RIGA TECHNICAL UNIVERSITY
Faculty of Civil Engineering
Institute of Heat, Gas and Water Technology

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LONG-TERM ASSESSMENT METHODOLOGY OF BUILDING STOCK THERMAL ENERGY CONSUMPTION

Summary of the Doctoral Thesis

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DECLARATION OF ACADEMIC INTEGRITY

I hereby declare that the Doctoral Thesis submitted for the review to Riga Technical University for the promotion to the scientific degree of Doctor of Science (Ph. D.) is my own. I confirm that this Doctoral Thesis had not been submitted to any other university for the promotion to a scientific degree.

Aleksejs Prozuments …………………………….

Date: ………………………

The Doctoral Thesis is written in English. It consists of Introduction; 10 chapters; Conclusions; 28 figures; 27 table; the total number of pages is 104. The Bibliography contains 121 titles.

CONTENTS

1. INTRODUCTION

Nowadays new construction projects are looked at from a rather market-driven and sustainability-oriented viewpoint, considering 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 in the long run 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 introduces cost savings to the building owners and stakeholders via implementation of energy-related government and local incentive programs and thus lower building operating expenses; the macro-scale aspect urges governments and building owners to meet the regulations on CO_2 emissions and comply with the international regulations that may 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 effectively become a separate industry and 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 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 to determine various building energy efficiency upgrades at individual and building-scale level.

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

Within the scope of this Doctoral Thesis an evaluation methodology of the building stock thermal performance and future savings potential under various thermal energy performance protocols is developed and adapted to the Latvian context.

2. GENERAL DESCRIPTION

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 consumption optimization measures. Upgrading building energy efficiency contributes to the reduction of energy consumption that in turn leads to lowering environmental impact and 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. As such, the present study aims to contribute to the research on the subject of building energy efficiency by presenting a 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/WOS databases.

3. LITERATURE REVIEW

Buildings in the EU-28 (as of Q3 of 2020) [1] account for approximately 55 % of total electricity consumption and roughly 40 % of total final energy consumption on average [2], [3]. Followed by transport and industry, the building industry is the third largest end-use energy sector in Europe. In Latvia, Estonia and Hungary buildings' energy use share is even higher (45 % to 50 %) due to the poor energy performance of the existing building stock that was built during and slightly after World War II (1945–1980) and is now obsolete with regards to meeting energy performance criteria [4]. Up until 2002 buildings in Latvia were designed in accordance with the USSR (Union of Soviet Socialist Republics) regulatory codes which were not stringent enough with regards to energy performance [5]. As a result, the bulk of the existing building stock that has not undergone deep renovation features poor thermal insulation, excessive outdoor air infiltration and condensation occurrence within the external wall structures [6]. Moreover, the absolute majority of the post-Soviet buildings (constructed between 1945 and 1991 when Latvia was part of the USSR) lack proper mechanical ventilation system, and thus the air exchange occurs primarily due to natural ventilation and/or outdoor air infiltration through the external elements (walls and roofs), which entails major thermal energy losses [7]. Other major sources of heat loss featured in the existing old buildings in Latvia are linear thermal bridges, window frames and single pane glazing.

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 [8].

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 [9]. Energy savings due to retrofits vary widely depending on the applied energy efficiency techniques, building's initial condition and climate. For instance, energy efficiency measures for households can reduce energy bills by 30 % with respect to their original energy consumption [10]. 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 [11]. 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 [12]. When stakeholders take the 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.

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 [13] sets the energy use objectives and optimal cost criteria to the individual building renovation.

The literature review section encompasses a wide spectrum of recently published articles on the topic of the building energy efficiency. Although the studies in the literature review section has an emphasis on the status and strategies of the building energy performance in the EU region, it also provides an insight into 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 economic 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, namely, to design a thorough thermal energy performance assessment tool of the building stock that would evaluate future potential energy savings under various building thermal energy consumption compliance scenarios, a comprehensive methodology was developed. The proposed methodology allows for a long-term building stock thermal energy performance evaluation of various types of buildings (residential, public, industrial, military, etc.) across the regions where the demand for space heating is present. A worklist consists of multiple interdisciplinary steps that are outlined in the flowchart in Fig. 4.1.

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 it into adapted methodology, i.e., linked to a specific case study.

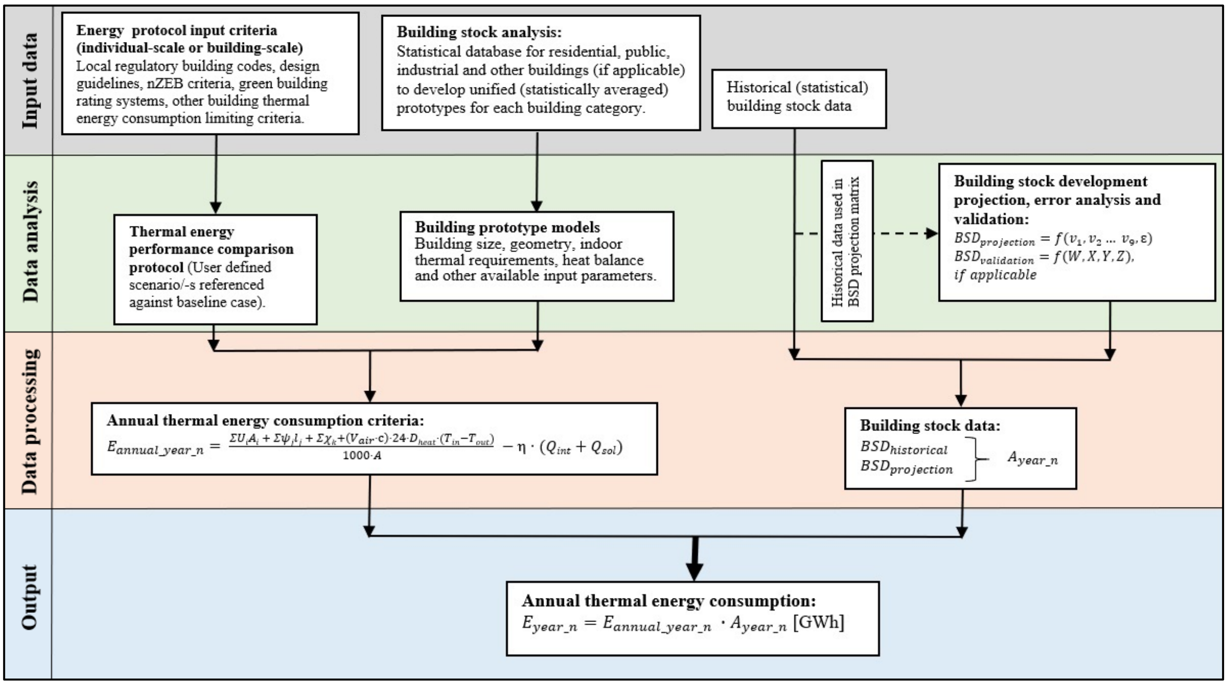

Fig. 4.1. Generalized flowchart of building stock thermal performance evaluation methodology.

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 further 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 summarizes how the design criteria (outlined in technical guidelines or regulatory building codes) pertaining to the 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 the 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.).

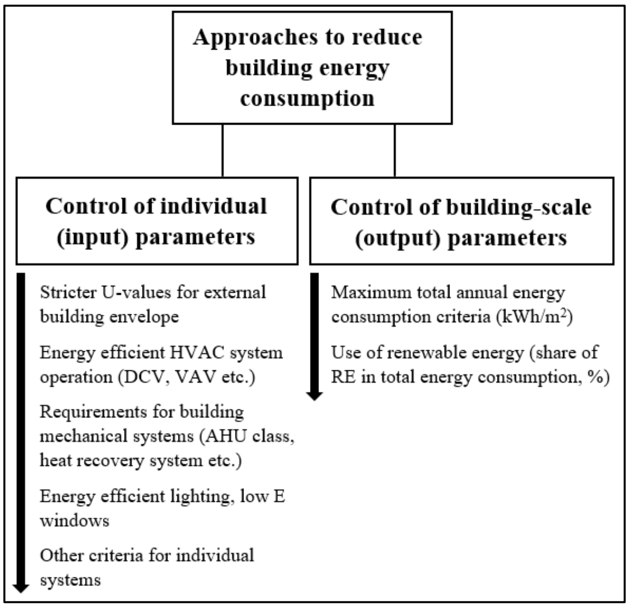

Fig. 4.2. Comparison of controlling individual and building-scale parameters within the regulatory building codes.

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 cannot 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 and 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 the HVAC system [14];
b) leading to high indoor humidity level and causing condensation occurrence on the surfaces of the external construction elements due to an insufficient air exchange rate [15].

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. Identification of the Input Parameters

The generalized long-term evaluation methodology of building stock thermal energy performance was adapted to the case of Latvia, which entailed modifications in the generalized methodology through the following activities:

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 and economic forecast analysis for construction market, 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 (acquired from Building Information System database);
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.

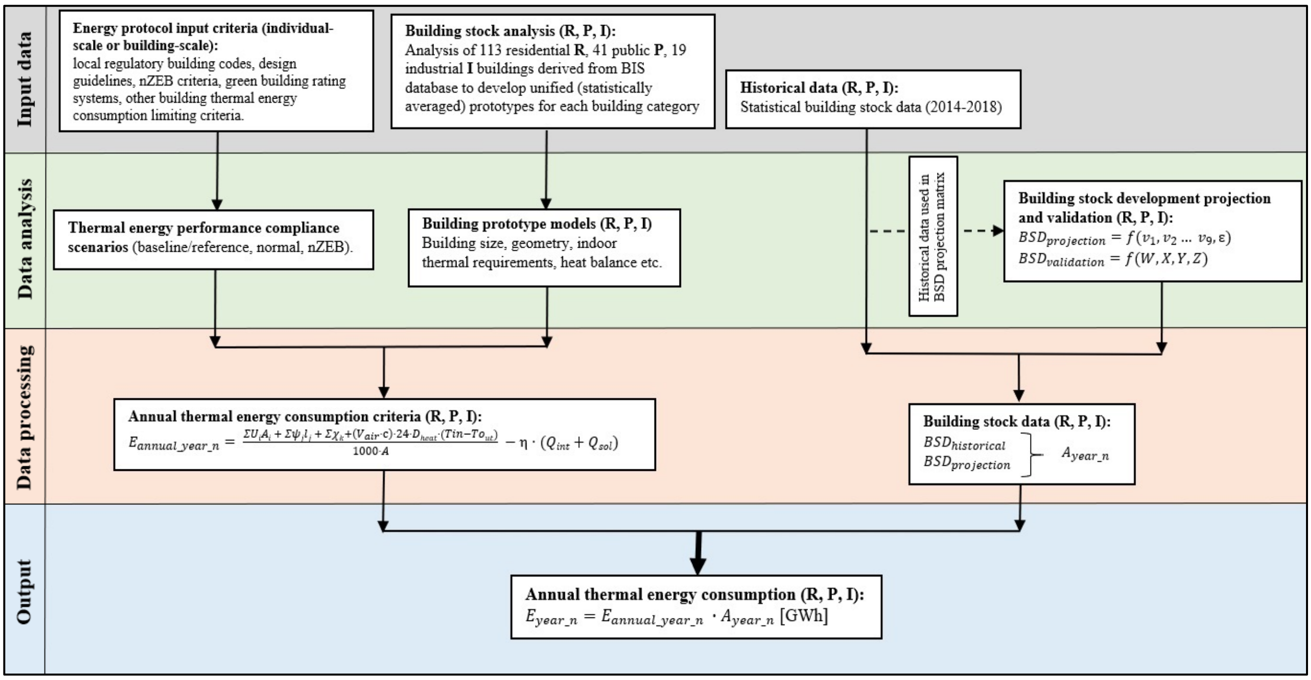

Fig. 4.3. Methodology flowchart adapted to the case of Latvia.

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. The Overview and the Timeline of Modeled Scenarios

The three building thermal energy consumption scenarios reviewed and analyzed within the scope of the proposed methodology (baseline, normal, nZEB) were designed based on various compliance criteria and are presented in Table 4.2.

Table 4.2

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.

* nZEB – nearly zero energy building.

The timespan for the reviewed scenarios starts with 2014, as there have 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 overriding the normative heat transmittance coefficients with their maximum threshold values) 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.

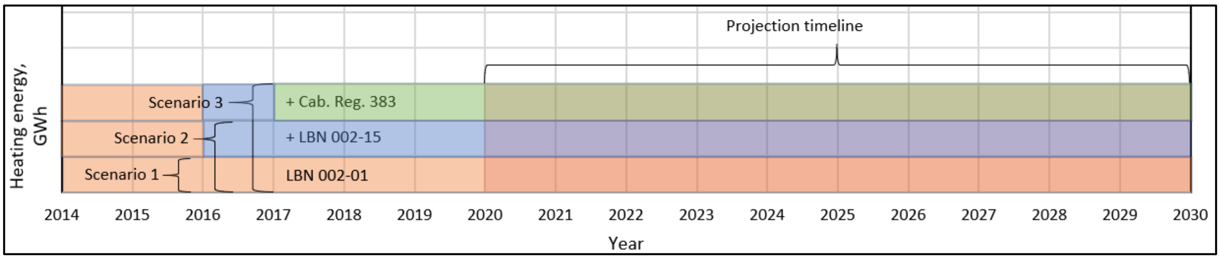

Fig. 4.4. The illustrative framework of the reviewed scenarios.

The calculation of thermal energy consumption was performed according to the "Methodology for Calculating the Energy Performance of a Building" [16]. 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 had to be carried out.

4.4. Building Stock Development Projection

In order to assess thermal energy savings due to the compliance with the reviewed regulatory building codes over the proposed timeline that extends to 2030, it was 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 was necessary to define the projection for the housing stock development (the dependent variable). This task involved identifying the key factors (variables) that affect building stock development over a long run:

- 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 %) (ε).

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

$$BSD_{\text{projection}} = f(v_1, v_2, \dots, v_9, \varepsilon). \tag{4.1}$$

The aforementioned variables (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 proposed projection matrix was approved and authorized by a third party (Ministry of Economics of the Republic of Latvia).

Based on the above listed factors and determinants that will influence the industry’s growth within the next decade, the building stock development projection for 2019–2030 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 4.3

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

4.5. Building Prototype Model Development

As there is no publicly available database containing construction data and energy performance characteristics of each individual building constituting all existing Latvian building stock, thorough and detailed prototype models had to be developed that would represent a typical residential, public and industrial building. The initial dataset on 113 residential, 41 public and 19 industrial buildings was acquired from building information system's database to develop typical building prototype models for all of the three categories. Furthermore, building prototype model development was necessary to run thermal energy consumption calculation for the reviewed building stock, as each building category had different structural characteristics and requirements with regards to building design, materials, heat transfer coefficients, indoor comfort level and other parameters affecting building's thermal balance.

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 002-15 (overridden by LBN 002-19). The required annual thermal energy (kWh/m^2) for each building prototype was calculated in accordance with Cab. Reg. No. 348, which is referred to in LBN 002-15.

Table 4.4

Input Parameters and Values for the Building Prototype Models

Defining parameter	Residential	Public	Industrial
Total effective floor area A, m^2	2462.50	12 485.42	3793.80
The average floor-to-ceiling height h, m	2.5	3.0	6.0
Total effective volume V_{eff}, m^3	6156.25	37 456.26	22 762.8
Indoor setpoint temperature for heating T_{in}, °C	19.0	19.0	17.0
Air exchange rate n, 1/h	0.55	1.50	2.00
Total air exchange volume V_{air}, m^3/h	3385.90	56 184.40	45 525.60
Internal heat gains in heating season Q_{int}, kWh/m^2	37.0	39.9	39.9
Total solar heat gains in heating season Q_{sol}, kWh/m^2	13.0	13.2	13.2
Heat gain coefficient η	0.86	0.86	0.86
Longevity of a heating period D_{heat}, days	205.8	205.8	205.8
Average outdoor temperature T_{out}, °C	–0.57	–0.57	–0.57

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 (E_{annual}) for a prototype building (kWh/m^2) can be determined by the following equation [16]:

$$E_{\text{annual}} = \frac{\sum U_i A_i + \sum \psi_j l_j + \sum \chi_k + (V_{\text{air}} \text{c}) \cdot 24 D_{\text{heat}} (T_{\text{in}} - T_{\text{out}})}{1000A} - \eta\left(Q_{\text{int}} + Q_{\text{sol}}\right), \tag{4.2}$$

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

l_j – 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, c = 0.34, Wh/(m^{3}K);

D_{heat} – number of heating days;

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

T_{out} – average external temperature in the calculation period, °C;

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

η – gain use coefficient for heating in accordance with EN ISO 13790:2009 L [17];

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.

5. RESULTS AND DISCUSSION

The results of the proposed methodology to evaluate long-term potential thermal energy savings under normal and nZEB scenarios referenced against the baseline scenario suggest, as expected, that the highest thermal energy savings in public and industrial buildings would be generated under nZEB scenario, whereas in residential buildings normal and nZEB scenarios would represent somewhat similar savings potential.

As a matter of fact, up until 2027 slightly greater savings in residential buildings would occur under normal scenario (134.89 GWh > 131.33 GWh), whereas in public and industrial buildings nZEB scenario kicks in early and as a result is projected to generate significantly higher annual thermal energy savings starting with 2017 (with the advent of Cab. Reg. no. 383). As such, by 2030 the potential cumulative savings for residential buildings under both scenarios are projected to differ by a very narrow margin (173.26 GWh at normal; 185.30 GWh at nZEB).

As for public buildings, the results indicate that significant difference between normal and nZEB scenarios begins to evolve in 2017 and remains a constant multiplier over the timespan between 2020 and 2030 throughout which a fixed nZEB criterion for public buildings sets in (energy consumption criterion of 118.30 kWh/m^2 under Scenario 2 and 45.00 kWh/m^2 under Scenario 3).

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. Thus, when it comes to industrial buildings, 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.

Figures 5.1 and 5.2 show the cumulative savings in residential, public and industrial buildings over the timeline of 2014–2030 under normal and nZEB scenarios.

Cumulative savings (2014-2030), GWh / Scenario 2				
Year	Residential	Public	Industrial	Total, GWh
2014	0.00	0.00	0.00	0.00
2015	0.00	0.00	0.00	0.00
2016	11.12	6.95	5.00	23.07
2017	19.24	12.25	9.48	40.97
2018	29.50	19.00	14.99	63.49
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				63.49
Total (2014-2020), GWh				111.55
Total (2014-2030), GWh				367.34

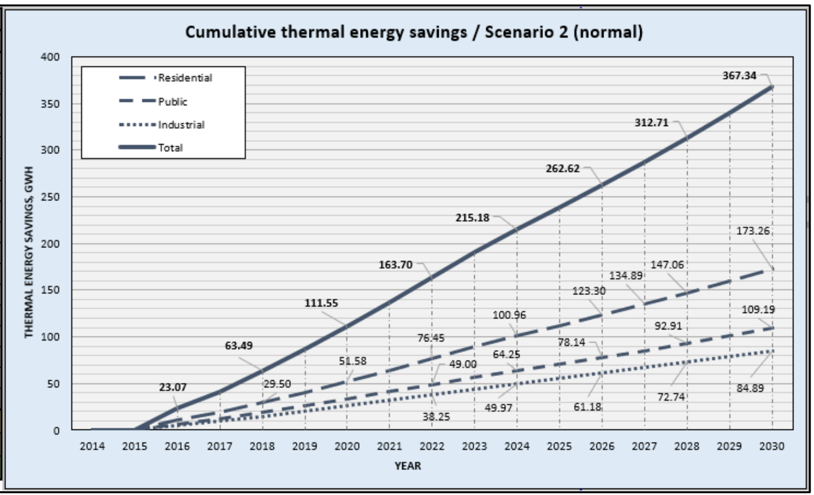

Fig. 5.1. Cumulative thermal energy savings in buildings under Scenario 2.

Cumulative savings (2014-2030), GWh / Scenario 3				
Year	Residential	Public	Industrial	Total, GWh
2014	0.00	0.00	0.00	0.00
2015	0.00	0.00	0.00	0.00
2016	11.12	6.95	5.00	23.07
2017	8.85	15.27	35.11	59.23
2018	11.71	27.97	73.55	113.23
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				113.23
Total (2014-2020), GWh				252.09
Total (2014-2030), GWh				1150.26

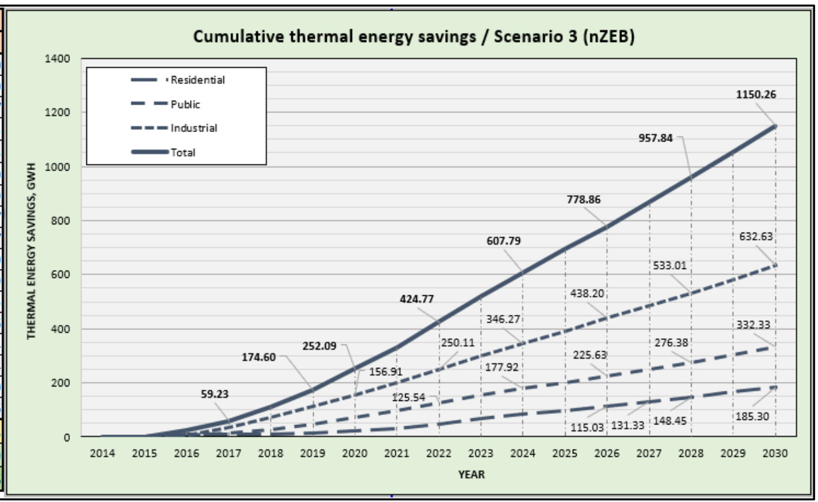

Fig. 5.2. Cumulative thermal energy savings in buildings under Scenario 3.

Scenario 3 presents substantially wider gaps among the curves representing cumulative thermal energy savings for each of the building category, 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 [18].

Another complexity stems from the factor that a limiting building-scale parameter instead of individual scale parameter (as per nZEB case) disregards the individual building's specifics, unique features, or exceptional factors attributable to its functional characteristics. 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 [19], i.e., securing a certain degree of resiliency with regards to daily building operations and reliable power delivery [20]. 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 [21].

In that regard, a normal scenario offers seemingly 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, would not incur substantial energy savings in the long run, as the thermal performance requirements imposed by LBN 002-15 standard are designed to meet solely the minimum thermal performance requirements of a building envelope [18], [22].

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 [23].

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 [24], [25]. 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 [26]. These considerations, however, are not within the scope of this work, as this study primarily evaluates the long-term impact of applying different regulatory code compliant building energy performance scenarios.

6. CONCLUSIONS

1. Following the outlined preconditions and considering the error assessment, the methodology of evaluating thermal energy saving potential across residential, public and industrial building stock in Latvia was developed over the timeline of 2014–2030 roadmapping the potential thermal energy savings for newly constructed and renovated buildings at different energy consumption compliance scenarios.
2. The building stock development projection matrix suggests a gradual increase in the new construction and renovation projects over the next years that will continue a linear upward trend 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 an uncertainty among investors and other construction industry stakeholders. Nevertheless, it is projected that the construction sector will be recovering at a steady rate from this slight stagnation and will reach a firm growth level by 2030.
3. The positive building stock development curve translates into the building industry being at the central role for strategies targeting energy conservation measures. Building energy efficiency and the associated long-term benefits has been an emphasis for building owners, operators, facility management and customers, i.e., end-users.
4. The study results highlight that regulatory building codes are an effective policy measure for reducing energy consumption in buildings. It is noted, however, that roadmapping one particular scenario across the whole reviewed building stock is not an optimum concept over the long term in pursuit of achieving higher energy savings, as it can be rather challenging to maintain the economic feasibility while complying with the imposed energy performance criteria.
5. Many countries have been adopting more stringent building energy codes over time, which have resulted in more efficient and market-appealing building stock. Yet, the findings of the current study along with the reviewed literature within this work suggest that exclusive adherence to local building regulatory standards or government-imposed building energy efficiency policies do not guarantee the most energy efficient buildings.
6. 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 standpoint, 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.
7. The calculation results of cumulative thermal energy savings show that Scenario 2 would generate 367.34 GWh of thermal energy offset by 2030, while Scenario 3 would result in 1150.26 GWh of generated thermal energy savings by 2030. Though, 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 ultimately may not be feasible from the economic perspective. Scenario 3 roadmaps

a nearly zero energy building (nZEB) pathway, which is a 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 threat 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. It is important to note, however, that the development dynamics of the construction industry may take a different path and, as a result, the cumulative energy savings may deviate to a rather high degree from those presented in the current study.

8. Even though there is a 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 such as a) continuous preparation of highly skilled building energy efficiency professionals; b) education campaigns and basic training programs for non-professionals; c) building energy performance monitoring and energy auditing; d) establishing clear and attainable regulatory environment; e) setting and adhering to national approaches on low energy buildings as a supplementary enforcement measure; f) identification of all financial instruments available to perform either building energy performance auditing or implement certain energy efficiency strategies.

RECOMMENDATIONS AND FURTHER STUDIES

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.

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