



ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE
LABORATORY OF INDUSTRIAL PROCESS AND ENERGY SYSTEMS ENGINEERING
(IPESE)

Performance gap in the building sector and its impact on investment decisions for heating requirements

MASTER THESIS
ELECTRICAL AND ELECTRONIC SECTION
ENERGY SCIENCE AND TECHNOLOGY

Lara Carole Nadège BERNATH
Supervisor: Cédric TERRIER
Direction: François MARÉCHAL
Expert: Sergi AGUACIL
EPFL Wallis February 2, 2024

Abstract

Between the ideal and reality lies the decisive world of the *performance gap*. This project is conducted within the framework of a Master Thesis at the Industrial Processes and Energy Systems Engineering (IPESE) laboratory of Ecole Polytechnique Fédérale de Lausanne (EPFL). The objective is to evaluate the energy performance gap, with a static approach, of the building sector and understand its impact on the global energy system in the context of energy transition. The challenge lies in the conservative assumptions regarding the thermal transmission coefficients and construction details of existing buildings in modelling tools. This study is based on two detailed surveys, one on swiss architectural elements[1] and the other on new thermal transmission coefficient ranges[2]. A methodology is designed and integrated to the existing optimization model: *Renewable Energy Hub Optimizer* (REHO) for different types of buildings, each having particular features. The idea is to integrate to the REHO model a static approach by varying the thermal transmission coefficients and develop a new method concerning the link between the thermal envelope and energy reference area. In result, the impact of the thermal envelope and the form factor of buildings on space heating requirements is researched. The investment and operation uncertainties resulting from the modelling gap are assessed. Finally, the static model developed in this study is compared with a regulatory approach and real on site data from a clustered neighbourhood in Geneva. The results show an improvement of 13,4 % with a change of method.

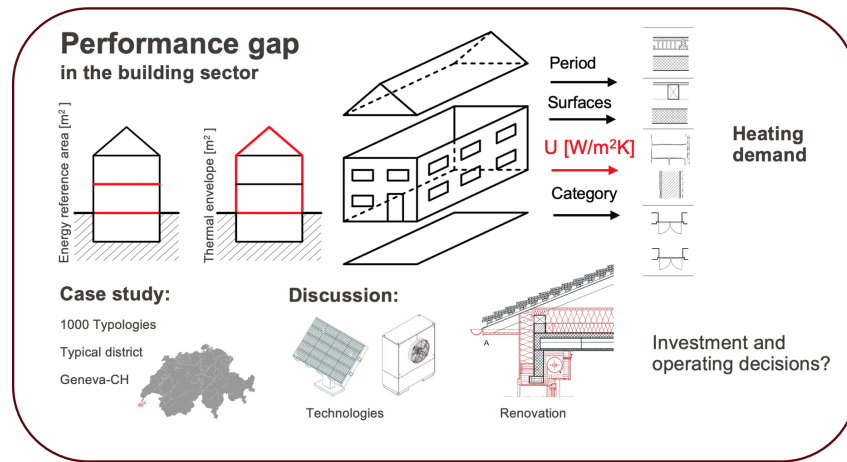


Figure 1: Graphical abstract

Acknowledgements

This master thesis has been done under the supervision of Mr. Cédric Terrier, I could not have wished for a better guidance, thank you for your time, your precious help and everything you have taught me. Thank you aswell to professor François Maréchal for giving me the opportunity to work in the IPESE laboratory and on this project. Thanks to all the colleagues of IPESE lab for all the fun work lunches and a special thank you to Joseph, a great friend and support during this master thesis.

Contents

1	Introduction	3
1.1	Context	3
1.2	Problem statement	4
2	Literature review	5
2.1	Performance gap	5
2.2	Standards for heating requirements	7
2.3	Architectural identity	9
3	Methodology	11
3.1	Overview	11
3.2	Performance Gap: Uncertainty Assessment	12
3.3	Heat transmission coefficient estimation	13
3.4	Modeling - Energy reference area and thermal envelope	15
3.5	Case study	17
3.5.1	Building Archetypes	17
3.5.2	Archetypes for the comparison between static and regulatory models	18
3.5.3	Typical buildings	19
4	Results and discussion	21
4.1	Identification of building energy system configuration trends	21
4.2	Quasi-Monte Carlo on multi-family and single-family categories	24
4.3	Performance gap and uncertainties of regulatory and static models	25
5	Conclusion	30
A	Appendix	31

Abbreviation	Definition
REHO	Renewable Energy Hub Optimizer
SIA	Swiss society of engineers and Architects
ERA	Energy Reference Area
IDC	Heat expenditure Index
CEB	Building Energy Concept
CECB	Cantonal Energy Certificate for Buildings
MoPec	Model energy regulations for cantons
LHS	Latin Hypercube Sampling
qMC	quasi-Monte Carlo
DHW	Domestic Hot Water
SH	Space Heating
PCA	Principal Component Analysis
PV	PhotoVoltaic
HP	Heat Pump
NG	Natural Gas
RMSE	Root Mean Square Error
GWP	Global Warming Potential
σ	Standard deviation

Table 1: Nomenclature

1 Introduction

1.1 Context

Climate change, resource scarcity, loss of biodiversity, there are numerous factors showing that modern and rich societies need to change consumption behaviors as well as provisioning systems. The building sector contributes substantially to those environmental risks, from the construction, utilization and end of life of building structures. In Switzerland, this sector represents on third of the total CO₂ emissions and 40 % of the total end-energy demand [3]. In the context of the energy transition and a sustainable future, optimising our energy consumption is urgent. Energy efficiency and integration of green energy in the building sector is an urgent matter.

It is well known, that building renovation is a major contribution for reducing the environmental impacts associated within the construction sector [4]. In Switzerland, the annual rate of renovation improving the energy performance for existing buildings is around 1% [5] [6]. This number needs to be at least doubled to reach the goals of Energy Strategy 2050 on time. There is a lack of interest for energy renovations mainly because it represents a considerable investment [7]. Furthermore, property owners often lack a precise assessment of the energy quality of their building and buildings undergoing extensive renovations are typically uninhabitable during the construction phase [8]. Moreover, there appears to be a challenge within energy policies to adequately recognize the practical realities on the ground and to effectively implement measures in this domain. The first SIA¹ recommendations for energy savings were issued after the oil crisis in 1973 and followed by cantonal requirements [9][1]. In 1998 the first federal law regarding energy regulation in buildings was put into place. Nowadays in the context of climate emergency and the geo-politic context high energy standards are required for new building constructions. In contrasts, for existing structures, owners are under no strict regulations to renovate their property energy wise and lack information about financial incentives they are entitled to receive [10]. This is why renovating and optimizing existing structures, considering their larger number and lack of strict regulations has a high potential for effective improvements in the energy sector.

Various strategies are implemented to reduce the impact of buildings in terms of their demand for fossil energy [11]. These encompass technical solutions such as integrating solar panels, upgrading heating systems and ventilation. Architectural improvements, including effective building insulation, smart space utilization and material use. Additionally, social initiatives, such as promoting behavioral shifts or incentive of self-consumption during green energy production, play a crucial role in minimizing consumption. Governments, engineers, and architects are actively engaging in implementing these measures and assessing their impact. Governments play a pivotal role in establishing the legal framework for standardized energy-efficient practices. A significant challenge emerges in the form of the *performance gap* - the disparity between calculated and implemented measures [12]. Understanding and addressing the performance gap is imperative for informed decision-making in designing energy policies that align with the realities on the field and acknowledge uncertainties inherent in modeling [13]. It is expected that a better understanding of this gap for existing buildings will enable more targeted and therefore more cost-effective refurbishments and accelerate the

¹Swiss Society of Engineers and Architects

decarbonization of the building stock as a whole.

1.2 Problem statement

In Switzerland a third of the final energy consumption is allocated for heating and domestic hot water needs in the building sector [14]. Given the substantial energy consumption, it is crucial not only to enhance energy efficiency but also to improve energy conservation within the building. This becomes particularly essential because of the significant performance gap observed in heating requirements. According to recent studies[15], the actual heating energy consumption for old buildings is considerably overestimated by energy models. The risk is installing technologies that are not properly sized for the needs. On the other hand, the heating demand tend to be underestimated for renovated buildings, preventing an accurate prioritization of refurbishment measures in regard to their cost-effectiveness or CO₂ reduction potential. The main issue of the study is to examine the factors and parameters contributing to the disparity between measured energy consumption and calculated values. This understanding is crucial for refining calculations, improving predictions, and anticipating future scenarios more accurately. In essence, the study centers on the performance gap in the building sector and its impact on investment decisions for heating requirements.

2 Literature review

2.1 Performance gap

The concept of performance gap covers diverse industries and systems, highlighting the variance between anticipated or modeled performance and the actual realized outcomes [16][17]. Within the building sector, the energy performance gap focuses on the difference between the expected energy efficiency calculated during planning stages and the actual energy performance observed in operation of buildings [18].

It is crucial to acknowledge that the performance gap is not a tangible reality but rather a metric stemming from the conceptualization of the real world within a virtual context. To comprehend this disparity, three interpretations are introduced of how the calculated energy consumption in the building sector is modeled and compared to reality [19]:

- The regulatory performance gap: Compares the performance of a building under standardized national conditions. It relies on default building model values defined in norms. It assesses influences of the national assessment procedure on the performance gap.
- The static performance gap: Compares predictions from more complex performance modeling to measured energy use, is built to overcome limitations of norms by using realistic building conditions. Utilizes building performance simulation models that consider actual operating conditions.
- The dynamic performance gap: Compares predictions from an advanced, calibrated, dynamic building model to measured energy use, taking into account time-dynamic properties of the building. It requires calibration over several years using in-situ measurements to refine the model with actual operating conditions

While the regulatory model focuses on meeting national standards, the static and dynamic models provide more detailed analyses, considering different aspects of a building's life and operation. This allows for a more nuanced understanding of how the building performs under real-world conditions. Since most studies about the performance gap use a regulatory approach, the reality of the field is not well represented. The modelling tool plays a significant role when calculating buildings energy demand. For instance with the same input and different models, two computer programs (Lesosai and dynamic IDA ICE) showed a 15% difference in the yearly heating requirements[20]. Models and standards for heating requirements will be further discussed in the next section (2.2)

While the concept of energy performance gap highlights the limitations of models in accurately representing certain realities, its manifestation in the building sector involves various components influencing this energy performance. In the context of this study, a particular focus is directed towards space heating (SH) and domestic hot water systems (DHW). These aspects play a pivotal role in the overall energy dynamics of buildings. The components influencing SH and DHW can be classified into different types of gaps, each revealing a specific aspect [15]:

- Behavioral gap : Arises from disparities between the users behavior assumed in the model and the actual behavior. For instance, deviations may occur if users heat rooms at higher temperatures or open windows more frequently than anticipated in the model.

- Technical gap : Is due to the fact that the building is not completely built and operated according to plan. For instance, poorly adjusted heat pumps or false assumptions regarding insulation may lead to discrepancies between the model and actual conditions.
- Climate gap : Is due to the assumed weather conditions of the model and the real weather. For instance if the winter is warmer than expected by the model.
- Modeling gap : The calculation tool does not perfectly represent reality. This gap is inherent to the limitations of the calculation tool itself . Unlike the other factors it is not the data input in the model but the model itself. For instance there is a variety of modeling tools whose calculations result differ.

These categories represent the various factors that contribute to the energy performance gap in the building sector and can lead to the measured differences. The most influential factor for new building constructions is the behavioural gap [15] and for existing buildings it is the technical gap [2].

As mentioned, older buildings with poor thermal insulation tend to have an actual consumption that is lower than their theoretical needs [2]. This is primarily caused by conservative assumptions regarding the thermal transmission coefficients of old buildings (technical gap). On the other hand, heating requirements are underestimated in buildings that have undergone thermal renovation due to unrealistic assumptions regarding user behavior (room temperatures, use of blinds and ventilation). The combination of these two performance gaps in old buildings results in an overestimation of the heating savings actually achieved through building renovations. Therefore, it is preventing an accurate prioritization of investment decisions in regard to their cost-effectiveness or CO₂ reduction potential. To prioritize the most impactful renovations, it is crucial to precisely identify and understand these performance gaps. This ensures that renovations aligning with the intended impact are not overlooked, facilitating a more accurate allocation of resources and efforts.

The assumed users behavior is an important parameter, it determines the temperatures set in the rooms, how often the windows are opened or how often the blinds are closed. In Switzerland, when calculating the heating requirements for the building permit, standard behavior are used according to SIA norms. The standard requirement calculated is then compared with legal limit values. The understanding of the behavioral gap is thus based on these requirements and how they are computed. The different values for heating demand are defined in the SIA 380/1 [21], and, depending on the canton, different requirements are requested for the building permit. It appears that for new building constructions with high energy standards, additional technical improvements to the building envelope leads to lower real savings, as the user and their behavior are the relevant factors in thermally efficient buildings [15]. This example underscores the inadequacy of current energy policies mistargeting the real energy reduction improvements. Energy policies should address social aspects, recognizing that meaningful energy reduction improvements require not only technical measures but also targeted information campaigns and social measures.

The issue with the standards from the SIA 380/1 is that they are constrained to a single value with no range of uncertainties. In reality there exist a range of thermal coefficients within the building stock and this diversity is in the heart of the understanding the energy

performance gap. For a more accurate estimation of the real future demand, it is necessary to calculate the demand by adjusting the input data to more relevant transmission coefficients. Standards should be more representative of the reality and provide a range of values for the buildings thermal envelope.

Construction techniques through time and trends can be very valuable to identify thermal properties of the materials used. Various studies show that within the building sector the performance gap is different between the building types. Buildings types can be categorised as industries, as services or as part of the housing sector. The housing sector is especially studied since it represents the largest portion of the building sector. For instance in 2020, in Geneva, the housing sector represented 73% of the buildings land use, the buildings used for services represented 12% and the buildings used for industry accounted for 15% [22]. In addition, within the housing sector, there is a distinction between single or multifamily houses. In fact, regardless of the average for all buildings, individual buildings have very high consumption levels and in some cases massively exceed the limit values [15]. The distinction between the different categories are due to their function, architectural identity and how the space is used.

Performance gap	Existing build.	Const. trends	Uncertainties	Reference
Regulatory	✓	✗	✗	[19]
Regulatory	✗	✗	✗	[23]
Regulatory	✗	✗	✗	[24]
Regulatory	✓	✗	✗	[25]
Regulatory	✗	✗	✗	[26]
Static	✓	✗	✓	[2]
/	✓	✓	✗	[1]
Static	✓	✓	✓	This study

Table 2: Literature review on the performance gap in the building sector in Switzerland and literature on construction elements. *Performance gap* indicates the type of performance gap (if it is assessed): Regulatory, static or dynamic. *Existing build.* indicates if the study takes into account existing buildings or only new constructions. *Const. trends* indicates if construction detail trends are taken in consideration. *Uncertainties* indicates if there is a variability in the values computed for the performance gap

2.2 Standards for heating requirements

In Switzerland, each canton has distinct energy requirements governing construction permits, all based on federal regulations but tailored to their specific needs [27]. Among the Swiss cantons, Geneva outstands in terms of energy legislation, particularly due to the implementation of the heat expenditure index (IDC) [28], making it a pertinent focus for the literature review. One of the issues revealed are the concerns about the effectiveness of the energy certificate in predicting or ensuring the actual energy performance of the buildings. In the study of 65 multifamily buildings, the measured heating consumption were on average 44% higher than the standard requirement in the energy certificate [20]. Indeed the SIA 380/1 is not intended as a predictive tool, but as a benchmark for the authorities.

In the canton of Geneva, the construction of new buildings, their renovation² or their

²Renovation of more than 15% of the above-ground thermal envelope and/or for a change of the heat production system.

extention³ is subject to a building energy concept (CEB) form [29]. This form includes one variant that complies with a high energy performance standard and one that complies with a very high energy performance standard. Both of these standards require to respect either Minergie labels, CECB⁴, MoPEC⁵ SIA standards, or equivalent labels. As visible on Appendix 18, all of these labels require a calculation of the admissible heat expenditure index, IDC given in MJ/m² year. The IDC is calculated by dividing the building's annual thermal energy consumption for space heating and domestic hot water by the the energy reference area (ERA) and is corrected according to climatic data (degree-days) for the considered year [30].

$$\text{IDC [MJ/m}^2\text{.year]} = \frac{(\text{heating} + \text{domestic hot water}) \text{ [MJ/year]}}{\text{ERA [m}^2\text{]}} \quad (1)$$

The higher the IDC, the more energy the building consumes. Since the 1st. September, 2022, a new regulatory standard has set the limit of IDC to 450 [MJ/m².yr][31]. The limit is set to encourage the construction and renovation of more energy-efficient buildings and a gradual reduction is set for the long term. The ERA is widely used for heating requirements, not only for the IDC but also for dimensioning of radiators, underfloor heating or heat pump capacity. The ERA is calculated in accordance with SIA standard 380 [32], it is the sum of all the areas of floors and basements included in the building's thermal envelope, and whose use requires conditioning. A room requiring conditioning is a room that has a defined indoor climate (temperature and/or humidity). Actively heated rooms such as living room, bedrooms, kitchen and bathrooms are instinctively part of the energy reference area. Unheated ancillary rooms within the insulated perimeter, such as stairwells and corridors, are also included in the ERA but laundry rooms, technical rooms, garages, storage rooms, attics and warehouses are not considered in the ERA[33].

To qualify for the Minergie label, there are two accepted labels for the construction permits in Geneva: Minergie[®]P-Eco or Minergie[®]A [34]. They comply for buildings with low levels of energy consumption due to a performing building envelope and above average requirements for energy efficiency. Maximum energy independence is also a parameter, based on optimised building systems technology and , for instance, installation of photovoltaic panels. Other parameters are also taken into consideration like healthy and green building materials, sustainable construction and a maximum of comfort. For both categories of the Minergie label, the thermal requirements are calculated on the base of the thermal envelope by performing a CECB. The CECB certification indicates the quality of a building's envelope and overall energy balance, as well as its direct CO₂ emissions. The evaluation is conducted on a graded scale from A to G, providing a standardized representation of the building's energy performance[35]. Among the regulations for the construction, renovation or extension of buildings the MoPEC is also a reference. It is a set of energy regulations drawn up jointly by the cantons on the basis of their experience in building implementation can also lead to a construction permit (Appendix 18). The SIA 380/1 is still in the heart of the regulations for the thermal envelope and most forms are based on it: EN-102a or even for modeling tools like Lesosai [36]. The thermal envelope is modeled with the previously mentioned thermal transmission coefficient (U-Values and b-values).

³Extention representing more than 15% of the energy reference area (ERA) of the existing building or exceeding 500m².

⁴CECB: Cantonal energy certificate for buildings

⁵MoPEC: Model energy regulations for cantons

The thermal envelope is defined as the boundary of the building, which protects the thermal and acoustic comfort of its interiors. It is made up of walls, floors and ceilings (roof). These elements are also implemented by punctual operable elements: doors and windows. The uniformity of the thermal envelope is broken by thermal bridges, which are characterized by geometric variations or material transitions that facilitate the passage of heat. This assembly of construction elements constitute the thermal envelope of a building and are all defined by a transmission coefficient (U-value). The general formula for calculating the U-Value is:

$$U \text{ [W/m}^2\cdot\text{K]} = \frac{1}{R_t} \quad (2)$$

With R_t , the total thermal resistance of the element composed of layers:

$$R_t \text{ [m}^2\cdot\text{K/W]} = R_{si} + R_1 + R_2 + \dots + R_n + R_{se} \quad (3)$$

R_{si} and R_{se} are thermal resistances of the interior and exterior surfaces, that depend on the climatic zone. Individually each thermal resistance R is defined by:

$$R = \frac{\text{Material thickness [m]}}{\text{Thermal conductivity of the material [W/K}\cdot\text{m]}} \quad (4)$$

Each element of the thermal envelope have specific qualities that are decisive in the thermal behavior of buildings as a whole. This U value lies in the heart of all the thermal modeling systems previously mentioned. They can be modeled from scratch, by assembling each composition of material with its own performance and outside perturbation. They can be indicated on the data sheet of the material or a default value from norms.

The calculations for heating requirements in building constructions require the evaluation of the energy refence area (ERA) and the Thermal envelope. It is in the center of all the models and standards, and are unique for each building . Both these factors rely on the design of the building and the intrinsic properties of the materials. These properties vary across urban characteristics, affectations of the rooms, the identity of architectural elements and of course the dimension of the building. In the following section, the identity of architectural elements are described.

2.3 Architectural identity

The architectural heritage of a city is influenced by various factors including technological advance, cultural choices, environment, material availability, knowledge and construction laws. The architectural identity of a building is the result of all these factors and on a larger scale they define also districts and cities. The structures and buildings preserved, maintained or modified over time are the memory of their context in that timeframe. To analyse the urban areas, understand the aggregation of construction elements, and their materiality it is necessary to gather information about the historical evolution of that area in the construction sector.

The constructive details trends for the French-speaking Switzerland are identified with the help of surveys, scientific reports [15], architecture treatise[37] and the work carried out on the building envelope by experts and scientists [1][38]. Until 1920, traditional architectural

elements of the facade were primary out of massive stone with thicknesses ranging from 45 to 70 centimeters. The use of natural stone involved simple carving techniques but solid walls were also made of rubble stone or bricks. For floors and roofs, wood was used extensively. The structural composition of floors required wood due to its flexibility and traction properties, while roofs utilized wood for its suitability in managing slopes and intricate carpentry. From the beginning of the 20th century, under the economic expansion and the demographic push, the introduction of reinforced concrete led to a revolution in construction [39]. The static properties of armed concrete were demonstrated by numerous applications and its cost-effective application contributed to its rapid spreading. Bridges, railway structures and complex infrastructures were the first application of concrete. Before concrete became a dominant structure in housing, cement slabs and hourdis were the main elements for basement slabs. From 1920-1945, the architectural trends were modernism, simplicity and functionalism. The use of concrete became more and more widespread in housing and the first flat roofs appeared as precursors. Nevertheless, the traditional sloped roof were still the most common. The thickness of walls was progressively reduced and the hollow bricks were the most common for their better thermal properties and less material usage. After the war (1945), Switzerland experienced an economic prosperity reflected in the urban structure of the city. In housing, concrete became a dominant structure for floors. The facades of the buildings became even thinner thanks to the principle of the "air gap"⁶ between the walls improving the thermal properties of the building while using less material. The roof slopes were lowered, the attics were no longer habitable and the reduced space was used as a buffer space. In the Seventies, the oil crisis encouraged energy savings and the first SIA recommendations (180 ed. 1970) on *thermal insulation of buildings* was introduced [9]. At this time the mineral fiber insulation gradually replaces the "air gap". The facades in prefabricated concrete make their appearance in the Sixties, followed by the facades in poured concrete in the Seventies, used in high buildings. In 1985, models for heat requirements were standardized and in 1998 the first federal energy law was passed. The label *Minergie* has been created in 1998 and became progressively a reference. Nowadays, energy requirements are well-framed for new construction but the construction elements are highly diverse.

Due to the diversity of building elements and construction trends, building modeling and performance gap is highly heterogeneous among the building stock. Since most studies about the performance gap use a regulatory approach, the reality of the field is not accurately represented. Also, existing buildings have significant potential for energy improvement, and there is a lack of incentives and regulations for renovation in the legislation. Finally as pointed out by various studies, there exists a large uncertainty in models that can be overcome by adjusting the input data with more relevant thermal transmission coefficients. Based on the knowledge gaps identified in the literature review, the present report aims at answering the following research questions:

- How does space heating demand vary with the performance of the thermal envelope and form factor of buildings?
- What are the investment and operation uncertainties resulting from a modeling performance gap?
- How does a static model reduce the performance gap compared to a regulatory approach?

⁶The "air gap" is a construction detail also referred to as "ventilated facades"

3 Methodology

3.1 Overview

In order to formulate effective energy-wise recommendations, it is crucial to have tools supporting efficient decision-making. This challenge is being addressed by optimisation models. This project integrates itself into one of these models, the *Renewable Energy Hub Optimizer* (REHO) developed by the IPESE laboratory at EPFL and based on the work by Luc Girardin [40], Paul Stadler [41] and Luise Middelhaue [42]. REHO is an optimization tool for the design and operation of urban energy systems, interconnecting multi-energy streams and conversion units to supply multi-service demands.

The model is a Mixed Integer Linear Programming (MILP) formulation designed to optimize both the design and operations of building and district energy systems. It takes into account three types of energy demands: space heating (SH), domestic hot water (DHW), and electricity. The energy demands are met through two utility grids, natural gas and electricity, and various energy conversion units. The conversion units include air-water heat pumps, gas boilers, electrical heaters, thermal tanks and lithium ion batteries. The MILP formulation, focuses on efficiently investing in conversion units and managing the operation of the energy system. The main constraints include energy balance, mass balance, and heat cascades, compelling the energy system to align the demand with supplies from both utilities and conversion units. More details are available here [42]. Equation 5 explicitly outlines the space heating demand. For all equations, bolded fonts represent decision variables, positive symbols indicate imports and negative symbols exports. The sets considered are: buildings B , layers of energy carriers L , typical periods P , timesteps T , the number of replacements over the time horizon R and the units U . The terms specific to the equation are positioned beneath it.

$$\dot{Q}_{b,p,t}^{SH} = \dot{Q}_{b,p,t}^{gain} - U_b \cdot S_b^{era} \cdot (T_{b,p,t}^{int} - T_{p,t}^{ext}) - C_b \cdot S_b^{era} \cdot (T_{b,p,t+1}^{int} - T_{b,p,t}^{int}) \quad \forall b, p, t \in B, P, T \quad (5)$$

\dot{Q}^{SH} is the space heating, \dot{Q}^{gains} contains the internal and solar heat gains, U is the thermal transmission coefficient, S^{era} is the energy reference area, T is the temperature, C is the thermal capacity of the house.

The main objective function is the total costs (TOTEX). In addition, multi-objective optimization (MOO) is performed between the operating (OPEX) and capital (CAPEX) costs objectives.

$$\underbrace{C^{tot}}_{TOTEX} = \underbrace{C^{op}}_{OPEX} + \underbrace{C^{cap}}_{CAPEX} \quad (6a)$$

$$C^{op} = \sum_{b \in B} (c_{b,l,p,t}^+ \cdot \dot{E}_{b,l,p,t}^{gr,+} - c_{b,l,p,t}^- \cdot \dot{E}_{b,l,p,t}^{gr,-}) \cdot d_p \cdot d_t \quad \forall l, p, t \in L, P, T \quad (6b)$$

c^+ is the electricity and gas retail tariffs and c^- is the feed-in tariff. \dot{E}^{gr} corresponds to the energy exchange from the grid. d_p is the typical day frequency and d_t is the timesteps duration.

$$\mathbf{C}^{cap} = \frac{i(1+i)}{(1+i)^n - 1} (\mathbf{C}^{inv} + \mathbf{C}^{rep}) \quad (6c)$$

n are the years over which the costs are annualised. i is the interest rate.

$$\mathbf{C}^{inv} = \sum_{u \in U} b_u \cdot (i_u^{c1} \cdot \mathbf{y}_u + i_u^{c2} \cdot \mathbf{f}_u) \quad (6d)$$

C^{inv} is the investment cost and is linearized with fixed (i_u^{c1}) and variable (i_u^{c2}) costs. y_u is the binary decision to install a unit or not. f_u is the installed capacity.

$$\mathbf{C}^{rep} = \sum_{u \in U} \sum_{r \in R} \frac{1}{(1+i)^{r \cdot l_u}} \cdot (i_u^{c1} \cdot \mathbf{y}_u + i_u^{c2} \cdot \mathbf{f}_u) \quad (6e)$$

C^{rep} is the replacement cost. l_u is the lifetime of the conversion unit.

Multi-objective optimization is conducted to explore the solution space, navigating the interplay between two conflicting objectives: OPEX and CAPEX. One objective is constrained by an upper limit using an ϵ -constraint, while the other is minimized. The generation of Pareto fronts involves adjusting the ϵ -constraints and swapping the objectives that are constrained and minimized.

REHO requires input data regarding buildings, including parameters like the Energy Reference Area (ERA), building type, and energy needs for domestic electricity and domestic hot water. This information is available in the GIS database *Quantum Buildings*[43], characterizing the urban building stock utilizing datasets available at both national and regional levels. It incorporates information from the Swiss federal register of housing and buildings [44], Sonnendach [45], and the SIA 380/1 standard for heat requirements.

3.2 Performance Gap: Uncertainty Assessment

The optimization model is based on a single heat transfer coefficient U_b , normalized per ERA. To consider architectural details, the following methodology has been applied. The aim is to aggregate the thermal envelope performance $U_b^{th.env}$ to a thermal performance of energy reference area U_b^{era} .

1. Introduce construction elements and uncertainties in their heat transmission coefficient based on [1] and [2].
2. Calculate the transmission coefficient of the thermal envelope based on data from *Quantum building* database
3. Define the relation between the thermal envelope and energy reference area
4. Calculation of the coefficient U_b^{era}

3.3 Heat transmission coefficient estimation

Buildings are composed of versatile structural and architectural elements with non-uniform properties and aggregated differently based on their form factors. To model the thermal envelope, buildings are first decomposed into their main elements: Slab, Facades, Windows and Roof, as depicted on Figure 2. The methodology does not consider doors nor thermal bridges in the modeling of the thermal envelope.

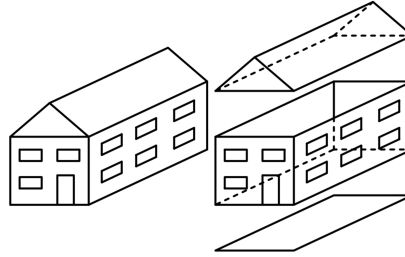


Figure 2: Separation of building elements composing the thermal envelope

Data used for the calculation of the buildings thermal properties is based on two surveys providing a detailed overview of construction elements over time. First, a survey over 193 buildings in the french speaking part of Switzerland is used. This study classified construction elements in relation with their construction period [1] (Appendix 16). Secondly, the survey of 200 energy-related refurbishment projects of the Stadt Zürich proposed new U and b value range to adjust the input data in SIA 380/1 for construction elements [2] (Appendix 17). The assembly these two surveys is summarized on Figure 3. Construction elements with their corresponding U-values are classified depending on the construction year.

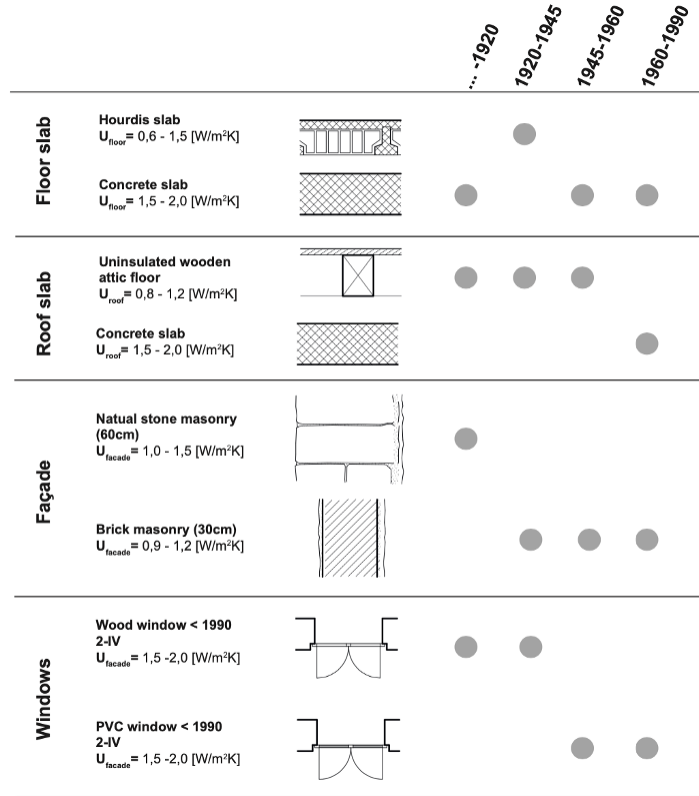


Figure 3: Building elements and their U-values according to the years of construction.

The surfaces corresponding to each construction element are available on the *Quantum Buildings* data. The data in *Quantum Buildings* as $S^{\text{façade}+\text{windows}}$ aggregates opaque walls (façade) and its operable elements (windows). For the integration into the REHO model, the windows and the façade need to be separated. Table 3 gives an overview of the thermal transmission coefficients ranges: U-value, b-value (elements against unheated rooms), g-value (the radiated energy) and the separation between Façade and Window elements, as described in Reference [2].

	-1920	1920-1945	1945-1960	1960-1990	$\eta^{b,g\text{-values}}$
Floor slab	1.5-2.0	0.9-1.5	1.5-2.0	1.5-2.0	0.4-0.7
Roof	0.9-1.35	0.9-1.35	0.9-1.35	1.5-2.0	1
Façade	1.0-1.5	0.9-1.2	0.9-1.2	0.9-1.2	0.4-0.7
Windows	1.5-2.0	1.5-2.0	1.5-2.0	1.5-2.0	0.3-0.6

Table 3: Ranges of U-values, b-values and g-values [2]

The U-values are classified by their construction period and the $\eta^{b,g\text{-values}}$ column (for the b-value and the g-value) considers the same value for each period. Floor slabs are assumed to always be against unheated rooms (basements).

The average U value of the thermal envelope ($U_b^{\text{th.envelope}}$) is computed based on the actual surfaces from *Quantum Buildings*:

$$U_b^{th.envelope} \left[\frac{W}{m^2K} \right] = \frac{(S_b^{windows} \cdot U_b^{windows} + S_b^{facade} \cdot U_b^{facade} + S_b^{slab} \cdot U_b^{slab} + S_b^{roof} \cdot U_b^{roof})}{\underbrace{(S_b^{windows} + S_b^{facade} + S_b^{slab} + S_b^{roof})}_{\text{Surface of the th.envelope [m}^2\text{]}}} \quad (7)$$

With S_x [m²] the surface of each element and U_x [$\frac{W}{m^2K}$] the transmission coefficient, with x the corresponding construction element.

3.4 Modeling - Energy reference area and thermal envelope

As mentioned in chapter 2.2, the ERA and the thermal envelope are essential elements in the context of building energy efficiency and heating requirements. Both of these parameters are expressed in [m²] and are widely used for building energy calculations. The ERA represents the heated floor area while the thermal envelope is the actual thermal boundary of the building with the outdoor environment. The REHO model only uses the ERA for the heating requirements, therefore $U_b^{th.envelope}$ should be reformulated as U_b^{era} .

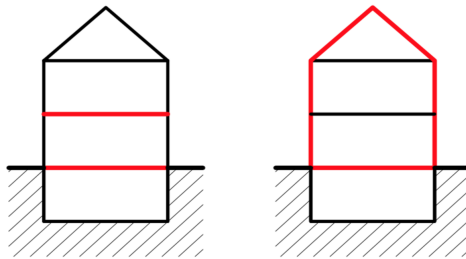


Figure 4: *Left:* The Energy Reference Area. *Right:* The thermal envelope.

Figure 4 illustrates the two factors needed to calculate heating requirements, $S_b^{th.envelope}$ and S_b^{era} . Both of the surfaces are, by definition, in 2D, each representing two visions related to heating requirements. The conflict resides in the fact that a building is a 3D volume and that the actual heated space is also a volume. So there is a dimension missing and the relation between these two factors will be further investigated.

In Figure 5, the ERA data available on *Quantum Buildings* is linked to the thermal envelope as defined in 3.3. The ratio between the two parameters is classified in four different building categories according to the SIA 380. Multi-family is defined by class I; Single-family is defined by class II; Industrial is defined by class IX and Service includes classes III, IV, V, VI, VII, VIII, X, XI and XII.

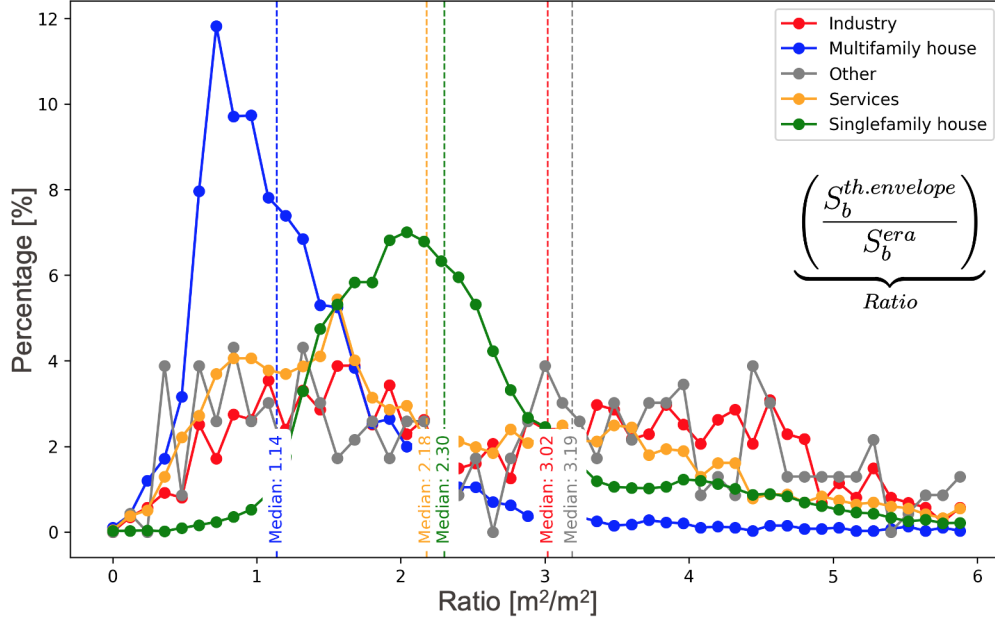


Figure 5: Histogram of Ratio ($S_b^{th.envelope}/S_b^{era}$) for Geneva

Based on the Figure 5, the most relevant ratios for each category are extracted in increments of 0.5. There is a wide range of ratios for each category of buildings. The architectural identity of a building especially affects the housing sector. The Industry and Services are following the same trend and have uniformly distributed ratios. Multifamily buildings observe a peak in their ratio and have a median value of 1.14. This means multi-family buildings tend to have a thermal envelope almost the same size than the ERA. The Single-family buildings also have a peak but shifted with a median value of 2.3. This means that Single-family buildings tend to have a thermal envelope almost twice the size of their ERA. The range of ratios corresponding to each building category is summarized in Table 4

Category	Ratio ($S_b^{th.envelope}/S_b^{era}$)
Multifamily	0.5, 1, 1.5, 2, 2.5
Singlefamily	1, 1.5, 2, 2.5, 3, 3.5, 4, 4.5
Industry and Service	0.5, 1.5, 2.5, 3.5, 4.5, 5.5

Table 4: Extracted Ratio for each building category.

Based on these ratios, the U_b^{era} can be linked to the coefficient $U_b^{th.envelope}$ with the following equation. Therefore, the coefficient U_b^{era} becomes a function of the buildings compactness and of the thermal property of the buildings envelop.

$$U_b^{era} \left[\frac{W}{m^2 K} \right] = U_b^{th.envelope} \cdot \underbrace{\left(\frac{S_b^{th.envelope}}{S_b^{era}} \right)}_{Ratio} \quad (8)$$

The notion of form factor can be broken down according to the architectural elements making up the thermal envelop of the building. Using the same approach as above, the

surfaces of each element can be compared to a single one: the surface of the basement slab (S_b^{slab}).

$$\underbrace{\left(\frac{S_b^{th.envelope}}{S_b^{era}} \right)}_{Ratio} \left[\frac{m^2}{m^2} \right] = \left(\frac{S_b^{roof}}{S_b^{slab}} + \frac{S_b^{facade+windows}}{S_b^{slab}} + \frac{S_b^{slab}}{S_b^{slab}} \right) \cdot \frac{S_b^{slab}}{S_b^{era}} \quad (9)$$

The building categories greatly impact the ratio due to their architectural identity. The latter is represented in the model by the different elements composing the thermal envelope. The footprint is tangible and representative of the buildings space use among all the categories. The surface of the floor slab comes closest to the footprint surface and is the most relatable value to have as a reference. With the data of *Quantum Buildings*, the following ratios for the S_b^{roof} and the $S_b^{facade+windows}$ are extracted. The surfaces are divided by the S_b^{slab} for each building category as described in Equation 9. The results are presented in Table 5.

Category	(S_b^{roof}/S_b^{slab})	$(S_b^{facade+windows}/S_b^{slab})$
Multifamily	1.18	2.12
Singlefamily	1.38	1.71
Industry	1.10	1.24
Services	1.16	1.33

Table 5: Surface ratios for S_b^{roof} and $S_b^{facade+windows}$

3.5 Case study

In order to measure the impact of the building thermal property on energy demands and technology deployment, both archetype and typical buildings are defined. Archetypes are used to assess in a controlled environment the trends between energy demands and building morphology. However, due to their fictive nature, archetypes tend to lack of context. Therefore, typical buildings are used to complement the analysis with an in-field case study contextualising the results for the Geneva canton.

3.5.1 Building Archetypes

Figure 6 illustrates the archetype generation process. Three elements are needed for the calculation of the U_b values. In the first column, the four construction periods are represented, they are essential to define the heating transmission coefficient assigned to construction elements (Figure 3). Each construction period is uniformly assigned to a set of ratios. The ratios are organised into three distinct sets, each set is then associated with its corresponding construction category, whether Multifamily, Singlefamily, Services or Industry (Table 4). The ratios are essential for the conversion of the $U_b^{th.envelope}$ into U_b^{era} . The category is essential to the ratios but especially because it is the representation of the different forms and dimensions of a building (Table 5). In this way, the process generates a total of 100 different building archetypes, each characterized by the ratios assigned to its specific category and construction period.

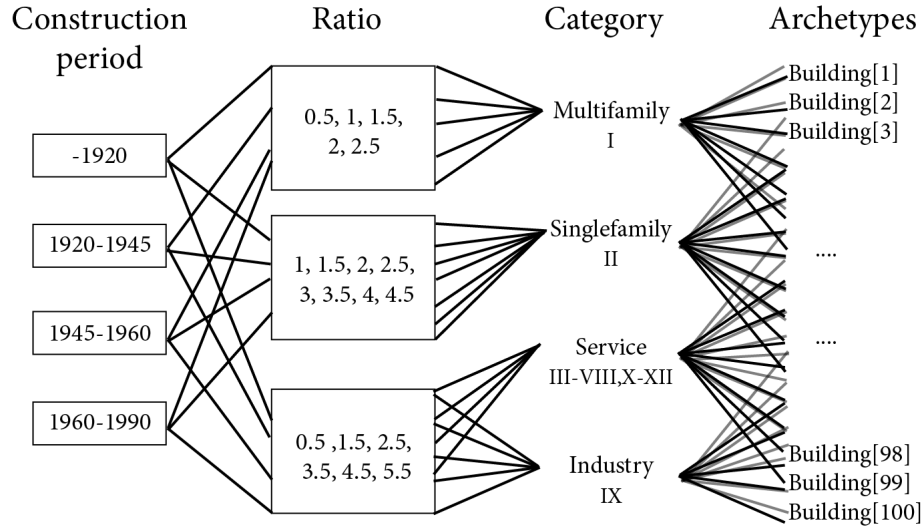


Figure 6: Archetype generation process

3.5.2 Archetypes for the comparison between static and regulatory models

One objective of this project is the comparison between regulatory and static approaches. The regulatory model is based on U_b^{era} values given by previous thesis related to building energy systems (Luc Girardin [40] and Paul Stalder [41], Appendix 19). The coefficients U_b^{era} are defined over four construction years for both Multi-family and Single-family dwellings (Table 6). Therefore, the regulatory model contains a total of four archetypes.

Period	U_{era} [kW/°C·m ²]	T_{supply} [°C]	T_{return} [°C]
>1920	1.93	65	50
1920-1970	2.14	65	50
1970-1980	2.04	65	50
1980-2005	1.62	65	50

Table 6: Values of the thesis of Luc Girardin and Paul Stalder (Appendix 19)[40]

On the other hand, the static model differentiate multi-family and single-family dwellings for each construction period. In addition, for each category, the range of ratio is included in the sampling based on the values in Table 7. Combining construction years and building categories, the static model contains a total of 8 archetypes.

	Category	
Ratios	Multifamily	Singlefamily
Min	0.5	1
Max	2.5	4.5

Table 7: Ratio uncertainty of Multifamily (I) and Singlefamily (II) buildings

Data input for the static approach is given in Table 8.

Input in the model	Typologies _{static}
S_b^{era} [m ²]	S_b^{era}
Temperature heating supply [C°]	65.0
Temperature heating return [C°]	50.0
$S_b^{facade+windows}$ [m ²]	$S_b^{facade+windows}$
S_b^{roof} [m ²]	S_b^{roof}
Temperature interior [C°]	20.0
ID class	<i>Category</i>
Solar gain factor signature [m ²]	0.07
Thermal specific capacity [Wh/m ² K]	119.4
Thermal transmittance signature [kW/m ² K]	U_b^{era}

Table 8: In *italic*, the parameters calculated with the methodology developed in this study and input into the model. In black the parameters fixed by standard values

In addition to building parameters, energy tariffs are assumed constant and are provided in Table 9. The correspond to the mean values of electricity and natural gas tariffs from the period 2021-2023.

	Cost demand	Cost supply
Electricity	0.1645	0.279
Natural gas	0	0.14

Table 9: Standard price [CHF/kWh] of electricity and natural gas

3.5.3 Typical buildings

Clustering is an analytical technique used to group similar data points together based on specific characteristics. Within this case study, the aim is to identify the most representative district of Geneva based on various factors. Districts are determined by the aggregation of buildings sharing the same low-voltage electrical network. A k-medoids clustering algorithm, implemented through a geographic information system, is employed to categorize and group transformers based on urban and geographical characteristics [46]. The dataset is normalized by the mean value and standard deviation for each characteristic. The features considered in the clustering are listed in the following:

- Urban density: the density of low, medium and high voltage grids
- Weather features: the mean annual temperature and annual irradiation on the roofs of the buildings.
- The usage purpose of buildings: the share of residential, service and industrial buildings in the districts.
- The geometry of the buildings : (S_b^{roof}/S_b^{era}) , $(S_b^{facade+windows}/S_b^{era})$, (S_b^{slab}/S_b^{era})

The district defined is located in the municipality of Veyrier, near the french border (Figure 7). The buildings considered are labeled in black and the district location is in yellow. The district contains 201 buildings. However, IDC data is available for only 58 buildings out of

the 201. Since the aim of this case study is to compare the energy demand of the model with real measurements, the case study will focus on these 58 buildings with data availability.

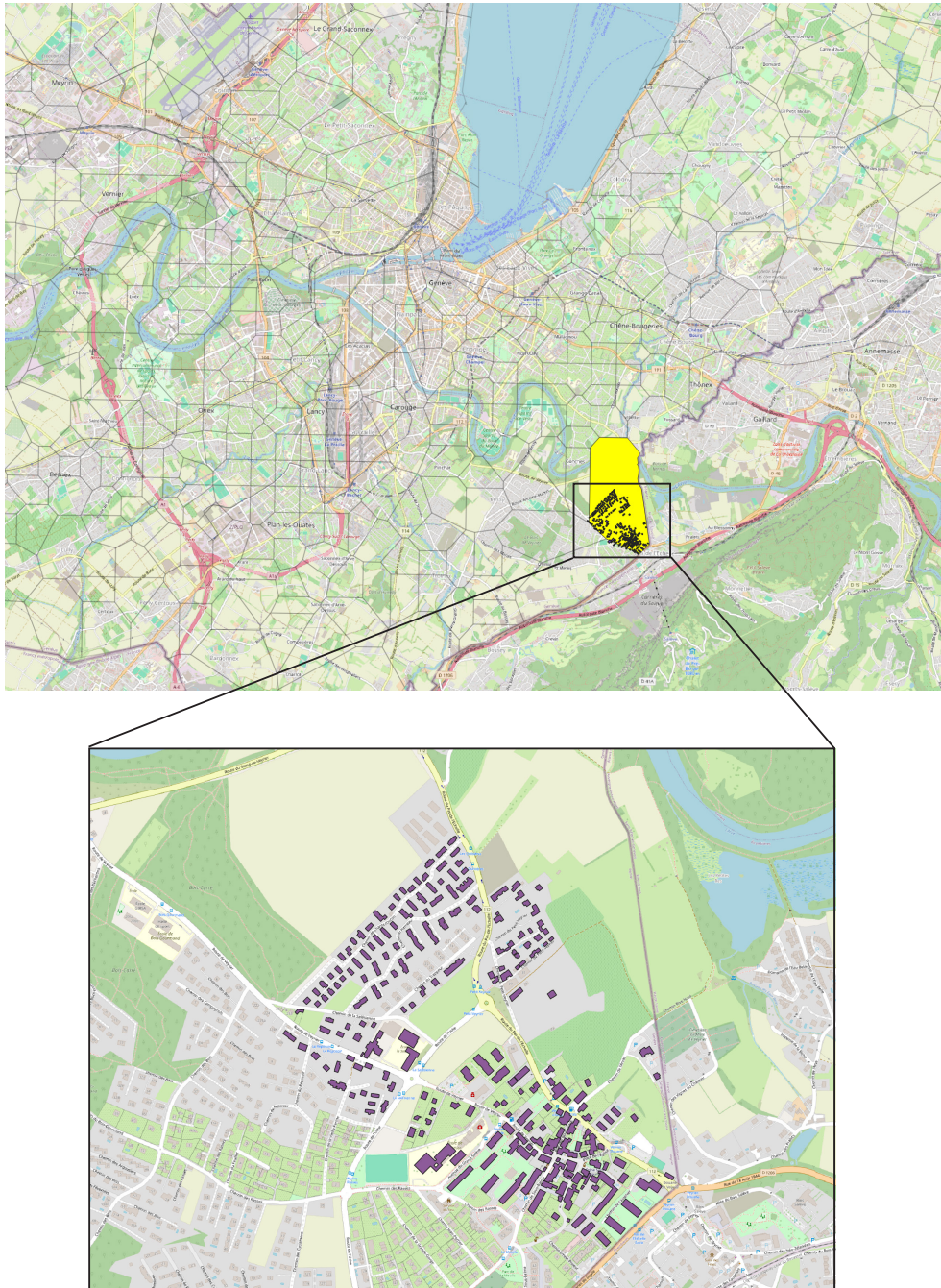


Figure 7: The typical district defined with the clustering algorithm

4 Results and discussion

The objective is to discuss the modelling performance gap on the REHO model for existing buildings. First the relation between the SH and the thermal envelope U_b^{era} is discussed. To identify tendencies of investment and operation, a principle component analysis is applied. Correlations between installed technologies, heating requirements, storage capacity and energy flux are analysed. Then, the modelling performance gap is evaluated for both regulatory and static approaches. Results are compared with on site data about heating demands (SH+DHW). Finally uncertainties on investment and operation of the buildings energy system are assessed.

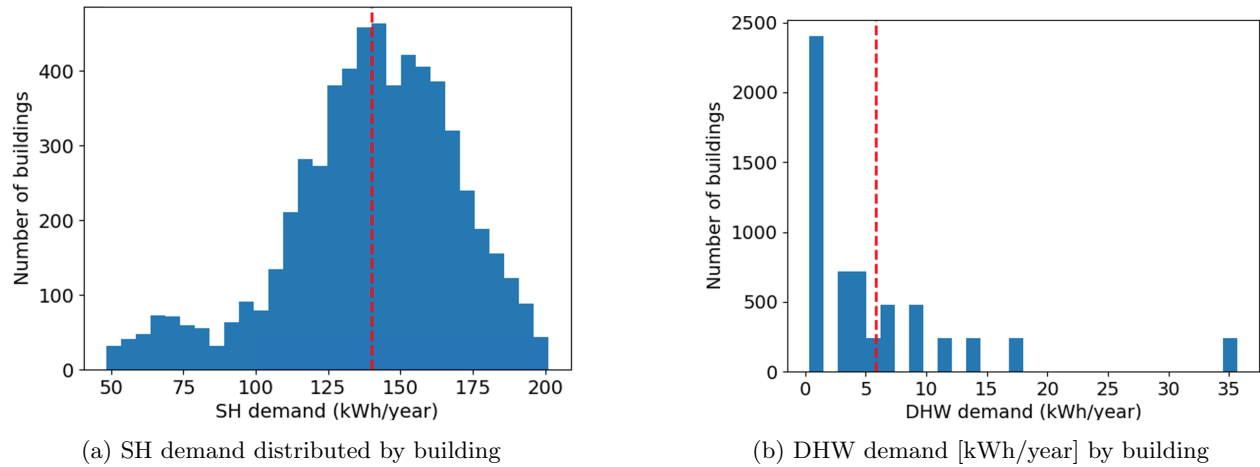
4.1 Identification of building energy system configuration trends

In order to understand the tendencies of the technologies installed, a principal component analysis is applied. The latter allows identifying and extracting the most significant features and their relationships, thereby revealing key insights on the interdependencies and variations among installed technologies.

A total of 100 archetypes are defined with the previous methodology (Section 3.4). The range of values for the U, b and g-values of construction elements are sampled with Latin Hypercube Sampling (LHS). LHS is often used to efficiently explore parameters in a balanced way. It ensures good coverage of the parameter space, enabling the analysis of general trends of the model. This is particularly useful for understanding how parameter variations affect model results. Ten samples are computed for each archetype within the ranges of U, b and g-values defined in Section 3, resulting in a total of 1'000 archetypes (100·10). The areas of roofs (S_b^{roof}) and of facade+windows ($S_b^{facade+windows}$) being constrained by their relation with the area of the floor slab (S_b^{slab}), the footprint is fixed to 400 m².

The cost of electricity and natural gas constrain the system to a single economic situation. To generate meaningful and versatile building energy system configurations, multi-objective optimization is conducted and pareto fronts are obtained. The latter allows to prioritize objectives, be it operational costs (OPEX) or capital costs (CAPEX). Six pareto points are extracted to identify tendencies of investments and operation. Each point representing an optimal trade-off between the two objectives. This allows examining the implications of energy system configurations on energy performances for each archetype. A total of 6'000 building archetype configurations (1'000·6) are analysed.

Figure 8a, represents the SH demand for the 6'000 system configurations obtained with the LHS sampling. The curve is similar to a Gaussian curve with a peak at the mean value of 140 kWh/year. This behaviour is expected since the archetypes are meant to represent a large portion of different architectural features potentially impacting the heating requirements. The Figure 8b, represents the DHW for the 6'000 building archetypes with the LHS sampling. The mean value is of 5.86 kWh/year and the distribution is more sparse, which is expected since it is independent of the architectural identity of buildings. It rather depends on the class of the building.



In the following, an analysis on the relationship between space heating and the coefficient U_b^{era} is provided. Figure 9b represents this relation and highlight the diversity of archetypes. Low U_b^{era} values result in low SH demand. Around 150 kWh a plateau is reached and the dispersion of results increases with the U_b^{era} value. This situation can be explained with the figure 9b. In fact, the U_b^{era} value is influenced by 2 factors: the thermal performance of the construction elements ($U_b^{th.envelope}$) and the compactness of the building (Ratio). When the value of U_b^{era} increases, a mix of $U_b^{th.envelope}$ performance and compactness of the building is obtained for the same U_b^{era} value. This explains the scattered results. What is interesting is that for a given ratio, the relationship between U_b^{era} and SH is linear, which is to be expected. So the greater the heat transfer of the envelope, the greater the demand for space heating for a given ratio. This combination of ratio and $U_b^{th.envelope}$ give the impression of a plateau, when in fact the relation is linear.

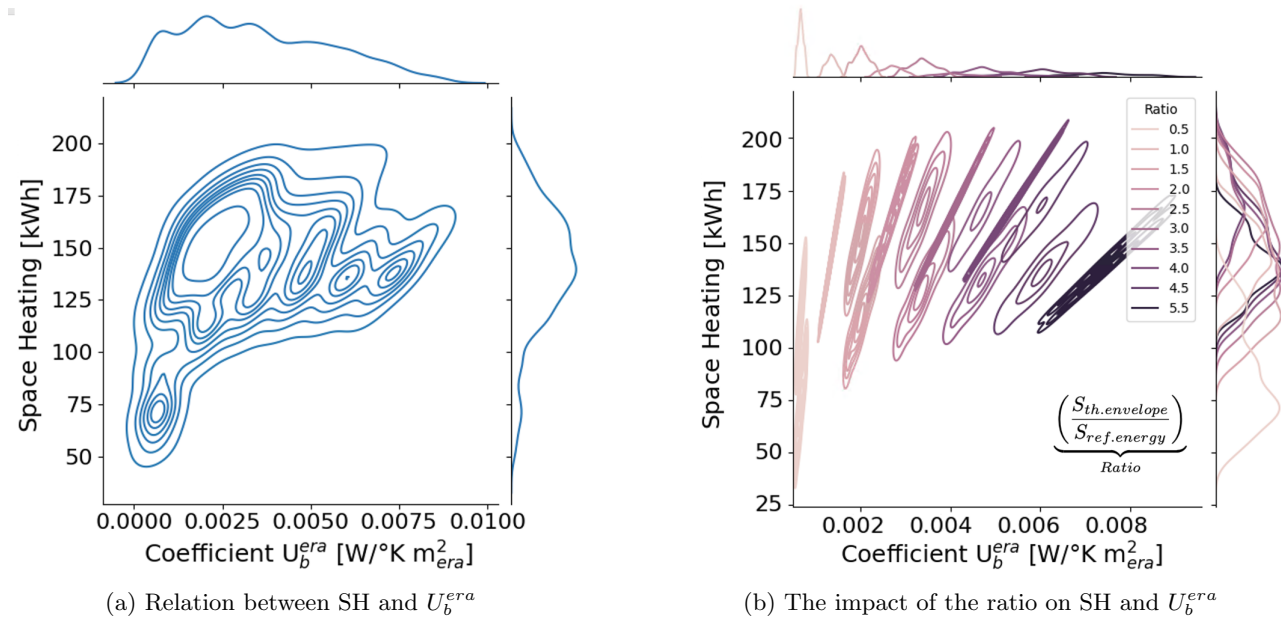


Figure 9: Space Heating demand, thermal coefficient U_b^{era} and ratio

Now that the relation between U_b^{era} and SH is understood, the relationships between tech-

nologies and energy flows are analysed. Figure 10 shows the explained variance ratio of the PCA for the ten first dimensions. The explained variance ratio helps to understand how well each principal component represents the original data. It aids in deciding how many components to retain for further analysis or visualization. In this case, the first four dimensions (dim0, dim1, dim2, and dim3) are the most relevant for analysis. The first dimension (dim0) explains more than 30% of the variance, implying that it retained a significant amount of information. The following dimension, dim1, drops and is half as impactful as dim0. After dim3, there is another drop, with dim4 being under 10%. The dimensions 4 and above will be neglected in the following analysis.

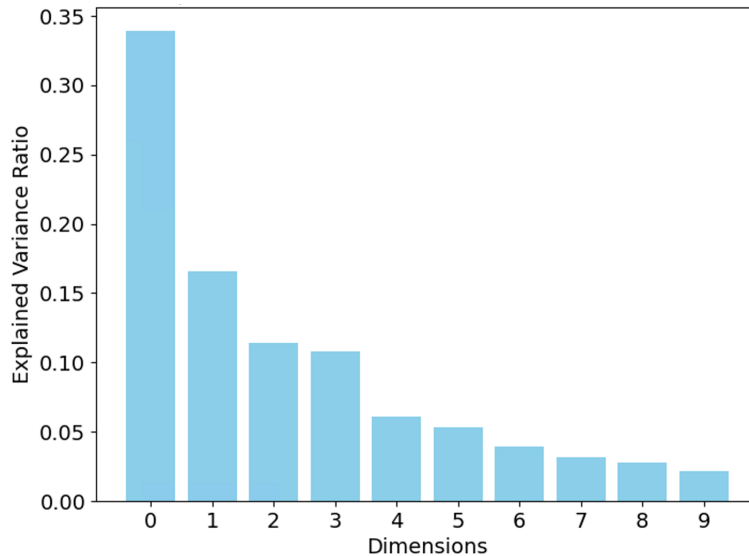


Figure 10: Explained variance ratio for each dimension

The Figure 11 presents the PCA of dim1, dim2 and dim3 with respect to dim0. The grid demand (electricity export) is always and almost perfectly aligned with dim0 and with a large intensity. On the opposite side, the grid supply (electricity import) is negatively correlated to the grid demand. The Heat Pumps (HP) and Photovoltaic (PV) capacity along with their energy supply to the system are pointed in the same direction than the grid demand with high intensity. On the other side, the boiler capacity and heat supply are on the opposite direction, so negatively correlated. This suggest that dim0 represents the dimension of renewable energy penetration and its impact on the electricity exchanges with the grid. In complement, dim1 seems to be related to the annex heating capacity type, being activated during peak heating demands. The boiler and electrical heater are aligned and negatively correlated to dim1, meaning that they are two competing technologies. The electrical heater and boiler serve similar purposes in meeting power demand during peak periods, but the boiler has a higher investment cost and the electrical heater a higher operation cost, this is why they are installed in different economical context. The dim2 is related to the SH and DHW demands since they are both highly correlated with this dimension. The decorrelation between heating demands and technological choice indicates that the available capital and the economical context are the main factors driving the selection of equipment. Finally, the analysis on the dimension 3 is less straightforward since there is no feature directly correlated to this dimension. A possible interpretation could be linked to the operation of the

heat pumps and storage tanks. The heat pump and water tank capacities as well as the heat supply from NG boilers are correlated to dim3. It could indicate a system where heat pumps with large capacities are activated when renewable electricity is present, while storage water tanks and NG boilers are covering the rest of the heating demand over the day. On the contrary, the heat supply from heat pump is the only feature decorrelated to dim3, and would correspond to a system where average size heat pumps are operated all over the day, therefore reducing the capacity of storage tank and NG boilers. It should be mentioned that the dimensions of the PCA do not necessarily possess a physical interpretation. Dimension 3 shows the limits to the explanations of the physics and tendencies of the energy system configurations.

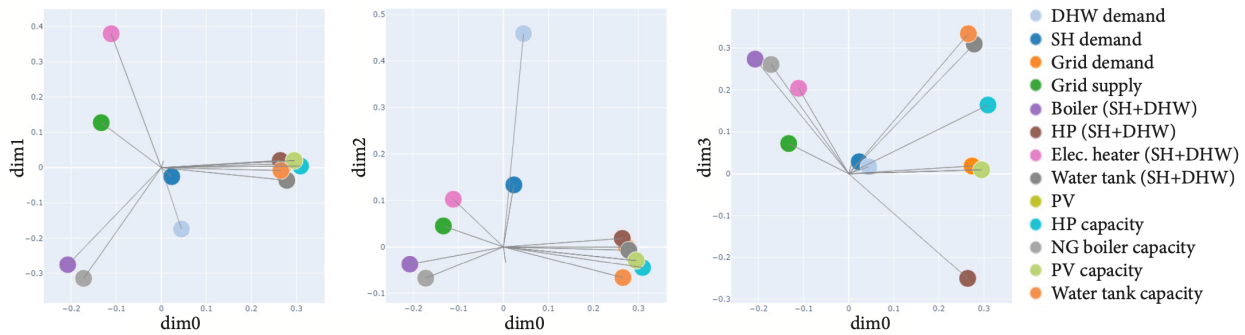


Figure 11: Principal component analysis of dim1, dim2 and dim3 compared to dim0

Renewable penetration constitutes the most influential dimension in the system. The trends show that demands for SH and DHW do not play a significant role in this dimension, they are almost independent. SH demand is not impacting the selection of heating system. Yet, HP and PV are required for the energy transition. So far, only trends between system configuration characteristics were analysed. Therefore, besides reducing energy consumption with improved thermal envelope, more work should be done concerning the economic signals promoting the right technological choice for SH and DHW demand. In the following, the uncertainties of technological deployment and energy flows will be assessed and compared with real measurements

4.2 Quasi-Monte Carlo on multi-family and single-family categories

The 4 archetypes defined by the thesis of Luc Girardin and Paul Staler [40][41] are considered as the regulatory model (Section 3.5). Regarding the static one, the range of values for the U_b and g -values of construction elements are sampled with quasi-Monte Carlo (qMC) method with a Sobol sequence. Using qMC and Sobol sampling is an effective method to assess probabilities and uncertainties, which is the aim of this section and the following one. Sobol sampling reduces the variance of estimates, providing more reliable results than a simple Monte Carlo. The number of samples needs to be a power of two because of the Sobol method.

Before starting the case study, the relation between the SH and the U_b^{era} is computed. Similarly as in Section 4.1, the ratio, U_b and g -values are sampled in 512 entities for each archetype, resulting in 4'096 archetypes (8·512). In Figure 12, the relation between SH and

the U_b^{era} is analysed with the perspective of the two different classes: Multi-family (II) and Single-family (I). It is noticeable that there is a distinct shift between the two categories. Consequently, the dimension of form factor attributed to each class in the methodology plays a role. The dimensions between the categories are defined in Table 5 of the methodology. The form factor directly impacts the $S_b^{th.envelope}$ and the ratio ($S_b^{th.envelope}/S_b^{era}$) used to define U_b^{era} . Multi-family buildings tend to be more compact, space is thought out in an optimized way and they result in lower U_b^{era} values. This shift between categories was already observed in the real data computation in figure 5. This indicates that the archetypes are representing the diversity of the real built environment regarding the categories. Concerning the approach with a range of ratios sampled with qMC, it is visible that the SH and U_b^{era} values are less aggregated and more uniformly distributed but the trend remains similar than in figure 12. The conclusion of this analysis is the similarity between the results obtained with the LHS and qMC methods. In the following, the qMC method is applied on a real district to validate the trends obtained in Section 4.1.

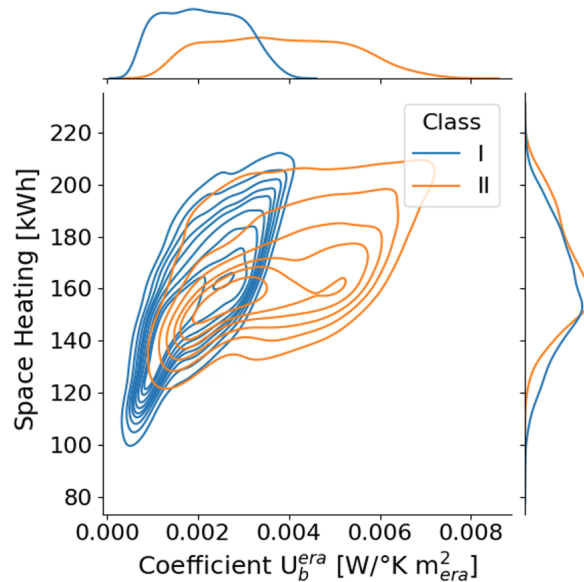


Figure 12: SH demand and thermal U_b^{era} value in function of their building category

4.3 Performance gap and uncertainties of regulatory and static models

The objective of the following analysis is the comparison of the regulatory and static models to real measurements (IDC) from the Territorial Information System in Geneva (SITG) [47]. This will allow to quantify uncertainties and link them to the dependencies identified in the previous section.

For the case study, the static approach accounts 128 samples for each building within the typical district and possessing an IDC (58 buildings). In total, 7'424 system configurations (58·128) are computed. For the regulatory model, the values of the non renovated buildings are considered. The reference SH and DHW heating requirements are taken from real IDC measurements. For the IDC measurements the average over the three last years is computed. The SH and DHW values undergo normalization by the ERA, since the ERA from the IDC and Qbuilding are slightly different among buildings. It also facilitates the comparison of

buildings with distinct dimensions.

Figure 13a is meant to display the difference between the static and regulatory approaches. It presents the distribution of thermal transmission coefficients U_b^{era} and SH and DWH demands. Figure 13b, introduces real data of heating consumption together with the estimated demands obtained with the static and regulatory models. In Figures 13, the regulatory approach tends to overestimate U_b values, consequently inflating space heating requirements. In contrast, the static approach yields results with a median closely aligned with measured values. However, the variation is narrower between the static and real data. It is likely attributed to the single interval of U_b value given in Table 3. While construction periods are considered, intervals of U_b are considered homogeneous among all building categories, therefore it is not considering the whole versatility of the building stock. While these intervals are well-centered around real U_b value, the medians are similar, they still inadequately capture the diversity of buildings. Even when considering construction years and specific details, further efforts are needed in the field to establish U_b value intervals for each building type.

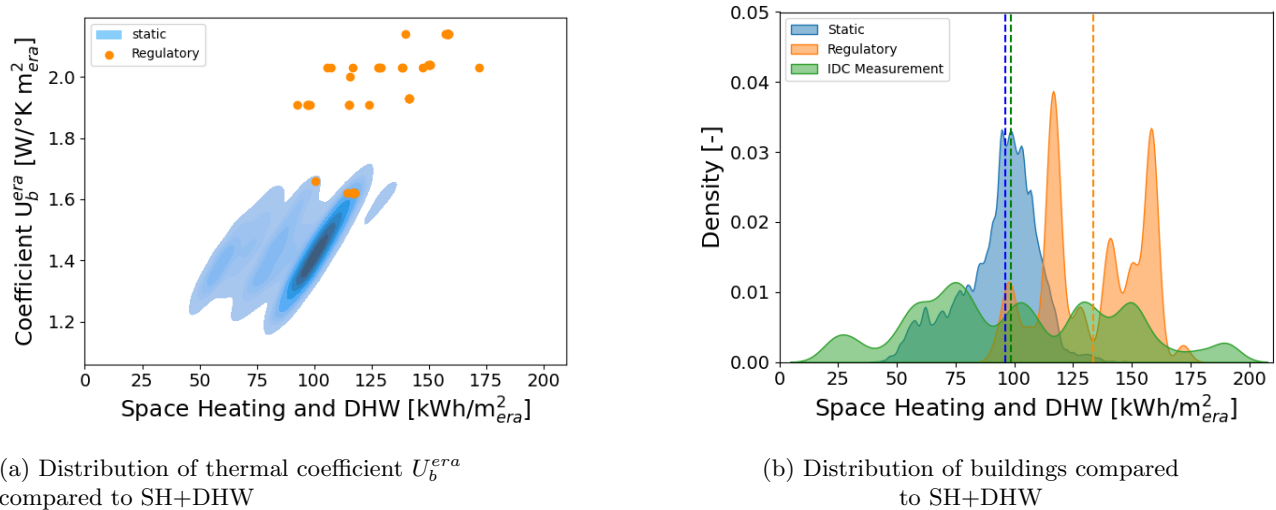


Figure 13: Comparison of the static, regulatory and IDC measurements

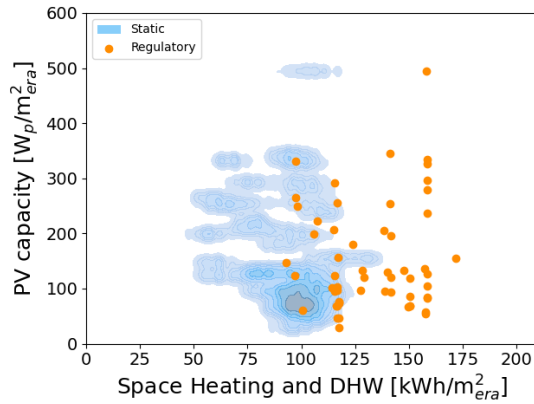
In table 10, the median values, mean values, standard deviation and the Root Mean Square Error between results and measurements are displayed. The median, mean and standard deviation for the static approach are always closer to the IDC than for the regulatory one. The result of the RMSE indicates that a change in the modeling approach decreases the energy gap by 13.4%.

	Static	Regulatory	IDC
Median value [Wh/m ²]	96.2	133.8	98.7
Mean value [Wh/m ²]	93.2	132.7	101.3
Standard deviation [Wh/m ²]	16.4	21.6	43.1
RMSE [kWh/m ²]	43.8	50.6	/

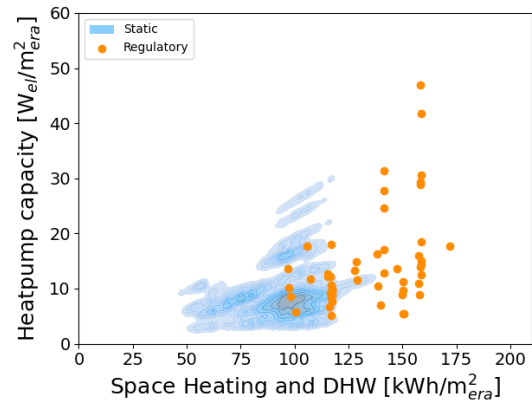
Table 10: RMSE and comparison of data from the static and regulatory approach with the IDC

Figures 14 and 15 display the energy technology deployment and associated annual energy

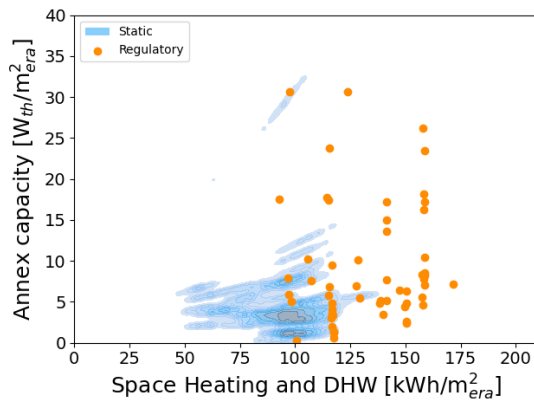
flows with respect to SH and DHW demand for both the static and regulatory approaches. The technology deployment is presented with PV capacity, HP capacity in figure 14a and 14b respectively. The annex capacity is presented in figure 14c and the water tank storage in figure 14d.



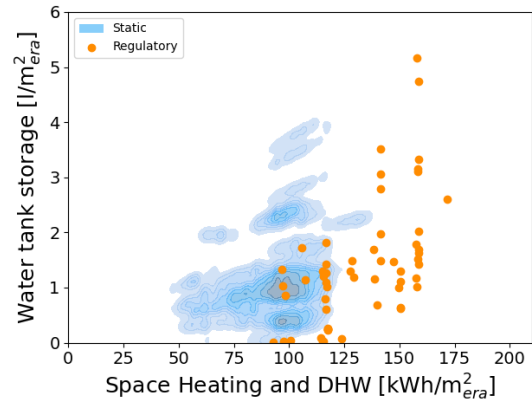
(a) PV installed capacity and SH+DWH for static and regulatory approach



(b) HP installed capacity and SH+DWH for static and regulatory approach



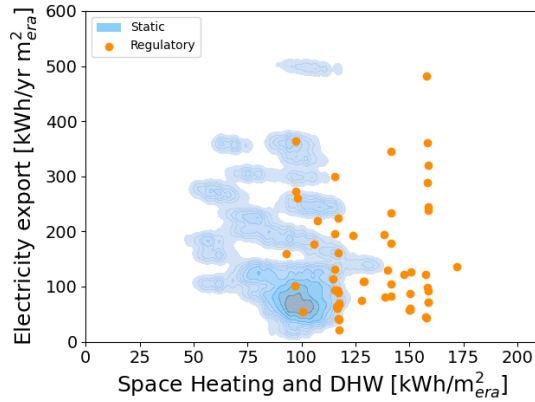
(c) Annex installed capacity and SH+DWH for static and regulatory approach



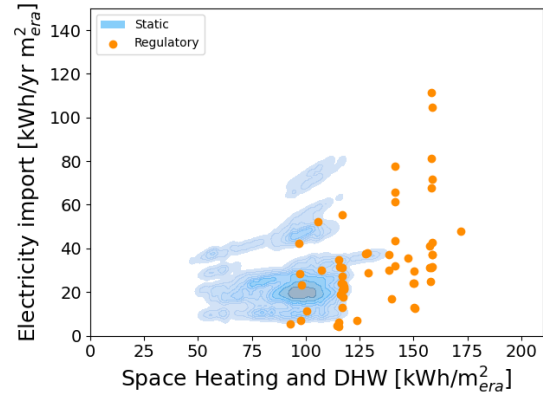
(d) Water tank storage capacity and SH+DWH for static and regulatory approach

Figure 14: Energy technology deployment for the regulatory and static approaches. The results for the static approaches is a distribution of configuration for each building, while the regulatory approach provide a single system configuration.

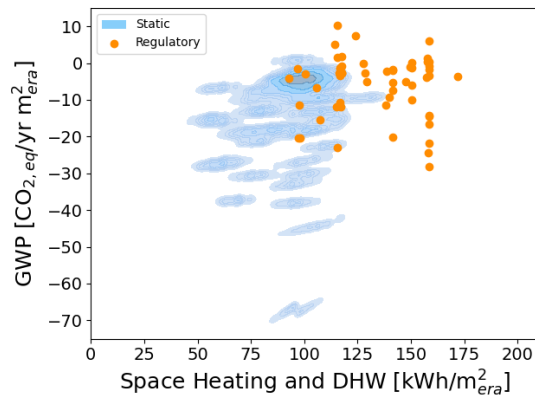
The energy flows are presented with the export and import of electricity in figure 15a and 15b, and the Natural Gas (NG) supply in figure 15d. Finally, the Global Warming Potential (GWP) considers grey emissions and emissions due to system operation, and is displayed in figure 15c.



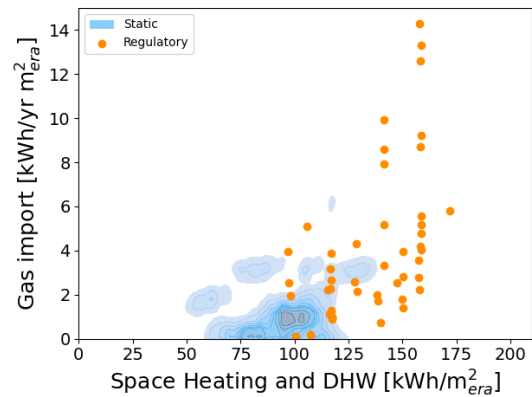
(a) Electricity export and SH+DWH for static and regulatory approach



(b) Electricity supply and SH+DWH for static and regulatory approach



(c) GWP and SH+DWH for static and regulatory approach



(d) NG supply and SH+DWH for static and regulatory approach

Figure 15: Energy flows and global warming potential for the regulatory and static approaches.

To quantify the uncertainty of the technology capacity, the energy flux and GWP with the static methodology, the mean standard deviation and the mean max-min are computed. Each of the 58 buildings possess 128 system configurations. Therefore, the standard deviations (σ) of the technologies capacity and associated energy flows are computed for each building. Then, the mean value among all buildings gives the mean standard deviation (mean σ). The same principle to obtain the mean min-max difference. The delta between min and max values are calculated for each of the 128 configurations and the mean value for all the 58 buildings gives the mean max-min. The values are displayed in table 11 for the technology deployment, for annual energy flows and GWP.

	Mean σ	Mean max-min
PV [W_p/m_{era}^2]	0	0
HP [W_{el}/m_{era}^2]	0.7	3.1
Annex [W_{th}/m_{era}^2]	0.4	2.0
Water tank [l/m_{era}^2]	0.06	0.2
Elec. supply [$kWh/yr m_{era}^2$]	1.4	7.1
Elec. demand [$kWh/yr m_{era}^2$]	0.9	4.5
NG supply [$kWh/yr m_{era}^2$]	0.5	2.2
GWP [$CO_{2,eq}/yr m_{era}^2$]	0.06	0.3

Table 11: Mean standard deviation and max-min for building capacities, energy flux and GWP

Table 11 illustrates that the maximum uncertainty on the heatpump capacity is $3.1 W_{el}/m_{era}^2$, with a standard deviation of $0.7 W_{el}/m_{era}^2$. On the figure 14b the scale of this uncertainty is visible and quite consequent since the average heatpump size is around $10 W_{el}/m_{era}^2$. It is important to note that the maximal uncertainty is more than three times higher than the mean σ , this indicates the potential for higher variability. Regarding electricity supply (Figure 15b), the mean σ and mean max-min are respectively 1.4 and 7.1 kWh/yr m_{era}^2 , this shows as well a high uncertainty with respect to the mean value of 21.2 kWh/yr m_{era}^2 . This behaviour is explained by the high uncertainty on the heatpump capacity generating a cascading uncertainty effect on electricity imports. In contrast, electricity exports displayed on Figure 15a, demonstrate a low uncertainty, with a mean σ and mean max-min of 0.9 and 4.5 kWh/yr m_{era}^2 to be put in perspectives with the large amount of annual electricity exports, mainly located between 76 and 150 kWh/yr m_{era}^2 . The same trend occurs for the PV capacity, with a mean σ and mean max-min of 0. Figure 14a further demonstrates the independence of the installed PV capacity with respect to heating demand. This behaviour is due to the high feed-in tariff, promoting a large deployment of PV capacity for an heating demand. This high tariff provides a guarantee on investment, making investment uncertainty negligible. Due to the high uncertainty on energy tariffs, this artificial situation is dangerous since it is hiding investment risk in a situation of favorable economic context. Further work should be accomplished in correlating investment and operation uncertainty with the economic conditions.

The increase in SH demand increases self-consumption of renewable electricity. This decreases the amount of electricity exports. However, due to the four-fold factor between electricity imports and exports, this effect is nearly negligible compared to the large amount of renewable electricity present in the building energy system (figure 15a and 15b). In addition, the profitability of solar panels is guaranteed, even when self-consumption decreases due to a lower heating demand. On the other hand, while the PCA showed a decorrelation between the choice of heating equipment and heating demand, Figure 14b, 14c and 14d indicates that once a technology is selected, its capacity does depend on the heating needs. The annex installed capacity is meant for peak demand and in this case, it represents the NG boiler and electrical heaters.

GWP experiences a slight increase with heating demands due to growing energy imports. For PV, the metrics remain relatively constant, a trend attributed to the higher electricity tariffs that encourage widespread PV deployment. Therefore, there is a substantial surplus

of electricity, particularly during periods of lower heat demand (summer/daytime). This explains the metric's low sensitivity to heat demands.

5 Conclusion

The initial goal was to assess the performance gap of a modelling tool with a static approach, in order to have more accurate results and better forecast to make decisions. For the REHO modelling tool, it meant improving the method to assess the thermal transmission coefficient U_b and its input data. The results show an improvement of 13,4 % with a change of method.

The study also assessed the variation SH with the thermal envelope, the form factor and how the developed methodology impacts their behaviour. The tendencies of investment and operation, for installed technologies, heating requirements, storage capacity and energy flux were analysed with the help of a principle component analysis. Through the study, the sampling method and the archetypes were adapted to assess uncertainty. Finally the methodology was compared to previous regulatory studies and with on site data.

The impact that improving the thermal envelope performance of existing buildings would have on their energy requirements and installed technologies was a starting point to develop the methodology. This is what lead to decompose the construction elements with a more accurate range of U_b values and the introduction of the form factor. Possible improvements could include integrating a more in-depth form factor and including thermal bridges with the 3D model on REHO. Include human behaviour and ventilation systems could also be a following improvement of the energy model.

Efforts and improvements in the construction sector regarding energy efficiency include not only technical solution but also social, political and economical. Combined efforts will lead to the overall improvement of energy in the building sector.

A Appendix

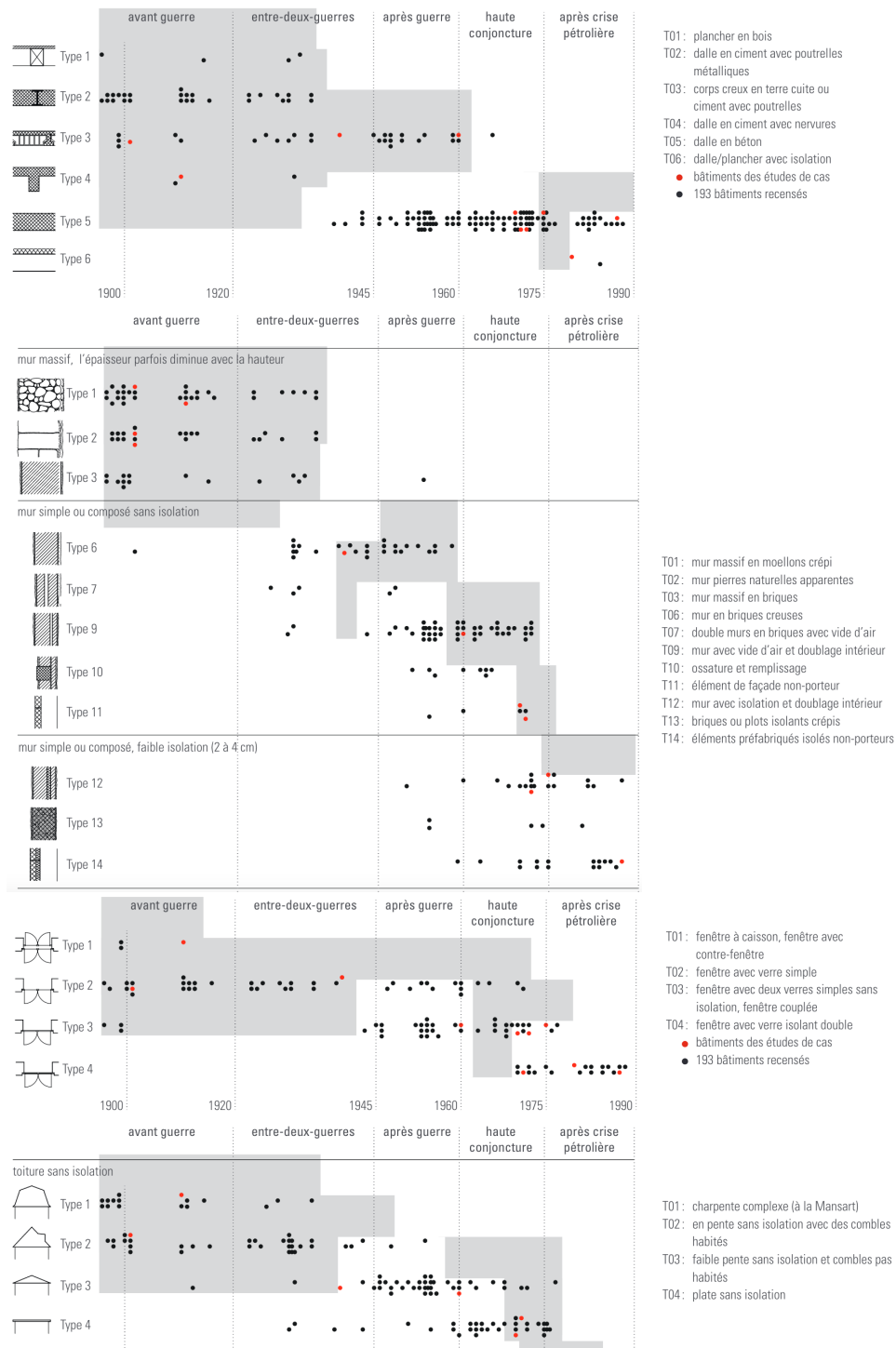


Figure 16: Construction details from 1900 to 1990 surveyed for 193 buildings[1]

5.1 Eingabedaten für SIA 380/1

Die folgende Tabelle enthält die vorgeschlagenen Wertebereiche für die Anpassung der Eingabedaten in SIA 380/1, mit dem Ziel, einer Reduktion des negativen Energy Performance Gap bei unsanierten Altbauten.

Tabelle 1: Eingabedaten zur Reduktion des EPG bei der Berechnung des Heizwärmebedarfs gemäss SIA 380/1

Gebäudekategorie: Mehrfamilienhaus		Standardwert	Wertebereich ⁴
U-Wert typischer Altbaukonstruktionen ¹			
Backsteinmauerwerk 30 cm	W/m ² K	1.05	0.9 – 1.2
Natursteinmauerwerk 60 cm	W/m ² K	1.6	1.0 – 1.5
Steildach mit Beplankung	W/m ² K	1.85	1.0 – 1.5
Estrichboden Holz ohne Dämmung	W/m ² K	2.0	0.8 – 1.2
Fenster Holz < 1990 2-IV	W/m ² K	2.7	1.5 – 2.0
Fenster Kunststoff < 1990 2-IV	W/m ² K	2.8	1.5 – 2.0
Betondecke	W/m ² K	3.4	1.5 – 2.0
Hourdisdecke	W/m ² K	1.6	0.9 – 1.5
Holzsparrendecke	W/m ² K	2.0	0.9 – 1.5
b-Wert von Bauteilen gegen unbeheizt			
Decke gegen Estrich	-	0.9	0.7 – 0.9
Decke gegen Keller teilweise im Erdreich		0.8	0.5 – 0.7
Decke gegen Keller im Erdreich	-	0.7	0.4 – 0.7
Aussentemperatur (Stadt)		SIA 2028	SIA 2028 + 2K
Raumtemperatur	°C	20	21 - 24
g-Wert Verglasung und Sonnenschutz ²	-	0.7	0.3 – 0.6
Aussenluft-Volumenstrom	m ³ /m ² h	0.7	0.4 – 1.0
Elektrizitätsbedarf x Reduktionsfaktor ³	kWh/m ²	28 x 0.7 = 20	10 - 25

¹ Standard-U-Werte für Altbaukonstruktionen ohne Wärmedämmung gemäss GEAK-Online-Tool

² In SIA 380/1 wird der Sonnenschutz nicht berücksichtigt. Untersuchungen zeigen (z.B. Carisch L., et al. 2018), dass der aussenliegende Sonnenschutz auch im Winter regelmässig geschlossen bleibt und die solaren Wärmegewinne daher in der Praxis tiefer ausfallen als in der Berechnung.

³ Der Elektrizitätsbedarf wird in SIA 380/1 mit einem Reduktionsfaktor multipliziert. Dieser berücksichtigt, dass ein Teil der Elektrizität ausserhalb der thermischen Gebäudehülle verbraucht wird und daher nicht als interner Wärmege Gewinn zur Reduktion des Heizwärmebedarfs beiträgt.

⁴ Wertebereich = Erfahrungswerte des Verfassers aus 200 energetischen Instandsetzungsprojekten

Figure 17: New U and b value range to adjust the input data of SIA 380/1 [2]



REPUBLIQUE ET CANTON DE GENEVE
Département du territoire
Office cantonal de l'énergie

**Version valable uniquement pour une dépose
papier**

Documents minimums à fournir suivant les cas de travaux		
Type de travaux	Variante	Documents à fournir
Neuf	HPE – MINERGIE ou label équivalent	1 2 7 11
Neuf	HPE - CECB	1 2 3 7 9 12
Neuf	HPE - MOPEC	1 2 3 4 6 7 8
Neuf	HPE - SIA	1 2 3 6 7 8
Neuf	THPE – MINERGIE-A/P-ECO ou label équivalent	1 2 7 11
Neuf	THPE - CECB	1 2 3 7 9 12
Neuf	THPE - MOPEC	1 2 3 4 6 7 8
Extension	HPE-Extension	1 2 3 6 7 8
Rénovation	Performances ponctuelles SIA 380/1	5 7
Rénovation	Performance globale SIA 380/1	6 7
Rénovation	HPE-Réno – MINERGIE-Réno ou label équivalent	1 2 7 11
Rénovation	HPE-Réno - CECB	1 2 3 7 9 12
Rénovation	HPE-Réno - MOPEC	1 2 3 4 6 7 8
Rénovation	THPE-Réno – MINERGIE-A/P-ECO-Réno ou label équivalent	1 2 7 11
Rénovation	THPE-Réno – CECB	1 2 3 7 9 12
Rénovation	THPE-Réno – MOPEC	1 2 3 4 6 7 8
Neuf ou Rénovation	Si SRE totale > 2'000m ² ou 3'000m ² pour habitations	10

Remarques et explications	
	Emplacement des formulaires "EN" : https://www.endk.ch/fr/professionnels/justificatif-energetique/en-101-a-en-141-mopec-2014
	SRE (m2) Surface de référence énergétique en m ²
1	Justificatif de production propre d'électricité : Formulaire EN 104 à fournir pour apporter la preuve de la pose d'un taux de production propre d'électricité d'au moins 10W/m ² de surface de référence énergétique.
2	Preuve d'autoconsommation photovoltaïque : Seule la production d'électricité autoconsommée au profit de la production d'énergie thermique du bâtiment est comptabilisée pour la part d'énergie renouvelable dans le formulaire EN 101b et annexes demandées. PVOpti téléchargeable sur le site www.minergie.ch Toute autre méthode de calcul est acceptable si les hypothèses et résultats y sont explicités.
3	Preuve de la couverture d'eau chaude sanitaire par solaire thermique : Equipement des bâtiments en capteurs solaires thermiques permettant de couvrir au moins 30% des besoins de chaleur admissibles pour l'eau chaude sanitaire du bâtiment (L 2 30 Art. 15 al. 2). Le formulaire EN 101b et annexes demandées.
4	Preuve du respect des valeurs limites des besoins d'énergie annuels pondérés pour le chauffage, la préparation de l'eau chaude sanitaire, la ventilation et le rafraîchissement : Les besoins d'énergie annuels pondérés pour le chauffage, la préparation de l'eau chaude sanitaire, la ventilation et le rafraîchissement dans les bâtiments à construire ne doivent pas dépasser les valeurs définies dans le MOPEC 2014.
5	Justif. de l'enveloppe thermique : performance ponctuelle ou performance globale : Justification par performances globale (Justificatif thermique par logiciel certifié) ou ponctuelles (EN-102a), Selon la norme SIA 380/1, édition 2016.
6	Calcul de l'indice de dépense de chaleur admissible, IDCa : Calcul libre selon directive : https://www.ge.ch/calculer-indice-depense-chaleur-admissible-chauffage-eau-chaude
7	Justif. de conformité à la SIA 387/4 pour l'éclairage : Grâce au formulaire EN-111a pour les performances ponctuelles ou SIA TEC TOOL pour les performances globales
8	Justif. de conformité de la puissance électrique maximale de climatisation : Le non dépassement de la puissance électrique de 7W/m ² est prouvé grâce au formulaire EN-110 et annexes demandées
9	Concept énergétique de bâtiment : Le concept énergétique est à produire sur document libre selon la directive disponible sur www.ge.ch ou sur le format CECB+
10	Standard Minergie, -P, -A, -ECO : Cas échéant, si le projet est au bénéfice d'un label Minergie, annexer la copie du certificat provisoire ou définitif. Pour les autres cas, https://www.ge.ch/dossier-energetique-nouvelle-construction-extension/extension-50m2-20-existant
11	Justif. de conformité à la SIA 380/4 pour la ventilation : La justification est à fournir grâce au SIA TEC TOOL
12	Locaux frigorifiques : Formulaire EN-112 et annexes demandées
13	Serres ou halles gonflables chauffées : Formulaire EN-131 (serres chauffées) ou EN-132 (halles gonflables chauffées) et annexes selon directive disponible sur www.ge.ch
14	

Office cantonal de l'énergie • Rue du Puits-Saint-Pierre 4 • 1204 Genève
Tél. +41 (0) 22 327 93 60 • Fax +41 (0) 22 327 93 61 • E-mail ocen@etat.ge.ch • www.ge.ch/energie

Figure 18: Form L00 - Energy data by building [48]

Table B.1 – National representative building classes

Age	Ref.	Use	U	T ^s	T ^r	Use	U	T ^s	T ^r
			[kW/°C·m ²]	[°C]	[°C]		[kW/°C·m ²]	[°C]	[°C]
>1920	×	SFH/MFH	1.93	65	50	MIX	1.91	65	50
1920-1970	×		2.14	65	50		2.03	65	50
1970-1980	×		2.04	65	50		2.00	65	50
1980-2005	×		1.62	65	50		1.66	65	50
2005-2020	×		1.00	41.5	33.9		1.07	41.5	33.9
>1920	✓		0.94	54.4	44.1		1.02	54.4	44.1
1920-1970	✓		1.17	54.4	44.1		1.23	54.4	44.1
1970-1980	✓		1.11	53.8	43.8		1.18	53.8	43.8
1980-2005	✓		1.21	56.3	45.3		1.27	56.3	45.3

Figure 19: Values for SingleFamily and MultiFamily House - p.145 of the thesis [41]

Contents

References

- [1] Stefanie Schwab et al. *Rénovation énergétique : approche globale pour l'enveloppe du bâtiment*. Institut d'architecture TRANSFORM. 2016.
- [2] Stadt Zurich Amt für Hochbauten. "Energy Performance Gap bei Instandsetzungen". In: (2022).
- [3] Swiss Federal Office of Energy. *Buildings*. 2022. URL: <https://www.bfe.admin.ch/bfe/en/home/efficiency/buildings.html> (visited on Dec. 29, 2023).
- [4] Vaclav Hasik et al. *Comparative whole-building life cycle assessment of renovation and new construction*. 2019. URL: <https://www.sciencedirect.com/science/article/pii/S0360132319304287> (visited on Jan. 5, 2024).
- [5] Hans-Rudolf Schalcher. *La cadence de rénovation des bâtiments doit s'accélérer*. Virage énergétique - PNR. 2019. URL: <https://www.nfp70.ch/fr/VMLfA4o6dXdmfYQx/news/191017-news-nfp70-la-cadence-de-renovation-des-batiments-doit-sacclerer> (visited on Jan. 5, 2024).
- [6] EnDK Conférence des directeurs cantonaux de l'énergie. *Nouvelle construction*. 2021. URL: https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&ved=2ahUKEwj0i7LG2f2DAxXM-LsIHbezBBsQFnoECA4QAQ&url=https%3A%2F%2Fpubdb.bfe.admin.ch%2Ffr%2Fpublication%2Fdownload%2F7353&usq=A0vVaw1Cmexo-q30mS290LLG8R9_&opi=89978449 (visited on Jan. 27, 2024).
- [7] Contrôle Fédéral des Finances. *Efficacité des aides financières accordées pour la réduction des émissions de CO₂ des bâtiments conformément à l'art. 34 de la loi sur le CO₂*. 2016. URL: https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&ved=2ahUKEwj11o617_2DaxWYh_OHHRBLCJOQFnoECAwQAQ&url=https%3A%2F%2Fwww.bafu.admin.ch%2Fdams%2Fbafu%2Ffr%2Fdokumente%2Fklima%2Ffachinfo-daten%2Fwirksamkeit_der_finanzhilfenzurverminderungderco2-emissionenbeig.pdf.download.pdf%2Fefficacite_des_aidesfinancieresaccordeespourlareductiondesemissi.pdf&usq=A0vVaw25LrQ8rgPTlJqBCsZLzcAY&opi=89978449 (visited on Jan. 27, 2024).
- [8] Swiss Energy Scope. *Pourquoi le taux de rénovation des bâtiments est-il si faible malgré le programme de subsidence ?* 2023. URL: <https://www.energyscope.ch/fr/questions/pourquoi-le-taux-de-renovation-des-batiments-est-il-si-faible-malgre-le-programme-de-subsidence/#:~:text=De%20ce%20point%20de%20vue,1%27ampleur%20de%20la%20r%C3%A9novation.> (visited on Jan. 27, 2024).
- [9] Monika Gisler. *Comment la Suisse a géré la crise pétrolière de 1973*. swissinfo. 2022. URL: <https://www.swissinfo.ch/fre/culture/comment-la-suisse-a-g%C3%A9r%C3%A9-la-crise-p%C3%A9troli%C3%A8re-de-1973/47959150> (visited on Jan. 22, 2024).
- [10] Luigi Jorio. *Why most Swiss buildings are environmentally inefficient*. SWI swissinfo. 2020. URL: https://www.swissinfo.ch/eng/society/climate-crisis_why-it-may-take-100-years-to-renovate-every-building-in-switzerland/45481906 (visited on Jan. 27, 2024).
- [11] Brenda V.F. Silva et al. *Sustainable, green, or smart? Pathways for energy-efficient healthcare buildings*. ScienceDirect. 2024. URL: <https://www.sciencedirect.com/science/article/pii/S2210670723006248> (visited on Jan. 27, 2024).
- [12] Office fédéral de l'énergie. *Qu'est-ce que l'écart de performance ?* suisseénergie. 2023. URL: <https://www.suisseenergie.ch/technique-du-batiment/> (visited on Jan. 27, 2024).
- [13] Stefano Cozza et al. *Measuring the thermal energy performance gap of labelled residential buildings in Switzerland*. ScienceDirect. 2020. URL: <https://www.sciencedirect.com/science/article/abs/pii/S030142151930672X> (visited on Jan. 27, 2024).
- [14] Swiss Energy Scope. *How much energy does Switzerland consume? For what purposes?* 2018. URL: <https://www.energyscope.ch/en/questions/how-much-energy-does-switzerland-consume-for-what-purposes/> (visited on Jan. 10, 2024).

- [15] Dr. Sabine Perch-Nielsen et al. “Energie Performance Gap in Neubauten”. In: (2019). URL: https://www.minergie.ch/media/2019_performance-gap_in_neubauten_ebp.pdf (visited on Oct. 9, 2023).
- [16] Songsong Cheng et al. *Performance Gap and Innovation Ambidexterity: A Moderated Mediation Model*. 2023. URL: <https://www.mdpi.com/2071-1050/15/5/3994> (visited on Jan. 27, 2024).
- [17] *Performance Gap to Needs Analysis*. ceriusexecutives. 2024. URL: <https://ceriusexecutives.com/performance-gap-needs-analysis/> (visited on Jan. 27, 2024).
- [18] Marcel Janser et al. *Call for a Definition and Paradigm Shift in Energy Performance Gap Research*. 2020. URL: https://digitalcollection.zhaw.ch/bitstream/11475/21306/2/2020_Janser-et-al_Definition-paradigm-shift-energy-performance-gap-research.pdf (visited on Jan. 28, 2024).
- [19] Swiss Federal Office of Energy SFOE. *Energy Performance Gap in existing, new, and renovated buildings*. 2019. URL: https://www.minergie.ch/media/2019_gapxplore_langversion.pdf (visited on Jan. 6, 2024).
- [20] Swiss Federal Office of Energy SFOE. *Einfluss der Kombination aus Nutzerverhalten und Gebäudetechnik auf den Performance Gap bei Mehrfamilienhäuser*. ImmoGap. 2018. URL: https://www.minergie.ch/media/501469_haller_sb_immogap.pdf (visited on Jan. 20, 2024).
- [21] Société suisse des ingénieurs et des architectes. “SIA 380/1 - Besoins de chaleur pour le chauffage”. In: (2016).
- [22] Federal Statistical Office. *Settlement and urban areas*. 2020. URL: <https://www.bfs.admin.ch/bfs/fr/home/statistiques/espace-environnement/utilisation-couverture-sol/surfaces-habitat-infrastructure.html> (visited on Jan. 15, 2024).
- [23] Swiss Federal Office of Energy SFOE. *Erfolgskontrolle Gebäudeenergiestandards*. 2014-2015. URL: <https://www.news.admin.ch/newsd/message/attachments/43534.pdf> (visited on Jan. 20, 2024).
- [24] Schweizerischer Verband für Wärme und Wasserkostenabrechnung. *Energetische Erfolgskontrolle in Mehrfamilienhaus-Neubauten ab 5 Bezüger*. SVWASC. 2016. URL: <http://svw-asc.ch/Portals/0/Dokumente/Downloads/SVW-Studie-Neubauten.pdf> (visited on Jan. 20, 2024).
- [25] C.Hoffmann and A.Geissler. *The prebound-effect in detail: real indoor temperatures in basements and measured versus calculated U-values and measured versus calculated U-values*. 2017. URL: <https://irf.fhnw.ch/server/api/core/bitstreams/9bf27939-902d-45a1-8b3b-10f52c028d14/content> (visited on Jan. 28, 2024).
- [26] L.Thaler and D.Kellenberger. *Addressing performance gaps: User behavior and sufficiency in the planning and operation phase of a 2000-Watt Site*. 2017. URL: <https://www.sciencedirect.com/science/article/pii/S1876610217333957> (visited on Jan. 28, 2024).
- [27] Conférence des directeurs cantonaux de l’énergie. *Politique énergétique des cantons*. EnDK. 2022. URL: <https://hubenergiebatiment.ch/politique-energetique-des-cantons/> (visited on Jan. 4, 2024).
- [28] *Genève est le premier canton à introduire une obligation d’assainissement des bâtiments*. Organisation faîtière de l’économie des énergies renouvelables et de l’efficacité énergétique. 2022. URL: <https://aeesuisse.ch/fr/news/geneve-est-le-premier-canton-a-introduire-une-obligation-d-assainissement-des-batiments/#:~:text=L%27IDC%20est%20abaiss%C3%A9%20%C3%A0,travaux%20de%20r%C3%A9novation%20d%C3%A8s%202022.> (visited on Jan. 28, 2024).
- [29] République et Canton de Genève. *Demander une autorisation de construire*. 2023. URL: <https://www.ge.ch/demander-autorisation-construire/documents-formulaires-joindre> (visited on Jan. 4, 2024).
- [30] *Optimiser la consommation de chaleur d’un bâtiment*. République et Canton de Geneve. 2023. URL: <https://www.ge.ch/optimiser-consommation-chaleur-batiment/comment-calculer-son-idc> (visited on Jan. 21, 2024).
- [31] *Nouvelle réglementation pour le bâti*. République et Canton de Geneve. 2023. URL: <https://www.ge.ch/nouvelle-reglementation-bati-qu-est-ce-qui-change/abaissement-du-seuil-idc> (visited on Jan. 21, 2024).

- [32] *SIA 380 - Bases pour les calculs énergétiques des bâtiments*. Société suisse des ingénieurs et des architectes. 2022. URL: <https://shop.sia.ch/normenwerk/architekt/sia%20380/f/F/Product/> (visited on Jan. 20, 2024).
- [33] *Détermination de la surface de référence énergétique*. SIA 380:2015. 2015. URL: https://www.local-energy.swiss/dam/jcr:9d3f7e29-c520-4ad0-a5e4-326a2e4c1651/EnerCoach_SRE%20batiment.pdf (visited on Jan. 21, 2024).
- [34] *The Swiss standard for comfort, efficiency and value preservation*. Minergie. 2017. URL: https://www.minergie.ch/media/20170906_flyer_minergie_allgemein_en_rgb.pdf (visited on Jan. 20, 2024).
- [35] Association CECB. *Le Certificat énergétique cantonal des bâtiments*. 2024. URL: <https://www.cecb.ch> (visited on Jan. 4, 2024).
- [36] *Logiciel de certifications et de bilans écologiques et énergétiques de bâtiments*. Lesosai. 2024. URL: <https://lesosai.com/logiciel/> (visited on Jan. 20, 2024).
- [37] K.H. Krauser R.Ahnert. *Typische Baukonstruktionen von 1860 bis 1960*. Verlag für Bauwesen. 2000-2002.
- [38] Monika Gisler. *Comment la Suisse a géré la crise pétrolière de 1973*. swissinfo. 2022. URL: <https://www.swissinfo.ch/fre/culture/comment-la-suisse-a-g%C3%A9r%C3%A9-la-crise-p%C3%A9troli%C3%A8re-de-1973/47959150> (visited on Jan. 22, 2024).
- [39] Hans Ulrich Jost Pierre Frey. *Les débuts de l'application du béton armé en Suisse: contribution à une histoire sociale et culturelle des techniques*. DA-EPF, UNIL. 2001. URL: https://www.unil.ch/files/live/sites/hist/files/shared/recherches/BETON_UNIL_EPFL.pdf (visited on Jan. 5, 2024).
- [40] Luc Girardin. "A GIS-based Methodology for the Evaluation of Integrated Energy Systems in Urban Area". PhD thesis. EPFL, 2012. DOI: 10.5075/epfl-thesis-5287. URL: http://infoscience.epfl.ch/record/170535/files/EPFL_TH5287.pdf.
- [41] Paul Michael Stadler. "Model-based sizing of building energy systems with renewable sources". PhD thesis. EPFL, 2019. DOI: 10.5075/epfl-thesis-9560. URL: http://infoscience.epfl.ch/record/267499/files/EPFL_TH9560.pdf.
- [42] Luise Middelhaue et al. "Grid-Aware Layout of Photovoltaic Panels in Sustainable Building Energy Systems". en. In: *Frontiers in Energy Research* 8 (Feb. 2021), p. 573290. ISSN: 2296-598X. DOI: 10.3389/fenrg.2020.573290. URL: <https://www.frontiersin.org/articles/10.3389/fenrg.2020.573290/full> (visited on Jan. 22, 2024).
- [43] Joseph Lousteau. *Qbuilding*. EPFL-IPESE. 2022. URL: <https://ipese-web.epfl.ch/lousteau/qbuildings.html> (visited on Jan. 20, 2024).
- [44] Swiss Federal Statistical Office. *Federal Register of Buildings and Dwellings*. 2024. URL: <https://www.bfs.admin.ch/bfs/en/home/registers/federal-register-buildings-dwellings.html> (visited on Jan. 23, 2024).
- [45] Swiss Federal Office of Energy SFOE. *Sonnendach*. 2022. URL: <https://www.bfe.admin.ch/bfe/en/home/supply/statistics-and-geodata/geoinformation/geodata/solar-energy/suitability-of-roofs-for-use-of-solar-energy.html> (visited on Jan. 23, 2024).
- [46] Cédric Terrier Joseph Lousteau Dorsan Lepour and François Maréchal. *From Local Energy Communities Towards National Energy System: A Grid-Aware Techno-Economic Analysis*. 2023. URL: <https://www.preprints.org/manuscript/202312.0456/v1> (visited on Jan. 31, 2024).
- [47] SITG. *Indice de dépense de chaleur (IDC) des bâtiments - moyenne*. 2023. URL: https://ge.ch/sitg/sitg_catalog/sitg_donnees?keyword=&geodataid=3506&topic=tous&service=tous&datatype=tous&distribution=tous&sort=auto (visited on Jan. 31, 2024).
- [48] Office cantonal de l'énergie. *Formulaire L00 - Justificatifs énergétiques par bâtiment*. République et canton de Genève. 2023. URL: <https://www.ge.ch/document/energie-formulaire-100-justificatifs-energetiques-batiment> (visited on Jan. 20, 2024).