussion with the industry partners from the real estate sector on how the scientific methods developed could be transferred and applied in practice.

7. Publications

Out of this project the following five scientific articles have been published:

Publication Nr. 1

Petkov, I., Knoeri, C., & Hoffmann, V. H. (2021). The interplay of policy and energy retrofit decision-making for real estate decarbonization. *Environmental Research: Infrastructure and Sustainability*, *1*(3), 35006. https://doi.org/10.1088/2634-4505/ac3321

Publication Nr. 2

Petkov, I., Mavromatidis, G., Knoeri, C., Allan, J., & Hoffmann, V. H. (2022). MANGOret: An optimization framework for the long-term investment planning of building multi-energy system and envelope retrofits. *Applied Energy*, *314*. https://doi.org/10.1016/j.apenergy.2022.118901

Publication Nr. 3

Mavromatidis, G., & Petkov, I. (2021). MANGO: A novel optimization model for the long-term, multi-stage planning of decentralized multi-energy systems. *Applied Energy*, *288*, 116585. https://doi.org/10.1016/J.APENERGY.2021.116585

Publication Nr. 4

Lerbinger, A., Petkov, I., Mavromatidis, G., & Knoeri, C. (2023). Optimal decarbonization strategies for existing districts considering energy systems and retrofits. *Applied Energy*, *352*, 121863. https://doi.org/10.1016/j.apenergy.2023.121863

Publication Nr. 5

Petkov, I., Lerbinger, A., Mavromatidis, G., Knoeri, C., & Hoffmann, V. H. (2023). Decarbonizing real estate portfolios considering optimal retrofit investment and policy conditions to 2050. *IScience, 26 (5),* 106619. https://doi.org/10.1016/j.isci.2023.106619

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