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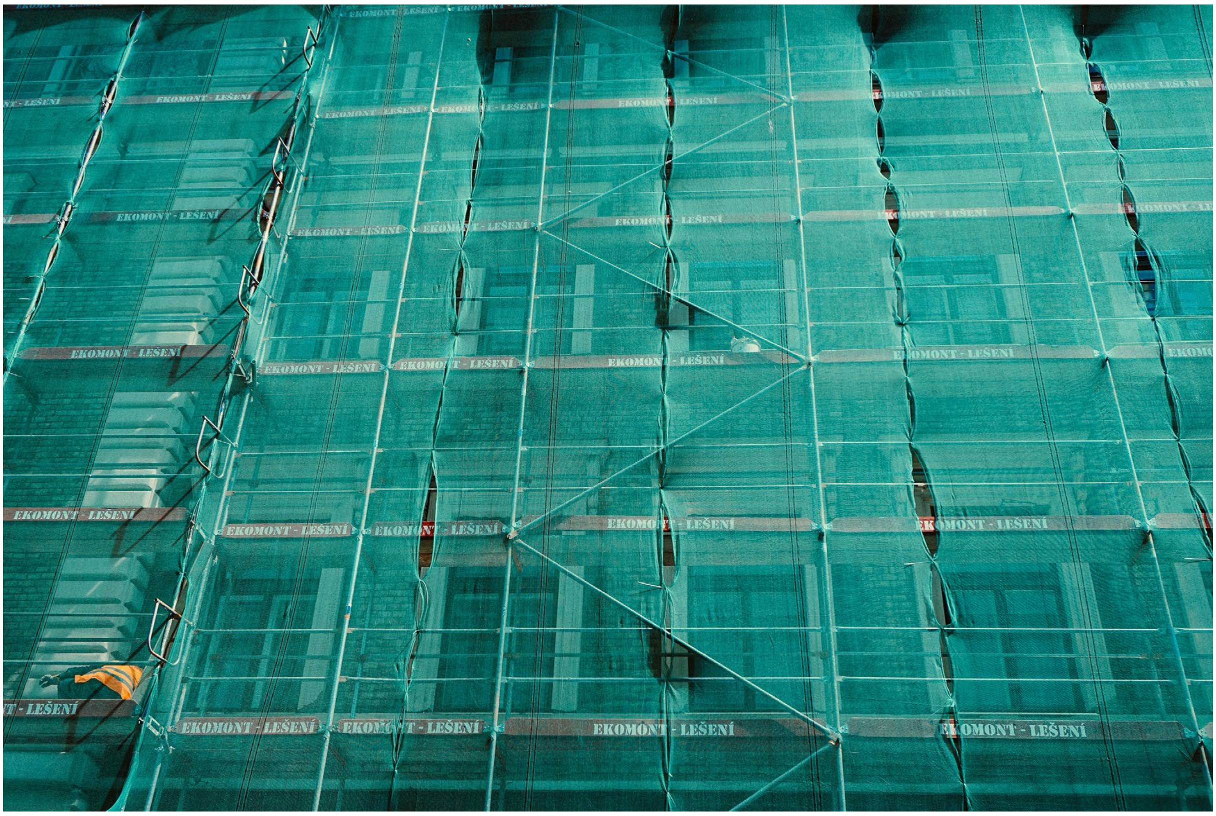
PACE REFITS

Policies for accelerating renewable and efficient building & district retrofits



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Swiss Federal Office of Energy SFOE
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Subsidy recipients:
ETHZ
SusTec (Group for Sustainability and Technology)
Weinbergstrasse 56/58
8006 Zürich ETH-Zentrum
https://sustec.ethz.ch/

EMPA
Urban Energy Systems Laboratory
Ueberlandstrasse 129,
8600 Dübendorf
https://www.empa.ch/web/s313/ues-home

Authors:
Ivalin (Evan) Petkov, ETHZ SusTec, epetkov@ethz.ch
Dr. Christof Knoeri, ETHZ SusTec, cknoeri@ethz.ch
Prof. Dr. Volker Hoffmann, ETHZ SusTec, vhoffmann@ethz.ch

SFOE project coordinators:
Yulia Blondiau, yuliya.blondiau@bfe.admin.ch
Anne-Kathrin Faust, anne-kathrin.faust@bfe.admin.ch

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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.

Dieser zweite Zwischenbericht des 3-Jahres Projekts gibt einen Überblick über die getätigten Arbeiten im zweiten Jahr. Weiter präsentieren wir erste Resultate wie techno-ökonomische und regulatorische Rahmenbedingungen energie-effiziente und erneuerbare Sanierungen von Grossinvestoren beeinflussen. Resultate aus dem ersten Arbeitspacket sind abgeschlossen während das neu entwickelte multi-stage Optimierungsframework in den Arbeitspacketen 2 und 3 weitergeführt wird.

Im Rahmen des ersten Arbeitspackets haben wir die Interviewkampagne betreffend dem Entscheidungsverhalten, Motivation und Hinderungsgründe von Grossinvestoren für energetische Sanierungen abgeschlossen. Dabei konnten drei Phasen der Dekarbonisierung des Real-Estate Sektors identifiziert werden. Weiter wurden die Investitionsplanung auf der Asset- und Portfolioebene als Schlüsselprozess in der Entscheidungsfindung von Grossinvestoren untersucht. Dabei 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.

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, welche dann in die modell-basierten Arbeitspackete 2 und 3 einfliessen. Dies wird ergänzt mit einer retrospektiven Untersuchung der Effizienz verschiedener Politikmassnahmen im Vergleich zu gemessen Energieeinsparungen in Zusammenarbeit mit dem Kanton St. Gallen.

Aufbauend auf den qualitativen Ergebnissen aus dem ersten Arbeitspacket 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. Im Moment wird MANGO erweitert damit sanierungs-spezifische Aspekte adressiert werden können (MANGOret). Nachdem wir detaillierte Portfoliodaten eines Grossinvestors akquirieren konnten, wird MANGOret nun zu einer skalierbaren Real-Options Methode weiterentwickelt. Die Skalierbarkeit der Methode wird dabei von einer Datenbank von Energieprofilen von Gebäudearchetypen unterstützt. Weiter wurde in Arbeitspacket 3 mit der Studie von Sanierungsaspekten auf der Areal Ebene begonnen.

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.

This 2nd interim report of this 3-year project presents a project update and preliminary results into the techno-economic and regulatory conditions to support investments into renewable and energy-efficient retrofitting technologies in the existing building stock. Results for work package (WP) 1 are finalized, along with the optimization modeling framework which will be expanded for WPs 2 and 3.

Starting with work package (WP) 1, we finalized an interview campaign relating to large-scale investors' (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. First, we categorized three phases of real estate decarbonization. Next, we unpacked the LSI retrofit decision-making process to shed light on the investment planning mechanism at the asset and portfolio levels as a key aspect for LSIs to accelerate deep retrofits. 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.

Further, we conducted a policy scenario workshop to explore the role of regulations, polices, and norms for their influence on the LSI decarbonization strategies in order to later quantify them for the subsequent modeling-based WPs 2 and 3. Here, we developed and validated three distinct scenarios using a policy toolkit including regulatory, market-based, as well as financial incentives and fiscal instruments. This is supplemented by retrospectively testing the efficacy of a building energy incentive program for retrofits on measured energy savings in the Swiss canton St. Gallen.

Building on the qualitative findings of WP1 relating to real estate decision-making, we have developed and published 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 are now extending 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 will be adapted to become a scalable real options method to consider uncertainties for any Swiss real estate portfolio. The scalability is aided by the development of a Swiss archetypal energy demand database. Further work for WP3 has recently begun to study retrofit considerations for district scale energy systems.

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; Prognos; Infras; TEP Energy; 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., 2012), 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., 2020) and DRES are demonstrating their potential on the neighborhood to city scales (von Wirth et al., 2018). 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., 2012). 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., 2018). 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 50b invested in buildings in 2016, LSIs constituted the largest share investments (16% public and 57% commercial), with approximately one third of investments going into existing buildings and two thirds into new construction (BFS, 2018). 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., 2020). 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., 2020).

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

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

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.

1.2 Current situation

The project is now two-thirds of the way complete with project progress thus far going according to the timeline, with all major checkpoints met as discussed in the further sections.

Specifically, the results from WP1 have been finalized (paper submission), and the policy scenarios are nearly finalized for quantification to the models. Further, due to advantageous access to building energy incentive data from a cantonal energy department, we have recently begun to to test the efficacy of a cantonal building energy incentive program for retrofits on measured energy savings with canton St. Gallen. While this was not planned as part of the proposal, it is part of PACE REFITS.

Relating to WPs 2 and 3, we have advanced at key points in the methodological developments which allow us to answer the research questions set forth in the project. These developments relate to the archetypal energy demand database, all input data relating to the LSIs' portfolio and otherwise necessary for the model, along with the optimization algorithms of which a part of (the MANGO model) has been published in *Applied Energy* as paper 3.1 (Mavromatidis & Petkov, 2021). The remaining focus of the project relates to model development and results analysis for WPs 2 and 3.

1.3 Purpose of the project

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

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

(1) What are is the interplay of LSIs' retrofit and 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?

The findings will be synthesized 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 will 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).

1.4 Objectives

The objective of this project would be 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

Here we outline the procedures and methods while providing the logistical status for each WP. In the following section, we present formalized results.

Work Package 1

The goal of this WP is 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. Since the last project report, we have finalized this WP and present a condensed version of procedures and methodology, and results in the following section.

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 present the methods for each subsection.

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 – covered in the previous project report. 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.

This is supplemented by the recently begun project on testing the efficacy of a building energy incentive program for retrofits on measured energy savings in a Swiss canton.

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. Such a qualitative approach allows for an integrated analysis of the interplay between policy and institutional efforts towards decarbonization, highlighting the roles that both policymakers and real estate owners play in the transformation towards a decarbonized building stock. While this does not allow us to comment on the efficacy of a particular policy instrument, as in a quantitative study, it does allow for a high-level narrative about the influence of policy on LSIs' retrofitting decision-making processes.

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. Policymakers were split based on the structure of Swiss energy regulation, focusing on interviewees in administrative roles rather than political appointees to leverage technical regulatory expertise.

While main interview questions focused on incorporating aspects from the relevant sector, subsector, and roles, they can be categorized in the following:

(1) Real estate department budgetary and decision-making workflows, with considerations for organizational structure, processes, and role involvement.

(2) Within portfolios, describing processes for budgetary distributions across various interventions (i.e. transactions, new, replacement, retrofits).

(3) How buildings are selected from the portfolio to be retrofitted, and how decisions are made about what components go into the building.

(4) Project-level retrofit decision-making workflow, with specific focus on internal/external stakeholders' involvement, tools, and regulatory considerations.

The interview campaign was completed in November 2020. Developing good relationships with the real estate industry and building trust proved to be crucial to gain access to interviewees. Therefore, the progress in the interview campaign was delayed longer than what we hoped for, especially considering the Coronavirus pandemic. 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. Table 1: Interview data sources across sectors, company types, and roles provides a list of the interviewees with company sector, subsector, and role.

Table 1: Interview data sources across sectors, company types, and roles.

Sector	Company type	#	Role
Large-scale investors	Bank – global	6	1. Head of real estate ESG and strategic projects 2. Head of construction management 3. Head of portfolio management & portfolio manager – ESG fund 4. Portfolio manager – traditional fund 5. Asset manager 6. Construction manager
	Insurance – Europe	4	1. Head of real estate ESG 2. Portfolio manager – fund 3. Portfolio manager – foundation 4. Construction manager
	Insurance – global	4	1. Head of construction management 2. Head of transaction management & portfolio manager 3. Senior asset manager with sustainability focus 4. Construction manager with sustainability focus
	Public – Swiss	4	1. Project leader of sustainable building department 2. Portfolio manager – rented properties 3. Portfolio manager – self-used properties 4. Group leader – construction management (renovation)

Energy	Energy developer & consultancy 1	2	1. Senior consultant for real estate sustainability 2. Building & district energy systems engineer
	Energy developer & consultancy 2	2	1. Leader of integrated energy & mobility solutions 2. Product manager of strategic solutions
Real estate	Property management company	3	1. Head of project management & sustainability 2. Property manager for LSI portfolios 3. Construction manager
	Real estate consultant	1	1. Head of sustainability services
	Real estate valuator	1	1. Director of valuation with sustainability specialization
Association	Building owner	1	1. Director of building & energy department
	Tenant	1	1. Head of tenant association
Regulatory	Federal	1	1. Program manager for building energy
	Cantonal	2	1. Head of cantonal energy department 1 2. Head of cantonal energy department 2
Total		**32**	October 2019 – November 2020

Policy scenario development and stakeholder workshop

In the previous project report which was submitted before the project workshop occurred, we began preliminary conceptualizations of the policy scenarios. Now that the workshop has occurred, we have finalized the qualitative aspects of the scenarios and began quantification. We present a condescend summary here.

Building on the structured literature review and semi-structured interviews, we explore the role of regulations, polices, and norms for their influence on the top-down LSI decarbonization strategies and real estate industry bottom-up decision-making processes. As part of this exploration, we are developing future policy scenarios relevant to retrofitting which LSIs could use in their multi-year planning in order to quantify the impact of policy uncertainty. These scenarios will be quantified for WPs 2 and 3.

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 expert workshop was originally planned for Spring 2020, but due to the Coronavirus pandemic was postponed. The project Board consists of the majority of the companies / organizations interviewed in WP1, of which at least one representative joined the Board meeting (total 14 representatives).

To advice LSIs and policymakers on how to intervene under future uncertainty, the focus of consideration needs to be broadened through the use of policy scenarios (Moss et al., 2010; Swart et al., 2004), defined as alternative images of how the future might unfold. Therefore, a set of scenarios assists in the understanding of possible future developments of complex systems (IPCC, 2000). Further, the adoption of climate change-related scenarios in the long-term planning methods for buildings necessitates the development of relevant policy scenarios. The appropriate reference scenario for mitigation analysis must be taken in order to compare impacts (Grant et al., 2020).

Scenarios integrate qualitative narratives and must be combined with quantitative formulations of policy instrument developments (Drouet et al., 2015). The large bulk of the policy scenario development description is published in the Masters thesis of Thomas Gürber, "*The impact of future uncertainty on retrofit decision-making in the context of real estate valuation*", attached in the Appendix of this report.

We take their strategy of (i) a *current policy* scenario (Scenario 1), (ii) a *current ambition* scenario (Scenario 2), and (iii) a *central mitigation* scenario (Scenario 3) to ensure the findings are relevant to the Swiss and European climate and energy policy context. These are chosen not to predict the future, but to understand it as an accumulation of different futures representing different costs and benefits. The following three subsections briefly present the policy scenario development process.

Policy scenario framework

Frameworks are needed to contextualize the scenarios, aiming to assess the implications of future Swiss policy changes on building retrofitting decision (Van Notten, 2006). To provide consistency throughout the elaborated scenarios, this thesis is based on two different publications: (i) IPCC SRES from (IPCC, 2000), and (ii) the Swiss Energy Strategy 2050 (ES2050) accepted by the Swiss electorate in 2017 (SFOE, 2020). In the following, the focus is set on the most relevant Swiss regulatory instruments for evaluating exiting building retrofitting investments such as BECs, climate regulations, incentives and subventions, along with tenant as well as real estate market regulations.

Historical narratives

Narratives give descriptive guidance on constructing scenarios and act as the projection boundary for each key variable of the scenarios (Mahmoud et al., 2009). Furthermore, they help reveal and address critical questions through its texture and richness, leading to a broader perspective (Swart et al., 2004). A detailed description of historical and current laws and norms, relating to building stock decarbonization and retrofitting in Switzerland is provided in Thomas Gürber's Masters thesis. Simultaneously, the policy instrument toolkit is built from the narratives, which is needed to develop the policy scenarios.

Policy scenario development

In total, three policy scenarios are developed, each of them characterizing dissimilar emission pathways. The scenarios are derived in four steps:

1. 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). These approaches seem to be appropriate for visioning futures and identifying long-term risks whilst identifying initial conditions, drivers of change, and the bandwidth of initial trajectories towards long-term sustainability goals (Swart et al., 2004).
2. Second, once the intermediate and the 2050 GHG emission goals for the three scenarios are defined, specific policy measures are developed for each scenario. Simultaneously to the narratives, we developed the policy toolkit focusing on regulatory, market-based and financial incentive instruments.
3. Third, as the characteristics of the building stock are highly dependent on different trends related to socio- and macro-economic factors, forecasts should reflect as much as possible the current economic and social circumstances (Romano et al., 2019). Thus, 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.
4. The fourth and last step involves the verification of internal consistency and the alignment with the historical narratives. Finally, the three scenarios are cross-checked on disparities and their distinctiveness.

Proceeding from qualitative scenario narratives to quantitative-projection scenarios is seen as one of the most challenging issues in constructing and applying scenarios in models (Mahmoud et al., 2009).

Hence, the developed scenarios were validated through an expert elicitation workshop to decide upon the most relevant regulatory instruments for evaluating future LSI retrofitting investments. Therefore, the workshop aimed to receive feedback from the experts on the proposed scenarios to refine and quantify the regulatory measures for the modelling.

The workshop participants received the scenario narratives and a summary table with the policy toolkit trends a few days before the meeting, allowing them to familiarize themselves with the workshop content in advance. At the beginning of the workshop, the experts were asked to give their opinion on the completeness of the used policy instrument toolkit. The focus was on complementing, from their perspective, other vital instruments. This short intro was followed by the main scope of the workshop - the experts were divided into three groups and asked to discuss and complete the prepared worksheet. A total of four discussion questions were presented:

i. Are the scenario narratives distinct from each other? If not, what could be improved?
ii. Are the considered policy instruments in the toolkit comprehensive? Should some be added or removed?
iii. Do you agree with the policy instrument trends (arrows) within each scenario?
iv. Are the trends within each scenario internally consistent (i.e. do some conflict with each other)?

Questions (ii) and (iii) were designed to validate the prior developed scenarios and quantify the proposed level and timing of regulatory measures. Questions (i) and (iv) aimed to compensate for any inconsistencies and adjust the scenarios to each other. At the end of the workshop, the main findings of the three groups were discussed in the plenum.

Next, the scenarios will be adapted and quantified for use in the modeling WPs 2 and 3.

Building energy policy efficacy

As part of PACE REFITS, we are developing a statistical methodology to test the efficacy of a Swiss canton’s building energy incentive program on actual measured energy savings from district heating meter data. We have collected most of the relevant data and are currently in the pre-processing phase before we apply the prospective methodology. Data richness includes quarterly heating data (pre- and post-retrofit) for 1,400+ buildings in St. Gallen canton paired with retrofit incentive data for approximately 150 buildings (energy efficiency and renewable energy).

There is also the potential to analyze performance gaps by comparing expected (i.e. calculated) with measured energy savings through connection with the archetypal energy demand database described in the following WP2. Linking these two types of data (energy data and incentives) presents a unique opportunity to evaluate the efficiency and effectiveness of financial incentives on retrofit measures.

Work Package 2

This WP has two methodological and contextual targets:

(1) Developing a dynamic, long-term, and scalable “real options” retrofit planning method to substitute LSIs’ static multi-year planning for optimal portfolio decarbonization strategies under uncertainty, and

(2) Testing various policy scenarios to determine recommended policy pathways for cost-effective decarbonization of the existing building stock.

The goal is to build a scalable real options (RO) method for optimal planning strategies for Swiss real estate portfolios while demonstrating the uncertain regulatory trade-offs between optimal retrofit speed and depth in decarbonization pathways. This requires first the development of the methodology and second the testing and implementation with a real-world application.

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. This will be 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.).

We have brought forward the development of WP2 and are progressing with the formulation of the model which present a novel methodological advancement. Conceptualization has been completed with prototyping in advanced stages.

The project team has conceptualized the models for PACE REFITS in a modular way, with the base model (MANGO) already published. This base model acts as the ‘engine’ of the multi-stage optimization framework and will serve as a basis for the building and portfolio level optimization along with for WP3 (Mavromatidis & Petkov, 2021). In Section 3, we outline a description of the modular structure of MANGO with the focus of future modeling ventures on MANGOret.

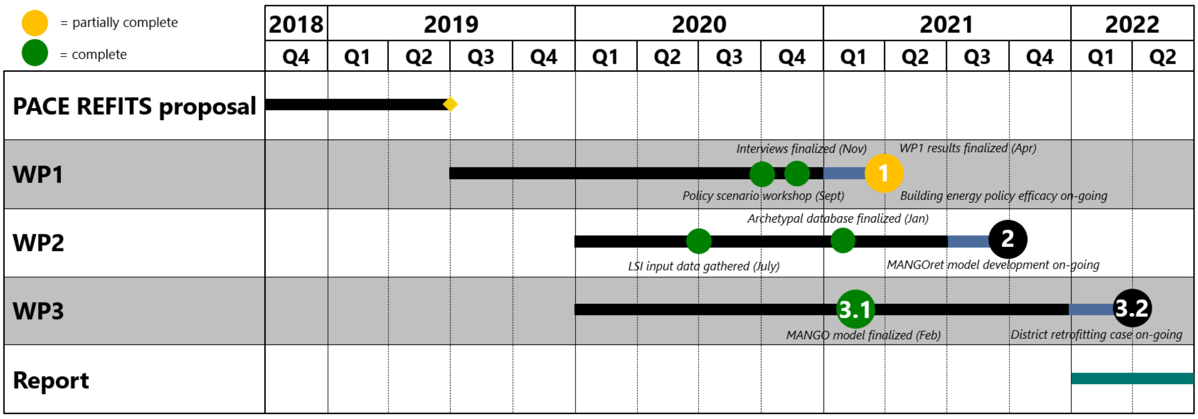
The model development is partially aided by our project partners at Empa UESL through building a database of energy demand profiles for pan-Swiss building archetypes which will allow for the scalability of the optimization tool.

Work Package 3

The methodological development for WP3 has begun in parallel with WP2, as the same multi-stage and multi-objective model ‘engine’ will be used at both the building- and district-scales, although with slight variations with the detailed methodology presented in (Mavromatidis & Petkov, 2021).

Similar to WP2, data will be taken from an LSI’s district where we could evaluate the retrofitting energy system investment strategies over time. While the multi-stage optimization has been developed, we have begun working in May 2021 on the retrofitting-specific research questions of WP3 with the addition of a new Masters student, Alicia Lerbinger. Further, we have begun discussions with Empa UESL about a preliminary case study to be used for WP3.

3 Activities and results



The timeline above presents the updated 2nd interim report project workflow, with both partially complete and fully complete main WP result checkpoints. For WP1, these checkpoints are the policy scenario workshop (September 2020), the finalization of the interview campaign (November 2020), and the finalization of WP1 results (April 2021) through a journal paper submission. Further, the building energy policy efficacy project is on-going, so this WP was marked partially complete.

Regarding WP2, the relevant LSI input data was gathered in July 2020 along with other necessary data for the MANGOret model development (on-going) such as the finalization of the archetypal energy demand database (January 2021). Regarding WP3, The MANGO multi-stage optimization model framework was finalized and published in *Applied Energy* in February 2021 (Paper 3.1), with the district retrofitting case study on-going. Continual progress is now being made on WPs 2 and 3 with significant steps being made in methodological development. Below we present preliminary results for all WPs.

Work Package 1

The results of WP1 are broken up into the (i) submitted paper in April, 2021 titled "*The interplay of policy and retrofit decision-making for real estate decarbonization*" and (ii) the policy scenario stakeholder workshop. We address results here with the WP1 high-level findings to build on our previous progress report without publishing figures as the submitted paper is under review in a journal.

Our goals were to (i) uncover firm-level retrofit decision-making processes of LSIs in order to (ii) better understand their interplay with the overarching retrofitting policy mix. This involves a deep-dive into LSIs' institutional strategies and decision-making processes relevant to retrofitting. Further, we analyzed the interplay of their decision-making with the overarching policy mix, looking individual energy policy instruments which proved to be a vital finding of the WP.

In the following we present high-level results of the submitted paper along with the results from the policy scenarios developed in the stakeholder workshop. Since the building energy policy efficacy project has just begun and in the data pre-processing phase, we have no findings to report.

High-level findings

To better frame policies targeted at accelerating LSIs' retrofitting 'speed' and 'depth', we discuss organizational perspectives between four LSI types with various real estate focuses (e.g. bank - global, insurance - Europe, insurance - global, and public - Swiss) to extract strategies, decision-making processes, motivations, and barriers for retrofitting. In the following we outline the high-level findings from semi-structured interview campaign which constitute the submitted paper, building on the previous project report. While we describe many of these aspects in detailed Figures, unfortunately we are unable to report them here due to journal embargo rules.

Three phases of real estate decarbonization

After synthesizing results from all interviews, we were able to categorize three phases of real estate decarbonization – (1) Niche ESG Implementation, (2) Institutionalizing decarbonization, (3) Mainstream net-zero CO_2 requirement. The first two phases were *observed* from interviews, not unlike the transitional phases outlined by (Markard, 2018) for the energy sector: emergence followed by maturation. The third phase was *envisioned* by interviewees as necessary to achieve net-zero CO_2 in the long term. We were able to generalize each phase by three key features in the categories of ESG considerations, management strategies, and CO_2 topics. Further, we identified the key transitional drivers between phases 1 and 2.

Phase 1 (Niche ESG Implementation) is marked by selected portfolio ESG reporting, niche high-value assets with green building labels, and the possible creation of separate ESG portfolios. This is followed by Phase 2 (Institutionalizing decarbonization), marked by a predominant focus on CO_2 in ESG strategies through common practice ESG monitoring, reporting, long-term CO_2 goals, and sustainable construction guidelines. Phase 3 (Mainstream net-zero CO_2 requirement) represents the future achievement of net-zero CO_2 emissions goals — requiring low CO_2 ratings for all assets, not just lighthouse projects. To transition to Phase 3, real estate teams must be able to effectively align today's investment decisions — for example, on replacing a heating system or redeveloping a façade — to long-term CO_2 goals. This could correspond to earlier-than-planned retrofits with consideration of embodied emissions in order to stay competitive in the real estate market.

Our results show the increased decarbonization pressure on LSIs, moving from niche implementation (Phase 1) to institutionalized decarbonization (Phase 2). By unpacking the LSI retrofitting "black box," we observe that this phase transition has generated incongruencies around integrating decarbonization into the value-driven retrofit decision-making process, described further in the following. Findings point to the importance of asset managers' planning decisions as a key mechanism for policymakers to focus on when setting building-sector policy in the framework of real estate management.

Transforming real estate retrofit decision-making

We found that integrating decarbonization considerations into real estate decision-making presents different challenges in each phase of the transition. From the interviews we were able to generalize traditional retrofit decision-making process, highlighting four main decision points for all real estate team members ranging from high-level real estate strategies to portfolio budgeting and asset-level strategies. Developed over decades, this complex process is typified by fragmented role priorities and externalization from the LSI, typically through reliance on consulting services and property managers to make decisions. Some interviewees describe these features of fragmentation and externalization in the decision-making process as hindering a definitive retrofitting decision, making it difficult to align retrofits towards top-down CO_2 goals.

We found that the mechanism of investment planning at the asset and portfolio levels are key for LSIs to accelerate deep retrofits. On a granular level this is driven by asset retrofitting strategies which are highly contextual and value-driven. Real estate teams negotiate retrofitting options with a focus on maximizing building value and smoothing portfolio capital expenditure budgets, explicitly contradicting academic studies utilizing payback periods or returns (ROI) on energy retrofits as the sole economic decision-making metrics.

Interviewees stated that considering CO_2 presents new challenges to the economically focused retrofit decision-making process, culminating in the adjustment of both asset strategies and multi-year plans. From an organizational perspective, we find significant barriers relating to the engrained tacit real estate industry knowledge (e.g., an attitude of “We always do it this way”) and aptitude (e.g. achieving a key performance indicator (KPI)) for deep retrofits.

Despite better-integrated policy mixes, LSIs’ current Phase 2 strategies might not be sufficient to meet both internal and global CO_2 goals. LSIs have the ability to transform decision-making processes to integrate decarbonization with (i) integrated multi-year planning, (ii) internal CO_2 tax transfers, and (iii) deep retrofitting role KPIs. Interviewees agree that if value-driven economic criteria remain the key decision-making metrics, deep retrofits will never become feasible for some properties — especially in “low-value” markets where the possible increases in rent cannot (at the market rate) are not sufficient to do a deep retrofit. This raises questions about how policies from the energy domain and beyond influence retrofitting decisions.

Limited impact of direct policy instruments on LSIs’ retrofits

We observe the limited impact of direct policy instruments on retrofitting decisions, highlighting the importance of instruments that target retrofits indirectly, such as those with different policy objectives. Elements of the policy scenario stakeholder workshop were utilized to develop the overarching retrofitting policy mix relevant to LSIs in Table 2 which have both direct (energy and emissions-focused) and indirect (non-energy-focused) policy instruments.

For example, many interviewees agreed that building energy codes (BECs) are not decisive for altering retrofitting options, and are instead perceived as boundary conditions for depth. Furthermore, LSIs did not see potentially more stringent BECs as a threat, since their orientation towards labels in construction guidelines puts them “ahead of the game” from a regulatory risk perspective. Thus, BECs are mostly relevant for low-value markets as minimum thresholds for EE and RE.

Our findings suggest that instruments tied to CO_2 benchmarks have the most influence on retrofit decision-making. All LSIs agreed that high CO_2 taxes accelerate the switch to emission-free heating, but presently have little influence on EE investments. Further, interviewees mentioned the influence of high-level investment taxonomies (e.g. the EU Sustainability Taxonomy) on portfolio budgeting through reduced interest rates. Financial incentives related to building components or general retrofit depth were deemed indecisive for retrofitting depth and speed; most LSIs considered them a “nice to have,” due to their minimal influence on budgeting. Most interviewees expressed strong aversion to more restrictive types of direct instruments, such as technology mandates and retrofitting obligations.

In contrast to direct instruments, indirect policies from other domains crucially impact retrofitting decisions primarily relating to affordability, tenant security, and urban planning instruments as they influence real estate valuations that are critical to asset retrofitting strategies and multi-year planning. Such policies include rent controls, component pass-on costs, eviction notice periods, permitting processes, and zoning densification financial incentives. Both private and public LSI interviewees expressed particular concern over the influence of affordability policies such as rent controls — but not over tenant security laws such as eviction notices and component pass-on rates.

Local jurisdictions' rent controls were deemed the most influential indirect instrument, directly decreasing residential retrofitting investments through the mechanism of distorting building value. At the other extreme, the consequential rising rents from LSIs' short-term pursuit of value maximization — partly due to high-value "green" buildings — could lead to "green gentrification" processes and, in the long run, to political initiatives for rent controls. LSIs are clearly aware of this potential negative feedback loop. All LSIs reiterated their fear of the regulatory uncertainty of politically driven rent controls on multi-year planning processes.

The interviewed policymakers struggle with the dilemma of how to regulate real estate markets in light of various policy objectives. Significant affordability-friendly policies counteract market drivers for deep retrofits, endangering the (planned) retrofitting rate and future profits. In contrast, over-liberalized real estate markets allow disproportionate rent increases from (potentially deep) retrofits. Considering this, interviewees called for instruments from various domains to be aligned in order to meet CO_2 goals.

Table 2: Retrofitting policy mix comprised of direct and indirect policy instruments.

Policy instrument type	**Policy objective**	**Policy category**	**Policy instrument examples**
Direct	Energy and emissions	Regulatory and control mechanisms	**Building Energy Codes (BECs):** heating efficiency performance (kWh/m²), CO_2 performance (kgCO_2/m²), renewable heat production requirements (W/m² or %), on-site RE production requirements (W/m² or %)
			Retrofitting obligations (kWh/m² or EPC-level by certain year)
			Technology bans (e.g. electric resistance heaters, oil boilers) or mandates (e.g. solar PV)
		Market-based instruments	Energy Performance Certificates (EPCs)
			Green building labels (e.g. LEED, BREEM, DGNB, etc.)
			Energy performance contracting
		Fiscal instruments and incentives	**Component-based financial incentives:** insulation, windows, RE heating generation systems (e.g. heat pumps, biomass boilers) and electricity generation systems (e.g. solar PV)
			Retrofit depth-based financial incentives (e.g. based on EPC-level or label achievement)
			Electricity self-consumption-based incentives
			CO_2 taxes on fossil heating and process fuels (EUR/tonCO_2)
			Fiscal instruments for sustainable investments (e.g. lower debt interest rates, tax benefits)
		Support, information, and voluntary action	Informational and education campaigns
			Mandatory energy audits and disclosures

Indirect	Affordability and tenant security	Regulatory and control mechanisms	**Tenant laws:** eviction notice periods (years), component or retrofitting pass-on rates (% — vary by intervention) **Real estate market regulations**: rent controls and caps Permitting processes
	Urban planning	Fiscal instruments and incentives	Zoning densification financial incentives (%)
	Financial security	Fiscal instruments and incentives	Required annual reinvestment in portfolios (e.g. ~2%, depends on portfolio investment vehicle type such as insurance, pension, or stock-market listed funds)

Integrated policy mixes for retrofits

Our findings suggest that direct and indirect instruments potentially interfere at various leverage points in LSIs' value-driven retrofitting decisions. Direct instruments act as framework conditions for the energy aspects of the value-increasing retrofit investment, with BECs setting minimum standards and financial (dis)incentives reducing costs for deep retrofits. In contrast, indirect instruments generally affect the profit margin and final building value.

We outline an initial attempt at a pathway for an integrated policy mix to encourage broader market penetration of deep retrofits while accounting for various policy objectives such as affordability, densification, and decarbonization. We conceptualize the effects of (in)coherent policy mixes relating (relating to various social objectives) on the LSI retrofitting decision. The possible constellations of policy instruments can result in shallow or deep retrofitting decisions through interactive mechanisms. An integrated retrofitting policy mix must strive for improved coherence between policy objectives by considering the inconsistencies between (direct and indirect) policy instruments to effectively address LSI value-driven decision-making.

Such an approach requires an in-depth understanding of instrument interactions to meet multiple "holistic sustainability" objectives from different policy domains and involved real estate stakeholders. Improving coherence between objectives that are currently seen as divergent would address socioeconomic and political questions regarding affordability in the context of deep retrofits. Further, policymakers must break down policy silos at various jurisdictional levels in order to align affordability (local) and decarbonization (national) objectives. For example, this would implicate policymakers from local real estate market regulations coordinating with national policymakers focusing on building-sector energy and climate goals. This would provide clarity for LSIs and alleviate organizational tensions in real estate markets with different instruments at play. On the instrument level, we urge policymakers to reduce interference between instruments, or otherwise move towards instruments that can address multiple objectives. For example, jurisdictions have already been using multi-objective instruments such as density bonus incentives to promote affordable housing (Debrunner & Hartmann, 2020; Jeddi Yeganeh et al., 2019) as well as relaxing zoning laws for densification if a green building label is achieved (i.e. exaction) (Conticelli et al., 2017). In terms of rent controls for affordability, limited evidence suggests that other instruments may be better suited to incentivize affordability without unintended consequences — for instance, through rent subsidies (Diamond et al., 2019).

However, in terms of real estate market regulations, we need instruments that address multiple objectives such as affordability and retrofitting depth. One potential innovative example of such an instrument, paired with existing CO_2 taxes which have been shown to be insufficient when used in isolation (Bataille et al., 2018), could be a rent subsidy linked to achieving a green label or EPC. In such a case, LSIs could still charge the market rate (at a controlled return), while CO_2 tax revenue would be redistributed to low-income tenants. This combined direct and indirect instrument would directly target multi-year planning, allowing LSIs to effectively budget for deep retrofits.

There are still open questions for policymakers as to what kind of policy mixes are needed and how they should evolve, along with the role of various regulatory domains in coordinated real estate market decarbonization. Transitioning to net-zero CO_2 emissions (Phase 3) underlines the importance of the cross-impacts of policy silos and conflicting social goals. When political action is taken to assure affordability through rent controls, policymakers could reduce instrument interference by moving towards multi-objective instruments which provide some sort of financial incentive that will maintain the pace of deep retrofitting.

Policy scenarios and stakeholder workshop

In the framework of the Swiss ES2050 and IPCC SRES, we are still finalizing three scenarios for possible futures that are distinct and characteristic of future directions, to provide relevant bases of reference for LSI techno-economic modeling of retrofitting risks relating to climate, energy and real estate aspects to demonstrate retrofit policy trade-offs. While the qualitative aspects of contextualizing frameworks, relevant historical narratives and the elaborated scenarios are mainly presented in Thomas Gürber's Masters thesis and are complete, we are still working on their quantification for the modeling.

We build on the previous project report as the workshop has been completed. These scenarios were further validated and improved in the stakeholder workshop with input from 14 industry experts. From these results, we have consolidated and further refined these scenarios, checked their internal consistency, and aligned them with the historical narratives.

Here we describe the scenarios on a high-level. These scenarios are not based on likelihood or measured, but simply characterize rough future trends. Thus, the scenarios are expected to reveal the relative policy implications of alternative energy futures (Robinson, 1982). Three distinct emission goals to be achieved by year 2050 are qualitatively defined and set the particular desired future end-point for the individual scenarios.

i. Scenario 1 (*Policy stagnation*) reflects the 2020 status quo with a focus on the depth of retrofitting regulations without incentivizing speed. The NetZero 2050 target is not met.

ii. Scenario 2 (*NetZero 2050*) represents the ES2020 and Swiss CO_2 law policy objectives through accelerated retrofitting with relevant regulations in order to meet intermediate goals to NetZero 2050.

iii. Scenario 3 (*NetZero 2040*) represents maximum ambition interventions to the existing retrofitting-relevant regulations, meeting the NetZero 2050 emission target as early as 2040.

The dissimilar emission pathways, representing these three scenarios, are qualitatively represented here. Each scenario is supplemented with qualitatively characterized policy measures using the developed policy toolkit from the historical narratives. The available policy toolkit includes regulatory, market-based, as well as financial incentives and fiscal instruments. The following Figure 1 summarizes the defined policy toolkit and provides a comparative overview of the qualitatively defined instrument trends per scenario.

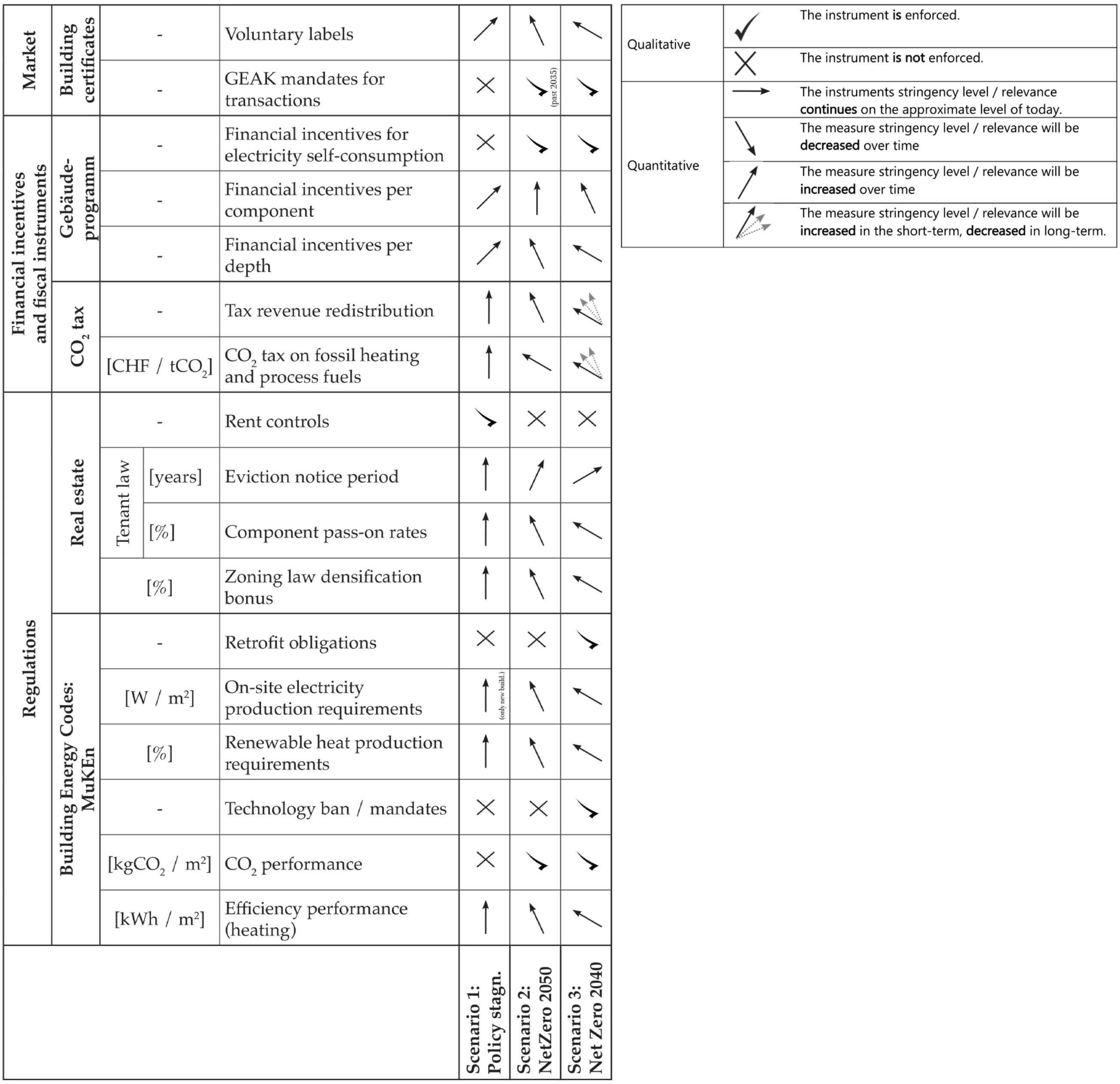


Figure 1: Qualitative comparison of the scenario-specific policy instrument trends (left) and description of the applied trend symbols (right).

Next, we present the written narratives on the qualitatively developed policy scenarios.

Scenario 1 (Policy stagnation)

By and large, this scenario keeps the relevant MuKEn 2014 depth metrics for existing buildings. Maximum energy consumption per building type and renewable heat production requirements are kept at constant levels, while electricity self-production is not mandated for retrofits.

Albeit, due to the failure of meeting intermediate emissions targets, the CO_2 tax would be increased to a maximum value under the present legislation. However, it is assumed that political efforts will be made to prevent such a significant increase in CO_2 taxes and therefore, the taxes levied are likely to remain constant. Thus, the long-term continuation of the Building Program after 2025 is guaranteed by the constant available tax revenue. Through the available budget and increasing number of applications for the Building Program, we assume that the granted incentives per depth and component will be slightly decreasing.

Due to stagnating political realities, the current zoning law densification incentives, component pass-on rates, and eviction notice periods do not exhibit significant changes. Rental control initiatives continue to be passed in urban centers, forcing municipalities towards a regulated approach in support tenants' concerns about affordable housing. Overall, the retrofitting rate stays similar at the current level of approximately 1%. Due to the stagnation in almost all segments, the NetZero target will not be met by 2050.

Scenario 2 (NetZero 2050)

New legal frameworks for MuKEn focus on both depth and speed through a mix of different metrics, as explicit technology bans (e.g. oil boilers) or mandates (e.g. decarbonized heating) remain politically unfavorable. MuKEn maximum energy consumption requirements undergo a slight derating to bring new and existing building rates closer together, whilst increasing renewable heat production requirements for retrofits. Further, MuKEn introduces light retrofit mandates for inefficient and highly emitting buildings based on performance metrics in order to meet the climate goals. Simultaneously, electricity self-production is also mandated for retrofits.

The CO_2 tax is heavily increased in the short-term, as emission goals are not met. This increases the budget for the continuation of the Building Program after year 2025, leading to increased available budgets for incentivizing retrofit components and integrated projects (i.e. efficiency and renewable) to promote depth. In addition, electricity self-consumption is incentivized through subsidies upon achievement of a certain level (e.g. >80%). In order to further promote the speed of integrated projects, a supplementary incentive program is introduced by 2035 to increase the retrofit rate for retrofits skipping at least two GEAK categories. Cantonal zoning laws follow a similar path with densification incentives coupled to achieved GEAK levels. Consequently, the overall demand for voluntary building labels is increasing.

Tenant laws, including component pass-on rates (increased) and eviction notice periods (decreased), are slightly relaxed in the interest of the property owners. All of these factors lead to an increasing retrofitting rate in urban centers, forcing municipalities to shift political and budgetary attention to support lower-income renters for affordable housing. The retrofitting rate stagnates in rural areas due to decreased potential for rent increases in the market.

Scenario 3 (NetZero 2040)

Analogous to Scenario 2, both depth and speed metrics are enhanced with the goal of achieving the full technical maximization of energy and CO_2 metrics for all buildings in MuKEn. These rather disruptive legal frameworks enable the NetZero goal to be achieved as early as 2040.

Efficiency performance requirements are heavily increased whilst introducing new CO_2 performance metrics, along with an outright retrofit obligation for specific building types. This is coupled with an increase in renewable heat production requirements and the electricity self-production metric for retrofits. In order to fully synchronize standards between new and existing buildings, the EnDK move towards removing original MuKEn derating factors (initially ranging between 125-150%).

The CO_2 tax is heavily increased in the short-term, but will be relaxed in the long-term, as CO_2 emission targets are achieved ahead of schedule. The available budget and its reallocation of the continued Building Program behave similarly to Scenario 2. A supplementary incentive program to increase the retrofit rate per depth (e.g. skipping at least two GEAK categories) and high incentives for self-consumption are introduced immediately. Cantonal zoning laws shift towards increased parcel utilization factors (density) for green buildings similar to Scenario 2, but with extensive measures. Thus, the retrofit rate is increased, and voluntary building labels are in high demand.

The political tension, relating to the environment and economy, intensifies due to increasing neoliberal agendas in urban centers. To promote sustainable retrofitting, most urban municipalities are focused on relaxing rent controls coupled with loosening tenant laws relating to increased component pass-on rates and significantly reduced eviction notices. Due to increased rental prices based on real estate rental market liberalization, municipalities are forced to further step-in to subsidize 'green' affordable housing mandates for low-income renters. The increased retrofit activities are still mainly observed in urban centers, but retrofitting in rural areas is further promoted by incentive programs as it is difficult to demonstrate significant retrofitting value potential.

The expert elicitation workshop successfully helped to validate the scenarios. The workshop promoted valuable discussions between experts with different competencies and responsibilities. From the discussions and feedback on the worksheets, the following conclusions can be drawn from the workshop: The scenario narratives are verified to be distinct from each other. The policy instrument toolkit is confirmed to be comprehensive, whereby individual instruments could be split into additional subgroups (e.g. specific cantonal tenancy regulations). Additionally, a few relevant elements such as sustainable taxonomy regulations have to be included.

The expert opinions are relatively diversified for most proposed scenario-specific policy instrument trends. This disparity is very pronounced in the categories of real estate elements and financial incentives and building certificates. Many disagreements are expressed on the building certificate developments, as the majority expects them to increase in future.

Parallel to WPs 2 and 3 optimization modeling development, we are determining the best way forward for scenario quantification. Thus, these scenarios are not finalized.

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*" with PACE REFITS acknowledged (Mavromatidis & Petkov, 2021). This is considered Paper 3.1 in the project with results described in the following.

For both WPs, we expand on MANGO to answer the research questions. We are actively developing MANGO to include retrofitting aspects (preliminarily called MANGOret) and will have a prototype for WPs 2 and 3 in summer 2021 in order to generate results and insights in the last year of the project. As such, we briefly describe MANGO's functionality.

MANGO (Multi-stAge eNerGy Optimization) is a novel optimization model that incorporates a multi-year planning horizon, along with flexible, multi-stage investment strategies for the effective, long-term design of decentralized multi-energy systems. We utilize optimization (mixed integer linear program – MILP) as a method to determine the retrofitting and energy system solution. In the paper, we take retrofitting as a scenario to showcase the model capabilities without explicitly modeling the retrofitting decision.

By considering the dynamic surrounding energy and techno-economic landscape that evolves over time, MANGO harnesses the strategic value of investment flexibility and can optimally phase decentralized multi-energy system investments in order to benefit, for instance, from projected future reduced technology costs and technical improvements. To achieve this, the model considers the most relevant

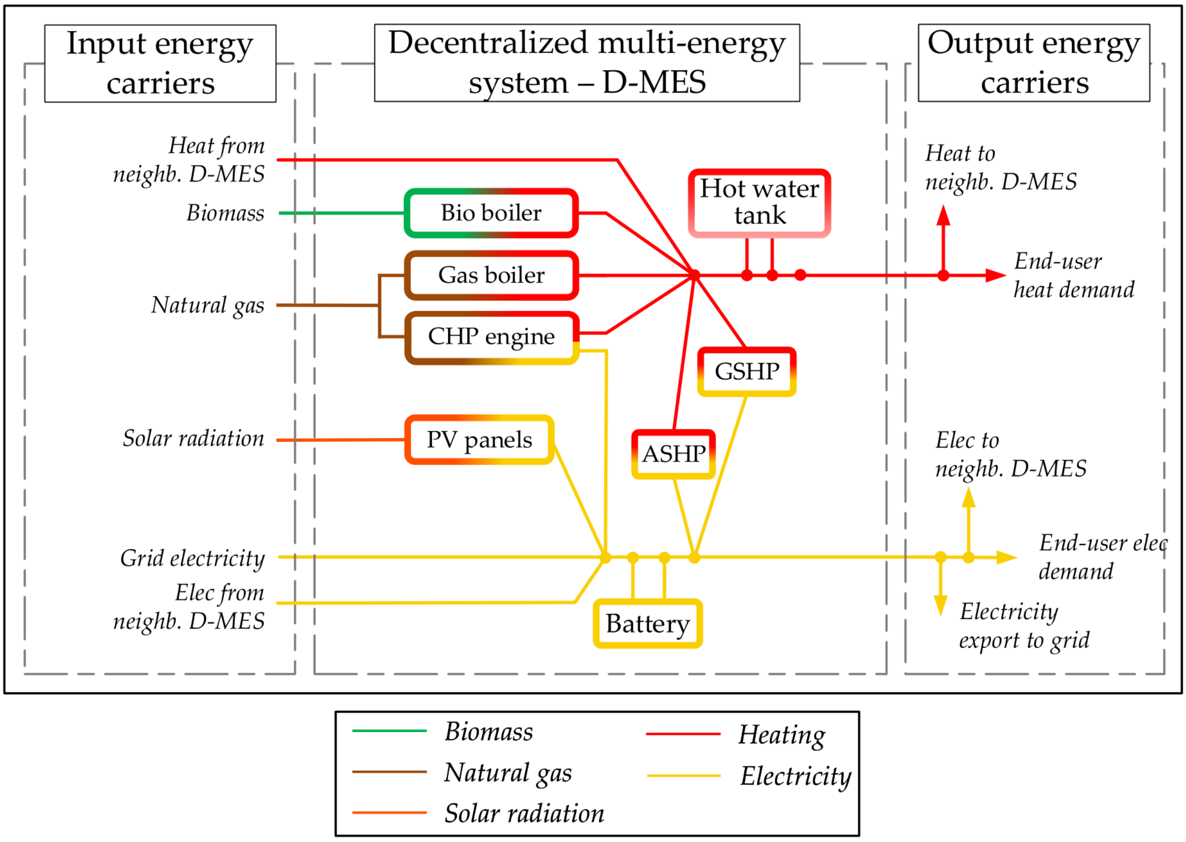


Figure 2: Superstructure representation of candidate energy conversion and storage technologies for the composition of a D-MES.

dynamic aspects, such as year-to-year variations in energy demands, changing energy carrier and technology prices, technical improvements and equipment degradation. MANGO is also capable of optimizing the design of complex configurations composed of multiple, interconnected decentralized multi-energy systems installed at different locations. Finally, the model's formulation also addresses end-of-horizon effects that can distort solutions in multi-stage energy system models. The model's D-MES candidate energy conversion and storage technologies are shown in Figure 2, with the possibility of exchange between multiple D-MES sites shown in Figure 2.

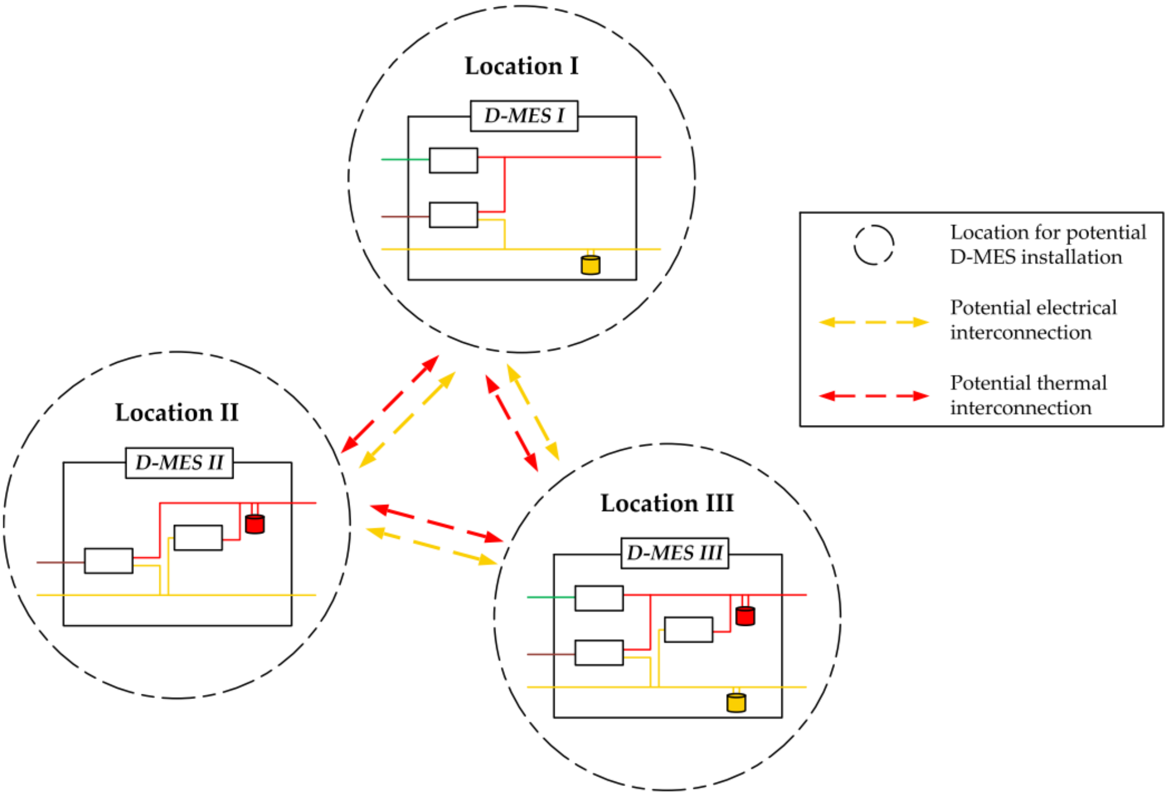


Figure 3: Conceptual representation of multiple, interconnected D-MES exchanging energy with each other.

In the preliminary paper (Mavromatidis & Petkov, 2021), besides presenting the key aspects and the mathematical formulation of MANGO, we also use the model to develop a six-stage energy design plan, along a 30-year project horizon, for an urban district composed of 3 sites in Zurich, Switzerland. One candidate decentralized multi-energy system is considered per site and different scenarios are examined regarding building retrofitting and interconnections.

WP2 does not currently have analytical results as we are actively developing the methodology for building- and portfolio-level multi-stage optimization to consider the specificities of retrofits.

Specifically for WP2, MANGO will be adapted in 5 main steps to become MANGOret, in order to utilize the multi-stage optimization framework to specifically consider retrofitting-relevant technologies, managerial considerations, and contextual aspects along with a real options methodology:

1. **Input data**
    a. From LSI:
        i. Building information (location, use, type, age, market value / rent)
        ii. Component information (types, ages (past retrofits), roof area)
        iii. Energy demands (electricity, heating, cooling)
    b. From SusTec:
        i. Techno-economic and context parameter database (uncertainty ranges for cost, efficiency, and lifetimes of retrofits and all energy systems) along with real estate market rental prices
        ii. Future policy scenarios
2. **Building archetype energy demand database**
    a. Described in detail in the following, with significant assistance from Empa UESL
3. **Building-level optimization**
    a. WHEN – flexible interventions
        i. Determine flexible windows of opportunity using the Schroeder method of component degradation based on natural renovation cycles. This is used to constrain the years to optimize for.
    b. WHAT – technical retrofit potential
        i. Adapt MANGO to also include a retrofit potential based on relevant energy demands - MANGOret. We optimize each building with at least a 30-year horizon (e.g. 2020 to 2050) to determine WHAT to do WHEN based on the interdependency of component retrofits (reducing demand) and energy system improvements. We typically optimize at the most granularity in 5-year time steps (called stages).
            1. This outputs a Pareto front of circa 5 options of 30 year plans for the building retrofit and energy system development on a cost vs. CO_2 vs. value spectrum.
4. **Portfolio-level optimization**
    a. While the building-level optimization is done for each building in a portfolio, the portfolio-level loop has different constraints such as total budget per year (portfolio solvency), number of retrofits per year (manpower), etc. Thus, we need to prioritize building-level solutions to determine a 30-year decarbonization pathway.
5. **Incorporating uncertainty**
    a. Generally optimization models are first developed deterministically as uncertainty can add significant computational constraints. While we have not fully determined how to incorporate parametric uncertainty, we will likely utilize Monte Carlo simulations based on PERT distributions of all parameters. Policy and climate scenarios will be modeled as such with various constraints based on the quantified scenarios.

At the time of writing, we have successfully completed steps 1, 2, and 3.a, with active development on 3.b and 4. Step 5 is currently less clear due to computational constraints relating to steps 3 and 4, but will be addressed in due time.

Step 1 – Input data

Step 1 has been accumulated over the past year from our main LSI partner, from Thomas Gürber's semester and Masters theses, and policy scenario stakeholder workshop. The Masters thesis served as an initial conceptual venture into building valuation methodologies as a critical aspect for retrofit evaluation for LSIs, a key finding from WP1. Further, we demonstrated the value of retrofit decision-making under various uncertainties such as policy scenarios (from stakeholder workshop), real estate markets, along with techno-economic and context parameters. This thesis was done in partnership with the leading Swiss real estate valuation firm Wuest Partner (as part of the PACE REFITS project). All data is structured to be utilized in the adapted MANGOret optimization model.

Step 2 - Building archetype energy demand database

We refer to Step 2 in the long-form as a temporal, spatial, and retrofit-specific Swiss building energy demand database with an hourly resolution.

Since our goal is to create a scalable method for optimal retrofitting planning for any Swiss real estate portfolio, down to the building-level, we need hourly energy demand profiles (heating, cooling, electricity) across different retrofitting scenarios for the particular building. Such high-resolution data is not available, especially considering how this could change over time considering, for example, climate change scenarios.

As reliable input data, ETHZ SusTec and Empa UESL have created 2,124 Swiss building archetypes based on several databases - 16 building types, 7 Swiss location zones, 9 age categories (archetype = building type + location zone + age category). Empa UESL was responsible for developing these archetypes using a clustering method applied across Swiss building stock data extracted from multiple databases (GWS[2], STATENT[3], and OpenStreetMap[4]). According to the applied method, buildings are clustered based on their location, type, age floor area and occupants/employees. The clusters are identified using the k-medoids technique, which identifies a maximally representative building for each cluster, and assigns this as the archetype. Lastly, a k-Nearest Neighbors classification algorithm is trained to assign each building of a certain location, type and age category to the nearest centroid (archetype).

SusTec have simulated these archetypes with EnergyPlus (EnergyPlus, 2020) from 2020-2060 (10 year time-steps), over 8 retrofitting scenarios, 2 retrofit depths (minimum, target) and 3 climate change scenarios (RCPs 2.6, 4.5, and 8.5). All optimization model runs were performed on the Euler cluster managed by the HPC team at ETH Zurich.

Importantly, we can match any Swiss building to an archetype through the clustering parameters and then scale the archetypal energy demands by the ratio of floor areas between the (building / archetype). This database is completed and functional for usage in Step 3. An example of the data richness of the database is shown for one building for RCP 2.6 in Figure 3.

[2] https://www.bfs.admin.ch/bfs/de/home/statistiken/bau-wohnungswesen/erhebungen/gws2009.html

[3] https://www.bfs.admin.ch/bfs/de/home/statistiken/industrie-dienstleistungen/erhebungen/statent.html

[4] https://www.openstreetmap.org/

Step 3 - Building-level optimization

First, we start when Step 3.a. (WHEN). To determine when to conduct a retrofit project, a method is needed to screen ‘windows of opportunity’ for interventions. Generally, property and asset managers use some sort of component lifetime degradation method to plan when each relevant component needs to be replaced. The method outlined by Schroeder (Schroeder, 1989) is used widely in the real estate industry for supporting strategic maintenance and renovation decisions for mixed-use portfolios (Christen et al., 2014). Here, we utilize this to ‘screen’ windows of opportunity to constrain the optimization.

Step 3.b. (WHAT) relating to the technical retrofit potential of the building is under active development. Further, Steps 4 and 5 are under development.

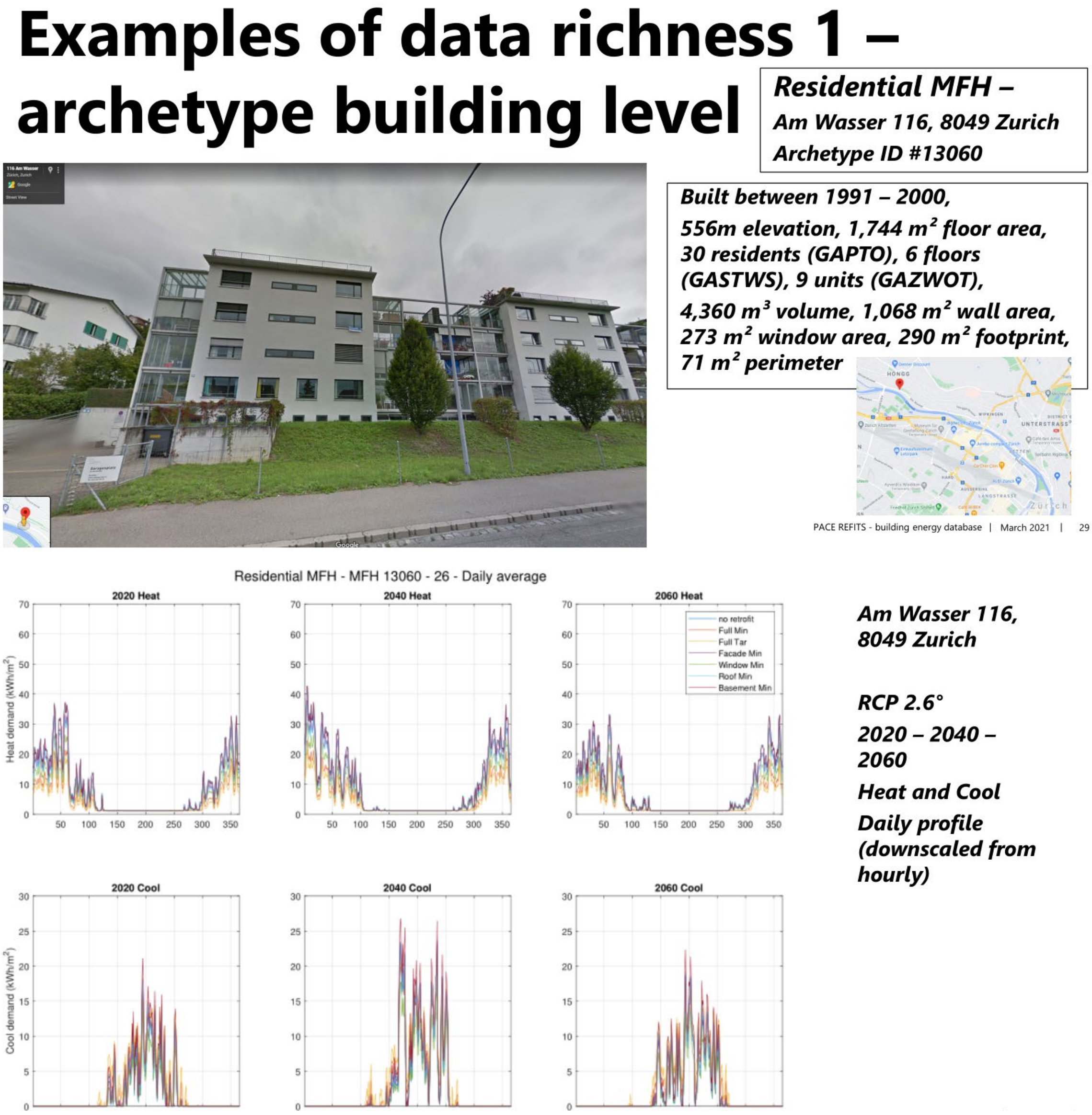


Figure 4: Example of database data richness for a residential MFH building in Zurich, with RCP 2.6 (also 4.5 and 8.5 available) demands shown for various retrofitting scenarios over the years 2020, 2040, 2060.

Work Package 3

As previously mentioned, the MANGO model will be utilized for WPs 2 and 3. While we do not have analytical results on Paper 3.2, relating to the trade-offs of centralized (district networks) vs. decentralized (individual buildings) heating systems, we present high-level results for the case study in (Mavromatidis & Petkov, 2021).

The envisioned energy system for the case study urban district is composed of three decentralized multi-energy systems (D-MES), each of which will be installed at one respective site and will supply the site's buildings with thermal and electrical energy to cover their heat (space heating and hot water) and electricity (appliances, lighting and air-conditioning) demands. The technology portfolio that is considered for each site's D-MES are given in a superstructure representation in Figure 2.

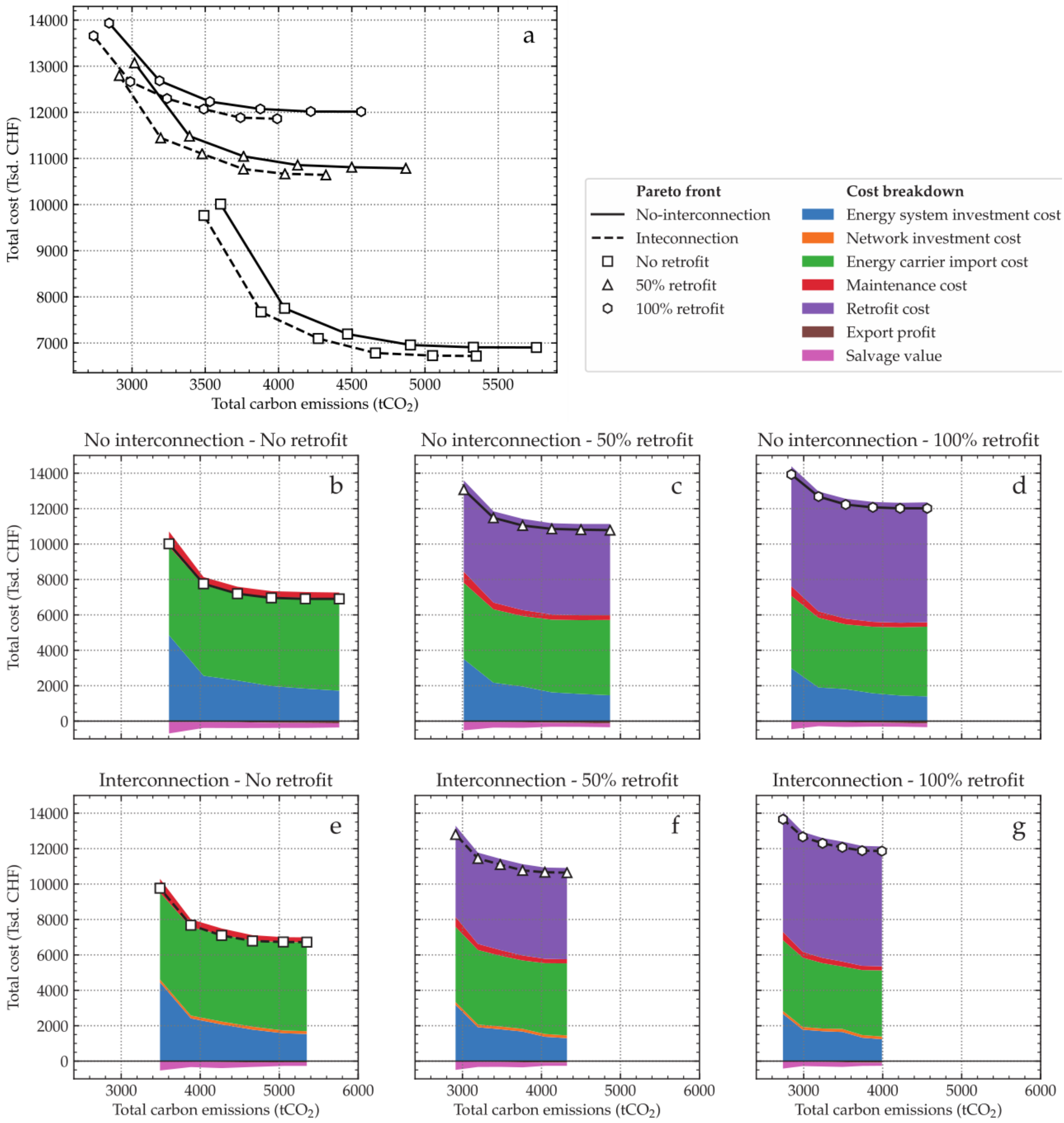


Figure 5: (a) Pareto front illustrating the total system cost and CO_2 emissions for the optimal D-MES designs in the six interconnection–retrofit scenarios. (b-g) Breakdown of total system costs along the Pareto front for the six scenarios.

In terms of conversion technologies, the candidate technologies include electrically-driven air-source heat pumps (ASHP), ground-source heat pumps (GSHP), natural gas and biomass boilers, and gas-fired combined heat and power (CHP) engines. In terms of renewable energy technologies, photovoltaic (PV) panels are considered. Additionally, hot water thermal storage tanks and lithium-ion batteries are considered to store thermal and electrical energy, respectively. Each D-MES can import biomass from external sources and is connected to the natural gas and the electricity grid, allowing for imports of natural gas and imports and exports of electricity. Finally, the option for interconnecting the three D-MES is also included in the case study to consider the possibility of sharing resources and ex- changing energy during low energy demand times at one site and high energy demand times at another.

Results overall show that retrofitting leads to lower emission levels, but significantly higher costs. On the other hand, district heating network interconnections improve both the economic and the environmental system performance. Finally, regarding optimal decentralized multi-energy system configurations, a variety of technologies is used, with combinations of air-source heat pumps and natural gas boilers leading to better economic performance and combinations of ground-source heat pumps and biomass boilers to more environmentally-friendly designs.

Figure 5a presents optimal Pareto fronts for all retrofit and interconnection scenarios that illustrate the direct trade-offs between D-MES costs and CO_2 emissions. Overall, in all cases, starting from the cost-optimal point, emission reductions can be achieved with small increases in the total system cost. For instance, for an emission reduction of approximately 20%, costs increase 2–5.5% in all scenarios. However, CO_2-optimal points lead to sharp cost increases that are 15% higher than the cost-optimal points in the case of the '100% retrofit' scenarios and even 45% higher in the 'No retrofit' scenarios. The influence of interconnections and retrofitting on the system cost and emissions is further illustrated in Figure 5b-g, which show the breakdown of costs across all Pareto points and scenarios. Across the same interconnection scenarios, retrofitting leads to reductions of the D-MES-related costs, which are, however, offset and exceeded by the retrofit costs themselves, leading to overall increased costs. Under the same retrofit scenario, however, allowing D-MES interconnections adds a comparatively low cost for the network technologies, but, by reducing primarily the investment costs, leads to overall lower system costs and CO_2 emissions. Finally, across all cases, the energy carrier import costs are the most dominant D-MES cost category, responsible for 50% to 75% of the total system cost (excl. retrofit cost) across all cases, followed by the energy technology investment costs, which correspond to 23% to 48% of the total system cost (excl. retrofit cost).

Besides the overall economic and environmental performance of the studied systems, MANGO, with its multi-year perspective, also provides information regarding the evolution of the system costs. For a few selected scenarios, Figure 6 presents the evolution of the operating costs and revenues for the D-MES of all sites and the yearly retrofit costs for site A.

Overall, MANGO facilitates decentralized multi-energy system decision-making at the strategic level by delivering flexible multi-stage investment strategies, at the economic level by providing detailed information about the systems' economic performance during each project year and, finally, at the technical level by specifying the optimal technical configurations of each decentralized multi-energy system and their optimal operating schedules. With its long-term perspective, MANGO can offer insights that closely match the dynamic class of real-world energy system design projects led by energy developers.

For WP3, MANGO will be further adapted to include the building-level retrofitting aspects from WP2 (MANGOret) with a real-world case study to answer the research question. Empa UESL is in the process of collecting and preparing the data for this case study, which will focus on the city of Chur, Switzerland. In parallel, Empa UESL has been further developing an alternative building simulation and multi-energy systems optimization toolchain based on its building stock linked data platform, CESAR-P software and

Ehub Tool software. This toolchain, which builds on similar methods but in certain cases different assumptions with respect to MANGO and MANGOret, will be applied in WP3 to the Chur case study. Comparison of the results from Empa's toolchain with those of MANGO will facilitate better understanding of the effects of model uncertainties, and aid identification of critical assumptions in retrofit modelling and D-MES optimization.

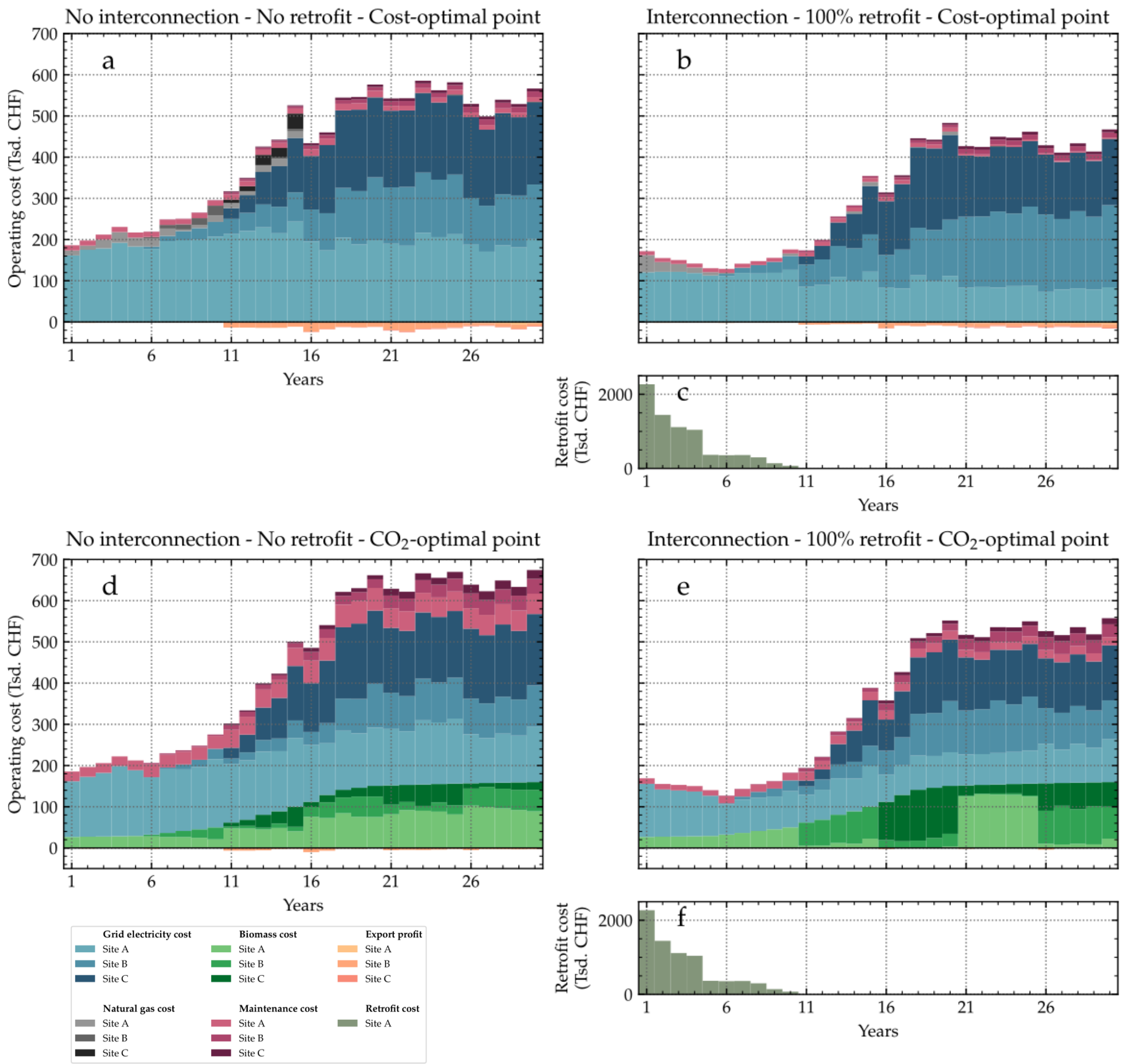


Figure 6: Operating (a-b, d-e) and retrofit costs (c, f) over the 30-year planning period for two interconnection–retrofit scenarios and for the cost- and CO_2 optimal Pareto points. The costs in this figure correspond to nominal, undiscounted expenditures

4 Evaluation of results to date

Project progress thus far is going according to the timeline, with all major checkpoints met. Specifically, the results from WP1 have been finalized with a paper submission. Interestingly, a new project part of PACE REFITS has sprouted to test the efficacy of building energy policy incentives due to advantageous data availability from a cantonal energy department.

Relating to WPs 2 and 3, we have advanced at key points in the novel methodological development. Further, the archetypal energy demand database is complete. Currently there are no direct analytical results for these WPs, although we are able to present model capabilities with the utilized case study.

Major project risks, especially with the difficulty in making industry partnerships, have been managed accordingly and allow sufficient progress. This mainly involved gathering interview data along with relevant case study data for WPs 2 and 3. For WP2, we have secured a significant amount of data relating to buildings from an LSI.

Learnings and advancements on the conceptual and modeling sides are complementary allowing for a cohesive relationship between WPs 1 and 2. Specifically, the major gaps in LSIs' retrofit decision-making processes such as the lack of integrated retrofit multi-year planning processes are addressed in the methodological developments of WP2. There is potential for commercialization of the tool which is being explored, but due to active prototyping cannot be commented on further.

Work Package 1

The results of this WP have been finalized with the policy stakeholder workshop held in September 2020 and the interview campaign finalizing in November 2020, concluding in a paper submission in April 2021.

WP1 results were presented in the following outlets:

- December 1, 2020: "Decarbonizing real estate: the interplay of energy retrofit decision-making and policy", GreenBuzz Zurich: Sustainable Buildings - Making Retrofitting the New New! (I. Petkov).
- November 2-4, 2020: "Large-scale investors' decision-making strategies for portfolio-level energy retrofitting", Poster at the Beyond2020 World Sustainable Built Environment Conference, Gothenburg, Sweden (digital). (I., Petkov, C. Knoeri). The poster can be found here.

Work Package 2

The methodological development of this WP is progressing, with the WHY and WHAT questions about the model already answered. Due to the advanced stages of the prototype, we are nearly finalizing HOW to formulate this increasingly complex model. Market potential for the method has been demonstrated as we received significant interest from various players to industry to get access to the method, particularly in the stakeholder workshop and presentation:

- March 25, 2021: Decarbonizing real estate portfolios: Optimal retrofit investment planning", Innovationspark Zentralschweiz – Building Excellence (I. Petkov).

We completed a major aspect of the data backbone of MANGOret from the completed semester thesis by Thomas Gürber on: "*Uncertainty characterization of building-level retrofitting technologies - a Swiss case study*", and the database of energy demand profiles in collaboration with Empa UESL.

The uncertainty database includes a robust database framework for retrofitting technologies for a Swiss scope, which will be used in the RO model. Importantly, we have also received and completed analysis on the first package of building portfolio data from our main LSI project partner and are beginning to analyze and incorporate the data.

Work Package 3

Since WP3 is split into a methods and case study papers, Paper 3.1 was published in February 2021 (Mavromatidis & Petkov, 2021). We have had a new Masters student (Alicia Lerbinger) start in May 2021 on the retrofitting-specific research questions of WP3. We are determining the best case study for this WP, due to intensive data requirements for a district-scale study which is assisted by Empa UESL.

5 Next steps

The goal for the remaining of 2021 is to nearly finalize all WP results before project end in summer 2022:

- Publish Paper 1 (WP1), potentially along with a practitioner article.
- Submit paper on building energy policy incentive efficacy.
- Complete the fully functional models for WPs 2 and 3.
- Rigorously test the WP2 model with LSI partners to verify results after the prototype is complete, submit the Paper 2 before end of year.
- Complete preliminary case studies for WP3 with the new Masters student. At end of year have a working paper draft of Paper 3.2.

6 National and international cooperation

Research collaboration with the Empa UESL is on-going 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 is 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.

7 Communication

The main communication about the research project happened so far through our research and industry collaboration but will be broadened by practitioner articles ones the results are established. Newsletters have been sent out to update on project developments and Board meeting announcements. Further, presentations have been given at industry networks such as Innovationspark Zentralschweiz and GreenBuzz Zurich.

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