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LONG-TERM ASSESSMENT METHODOLOGY OF BUILDING STOCK THERMAL ENERGY CONSUMPTION

Doctoral Thesis

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ANNOTATION

Energy efficiency in the building stock is a substantial contributor to infrastructure sustainability. In Latvia, buildings' thermal energy use for space heating accounts for 80% of total building energy use in the cold season. Therefore, reducing thermal energy consumption for space heating needs through the implementation of energy efficiency measures, enforcement of local building codes and regulations can ultimately lead to cost savings for building owners and stakeholders.

The present PhD thesis introduces a methodology of evaluating thermal energy saving potential in the long run across residential, public, and industrial building stock under various thermal energy consumption compliance scenarios. These scenarios were developed based on three different building code protocols with a 10-year forecast analysis.

Evaluation of the proposed building code implementation practices and their feasibility in Latvian building stock is discussed for these buildings with regards to their long-term thermal energy savings potential.

This doctoral thesis is written in English and contains introduction, 10 chapters, conclusions, references, 28 figures and 27 tables for a total of 104 pages. Bibliography lists 121 reference.

ANOTĀCIJA

Ēku energoefektivitāte ir būtisks faktors infrastruktūras ilgtspējības nodrošināšanai. Latvijā ēku siltumenerģijas patēriņš apkurei sastāda 80% no kopējā ēku energopatēriņa aukstajā gada periodā. Tādējādi, ēku siltumenerģijas patēriņa samazināšana energoefektivitātes pasākumu, vietējo būvnormatīvu un saistīto noteikumu ieviešanas rezultātā var sniegt izmaksu ietaupījumus ēku īpašniekiem un ieinteresētajām pusēm.

Šajā promocijas darbā tiek aprakstīta metodoloģija siltumenerģijas taupības pasākumu potenciāla novērtēšanai ilgtermiņā dzīvojamām, sabiedriskajām un rūpnieciskajām ēkām pie atšķirīgiem siltumenerģijas patēriņa scenārijiem. Šie scenāriji tika izstrādāti, balstoties uz trim ēku siltumenerģijas patēriņa kritērijiem ar analītisku prognozi tuvākajiem 10 gadiem.

Darbā tiek analizēti apskatīto būvnormatīvu ieviešanas pasākumi un to ilgtermiņa tehniski-ekonomiskais novērtējums, ņemot vērā siltumenerģijas taupības potenciālu.

Promocijas darbs ir uzrakstīts angļu valodā, tajā ir ievads, 10 nodaļas, secinājumi, literatūras saraksts, 28 attēli, 27 tabulas, kopā 104 lappuses. Literatūras sarakstā ir 121 avots.

Contents

1. INTRODUCTION

Nowadays new constructed buildings are looked at from a rather market-driven and sustainability-oriented viewpoint, given that buildings provide temporary or permanent living environment and are major energy consumers. As a matter of fact, the building sector accounts for approximately 40% of total final energy use across the developed countries, constituting up to one-third of the worldwide greenhouse gas emissions. Therefore, energy efficient buildings imply not only significant cost savings due to lower energy consumption, but also an added market value and a “green label” associated with the owners and stakeholders instituting a positive image and public relation reference.

As such, building energy efficiency has been a priority topic for both micro and macro scale stakeholders. The micro-scale aspect allows for cost savings to the building owners and stakeholders, considering energy-related government and local incentive programs, and thus, lower building operating expenses; the macro-scale aspect, on the other hand, allows governments and building owners to meet the regulations on CO_2 emissions and comply with the international regulations that ultimately lead to significant financial savings and allow to relocate the stakeholders’ financial resources to develop other priority areas on agenda.

Building energy efficiency is a dynamically and rapidly growing field and has certainly become a separate industry and a research area over recent decades, as it requires an involvement of highly skilled professionals and continuous research and development activities. In line with the industry’s growth, the market availability and promotion of sustainable and energy-efficient products and solutions increases. This development is in large part driven by national and regional energy and environmental building codes and regulations. Regulatory building codes have proven to be an effective way to promote energy efficiency in buildings. Many governments across the world have put forward nationwide long-term energy use reduction goals for newly constructed and existing building stock that are reinforced by stringent UN regulations aimed at addressing environmental impact and climate change.

The present doctoral thesis examines the currently adapted strategies aimed at improving the energy efficiency of the building stock in Latvia and their projected effect over the next decade.

The research work is based on the hypothesis that the long-term thermal energy savings in residential, public and industrial buildings can be evaluated by developing a methodology which determines various building energy efficiency upgrades at individual and building-scale level. Within the scope of this doctoral thesis an evaluation methodology of the building stock thermal performance and future savings potential under various thermal energy consumption protocols is developed and adapted to Latvian context.

The methodology consists of a multi-step process within which a study on the effect of Latvian regulatory building codes related to energy efficiency on the thermal energy savings in residential, public and industrial buildings is carried out. For this purpose, a long-term building thermal energy performance analysis is developed based on three regulatory building code compliance scenarios (baseline, normal and nZEB) with a 10-year building stock development projection.

This study contributes to better knowledge on the subject by providing initial benchmark and understanding of the significant thermal energy saving potential across the building stock in Latvia. Moreover, the methodology allows to introduce variable input data (user defined parameters) so that it can be applied to other regions as well, therefore the relevance and applicability of this study extends beyond Latvian context.

2. THE OBJECTIVE OF THE STUDY

Topicality. Building sector is a major energy consumer accounting for approximately 40% of total final energy use across the developed countries and therefore it holds a substantial energy saving potential via energy optimization measures. Addressing building energy efficiency contributes in reducing building energy consumption that in turn leads to lowering environmental impact and to significant cost savings in the long run.

Objectives and main tasks. The aim of this study is to develop a comprehensive and widely applicable evaluation methodology (research subject) of the building stock thermal consumption and future energy savings potential under various thermal energy performance protocols. The scope of the study encompasses thermal energy performance evaluation of residential, public and industrial buildings in Latvia.

The main objective of the energy efficiency measures in buildings is to reduce energy consumption for heating, cooling and electricity needs without compromising the occupant comfort and satisfaction level with the quality of the indoor environment. Yet, the developed methodology is limited to understanding building space heating energy as an initial step and does not consider lost heat through the hot water supply systems and auxiliary use of electricity due to following factors:

- energy used for space heating constitutes approximately 80% of total building's energy use in Latvian climate conditions during the cold season, which typically lasts from early October thru mid-April;
- a substantial share of supplied heating energy to the building is lost through the building envelope (external walls, ground floor, roof), windows and thermal bridges, whereas domestic hot water and electricity use does not depend on the quality of building's thermal performance (unless electric heaters are used, which is not typical in Latvia);
- hot water and electricity use are tied to individual choices, preferences, consumption habits that fluctuate extensively and thus have to be modeled separately;
- there is a well developed and industry-accepted methodology to calculate heating energy consumption in the building, based on the average outdoor and desired indoor temperatures, as well as building's thermal performance that is regulated by Latvian Building Standard.

As such, the present study aims to contribute to the research on the subject of building energy efficiency by presenting a comprehensive and widely applicable methodology of evaluating thermal energy saving potential in the long run across different building categories when adhering to various thermal energy compliance scenarios across broad regional spectrum.

Scientific novelty. This work introduces a comprehensive methodology for the evaluation of potential thermal energy savings upon implementation of various building energy efficiency upgrades. Currently existing tools do not stipulate evaluation of building renovation strategies across individual scale and building scale components over a long run. Moreover, there is a lack of validated comparative calculation tools for stakeholder use to evaluate building energy efficiency renovation strategies across individual and building scale components. The methodology presented in this work, on the other hand, allows to compare and prioritize strategies to develop streamlined approach for regional and national building stock energy efficiency roadmaps. It is applicable across wide regional spectrum encompassing mild and cold climate regions to evaluate potential thermal energy savings across the building stock of interest over the extended timeframe, while applying various building energy consumption reduction protocols.

Practical application. The developed methodology is primarily intended for the stakeholders such as building industry professionals and policy makers in developing national building stock energy efficiency roadmaps and in reviewing regulatory environment related to the building stock energy efficiency. The methodology is particularly useful for governments and public entities experiencing challenges with the existing building stock's compromised energy performance and facing uncertainty over implications resulting from stringent policy measures.

Approbation. The findings and the results of this study have been presented at 5 international conferences, with the conference proceedings indexed in Scopus database.

3. LITERATURE REVIEW

A comprehensive literature review was carried out within the framework of this doctoral thesis to demonstrate the importance, originality, and relevance of the proposed research. The literature review contains prior research in the field of building stock energy efficiency.

Since the subject of building energy efficiency is becoming more relevant across the world, building energy policies and strategies develop and change at a fast rate. Given these circumstances, the subject of the study is time sensitive. Information and scientific analysis may become outdated or irrelevant in a short time after being published. Therefore, in order to include the most up to date information and scientific articles published mainly after 2010 were reviewed in detail.

This literature review chapter is organized in the following way. Section 3.1. provides an overview of the current status of the building stock energy performance across the EU region. Section 3.2. elaborates on the efficiency upgrade and renovation measures in the building stock. Section 3.3 introduces building energy performance policies in Latvia. Section 3.4. provides a summary of some recent studies on energy efficiency strategies for buildings across various regions worldwide. Section 3.5. summarizes the general findings in the reviewed literature. Figure 3.1 shows the flowchart of the three-stage literature review performed to identify the articles related to this research work.

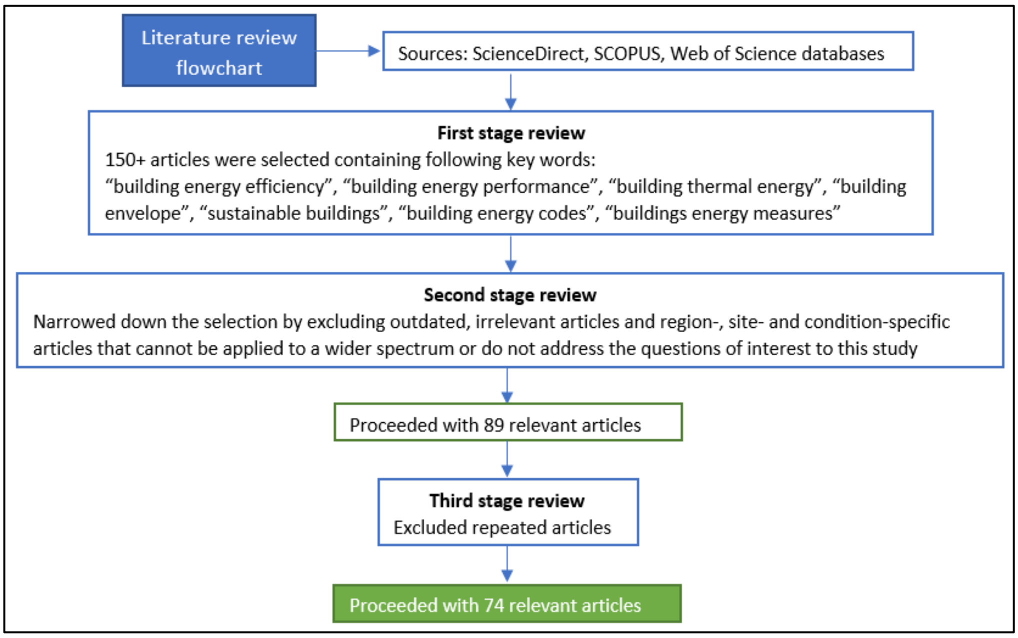

Figure 3.1: Literature review flowchart.

3.1 Building stock energy performance in the EU region

Building energy efficiency subject goes well beyond the building stock-related boundaries and is a major driver to facilitate economic and social development of the regions. Geographic regions with the prolonged heating season and high heating demand, for instance, require different approach to address the energy efficiency of their building stock from the regions with hot and humid climate, hence regional specifics and climatic variations have to be considered a priori [1]. In pursuing the grounds for energy efficiency project implementation potential in a certain region the historical, existing and prospective barriers to implementation of building code compliant renovation and modernization project execution have to be examined considering the regional context, current investment potential and government support. Short and long-term measures to overcome these barriers have to be put forward in order to develop a strategic action plan [2].

Energy efficiency strategies in buildings include but are not limited to the following measures that have a direct and indirect impact on buildings' embodied and operational energy use [3], [4]:

- proper design and insulation of building envelope;
- high performance glazing and windows;
- elimination of thermal bridges;
- high efficiency heating, ventilation and air-conditioning (HVAC) systems;
- low-energy equipment (lighting, electrical equipment etc.);
- building management system (BMS);
- building automation and control (BAC) systems;
- water supply and consumption management;
- eco-friendly waste management;
- proper system maintenance plan and execution;
- efficient facilities management and operation;
- seamless communication tools between building users and facilities management.

The above-listed measures have direct and indirect impact on buildings' energy efficiency: i.e., an efficient HVAC system will have a direct effect on lowering the building's energy bill, whereas an eco-friendly waste management plan will affect the building's energy efficiency indirectly by generating lower carbon footprint as a result of advanced and environmentally friendly waste handling.

Buildings in the EU-28 (as of Q3 of 2020) [5] account for approximately 55% of total electricity consumption and roughly 40% of total final energy consumption on average [6],

[7]. Followed by transport and industry, the building industry is the largest end-use energy sector in Europe. In Latvia, Estonia and Hungary buildings' energy use share is even higher (45%) due to the poor energy performance of the existing building stock that was built during and slightly after the World War II (1940-1960s) and is now obsolete with regards to meeting energy performance criteria [4]. Up until 2002 buildings in Latvia were designed in accordance with USSR (Union of Soviet Socialist Republics) regulatory codes, which were not stringent enough with regards to the thermal performance [8]. As a result, the bulk of the existing building stock that has not undergone deep renovation feature poor thermal insulation, excessive outdoor air infiltration and condensation occurrence within the external wall structures [9], [10], [11]. Moreover, the absolute majority of the post Soviet buildings (buildings constructed between 1945 and 1991 when Latvia was part of USSR) lack proper mechanical ventilation system, and thus the air exchange occurs due to natural ventilation and/or outdoor air infiltration through the external elements (walls and roofs), which entails major thermal energy losses [12], [13]. Other major sources of heat loss featured in the existing old buildings in Latvia are linear thermal bridges, window frames and single pane glazing. A study conducted by Tallin Technical university has shown that linear thermal bridges account for up to 25% of the total transmission heat loss of the buildings in Eastern European region (in some of the studied buildings this share reached even 34%) [14]. Transmission heat loss through the windows in the old building stock oftentimes lies in the ballpark of 30-40% of the total building heat loss [15]. That largely depends on the window and wall area ratio, as well as the thermal performance of the elements of the building envelope and thermal characteristics of the individual components.

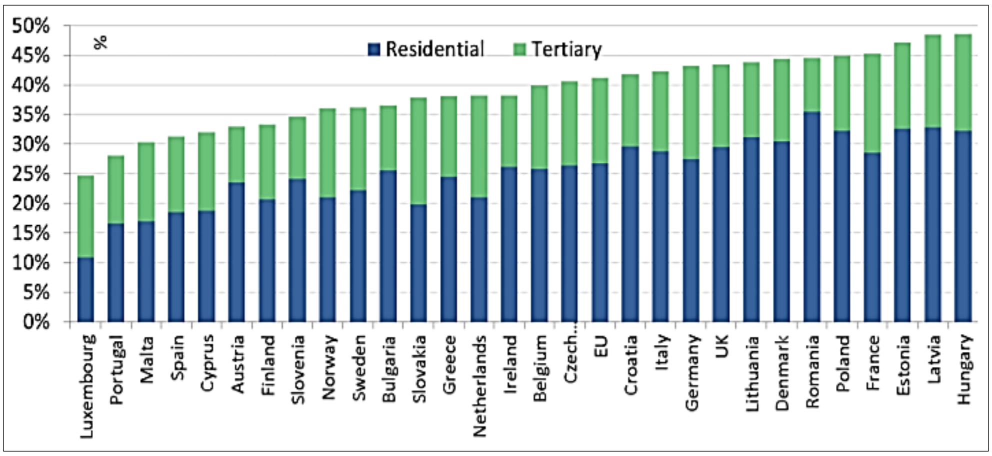

Figure 3.2: Buildings' energy consumption share of total energy: The distribution profile for residential and tertiary (public) buildings across the EU-28 [4].

However, implementing overly stringent energy efficiency measures may have an adverse effect on building's embodied energy and life cycle energy (LCE), therefore when applying energy efficiency measures in buildings, it is highly important to take into consideration a trade-off interrelation between embodied and operational energy use. Furthermore, to minimize the LCE of a building, decisions with regards to energy efficiency strategies have to be made early in the design phase. [16]

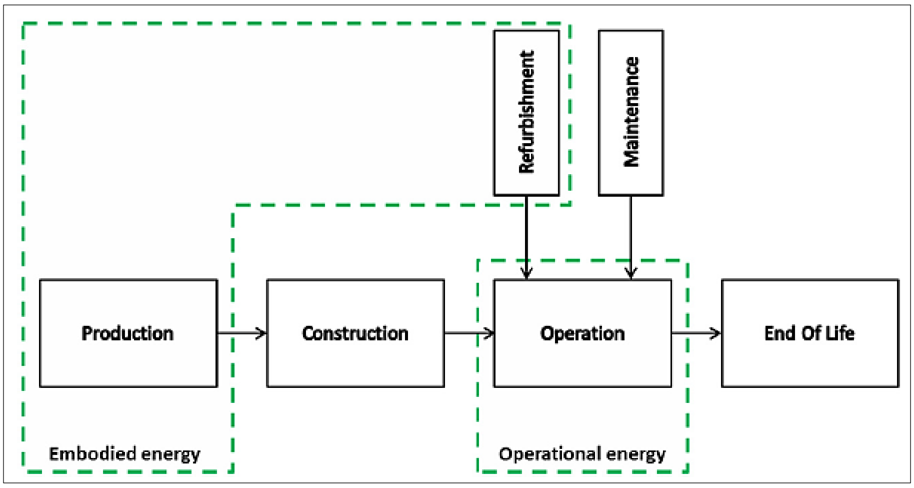

Figure 3.3: Embodied and operational energy interrelation in building's life cycle. [16]

Early research work on energy use associated with buildings tended to focus on the operational phase of the building life cycle, while the significance of the embodied energy phase has been omitted [3]. The ratio between embodied and operating energy in the buildings is usually 80-90% (for operational energy) and 10-20% (for embodied energy). This factor is often omitted among the stakeholders when it comes to justification of various energy efficiency strategies and measures, therefore it is suggested that buildings' LCE demand is reduced by the use of active and passive technologies that can ultimately lower buildings' operating energy, even though this may increase the share of embodied energy to some extent [17]. For instance, by implementing various building envelope design strategies, a reduction of 20% to 50% in total building energy consumption can be achieved. Those strategies include special building envelope components, thermal insulation layer, air layer in building envelopes, phase-change materials, building integrated PV modules etc. [18]. Active building envelope systems can utilize energy input to manage cooling and heating loads, directly reducing the energy demand of central HVAC unit and convert energy from solar or wind source into conventional energy that can be used to operate building mechanical systems (HVAC, lighting, other electrical equipment). However, active building envelope systems are not standalone systems, and hence, as a precondition, passive building envelope technologies have to be integrated [18]. On the other hand, an excessive use of these technologies in the buildings may result in adverse implications, as in the life cycle energy context low energy demand buildings often perform even better than zero operating energy buildings [3]. The two main subsystems responsible for energy consumption in buildings are energy passage through the building envelope (separation of indoor and outdoor environments) and energy use by the facilities and equipment in the buildings (operational energy). It is also noted that with the continuous urbanization in both the developed and developing countries the total building energy consumption will only rise and will comprise even larger portion of total energy consumption (fig. 3.2) [19].

As of today, in European countries approximately 40 percent of total energy demand is attributed to buildings, and this trend is very similar across all developed countries. Moreover, buildings account for around 36 percent of greenhouse gas emissions and therefore building sector presents a very high energy saving potential in line with other sectors such as transport and production industry [20]. Moreover, building sector has a significant potential to mitigate impact on climate change through the implementation of energy efficiency measures and integration of on-site renewable energy sources (RES) such as wind, solar PV and geothermal [21]. Nevertheless, the current rate of improvements in buildings' energy efficiency is rather low in Europe and it is often associated with insufficient technical knowledge of responsible parties, poor and dysfunctional regulation system and even disinterest by public sector actors. As a matter of fact, according to a recent study, these factors were found to be the most common barriers that are slowing down the building-level energy efficiency improvements in Finland [2], however, the authors suggested that these same factors can be applied to all EU region and may vary in a rather narrow range country by country.

Even though there are often rigid technological interventions implemented to cut energy consumption in buildings (e.g. added insulation layer, HVAC system installation or retrofit), regular systems' maintenance is often the key to reduce energy demand in buildings. To facilitate the implementation of energy efficiency measures in the early stages of building design, planning and management, a relevant education and professional training has to be ensured. This highlights the importance of embedding energy efficiency strategies as an integral part of the building construction phase, rather than an add-on. Also, more active and target-oriented communication between policy makers and building stakeholders (building professionals, contractors, designers, clients, end-users etc.) is required to address the barriers related to non-functional regulation and poor interest [2].

Another study that examined the trade-off between operational and embodied energy emphasized that an increase of the energy embodied in the production process of the building materials and elements usually offsets the reduction of the energy consumption throughout the building operational cycle [22]. Consequently, the authors suggested that it is necessary to evaluate whether the balance between the embodied and operational energy use is worthwhile from the LCA aspect. Otherwise, the transition to high-performance buildings with regards to relation between embodied and operational energy may have a rebound effect and therefore is non objective, i.e., substituting a certain amount of operational energy with proportionally equivalent amount of embodied energy that does not lead to meaningful energy savings in the long run throughout the building's life cycle.

Meeting buildings' energy requirements is another matter of dispute that often raises between the building stakeholders, i.e., the client and the contractor. The disputes are triggered if a new building fails to comply with its designed energy performance criteria. As numerous studies have shown, there is often a discrepancy between the actual monitored energy consumption and the calculated, i.e., projected specific energy use of a building in the design phase. One of the main reasons for such discrepancy is the mismatch between the actual energy behavior of the occupants and the values modeled and projected in building energy performance simulations [23]. This underlines the importance of considering occupant behavior factors, that affect energy use of a building, as well as educating the occupants on effective ways to save energy without compromising their satisfaction level with indoor environment [24]. Another study proposed that building energy efficiency should only be determined according to the actual energy consumption and not based on the projected energy performance, as the actual and monitored energy-use data often diverges. Due to the aforementioned factors authors argue that the government building design standards in evaluating building energy potential are often far less relevant than they are intended to [25].

Modern day buildings are highly energy intensive, therefore, governments across the developed countries are undertaking more aggressive policies in order to reduce energy consumption in the existing building stock. For instance, several cities across the U.S. have mandated large building owners to disclose the energy performance of their properties. This has positive implications on emphasizing the benefits of energy efficiency measures in terms of making the market more transparent and thus allowing to develop more effective and data driven policies based on the performance of the reference buildings [26]. Buildings are major consumers of electricity, thereby a reliable cost and benefit analysis of energy savings from energy efficient buildings are of great importance for policy makers to evaluate the financial feasibility of numerous incentives addressed to invest in buildings energy efficiency [27]. Cities in the developed countries have an existing building stock that will last for many decades, hence an increasing focus will be addressed towards major energy retrofitting programs of the existing buildings, driven by the long term cost benefit [28]. On the other hand, it is projected that by 2050 in Europe and the U.S. the large portion of the existing building stock will be either renovated or replaced by new buildings, therefore it will be new building stock that will dominate the urban energy demand in the developing regions [29]. The rate at which energy efficiency policies are being adapted and implemented in practice very strongly depends on the social, economic and technological development of the region [30]. Compact and high-density urban environments positively impact the economic and technological development of the cities, which in turn increases the market demand for the expansion of the building stock with the integration of innovative and energy efficient measures. Moreover, intensely populated urban areas are associated with higher level of public engagement, social interaction and hence knowledge spill-over, which results in a social impact as a driving force on higher public awareness on the importance of building energy efficiency [29].

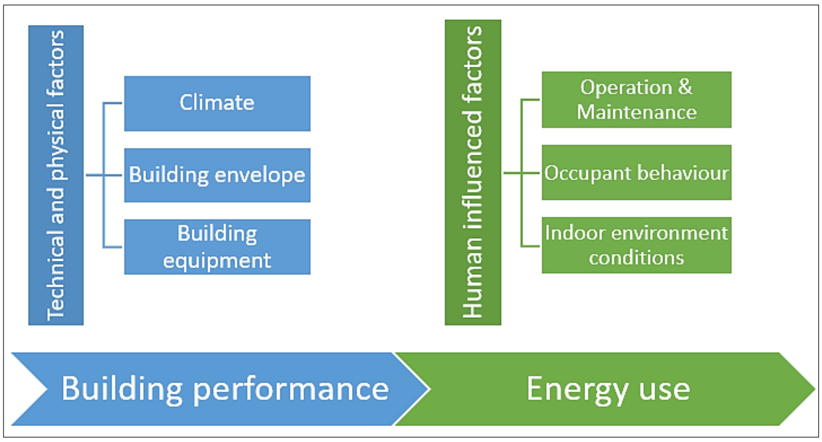

Figure 3.4: Influencing factors on building energy consumption [31].

The factors influencing building's energy use are illustrated in figure 3.4. Energy consumption is directly associated with the building's energy performance; hence, it is critical to apply energy conservation measures in the design stage (building envelope, mechanical systems, energy recovery etc.). With better energy conservation-oriented design building's energy use will be lower, however, there are numerous human influenced factors that have to be addressed: occupant behavior, operation, maintenance, and indoor environment conditions. Those are solely dependent on the social or human influenced factors such as overall public awareness of energy conservation benefits, individual indoor climate preferences, occupant education and facility management competence level [31]. Building operation and occupant behavior are the main factors that influence and as a consequence may disbalance the projected energy use in buildings [32]. However, those two components are interrelated and therefore proper retrofit evaluation and system balancing has to be ensured, as it is observed that in many buildings that have been subjected to energy efficiency improvements and retrofits there is a decrease in indoor air quality, thus leading to productivity drop for building occupants, i.e., if mechanical ventilation system is employed, there is a trade-off between reducing energy consumption and supplying sufficient amount of fresh air indoors [27], [33].

This again highlights that in order to optimize the life cycle energy of the building it is critical to evaluate the balance of both the embodied and the operational energy, as the two values are negatively correlated. If this balancing is done correctly, not only it will lead to reduced environmental footprint of the building, but also to reduced energy consumption over the building's life cycle [34]. This once again emphasizes the critical importance of an early decision making in the building's design, where the choice of building materials and mechanical equipment have to be made based on the correlation between the energy consumed during the construction cycle and the energy saved throughout the building's operation cycle [35]. A study conducted in Sweden showed that amongst other intervention measures for building's energy efficiency, retrofit ventilation heat recovery presented the largest final operational energy savings for the building, followed by energy efficient windows [36]. Proper design and capture of daylighting can also substantially reduce the operational building energy use [37]; however, a thorough solar heat gain analysis has to be modeled at the design stage to ensure that energy saved for lighting will not be counterbalanced by the energy needed for cooling.

Low embodied and operational energy are the focus of the modern building design in the developed world, therefore along with the local regulatory policies, clear government incentive programs and promotion of integrated renewable energy systems have to be developed in order to accelerate the adoption and implementation of the energy efficiency measures in practice [38]. A study by the Green Building Program that encompassed 533 partners and 1054 non-residential buildings in Europe of different age, size, use and type (offices, hotels, industrial buildings etc.) was launched to implement a combination of energy efficiency measures and track the energy balance from the project's start in 2006 through its completion in 2014. The initiative went in line with the European roadmap to reduce greenhouse gas emissions by 80% by 2050 against 1990 levels. Various renewable technologies were applied to the participating buildings (solar PV and solar thermal, air and ground source heat pumps, geothermal and heat recovery technology) which resulted in annual savings of 985 GWh [39].

Web platforms can also promote energy renovation mechanisms and stimulate investments in the energy retrofitting of buildings. A study presented a web platform that allows to connect demand and supply side actors by providing up to date information on the energy efficiency guidelines and building codes, the energy performance evaluation in buildings, low energy and nearly zero energy buildings, related statistical data and etc. [40]. This platform presents another approach to raise public awareness and to facilitate energy efficiency renovation measures in buildings.

Integration of BIM tools throughout the building design stage would effectively facilitate coordination amongst parties involved in the design process, enhance the quality of the building design model, eliminate errors, and improve overall accuracy of the design model. However, building design process implies close collaboration between architects and engineers, and while timely and consistent feedback throughout the building design process effectively improves building's energy performance, current building codes and design guidelines are usually not available in digital rule form, which in turn prevents the automated checking and quality validation of the design material [41]. Technical limitations, prevalence of conventional design practices and overall industry's resistance to innovation are the main factors that slow down the faster and smoother transition to implementing the higher degree of digitalization in building design process, and thus oftentimes compromising early and critical decision making addressed towards energy efficiency.

3.2 Upgrade and renovation of the existing building stock

As previously noted, building sector is the most energy-hungry end-use sector as it accounts for approximately 40% of total energy use: buildings are responsible for 38.9% of the total energy consumption, followed by transportation (33.1%) and production industry (23.3%) [42].

When it comes to evaluation of building energy efficiency strategies on a national or regional scale, reliable and objective building stock data is of utmost importance. However, many countries lack accurate building stock dataset [43]. Another hindering factor to improving building energy efficiency is that retrofit and renovation projects often lack clear and long term strategies that in turn results in low incentive influx from the government funds and other instruments aimed at supporting renovation projects. This leads to relatively low building renovation rate across the EU region, e.g., in Lithuania only 3% of all multi apartment building stock has been renovated over the last decade [44] and this figure is somewhat similar across Post Soviet and Eastern European countries. A study carried out to project potential energy savings for space heating and hot water use for the Lithuanian building sector through the implementation of energy efficiency measures revealed that the most cost effective approach is to renovate the old multi family houses that use district heating, as these buildings dominate the Lithuanian building stock, they have very poor energy performance and they require relatively low investment costs [45]. This approach is found to be relevant in Baltic states and in most of the Eastern European region where old buildings (built before 1990s) present very high share of the total building stock.

There is an increased display of acknowledgement that to address buildings' energy efficiency on a national and regional scale an increased focus has to be directed onto the improvements and sustainable upgrades of the existing building stock. In the developed countries newly constructed buildings comprise approximately 1-2% of total building stock, e.g., in Australia new buildings account for only 2% of the total building stock, in the UK and the United States this figure is 1% according to Office of National Statistics and Energy Information Administration (EIA). Therefore, to achieve environmental and infrastructure sustainability requires sustainable upgrade measures of existing built environment as it accounts for 98-99% of the total building stock across the world. These measures include improving (i.e., reducing) heat transfer coefficients of building envelope, windows and thermal bridges, use of higher quality insulation materials, HVAC retrofits, integrating on-site renewables etc. [46]. Numerous studies underscore the importance of addressing existing building stock across European countries in the first place to reduce buildings' energy consumption load. Previous experience shows that sustainable upgrade of the existing buildings has a high potential in reducing energy consumption – after the introduction of stricter building regulations and energy requirements across the EU member states residential buildings built in 2000s consume 24% less energy than those built in 1990s [47]. However, despite the outstanding energy saving potential that can be achieved by implementing various renovation measures the estimated building renovation rates across Europe is relatively low [48] – within the range of 0.5% and 2.5% of the building stock renovated annually [49], [50].

Although it is estimated that renovation projects account for 57% of all construction activity in Europe, the majority of these renovation projects do not imply any energy efficiency interventions and therefore they do not utilize any meaningful energy saving potential [51].

The existing building stock in Europe is highly inefficient in terms of energy conservation, thereby in order to reduce the high energy consumption share of the building sector, upgrading the existing European building stock is the key. Besides the positive environmental impact, an added value of energy efficiency upgrades in buildings is a positive effect on the economical development [47]. A more detailed breakdown of buildings' energy consumption reveals that tertiary buildings, i.e. public and private offices, shops, schools, hospitals etc., consume over 40% more energy (kWh/m^2) than residential buildings, and they account for 25% of the total building stock [52], [4].

Over the recent years the policies for the support of energy efficiency upgrades in buildings have been becoming more stringent, emphasizing the importance of running the feasibility study of the planned measures at the early building retrofit design stage in order to reach projected energy goals with clear economic sense [53]. Energy savings due to retrofits vary widely depending on the applied energy efficiency techniques, building's initial condition and climate. For instance, according to the study, in more arid climate energy efficiency measures for households can reduce energy bills by 30% with respect to their original energy consumption [54]. However, there are certain socioeconomic and technical barriers that slow down the faster implementation of energy efficiency strategies in buildings, such as timeline of return on investment for the stakeholders, accurate monitoring, reporting, verification and quality assurance of the implemented retrofits [55]. To facilitate successful building energy efficiency and retrofit programs governments have to develop mandatory policies and present effective financing mechanisms, as well as to ensure that industry does not lack highly qualified building professionals [56].

The EU has set an improvement of energy efficiency in buildings as one of the target actions to meet the regions' long term environmental, economical, and geopolitical development goals. The Energy Performance of Buildings Directive [57] sets the energy use objectives and optimal cost criteria on the individual building renovation. When a single stakeholder takes responsibility for building energy renovation project, a set of interventions are to be carried out considering individual energy profile of each single building subjected to renovation.

3.3 Building energy policy development in Latvia

Building energy consumption levels (kWh/m^2 year) across the EU member states differ within a rather wide range. Also, the rate of improvement in buildings' energy efficiency differs quite extensively, e.g., Latvia and Hungary present the fastest reduction of energy consumption in buildings if referenced against 1990s levels. This, however, makes sense, provided that up until 1990s all buildings in Latvia and Hungary were designed and constructed according to USSR regulations (as stated earlier). In early 1990s Hungary began to follow the path of Western European countries by imposing more stringent regulations in place of the outdated building energy standards. Whilst shortly after the collapse of Soviet Union in 1991, the Ministry of Architecture and Construction of Latvia began instituting new local energy efficiency regulations and over the coming years a national energy efficiency roadmap was developed which implied notably stricter building regulations. In 2003, a new Latvian Building Norm (LBN 002-01) came in force which even further tightened the existing building regulations, setting new construction standards for new buildings, reconstructed and renovated buildings, primarily by introducing new U-values (heat transmission coefficients) for all building elements (building envelope, windows, thermal bridges) [58], [59]. Following the common EU directive goals on energy efficiency and good practice from Western European countries that are often viewed as role-models in building energy efficiency advancements (Scandinavian countries and Germany), in 2015 a new amendment of LBN 002-01 became effective (LBN 00-15) that even further limited the U-values for all new and renovated buildings [60], that has been replaced by LBN 002-19 since 01.01.2020 [61].

Figure 3.5 presents the timeline of building energy policy evolution in Latvia and Hungary that have resulted in building energy consumption rate decrease in both countries.

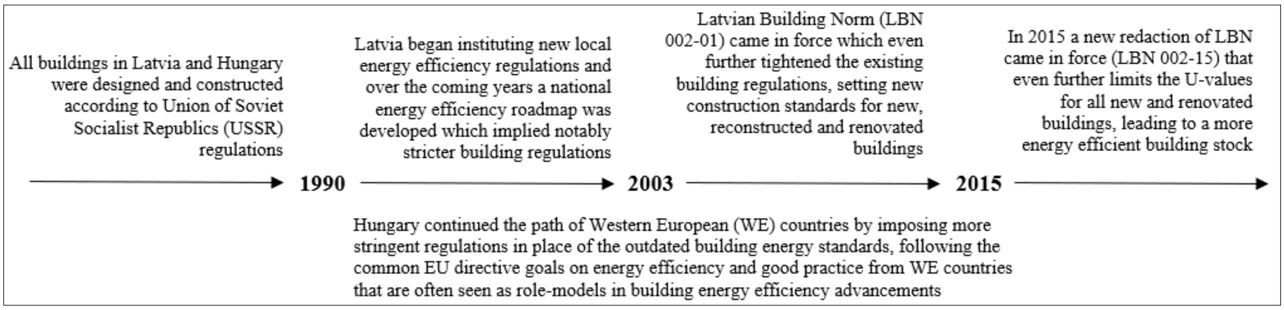

Figure 3.5. Roadmap of building energy policy evolution timeline in Latvia and Hungary.

Figure 3.6 shows the trend of energy consumption in residential buildings in Latvia and Hungary over the period of 1990-2016, using 1990 as a reference year. The construction activity in Latvia in the first years after regaining the independence was relatively low and therefore new regulatory building standards do not translate into reduced energy consumption immediately, however, the graph illustrates that residential building energy consumption in the two countries has been decreasing rather steadily [62].

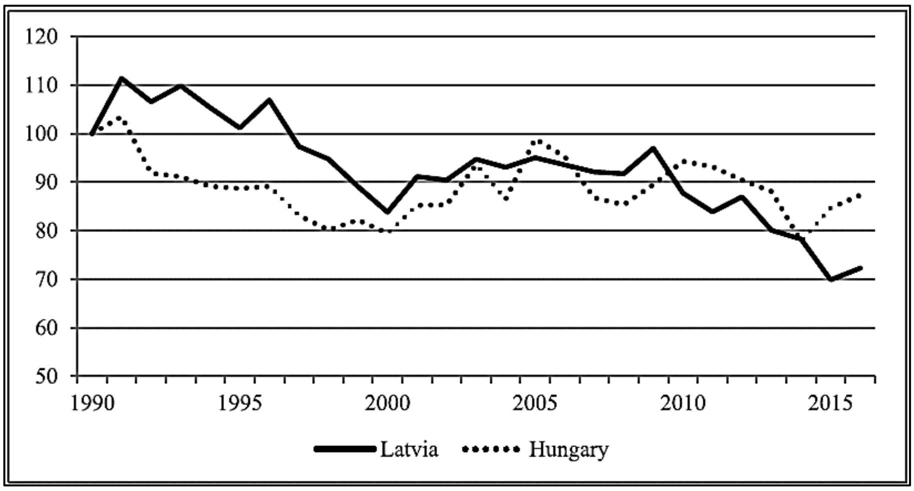

Figure 3.6: Residential Energy Consumption trend in Latvia and Hungary (1990–2016, Index: 1990=100), [62], [63].

The figures suggest that regulatory building standards are an effective policy measure for reducing energy consumption in buildings, however, due to the time needed to adopt and implement those regulatory standards for new buildings and major renovations their direct impact becomes evident over a longer timespan [62]. Also, there are various additional building energy conservation optimization measures not prescribed in the regulatory codes, that result in significant long-term energy savings. These measures are discussed in more detail in the next section.

3.4 Regulatory environment and other energy efficiency strategies

Energy performance and life cycle cost of a building ranges over wide spectrum given differences in building design and operational characteristics. This entails that reductions in buildings' energy consumption in majority cases are not proportional to the investment, therefore, special focus has to be attributed to the update of the energy efficiency related building codes [50]. Nationwide energy efficiency programs remain very important driver in reducing buildings' energy use. In addition to reducing buildings' energy bills, these programs also ensure building systems upgrades and thus, if properly implemented, improving indoor environmental quality (IEQ) [64]. Oftentimes, improved indoor environmental quality comes as an added premium of full building energy efficiency upgrade intervention.

Many countries have been adopting more stringent building energy codes over recent years, which have resulted in more efficient building stock [65]. Yet, adhering to the local building regulatory standards or government-imposed building energy efficiency policies does not guarantee the most energy efficient and high energy performance building that can be designed and constructed by implementing existing measures and technologies [66]. In the United States the most widely adapted measure in an attempt to make the buildings more efficient is the International Energy Conservation Code (IECC). However, a recent study suggests that with additional measures that go beyond meeting the IECC-2012 regulatory requirements (optimized window-wall ratio, improved glazing, Trombe walls, high quality insulation materials, advanced HVAC and lighting systems etc.) an additional 39% reduction of total energy consumption can be achieved in residential buildings [67]. In practice, the implementation of those additional measures is often lacking due to insufficient knowledge on the side of both the owners and the developers, as well as social, financial, technical and administrative barriers [2], [55], [67]. Thereby, an important driver in pushing the market towards adopting energy efficiency measures beyond regulatory requirements, a lifetime potential of various energy saving techniques has to be thoroughly analyzed [67]. That emphasizes the importance of considering energy efficiency techniques beyond improved insulation and U-values of the building envelope that reduce both heating and cooling energy demand, such as optimization of thermal mass, automated shading, demand controlled ventilation and high albedo roofs [65]. The transition to a more stringent energy efficiency regulatory environment for buildings leads manufacturers to come up with a range of state of the art building envelope techniques in place of the conventional ones, considering the rising market demand and long-term cost efficiency of adopting such techniques. However, whilst the conventional techniques (insulation materials, window shading and etc.) have proven their return on investment over time, the emerging energy saving technologies, for example, low emissivity windows and window films preventing from excessive solar heat gain penetration have yet to gain market approval through a thorough and comprehensive research and development stage to obtain extensive technical understanding of benefits and risks of this technology [68]. This factor is attributed to every emerging technology that has not been around long enough to prove its efficiency and feasibility.

Effective public campaigns for the building stakeholders (building professionals, investors, facility and operation managers, building occupants etc.) is a key driving mechanism for the successful implementation of the energy conservation measures (thermal insulation, weather proofing, energy efficient HVAC systems and lighting) [47]. In addition to building regulatory codes, public awareness, and government incentives towards energy conservation measures (ECMs), region's energy market plays a major role. In order to ensure high level of energy efficiency in any given building, a high degree of capital investment is required. Oftentimes there is a trade off between the conventional practice (low investment in ECMs, high building operation costs) and innovative practice (high investment in ECMs, low building operation costs). For instance, in Saudi Arabia where electricity prices are low and energy market is rather settled due to the abundance of oil reserves, it makes little sense for private sector to invest in energy efficiency, therefore an innovative financing mechanisms have to be introduced by the government to incentivize the public sector to invest in energy efficiency measures in the long term. Reducing or cutting the subsidies for energy prices and diverting financial resources towards financing energy efficiency programs instead, educating the public on energy conservation advantages based on the long term savings, creating energy service and auditing companies to enhance energy efficiency implementation strategies and monitoring building energy environment would incentivize public and private actors to cost effectively transit and invest in energy efficiency [69].

A number of EU member states have announced their nationwide long-term strategies to improve energy performance of buildings and reduce greenhouse gas emissions. These efforts include preparing highly skilled professionals, educating the society, conduct energy audits, building certification and regular inspections, run information campaigns, preparing building regulations and calculation, modeling tools, set and follow national approaches to low energy buildings, do the planning and financing analysis for the renovation of the existing building stock, conduct cost optimization and other tasks related to energy efficiency in buildings [70]. Under the Energy Performance of Buildings Directive the EU member states are obliged to set and follow minimum energy efficiency criteria for buildings and building engineering systems [71]. As an example, Ministry of Sustainable Development in Sweden has set a nationwide target to reduce energy consumption in buildings by 50% by 2050, using 1995 as a baseline [72].

When discussing advancements and innovation related to building energy efficiency the European countries, Far East region (China, Japan, South Korea) and the United States are typically at the forefront of the discussion. However, countries all over the world recognize the significance and most importantly long-term financial benefits of the energy efficiency measures in buildings. For instance, South American countries only recently began to turn their focus to improving energy efficiency and intensifying efforts to develop more demanding policies. This has mainly been driven by the region's prolonged political instability, economic segregation, energy supply intermittency and weak geopolitical climate reliability. Yet, it is rather challenging for the South American region to develop and implement energy efficiency strategies at a similarly steady rate as in the U.S. or EU countries, because there is no existing energy efficiency regulatory environment upon which the new and stricter policies can be built. Another issue that the region is facing is the lack of skilled building professionals and experienced control group to monitor the quality and check the quality and the compliance of construction projects with the set building standards [73]. For instance, in Hong Kong strict policy instruments adapted in early 2000s resulted in rapid increase in energy use efficiency, primarily due to the use of high efficiency cooling solutions within large scale commercial buildings [74].

3.5 Summary

Over 150 scientific articles were examined within the scope of this literature review in the first stage based upon the criteria of matching key words in their title, followed by filtering those articles in the second stage review based on their relevance and significance to the subject of the study. And finally, outdated, poorly relevant and repeated articles were excluded from selection that narrowed down the number of articles examined in this literature review section to 74 manuscripts.

The literature review section encompassed a wide spectrum of recently published articles on the topic of the building energy efficiency. Although the studies in the literature review section had an emphasis on the status and strategies of the building energy performance in the EU region, it also provided an insight from other regions across the world.

The reviewed articles provide a global standpoint on the importance and a long-term benefit of upgrading, renovating the existing building stock and having new buildings designed, constructed, operated, and maintained in an energy efficient way. The reviewed literature also emphasizes the importance of energy performance improvement and monitoring strategies through clear and thoroughly designed government policies, skilled taskforce, favorable investment environment and regular public campaigns.

However, the reviewed literature sources do not provide meaningful insight and distinctive quantitative metrics with regards to economical feasibility and efficiency of various building energy renovation measures over a long term timespan. Moreover, there is a lack of references in the reviewed literature containing any validated comparative calculation tools for stakeholder use to evaluate building energy efficiency renovation strategies across individual scale and building scale components.

Therefore, to address the subject of stakeholder-friendly building stock energy efficiency evaluation tool for new construction and renovation projects, this study introduces a methodology for evaluation of the potential thermal energy savings upon implementation of various building energy efficiency upgrades, that is applicable across the building stock of interest over the extended timeframe. As such, the proposed methodology fills the gap in the currently existing tools and scientific literature on the subject of building stock thermal energy conservation potential by providing a straightforward analytical long term projection tool for stakeholders such as building owners, operators, facility managers, utilities, investors etc.

4. METHODOLOGY

4.1 Generalized methodology

In pursuance of the outlined objectives set forward within the framework of this study and with the goal to fill the gaps in the currently existing tools, a comprehensive methodology was developed to design a thorough thermal energy performance assessment tool of building stock that would evaluate future potential energy savings under various building thermal energy consumption compliance scenarios. The proposed methodology allows for a long-term building stock thermal energy performance evaluation of various types of buildings (residential, public, industrial etc.) across the regions where the demand for space heating is present.

The general worklist within the long-term evaluation methodology of building stock thermal energy performance consists of multiple interrelated steps:

1) identifying building design guidelines (i.e., regulatory building codes) that determine and provide feasible metrics with regards to setting buildings' thermal energy performance criteria;
2) proposing thermal energy performance comparison protocol (scenario/-s) referenced against the baseline case for potential cumulative savings calculation;
3) obtaining the historical dataset on the building stock of interest (residential, public, industrial etc.) and arranging the dataset by new construction and major renovation projects (pertaining to the buildings that have undergone energy retrofits);
4) based on the acquired historical building stock dataset and other considerations (e.g., construction market, economic growth etc.) designing a projection matrix for the building stock development over a timeline of interest;
5) developing computed models that represent statistically averaged building prototypes for each of the building category;
6) applying the designed building stock development projection matrix to the modeled building prototypes in order to establish building stock thermal energy consumption profile for thermal energy performance comparison protocol (or for the proposed scenarios) defined in step 2.

Each of the outlined steps is elaborated in more detail in the subsequent sections (paragraphs 5-9). A detailed flowchart of the building stock thermal energy performance evaluation methodology is illustrated in figure 4.1.

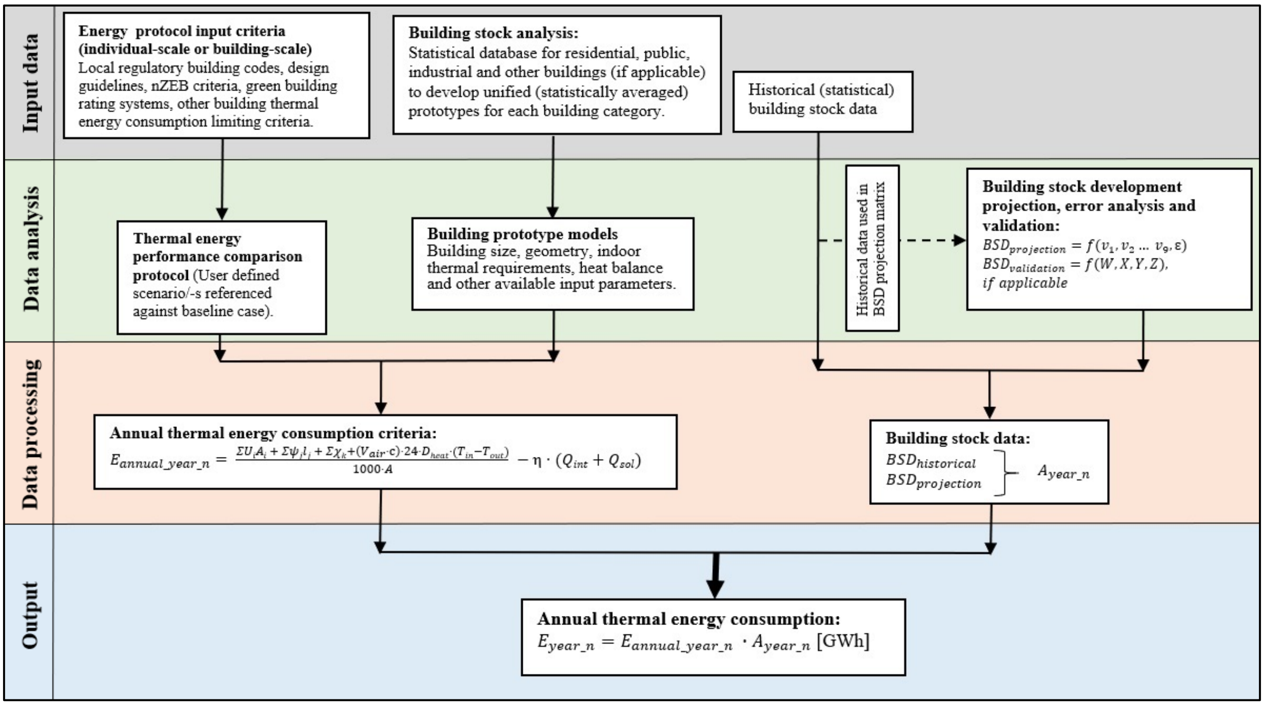

Figure 4.1. Generalized building stock thermal performance evaluation methodology flowchart.

At its core, the presented flowchart is applicable to general cases with input parameters and criteria entered by an authorized user. In this context, an “authorized user” is any stakeholder that employs the proposed methodology to run thermal energy savings calculation on a national (or regional) scale that is subject to present a decision-making significance (e.g., for financial risk evaluation, return-on-investment assessment, nationwide infrastructure development project feasibility study etc.). The stakeholders deemed as authorized users may include, but are not limited to energy utilities, power companies, government institutions, financial institutions, investment groups, city developers, architects etc. Once the user applies their input data in the methodology, the tool translates into adapted methodology tied to a specific case study.

At an input phase, it is essential that the dataset pertaining to the building stock of interest is accurate (and preferably validated by dataset provider or a third party) to avoid excessive deviations and errors from the real case when developing the building prototype models and building stock development projection in the data analysis and processing phase.

At the output phase, the proposed methodology generates an annual thermal energy consumption calculation for the whole building stock of the particular building category (e.g. residential), by multiplying the annual energy consumption criteria by the total floor area of the building category within the reviewed geographic region.

As the input data directly affects the accuracy and credibility of the output, this study also emphasizes the magnitude behind understanding the degree of the efficiency of the design guidelines and/or regulatory building codes and outlines the importance of controlling both the individual and the building-scale parameters that are frequently addressed in the regulatory environment.

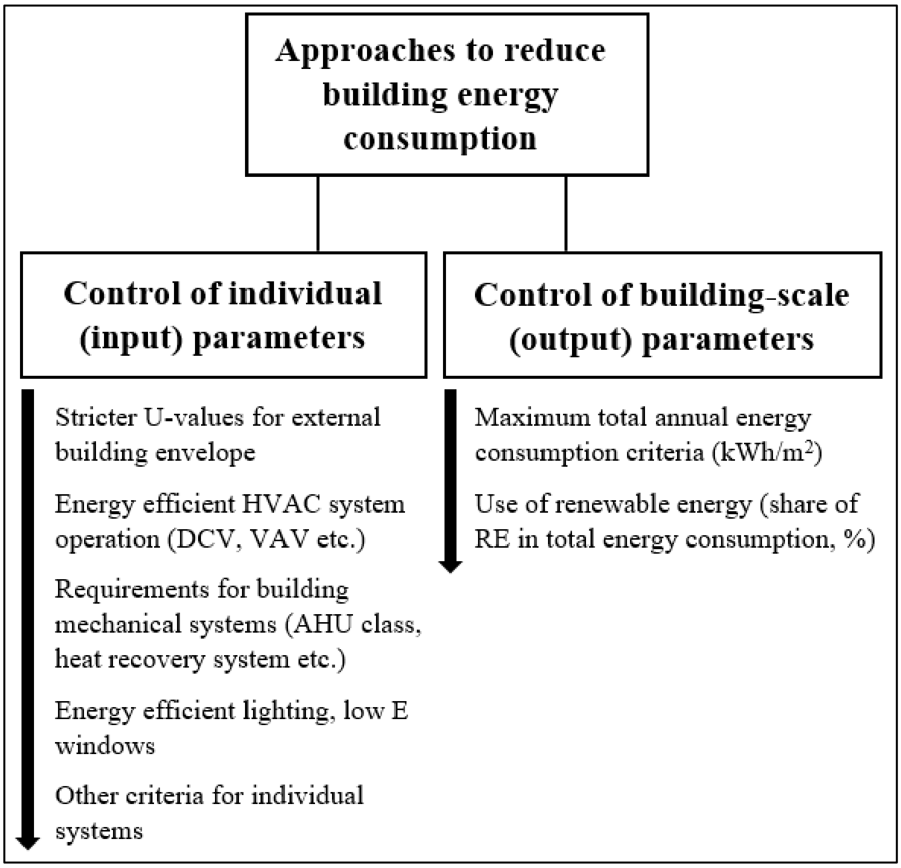

Figure 4.2: Comparison of controlling individual and building-scale parameters within the regulatory building codes.

Figure 4.2 summarizes how the design criteria (outlined in technical guidelines or regulatory building codes) pertaining building energy efficiency subject set the requirements for individual and building-scale parameters. In other words, the individual scale parameters are controlled at an input level of the building design (U-values of external building envelopes etc.) and the building systems design (VAV system for HVAC, low energy lighting etc.), while the building-scale energy efficiency and energy conservation parameters are set as output criteria in form of total building energy consumption requirements (as max kWh/m^2) and/or minimum share of on-site renewables (% of energy produced from solar, wind, geothermal etc.).

A comparative analysis of the presented approaches in fig. 4.2. is compiled in table 4.1, where advantages and disadvantages of each strategy are outlined in detail.

Table 4.1

A comparative analysis of controlling individual parameters and building-scale parameters.

Control of individual parameters		**Control of building-scale parameters**	
Advantages	**Disadvantages**	**Advantages**	**Disadvantages**
Every individual building element has a certain performance criterion to comply with, making this approach clear and straightforward	The inefficiency of an "underperforming" building element can not be compensated by an efficiency of an "overperforming" element	Convenient metric for setting and monitoring building energy use	In some instances, it may be difficult to comply with (in buildings of specific use, shape, design etc.) and control of individual parameters is suggested instead
Compliance with energy performance criteria for individual parameters often leads to higher level of building efficiency if compared to the building-scale parameter approach	Limited possibilities to adopt alternative solutions and to implement stringent requirements for historic buildings	The inefficiency of an "underperforming" building element can be compensated by an efficiency of an "overperforming" element	Occupant comfort may be significantly compromised, as this approach may result in low IAQ and overheating of indoor spaces in the summer due to low energy operation mode of HVAC system
This approach usually ensures higher IAQ and occupant comfort	Limited architectural design options	From a stakeholder/FM standpoint – meeting the kWh/m^2 and/or % of RE criteria is the ultimate goal (no need to seek for strategies beyond this benchmark)	This approach may result in high indoor humidity level and condensation occurrence on the surfaces of the external construction elements due to insufficient air exchange rate
Limits designers' ability to adjust individual systems' parameters therefore ensuring each individual system's compliance with the outlined requirements		Even after the target is met, building's energy efficiency can be improved further by upgrading building's individual parameters/ systems	

In broader terms, this study aims to underline the importance of controlling both the individual and building-scale parameters, as focusing on addressing just one single criterion may lead to a negative trade-off in the other criteria. For instance, according to table 4.1. setting the max energy consumption criteria for the whole building may result in the deterioration of the indoor environmental quality by:

a) compromising indoor air quality or leading to overheating of indoor spaces in the summer due to low energy operation mode of HVAC system [75], [76];
b) leading to high indoor humidity level and causing condensation occurrence on the surfaces of the external construction elements due to insufficient air exchange rate [11], [33].

While the present study incorporates solely the control of annual energy consumption (kWh/m^2) in its methodology, which is a building-scale parameter, the developed methodology and the study results can be expanded further to perform analysis on the effect of setting various scenarios for individual scale parameters, or setting the minimum energy input share from renewable energy sources.

As such, the generalized methodology presented in this study can be applied to any region across the world requiring space heating in the cold season after the acquisition and thorough evaluation of the critical input parameters (such as building energy efficiency criteria, building stock data etc.).

4.2 The adapted methodology: identification of input parameters

Within the scope of the current study, the generalized long-term evaluation methodology of building stock thermal energy performance (outlined in section 4.1.) was adapted to the case of Latvia, which entailed modifications in the generalized methodology as follows:

1) identifying local regulatory building codes that determine and provide feasible metrics with regards to the buildings' thermal energy performance;
2) proposing three building thermal energy performance compliance scenarios based on the identified regulatory codes (reference, normal, nZEB scenario);
3) obtaining the dataset on Latvian building stock from 2014 to 2019 and arranging the dataset by new construction and major renovation projects;
4) based on the acquired historic building stock data designing a projection matrix for the building stock development up till 2030;
5) developing computed models for residential, public and industrial building set that would represent statistically averaged building prototypes for each of the building category;
6) applying the designed building stock development projection matrix to the modeled building prototypes in order to establish building stock thermal energy consumption profiles for each of the proposed scenarios.

A detailed flowchart of the building stock thermal energy performance evaluation methodology employed in this study is illustrated in figure 4.3.

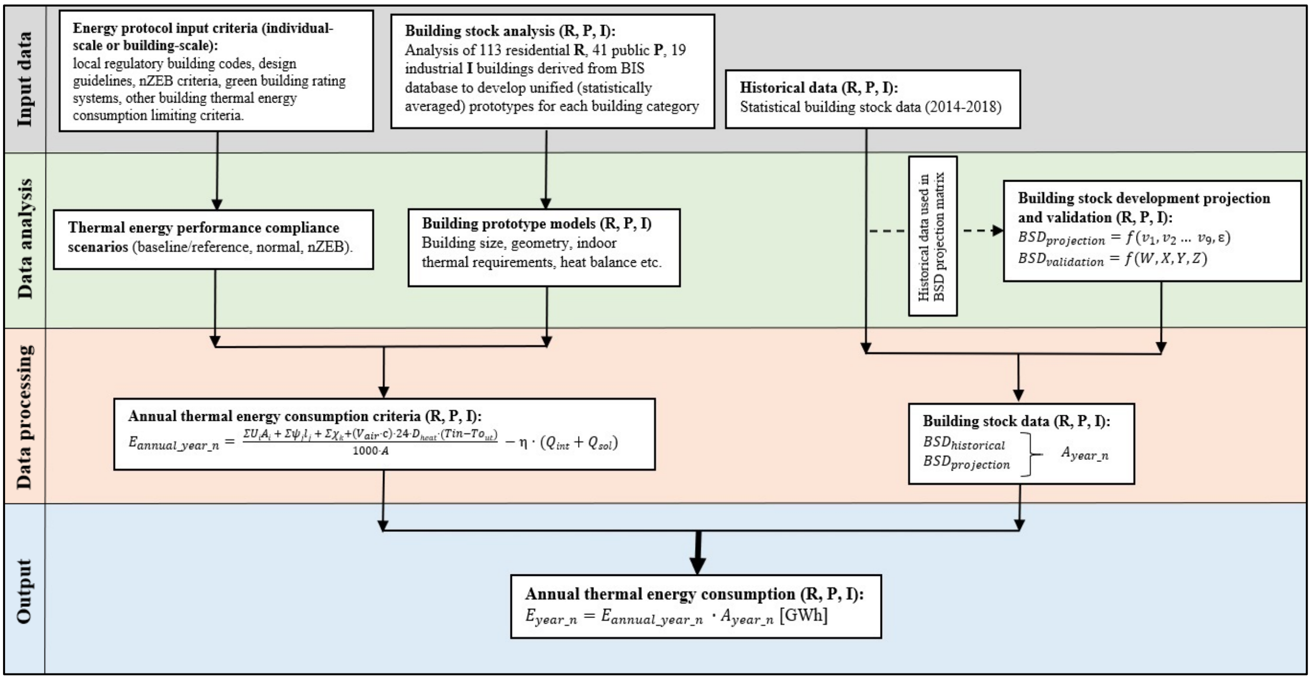

Figure 4.3. Methodology flowchart adapted to the framework of the current study.

As specified, the flowchart presents a methodology adapted and elaborated for the case of Latvia, reviewing the relevant regulatory environment, and utilizing the respective national building stock dataset.

4.3 Summary

In order to design a thorough building thermal energy performance assessment tool that would evaluate potential energy savings under various building thermal energy consumption compliance scenarios, a comprehensive methodology was developed.

The generalized methodology allows for thermal energy performance evaluation of various types of buildings across the regions with space heating demand over the user specified projection timeline. Several dependent variables can be integrated into the generalized methodology to project it to a specific case. In other words, the generalized methodology can be applied to a specific context and/or criteria, such as, geographic region, building category, performance and design guidelines to examine how a single or various dependent factors affect the thermal energy consumption across the reviewed building stock over the timeline of interest.

When the current methodology is employed, it is important to note that in order to ensure high degree of accuracy of the output (annual energy consumption), the validation of the input data (the reviewed building stock data) is of critical importance.

5. BUILDING THERMAL ENERGY PERFORMANCE DESIGN CRITERIA

5.1 Reviewed regulatory building codes

As a preliminary step in the implementation of the proposed methodology, the regulatory building codes that institute building thermal energy performance requirements in Latvia were reviewed and analyzed. The overview of the regulatory codes setting building energy efficiency standard in Latvia is compiled in table 5.1.

Table 5.1

The overview of the regulatory codes determining building energy efficiency in Latvia.

#	**Currently Effective Regulatory Code**	**Previous version**	**Type of the Regulatory Code**	**Comments**
1	Latvian Building Code LBN 002-19 “Thermotechnics of Building Envelopes” (Amended in 2019) [61]	Latvian Building Code LBN 002-15 (containing normative heat transfer coefficients that are overridden by the currently effective standard) and LBN 002-01 “Thermotechnics of Building Envelopes” (its original version, introduced in 2001, came into effect in 2003) [58], [60]	National Building Code	The Amended version is compared to the Original version. The Amended version LBN 002-15 introduced stricter specific heat loss coefficients compared with LBN 002-01, that directly affects the heating energy consumption in the buildings. LBN 002-19 that replaced LBN 002-15 limits only maximum permitted heat transfer coefficients, while normative values stipulated in LBN 002-15 ensure higher thermal energy performance, as they are stricter
2	Energy Efficiency Law [77]	N/A	Law	Institutes reduction in energy consumption in buildings through Cabinet Regulation No. 383
3	Regulations on Energy Certification in Buildings (Cabinet Regulation No. 383) [78]	N/A	Regulation	An energy efficiency assessment for new constructed buildings with regards to the max energy consumption per floor area (kWh/m^2), effective from 2017

4	Methodology for Calculating the Energy Performance of a Building (Cab. Reg. No. 348) [79]	N/A	Regulation	Does not set requirements on the reduction on energy efficiency in buildings. The regulation stipulates the assessment, calculation, and energy certification procedures in buildings.
5	Regulations on the Energy Efficiency Monitoring and Applicable Energy Management System Standard (Cabinet Regulation No. 668) [80]	N/A	Regulation	Does not set requirements on the reduction on energy efficiency in buildings. The regulation stipulates energy efficiency monitoring of systems' operation and energy management matter.

In order to determine the regulatory building codes that enforce the requirements or set the limit for building thermal energy use, a three-step flowchart was employed as shown in figure 5.1.

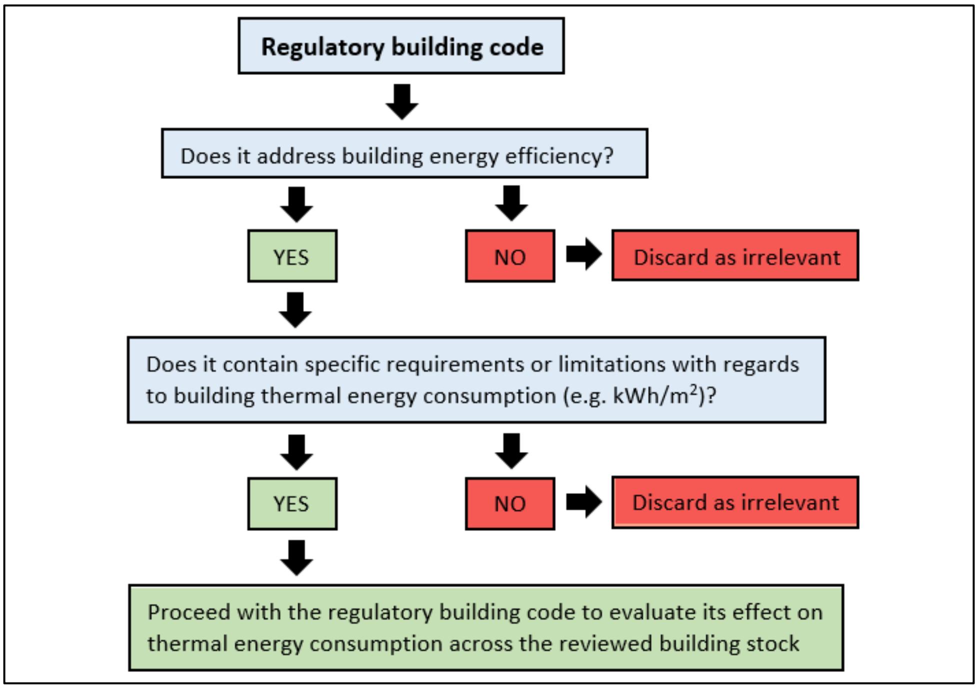

Figure 5.1. Relevant building code selection flowchart.

Table 5.2

The overview of the regulatory building codes addressing buildings' energy efficiency in Latvia.

Building code	**LBN 002-01**	**LBN 002-15**	**LBN 002-19**	**Cab. Reg. No. 383**
Introduced	2001	2015	2015	2016
Effective	2003-2015	2016-2019	2020-onwards	2017-onwards
Description	Procedures for thermotechnical design of external building envelopes	Stricter normative values of heat transmittance coefficients for construction elements	Kept only max values of heat transmittance coefficients for construction elements, phasing out normative values	Prescribes the energy performance requirements for nZEB
Application	NC and renovation	NC and renovation	NC and renovation	NC
Requirement	Mandatory	Mandatory	Mandatory	Voluntary (for energy certification purposes)

The building codes presented and summarized in table 5.2. were used as reference protocols for the building thermal energy consumption scenarios described in more detail in the following sections.

5.2 The proposed building thermal energy performance scenarios

5.2.1 Baseline and normal scenario

Latvian Building Code (or alternatively, Latvian Construction Standard) LBN 002-19 "Thermotechnics of Building Envelopes" [60], [61] prescribes the procedures for the design of construction elements of external building envelopes from thermal and technical standpoint for newly constructed and renovated heated buildings. The purpose of LBN 002-19 standard is to reduce energy consumption in buildings by increasing their energy efficiency, without compromising occupant comfort level. Construction elements are energy efficient when they protect the premises sufficiently well from cooling in winter and from overheating in summer. This building code does not apply to special structures in which people do not permanently reside during the heating season, to warehouses and production facilities with specific technological processes that require special heating [81]. The recent amendment of LBN 002-15 and its replacement with LBN 002-19 (effective as of 01.01.2020) overrides the normative values of heat transfer coefficients attributed to external building envelope and sets the maximum threshold for those coefficients. However, within the scope of this study the heat transfer values in normal scenario are reviewed as per LBN 002-15, as the compliance with normative coefficient values stipulated in LBN 002-15 ensures higher thermal energy savings potential compared to LBN 002-19 requirements.

In order to evaluate energy savings due to the adoption of LBN 002-15 in place of its original version LBN 002-01 [58], the thermal energy use in the buildings will be compared based on two scenarios – Scenario 1 (baseline scenario, as if all constructed buildings would comply with LBN 002-01) and Scenario 2 (normal scenario, as if all buildings would comply with LBN 002-15). The evaluation timeline is 2015-2019 (the starting timeline is determined by the adoption of the amended version of LBN 002-15).

LBN 002-15 "Thermotechnics of Building Envelopes" has introduced stricter normative values of heat transmittance coefficients for construction elements U_{RN}, W/(m^2 x K) and for linear thermal bridges Ψ_{RN}, W/(m x K). Lowering the normative values of heat transmission coefficients directly influences the reduction of energy consumption for space heating.

Table 5.3

Normative Values of Heat Transmittance Coefficients, LBN 002-01 (Original version, 2001) and LBN 002-15 (Amended version, 2015) [58], [60].

		Normative Values of Heat Transmittance Coefficients LBN 002-01			**Normative Values of Heat Transmittance Coefficients LBN 002-19 and LBN 002-15**		
No.	Construction elements	Residential houses, homes for the elderly, hospitals, and kindergartens	Public buildings, except homes for the elderly, hospitals, and kindergartens	Production buildings	Residential houses, homes for the elderly, hospitals, and kindergartens	Public buildings, except homes for the elderly, hospitals, and kindergartens	Production buildings
1	Roofs and coverings which are in contact with outdoor air	0,20 k*	0.25 k	0.35 k	0.15 k	0.20 k	0.25 k
2	Floors on the ground	0.25 k	0.35 k	0.50 k	0.15 k	0.20 k	0.30 k
3	Walls:				0.18 k	0.20 k	0.25 k
3.1.	at weights less than 100 kg/m^2	0.25 k	0.35 k	0.45 k			
3.2.	at weights 100 kg/m^2 and over	0.30 k	0.40 k	0.50 k			

4	Windows, doors, and glazed walls	1.80 k	2.20 k	2.40 k	1.30 k	1.40 k	1.60 k
4.2	Outside doors				1.80 k	2.00 k	2.20 k
5	Thermal bridges R	0,20 k	0.25 k	0.35 k	0.10 k	0.15 k	0.30 k

** k is temperature factor, that is calculated according to the equation 5.1.*

$$k = \frac{19}{t_{in} - t_{out}} \quad (5.1),$$

where: t_{in} – designed indoor temperature of a building, ^oC; t_{out} – average outdoor temperature throughout the heating season, ^oC.

The energy savings for space heating due to adoption of LBN 002-15 in place of LBN 002-01 will be determined by the following steps:

a) compiling data on Latvian building stock (paragraph 6);
b) developing prototype building models for residential, public and industrial building stock (paragraph 9);
c) determining the surface areas of building envelope construction elements for the developed prototype buildings
d) applying the respective heat transfer coefficients to the calculation methodology (paragraph 8).

5.2.2 nZEB scenario

Regulations Regarding Energy Certification of Buildings (Cabinet Regulation No. 383) [78] became effective in 2017. The regulation sets the energy performance requirements and the requirements for the use of high efficiency systems for nearly zero-energy buildings, as well as heating energy efficiency assessment for new constructed buildings. These requirements are effective for the newly constructed buildings that were put into service starting with 2017. The energy performance requirements differ for residential and non-residential buildings and have a progressively toughening thermal energy consumption limits (table 5.4.). The certification procedure is carried out on voluntary basis and therefore applies only to buildings seeking to obtain an energy performance certificate.

Table 5.4

The maximum annual energy consumption in new buildings, Cab. Reg. no 383.

The maximum energy consumption requirement in new buildings, annual kWh/m^2					
		Residential		Non-residential	
Time period of approval of a construction intention	Time period of putting building into service	Multiapartment buildings	Single apartment buildings	State-owned buildings	Other non-residential buildings
- 31.12.2016.	01.01.2017-31.12.2017	≤ 70	≤ 80	≤ 100	≤ 100
01.01.2017-31.12.2017	01.01.2018-31.12.2018	≤ 60	≤ 70	≤ 90	≤ 90
01.01.2018-31.12.2018	01.01.2019-31.12.2019	≤ 60	≤ 70	≤ 65	≤ 90
01.01.2019-31.12.2020	01.01.2020-31.12.2021	≤ 50	≤ 60	nZEB*	≤ 65
01.01.2021-		nZEB	nZEB	nZEB	nZEB

** nearly zero energy building (see nZEB criteria for Latvia in paragraph 10, section 10.1).*

5.3 Summary

Three building thermal energy consumption scenarios were reviewed and analyzed within the scope of this work, as described in the preceding sections: baseline, normal and nZEB scenario.

The timespan for the reviewed scenarios starts with 2014, as there has not been any major regulatory interventions between 2001 (the introduction of LBN 002-01) and 2015 (the substitution of LBN 002-01 with LBN 002-15, which was subsequently replaced by LBN 002-19) to address the reduction of building thermal energy consumption on a national scale, and therefore the three scenarios would follow the identical path. Moreover, the nZEB scenario begins to factor in only starting with 2017.

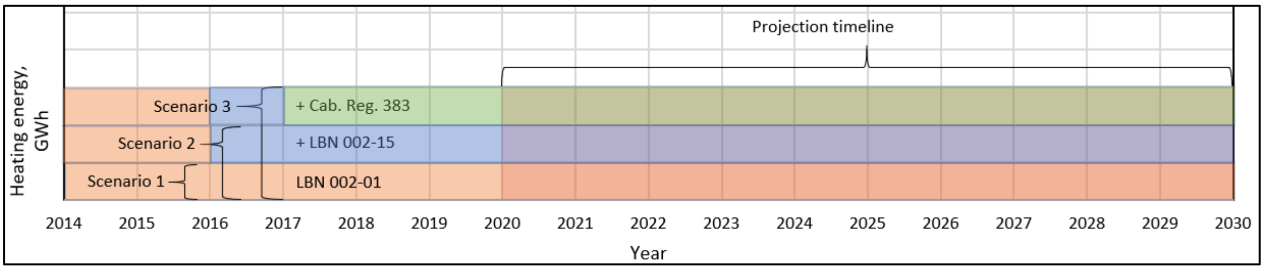

Figure 5.2. The illustrative framework of the reviewed scenarios.

The timeline for the three proposed scenarios is illustrated in figure 5.2. As it is shown, the timeline is split into two sections: historical – from 2014 to 2019, and projected – from 2020 to 2030. As highlighted in table 5.5, the baseline scenario continues all the way up till 2030 complying with the requirements set by LBN 002-01; the normal scenario progresses in line with the baseline scenario from 2014 to 2015 until the normative heat transfer coefficient requirements stipulated by LBN 002-15 come in force in 2016; the nZEB scenario follows the baseline scenario until 2015, and in 2016 it complies with the normal scenario, while starting with 2017 it follows the recently established Cab. Reg. no 383 requirements and takes on its own development roadmap.

Table 5.5

Overview of the modeled scenarios.

Reference		Notes
Scenario 1	Baseline	Building thermal energy consumption is calculated according to LBN 002-01 requirements, assuming that these requirements were effective as of today (disregarding LBN 002-15 that came in place on 2016).
Scenario 2	Normal	Building thermal energy consumption for 2014-2015 period is calculated according to LBN 002-01 (in line with the baseline scenario), 2016 onwards – according to LBN 002-15.
Scenario 3	nZEB	Building thermal energy consumption develops in line with Scenario 2 until 2016, from 2017 new buildings comply with Cab. Reg. 383, following the requirements attributable to nearly zero energy buildings development concept.
Projection		Building thermal energy consumption development across the three scenarios is projected over the course of 2020 – 2030, considering the dynamics of construction industry, investment climate, national economy growth projections, EU funding and other factors (paragraph 7).

The calculation of thermal energy consumption was performed according to the "Methodology for Calculating the Energy Performance of a Building". Yet, to obtain the necessary input data in order to apply the methodology over an extended projection timeframe 2020-2030 a separate building stock development projection analysis was carried out, which is described in more detail in paragraph 7.

6. ACQUISITION OF HISTORICAL BUILDING STOCK DATA

As an integral part of this study, it was necessary to acquire an accurate statistical building stock dataset on the effective floor area (m^2) for residential, public, and industrial buildings. The input array employed within this study consists of statistical data acquired from Central Statistical Bureau (CSB). The CSB database website offers publicly available data on various industries and services, from where the available statistical data on construction industry dynamics from 2014 to 2018 was derived [82]. The indexes in the tables were used to study the dynamics in the construction industry and the number and floor area (m^2) of commissioned buildings within the subjected timeline (2014-2018).

The acquired data was divided into two categories:

- new construction buildings (table 6.1);
- other buildings (including renovation, restoration, refurbishment and retrofit projects, table 6.2).

The two categories were further subdivided and arranged according to the building type:

- single apartment buildings;
- multi-apartment buildings;
- public buildings (commercial, office, wholesale, retail, education facilities, hospitals and other public buildings);
- industrial buildings and warehouses.

Table 6.1

Statistical data on the new construction buildings commissioned in the respective timeframe (CSB) [83].

New construction buildings, thousand m^2				
Year	Single apartment	Multi apartment	Public buildings	Industrial buildings
2014	319,8	143,5	553,6	269,3
2015	198,0	138,9	480,5	273,8
2016	247,4	127,3	216,2	122,9
2017	251,7	112,9	165,0	110,0
2018	273,0	181,1	210,2	135,5

Table 6.2

Statistical data on other buildings commissioned in the respective timeframe (CSB) [84].

Year	Other buildings, thousand m^2			
	Single apartment	Multi apartment	Public buildings	Industrial buildings
2014	195,6	256,3	558,7	190,2
2015	248,0	49,0	567,4	239,6
2016	100,7	56,5	230,3	226,8
2017	87,4	54,2	365,5	165,5
2018	105,0	66,0	249,2	147,1

There is no detailed breakdown available for “other buildings” (table 6.2) by subcategories (i.e., renovation, restoration, refurbishment, retrofit), which was confirmed after reaching out to the Industry and Construction Statistical Division representatives at the Central Statistical Bureau.

This adds the limitation to the accuracy of the input data in the present study with regards to subdividing:

a) retrofits that include energy efficiency interventions in the building (e.g., insulation of the envelope, upgrade of the mechanical systems etc.)
b) restoration projects that address building visual appearance (façade repair, repaint, decoration etc.) or re-design (layout adjustments, replanning etc.).

The difference between those measures is that retrofits (renovations and majority of refurbishment projects) are directly aimed at reducing energy consumption in buildings, whereas restoration projects do not specifically address building energy performance and thus do not result in energy consumption reduction.

As such, the data compiled in Table 6.2 among major renovation projects include minor renovation, restoration, and redesign projects, that have no effect on reducing buildings’ energy consumption. Therefore, it was necessary to acquire statistical data on retrofit projects involving deep energy intervention spectrum and examine it more thoroughly. For this purpose, Ministry of Economics (MoE) of the Republic of Latvia was contacted.

The MoE develops and implements economic structural policy, manufacturing policy, energy policy, external economic policy, domestic market policy (for goods and services), commercial development policy, competitiveness and technological development policy, consumer rights protection policy, and construction and housing policy. To achieve these goals, the ministry works closely with non-governmental organizations representing entrepreneurs and other social partners [85]. The communication process involved reaching out to different departments of the MoE. After negotiating and explaining the purpose of acquiring the data, MoE provided an information on the floor area of the renovated multiapartment buildings in Latvia, stating that data on other buildings is not under their primary supervision and that it is in fact negligible on the overall scale. It was also noted that the provided dataset includes all major renovation projects the ultimate goal of which was to reduce building's energy consumption.

Table 6.3

Renovated multiapartment buildings in Latvia (data provided by MoE).

Renovated multiapartment buildings, thousand m^2					
Year	2014	2015	2016	2017	2018
Thousand m^2	310,9	307,5	154,8	22,1	35,4

Other sources of information on construction industry dynamics were examined to check, verify and compare the information received from MoE and it was established that the information derived from the additional sources [86], [87] were in a good agreement with the data provided by MoE.

It is also important to note that the accuracy and reliability of the provided data could not be verified by other means, as MoE directly oversees and collects the information on commissioned buildings having undergone major renovation from municipalities across the country and maintains it for financial allotment and reporting purposes. As of yet, this information is not publicly available unless requested.

7. BUILDING STOCK DEVELOPMENT PROJECTION

7.1 Background factors

The construction industry dynamics over the last 20 years in EU countries have been fluctuating rather extensively due to an uneven financial environment and economic growth [88], increasing focus on reducing greenhouse gas emissions, introducing energy savings measures and digitalization platforms (building automation and control, BMS etc.) into the building sector [70]. The Baltic States in particular have been experiencing rather sharp growth in the construction industry since 2000 – largely triggered by the influx of the EU structural funds (although Latvia joined the EU in 2004, regional development funds were readily available for non-EU members and potential members), intense crediting and rather aggressive investment dynamics in real estate market. As a result, in 2008 the real estate market had tripled (referenced against 2000) [89], which is a clear indicator of the rapid pace of the growth, that the construction industry and real estate sector could hardly cope with. Shortly after this overwhelming rise, a financial crisis hit Europe, that stagnated the growth of all industries. Latvia was not immune to the crisis and experienced a very hard economic slowdown. This directly resulted in slowing down the growth of construction industry, halting many construction projects midway on national scale. The recovery was slow, and the following 4-5 years marked the adoption to the stagnancy and decline. Starting with 2012 the construction industry has been experiencing a gradual rise; however, the growth has been very sequential, and majority of the large scale projects are either fully or partially sponsored by EU funds, which is currently the main driver and determinant of the construction industry's growth dynamics in Latvia [90].

7.2 Projection methodology and determinants

In order to assess the thermal energy savings due to compliance with the reviewed regulatory building codes over the proposed timeline that extends to 2030, it is necessary to develop a building stock growth projection matrix, considering various boundary conditions.

Assuming that the regulatory building codes would remain constant (the control variable), it is necessary to define the projection for the housing stock development (the dependent variable). This task involved a close communication with the representatives from CSB and the MoE, that provided up to date information on the current state of the building stock dynamics and the projected growth. The sources of information for housing stock development projection included:

- expert forecasts (economic forecasts, construction industry development trends), *(v_1)*;
- EU funding projections (currently available and new financial tools), *(v_2)*;
- national progress report *(v_3)*;
- business and investment environment *(v_4)*;
- real estate market *(v_5)*;
- availability of mortgage (private housing loans), *(v_6)*;
- commercial and industrial loans *(v_7)*;
- regional development roadmaps and programs *(v_8)*;
- demographic analysis *(v_9)*;
- error margin (-5%/+5%), *(ε)*.

The building stock development projection matrix compiles wide ranged and complicated dependent factors representing the growth dynamics and comprehensive forecast analysis. Adopting the regular analysis method, the building stock development projection ($BSD_{projection}$) can be mathematically expressed in terms of a function in which the above listed factors serve as dependent variables (v_1.. v_9):

$$BSD_{projection} = f(v_1, v_2 \dots\ v_9,\ \varepsilon) \tag{7.1}$$

These factors ((v_1.. v_9) directly and indirectly impact the construction industry dynamics, therefore compiling them altogether into one projection matrix involved a third-party verification in form of a repetitive procedure of proposing, discussing, adjusting and reviewing the designed matrix. This procedure involved a series of iterations until the representatives from CSB and MoE came to a consensus of approving the proposed projection matrix.

The data validation matrix is shown in figure 7.1. Data items are labelled (W, X, Y, Z) and each item defines a unique factor determining the future development of the building stock (e.g., item X may define the projection for the EU funds influx throughout 2020 – 2030, while item Y may define demographic analysis including birth, death and migration patterns over the projected timeline etc.). The matrix flowchart shows that while one institution provided one set of data items (e.g., MoE: X, Y, Z), the other institution provided another set of data items (e.g., CSB: Y, Z, W). Thereby, while each institution missed one or a few input data items (or set of items), each institution also contained a unique data item (or set of items) that the other one lacked. Consequently, both of the institutions combined, possessed, and provided the necessary input data items to develop a credible projection scenario for building stock development up to 2030.

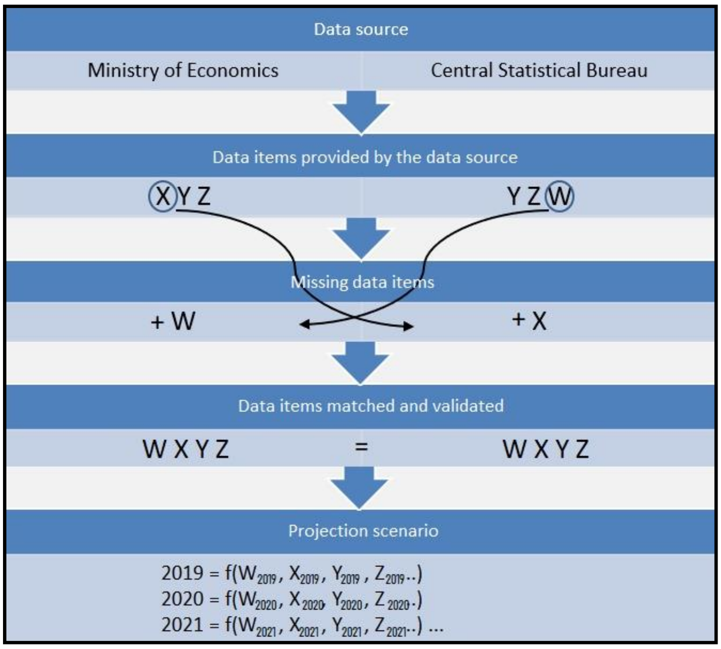

Figure 7.1. Data validation matrix for building stock development projection (2020 – 2030).

Upon completion of collecting the input data *(W, X, Y, Z..)* the projection scenario for 2020-2030 *f(W, X, Y, Z)* was developed (table 7.1) and validated with the Ministry of Economics and Central Statistical Bureau.

The information compiled by the Ministry of Finance of the Republic of Latvia indicates that the declining trend of the EU funded sponsorship for the construction projects within the previous planning period (2010-2014) will be gradually replaced by the increasing EU funded sponsorship during the 2014-2020 planning period [91]. As a result, the EU funding for public investments may return to the previous level (2010-2012). Ministry of Finance also points out that due to Brexit (and the uncertainty surrounding it), the intended funding may be reduced by 15-20%, in the pessimistic scenario – even up to 30%, however experts suggest that there is no grounds for concern that the EU will be cutting their funding to Latvia. Nevertheless, it is projected that the EU funding might decline again in 2024/2025, which marks the transition to the next planning period [89], therefore, as suggested by financial analysts and state counselors, government should look for another investment source before that deadline to ensure consolidated and consistent development of the construction industry, without rapid downturn that may hurt the nations' economy. Thus, to keep industry and export trend balanced upwards, it is important to find alternatives to the EU funded construction boost and development programs – with new financial instruments and outsourced investment tools [92].

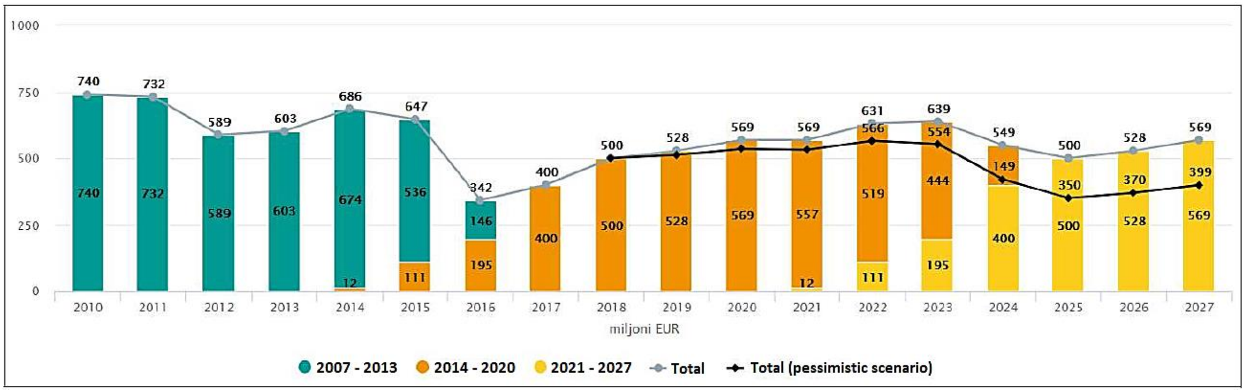

Figure 7.2. Public investments and EU funds in construction sector [89].

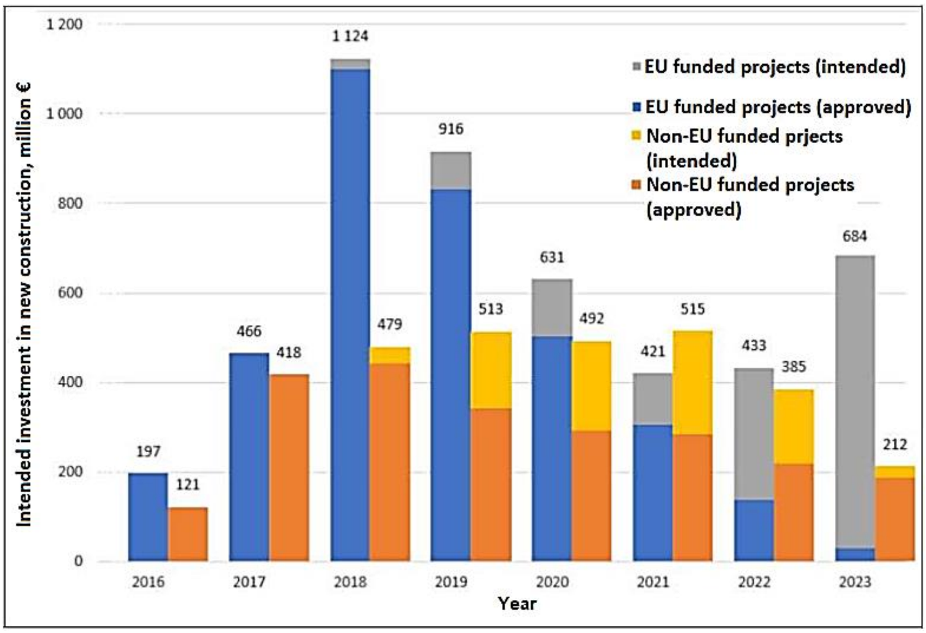

Figure 7.3. Intended and already approved public construction projects [91].

In a nutshell these determinants lead to a conclusion that MoE has to collaborate closely with the Construction industry to improve the industry’s competitiveness and boost future development through [92]:

- updating education materials and ensure preparation of high-profile field specialists;
- improving and monitoring quality of construction (incl. designing, building, monitoring, consulting etc.) services;
- implementation of ITC tools (CMR in logistics, automated HVAC systems, BIM tools etc.);
- developing clear and sustainable regulatory environment.

For consistent growth, the mid term goals for the construction industry are as follows:

- efficiency of the integration of digitalization processes;
- investment in innovations;
- consistent and balanced industry growth (slow and steady development, instead of rapid growth, that can lead to another downfall);
- quality of education, competence level.

If these mid term goals are adequately addressed and taken care of within the next five years (before the completion of the next planning period), then construction industry will continue to grow consistently even after the transition period (2024/2025) and will be less vulnerable to external factors and less dependent on the availability of the EU funding.

It is also important to note that the EU and national funding programs largely address the renovation (in the context of this study: retrofit, refurbishment) of the existing buildings, therefore the major renovation projects will have a significant impact on the energy efficiency dynamics and future thermal energy savings across the whole building stock, as they tend to comply with the energy performance requirements that are oftentimes more stringent than the existing building codes for new construction buildings.

7.3 Projection matrix

Based on the above-mentioned factors and determinants that will influence the industry's growth within the next decade, the building stock development projection for 2020-2030 timeline was designed. The three main building stock categories were singled out:

- Residential (single and multiapartment buildings, individual households);
- Public (government institutions, offices, hotels, hospitals, schools, kindergartens etc.);
- Industrial (production facilities, manufacturing, and power plants etc.).

Table 7.1

Building stock development projection matrix for 2020-2030.

Building stock relative growth referenced against previous year, %				
Year	**Residential**	**Public**	**Industrial**	**Comments**
2020	+5.0	+5.0	+2.5	Development dynamics continue at a steady rate
2021	+2.5	+2.5	+1.25	As the new planning period approaches, building industry's growth gradually slows down
2022	+2.5	+2.5	+1.25	As the new planning period approaches, building industry's growth gradually slows down
2023	+2.5	+2.5	+1.25	As the new planning period approaches, building industry's growth gradually slows down
2024	-10.0	-10.0	-5.0	Transition to the new planning period, the building industry experiences temporary decline
2025	-5.0	-5.0	-2.5	Transition to the new planning period, the building industry experiences temporary decline
2026	+2.5	+2.5	+1.25	As a result of new EU funding and rise in investment, building industry starts to recover
2027	+2.5	+2.5	+1.25	Though slowly, the recovery continues and attracts more mid-term and long-term investment sources
2028	+5.0	+5.0	+2.5	The industry stabilizes and the growth continues at a steady rate
2029	+5.0	+5.0	+2.5	The industry stabilizes and the growth continues at a steady rate
2030	+5.0	+5.0	+2.5	The industry stabilizes and the growth continues at a steady rate

As seen in the table 7.1, industrial sector has a lower impact rate (inertia) triggered by external drivers (market dynamics, investment climate etc.) compared to residential and public sectors, therefore the annual relative growth (+/-, %) varies with lower fluctuation in the projection matrix. This is due to the fact that the industrial sector has different investment sources from residential and public and is attractive to entities specifically involved in the business line the building is to be served to e.g., manufacturing plant or storage facility. Residential and public sector, on the other hand, has the investment influx from state government and private entities, where the business interest goes in line with the need for infrastructure development.

Nevertheless, all building categories experience similar growth trendline, as the external factors largely dictate the feasibility and profitability of the investment climate at the given time.

7.4 Life Cycle Assessment

Life Cycle Assessment methods can be directly applied to the building sector in form of building products, single buildings, and group of buildings. However, there is a lot of characteristics that serve to complicate the application of standard LCA method due to the following aspects [93]:

- the life expectancy of a building is both long and unknown that causes imprecision in doing LCA analysis (the energy sources and their efficiency change over time, thus the long-term projection of environmental impact is inaccurate);
- buildings are site specific, therefore many of the influencing factors have regional or even local-specific character, that has to be examined thoroughly, instead of being generalized;
- building and their components are heterogenous in their composition and thereby a lot of data has to be compiled with the regards to the associated products and their manufacturing processes (that vary greatly from one site to another);
- the building life cycle includes specific phases – construction, use and demolition, which all have variable consequences on the environment.

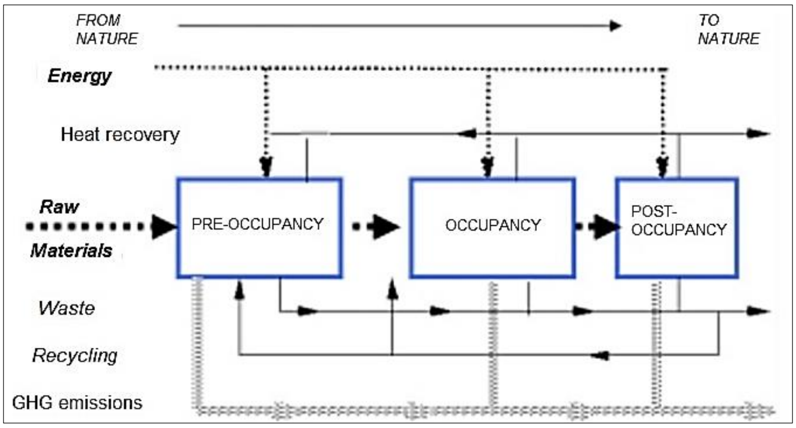

Figure 7.4. Life cycle assessment of a building [93].

In the context of this study, the environmental impact of the reviewed building stock was not evaluated as study focuses on the energy savings due to an implementation of different regulatory requirements.

Hence, the life cycle of the building for this study was narrowed and simplified to define the timeline from the construction phase to the demolition phase (end of use) of a building.

In general terms, the life cycle timeline for residential, public, and industrial buildings is within the range of 60 to 120 years and is influenced by the following factors:

- building category (residential, public, industrial or other);
- building's function (temporary or permanent);
- effective floor area of a building and number of floors (low-rise, mid-rise or high-rise building);
- the quality of a building project design, building materials and installation;
- further development of the surrounding infrastructure;
- regional socio-economic development;
- other factors (state of the national economy, building industry development, EU policies towards material safety and environmental protection, ground/soil stability etc.)

Given these considerations and the effective differences between the three reviewed building categories, the following projection was developed as to the life cycle of the buildings:

1) Residential buildings – 90 years;
2) Public buildings – 80 years;
3) Industrial buildings – 60 years.

7.5 Summary

In this chapter a building stock development projection matrix extending to 2030 was introduced for residential, public, and industrial buildings. The projection matrix was generated based on a thorough review and analysis of focal determinants. These wide ranging and complex dependent factors impact the construction industry dynamics in a direct and indirect manner, and therefore dictate the growth dynamics of the building sector, serving as dependent variables in the matrix (v_1.. v_9). As an output deliverable, the matrix produced a comprehensive construction market development forecast analysis. Thereby, as a precondition, a series of iterations and a third-party verification (conducted by MoE and CSB) were carried out to integrate the generated building stock development projection matrix into the proposed long-term building thermal energy performance evaluation methodology.

8. THERMAL BALANCE IN BUILDINGS

8.1 Calculation methodology

As there is no publicly available database containing construction data and performance characteristics of each individual building constituting all Latvian building stock, thorough and detailed prototype models had to be developed that would represent a typical residential, public and industrial building.

Furthermore, the building prototype models are necessary to perform thermal energy consumption calculation for the reviewed building stock, as each building category (residential, public, industrial) has different structural characteristics and requirements with regards to building design, materials, heat transfer coefficients, indoor comfort level and other thermal parameters.

The standardized heat transfer coefficients of building construction elements largely define the thermal energy consumption of a building, and therefore are at the base of the thermal energy consumption equation. These coefficients differ across the three building categories and are defined by the Latvian Construction Standard LBN 002 “Thermotechnics of Building Envelopes” (table 5.3, Normative Values of Heat Transmittance Coefficients).

The required annual thermal energy (kWh/m^2) for each prototype was calculated in accordance with Cab. Reg. no. 348 “Methodology for Calculating the Energy Performance of a Building” which is referred to in LBN 002-15.

The annual thermal energy consumption (kWh) across the given timeline for each building category (residential, public, industrial) was determined by calculating specific thermal energy consumption (kWh/m^2) and compiling statistical data (historic) on the building stock (m^2), separating new construction and renovated buildings.

Thus, the annual thermal energy demand for a prototype building (kWh/m^2) can be determined by the equation 8.1 [79]:

$$E_{annual} = \frac{\Sigma UiAi + \Sigma \psi jlj + \Sigma \chi k + (V_{air} \cdot \text{c}) \cdot 24 \cdot Dheat \cdot (Tin - Tout)}{1000 \cdot A} - \eta \cdot (Qint + Qsol) \qquad (8.1)$$

where: U_i – heat transfer coefficient of the building construction element (W/(m^2·K));

A_i – the area of the respective construction element of the building prototype model (m^2);

Ψ_i – heat transfer coefficient of the linear thermal bridge (W/(m·K));

l_i – length of the linear thermal bridge (m);

χ_k – heat transfer coefficient of the point thermal bridge (W/·K);

V_{air} – ventilation air volumetric flowrate (m^3/h);

c – air heat capacity per volume = 0.34 (Wh/(m^3×^{o}K));

D_{heat} – number of heating days;

T_{in} – average set-point temperature in the assessment (heating or cooling) period (^{o}C);

T_{out} - average external temperature in the calculation period (^{o}C);

A – total floor area of the building (m^2);

η - gain use coefficient for heating in accordance with Paragraph 99 of this Regulation or Standard LVS EN ISO 13790:2009 L [94];

Q_{int} – interior gains of the whole building in the assessment period t (Wh);

Q_{sol} – solar heat gains of the whole building in the assessment period t (Wh).

$$Q_{sol} = A_{sol} \cdot E_{sol} \tag{8.2}$$

where: A_{sol} – area of collecting useful solar energy of the building (m^2);

E_{sol} – solar irradiation in the assessment period t per area A_{sol} (Wh/m^2).

8.2 Heat transfer through the building construction elements

Thermal bridging through insulating layers greatly reduces the thermal performance of building assemblies. Hence it is of utmost importance for building designers, architects and engineers to determine the adverse impact of thermal bridging through energy performance simulation and modeling in the design stage of the building [76], [95].

Linear thermal bridges occur in a single linear direction e.g. floor slabs, structure corners, and transitions between assemblies that characteristic lengths can be simplified to a line. Essentially, the linear transmittance is described as a heat flow per length (W/(m·K)). Point thermal bridges take place only at single, infrequent locations, e.g., at beam or pipe penetrations or intersections of perpendicular linear thermal bridges. The point transmittance is described as a single and additive amount of heat flow (W/·K) [95].

Heat transfer through the building construction element is shown in figure 8.1. The process can be broken down in three steps, that are described in more detailed in this section.

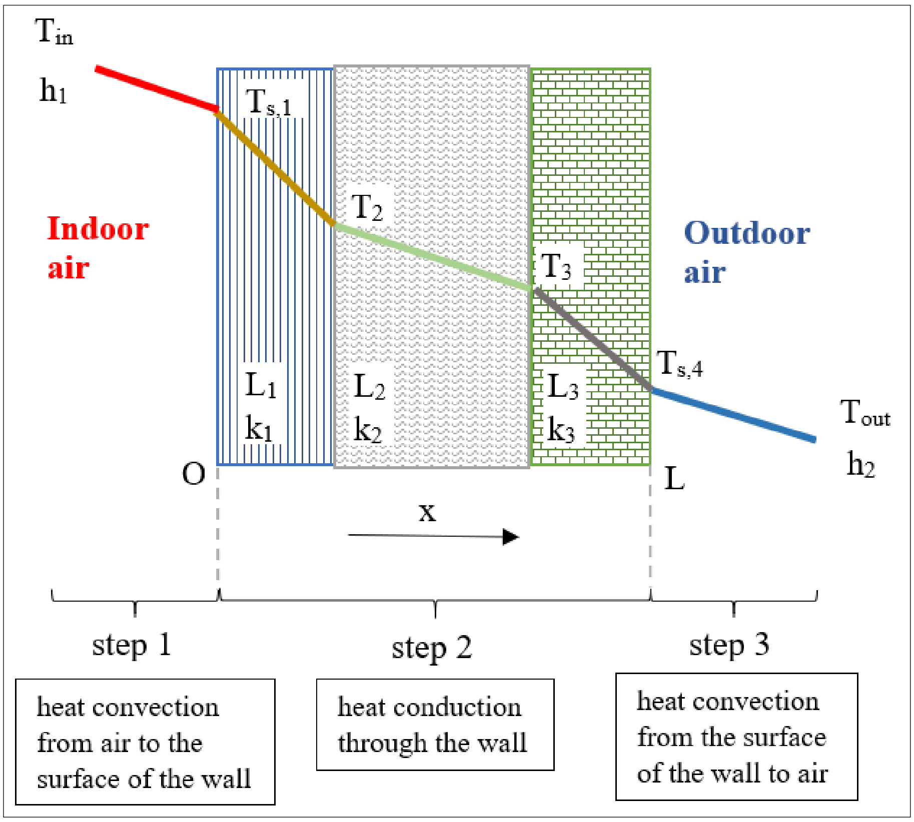

Figure 8.1. Heat transfer through the building construction element.

In step 1 the convective heat flux q [W/m^2] is proportional to the difference between the indoor air temperature and surface temperature of the wall (Newton's law of cooling):

$$q = h_1(T_{in} - T_{s,1}) \tag{8.3}$$

where: h_1 – convective heat transfer coefficient (W/(m^2·K)).

The coefficient (h_1) depends on the conditions in the boundary layer, that are affected by the geometrical characteristics of the wall surface and the nature of the air movement [96].

Step 2 describes heat conduction through the wall structure. For heat conduction, the rate equation is known as Fourier's law [97]. For the one-dimensional plane wall, having a temperature distribution T(x), the rate equation is expressed in equation 8.4 [10]:

$$q = -k \cdot \frac{dt}{dx} \tag{8.4}$$

where: q – local heat flux density (W/m^2·);

k – material's thermal conductivity (W/mK);

$\frac{dt}{dx} = \nabla T$ – temperature gradient (K/m).

The heat flux q is the heat transfer rate in the x-direction per unit area that is perpendicular to the direction of the transfer, and it is proportional to the temperature gradient (∇T) in this direction. The parameter k is the thermal conductivity [W/mK] and characterizes the wall material. The minus sign indicates that the heat is transferred in the direction of decreasing temperature. Under the steady state conditions the heat diffusion equation is as follows:

$$\frac{d^2T}{dx^2} = 0 \qquad (8.5)$$

Using the boundary conditions (as depicted in fig. 8.1):

$$T(0) = T_{s,1}, \quad T(L) = T_{s,4} \qquad (8.6)$$

which in turn can be rewritten as:

$$\frac{dt}{dx} = \frac{T_{s,4}-T_{s,1}}{L} \qquad (8.7)$$

and thus

$$q = -k \cdot \frac{T_{s,4}-T_{s,1}}{L} \qquad (8.8)$$

or

$$q = \frac{K}{L} \cdot (T_{s,4} - T_{s,1}) \qquad (8.9)$$

And thus, for the composite wall the equation 8.9 can be expressed as:

$$q = \frac{T_{s,4}-T_{s,1}}{\frac{L_1}{k_1}+\frac{L_2}{k_2}+\frac{L_3}{k_3}} \qquad (8.10)$$

Step 3 describes the heat convection from the surface of the wall to the air. Similarly, to step 1, the convective heat flux can be defined as:

$$q = h_2(T_{s,4} - T_{out}) \qquad (8.11)$$

Therefore, satisfying all the above, the total heat flux through the building construction element can be combined and expressed as one equation:

$$q = \frac{T_{in} - T_{out}}{\frac{1}{h_1} + \frac{L_1}{k_1} + \frac{L_2}{k_2} + \frac{1}{h_2}} \qquad (8.12)$$

Parameter U can be derived from the equation 8.12 and singled out as heat transfer coefficient of the building construction element (W/(m^2·K)) in a following way:

$$U = \frac{1}{\frac{1}{h_1} + \frac{L_1}{k_1} + \frac{L_2}{k_2} + \frac{1}{h_2}} \qquad (8.13)$$

Temperature gradient in equation 8.12 can be reduced to:

$$\Delta T = T_{in} - T_{out} \qquad (8.14)$$

Combining equations 8.13 and 8.14, and multiplying the equation 8.12 by the area of the construction element A (m^2) generates the heat transfer rate Q [W] for the whole construction element at interest (wall, floor, roof etc.):

$$Q = U \cdot A \cdot \Delta T \qquad (8.15)$$

where: U – heat transfer coefficient of the building construction element (W/(m^2·K));

A – the area of the respective construction element of the building (m^2);

ΔT – temperature gradient between indoors and outdoors (K).

8.3 Statistical analysis of heat gains

As stated earlier, the annual thermal energy demand for a prototype building (kWh/m^2) will be determined according to the equation 8.1, that accounts for heat loss through the building envelope considering the breakdown of heat transfer process and mathematical derivations described in section 8.2, and heat gains due to internal loads and solar irradiance that will be described in the current paragraph.

It is a common understanding that buildings featuring massive and heavy structured envelope require more energy for heating, while buildings featuring large external surface areas of glazed façade have higher requirement for space cooling [81], [98], as in the latter case solar heat gains effectively offset the thermal energy need for the buildings during the heating season (this particularly relates to modern highly-glazed buildings) [76]. While internal loads can be rather precisely accounted for during the design phase of a building or building space, solar heat gains present a number of complexities for their accurate assessment over the projected design timeline of the building [99]. This is especially relevant for highly glazed office buildings because of their greater window area [100], that in combination with the internal heat emissions from the electrical appliances leads to more energy needed for cooling the space throughout the year than it is needed for heating even in Nordic climates [98].

In order to develop an accurate and unified building heat transfer calculation model for the purpose of this study (that would be applicable to the three building prototype models), a comprehensive dataset of input and output parameters attributed to the internal thermal loads and solar heat gains during the heating season was acquired from the registered building energy audit analysis. The data was derived from Latvian Building Information system (BIS) [101]. The energy audit certificates containing the necessary data on actual buildings across all represented categories were used to evaluate internal heat loads, using information available in BIS database that required an authorized access. The energy audit data of 113 residential, 41 public and 19 industrial buildings was collected, averaged, and further employed in this study.

However, to verify the credibility and validate the further use of the acquired dataset on heat gains, a statistical analysis was conducted.

As it is shown in the normal distribution curve figures below, the collected dataset of internal heat loads (figure 8.2), solar heat gains (figure 8.3) and gain coefficient (figure 8.4) is grouped rather densely across the mean value yet maintaining some degree of asymmetry. Statistical analysis of normal probability density function indicated on 60,76% of probability, that a random value of internal heat gain dataset will fall within one standard deviation (+-1σ), and 100% of probability that a random value will fall within the range of +-2σ. For solar heat gains, the probability of a random value falling within a range of +-2σ is 95%, whereas for heat gain coefficient value – it is 97%.

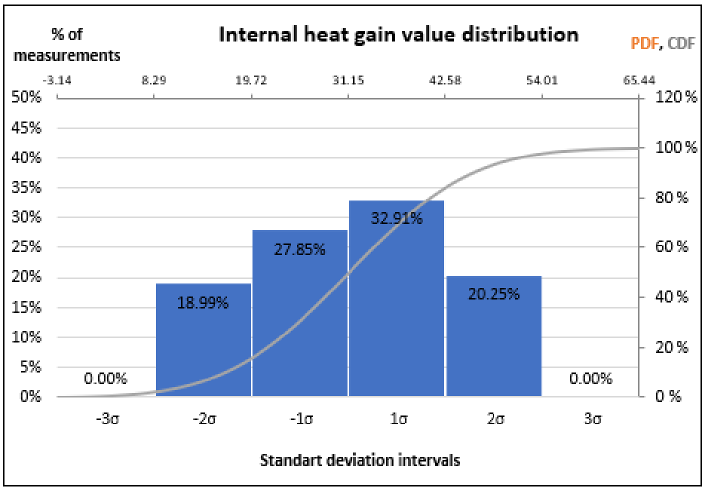

Figure 8.2. Error assessment of collected dataset on internal heat gains.

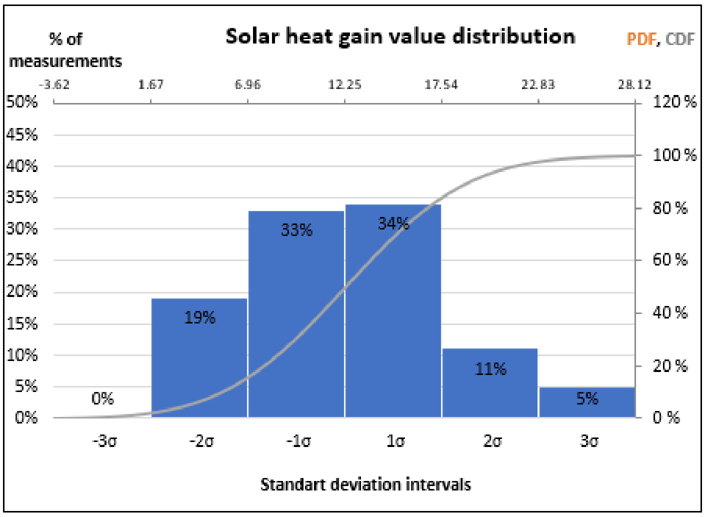

Figure 8.3. Error assessment of collected dataset on internal heat gains.

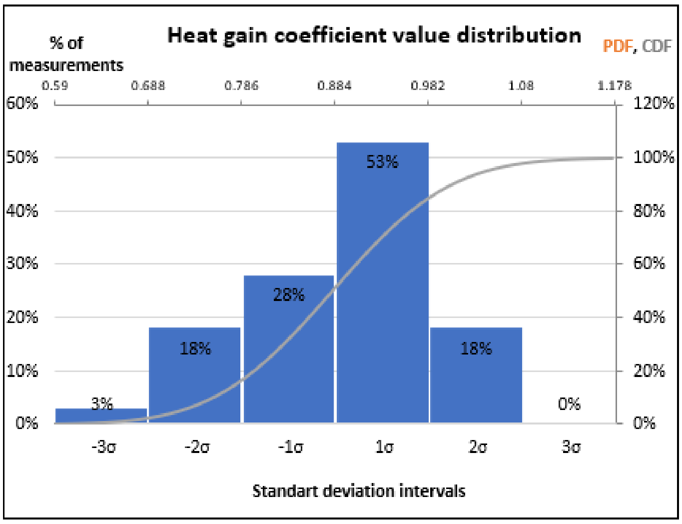

Figure 8.4. Error assessment of collected dataset on heat gain coefficient.

The statistical heat gain analysis performed for the validation of internal, solar and gain coefficient dataset suggests, that given the relatively small standard deviation and an acceptable degree of skewness across all parameters, the dataset is regarded as adequate to proceed further and to be applied in building prototype calculations.

8.4 Summary

Thermal energy performance of a given building is defined by the quality of the building envelope and combined heat gains. Within the scope of this study Cabinet of Ministers Regulations no. 348 "Methodology for Calculating the Energy Performance of a Building" were employed to compute annual thermal energy requirement for the prototype building. In accordance with those regulations, the annual thermal energy consumption (kWh) across the examined building categories (residential, public, industrial) over the reviewed timeline can be determined by computing specific thermal energy consumption (kWh/m^2) and compiling data on the commissioned building stock (m^2). The input values in the corresponding building thermal energy consumption equation have to be introduced considering the design criteria of heat transfer coefficients, climatic conditions, and heat gain analysis.

9. DEVELOPMENT OF BUILDING PROTOTYPE MODELS

The previous paragraphs thoroughly described the procedures carried out within the scope of this study of:

1) defining the three building thermal energy performance evaluation and compliance scenarios based on the identified regulatory codes (paragraph 5);
2) acquiring the historical dataset on Latvian building stock over the timespan of 2014 – 2019 (paragraph 6) and establishing a projection matrix for the building stock development up till 2030 (paragraph 7);
3) defining the input protocols and simplified metrics with regards to the heat transfer analysis in buildings for the development of statistically averaged building prototypes for each of the building category (paragraph 8).

The current paragraph presents the methodology of the development of the computed models for residential, public, and industrial building set that will represent statistically averaged building prototypes for each of the building category within the framework of this study. The prototype building models are generated with the aim of applying the designed building stock development projection matrix to those modeled prototypes in order to establish building stock thermal energy consumption profiles for each of the proposed scenarios.

Construction elements of external building envelopes employed in the building prototype development are the external walls, roofs, garret floors and coverings which are in contact with the outdoor air, floors above the unheated and cold cellars and floor on the ground, windows in the external walls, outside doors, as well as internal walls and other surfaces, provided that they delimit premises the temperature difference between them is 5°C at minimum [58], [60]. In the context of this study construction elements of external building envelopes (including linear thermal bridges) will be studied in building prototype model development.

9.1 Residential building prototype

A prototype model for a typical residential multi-apartment building was developed based on the statistically derived and averaged housing stock data from Building Information System (BIS) database [101]. 113 residential multi family buildings scattered across various cities in Latvia were incorporated in the dataset to perform an iteration to identify and generate a statistically averaged residential building model.

As a result of the iteration process, a 5-storey multi-apartment building was singled out as a residential building prototype for further energy consumption calculation.

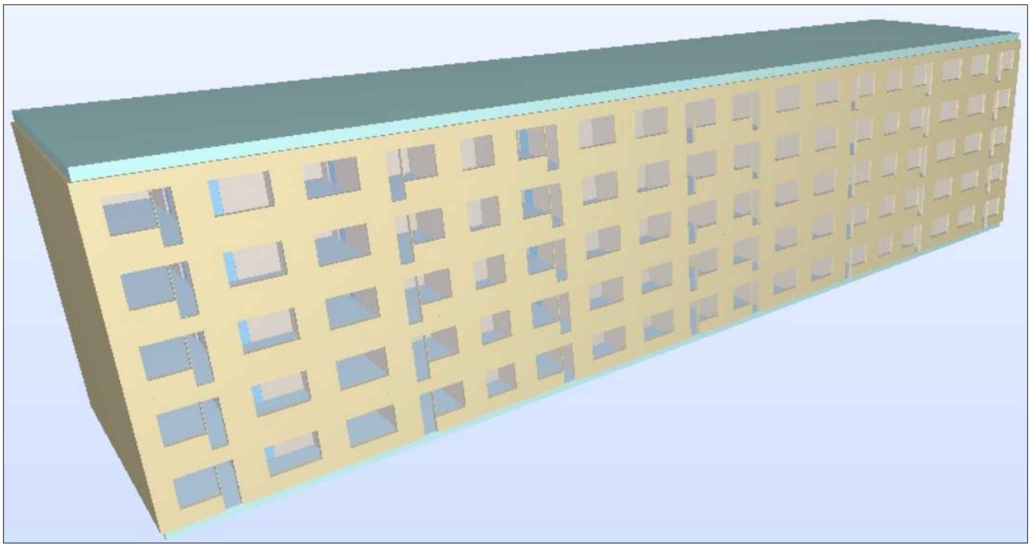

Figure 9.1. 3-dimensional model of a residential building prototype model (IDA-ICE).

The input parameters for the residential building prototype model were introduced in IDA Indoor Climate and Energy (ICE) v4.8 computer software tool to run a simulation and generate the output values to perform a thermal energy consumption evaluation.

The outdoor air temperature was determined by averaging outdoor air temperature across Latvia (during a heating season) in accordance with Latvian Construction Standard LBN 003-15 "Construction Climatology" [102], which specifies the average monthly climate data for 10 Latvian cities distributed evenly across the map.

The input data for the thermal energy consumption calculation of a residential building prototype is compiled in table 9.1.

Table 9.1

Input data for the thermal energy consumption calculation of a residential building prototype.

Total effective floor area A (m^2)	**2.462,5**
The average floor-to-ceiling height (m)	2,5
Total effective volume (m^3)	6156,25
Indoor setpoint temperature for heating T_h (°C)	19
Air exchange rate n (1/h)	0,55
Total air exchange volume (m^3/h)	3385,9
Total internal heat gains during heating period (kWh/m^2)	37,0
Total solar heat gains during heating period Q_{sol} (kWh/m^2)	13,0
Heat gain coefficient, η	0,86
Longevity of a heating period, days	205,8
Average outdoor temperature (°C)	-0,57

Table 9.2 summarizes surface areas and respective heat transfer coefficients of the construction elements of the building envelope for a residential building prototype. The annual thermal energy demand is calculated according to the equation 8.1 (see paragraph 8).

Table 9.2

Summary table of the thermal energy consumption of a residential building prototype in accordance with the Latvian Construction Standard LBN 002 "Thermotechnics of Building Envelopes" [58], [60].

Construction element	Area, m^2	Heat transfer coefficients in accordance with LBN-002 U, W/(mK)		Annual thermal energy demand (kWh/m^2)	
		LBN 002-01	LBN 002-15	LBN 002-01	LBN 002-15
Walls	1270	0,25	0,18	**70,72**	**49,74**
Windows	490	1,8	1,3		
Doors	18.5	1,8	1,8		
Roofs and coverings above the attic	560	0,2	0,15		
Floor above unheated cellar	560	0,2	0,15		
Thermal bridges*	1445 (m)	0,2	0,1		

** linear thermal bridges are expressed in length, m.*

9.2 Public building prototype

A prototype model for a typical public building was developed based on the statistically derived and averaged public building stock data, using 41 building datasets from BIS database that included buildings situated across different cities in Latvia. As a result, a 5-storey building was singled out as a public building prototype for further thermal energy consumption calculation.

The total effective floor area for prototype building is 12485,5 m^2 with the floor-to-ceiling height 3 m. The input data for the energy consumption calculation of a public building prototype is compiled in table 9.3.

Table 9.3

Input data for the thermal energy consumption calculation of a public building prototype.

Total effective floor area A (m^2)	**12.485,42**
The average floor-to-ceiling height (m)	3
Total effective volume (m^3)	37456,26
Indoor setpoint temperature for heating T_{apk} (°C)	19
Air exchange rate n(1/h)	1,50
Total air exchange volume (m^3/h)	56184,4
Total internal heat gains during heating period (kWh/m^2)	39,9
Total solar heat gains during heating period Q_{sol} (kWh/m^2)	13,2
Heat gain coefficient	0,86
Longevity of a heating period, days	205,8
Average outdoor temperature (°C)	-0,57

Tables 9.1, 9.2, 9.3 and 9.4 (see below) indicate that the major differences between the residential and public building prototype models are:

- floor-to-ceiling height (2.5 m in residential buildings, 3.0 m in public buildings);
- the large glazing area ratio against the total surface area (in public buildings).

Table 9.4 compiles the input data for annual thermal energy consumption calculation for a public building prototype. Given the large specific surface area of glazing (all glazed façade elements are referred to as windows) and higher standardized heat transfer coefficient values for building envelope construction elements, the calculated annual heating energy demand (kWh/m^2) for a public building prototype is substantially higher that of the residential building prototype.

Table 9.4

Summary table of the thermal energy consumption of a public building prototype in accordance with the Latvian Construction Standard LBN 002 "Thermotechnics of Building Envelopes" [58], [60].

Construction element	Area, m^2	Heat transfer coefficients in accordance with LBN-002 U, W/(mK)		Annual thermal energy demand (kWh/m^2)	
		LBN 002-01	LBN 002-15	LBN 002-01	LBN 002-15
Walls	997	0,4	0,2	**150,44**	**118,30**
Windows	4763	2,2	1,4		
Doors	15	2,2	2		
Roofs and coverings above the attic	1816	0,25	0,2		
Floor above unheated cellar	5071	0,35	0,2		
Thermal bridges*	7125 (m)	0,25	0,15		

** linear thermal bridges are expressed in length, m.*

9.3 Industrial building prototype

A prototype model for a typical industrial building was developed based on the statistically derived and averaged industrial building stock data acquired from BIS. Given that this building category has not been provided as adequate attention in terms of energy efficiency measures as residential and public buildings [13], the industrial building category is represented far less across the overall building stock [103], therefore the dataset for industrial building prototype consisted of only 19 items.

A typical production facility building was singled out as an industrial building prototype for further energy consumption calculation with the total effective floor area of 3793,8 m^2 and with the floor-to-ceiling height of 6 m.

It is important to note, however, that in Latvian practice a number of unclassified buildings (military facilities, barracks, shooting ranges, fire stations etc.) fall under industrial building stock category as in 1990s many of the abandoned and phased out industrial facilities have been repurposed to serve under unclassified building category, while sharing the design features of industrial buildings. In case of military facilities – certain façade strengthening, and ballistic resistance features might have been added that may have not necessarily improved the overall thermal energy characteristics of the building envelope [11], [104].

The input data for the thermal energy consumption calculation of an industrial building prototype is compiled in table 9.5.

Table 9.5

Input data for the thermal energy consumption calculation of a thermal building prototype.

Total effective floor area A (m^2)	**3.793,8**
The average floor-to-ceiling height (m)	6
Total effective volume (m^3)	22762,8
Indoor setpoint temperature for heating T_{apk} (°C)	17
Air exchange rate n(1/h)	2,00
Total air exchange volume (m^3/h)	45525,6
Total internal heat gains during heating period (kWh/m^2)	39,9
Total solar heat gains during heating period Q_{sol} (kWh/m^2)	13,2
Heat gain coefficient	0,86
Longevity of a heating period, days	205,8
Average outdoor temperature (°C)	-0,57

As it is seen from the table, the main differences if compared against residential and public are quite extensive, as industrial buildings are characterized by:

- high floor-to-ceiling height;
- relatively low glazing-versus-wall ratio;
- fewer number thermal bridges (due to large surface area of monolete wall), table 9.6;
- lower indoor thermal comfort requirements (lower indoor temperature setpoint);
- substantially higher heat transfer coefficients [105], table 9.6 .

Industrial buildings feature processes that are energy intensive and that may incur stringent requirements towards the supply of electrical and thermal energy. In addition, industrial buildings are oftentimes designed and constructed with lower degree of consideration and general responsibility towards energy efficiency [106]. As a result, poor construction quality in those buildings leads to insufficient building insulation and excessive air leakage, and thus, substantial energy losses [107], [108]. Therefore, in addition to the collected dataset outputs, the prototype industrial building was designed based on these low-energy performance considerations.

Table 9.6 summarizes surface areas and respective heat transfer coefficients of the construction elements of the building envelope for an industrial building prototype. The heat transfer coefficients define the energy consumption of a building, and as it can be seen in the table, the annual thermal energy demand in industrial buildings is in the ballpark of 30% higher than in public buildings.

Table 9.6

Summary table of the thermal energy consumption of an industrial building prototype in accordance with the Latvian Construction Standard LBN 002 “Thermotechnics of Building Envelopes” [58], [60].

Construction element	Area, m^2	Heat transfer coefficients in accordance with LBN-002 U, W/(mK)		Annual heating energy demand (kWh/m^2)	
		LBN 002-01	LBN 002-15	LBN 002-01	LBN 002-01
Walls	2212,04	0,5	0,25	**373,72**	**333,03**
Windows	297,8	2,4	1,6		
Doors	399,5	2,4	2,2		
Roofs and coverings above the attic	3998,8	0,35	0,25		
Floor above unheated cellar	4074,5	0,5	0,3		
Thermal bridges*	1183 (m)	0,35	0,3		

** linear thermal bridges are expressed in length, m.*

9.4 Summary

This chapter describes in detail a procedure of developing computed models for residential, public, and industrial building set that would ultimately be referenced as statistically averaged building prototypes for each of the reviewed building categories.

The statistical derivation approach was employed to acquire data sample from a rather extensive dataset in building information system (BIS) database, containing energy profile information on different buildings spread across various cities in Latvia. The examined dataset consisted of 113 residential, 41 public and 19 industrial buildings of different geometry (size, height etc.), age, technical condition, market value and other indicators determining building overall state. Generating the building prototype models was essential in order to perform thermal energy consumption calculation for the reviewed building stock to the highest degree of accuracy, as each building category features different structural characteristics and requirements with regards to building design, materials, heat transfer coefficients, indoor comfort level and other thermal parameters.

At the output of this derivation procedure, three prototype models were elaborated – representing typical residential, public, and industrial building.

10. RESULTS

The thermal energy consumption calculation methodology for residential, public, and industrial buildings was developed, based on the three main steps:

1) the proposed building thermal energy consumption scenarios (paragraph 5);
2) the building stock data on commissioned new construction and renovated buildings in Latvia (paragraphs 6 and 7);
3) the developed building prototypes (paragraph 9).

The calculation was performed for the two sets of timelines: 1) historical dataset (2014-2018) and 2) projected dataset (2020-2030), where scenario 1 was based on the heat transfer coefficients defined in LBN 002-01, and scenario 2 was based on the heat transfer coefficients defined in LBN 002-15, as stated earlier. It is important to note that in scenarios 1 and 2 the new construction buildings and renovated buildings were merged together as both building types have to comply with the LBN 002 requirements.

On the contrary, in scenario 3 the new construction and renovated buildings were analyzed separately, due to the following:

a) new construction buildings built after 2017 have to comply with Republic of Latvia Cabinet Regulation No. 383 “Regulations Regarding Energy Certification of Buildings” in order to obtain an energy certification;
b) renovated buildings have to comply with the newly adopted LBN 002-19 requirements, and unless special circumstances apply, the Cabinet Regulation No. 383 is not applicable.

In scenario 3, residential new construction buildings are split up further into single-apartment and multi-apartment buildings, as different maximum energy consumption requirements apply to these types of buildings as presented in table 5.4 (paragraph 5).

10.1 Thermal energy consumption in residential buildings

Annual thermal energy consumption for the developed residential building prototype under Scenario 1 was calculated based on the equation 8.1. as follows (refer to the tables 9.1 and 9.2 for the input values):

$$E_{residential\_baseline} = \frac{\Sigma UiAi + \Sigma \psi jlj + \Sigma \chi k + (V_{air} \cdot \mathrm{c}) \cdot 24 \cdot Dheat \cdot (Tin - Tout)}{1000 \cdot A} - \eta \cdot (Qint + Qsol)$$

$$= \frac{(1270 \cdot 0.25 + 490 \cdot 1.8 + 18.5 \cdot 1.8 + 560 \cdot 0.2 + 560 \cdot 0.2 + 1445 \cdot 0.2) + (6156.25 \cdot 0.55 \cdot 0.34) \cdot 24 \cdot 2058 \cdot (19 - (-0.57))}{1000 \cdot 2462.5} -$$

$$0.86 \cdot (37 + 13) = 70.72 \text{ (kWh/m}^2\text{)} \qquad (10.1)$$

Annual thermal energy consumption for the developed residential building prototype under Scenario 2 was calculated similarly to equation 10.1, replacing the LBN 002-01 values with those stipulated in LBN 002-15 as follows (refer to the tables 9.1 and 9.2 for the input values):

$$E_{residential\_normal} = \frac{\Sigma UiAi + \Sigma \psi jlj + \Sigma \chi k + (V_{air} \cdot \mathrm{c}) \cdot 24 \cdot Dheat \cdot (Tin - Tout)}{1000 \cdot A} - \eta \cdot (Qint + Qsol)$$

$$= \frac{(1270 \cdot 0.18 + 490 \cdot 1.3 + 18.5 \cdot 1.8 + 560 \cdot 0.15 + 560 \cdot 0.15 + 1445 \cdot 0.1) + (6156.25 \cdot 0.55 \cdot 0.34) \cdot 24 \cdot 2058 \cdot (19 - (-0.57))}{1000 \cdot 2462.5} -$$

$$0.86 \cdot (37 + 13) = 49.74 \text{ (kWh/m}^2\text{)} \qquad (10.2)$$

The annual thermal energy consumption criteria for residential buildings under Scenario 3 was determined by table 5.4 as maximum annual energy consumption in new buildings (Cab. Reg. no 383), while the annual thermal energy consumption criteria for renovated buildings under the same scenario would remain compliant with LBN 002-15.

The minimum energy performance criteria for new buildings laid out in LBN 002- 15 include requirements for building envelope U-values, while Cab. Reg. no. 383 sets minimum permissible level of energy performance of buildings. Nearly zero energy building (nZEB) concept in Latvia was revised in 2015 and the energy consumption threshold of nZEB for residential buildings is set to 40 kWh/m^2, while for non-residential buildings – 45 kWh/m^2 [109], [110].

Thermal energy consumption criteria for residential buildings for the three scenarios is compiled in table 10.1.

Table 10.1

Energy consumption criteria (kWh/m^2) for residential buildings.

Year	**Energy consumption criteria [$E_{\_annual\_year\_n}$], kWh/m^2**			
	Scenario 1	Scenario 2	Scenario 3	
			Multi-apartment	Single apartment
2014	70,72	70,72	70,72	70,72
2015	70,72	70,72	70,72	70,72
2016	70,72	49,74	49,74	49,74
2017	70,72	49,74	70,00	80,00
2018	70,72	49,74	60,00	70,00
2019	70,72	49,74	60,00	70,00
2020	70,72	49,74	50,00	60,00
2021	70,72	49,74	50,00	60,00
2022	70,72	49,74	40,00	40,00
2023	70,72	49,74	40,00	40,00
2024	70,72	49,74	40,00	40,00
2025	70,72	49,74	40,00	40,00
2026	70,72	49,74	40,00	40,00
2027	70,72	49,74	40,00	40,00
2028	70,72	49,74	40,00	40,00
2029	70,72	49,74	40,00	40,00
2030	70,72	49,74	40,00	40,00

Following the thermal energy consumption calculation methodology described in previous sections, table 10.2 compiles the summary of thermal energy consumption in residential building stock throughout the reviewed timeline (2014-2030) under baseline, normal and nZEB scenarios.

Table 10.2

Thermal energy consumption in residential buildings.

Year	Area [$A_{\_year\_n}$], thousand m^2					Thermal energy consumption [E_{year_n}], GWh		
	New construction	Renovated	Total	Single-apartment	Multi-apartment	Scenario 1	Scenario 2	Scenario 3
2014	463,3	310,9	774,2	319,8	143,5	54,75	54,75	54,75
2015	336,9	307,5	644,4	198	138,9	45,57	45,57	45,57
2016	374,7	154,8	529,5	247,4	127,3	37,45	26,34	26,34
2017	364,6	22,1	386,7	251,7	112,9	27,35	19,23	29,64
2018	454,1	35,4	489,5	273	181,1	34,62	24,35	31,74
2019	476,7	67,2	513,5	308,1	138,2	36,31	25,54	33,20
2020	500,5	70,6	539,2	323,5	145,1	38,13	26,82	30,18
2021	513,0	72,4	585,4	351,2	161,8	41,40	29,12	32,76
2022	525,8	74,2	600,0	360,0	165,8	42,43	29,84	24,72
2023	538,9	76,1	615,0	369,0	169,9	43,49	30,59	25,34
2024	485,0	68,5	553,5	332,1	152,9	39,14	27,53	22,81
2025	460,8	65,1	525,9	315,5	145,3	37,19	26,16	21,67
2026	472,3	66,7	539,0	323,4	148,9	38,12	26,81	22,21
2027	484,1	68,4	552,5	331,5	152,6	39,07	27,48	22,77
2028	508,3	71,8	580,1	348,1	160,2	41,02	28,85	23,90
2029	533,7	75,4	609,1	365,5	168,2	43,08	30,30	25,10
2030	560,4	79,2	639,6	383,8	176,6	45,23	31,81	26,36

The total thermal energy consumption of residential buildings on a given year [E_{year_n}] is calculated by the following equation:

$$E_{year\_n} = E_{annual\_year\_n} \cdot A_{year\_n} \tag{10.3}$$

where:

$E_{\_annual\_year\_n}$ – thermal energy consumption criteria on a given year (kWh/m^2), see table 10.1 for residential buildings;

$A_{\_year\_n}$ – total floor area of the new construction or renovated buildings on a given year (m^2), see table 10.2 for residential buildings.

Table 10.3 compiles the summary of thermal energy savings in residential building stock throughout the reviewed timeline (2014-2030) under normal and nZEB scenarios if referenced against the baseline scenario.

Table 10.3

Annual and cumulative thermal energy savings for residential building stock.

Year	Thermal energy savings, GWh			Cumulative savings, GWh		
	Scenario 1	Scenario 2	Scenario 3	Scenario 1	Scenario 2	Scenario 3
2014	0,00	0,00	0,00	0,00	0,00	0,00
2015	0,00	0,00	0,00	0,00	0,00	0,00
2016	0,00	11,11	11,11	0,00	11,11	11,11
2017	0,00	8,12	-2,29	0,00	19,23	8,82
2018	0,00	10,27	2,88	0,00	29,50	11,70
2019	0,00	10,77	3,11	0,00	40,27	14,82
2020	0,00	11,31	7,95	0,00	51,58	22,77
2021	0,00	12,28	8,64	0,00	63,86	31,41
2022	0,00	12,59	17,71	0,00	76,45	49,12
2023	0,00	12,90	18,15	0,00	89,35	67,27
2024	0,00	11,61	16,33	0,00	100,96	83,60
2025	0,00	11,03	15,52	0,00	111,99	99,12
2026	0,00	11,31	15,91	0,00	123,30	115,03
2027	0,00	11,59	16,30	0,00	134,89	131,33
2028	0,00	12,17	17,12	0,00	147,06	148,45
2029	0,00	12,78	17,98	0,00	159,84	166,43
2030	0,00	13,42	18,87	0,00	173,26	185,30

The cumulative thermal energy savings in residential buildings on a given year [$E_{savings\_year\_n}$] is calculated by the following equation:

$$E_{savings\_scenario\_2\_year\_n} = -(E_{scenario\_2\_year\_n} - E_{scenario\_1\_year\_n}) + E_{savings\_scenario\_2\_year\_n-1} \quad (10.4)$$

where: $E_{\_scenario\_2\_year\_n}$ – thermal energy consumption on a year *n* (GWh) under Scenario 2 (table 10.2);

$E_{\_scenario\_1\_year\_n}$ – thermal energy consumption on a year *n* (GWh) under Scenario 1 (table 10.2);

$E_{\_savings\_scenario\_2\_year\_n-1}$ – cumulative thermal energy consumption on a year prior to the given year *n-1* (GWh) under Scenario 2.

10.2 Thermal energy consumption in public buildings

Annual thermal energy consumption for the developed public building prototype under scenarios 1 and 2 was calculated similarly to residential building prototype (see equations 10.1 and 10.2, refer to the tables 9.3 and 9.4 for the input values). For thermal energy consumption requirements pertaining scenario 3 refer to table 5.4.

Thermal energy consumption criteria in public buildings for all three scenarios is summarized in table 10.4.

Table 10.4

Energy consumption criteria (kWh/m^2) for public buildings.

Year	Energy consumption criteria [$E_{\_annual\_year\_n}$], kWh/m^2		
	Scenario 1	**Scenario 2**	**Scenario 3**
2014	150,44	150,44	150,44
2015	150,44	150,44	150,44
2016	150,44	118,30	118,30
2017	150,44	118,30	100,00
2018	150,44	118,30	90,00
2019	150,44	118,30	65,00
2020	150,44	118,30	45,00
2021	150,44	118,30	45,00
2022	150,44	118,30	45,00
2023	150,44	118,30	45,00
2024	150,44	118,30	45,00
2025	150,44	118,30	45,00
2026	150,44	118,30	45,00
2027	150,44	118,30	45,00
2028	150,44	118,30	45,00
2029	150,44	118,30	45,00
2030	150,44	118,30	45,00

Total thermal energy consumption in public buildings on a given year [E_{year_n}] is calculated by the equation 10.3, and cumulative thermal energy savings in residential buildings on a given year [$E_{savings\_year\_n}$] is calculated by the equation 10.4.

Following the thermal energy consumption calculation methodology described in previous sections, tables 10.5 and 10.6 compile the summary of thermal energy consumption and energy savings in public building stock throughout the reviewed timeline (2014-2030) under the proposed scenarios.

Table 10.5

Thermal energy consumption in public buildings.

Year	Area [$A_{\_year\_n}$], thousand m^2	Thermal energy consumption [E_{year_n}], GWh		
	Public buildings	Scenario 1	Scenario 2	Scenario 3
2014	553,60	83,28	83,28	83,28
2015	480,50	72,29	72,29	72,29
2016	216,20	32,53	25,58	25,58
2017	165,00	24,82	19,52	16,50
2018	210,20	31,62	24,87	18,92
2019	220,71	33,20	26,11	14,35
2020	231,75	34,86	27,42	9,27
2021	237,54	35,74	28,10	9,50
2022	243,48	36,63	28,80	9,74
2023	249,57	37,55	29,52	9,98
2024	224,61	33,79	26,57	8,98
2025	213,38	32,10	25,24	8,54
2026	218,71	32,90	25,87	8,75
2027	224,18	33,73	26,52	8,97
2028	235,39	35,41	27,85	9,42
2029	247,16	37,18	29,24	9,89
2030	259,52	39,04	30,70	10,38

Table 10.6

Annual and cumulative thermal energy savings for public building stock.

Year	Thermal energy savings, GWh			Cumulative savings, GWh		
	Scenario 1	Scenario 2	Scenario 3	Scenario 1	Scenario 2	Scenario 3
2014	0,00	0,00	0,00	0,00	0,00	0,00
2015	0,00	0,00	0,00	0,00	0,00	0,00
2016	0,00	6,95	6,95	0,00	6,95	6,95
2017	0,00	5,30	8,32	0,00	12,25	15,27
2018	0,00	6,75	12,70	0,00	19,00	27,97
2019	0,00	7,09	18,85	0,00	26,09	46,82
2020	0,00	7,44	25,59	0,00	33,53	72,41
2021	0,00	7,64	26,24	0,00	41,17	98,65
2022	0,00	7,83	26,89	0,00	49,00	125,54
2023	0,00	8,03	27,57	0,00	57,03	153,11
2024	0,00	7,22	24,81	0,00	64,25	177,92
2025	0,00	6,86	23,56	0,00	71,11	201,48
2026	0,00	7,03	24,15	0,00	78,14	225,63
2027	0,00	7,21	24,76	0,00	85,35	250,39
2028	0,00	7,56	25,99	0,00	92,91	276,38
2029	0,00	7,94	27,29	0,00	100,85	303,67
2030	0,00	8,34	28,66	0,00	109,19	332,33

It is important to note that within the scope of this study and, thus, within the framework of relevance of the data collection, public buildings comprise buildings or structures in which more than 50 % of the total area of the building or structure are public premises. That includes offices and administrative buildings; educational and scientific buildings; medical treatment, health care, social care and rehabilitation institutions; hotels and other short-stay accommodations; cultural and entertainment institutions; trade, catering and household service buildings; athletics buildings and structures as per Annex 1 of Latvian Construction Standard LBN 208-00 "Public Buildings and Structures" [111].

10.3 Thermal energy consumption in industrial buildings

Industrial buildings feature high capacity and energy-intense processes, which in turn bear rather high energy demand for space heating, cooling and ventilation needs [106], as well as for other processes pertaining to the seamless operation of the manufacturing processes within the premises of the building. The industrial sector is of particular significance to the energy conservation subject, as recent studies show that total energy consumption for industrial needs (including electrical energy and thermal energy) constitutes more than 50% of global energy consumption [105], [112]. As such, industrial sector holds a great potential in reducing global greenhouse gas emissions, if proper energy efficiency interventions are carried out [106].

As stated in section 9.3, industrial buildings consume substantially more energy per floor area compared to residential and public buildings due to their high floor-to-ceiling height (usually >6 m) and high limit on normative heat transfer coefficient values of external construction elements (table 9.6).

Thermal energy criteria and consumption in industrial buildings were determined following the same principles as in residential and public buildings. Thermal energy consumption criteria in industrial buildings for each scenario is compiled in table 10.7.

Table 10.7

Energy consumption criteria (kWh/m^2) for industrial buildings.

Year	Energy consumption criteria [$E_{\_annual\_year\_n}$], kWh/m^2		
	Scenario 1	Scenario 2	Scenario 3
2014	373,72	373,72	373,72
2015	373,72	373,72	373,72
2016	373,72	333,03	333,03
2017	373,72	333,03	100,00
2018	373,72	333,03	90,00
2019	373,72	333,03	90,00
2020	373,72	333,03	65,00
2021	373,72	333,03	65,00
2022	373,72	333,03	45,00
2023	373,72	333,03	45,00
2024	373,72	333,03	45,00
2025	373,72	333,03	45,00
2026	373,72	333,03	45,00
2027	373,72	333,03	45,00
2028	373,72	333,03	45,00
2029	373,72	333,03	45,00
2030	373,72	333,03	45,00

As it is seen in table 10.7, maximum thermal energy consumption criteria for industrial buildings is significantly higher than the criteria for residential and public buildings, i.e., energy conservation requirement is far less stringent, however, scenario 3 imposes a rather sharp cut in energy consumption criteria and starting with 2022 it goes in line with the nZEB requirements, which implies a lot of strategic design considerations with regards to energy efficiency for newly constructed industrial buildings given the sharp drop from 333,03 kWh/m^2 threshold in 2016 to 45,00 kWh/m^2 threshold starting with 2022 to obtain energy performance certificate.

Tables 10.8 and 10.9 summarize thermal energy consumption and energy savings in industrial building stock throughout the reviewed timeline (2014-2030) under the proposed scenarios.

Table 10.8

Thermal energy consumption in industrial buildings.

Year	Area [$A_{\_year\_n}$], thousand m^2	Thermal energy consumption [E_{year_n}], GWh		
	Industrial buildings	**Scenario 1**	**Scenario 2**	**Scenario 3**
2014	269,30	100,64	100,64	100,64
2015	273,80	102,32	102,32	102,32
2016	122,90	45,93	40,93	40,93
2017	110,00	41,11	36,63	11,00
2018	135,50	50,64	45,13	12,20
2019	138,89	51,91	46,25	12,50
2020	142,36	53,20	47,41	9,25
2021	144,14	53,87	48,00	9,37
2022	145,94	54,54	48,60	5,84
2023	147,76	55,22	49,21	5,91
2024	140,37	52,46	46,75	5,61
2025	136,86	51,15	45,58	5,47
2026	138,57	51,79	46,15	5,54
2027	140,30	52,43	46,72	5,61
2028	143,81	53,74	47,89	5,75
2029	147,41	55,09	49,09	5,90
2030	151,10	56,47	50,32	6,04

Table 10.9

Annual and cumulative thermal energy savings for industrial building stock.

Year	Thermal energy savings, GWh			Cumulative savings, GWh		
	Scenario 1	Scenario 2	Scenario 3	Scenario 1	Scenario 2	Scenario 3
2014	0,00	0,00	0,00	0,00	0,00	0,00
2015	0,00	0,00	0,00	0,00	0,00	0,00
2016	0,00	5,00	5,00	0,00	5,00	5,00
2017	0,00	4,48	30,11	0,00	9,48	35,11
2018	0,00	5,51	38,44	0,00	14,99	73,55
2019	0,00	5,66	39,41	0,00	20,65	112,96
2020	0,00	5,79	43,95	0,00	26,44	156,91
2021	0,00	5,87	44,50	0,00	32,31	201,41
2022	0,00	5,94	48,70	0,00	38,25	250,11
2023	0,00	6,01	49,31	0,00	44,26	299,42
2024	0,00	5,71	46,85	0,00	49,97	346,27
2025	0,00	5,57	45,68	0,00	55,54	391,95
2026	0,00	5,64	46,25	0,00	61,18	438,20
2027	0,00	5,71	46,82	0,00	66,89	485,02
2028	0,00	5,85	47,99	0,00	72,74	533,01
2029	0,00	6,00	49,19	0,00	78,74	582,20
2030	0,00	6,15	50,43	0,00	84,89	632,63

As it is seen in table 10.9 the potential cumulative savings for industrial buildings under scenario 3 by 2030 would reach 632,63 GWh, which is 8-fold compared to 84,89 if scenario 2 takes place. The feasibility of such potential and projected implications if scenario 3 is enforced on a nationwide scale are discussed in paragraph 11.

10.4 Summary

The results of the proposed methodology to evaluate long-term potential thermal energy savings under normal and nZEB scenarios referenced against the baseline scenario indicate that the largest thermal energy savings in public and industrial buildings would be generated under nZEB scenario, whereas in residential buildings the normal and nZEB scenario would present somewhat similar savings potential. As a matter of fact, up until 2028 greater savings in residential buildings would occur under normal scenario (fig. 10.2), whereas in public and industrial buildings nZEB scenario kicks in and generates largest thermal energy savings right starting in 2017 with the advent of Regulations Regarding Energy Certification of Buildings (fig. 10.4 and 10.6).

The figures below show the annual thermal energy consumption (fig. 10.1, 10.3, 10.5) and cumulative savings (fig. 10.2, 10.4, 10.6) in residential, public, and industrial buildings over the timeline of 2014-2030.

As it is seen in figure 10.2, the curve for cumulative savings in residential buildings under scenario 3 is rising rather moderately, however, in 2022 it alters its shape towards steep and continuous increase (due to lower energy consumption at nZEB scenario starting with 2022, fig. 10.1) until the curve for cumulative savings under scenario 3 surpasses the curve for scenario 2 in 2028. As such, by 2030 the potential cumulative savings for residential buildings under the both scenarios are projected to differ by a very narrow margin (173,26 GWh at normal scenario; 185,30 GWh at nZEB scenario).

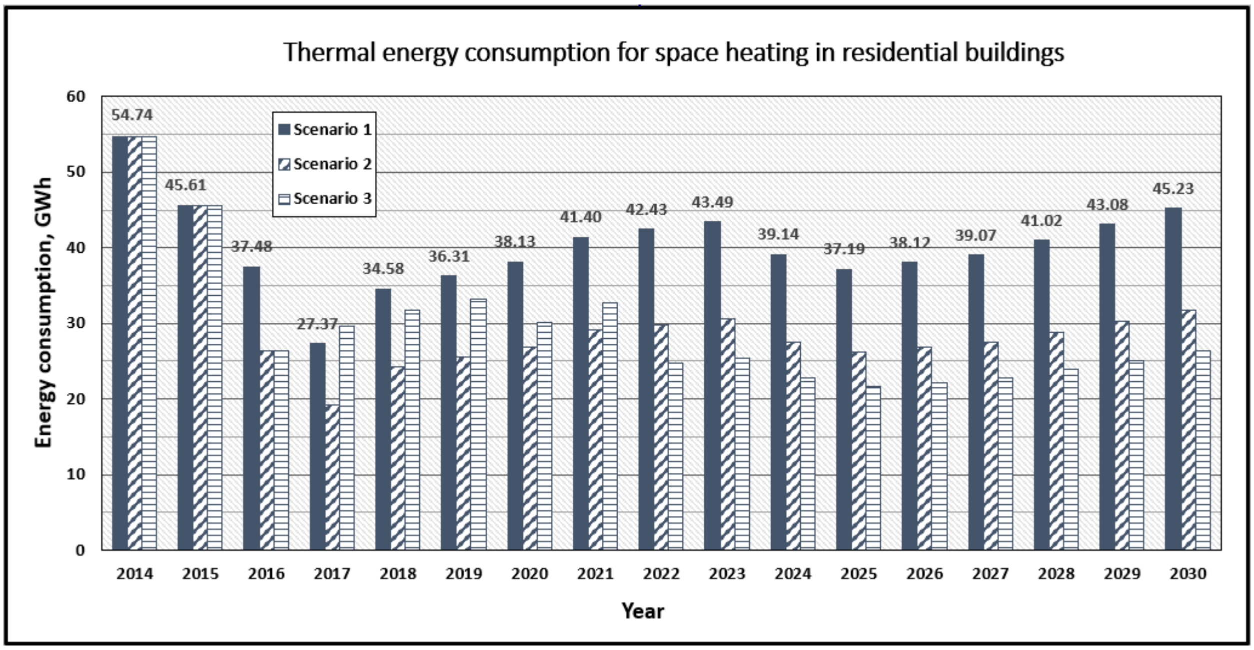

Figure 10.1. Thermal energy consumption in residential buildings (2014-2030).

Also, due to the fact, that under scenario 3 in 2017 the energy performance criteria for multi-apartment buildings is lower than it is defined in scenario 1 (80 kWh/m^2 and 70,72 kWh/m^2 respectively, see table 10.1) one can notice a slight decline in cumulative energy savings under scenario 3 in 2017. This is also highlighted in figure 10.1, where 2017 is the only occasion when energy consumption under nZEB scenario exceeds energy consumption under the baseline scenario.

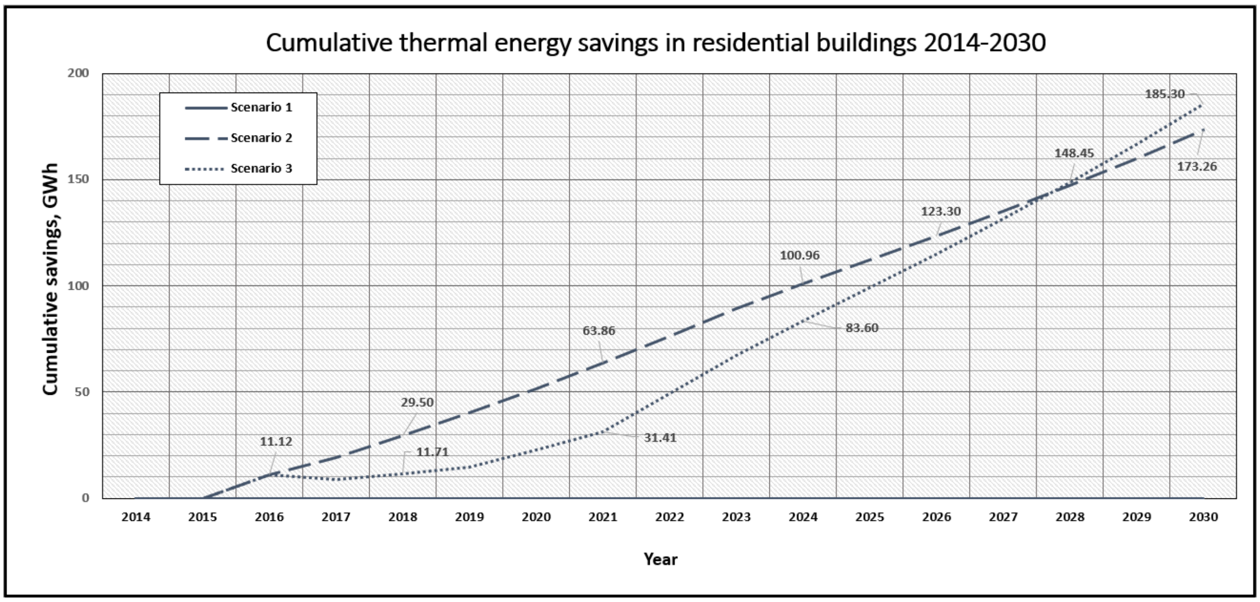

Figure 10.2. Cumulative thermal energy savings in residential buildings (2014-2030).

As for public buildings, figures 10.3 and 10.4 demonstrate that a significant divergence between normal and nZEB scenarios start to evolve in 2017 and remains a constant multiplier over the timespan between 2020 and 2030 when a fixed nZEB criteria for public buildings sets in (energy consumption criteria of 118,30 kWh/m^2 under scenario 2 and 45,00 kWh/m^2 under scenario 3, table 10.4).

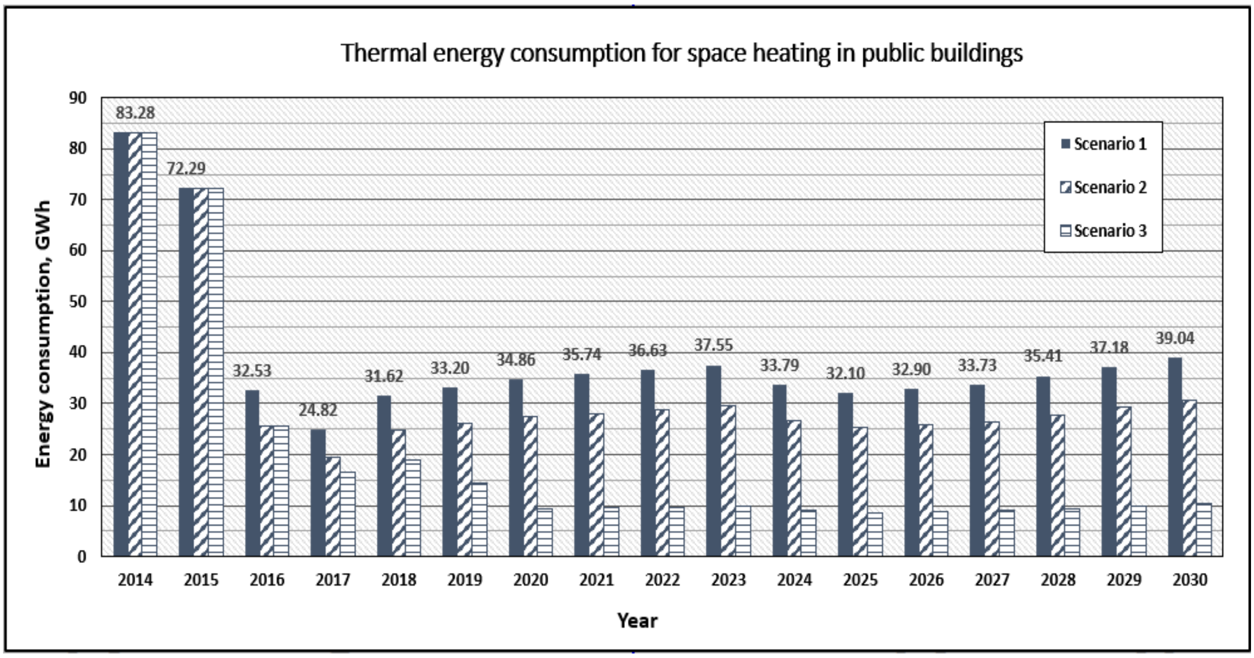

Figure 10.3. Thermal energy consumption in public buildings (2014-2030).

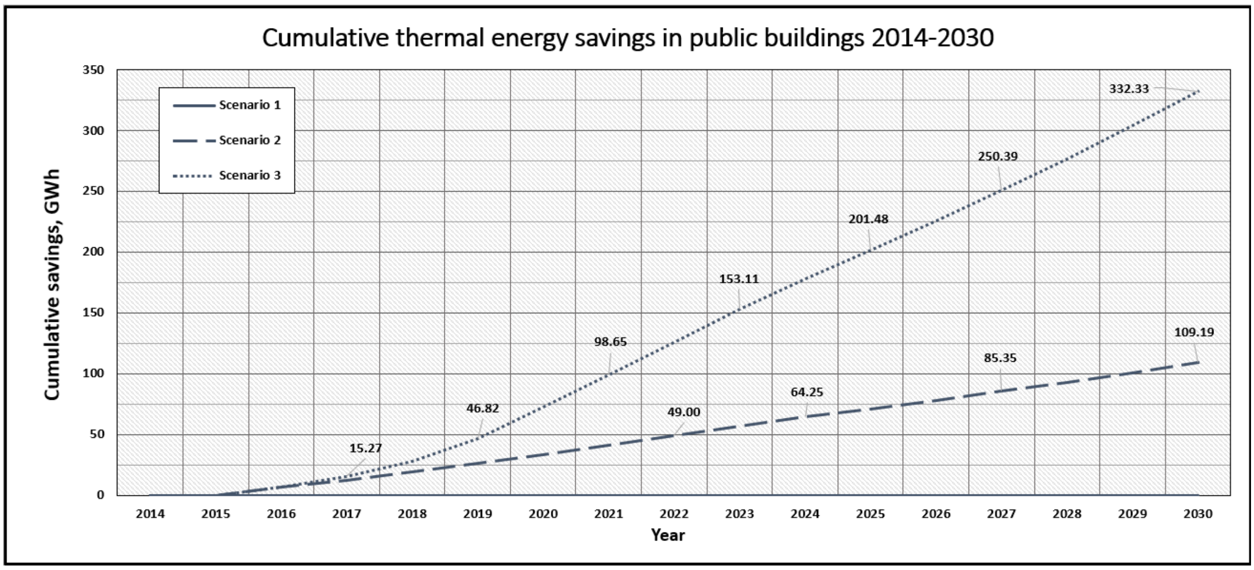

Figure 10.4. Cumulative thermal energy savings in public buildings (2014-2030).

Similarly, to the energy consumption and cumulative savings relation under normal and nZEB scenarios observed in public buildings, the curve for industrial buildings demonstrate a steep and continuous increase in potential savings, if nZEB scenario takes place. On the contrary, normal scenario develops a continuous, yet very gradual curve. As a result, nZEB scenario would generate 632,63 GWh of thermal energy savings, while the normal scenario would only provide 84,89 GWh of total thermal energy savings by 2030.

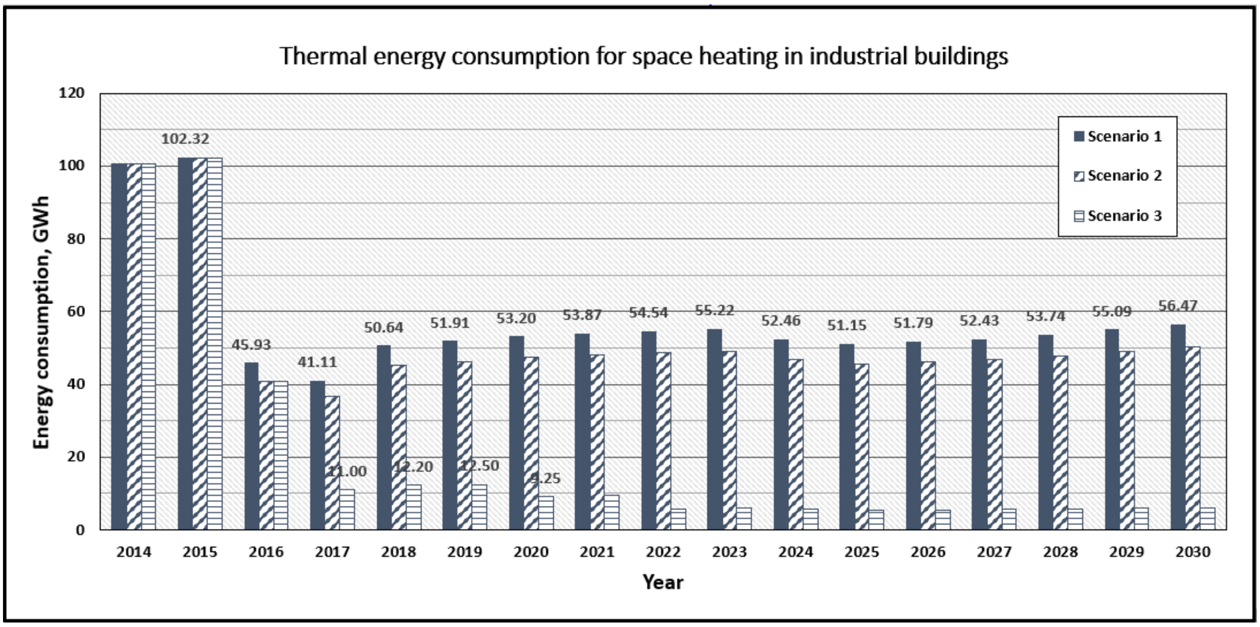

Figure 10.5. Thermal energy consumption in industrial buildings (2014-2030).

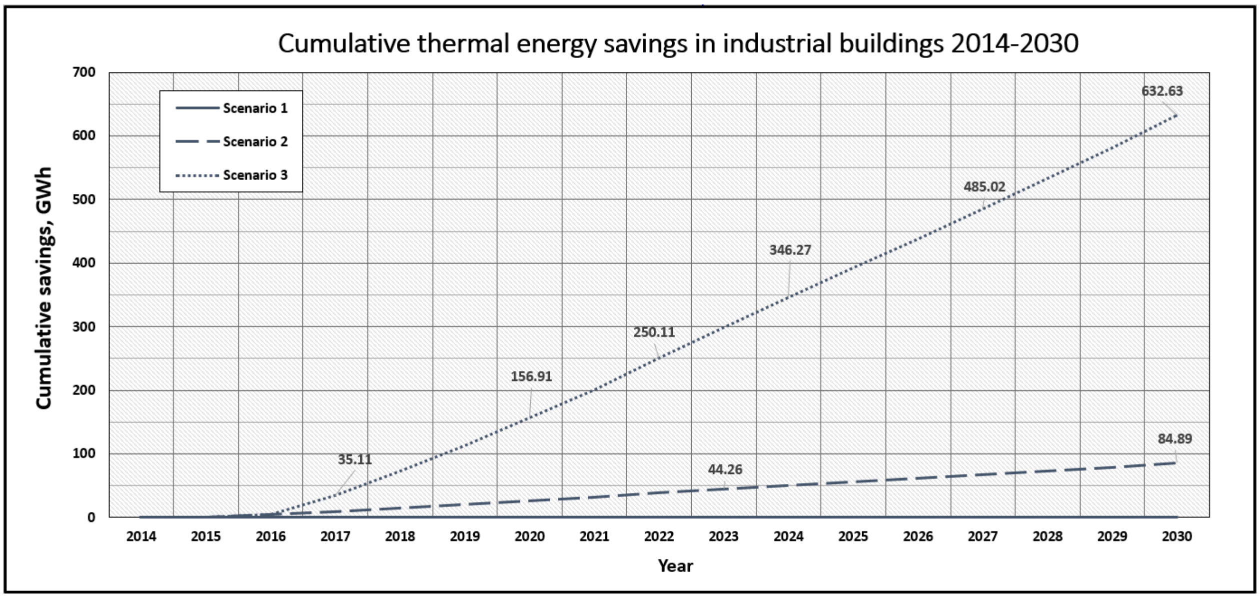

Figure 10.6. Cumulative thermal energy savings in industrial buildings (2014-2030).

11. DISCUSSION

The main objective of this study was to develop a comprehensive methodology that would determine and compute potential thermal energy savings across the selected building stock over the user defined timeline. The generalized methodology is applicable to any region with a heating demand in the cold season.

The specific steps involved in the development of the adapted methodology for the case of Latvia were as follows:

- compiling and analyzing the effective regulatory building codes in Latvia that address energy consumption in buildings and define limiting parameters either at building-scale or at individual scale;
- developing a calculation methodology of annual energy consumption and generated savings due to the implementation of the three proposed scenarios (baseline, normal, nZEB) based on the reviewed regulatory building codes for residential, public and industrial buildings;
- introducing a projection scenario for the building stock development and applying the calculation methodology over the extended timeline (by 2030).

As stated earlier, the adapted methodology relates to building's energy consumption for space heating, disregarding energy consumption for hot water and electricity due to the following preconditions:

- space heating accounts for over 80% of the supplied energy to the building in the heating period in Latvia;
- the majority of the supplied energy to the building is lost through the building envelope (external construction elements such as walls, roofs, windows, thermal bridges etc.), and therefore all major energy efficiency measures in buildings (during new construction and renovations) directly address interventions aimed at improving the thermal performance of a building envelope;
- hot water and electricity consumption in buildings are directly correlated to the individual habits of occupants and their usage pattern, that fluctuates irregularly.

The accuracy of the developed methodology and its applicability to the real case conditions is largely dependent on the credibility of the obtained building stock dataset, that includes both new construction and renovated buildings. The dataset for the current study within the framework of the adapted methodology for the case of Latvia was derived from the Central Statistical Bureau of Latvia (the existing building stock) and the Ministry of Economics of the Republic of Latvia (the renovated building stock) and the proposed methodology was verified and approved by these institutions. Nevertheless, that does not eliminate even minor degree of discrepancy in the provided dataset, therefore all inaccuracies in the provided data will incur an error in the presented results.

As there is no separate dataset available for each individual building commissioned starting with 2014 that would contain the data on the surface area of construction elements (external walls, windows, roofs, ground floors and thermal bridges) and the actual heat transfer coefficients of those elements, it was necessary to develop prototype models for residential, public and industrial buildings for energy performance scenario evaluation. The building prototype models were developed after thorough analysis to the extent that they would represent the average residential, public, and industrial building to the benchmark of the highest possible accuracy.

Other limiting factors that may have affected the inaccuracy of the developed methodology are listed below:

- variations in weather patterns that deviate from the input values that were used to create building prototype models (that includes deviations in average temperature, wind speed and direction, solar radiation and other meteorological fluctuations);
- internal heat loads (from humans, electric appliances etc.) – they vary continuously and largely affect the thermal profile of the premises;
- variations in setpoint temperatures (this variable is dependent on individual preferences and thermal comfort conditions in the building, and shall be attributed to human behavior);
- thermal energy consumption needed for the infiltration air.

This paragraph provides an analytical interpretation and significance of the findings laid out in the results section.

For the past decade, the construction industry's growth in Latvia and the Eastern European region has been greatly linked to the EU support and project funding, and according to the expert forecasting 15% of accumulated growth is projected for the region in the coming years, yet in some CEE countries the forecast for the annual growth is seen as gradually decelerating [113], [114]. Nevertheless, wide-range fluctuations in the new construction and renovation project growth rates are not expected across the region. As for the Baltic States the construction industry is seen to remain rather stable with minor stagnation expected between 2024 and 2025, as previously accentuated, due to the transition to a new planning period for the EU regional development funding [90], [115]. The intensity of major renovation projects will be largely dictated by the immediate funding availability to comply with the EBPD regulations [57], as the main legislative instrument to promote the energy performance of buildings and to boost renovation within the EU region, and by the government support in accordance to the national building energy efficiency roadmap [92].

Tables 11.1 and 11.2 summarize and compare cumulative thermal energy savings over the timeframe of 2014 – 2030 in residential, public and industrial buildings under scenarios 2 and 3. As stated earlier, scenario 1 does not generate any savings as it is the baseline case upon which the other two scenarios (normal and nZEB) are developed and compared against.

Thermal energy savings start to accumulate in 2016 when LBN 002-15 requirements become effective in place of LBN 002-01. Under scenario 2, the residential sector would generate the largest savings as the requirements set in Latvian Construction Standard pertaining heat transfer coefficients are far stricter for residential buildings than they are for public and industrial buildings. Additionally, the area of residential housing constitutes the largest share of the reviewed building stock and thus have a higher impact factor.

As such, if scenario 2 takes place, by 2030 the cumulative thermal energy savings in residential housing stock would be equivalent to the thermal energy savings that public and industrial buildings would have generated combined.

Table 11.1

Cumulative thermal energy savings across Latvian building stock under Scenario 2.

Cumulative savings (2014-2030), GWh / Scenario 2				
Year	Residential buildings	Public buildings	Industrial buildings	Total, GWh
2014	0,00	0,00	0,00	0,00
2015	0,00	0,00	0,00	0,00
2016	11,11	6,95	5,00	23,06
2017	19,23	12,25	9,48	40,96
2018	29,50	19,01	14,99	63,50
2019	40,27	26,09	20,65	87,01
2020	51,58	33,53	26,44	111,55
2021	63,86	41,17	32,31	137,34
2022	76,45	49,00	38,25	163,70
2023	89,35	57,03	44,26	190,64
2024	100,96	64,25	49,97	215,18
2025	111,99	71,11	55,54	238,64
2026	123,30	78,14	61,18	262,62
2027	134,89	85,35	66,89	287,13
2028	147,06	92,91	72,74	312,71
2029	159,84	100,85	78,74	339,43
2030	173,26	109,19	84,89	367,34
		Total (2014-2018), GWh		**63,50**
		Total (2014-2020), GWh		**111,55**
		Total (2014-2030), GWh		**367,34**

On the contrary to the normal scenario, scenario 3 sets the threshold to the energy consumption of the whole building, i.e., addressing the building-scale parameter. This approach is seen as more aggressive with regards to limiting the total energy consumption per area without individualized considerations of building specifics and materials used [116]. Also, nZEB scenario is viewed as significantly harder to achieve, since the energy consumption threshold for public and industrial buildings is quite rigid and therefore it counteracts to a certain degree to the building owners' and investors' interest of generating higher return on investment.

The cumulative thermal energy savings in residential buildings under scenario 3 by 2030 would be merely 7% higher compared to scenario 2 (table 11.2). However, a significantly higher thermal energy saving potential under scenario 3 would be generated in public (332 GWh against 109 GWh) and industrial buildings (633 GWh against 85 GWh).

Table 11.2

Cumulative thermal energy savings across Latvian building stock under Scenario 3.

Cumulative savings (2014-2030), GWh / Scenario 3				
Year	Residential buildings	Public buildings	Industrial buildings	Total, GWh
2014	0,00	0,00	0,00	0,00
2015	0,00	0,00	0,00	0,00
2016	11,11	6,95	5,00	23,06
2017	8,82	15,27	35,11	59,20
2018	11,70	27,97	73,55	113,22
2019	14,82	46,82	112,96	174,60
2020	22,77	72,41	156,91	252,09
2021	31,41	98,65	201,41	331,47
2022	49,12	125,54	250,11	424,77
2023	67,27	153,11	299,42	519,80
2024	83,60	177,92	346,27	607,79
2025	99,12	201,48	391,95	692,55
2026	115,03	225,63	438,20	778,86
2027	131,33	250,39	485,02	866,74
2028	148,45	276,38	533,01	957,84
2029	166,43	303,67	582,20	1052,30
2030	185,30	332,33	632,63	1150,26
		Total (2014-2018), GWh		**113,22**
		Total (2014-2020), GWh		**252,09**
		Total (2014-2030), GWh		**1150,26**

Tables 11.1 and 11.2 are plotted on a chart (see figures 11.1 and 11.2) to provide a better insight and a more comprehensive representation of the cumulative thermal energy saving dynamics under normal and nZEB scenarios.

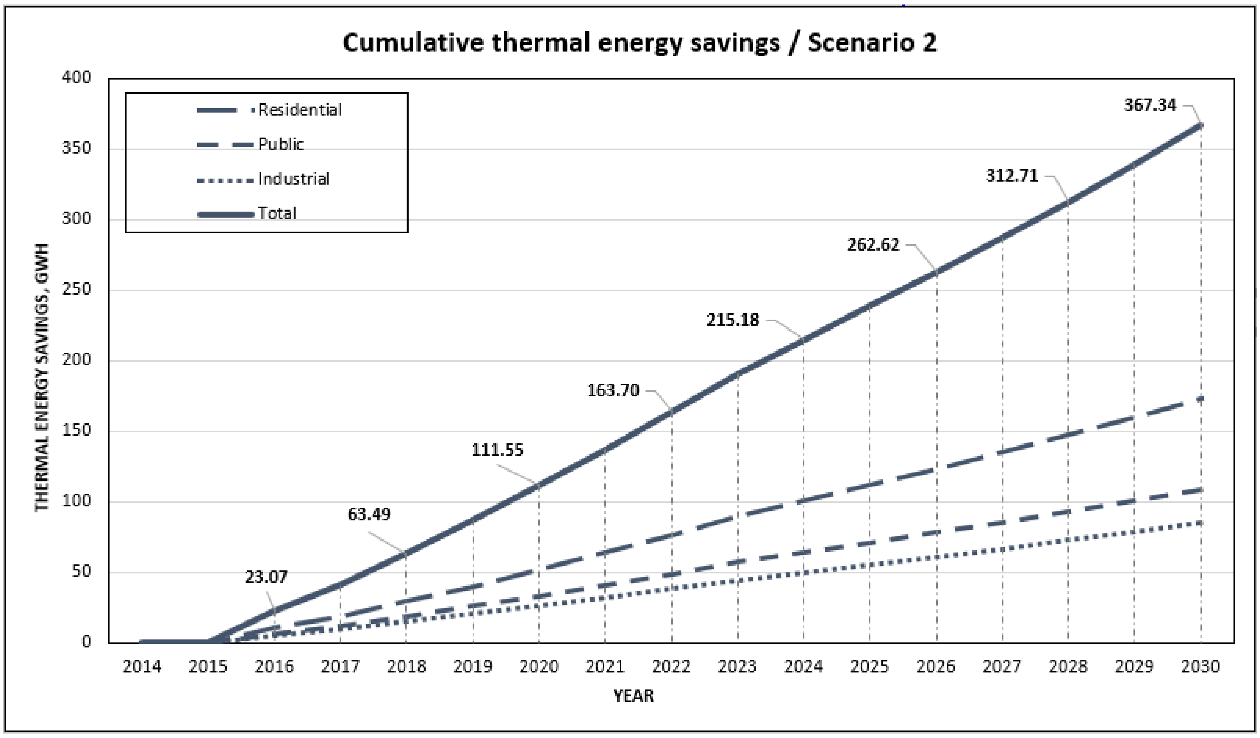

Figure 11.1. Cumulative thermal energy savings in buildings under Scenario 2 (2014-2030).

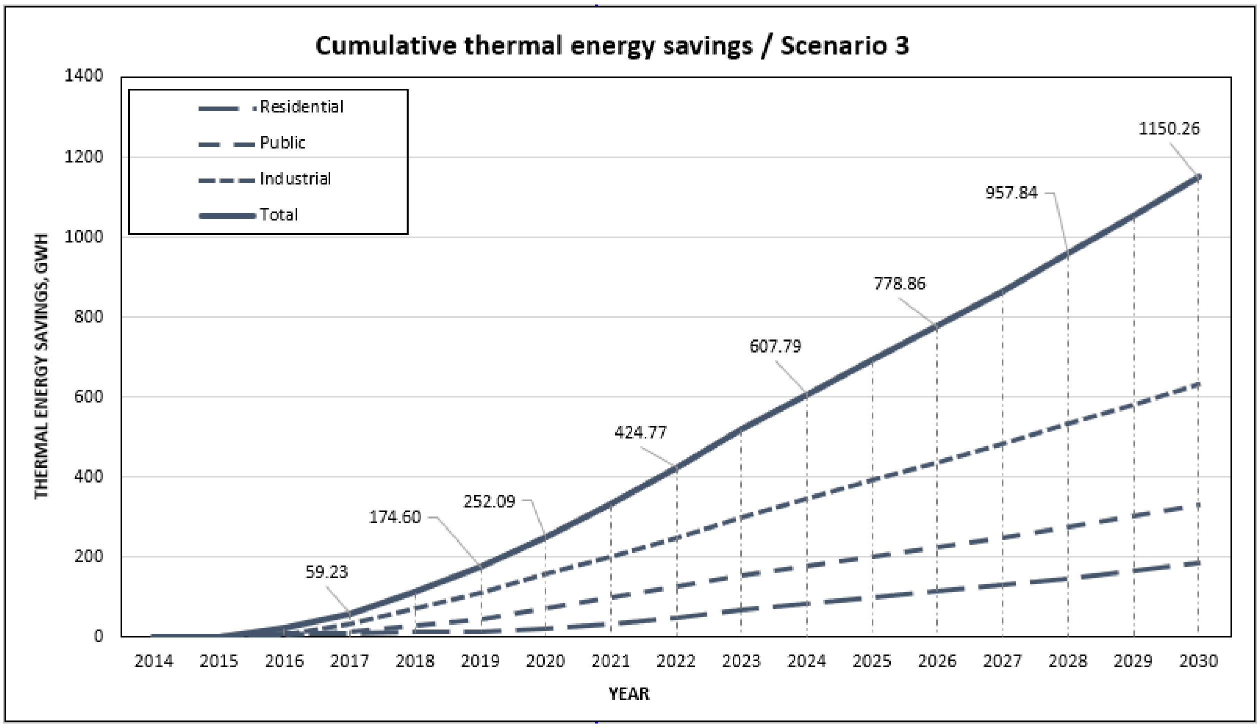

Figure 11.2. Cumulative thermal energy savings in buildings under Scenario 3 (2014-2030).

It is seen in figure 11.2 that the major difference in cumulative thermal energy savings under nZEB scenario begins to develop with the year 2017. This is related to the advent of new Republic of Latvia Cabinet Regulation No. 383 “Regulations Regarding Energy Certification of Buildings” that came into effect for commissioned new buildings seeking Energy Performance Certification. The new regulations strictly define maximum energy consumption level for newly constructed buildings, as presented in table 5.4. As stated earlier, these regulations are particularly stringent with regards to the energy consumption limitations for public and industrial buildings, therefore, in order to comply with these regulations, substantial energy efficiency improvement measures have to be introduced.

Thereby, scenario 3 presents a widely ranging and increasing gap between the curves representing cumulative thermal energy savings, with the industrial sector constituting the largest share of total cumulative savings (>50%). However, this scenario entails very rigid energy efficiency interventions and is deemed as rather over-optimistic and may deviate quite extensively from the real case scenario, as the Energy Certification is a voluntary measure and incurs thorough actions and significant investments in relation with meeting energy efficiency criteria set by the regulation [117].

Another complexity stems from the factor that limiting building-scale parameter instead of individual scale parameter (as proposed in scenario 3) disregards the individual building’s specifics, unique features, or exceptional factors attributable to its functional characteristics, that may lead to challenges such as inadequate indoor air quality and interstitial condensation occurrence [11]. If focus is solely addressed at achieving nZEB requirements in the reviewed building stock, several challenges can be identified. The short-term challenge is to match the energy performance of the design model with the completed building as closely as possible. In other words, the actual energy performance of the building has to meet the requirements set at the design stage to ensure steady energy performance over the extended timespan and under unforeseen conditions [118], i.e., securing a certain degree of resiliency with regards to daily building operations and reliable power delivery [119]. The long-term challenge of imposing building-scale parameter rather than addressing building’s energy performance at individual element level is the capability of buildings to respond to changes that incur from ageing over the building’s lifespan, retaining environmental and socioeconomic sustainability of a building [120].

In that regard, scenario 2 seemingly offers a more feasible and thereby more credible development roadmap, as it addresses individual scale parameters in buildings, namely, heat transfer coefficients of the external building elements. This scenario, however, will not incur substantial energy savings in the long run, as the thermal performance requirements imposed by the LBN 002-15 standard are designed to meet solely the minimum thermal performance requirements of a building envelope [66], [117].

The approach proposed by the normal scenario is limited to applying maximum heat transfer coefficient requirements to the external elements of a building, yet, supplemented by policies addressing low energy consumption practices, the potential savings in residential and public buildings may increase significantly [121].

Along with the improvements in the design of the building envelope to further reduce thermal energy consumption in buildings, the operation and efficiency of mechanical systems and indoor appliances need to be addressed. Deep renovation measures entail retrofit packages that may generate different outcomes depending on the applied package and type of the building [13], [108]. For instance, hospitals, laboratories, and military facilities may require enhanced ventilation system and heavy-duty ventilation equipment to comply with the specific requirements set for the operation of these buildings [104].

These considerations, however, are not within the scope of this work, as this study primarily evaluated the long-term impact of applying different regulatory code compliant building energy performance scenarios.

12. CONCLUSIONS AND RECOMMENDATIONS

This work was dedicated to developing a methodology applicable across wide regional spectrum encompassing mild and cold climate regions to evaluate potential thermal energy savings across the reviewed building stock, while applying various building energy consumption reduction protocols.

Along with the rapid population growth across the world, the building stock worldwide is growing at the fastest ever rate, which includes residential, public, industrial, unclassified, and other building types. In the developed countries the new construction buildings have to comply with stringent regulatory building codes that are being gradually toughened in line with the advent of new building materials, advanced engineering systems, energy-efficient building technology, building automation etc. Nevertheless, it is the existing buildings that will continue to dominate the building stock in the foreseeable future (accounting for >98% of total building stock) and their energy-efficiency is far lower than that of the newly constructed buildings. The energy-efficiency of the existing buildings is being improved through building energy renovation strategies that are also subject to compliance with the regulatory building codes. However, renovated buildings very rarely achieve the energy-efficiency level that matches the requirements for the newly constructed buildings at a time. While the newly constructed buildings have to meet certain energy criteria applied to the whole building without particular focus to single components (individual scale parameters) from the regulatory requirement standpoint, i.e., building-scale criteria approach with kWh/m^2 as a limiting factor; to reduce energy consumption in renovated buildings, an individual scale approach is more reasonable. It allows for energy efficiency improvement through replacing or adding new building components, such as windows, adding thermal insulation layer to the external envelopes, upgrading HVAC system, adding building automation system etc.

Following the outlined preconditions and considering the error assessment, the adapted methodology of evaluating thermal energy saving potential across residential, public, and industrial buildings in Latvia was developed over the timeline of 2014 – 2030. The methodology assessed the potential thermal energy savings for newly constructed and renovated buildings for different energy consumption compliance scenarios.

Thermal energy consumption scenarios were developed based on the currently employed regulatory codes - LBN 002-15 “Thermotechnics of Building Envelopes” and

Republic of Latvia Cabinet Regulation No. 383 "Regulations Regarding Energy Certification of Buildings". Thermal energy savings under scenario 2 (normal) and scenario 3 (nZEB) were assessed against scenario 1 (baseline), that represents Latvian Construction Standard LBN 002-01 "Thermotechnics of Building Envelopes, that is no longer effective.

The derived building stock data indicates that the total floor area of newly constructed residential building stock within 2014 – 2017 timeline has remained stable, whereas the number of renovated buildings has been on decline. Similarly, the downward trend is observed over the same timeline in the number of newly constructed public and industrial buildings. Given the decline in the commissioned new construction and renovated buildings over the period of 2014 – 2017, the total energy savings curve under the proposed scenarios does not develop steep increase. However, the projected building stock development figures compensate this decline and set a gradual increase that continues to grow linearly over the next decade with minor stagnation in 2024 – 2025 induced by a transition to a new planning period that is expected to backlash as uncertainty among investors and other construction industry's stakeholders. Nevertheless, it is projected that the construction sector will be recovering at a steady rate from this slight stagnation and by 2030 will reach firm growth level.

The positive building stock development curve translates into the building industry being at the central role for strategies targeting reduction of energy consumption. Building energy efficiency has been an emphasis for building owners, operators, facility management and customers, i.e., end-users of the building. Enforced by the legislative instruments to promote the energy performance of buildings and to boost renovation, such as EPBD (2018/844/EU) within the EU region and the local regulatory environment on a national scale, building industry contains a very high net combined energy saving potential and has been at the focal point for many years in both the developed and developing countries.

In the present PhD dissertation a methodology to assess potential long-term thermal energy savings was developed that evaluated the historic and projected building stock thermal energy saving potential in Latvia under various regulatory building code compliance scenarios related to building energy efficiency. The results of this study compared two thermal energy consumption roadmap scenarios in residential, public and industrial buildings referenced against the baseline case and provided projection profile for the both scenarios up until 2030.

The calculation results of cumulative thermal energy savings indicate that by 2018 scenario 2 would generate 63.50 GWh in total cumulative thermal energy savings referenced against scenario 1, by 2020 this figure would almost double – 111.55 GWh, and by 2030 the projected cumulative savings would result in 367.34 GWh of thermal energy offset. As a point of clarification, the two-fold increase in cumulative savings by 2020 would largely occur due to a projected increase in commissioned buildings in 2019 and 2020, following the building stock development figures outlined in projection matrix. Scenario 2 represents a normal projection path, that is considered as the most likely development pattern with regards to energy consumption in buildings, as it is based on the currently effective and mandatory regulatory building code.

Meanwhile, scenario 3 would result in 113.22 GWh of generated thermal energy savings by 2018, whereas by 2020 this figure would rise more than two fold – to 252.09 GWh and by 2030 – to 1150.26 GWh. However, the substantial savings presented in scenario 3 would be generated largely due to strict and difficult-to-implement energy efficiency criteria (for public and industrial buildings in particular), which may not be feasible from the economic perspective to construct such buildings in the first place, or renovate to meet the Energy Certification criteria rating. Scenario 3 roadmaps a nearly zero energy building (nZEB) pathway, which is hard-to-reach goal at the current state of the existing building stock, regional and local regulatory environment, stakeholder interest (such as investors and building owners) and stakeholder preparedness (such as building contractors, architects, designers and engineers). As such, scenario 3 presents a rather unlikely projection path, given the difficulties it poses to the stakeholders and consequently the potential danger to cause a slow down, or even, a stagnation in the building industry's growth, which will in turn negatively impact the investment attractiveness, job market, national GDP and overall economic growth rate of the country in the long run.

Nevertheless, it is important to note that the development dynamics of the construction industry may take another path and, as a result, the cumulative energy savings may deviate to a rather high degree from those presented in the current study.

Based on the analysis of the presented results, it can be concluded that roadmapping one particular scenario across the whole building stock is not an optimum concept in the long term in pursuit of achieving higher energy savings in the building stock while maintaining the economic feasibility of compliance with the imposed energy performance criteria.

The study results also suggest that regulatory building codes are an effective policy measure for reducing energy consumption in buildings. Many countries have been adopting more stringent building energy codes over time, which have resulted in more efficient building stock in those countries. Yet, the findings of the current study along with the reviewed literature within this work clearly indicate that adhering to the local building regulatory standards or government-imposed building energy efficiency policies does not guarantee the most energy efficient buildings.

Even though there are number of well known prescribed technological interventions implemented to cut energy consumption in buildings (e.g. added insulation layer, HVAC system installation or retrofit), regular and on-going maintenance is often the key to reduce energy consumption in buildings or to keep it at the designed levels. To facilitate the implementation of energy efficiency measures in the early stages of building design, planning and management, a relevant education and professional training has to be ensured. A number of EU member states have announced their nationwide long-term strategies to improve energy performance of buildings and to reduce greenhouse gas emissions. These efforts include multiple interdisciplinary steps outlined below (A, B, C, D, E, F).

A. Continuous preparation of highly skilled building energy efficiency professionals through institutions of higher education, regular training programs, workshops and webinars on regulatory requirements, advancements in new technology, and other experience and knowledge sharing platforms. This step includes the decision makers and implementers within the framework of building energy efficiency measures, such as designers, architects, engineers, contractors, subcontractors (suppliers, construction workers, system installers and integrators), facility managers, systems' performance and monitoring operators, operation and maintenance staff.

B. Education campaigns and basic training programs for non-professionals. That includes the building stakeholders that do not have a direct role in design, construction, or maintenance process of the building, but rather a role of end-users, as regular or temporary building occupants. Targeting this audience is believed to result in significant building energy savings due to changes in their energy consumption habits and increased responsibility and self-awareness of their individual role to make a positive impact on building energy use reduction. This also implies the power and the potential influence of good facilities management with regards to the end user activation and imposition of behavioral adjustment resulting in the energy efficiency increase of the buildings.

C. Building energy performance monitoring and energy auditing, that would comprehensively and accurately assess the use of electricity, water, gas, and any other utilities by the building in question. The output value of energy auditing is an evaluation of building's overall energy efficiency, proposal of clear actions for energy performance improvement and an analysis of cost savings and return on investment timeline. However, to complete an energy audit for a building is a rather costly initiative and thus buildings owned by private entities or individuals are rather rarely being subjected to energy auditing, thereby government funded programs or partial financial support in this matter would eventually lead to a substantially higher degree of energy efficient building stock.

D. Establishing clear regulatory environment aimed at improving building energy efficiency for new construction buildings and renovation projects with periodic review and amendments that are linked and strengthened in line with the advancements in new building technology and building materials. However, as it was discussed earlier, the mandatory requirements have to be thoroughly assessed by a multidisciplinary committee to ensure their net combined effectiveness and feasibility, eliminating the risk of economic downturn as it is argued if scenario 3 is enforced. This also stipulates a discussion on whether it is more reasonable and effective for the regulatory authorities to focus on the control of the individual-scale parameters in the buildings (such as U-values of external building envelopes, efficient HVAC systems, low energy lighting etc.) or on the building-scale energy efficiency and energy conservation parameters (such as setting the limit on total building energy consumption and/or minimum share of on-site renewables as laid out in section 4.1).

E. Setting and following national approaches on low energy buildings as a supplementary enforcement measure would facilitate the pathway to reach the goals discussed in sections C and D. This implies an establishment of short-term and long-term objectives (annual, 5-year and 10-year energy efficiency targets) either for different building categories or the national building stock as a whole. Failure of keeping up with the established goals within the allocated timeline would induce identifying the barriers and developing strategies (and rearranging priorities, if necessary) to effectively address the challenges and setting new targets for the next reporting timeline.

F. Identification of all financial instruments available to perform either building energy performance auditing or implement certain energy efficiency strategies in the project approved by the funding agency. Funding sources can originate either from the national budget or from external resources, such as EU funded programs (European Regional

Development Fund, European Social Fund, European Local Energy Assistance etc.) or various investment tools. Yet, finding financially viable solutions to implement energy efficiency measures in building stock is hampered by the following prerequisites: a) attracting private investors' interest in allocating funds to increase building energy efficiency is hindered by substantial upfront costs and some degree of uncertainty on return-on-investment with fluctuating energy prices; b) although there is a number of instances in the past demonstrating how numerous barriers have been overcome through specialized investment instruments, there is no 'one size fits all' solution and majority of the investment tools are context-specific. As a preliminary step before lining up for a financial support, it is essential to conduct a thorough and accurate project planning and financing analysis and conduct a series of cost-optimization measures shall any tradeoffs occur in the planning stage.

Although the subject of the present study focuses on the analysis and projection of the building stock development and the regulatory environment in Latvia, the study does not bear a regional-specific character and the findings along with the conclusions of this thesis are applicable and can be expanded to any region or a country by applying the generalized methodology outlined in chapter 5.

In broader scope the current study contributes to the research on the subject of building energy efficiency by presenting the methodology of evaluating thermal energy saving potential in the long run across different building categories when adhering to various thermal energy compliance scenarios. The study is intended for stakeholders such as building industry professionals and policy makers in developing national building energy efficiency roadmaps and in reviewing regulatory environment related to buildings' energy efficiency. The methodology is particularly useful for governments and public entities experiencing challenges with the existing building stock's poor energy performance and facing uncertainty of strict policy implications on the following key disciplines:

a) future building stock development figures in form of commissioned buildings (including new construction and renovation projects);

b) potential energy savings resulting from the implementation of the energy efficiency measures in compliance with the regulatory building codes;

c) overall state and projection of the economic growth of a country.

It is important to note that the proposed methodology is not limited to the scope of the current study and can be further elaborated to address specific reference conditions. Continuous energy auditing of the existing building stock in line with expanding the focus beyond residential and public building sector is going to contribute significantly for future research work in this field. Furthermore, as building energy performance regulations across developed countries are getting stricter, addressing technical aspects of the building envelope alone may not continue to ensure significant energy conservation effects, therefore in future more attention is going to be drawn towards stricter regulations in relation to building operation and maintenance, building equipment, mechanical systems etc. As such, modeling optimization strategies relating to buildings' life cycle analysis and CO_2 emissions should also be considered to elaborate on the current study.

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