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sweet swiss energy research for the energy transition

Summary

This document summarizes the objectives and findings of sub-task 2.3, conducted from September 2022 to October 2023, with a focus on developing a transition roadmap for Swiss building regulations. The primary aim of this research is to facilitate the achievement of higher Indoor Environmental Quality (IEQ) with minimal ecological footprint in the future generations of Swiss buildings. Through comprehensive analysis, this task has identified key performance metrics for energy and IEQ in buildings, categorizing them by type and usage specific to Switzerland. It also highlights current regulatory aspects that prioritize energy efficiency, potentially at the expense of IEQ. Additionally, a preliminary list of building elements potentially compromised in IEQ due to energy-focused regulations has been compiled for future in-depth analysis. Ultimately, the research outlines strategies aimed at refining existing regulations to enhance their synergistic potential for future analysis in subsequent steps, ensuring a balanced approach to energy efficiency and indoor environmental quality in Swiss buildings.

1 Introduction

The built environment has traditionally been the primary form of human structures created with the primary aim of protecting human life from natural hazards and improving human life by providing a desirably controlled environment. Millennia later, this shelter has become one of the most resource-consuming sectors in the world, consuming around 40% of the world's resources. In this context, numerous built-environment-related energy initiatives and decarbonization efforts have been developed as a global act toward protecting our worldwide resources, primarily focusing on minimizing non-renewable resource consumption in this sector. However, among all these initiatives that form the foundation for nationwide building norms and regulations, which in turn act as the guiding pattern for building practices in each nation, the comfort and well-being of occupants have been given marginal consideration. This is while the building's IEQ has a significant impact on the physiological health of its occupants, their overall life satisfaction and productivity, and consequently societal prosperity and welfare. Therefore, in recent years, efforts to integrate considerations that can enable improved levels of IEQ in buildings have been initiated to reassign the key role of building shelters to them while keeping resource consumption to a minimum level.

As part of a Swiss sustainability-driven consortium, the SWICE consortium [1] , the current sub-task titled "From existing to sufficient standards for indoor environmental quality" over a four-year horizon attempts to provide a guiding framework for enhancing Switzerland's current building legislation to better account for comfortable indoor conditions with minimal ecological impact in future generations of Swiss buildings. This enhancement aims for a higher level of indoor environmental quality (IEQ), considering four key aspects: thermal comfort, lighting efficiency, indoor air quality (IAQ), and acoustics, with minimum resource usage in Swiss residential, office, and school buildings, which accommodate the highest portion of the Swiss building population.

The current sub-task is part of work package 2, "Wellbeing, Standards, and Transition," within the SWICE consortium. On a larger scale, the Swiss national grand project of SWICE, over a period of 8 years and through collaboration between numerous academic and non-academic partners, aims to identify and quantify the energy-saving potential and opportunities for increased quality of life that can emerge from future urban and building scenarios. It considers the focus on the well-being of people as a crucial component of the energy transition and aims to propose environmental and technological solutions in three main sectors of change: the built environment, open spaces, and mobility, with people, considered the main agents of change in the ongoing energy transition.

This document details the project's first milestone, the "Report on Minimum Requirements for Energy and Indoor Environmental Quality (IEQ) in Existing Standards." Through this milestone, the document aims to accomplish four main foundational objectives of the current project:

1) This report attempts to comprehensively overview building codes, standards, and regulations with a particular emphasis on the criteria and guidelines for energy efficiency and comfort in buildings in Switzerland.

This foundational step will facilitate the identification of internationally recognized, widely adopted, and comprehensive performance metrics and targets for energy and IEQ with practical implications in Switzerland. These metrics are intended for use in subsequent stages of the research to evaluate the sufficiency of performance levels in a series of representative Swiss buildings.

2) Secondly, this study aims to examine the effects of energy efficiency-driven measures on indoor comfort based on an investigation of recent studies conducted in so-called green buildings and their conflicting performance metrics.
3) From the analysis of Swiss legislation for energy and comfort objectives in Swiss buildings, and through supplementary investigation of recent studies focused on the tension between energy and comfort performance in green buildings, this study will identify building-scale practices, supported by Swiss building regulations, that could potentially lead to a conflict between energy use and IEQ. These areas susceptible to conflict could potentially be improved through regulatory updates.
4) Ultimately, this part of the research will conclude with suggested future research directions based on the combination of existing solutions that can be promising for enhanced indoor conditions while keeping energy usage at a minimal level. These future directions will mainly focus on modulating and refining areas that currently aim to maximize energy efficiency but are susceptible to causing deficiencies for comfort objectives.

To address the above-mentioned objectives, the document will begin with a thorough review of Swiss building codes and standards pertaining to energy efficiency and comfort, with a major focus on the Swiss Society of Engineers and Architects (SIA) standards, regulations, guidelines, recommendations, and documentation, which are crucial for the Swiss construction industry. Section 2.3, will then delve into studies evaluated through surveys or simulations on the implications of energy-efficient practices on IEQ levels in buildings. Finally, the research will conclude with recommendations for potential enhancements to Swiss building regulations that not only account for the ecological integrity of the building but also for its occupant well-being.

2 Deliverable content

2.1 Review of Swiss regulations and guidelines for energy efficiency

In alignment with the project's first milestone, this section of the document begins by examining Swiss regulations and standards related to energy or comfort objectives in buildings. The aim is to identify potential tensions between the two in subsequent sections and to set the basis for exploring how to apply or reframe them to ensure a balanced functionality for buildings in later research phases. Recognizing that building regulation in Switzerland occurs at the federal level, as well as through laws and ordinances of the Cantons and municipalities, this section primarily analyzes the main regulations, standards, and voluntary labels affecting Swiss practices. These include the Swiss Society of Engineers and Architects (SIA) norms, the Cantonal Energy Directive (MoPEC), and the Minergie® labels. Due to the extensive collection of SIA documents, published over decades with comfort and energy information distributed within them, the analysis initially focused on the Swiss voluntary label of Minergie, which draws references from the Cantonal Energy Directive (MoPEC) and the Swiss Society of Engineers and Architects (SIA) documents. The process concludes with a review of the SIA documents, considered foundational for energy and comfort-related practices in Switzerland. This approach effectively narrows down the key SIA documents for detailed examination. Moreover, regional and communal regulations, mainly addressing spatial planning and territorial development practices, will be discussed in later versions of the report and subsequent project steps, where analysis of energy and comfort objectives will be conducted in real Swiss representative neighborhoods and building base cases to inform the Swiss buildings legislation of possible refinement directions based on the analysis results.

2.1.1 Swiss 2050 energy strategy and sectorial targets

The primary initiatives at the federal level in Switzerland regarding the energy performance of buildings correspond to the Swiss Energy Strategy 2050 and the related 2,000-watt Society concept. This concept has two main objectives for reducing energy consumption in relation to buildings by the intermediary year of 2050 [2]: 1) a 34% reduction in non-renewable primary energy use and 2) a 23% reduction in the Global Warming Potential (GWP) compared to the year 2005. Table 1 presents the Swiss 2000-Watt Society targets for annual total primary energy use and GHG emissions of a building for a future modeled year of 2150 and an intermediary year of 2050, aligning with the Swiss Energy Strategy 2050. This includes energy associated with the construction, operation, and mobility-induced energy usage of buildings. The calculation of the energy consumption index is based on the net-delivered energy to the building, the total amount of energy supplied to the building minus on-site renewable energy generation, considering any conversion losses and weighted by the total primary energy factor of the energy source. The primary energy factors for various fuel and electricity energy sources are elaborated on in Table 21, Table 22, and Table 23, in the Annex [2]. The primary energy factor of each energy network depends on the energy source category and the supply model, accounting for all system losses and auxiliary energy usage for extraction, transformation, refining, storing, transporting, and distributing the energy in the supply chain. In this respect, while non-renewable energy sources are penalized with factors ranging from 1-2.5, the use of renewable energy sources such as solar, geothermal, biological, and photovoltaics benefit from factors ranging from 0.05-1 [2]. This method for calculating the energy consumption index prioritizes the energy efficiency of building conditioning systems across SIA documents, highlighting two primary strategies: 1) enhancing efficiency in energy conversion and distribution systems, and 2) promoting investment in renewable energy sources to decrease reliance on fossil fuels. The Swiss 2050 energy strategy requires stricter regulations for non-renewable primary energy compared to total primary energy usage, thus, a key strategy for achieving the 2050 targets includes increasing the use of renewable primary energy to 1500 [W/p] by 2050, tripling the figure from 2005.

As shown in the tables in the Annex section, Switzerland's energy network for heating encounters the highest primary energy factors, given that building heating and domestic hot water consumption exceed 45% of the total energy use, with 80% being fossil-based (predominantly oil and gas) and imported [3]. Given these figures, building performance in this aspect has become the central focus of the Energy Strategy 2050. This focus is evident throughout the Swiss building regulatory framework, with many guidelines and prescriptions for building systems and enclosures designed mainly to address this primary aspect.

Table 1. Annual targets of the Swiss 2000-Watt Society for total primary energy consumption and GHG emissions.

Year		2005	2050	2150
Average annual energy consumption of total primary energy (renewable and nonrenewable)	[W/p]	6300	3500	2000
Average annual energy consumption of non-renewable primary energy	[W/p]	5800	2000	500
Average annual GHG emissions	[t/p]	8,6	2,0	1,0

The SIA 2040 document [2] supplements the objectives of the 2000-Watt Society by setting targets for different types of buildings in terms of operation, construction, and mobility-induced energy consumption, focusing on the intermediate goal for the 2000-Watt Society in the year 2050. Table 2, Table 3, and Table 4 introduce the sector-specific targets of the Swiss 2050 Energy Strategy for three main building categories: residential, office, and schools. The detailed assessment of embodied energy involved in the construction and disposal of buildings is addressed in Technical Specification SIA 2032 [4], focusing on the primary energy use per quantity of building material. Non-renewable primary energy use associated with building-location-dependent mobility is further elaborated on in Technical Specification SIA 2039 [2], corresponding to the primary energy use per kilometer traveled by a person or vehicle. Lastly, energy use for building operation, covering energy usage associated with heating, ventilation/air conditioning, lighting, and operating equipment in buildings, is addressed in SIA 2031 for non-air-conditioned buildings and in SIA 382/2 and SIA 2044 for air-conditioned buildings [5].

Table 2. Swiss sectoral guideline and target values for annual total primary energy use and GHG emissions in residential buildings.

	Primary non-renewable energy [MJ/m^2]		GHG emissions [kg/m^2]	
Residential	New building	Renovation	New building	Renovation
Guide value: Construction	110	60	8,5	5,0
Guide value: Operation	200	250	2,5	5,0
Guide value: Mobility	130	130	5,5	5,5
Target values	440		16,5	15,5

Table 3. Swiss sectoral guideline and target values for annual total primary energy use and GHG emissions in office buildings.

	Primary non-renewable energy [MJ/m²]		GHG emissions [kg/m²]	
Office	New building	Renovation	New building	Renovation
Guide value: Construction	130	80	10,0	6,0
Guide value: Operation	300	350	4,0	7,0
Guide value: Mobility	230	230	11,5	11,5
Target values	660		25,5	24,5

Table 4. Swiss sectoral guideline and target values for annual total primary energy use and GHG emissions in school buildings.

	Primary non-renewable energy [MJ/m²]		GHG emissions [kg/m²]	
Schools	New building	Renovation	New building	Renovation
Guide value: Construction	110	60	9,0	5,5
Guide value: Operation	180	230	2,5	5,0
Guide value: Mobility	60	60	3,0	3,0
Target values	350		14,5	13,5

As evident in Table 2, Table 3, and Table 4, the operation sector is the highest non-renewable energy consumer across all building categories. Accordingly, increasing energy efficiency and decarbonization in the building operation sector have become the central focus of Swiss building legislation. Furthermore, while the mobility-induced energy targets are identical for both renovation and new construction scenarios, the renovated scenarios are envisioned to result in lower GHG emissions in general, making renovation generally a more environmentally friendly option for compliance with Swiss energy targets.

In addition,

Table 5 drawn from 2024:2021[6] provides further detail on energy usage targets in the building operation sector for heating, ventilation/air conditioning, lighting, and operating equipment in the main zone types of three main building use categories: residential, office, and schools. The extended version of this table, providing a comprehensive overview of energy usage targets in the building operation sector for various building categories and zone usage types, is provided in Table 24 in the Annex section. Table 24 further elucidates that the heating and domestic hot water categories form the highest energy consumption sector across many zone types in the targeted horizon. While the 2050 energy strategy significantly emphasizes energy sources with the highest primary energy factors, particularly for heating, this emphasis is further reinforced by the substantial proportion of energy used for heating in buildings.

Table 5. Annual breakdown of net-delivered energy consumption targets by operational sectors (appliances, lighting, HVAC) across residential, office, and school building types

		Electrical energy			Thermal energy		
Zone type		Appliances E_A [kWh/m²]	Process plants E_{PS} [kWh/m²]	Lighting E_L [kWh/m²]	Refrigeration cooling Q_c [kWh/m²]	Heating Q_H [kWh/m²]	Domestic hot water Q_W [kWh/m²]
1.01	Multifamily housing	10,8	0	2,0	3,0	10,0	16,9
1.02	Single-family housing	8,9	0	2,0	1,2	15,5	13,5
3.01	Private and shared offices	17,5	0	2,8	5,3	10,2	2,6
3.02	Open space office	29,1	0	7,0	14,1	1,5	3,6
3.03	Meeting room	5,6	0	1,6	4,8	12,5	0
3.04	Service hall	5,8	0	3,2	3,0	8,6	0
4.01	School lobby	7,1	0	3,2	6,3	10,9	4,0
4.02	Staff room	3,0	0	1,2	3,1	17,2	0
4.03	Library	1,5	0	2,7	2,9	8,5	0
4.04	Auditorium	21,8	0	6,0	19,2	1,8	5,3
4.05	Classrooms	3,5	0	3,2	4,3	12,5	3,2

In this respect, in alignment with the SIA 2040 objectives, the mandatory standard SIA 380/1:2016 [7] offers two pathways for justifications: 1) adhering to efficiency values for the envelope, and/or 2) demonstrating, through energy performance simulation, that a certain limit value for the heating energy demand is met. The limit value for heating energy demand is defined through an equation involving factors related to the type of building (residential, office, etc.) and its shape factor[1] (ratio between thermal envelope and energy reference floor area), as well as the average outdoor temperature. Table 6 table shows the Swiss limit values for heating energy usage in newly constructed buildings. Limit values in Table 6 are set for an average annual temperature of 9.5°C, with a 6% adjustment for every 1°C deviation. Furthermore, the values presented in Table 6 correspond to the limit value for newly constructed buildings, while renovated ones face limits at 150% of these. Heating targets for new buildings are 60% of their limit values, and for renovations, they match the new construction limits.

[1] SIA 380/1:2016 defines the "envelope shape factors" as the ratio between the thermal envelope surface area, including surfaces in contact with the outside, with unheated zones, and with the ground, and the energy reference surface area.

Table 6. Swiss national limit values for the annual heating energy requirement by building category based on an average annual temperature of 9.5 °C.

Building category		Limit values	
		Base QH [kWh/m²]	Increase DQH [kWh/m²]
I	Multifamily housing	13	15
II	Single-family housing	16	15
III	Office	13	15
IV	School	14	15
V	Commercial	7	14
VI	Laboratory	16	15
VII	Conference hall	18	15
VIII	Hospital	18	17
IX	Industrial	10	14
X	Storage facility	14	14
XI	Sports facility	16	14
XII	Indoor pool	15	18

Table 6 presents two sets of limit values: a baseline and an increased value. These values respectively apply to buildings with envelope shape factors between 0.4 and 0.8, classified as compact buildings, and buildings with envelope shape factors exceeding 2, classified as low compact buildings. The latter are subject to stricter compliance values, thereby reducing their dominance in the Swiss legislative framework as a strategy to minimize the heating penalty associated with a higher surface-to-volume ratio in buildings. Furthermore, according to Table 6, multifamily houses, offices, and commercial buildings, despite their high occupancy rates, are assigned the lowest baseline values. This indicates that these building categories are targeted for stricter energy efficiency strategies. Consequently, if energy-efficiency-oriented strategies, some of which may conflict with comfort objectives, are adopted without careful consideration, these buildings are, therefore, more likely to experience deficient comfort levels. Table 6 also suggests that developing multifamily houses over single-family houses, due to their lower exterior surface area per dwelling unit, is a more effective strategy for energy conservation, thereby making quality densification of residential units an efficient approach for lowering heating energy usage in buildings.

The emphasis on implementing mechanisms to meet reduced heating energy targets is a common theme across many SIA documents. As a result, most guidelines related to building envelopes are also designed to support this focus, which could conflict with indoor comfort requirements. A detailed investigation of this topic is planned for Section 2.3. Additionally, to harmonize energy efficiency regulations throughout Switzerland, the "Conference of Cantonal Energy Directors" (EnDK) established model regulations in 2014 [8]. These are compiled in the "Model Energy Prescriptions of the Cantons" (MoPEC) and serve as a reference for various Swiss voluntary labels [9]. As a result, these voluntary labels adhere to the principles of the SIA regulation, mainly by limiting energy efficiency criteria and treating building comfort as a secondary concern.

Moreover, SIA 2050:201 [10] and related documents [11] outline the "quality densification" of built-up areas. This approach generally aims to increase the return on investment through efficient land use with compact buildings, thereby facilitating environmentally friendly mobility solutions and effective utilization of waste heat and local renewable energy sources. However, this practice is also associated with challenges such as solar obstruction, urban heat island (UHI) effects, wind blockage, and increased levels of air and noise pollution, which necessitate careful design adjustments to mitigate the adverse effects on the indoor climate [12], [13], [14], [15]. Switzerland's standards for land and territory occupation are based on municipal policies [16], and there are no federal or cantonal references for constructing a neighborhood model for analyzing and potentially adjusting factors related to urban densification. Nonetheless, the Conference of Architects of Construction, Planning, and the Environment (BPUK) adopted the Concordat "Inter-Cantonal Agreement on the Harmonization of Construction Terms (IVHB)" in 2005 to harmonize key construction terms and measurement methods across Switzerland [16].

In conclusion, consistent with the primary goals of the Swiss 2050 energy strategy, minimizing undesirable thermal loads from external ambient conditions remains the central focus of the specifications detailed across SIA documents. The main theme is the use of technical systems that avoid fossil fuels, employ energy-efficient systems, and implement energy-efficient building envelopes. Although recent versions of the Minergie voluntary label now emphasize the importance of healthy and ecological buildings, the main consideration still focuses on the ecological footprint of construction materials and the advocacy for eco-friendly materials. Thus, a promising strategy to enhance indoor climate quality in Switzerland, while aligning with the 2050 energy goals, seems to be an increased reliance on envelope-integrated renewable energy systems. Serving as mediators, these systems can compensate for part of the building's energy consumption, potentially allowing for more flexible building envelope regulations that primarily aim to meet the energy conservation targets from the SIA 2050 perspective.

2.2 Standards and guidelines for indoor comfort and health

Buildings with high levels of indoor environmental quality represent the next generation of green buildings designed to support the physical, psychological, and well-being of occupants. The design decisions in such buildings are driven not by the designer's aesthetic preferences, but by aspects that foster symbiotic functionality and support human well-being and productivity.

Research on the development of IEQ standards primarily employs laboratory instruments within controlled-environment test chambers for non-intrusive monitoring of selected environmental parameters over certain periods. This approach is complemented by subjective surveys that inquire about individuals' feelings or satisfaction with specific IEQ factors, following specific protocols [17]. In this respect, the evaluation of IEQ in buildings employs monitoring of environmental parameters of interest, supplemented by subjective surveys, drawing on principles from controlled-environment test chamber studies. The primary aim is to identify correlations between an adopted scenario and comfort perceptions and to compare indoor climates and comfort perceptions between "green buildings" and "conventional buildings," as well as before and after renovation interventions [17], [18], [19]. Findings from these surveys have, in fact, highlighted that non-environmental factors such as gender, age, climatic background, residence duration, and activity type, though not yet incorporated into the formulation of standard comfort indices, also affect occupants' satisfaction regarding IEQ parameters and their overall comfort perception [20], [21], [22].

Additionally, while physical measurements of indoor environmental parameters remain a dominant method for indoor IEQ estimation and metric development, the recent emergence of Building

Performance Simulation(BPS) tools, which use principles from on-site survey guidelines, has significantly enhanced the ability to anticipate IEQ through detailed investigations of the impacts of different design scenarios on multiple performance metrics. These BPS tools mainly rely on partial differential equations for energy, thermal, and IAQ calculations, [23] and for daylight and acoustics, they primarily operate based on physically based ray-tracing algorithms [24]. Ensuring high-resolution prediction for all indoor environmental parameters, however, remains a challenge in parametric workflows, leading to attempts to address this through models and tools founded on simplified assumptions. However, this approach increases the risk of a performance gap if the assumptions are not accurately formulated. Nonetheless, BPS tools have facilitated the integration of comprehensive indoor environmental assessments into the building design process, contributing to the development of the next generation of green buildings that account for occupants' health in addition to the ecological footprint.

This section offers an in-depth analysis of IEQ metrics based on SIA guidelines and recommendations, encompassing four core IEQ domains: Thermal Comfort, IAQ, Daylight, and Acoustics. It reviews the standards and regulations regarding these factors with practical implications in Switzerland. The definitions and targets for comfort metrics in these documents primarily derive from international standards set by ISO (International Organization for Standardization), CEN (European Committee for Standardization), and ASHRAE (American Society of Heating, Refrigerating, and Air Conditioning Engineers). In alignment with these standards, the State Secretariat for Economic Affairs (SECO)[25], a federal agency in Switzerland that oversees national and international economic policies and Swiss labor market laws, establishes specific policy frameworks and strategies to ensure safe and healthy working conditions for employees. As part of the Federal Department of Economic Affairs, Education, and Research (EAER), SECO aims broadly to contribute to sustainable economic growth, fair employment services, and working conditions, along with the protection of personal integrity in workplaces. SECO in Ordinance 3 to the Labour Law is focused on maintaining good IEQ in workplaces, drawing largely from the Swiss Federal Office of Energy (SFOE) guidelines and aligning with the SIA standards and requirements. In subsequent paragraphs, any comprehensive SECO guidelines on IEQ that do not reference existing SIA documents will be noted. The emphasis on IEQ in workplaces, backed by legal support in Switzerland, can lead to legal repercussions for workstations in Switzerland in cases of non-compliance, emphasizing the priority given to IEQ in these settings. Therefore, except for the legal support for IEQ provision in work environments, the rest of the IEQ-centered standards and guidelines are not mandatorily imposed in Swiss building practices. However, since SIA mandates specific levels of performance regarding thermal performance in buildings, guidelines related to aspects associated with this performance, specifically thermal comfort and IAQ due to their role in heat recovery in buildings, receive higher priority in execution.

2.2.1 Standards and guidelines for thermal comfort

In this regard, indoor thermal comfort in Switzerland is primarily assessed through the Predicted Mean Vote (PMV) and the Adaptive Comfort Model, corresponding to SN EN ISO 7730 [26], [27]. The PMV, a static approach based on surveys conducted in controlled laboratory conditions, ranges from cold (-3) to hot (+3), with -0.5 to +0.5 indicating the comfort range. PMV is a function of six parameters: air temperature, mean radiant temperature, relative humidity, air speed, metabolic rate, and clothing insulation [28]. While widely validated for mechanically cooled or heated buildings, it has yet to be significantly verified for naturally ventilated buildings [29]. In this respect, Figure 1 in SIA 180:2014 [27] presents the optimum operating temperature for conditioned rooms as a function of the type of activity and clothing insulation, for a relative humidity of 30-70% and an airspeed of less than 0.1 m/s in the occupied area.

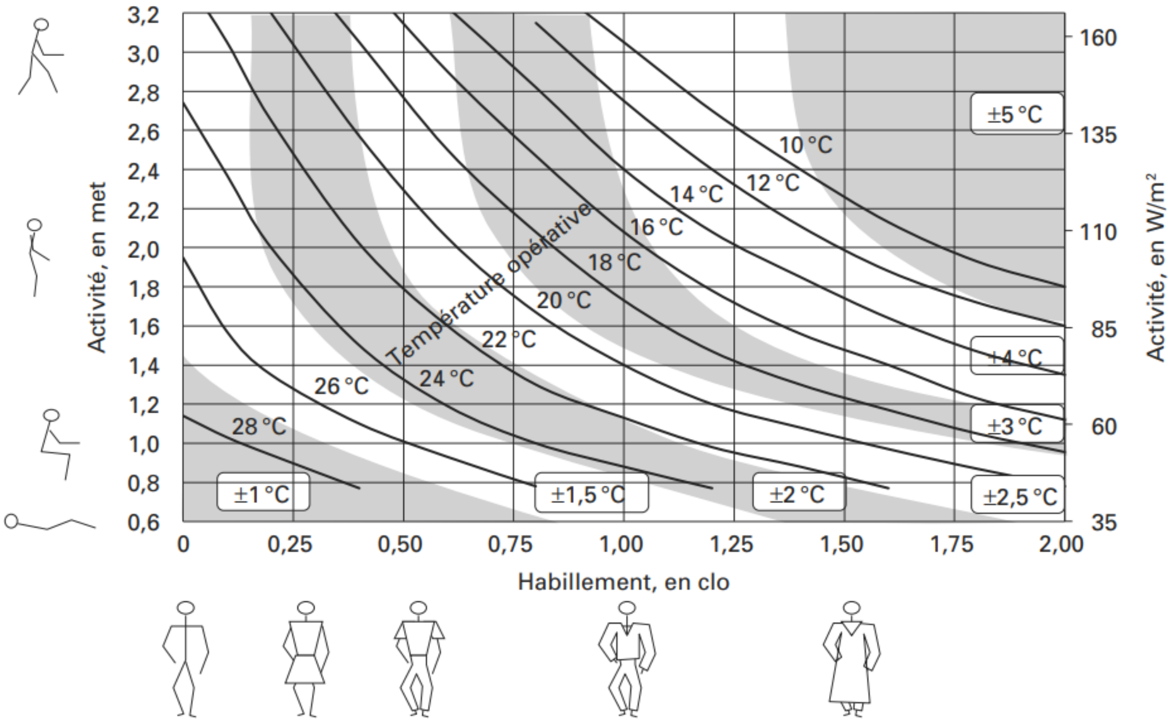

Figure 1. Graphical representation of the optimal thermal comfort zone based on varying levels of physical activity and clothing insulation. The contours indicate constant operative temperatures (θo) for thermal comfort.

SIA 4001:2022 [26] also sets thermal comfort performance criteria based on the PMV model in Switzerland. Table 7 outlines compliance criteria for thermal comfort based on EN 16798-1, emphasizing the significance of air temperature and localized thermal effects, and considers temperature differences between the head and feet and horizontal and vertical radiant temperature asymmetries in individual assessments. Specific criteria for these factors are also outlined, and while EN 16798-1 considered three distinct comfort categories, in SIA 180:2014 [27], the medium category II is selected as the evaluation basis for thermal comfort based on the PMV model in Switzerland.

Table 7. Compliance criteria for thermal comfort.

Category	Operative temprature		Air currents		Temperature at head level		Floor temperature		Radiant temperature asymmetry	
	PPD	PMV	DR %	Maximum air speed[a]		PD %	Temprature difference[b] [K]	PD %	Temperature range [C]	PD %
				Winter [m/s]	Summer[c] [m/s]					
I	< 6	—0,2 up to +0,2	10	0,10	0,12	3	2	10	19 up to 29	5
II	< 10	—0,5 up to +0,5	20	0,16	0,19	5	3	10	19 up to 29	5
III	< 15	—0,7 up to +0,7	30	0,21	0,24	10	4	15	17 up to 31	10

[a] Based on an activity of 1.2 met, a degree of turbulence of 40%, and an air temperature equal to the operating temperature of around 20°C in winter and 23°C in summer.

[b] Temperature difference between 1.1 m and 0.1 m above ground.

[c] At air temperatures above 25°C, higher maximum air speeds are permitted and often even preferred (the air current becomes a pleasant breeze), but only on condition that building users can directly adjust the air speed.

The Adaptive Comfort Model, particularly applicable to naturally conditioned spaces, allows outdoor climate to influence the comfort zone. This model accounts for occupants' behavioral adaptations and past thermal history, applicable when outdoor dry bulb temperatures range from 10–33.5°C [26]. This model calculates the comfort temperature according to a simple prevailing mean outdoor air temperature for a period between the last 7–30 days before the day in question. Limits of 80% and 90% are common values to choose the range of thermal acceptability [26]. In Switzerland, to ensure the provision of thermal comfort during the warm seasons, Table 8 drawn from SIA 382/1:2014 [30] proposes guidelines for assessing cooling requirements in buildings to prevent overheating and thermal discomfort. Three distinct ranges of internal heat gain per day (in Wh/m^2) are used to determine cooling requirements and, based on Table 8, when internal heat gain exceeds 200 Wh/m^2 per day, cooling is deemed necessary to ensure thermal comfort, regardless of whether natural ventilation is used.

Table 8. Guidelines for assessing cooling requirements in buildings to prevent overheating and thermal discomfort during warm seasons.

Internal heat gain per day, in Wh/m^2			Cooling
With window ventilation day and night	With window ventilation for occupied hours	Without window ventilation	
> 200	> 140	> 120	Necessary[a]
140-200	100-140	80-120	Desired[a]
< 140	< 100	< 80	Not necessary

[a] Cooling only permitted with systems with low power requirements.

2.2.2 Standards and guidelines for air quality

A commonly used IAQ evaluation in human habitats relates to the assessment of the concentration of carbon dioxide (CO2), total volatile organic compounds (TVOC), nitrogen dioxide (NO2), and ozone (O3), as well as inhalable particles (PM10), fine particles (PM2.5), all of which are associated with adverse health for humans [31]. In Switzerland, the predominant mechanism for ensuring optimal IAQ in buildings relies on mechanical ventilation. The focus is particularly on ventilation heat recovery systems, which, with a minimum efficiency of 70%, allow for temperature control of supply air and energy savings in colder months.

In this regard, SIA 384.201:2017 [32] provides default values for the Minimum Air Change Rates in different types of building units, in accordance with the widely recognized ANSI/ASHRAE Standard 62.1 [33]. The values defined in Table 9 are categorized based on the building status, being newly constructed or old, direct exposure of the zone to the building envelope, and the ventilation strategies implemented in the zone. SIA 384.201:2017 [32] suggests that, in general, mechanical ventilation, especially with heat recovery, is a superior option for maintaining adequate air quality, as it indicates that zones with this ventilation strategy require fewer air changes per hour. This implies the efficient performance of these systems in better-controlling airflow and the ability to filter and modify incoming air. Table 9 also suggests that an intermittent mechanical ventilation strategy would require higher air change rates than continuous systems, due to the need to compensate for the times when the ventilation system is off. However, SIA 384.201:2017 [32] mentions that the values in Table 9 are valid when air pollution reduction measures, depending on the main contributor to the contamination, have been taken and no extraordinary sources of indoor pollution are foreseeable.

Table 9. Swiss national recommended values for the minimum air change rates

Type of part		Minimum air change rate	
		New building according to SIA 180	Old buildings
		n_{min} [h^{-1}]	
Building unit without mechanical ventilation in baths and showers	Bathroom / shower	0,5	0,7
	Rooms with direct exposure to the building's envelope	0,3	0,5
	Rooms without direct exposure to the building's envelope	0	0
Building unit with intermittent mechanical ventilation in baths and showers	Rooms with direct exposure to the building's envelope	0,35	0,55
	Rooms without direct exposure to the building's envelope	0	0
Building unit without bath or shower	Rooms with direct exposure to the building's envelope	0,3	0,5
	Rooms without direct exposure to the building's envelope	0	0
Building unit with mechanical ventilation with heat recovery	For all rooms	0,1	0,3
Building unit with mechanical ventilation	Rooms with direct exposure to the building's envelope	0,4	0,6
	Rooms without direct exposure to the building's envelope	0	0

Apart from airflow rate, CO2 concentration is widely utilized as an IAQ indicator (usually set between 800 ppm and 1200 ppm) [34], since CO2 concentration, where human occupancy is the sole source of CO2, can serve as an alternative ventilation metric reflecting the effectiveness of the ventilation strategy [31]. In this context, Table 26 in the annex section, which is drawn from SECO requirements [25], provides further details specifying the levels of CO2 concentration that must be maintained in workplaces to ensure adequate IAQ.

In addition, in Switzerland, there are no binding limit values for indoor air pollutants, except for radon: the radon concentration in occupied spaces should not exceed 300 Bq/m3 [30]. Additionally, specific concentration limits for traffic-related pollutants of nitrogen dioxide (NO2) and particulate matter (PM10), which are of particular concern in areas where limit values are exceeded, are outlined in the Ordinance on Air Pollution Control (LRV) according to SIA 382/1:2014 [30]. Table 10 shows a leveled approach to NO2 and PM10 limits, with a standard long-term (annual mean) limit and an additional limit for short-term exposure (24-hour mean). Hourly mean atmospheric pollution data can be obtained from the National Air Pollution Monitoring Network (NABEL) database in Switzerland [35]. Table 25, in the Annex section, presents mean values of NO2 and PM10 concentrations from various measuring stations categorized by location types in Switzerland. Table 25 shows a clear pattern; the concentrations of NO2 and PM10 decrease as the location becomes more rural and elevated, which can be attributed to lower traffic volumes and industrial activity and the dispersion effects at higher altitudes. Based on Table 25, except for the Härkingen-A1 station in the canton of Solothurn in Switzerland, most measuring stations report NO2 and PM10 concentrations within the Swiss national limit values.

Table 10. Swiss national immission limits for traffic-related pollutants in indoor areas with concerning outdoor pollution levels

Pollutant	Immission limit value	Statistical definition
Nitrogen dioxide NO_2	30 µg/m³	Annual mean (arithmetic mean)
	100 µg/m³	95% of the hourly mean values over a year must not exceed 100 µg/m³
	80 µg/m³	The 24-hour mean value should not be exceeded more than once annually
Suspended particulate matter PM_{10}	20 µg/m³	Annual mean (arithmetic mean)
	50 µg/m³	The 24-hour mean value should not be exceeded more than once annually

2.2.3 Standards and guidelines for daylighting

Daylight availability in space has a critical contribution to human health through productivity enhancement and maintenance of circadian rhythms. SIA 4001:2022 [26] and SIA 2056:2019 [36] provide insights on achieving desired levels of daylight in buildings. SIA 4001:2022 [26] and SIA 2056:2019 [36], in line with the SN EN 12464-1 standard [37] and SN EN 17037 [38], provide guidelines on achieving desired daylight levels in buildings. Specifically, SN EN 17037 offers recommendations on daylight provision in buildings across four categories: daylight provision, access to direct sunlight, view access, and protection from glare, while SN EN 12464-1 establishes required illuminance levels for various workplace tasks. Table 11, drawn from SIA 4001:2022, provides a range of recommended illuminance levels for various types of premises and activities, considering the complexity and precision of tasks performed in space. Additionally, highlighting the significant influence of light on synchronizing physiological processes such as metabolism, circulation, hormonal balance, and immune system function, as well as the psychological well-being of employees, SECO [25] provides a more comprehensive version of Table 11 for working environments, featuring more intervals that are specified for various workspaces based on the activities conducted within them. Further details can be found in Table 27 in the annex section.

Table 11. Recommended average illuminance levels from combined natural and artificial lighting sources by building zone usage.

Type of premises and activity	Recommended illuminance [lux]		
	Minimum	Medium	High
Circulation areas, corridors, theaters, concert halls	50	100	200
Workshops, conference halls, warehouses	200	300	400
Schools, offices, spaces for routine activities such as reading, writing, and computer work	300	400	500
Spaces for detailed activities such as drawing, tracing, technical work	500	750	1000
Precision workshops, color inspection, visual quality control	1000	up to	5000

Spatial Daylight Autonomy (sDA) is a comprehensive metric used in SN EN 17037 to evaluate daylight provision conditions under varying sky conditions annually, considering the time spent in those conditions and occupancy patterns. In this respect, Table 12, in alignment with European standard SN EN 17037, presents general recommendations for daylighting in living space. Table 12 suggests that 50% of the surface area should meet the recommended illuminance level and that 50% of the time during occupancy should be exposed to natural daylight. It also implies that as the need for higher illuminance increases, the design of the space must accommodate a higher daylight factor, potentially affecting daylighting strategies that can capture and transmit more daylight into the interior space. These recommendations, outlined in SIA 4001:2022 [26] and SIA 2056:2019 [36], also emphasize the importance of optimizing sunlight hours to reduce reliance on artificial lighting; however, they remain as suggestions, without providing an explicit mechanism for their application or for reaching the proposed illuminance levels.

Table 12. General recommendations for daylighting in living spaces via vertical and inclined openings.

Class requirement	Recommended illuminance [lux]	Surface area at recommended illuminance level	Time spent in natural light	Corresponding daylight factor
Minimum	300 Lux	50%	50%	1,9 %
Medium	500 Lux	50%	50%	3,1 %
High	750 Lux	50%	50%	4,7 %

Furthermore, in relation to access to direct sunlight, view access, and protection from glare, SIA 2056:2019 [36] highlights that detailed information is available in Standard SN EN 17037. Tables in the Annex section, Table 27, Table 28, Table 29, and Table 30 provide more specific recommendations for aspects of building design related to daylighting, direct sunlight access, views, and glare protection in accordance with Standard SN EN 17037. The selected method for predicting glare discomfort is the Daylight Glare Probability (DGP) index [39]. Furthermore, assessing the view outside involves three key aspects: horizontal sight angle, outside distance of view, and the number of view layers. The view metric provides minimum, medium, and high levels determined by a combination of these three factors. While these latter two metrics are vital for effective daylighting strategies yielding positive perceptual or physiological effects, they aren't directly referenced in SIA documents, likely due to their intricate nature and dependence on the field of view and/or time-intensive simulations.

2.2.4 Standards and guidelines for acoustics

Lastly, acoustic comfort metrics are primarily evaluated through parameters such as reverberation time, sound pressure levels, and the speech transmission index. Reverberation time, the most prevalent acoustic metric, is defined as the time required for the sound pressure to decrease by 60 dB from the initial level and is a function of room volume and equivalent absorption surface. SIA 181:2020 [40] provides minimum requirements for effective sound isolation, encompassing both airborne and impact noises. Table 13 provides details on the minimum standards for airborne sound insulation to protect against external noise. In addition, Table 31 and Table 32, placed in the annex section, outline the minimum requirements for airborne sound insulation against internal noise and impact sound insulation, respectively. These specify requirement values across different levels of noise pollution intensity and noise sensitivity.

In these tables, sound insulation is measured as the standardized sound level difference in dB between a source room and a receiving room, standardized to a reference reverberation time of 0.5 s and a reference sound pressure of 20 μPa. Generally, spaces expected to experience higher noise pollution or those with a higher noise sensitivity class require higher sound insulation levels. Moreover, the requirement values for minimum airborne sound insulation against external noise vary not only by noise sensitivity class and noise pollution intensity but also by time of day. Spaces with a high noise sensitivity class require greater sound insulation to accommodate typical human activity patterns and the need for rest. Lastly, Table 14 sets guidelines for protection against continuous noise from ventilation systems, quantified using sound level differences and standardized sound pressure levels, with a reference reverberation time of 0.5 seconds.

Table 13. Minimum airborne sound insulation standards for protection against external noise

External noise intensity	Small to moderate		Considerable to very strong	
Assessment period	Day	Night	Day	Night
Rating level [dB]	L_r <= 60	L_r <= 52	L_r > 60	L_r > 52
Noise sensitivity class	Requirement values D_e			
Minimum	22 dB	22 dB	L_r - 38 dB	L_r - 30 dB
Medium	27 dB	27 dB	L_r - 33 dB	L_r- 25 dB
High	32 dB	32 dB	L_r - 28 dB	L_r- 20 dB

Table 14. Minimum standards for continuous noise control for protection against ventilation systems

Noise sensitivity class	Type of premises	Requirement values L_H	Increased level L_H
Minimum	Bathroom/shower/WC, kitchen without living area	33 dB	29 dB
Medium	Living room, bedroom, kitchen	28 dB	25 dB

From a broad perspective on IEQ research in green buildings, previous studies have shown that occupants of green buildings, constructed to higher energy standards, typically tend to show higher satisfaction with air quality and thermal comfort compared to those in conventional buildings [41], whereas satisfaction with lighting shows little difference between certified and 'non-green' buildings [21]. Most notably, there is a clear trend toward decreased acoustic satisfaction in green buildings [42], [43]. This difference may be explained, at least in part, by the priorities, and thus incentives, given in green building standards to these comfort aspects due to their respective impacts on the building's overall energy consumption. Indeed, while heating and cooling account for approximately 50% of a building's total operational energy consumption [2], prioritizing thermal comfort, acoustics do not directly impact energy consumption. This means that buildings labeled as energy-efficient may overlook potential acoustic enhancements. Additionally, due to penalties associated with increased artificial lighting, which accounts for about 15% of energy consumption [2], there is only a marginal emphasis on natural daylighting. However, there are definite incentives to incorporate controllable ventilation systems for airflow modulation, as this is integral to thermal management. The use of mechanical ventilation, while aiding in maintaining IAQ, can also facilitate energy savings through heat recovery in winter, making it an energetically superior option to uncontrolled window ventilation.

Overall, comfort in indoor spaces is an intricate aspect that encompasses different factors such as source environment (ambient surroundings, light and sound sources, and contaminant origins), the building's geometric configuration, surface properties (thermal, optical, and acoustic), airflow characteristics, HVAC specifics, and humans as the end receivers. While the source environment establishes the setting, elements like zone dimensions, surface properties, and forces such as wind, buoyancy, mechanical ventilation, and internal gains significantly influence indoor climate conditions. Recent research has also highlighted that an individual's unique characteristics influence comfort perception in these settings. While physical measurements of indoor environmental parameters remain a prominent method for indoor IEQ estimation, the emergence of BPS tools has significantly enhanced the ability to anticipate indoor conditions through detailed investigations of the impacts of variables on multiple performance metrics. The research in this filed has ultimately facilitated the integration of extensive indoor environmental assessments into the building design process, contributing to the development of the next generation of green buildings that prioritize occupants' health in addition to minimizing the ecological footprint.

2.3 Exploration of the implications of energy efficiency measures on indoor comfort

This section reviews recent studies on the implications of energy efficiency measures, advocated by legislative frameworks for building practices, on indoor comfort and life cycle greenhouse gas emissions. It aims to identify areas in the current regulatory framework that prioritize energy efficiency but may compromise indoor conditions. This section primarily examines the main SIA directives that regulate or recommend specific requirements for building architectural, construction, and operational properties. It then presents findings from studies focused on the tension between regulated requirements and IEQ requirements. According to literature findings, while energy-oriented mandates and recommendations sometimes conflict with achieving adequate IEQ levels, in most cases, they either limit design options that could enhance synergy between IEQ and energy in buildings or may lead to interpretations in practice that risk buildings' synergistic performance. This section first addresses practices at the neighborhood scale that pose a risk to IEQ provisions and then continues with building-scale practices. The dedicated section on building practices begins by examining the strictest requirements regarding building practices within the Swiss building legislation and concludes with the aspects for which no predefined values exist, but where misinterpretation of these aspects in practice has sometimes led to deficient outcomes for indoor comfort.

Urban densification, aimed at enhancing energy efficiency in urban settings primarily through the reduction of transportation emissions, has been investigated in many previous studies [12], [14], [44], [45], [46] as a practice that carries implications for building microclimates and poses a risk to IEQ. Generally, dense urban morphology increases risks of solar obstruction, urban heat islands (UHI), wind flow blockage, and traffic-related air and acoustic pollution. However, previous research [12], [13], [14], [44], [45], [46], [47] has shown that in neighborhoods with similar densities, the negative impact of densification on environmental quality can be alleviated by adjusting specific morphological descriptors, each having a specific weight on each environmental quality aspect. The impact magnitude and the level of adjustment of these morphological factors vary based on site specifics. In previous studies, the focus has often been on building footprint ratio, mean building height, complexity, compactness, sky view factor, front area ratio, enclosure degree, etc. for improving micro-climate responses in neighborhoods [43], [44], [45], [46], [47], [48]. Additionally, these studies commonly used predictive metamodels as an alternative method for managing large-scale simulations [50], [51]. These metamodels, trained on real data from urban forms with identical density but varied layouts, allowed for the determination of the statistical significance of examined morphological indicators, highlighting the primary morphological features that govern urban interactions with the microclimate. Therefore, developing meta-models to create efficient densification intervention scenarios for representative Swiss neighborhood models appears to be an effective approach. This method aims to highlight the most significant descriptors correlated to microclimate responses and reconcile these two conflicting needs in neighborhood fabrics. Informing the Swiss legislative framework of effective layout and terrain development models will be one of the focus of the study's next step.

In addition to neighborhood morphology, building morphology and massing type in neighborhood settings are also identified as key factors affecting building load exchange rates with the ambient environment and, correspondingly, building comfort levels [49], [52], [53], [54]. Green building practices often require compact building footprints to reduce energy use for building conditioning, particularly heating, as the increase in building exterior wall areas can potentially lead to higher heat losses. SIA 380/1:2016 [7]also states stricter heating energy requirements for buildings with higher exterior surface-to-total volume indices as presented in Table 6. However, higher surface-to-volume ratios, on the other hand, increase opportunities for larger exterior wall areas, allowing for narrower floor plate depths and supporting higher levels of natural daylighting and cross-ventilation in buildings [55]. Meanwhile, research focused on the synergistic potential of energy and IEQ has shown that for each building morphology, a unique set of technological interventions can be identified. Even variants with lower surface compactness, with efficient consideration, can achieve the same energy performance level as more compact variants while generally providing better indoor conditions [49], [53], [56], [57], [58]. This indicates that in addition to focusing solely on minimizing building surface exposure to the outdoors and potentially impairing daylight and IAQ levels, legislative updates may consider more flexibility in building footprint design so that achieving functional balance in the future generation of buildings becomes a task with fewer complications.

In this respect, SIA 380/1:2016 [7] mandates specific U-values for various building envelope elements. In this regard, Table 15 provides the limit values for thermal transmittance for newly constructed buildings for different building elements in Switzerland. Compliance with these limit values is mandatory in Switzerland; in addition, the recommended target values for the U-values of building elements in Switzerland are presented in Table 16. Due to the lower required heat flow for unheated zones and zones buried more than 2 meters, these elements are subjected to less stringent requirements in terms of insulation levels according to Table 15. Furthermore, based on Table 15, windows and glass doors, compared to opaque envelopes, have much higher U-values, resulting in heating energy penalties in buildings as the limitations of currently available technologies do not allow for any stricter requirements. To control the thermal load exchange through the envelope, SIA 380/1:2016 [7] also defines specifications on the linear thermal transmittance for various types of thermal bridges in a building's structure, as specified in Table 33, in the annex section. Based on Table 33, four types of thermal bridges are defined, each with a specific limit value. In this context, a window sill adjoining a wall has the lowest limit value, suggesting that this element is a critical thermal bridge location where strict insulation standards are required.

This results in considering these elements as potential weak points in building facades. Therefore, green building practices in Switzerland implicitly dictate low window-to-wall ratios (WWR) so that compliance with the heating energy demand limits will be attainable. Furthermore, to comply with the current level of limit values and target values for transparent elements of the building, aspects related to daylight and view should be compromised, as the currently available generation of fenestration solutions with the U-values in the regulated range, which are triple glazing systems, have T-vis lower than the normal single or double glazing options with less energy efficiency [59]. However, as building openings play a crucial role in managing daylighting and air quality as well, this area is highlighted as one of the main and most critical areas of focus for researchers and developers to holistically meet sustainability goals.

Table 15. Limit values for thermal transmittance coefficients for new buildings for an indoor temperature of 20°C.

Elements against	U limit values with proof of thermal bridges [W/(m^2K)]

Element	Outside or buried at less than 2m	Unheated rooms or rooms buried at more than 2m
Opaque elements (roof, ceiling, ground)	0,17	0,25
Windows, glass doors	1,0	1,3
Doors	1,2	1,5
Doors (Compliant with SIA 343)	1,7	2,0
Shading enclosures	0,50	0,50

Table 16. Target values for thermal transmittance coefficients for new buildings for an indoor temperature of 20°C.

Building element	U target values [W/(m²K)]
Opaque elements (roof, ceiling, walls, floor)	0,10
Transparent elements (windows, patio doors, doors)	0,80

The sole focus on compliance with the U-value also poses the risk of intensive embodied energy use in buildings, as this mandatory requirement does not account for the carbon impact emissions of materials used in the construction set. Table 34, located in the annex section of this document and part SIA 2032 [4] document, presents a breakdown of various construction elements and their impacts on embodied non-renewable primary energy consumption and GHG emissions per year. According to Table 34, façade systems are categorized as one of the main embodied energy-intensive elements of the building. By comparing insulated and non-insulated variants of construction elements such as foundations, walls, and roofs, it is evident that insulation, despite resulting in operational energy savings, consistently leads to higher embodied energy use and GHG emissions due to the energy-intensive production process of insulation materials. This risk has been the subject of many studies, for example, Rivera et al. [60] in a study analyzing 16,128 envelope variants across three high-rise residential buildings using the One Click LCA tool, found that, in cases of using GHG-intensive materials for insulation, insulation thickness beyond 51-102 mm could increase GHG emissions more than the energy saved in operation. Findings from this study and similar ones suggest the need for consideration of the trade-off between energy use and comfort and embodied objectives in buildings and the necessity of pre-selecting construction materials based on their GHG emissivity prior to their thermal transmittance properties before using them in the construction set.

Additionally, a predominant feature of buildings located in cold climates is that envelope permeability is controlled through strict regulations. SIA 384.201:2017 [32] sets limit and target values for envelope permeability for new and renovated buildings in Switzerland, as presented in Table 17 and Table 18. Table 18 presents specific envelope airtightness target values, using the air change rate (n50) as a metric for airtightness, for new and renovated buildings, based on the building category. Table 17 suggests that buildings with mechanical ventilation should have more stringent requirements as mechanical ventilation requires energy consumption, and therefore, more controlled and more airtight structures should be integrated into these buildings. In addition, due to the challenges and constraints involved in improving existing structures, limit values for renovated buildings are set higher than for new buildings.

Table 17. Limit and target values for building envelope permeability for new and renovated buildings

	Limit value		General target value qa50 [m³/(hm²)]
	Natural ventilation qa50 [m³/(hm²)]	Mechanical ventilation qa50 [m³/(hm²)]	
New buildings	2,4	1,6	0,6
Renovation	3,6	2,4	1,2

However, previous studies, notably a study [32] that conducted a comprehensive Post-Occupancy Evaluation (POE) with a major emphasis on IAQ, show that this practice significantly contributes to poor IAQ conditions in buildings built to higher standards. The findings of these studies highlight that optimal envelope airtightness is context-dependent; while it serves both IEQ and energy goals in areas with significant outdoor pollution, the desired level of airtightness and window opening frequency should be defined based on the building's specific context [61], [62], indicating that single threshold values cannot be universally beneficial.

Table 18. Specific envelope airtightness target values for new and renovated buildings by category

Category of work	Air change rate n_{50} [h^{-1}]			
	New Buildings	Old non-renovated buildings		
	According to SIA 180	Good sealing	Moderate tightness	No sealing
Single family housing	1,5	4,0	7,0	10,0
Other categories	0,8	2,0	4,0	5,0

Furthermore, in Switzerland, SIA 180:2014 [27] also suggests limiting values for the window-to-wall ratio (WWR) and solar heat gain control (SHGC) for buildings based on their usage type and climate region, which translate into more restrictive values in green certification practices in Switzerland like Minergie [9]. As Table 19 presents, the Swiss building legislation offers limiting recommendations for the maximum glazing percentage on facades based on space thermal capacity and solar protection control method to control heat exchange through the envelope and ensure a building's heating energy performance meets the desired criteria. According to Table 19, in general, residential spaces are allowed a higher percentage of glazing than office or educational buildings with the same level of thermal mass, which can be attributed to the occupancy patterns and relatively less strict thermal comfort requirements in residential spaces on average based on Table 6. In addition, generally, for windows facing south directions, which are typically considered ideal orientations for maximizing solar gain during winter in the Northern Hemisphere, the area limit can be increased by 20% if the opening has an eave or balcony that provides shading extending outward at least to half the height of the window. Furthermore, Table 19 suggests a strategy to limit overall solar exposure from multiple directions, as glazing percentage recommendations are stricter when windows are on several facades. Lastly, as, generally, higher glazing percentages are allowed for windows with automatic control and for buildings with high thermal capacity, the implementation of these two strategies seems to allow for a significant increase in glazing percentages, up to 20% more in some cases, suggesting an effective way to reconcile daylighting performance with energy efficiency in Swiss buildings.

Table 19. Recommended maximum glazing percentage for solar protection on facades by space type and control method

		Glazing percentage for solar protection on facades	
Type of space	Windows on	manually operated	with automatic control
Residential with high thermal capacity	a single facade	50%	70%
	several facades	30%	50%
Residential with average heat capacity	a single facade	40%	60%
	several facades	30%	40%
Office, meeting room, school, with medium thermal capacity	a single facade		30%
	several facades		30%
Office, meeting room, school with high thermal capacity	a single facade		40%
	several facades		30%

Furthermore, SIA 180:2014 [16] represents the maximum allowable total solar transmittance for façade windows with solar shading, which is correlated with the proportion of the façade that is glazed (fg) and the orientation of the façade. According to Figure 2. Graphical representation of the maximum allowable total solar transmittance (g-value) for façade windows with solar shading, correlated with the proportion of the facade that is glazed (fg) and the orientation of the facade (North, Northeast, Northwest, as the glazing proportion increases, the allowable g-values significantly decrease, necessitating effective solar shading or lower transmittance glazing for façades to ensure a building's thermal performance meets desired criteria. In this regard, Figure 2. Graphical representation of the maximum allowable total solar transmittance (g-value) for façade windows with solar shading, correlated with the proportion of the facade that is glazed (fg) and the orientation of the facade (North, Northeast, Northwest also suggests that northern orientations can have a higher g-value for any given proportion of glazing compared to other orientations in Switzerland, considering that North facing façades receive less direct sunlight throughout the year due to Switzerland's latitude. That being said, previous research criticizes the current trend in opening design followed in green buildings for poor occupants' visual comfort satisfaction. A study conducted in 144 buildings (65 LEED certified) that gathered 21,477 individual occupant responses generally showed lower satisfaction with daylight availability compared to non-LEED buildings [20]. This finding is consistent with previous studies that reported no improvement in lighting satisfaction in green-certified buildings compared to conventional buildings [63], [64]. Altomonte's study [20] acknowledged that the emphasis on energy-related credits in recent versions of green certification may have influenced the lower satisfaction levels with daylight availability observed in green buildings compared to conventional buildings, highlighting the need for future improvements in green practices to synergistically address occupant needs and building efficiency.

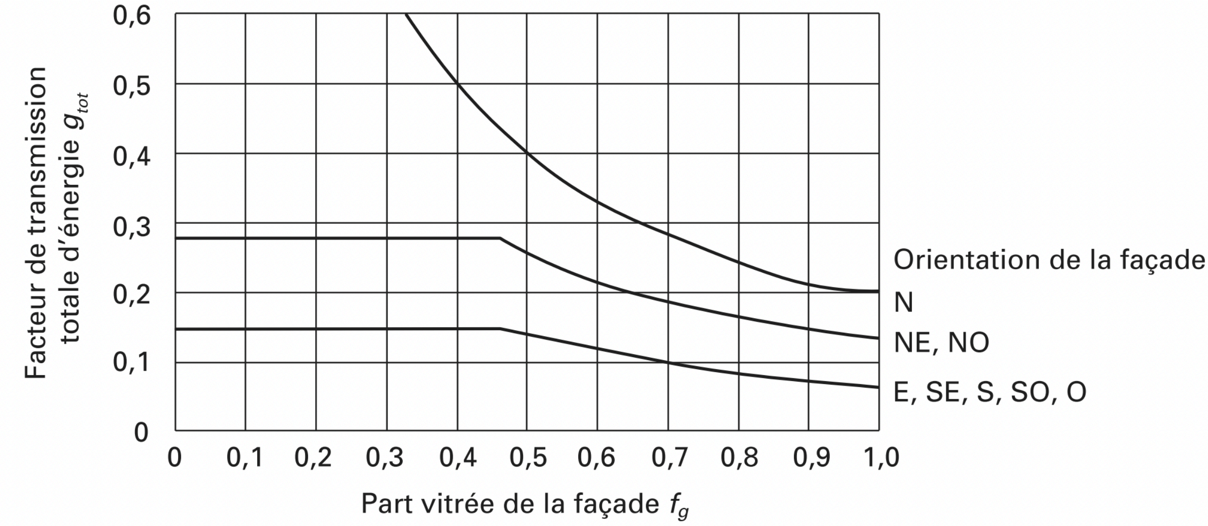

Figure 2. Graphical representation of the maximum allowable total solar transmittance (g-value) for façade windows with solar shading, correlated with the proportion of the facade that is glazed (fg) and the orientation of the facade (North, Northeast, Northwest

However, the glazing ratio, on the other hand, impacts thermal comfort in buildings in the opposite direction. A POE study conducted across 180 suites in North America found significant variation in thermal discomfort based on a higher fenestration ratio in buildings [65]. Additionally, the fenestration ratio has been identified as a major contributor to building embodied emissions, further complicating the trade-off between energy and daylight access [60]. For instance, research focusing on three high-rise buildings in North America demonstrated that a decrease in the WWR from 50% to 20% resulted in a 28% reduction in emissions [60]. Nevertheless, another study conducted in Switzerland employing the KBOB material database found, through sensitivity analysis of base case variants, that the WWR, although significantly impacting the spatial Daylight Factor (sDF), the percentage of space that reaches a DF greater than or equal to the threshold, has a marginal effect on embodied carbon emissions [66].

In addition to strict energy-centric regulations, which can potentially conflict with demands for indoor human comfort, some regulations lack predefined values but often lead to conflicting results concerning energy efficiency and indoor comfort due to misinterpretations in practice. The SIA 2032 [4], which introduces the carbon impact factor of building materials, emphasizes the utilization of waste-based, recycled, or reused materials. It can be inferred from Table 34, placed in the annex of this document, that the use of bio-circular alternatives instead of conventional building materials significantly contributes to the reduction of embodied emissions in buildings. This focus is further emphasized in voluntary labels, contributing to higher scores. However, despite the potential for CO2 emission reduction associated with embodied material emissions, this practice carries the risk of increased exposure to indoor pollutants [62]. For instance, using fly ash in concrete has been shown to increase the gamma exposure risk [67], and linoleum has been found to emit volatile organic compounds (VOCs), which react with ozone to create aldehydes [62]. Thus, research necessitates the consideration of pollutant emissivity from finishing materials, in addition to their embodied carbon factor, to ensure the biological health of occupants in addition to the ecological integrity of the building. Previous studies (e.g. [31], [68], [69]) provide indoor source data on material pollutant emissivity, particularly focusing on VOC emissions as a major source of indoor pollution.

Additionally, restrictive requirements for heating energy use and the prevention of overheating have encouraged the use of materials with high thermal inertia to increase thermal capacity in buildings. However, the use of these materials can conflict with acoustic requirements due to the longer reverberation time of materials with higher volumetric heat capacity [22], [70]. A study examining the impact of thermal inertia on room acoustics in an office building in Switzerland found that covering more than 50% of the interior ceiling with roughcast concrete, while improving thermal comfort, negatively affected the room's acoustics. The findings of the study underline the necessity of choosing an optimal level of interior surface coverage with thermal inertia materials to ensure that thermal comfort is not achieved at the expense of acoustic requirements in indoor spaces.

Lastly, some studies have also reported on operative features of buildings that serve energy efficiency but have shown contradictory results for IEQ. In this context, some POE studies [62], [71] reported that certain ventilation strategies could compromise acoustic comfort in mechanically ventilated buildings, necessitating the maintenance of sound isolation levels in ventilation systems. To bring all these elements together, Figure 3, as an illustrative qualitative summary, presents the risks posed by energy-centric directives to indoor comfort and embodied energy, derived based on findings from the investigation of Swiss regulation and standards for energy and IEQ, supplemented by an investigation of studies focused on the tension between the two. Our research will hence focus in subsequent phases on technological interventions that can reconcile the need for energy efficiency with IEQ considerations, aiming to inform and refine the existing legislative framework governing building practices for a more holistic approach in the future generation of green buildings in Switzerland.

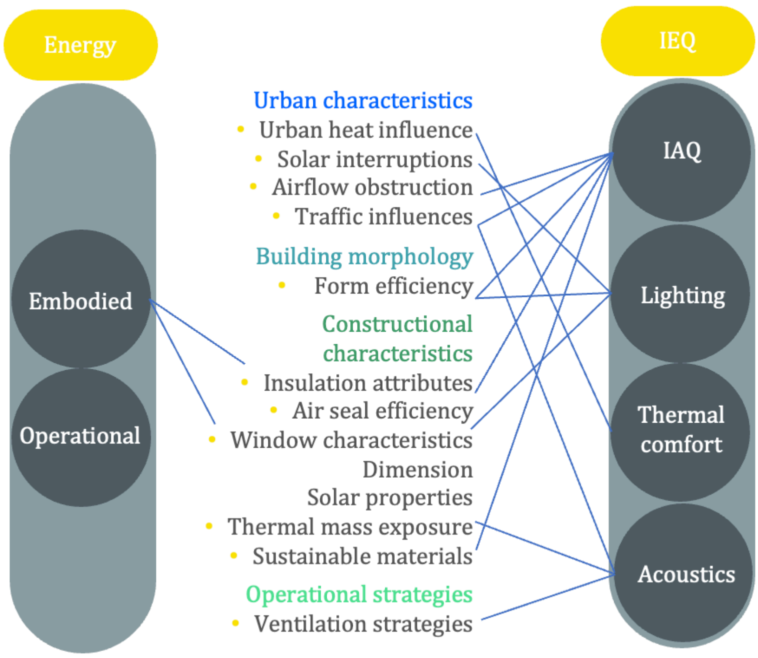

Figure 3. Qualitative illustration of the potential risks of energy-centered directives on indoor comfort and embodied energy.

In terms of strategies that can bring about reconciliation, recent research broadly suggests that no single solution can meet all performance objectives. Instead, solutions align with a Pareto curve, each providing varied emphasis on different objectives and thus contributing differently to various objectives based on site context [49], [53], [56], [57], [58]. Specifically, while fenestration components are viewed as potential weak points in the regulatory framework for buildings in colder climates facing restrictions, many studies exploring the direction for reconciling energy with IEQ objectives highlight fenestration as a crucial and impactful area for achieving functional balance [72], [73], [74]. In fact, they suggest that the effective employment of existing scenarios based on building context specifications can offer efficient synergistic potentials and opportunities, necessitating deeper investigation into balancing measures for envelope-related directives to achieve better building functionality.

2.4 Future steps and outlook

Subsequent research will focus on fenestration systems capable of achieving higher visible light transmission with minimal heat loss. This includes exploring the role of sun-shading systems, especially their control methods/schedules, in managing solar gains across the building boundary layer and high-performance glazing systems, using both dynamic and static methods, to enhance visual comfort while minimizing heating energy penalties.

Additionally, the research will delve into integrated solar envelope systems that support small-scale energy production through the building envelope, utilizing daylight as a primary renewable resource for on-site energy generation. Such systems can offset a portion of the building's energy consumption, thereby enabling greater flexibility in designing openings in the building envelope without compromising thermal efficiency [34], [56], [75]. Table 20 presents a summary of the main investigation variables and exploration objectives for subsequent research steps. The exploration objectives in Table 20 are based on the most comprehensive ones reviewed in Sections 2.1 and 2.2 of the document, and the investigation variables include both elements with potential tension, as discussed in Section 2.3, and those that, according to the literature, can offer synergistic potentials for energy efficiency and IEQ in buildings. Hence, our research outcomes, by emphasizing the often-overlooked trade-off between energy efficiency and IEQ within building legislative frameworks, aim to refine and improve the existing legislative framework to ensure balanced functionality in buildings that enhance occupant well-being alongside environmental sustainability.

Table 20. Overview of research's exploration objectives and investigation inputs in subsequent steps.

Factor	Type	Description	
Exploration variables	Opaque enclosure	façade cladding, envelope insulation, envelope airtightness; wall coating, floor finish, ceiling finish	
	Transparent envelope	glazing ratio, glazing type, shading type, shading control	
Exploration objectives	Energy use	heating, ventilation, and lighting energy consumption; on-site renewable energy generation	
	Indoor comfort	IAQ	CO_2 concentration
		Thermal comfort	Adaptive comfort model Predicted mean vote dissatisfied
		Daylighting	DA_{300}, $DGP_{e<5\%}$
		Acoustics	Reverberation time

3 Conclusion

Through an extensive examination of the Swiss building norms, regulations, and standards related to energy and Indoor Environmental Quality (IEQ) within Switzerland, this study has shown that the Swiss 2050 energy strategy and its sectoral targets have predominantly shaped the focus areas of Swiss building legislation, as well as its sustainable transition plans for the 2050 and 2150 horizons. In this context, Swiss building legislation, aiming to meet mobility-induced energy targets, has emphasized urban densification. In Switzerland, standards for land and territory occupation rely on municipal policies, lacking federal or cantonal directives to mandate urban densification practices. However, the relationship between urban densification and the microclimate has been an overlooked aspect of Swiss building legislation. Meanwhile, research on the impacts of urban density on environmental quality in urban blocks highlights the significant role of urban densification patterns and the influence of specific morphological indicators on the synergy between comfort and energy performance, highlighting the need for greater consideration of these aspects in the legislative framework to alleviate the negative effects of densification on the indoor climate. Future research will thus aim to identify effective densification models for typical Swiss neighborhoods that support comprehensive IEQ and energy goals at both the building and neighborhood levels.

Additionally, Swiss building regulations focusing on building operations are largely influenced by the 2050 energy strategy's targets for heating energy use, as the provision of heating energy in Switzerland still primarily depends on fossil fuel imports [3]. In this context, two aspects of IEQ, thermal comfort, and Indoor Air Quality (IAQ), have gained more significant attention due to their association with heating energy use targets. The emphasis on IAQ management in buildings, to improve heating energy efficiency, stems from Switzerland's main IAQ regulation mechanism, which relies on mechanical ventilation with a heat recovery stage. This not only prevents unwanted air entry through natural ventilation and reduces temperature fluctuations but also recycles energy by exchanging heat between expelled and incoming air, thus enhancing thermal regulation.

On the other hand, for daylighting and acoustics, the standards are implicitly suggested, lacking strong and strict compliance mechanisms. Acoustics is given minimal focus as its adequacy does not directly relate to any aspect of a building's operational energy use. Conversely, inadequate daylighting can increase a building's operational energy use due to higher lighting energy requirements. However, a critical aspect of daylighting's provision is that its key improvement strategies often negatively affect a building's thermal performance, leading to heating or overheating penalties. In this context, building fenestration is subjected to restrictions in terms of both total surface area and thermophysical properties, while vertical fenestration in buildings, especially in densely built urban districts, serves as a primary source of daylight access. Moreover, the current generation of options that meet thermal performance targets often compromises aspects of view and daylight quality to manage energy and glare. In addition to fenestration, opaque building envelopes also face energy-centric constraints to heat losses from the envelope, thereby reducing the need for space heating. This is while building envelopes, serving as intermediate layers between indoor and ambient environments, play an important and beneficial role in regulating IEQ in buildings as well.

Based on a review of Swiss regulations for energy and comfort, along with an examination of the literature on the impact of energy efficiency on IEQ in green buildings, a preliminary list of factors pivotal in IEQ management, yet constrained by energy-focused limitations, has been identified for further investigation. Exploring comprehensive façade solutions, particularly fenestration, to balance comfort with energy goals emerges as a sustainable and reliable approach for future research. Previous studies suggest that efficient solutions seeking a balance between functionality, considering various aspects of energy and comfort, often follow a Pareto curve. Each solution assigns different weights to the objective functions, thereby contributing differently to various goals. Future research will therefore aim to identify and propose balanced compromises for building elements currently subjected to strictly energy-focused directives. Moreover, in pursuing balanced solutions for the building envelope, the critical role of adopting preventive measures to minimize embodied carbon and indoor pollutant emissions during construction should be acknowledged for a holistic approach. Prioritizing metrics for these aspects in the pre-construction phase is essential for maintaining ecological integrity in buildings and ensuring the physiological well-being of occupants.

Lastly, a promising strategy to enhance indoor climate quality in Switzerland, while aligning with the 2050 energy goals, appears to be an increased dependence on envelope-integrated renewable energy systems. Such systems, enabling on-site renewable energy generation, represent an advancement in façade strategies that can offset a portion of the building's energy consumption. This may, in turn, allow for more flexible regulations on building envelopes and fenestration, which are currently mainly constrained by energy conservation targets. Thus, future research will delve deeper into the mentioned strategies, including preventative measures, balanced compromise approaches, and integrated solar-envelope strategies, to develop a refined sub-framework for Swiss building legislation that considers both building energy efficiency and occupant well-being, leading to more comprehensive directions in Swiss building practices.

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Appendix

This section provides additional details on metrics related to energy and comfort for Swiss buildings.

Additional details on Swiss regulations and guidelines for energy efficiency

Table 21, Table 22, and Table 23 detail the primary non-renewable energy factor and GHG emission coefficients for various fuels and electricity production models, as well as for various district heating sources, respectively according to SIA 2040 [2]. The data illustrates a clear distinction between renewable and non-renewable energy sources. In the electricity sector, renewables like hydroelectric and wind energy showcase optimal sustainability with low primary energy factors and minimal GHG emissions, while nuclear and pump storage show high primary energy factors despite their low emissions. Within fuels, biogas stands out for its lower primary energy factor and GHG emissions, offering a cleaner alternative to traditional fossil fuels, lastly, systems utilizing waste incineration and biogas-fired technologies emerge as efficient solutions with lower environmental impacts for the district heating sector.

Table 21. Swiss national primary energy factors and GHG emission coefficients for various fuel sources.

Fuels		Primary non-renewable energy factor -	GHG emission coefficient [kg/MJ]
Liquid	Heating oil, extralight	1,23	0,083
	Propane / butane	1,18	0,078
Solid	Coal coke	1,68	0,120
	Coal briquettes	1,20	0,108
	Firewood	0,05	0,004
	Woodchips	0,06	0,003
	Pellets	0,21	0,010
Gaseous[a]	Natural gas	1,11	0,066
	Propane / butane	1,18	0,078
	Biogas (with natural gas quality[b]	0,37	0,045
Electricity	CH consumer mix[c]	2,64	0,041

[a] Values in standard state (0°C, 101300 Pa).

[b] According to the Swiss Gas and Water Industry Association SVGW, standard G13.

[c] The CH consumer mix does not include the amounts of energy supplied to consumers on the basis of ecological supply contracts.

Table 22. Swiss national primary energy factors and GHG emission coefficients for various electricity production models.

	Primary non-renewable energy factor -	GHG emission coefficient [kg/MJ]
Nuclear power station	4,07	0,005
Natural gas combined cycle power station (gas and steam)	2,33	0,135
Coal-fired power station (steam)	3,99	0,344
Oil-fired power station	3,84	0,277
Waste incineration	0,02	0,002
Heating power station, wood-fired	0,16	0,032
Combined heat and power station, diesel-fired	3,34	0,231
Combined heat and power station, gas-fired	3,28	0,205
Combined heat and power station, biogasfired (natural gas network)	0,98	0,135
Photovoltaic	0,40	0,026
Wind power	0,11	0,008
Hydroelectric	0,04	0,004
Pump storage	3,81	0,061
Geothermal heating power station	0,19	0,009
UCTE mix[a]	3,33	0,165

[a] Swiss electricity generation scenarios (mix CH, mix UCTE, nuclear power CH, combined gas power UCTE, coal UCTE, PV CH)

Table 23. Swiss national primary energy factors and GHG emission coefficients for various district heating sources.

	Primary energy factor non-renewable -	GHG emission coefficient [kg/MJ]
District heat using heat from waste incineration	0,80	0,045
Heating plant, oil-fired	1,68	0,112
Heating plant, gas-fired	1,56	0,087
Heating plant, wood-fired	0,10	0,013
Heating power station, wood-fired	0,10	0,011
Heating plant, electric heat pump, air/water (JAZ 2.8)[a]	1,19	0,028
Heating plant, electric heat pump, geothermal probe (JAZ 3.9)[a]	0,89	0,021
Heating plant, electric heat pump, waste water (JAZ 3.4)[a]	0,90	0,015
Heating plant, electric heat pump, groundwater (JAZ 3.4) [a]	1,00	0,022
Geothermal heating plant	0,17	0,006
Geothermal heating power station	0,12	0,004
Combined heat and power station, diesel-fired	0,62	0,040
Combined heat and power station, gas-fired	0,64	0,038
Combined heat and power station, biogasfired (natural gas network)	0,23	0,025

a Electricity mix: CH consumer mix

Table 24. Annual breakdown of energy consumption targets by operational sectors (appliances, lighting, HVAC) across various building types.

Zone type		Electrical energy			Thermal energy		
		Appliances E_A [kWh/m²]	Process plants E_{PS} [kWh/m²]	Lighting E_L [kWh/m²]	Refrigeration cooling Q_c [kWh/m²]	Heating Q_H [kWh/m²]	Domestic hot water Q_W [kWh/m²]
1.01	Multifamily housing	10,8	0	2,0	3,0	10,0	16,9
1.02	Single-family housing	8,9	0	2,0	1,2	15,5	13,5
2.01	Hotel room	1 1,0	0	2,7	4,3	10,2	39,5
2.02	Reception area	9,0	0	13,5	18,4	3,7	0,0
3.01	Private and shared offices	17,5	0	2,8	5,3	10,2	2,6
3.02	Open space office	29,1	0	7,0	14,1	1,5	3,6
3.03	Meeting room	5,6	0	1,6	4,8	12,5	0
3.04	Service hall	5,8	0	3,2	3,0	8,6	0
4.01	School lobby	7,1	0	3,2	6,3	10,9	4,0
4.02	Staff room	3,0	0	1,2	3,1	17,2	0
4.03	Library	1,5	0	2,7	2,9	8,5	0
4.04	Auditorium	21,8	0	6,0	19,2	1,8	5,3
4.05	Classrooms	3,5	0	3,2	4,3	12,5	3,2
5.01	Feed store	4,0	321	38,8	31,9	0	2,7
5.02	Retail store	3,6	0	38,8	31,5	0	2,7
5.03	Home improvement and garden store	3,4	0	31,0	15,6	0,2	1,5
6.01	Restaurant	2,3	0	6,1	10,9	10,0	108,9
6.02	Cafeteria	1,8	0	3,2	6,0	6,2	108,9
6.03	Restaurant kitchen	25,3	354	13,8	9,4	15,6	0
6.04	Cafeteria kitchen	17,3	242	9,9	6,9	7,2	0
7.01	Concert hall	2,3	0	13,5	17,2	2,4	7,3
7.02	Multi-purpose hall	5,8	0	9,0	21,2	5,6	7,3
7.03	Exhibition hall	8,7	0	25,3	32,4	2,8	7,3
8.01	Hospital room	7,0	0	3,5	11,7	5,8	67,7
8.02	Hospital administrative office	15,8	0	36,9	55,6	0,8	0
8.03	Medical facilities	21,8	11	14,0	18,2	4,2	0
9.01	Heavy manufacturing plant	16,8	34	10,6	5,0	7,0	2,4
9.02	Precision manufacturing plant	12,2	12	5,6	4,1	6,6	2,4
9.03	Laboratory	12,2	24	3,7	3,5	12,4	2,4
10.01	Warehouse	3,2	0	2,1	0	8,9	0,9
11.01	Gymnasium	0,0	0	9,1	0	22,7	63,5
11.02	Fitness center	3,4	0	7,5	1,4	10,4	87,1

11.03	Indoor swimming pool	6,8	171	6,4	3,0	25,8	145,2
12.01	Buffer zone	0,0	0	1,5	1,2	6,1	0
12.02	24-hour buffer zone	0,0	0	7,1	4,3	4,4	0
12.03	Stairwell	0,0	0	1,5	0	4,8	0
12.04	Auxiliary spaces	0,0	0	0,6	0	9,5	0
12.05	Kitchen, kitchenette	42,9	0	0,5	0	0,3	0
12.06	Bathrooms, showers	0,0	0	0,6	0	50,1	0
12.07	WC	0,0	0	1,0	0	27,5	0
12.08	Changing room and shower	0,0	0	0,7	0	23,0	0
12.09	Shared garage	0,0	0	0,7	0	0	0
12.1	Laundry room with dryers	25,8	0	1,7	0	2,4	0
12.11	Refrigerated room	0,0	254	0,1	0	7,9	0
12.12	Server room	0,0	701	0,1	0	14,7	0

Additional details on Swiss standards and guidelines for indoor comfort

– This section provides further information on Swiss standards for air quality.

Table 25. Mean values of NO_2 and PM_{10} concentrations at various location types in Switzerland.

Location type	Measuring station	NO_2 [µg/m³] Annual mean value	PM_{10} [µg/m³] Annual mean value
Urban, congested	Bern-Bollwerk	47	28
	Lausanne-César-Roux	39	22
Urban	Lugano-Universitå	32	22
	Zurich Barracks	33	20
Suburban	Basel-Binningen	23	18
	Dübendorf-Empa	28	19
Rural, Highway	Härkingen-A1	41	21
	Sion-Aéroport-A9	36	21
Rural, below 1000 m	Magadino-Cadenazzo	21	21
	Payerne	15	18
	Tänikon	15	17
	Lägeren	12	
Rural above 1000 m	Chaumont	6	9
	Rigi-Seebodenalp	7	10
	Davos-Seehornwald	4	

High mountains	Jungfraujoch	< 1	3
Limit value		30	20

Table 26. Air quality classification based on the zone's CO2 concentration.

CO2 Concentration [ppm]	General Air Quality	Classification According to SN 546 382/1
≤ 1,000	Good to very good	High
1,000–1,400	Average	Average
1,400–2,000	Low	Low
> 2,000	Unacceptable - Hygiene risk, health risk.	Unacceptable hygiene.

– This section provides further information on Swiss standards for daylighting.

Table 27. Required illuminance values for nominal lighting in premises.

Type of premises and activity	Required illuminance (lux)
	Minimum
Workplaces with installations without manual activity	≥ 50
Storage rooms	≥ 100
Workplaces with occasional manual intervention on installations, stairwells:	≥ 150
Workplaces with continuous manual intervention on installations, archive rooms	≥ 200
Workplaces with basic operations or those requiring simple visibility (Packing, shipping, assembly, living spaces)	≥ 300
Workplaces for tasks requiring moderate precision or good visibility (reading, writing, data processing, CAD/CAM, infirmary facilities)	≥ 500
Workplaces for precision work	≥ 750
Workplaces for activities requiring very good visibility	≥ 1000

Table 28. Recommendation for daily sunlight exposure.

Level of recommendation for exposure to sunlight	Sunlight exposure [h]
Minimum	1,5
Medium	3,0
High	4,0

Table 29. Assessment of the view to the outside from a given position.

Parameter[a]

Level of recommendation for view out	Horizontal sight angle [°]	Outside distance of the view [m]	Number of layers to be seen from at least 75 % of occupied area: - Sky - Landscape (urban and/or nature) - Ground
Minimum	≥ 14	≥ 6	At least landscape layer is included
Medium	≥ 28	≥ 20	Landscape layer and one additional layer is included in the same view opening
High	≥ 54	≥ 50	all layers are included in the same view opening

[a] For a space with room depth more than 4 m, it is recommended that the respective sum of the view opening(s) dimensions is at least 1,0 m x 1,25 m (width x height).

– This section provides further information on Swiss standards for acoustic.

Table 30. Proposed different levels of threshold DGPe < 5 % for glare protection.

Level of recommendation for glare protection	DGPe < 5 %
Minimum	0,45
Medium	0,40
High	0,35

Table 31. Minimum standards for airborne sound insulation for protection against internal noise.

Noise pollution intensity	Minimum	Medium	High	Very high
Expected noise level	Low-noise environment	Standard noise environment	High-noise environment	Extremely noisy environment
Examples of emission side space type and use	Reading, waiting room, archive, storage room, storage and basement room, bike room	Living room, bedroom, kitchen, Bath, shower, WC, corridor, Elevator shaft, upper-level gym, stair house, winter garden, one parking hall, office room, meeting room, laboratory, salesroom without acoustic dampening	Hall, school room, children's crib, children's garden, technical room, Restaurant without background sound system, salesroom with sound system and adjacent soundproofed rooms, multi-use hall with advertising displays	Commercial drive, workshop, Music practiceroom, sports hall, restaurant with Besound and associated Development- rooms
Noise sensitivity class	Requirement values D_i			
Minimum	42 dB	47 dB	52 dB	57 dB
Medium	47 dB	52 dB	57 dB	62 dB
High	52 dB	57 dB	62 dB	67 dB

Table 32. Minimum standards for impact sound insulation.

Noise pollution	Minimum	Moderate	High	Very high
Expected noise level	Low-noise environment	Standard noise environment	High-noise environment	Extremely noisy environment
Examples of emission side space type and use	Reading, waiting room, archive, storage room, storage and basement room, bike room	Living room, bedroom, kitchen, Bath, shower, WC, corridor, Elevator shaft, upper-level gym, stair house, winter garden, one parking hall, office room, meeting room, laboratory, salesroom without acoustic dampening	Hall, school room, children's crib, children's garden, technical room, Restaurant without background sound system, salesroom with sound system and adjacent soundproofed rooms, multi-use hall with advertising displays	Commercial drive, workshop, Music practiceroom, sports hall, restaurant with Besound and associated Development- rooms
Noise sensitivity class	Requirement values D_i			
Minimum	63 dB	58 dB	53 dB	48 dB
Medium	58 dB	53 dB	48 dB	43 dB
High	53 dB	48 dB	43 dB	38 dB

Additional details on the implications of energy efficiency measures on indoor comfort

Table 33. Limit values for linear thermal transmittance for various types of thermal bridges in a building's structure.

Linear thermal transmittance	Limit value [W/m-k]
Projecting parts, such as balconies or eaves	0,30
Discontinuities in thermal insulation due to wall slabs or ceilings	0,20
Insulating envelope breaches at horizontal or vertical edges	0,20
Window sill adjoining wall	0,15

Table 34 is a breakdown of various construction elements and their respective impacts on embodied non-renewable primary energy consumption and GHG emissions per year. Each row represents a different element of building construction, ranging from preparatory work to installations. The life cycle stages considered in Table 34 are production (raw material procurement, manufacturing, transportation), construction (transportation, construction/installation process), stage of use (replacement), and end-of-life stages (demolition/deconstruction, transport, waste processing, and disposal). In addition to the implications of this guideline for the thermal transmittance and pollutant emissivity of the construction set, discussed in detail in Section 2.3, from this guideline, it can also be implied that technical systems for HVAC show lower embodied energy use and GHG emissions compared to structural elements. On the other hand, the photovoltaic system poses a high initial energy and GHG footprint, but considering its role in investment in on-site renewable energy generation, its careful implementation can also lead to significant energy savings and GHG emission reductions over time.

Table 34. Assessment guide: embodied energy and GHG emissions by building element category during the construction phase.

					Non-renewable primary energy per year	GHG emissions per year
	eCCC-Bât element group	Description	Reference size[a]	Unit	kWh per unit	kg per unit
Preparatory work	B06 / B07.02	**Excavation**				
		Excavations	Volume	m^3	0,03	0,01
		Excavation enclosures (retaining wall)	SEC	m^2	11,29	3,06
		Foundation piles (bored micropiles)	Radier	m^2	2,90	0,77
Underground building envelope	C01	**Foundations and inverts**				
		Non-insulated	SEC	m^2	4,50	1,63
		Insulated	SEC	m^2	7,37	2,71
	C02.01 (A) / E01	**Underground exterior walls**				
		Non-insulated	SEC	m^2	4,62	1,51
		Insulated	SEC	m^2	8,27	2,74
	C04.04 / F01.01	**Underground roofs**				
		Non-insulated	SEC	m^2	5,84	1,91
		Insulated	SEC	m^2	11,34	3,62
Building envelope excluding land	C02.01 (B)	**Above-ground exterior walls**				
		Concrete wall (with interior rendering)	SEC	m^2	3,59	1,23
		Clay brick wall (with interior rendering)	SEC	m^2	3,28	1,09
		Wooden wall (with interior plaster coating)	SEC	m^2	1,19	0,27
		Insulating monolithic masonry (with interior rendering)	SEC	m^2	7,04	1,98
		Support beams for lightweight facades	SEC SPE[b]	m^2	0,55	0,14
Building envelope excluding land	E02	**Facade cladding**				

		Exterior plaster	SEC	m^2	0,58	0,20
		External thermal insulation, rendering	SEC	m^2	4,40	1,14
		Wood cladding, ventilated	SEC	m^2	2,55	0,46
		Fiber cement / natural stone cladding, ventilated	SEC	m^2	4,78	1,04
		Metal/glass cladding, ventilated	SEC	m^2	8,20	1,79
		Double-skinned wall, outer skin	SEC	m^2	8,01	2,54
		Facade system	SEC	m^2	26,00	5,94
	E03 / F02	**Windows**				
		Average value triple-pane insulated glass including solar shading	SEC	m^2	22,51	5,24
	C04.04 / C04.05	**Roofs (load-bearing structure)**				
		25 cm concrete slab (with interior rendering)	SEC	m^2	4,15	1,45
		40 cm concrete slab (with interior rendering)	SEC	m^2	7,44	2,42
		Corrugated sheet-concrete	SEC	m^2	5,34	1,40
		Solid wood flooring (with plaster coating on underside)	SEC	m^2	2,69	0,52
		Wooden joist floor (with plaster coating on underside)	SEC	m^2	2,70	0,57
	FOI.02 / FOI.03	**Covers**				
		Insulated flat roof	SEC	m^2	1 1 ,55	2,94
		Uninsulated flat roof	SEC	m^2	4,81	1,23
		Insulated pitched roof	SEC	m^2	4,06	1,00
		Uninsulated pitched roof	SEC	m^2	1,60	0,51
Interior and exterior construction	C02.02 / G03	**Interior walls, wall coverings**				
		Load-bearing (medium-weight) walls (with interior plaster)	SEC	m^2	3,67	1,22
		Non-load-bearing (medium-weight) walls (with coating)	SEC	m^2	4,93	1,10
	C04.01	**Floors**				
		25 cm concrete slab (with interior rendering)	SEC	m^2	4,15	1,45
		Wooden floor elements (with plaster coating on underside)	SEC	m^2	1,54	0,32
		Mixed wood-concrete system (with plaster coating on underside)	SEC	m^2	2,16	0,66
	G02 / G04	**Floor and ceiling coverings**				
		Finished flooring (without supports)	SEC	m^2	1,77	0,37
		Substrates and floor coverings	SEC	m^2	4,13	1,20

		Insulation against unheated	SEC	m2	1,68	0,25
		Technical suspended ceilings (average)	SEC	m2	2,79	0,62
	C04.08	**Balconies, eaves**				
		Balconies including fall-protection systems	SEC	m2	12,29	3,52
Installations	D01	**Electrical installations**				
		Residential electrical installations	SRE	m2	1,85	0,42
		Office electrical installations	SRE	m2	3,79	0,80
		Photovoltaic system (1 m2 = 0.14 kWp)	SEC	m2	37,43	10,83
	D05	**Technical heating systems**				
		Heat generation	SRE	m2	0,34	0,08
		Residential heat distribution and output	SRE	m2	1,22	0,27
		Office heat distribution and emission	SRE	m2	1,85	0,44
		Geothermal probes	SRE	m2	1,63	0,35
		Solar collectors	SEC	m2	23,17	5,17
	D07	**Ventilation and air conditioning systems**				
		Kitchen and bathroom mechanical extraction	SRE	m2	0,50	0,11
		Home ventilation system	SRE	m2	1,82	0,42
		Office ventilation system	SRE	m2	3,08	0,72
	D08	**Technical installations for water distribution**				
		Sanitary installation	SRE	m2	1,62	0,38
		Office sanitary installation	SRE	m2	1,10	0,27

[a] SEC surface area of building components, SRE energy reference surface area

[b] SEC SPE outer wall surface