RIGA TECHNICAL UNIVERSITY
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ENERGY EFFICIENCY – INDOOR AIR QUALITY DILEMMA IN EDUCATIONAL BUILDINGS

Summary of the Doctoral Thesis

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DOCTORAL THESIS PROPOSED TO RIGA TECHNICAL UNIVERSITY FOR THE PROMOTION TO THE SCIENTIFIC DEGREE OF DOCTOR OF SCIENCE

To be granted the scientific degree of Doctor of Science (Ph. D.), the present Doctoral Thesis has been submitted for the defence at the open meeting of RTU Promotion Council at 2 p.m. on December 17, 2020 at the Faculty of Electrical and Environmental Engineering of Riga Technical University, Azenes Street 12-1, Room 115.

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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.

Līva Asere ……………………………. (signature)

Date: ………………………

The Doctoral Thesis has been written in Latvian. It consists of an introduction; 3 chapters; Conclusions; 53 figures; 6 tables; 6 appendices; the total number of pages is 76. The Bibliography contains 95 titles.

CONTENTS

Scientific publications used in the Doctoral Thesis

Publication 1. L. Asere and A. Blumberga. Government and municipality owned building energy efficiency system dynamics modelling (2015) *Energy Procedia*, 72, 180–187.

Publication 2. L. Asere, T. Mols, and A. Blumberga. Assessment of energy efficiency measures on indoor air quality and microclimate in buildings of Liepāja municipality (2016) *Energy Procedia*, 95, 37–42.

Publication 3. L. Asere, T. Mols, and A. Blumberga. Assessment of indoor air quality in renovated buildings of Liepāja municipality (2016) *Energy Procedia*, 91, 907–915.

Publication 4. L. Asere and A. Blumberga. Energy efficiency – indoor air quality dilemma in public buildings (2018) *Energy Procedia*, 147, 445–451.

Publication 5. L. Asere and A. Blumberga. Does energy efficiency – indoor air quality dilemma have impact on the gross domestic product? (2020) *Journal of Environmental Management*, 262. ISSN: 03014797.

Publication 6. L. Asere and A. Blumberga. Energy Efficiency – Indoor Air Quality Dilemma in Educational Buildings: A Possible Solution. (2020) *Environmental and Climate Technologies*, 24(1), 357–367.

INTRODUCTION

Actuality

The largest energy consumer in Europe is the building sector, which uses about 40 % of total energy consumption and generates around 36 % of total CO_2 emissions in the EU [1], [2]. Rising trends in energy consumption can be observed globally due to the demand of citizens for increased comfort, wider use of electrical equipment as well as other reasons. As energy consumption increases, climate change is promoted. In a number of areas energy could be used more efficiently, minimizing its consumption and, thus, resulting in a reduction of greenhouse gas emissions. To achieve carbon neutrality in 2050 in European Union, ambitious targets have been set, such as improving energy efficiency by 41 %, using 100 % of renewable energy sources and reducing greenhouse gas emissions of 80 % to 100 % [1], [3], [4].

Energy efficient buildings help to reduce heat consumption. State and local authorities need to set an example by improving the energy efficiency of their own buildings in order to encourage changes in other buildings as well. Moreover, the introduction of energy efficiency measures in buildings owned by the public sector contributes to the objectives of national climate policy.

Educational institutions contain a high density of pupils in the building premises who emit carbon dioxide whilst breathing. In the past, schools were able to ensure satisfactory air quality using natural ventilation. Buildings relied on open ventilation ducts and air circulation was carried out without mechanical assistance, i.e., by the means of outdoor and indoor pressure differential. If the air pressure outdoors is lower than indoors, natural air exchange occurs with the heat escaping through the open ventilation ducts. Over time a butterfly effect has emerged – introducing energy efficiency measures, for instance, replacement of newer and denser windows, have reduced the supply of fresh air through natural infiltrations. Therefore, reconstruction of the mechanical ventilation systems is necessary to ensure high indoor air quality.

The human thermal comfort indicates how satisfied they are with the room’s microclimate. If a person does not feel comfortable in the microclimate, writing and thinking performance drops. It is possible to increase performance by supplying larger volumes of air to the room. By providing educational buildings with the lowest required air supply rates in accordance with Latvian normative regulations, it is possible to improve performance. However, due to the high operating costs, such ventilation systems are not being used.

Although improving the energy efficiency of buildings cuts the expenses, it is also necessary to ensure appropriate indoor air quality in insulated buildings. Both factors result in energy efficiency – indoor air quality dilemma in buildings.

Construction of educational institutions has to be based on a sustainability principle. Future specialists spend most of their time in these buildings, so it is particularly important to make a variety of environmental improvements. The best solution is to increase energy efficiency while also ensuring high indoor air quality by operating mechanical ventilation, since the growth of the gross domestic product provides financial sources for future energy efficiency measures.

By transforming educational buildings to prosumers, it is possible to reduce greenhouse gas emissions, ensure the use of renewable energy sources and promote energy efficiency in such a way that a high level of indoor air quality is ensured at the same time.

Purpose and Tasks of the Work

The objective of the Thesis is to perform an assessment on energy efficiency – indoor air quality dilemma in educational buildings, its impact analyses on national prosperity, and to propose a solution to the prevention of the dilemma.

To achieve the objective, the following tasks were defined:

1) to evaluate indoor air quality and microclimate in municipal educational institutions where energy efficiency measures have been carried out;
2) to assess the indoor air quality and the microclimate impact on the performance of visitors in energy-efficient municipal education institutions;
3) to analyse the dynamics of the government and municipality-owned building stock energy efficiency improvement, including the impact on reducing greenhouse gas emissions and indoor air quality;
4) to analyse the impact of indoor air quality on the country's gross domestic product and on reducing greenhouse gas emissions;
5) to develop a solution on how to reduce the energy efficiency – indoor air quality dilemma in educational institutions.

Hypothesis

Hypothesis 1. Introduction of energy efficiency measures in buildings owned by government and municipalities ensures that the national climate policy objectives are achieved.

Hypothesis 2. Following the introduction of energy efficiency measures, a dilemma of energy efficiency and indoor air quality is forming in educational institutions.

Hypothesis 3. Energy efficiency – indoor air quality dilemma has a long-term impact on the country's gross domestic product.

Hypothesis 4. Energy efficiency – indoor air quality dilemma can be solved by buildings becoming prosumers using renewable energy.

The hypotheses have been investigated with various methods and are further reflected in the scientific publications.

Hypothesis 1

1. Analysis of scientific literature and regulatory acts.
2. Collection and analysis of data from already implemented energy efficiency improvement projects.

3. Development of a model of system dynamics for the assessment of energy efficiency in government and municipality-owned buildings.
4. Simulation of policy instruments in a system dynamics model.

The research methods and the obtained results are described in the following publications.

Publication 1. (L. Asere and A. Blumberga. Government and municipality owned building energy efficiency system dynamics modelling (2015) *Energy Procedia*, 72, 180–187) A system dynamic model for implementing energy efficiency measures in government and municipality-owned buildings and impact analysis of the policy instruments and possible financial sources have been developed in the study. The model simulates the change in the total heated area and its impact on greenhouse gas reduction.

Publication 4. (L. Asere and A. Blumberga. Energy efficiency – indoor air quality dilemma in public buildings (2018) *Energy Procedia*, 147, 445–451) The study complements the system dynamics model developed in Publication 1, dividing the total stock of public buildings into four submodules based on construction periods. For each of these, the calculated profitability ratio of energy efficiency measures describes the dynamics of the implementation of energy efficiency measures. In addition, the model has an integrated module, which requires an introduction of a ventilation system when energy efficiency improvement measures are taken. The model simulates the change in the total heated area and its impact on greenhouse gas reduction.

Hypothesis 2

1. Analysis of scientific literature and regulatory acts.
2. Indoor climate measurements in educational institutions.
3. Determination of the air exchange rate by the tracer gas method.
4. Determination of the air-tightness of the building through a blower door test.
5. Surveys and interviews in educational establishments.
6. Estimates of the predicted mean vote.

The research methods and the obtained results are described in the following publications.

Publication 2. (L. Asere, T. Mols, and A. Blumberga. Assessment of energy efficiency measures on indoor air quality and microclimate in buildings of Liepāja municipality (2016) *Energy Procedia*, 95, 37–42) In the study, microclimate and CO_2 measurements were carried out in energy-efficient educational institutions in the city of Liepāja. The tracer gas method was used to determine the air exchange rate. A blower door test was carried out to determine the airtightness of the building.

Publication 3. (L. Asere, T. Mols, and A. Blumberga. Assessment of indoor air quality in renovated buildings of Liepāja municipality (2016) *Energy Procedia*, 91, 907–915) During the study interviews with the responsible persons of Liepāja educational institutions were conducted to obtain information about the buildings, including the type of buildings, the total area, the taken energy efficiency measures, and the operation of ventilation systems. In addition, users in certain rooms were interviewed to find out their subjective views on the indoor microclimate at a given moment. The study makes an estimate of the predicted mean vote, which allows to compare theoretical comfort level parameters with the subjective feelings of a person.

Hypothesis 3

1. Analysis of scientific literature and regulatory acts.
2. Surveys and interviews in educational establishments.
3. Estimates of the predicted mean vote.
4. Performance loss calculations.
5. The economic impact of performance changes and cost-benefit analysis.
6. The development of educational institutions' buildings system dynamics model on energy efficiency.

The used research methods and the obtained results are described in the following publications.

Publication 3. (L. Asere, T. Mols, and A. Blumberga. Assessment of indoor air quality in renovated buildings of Liepāja municipality (2016) Energy Procedia, 91, 907–915) As part of the study, users in certain rooms were interviewed to find out their subjective views on the indoor microclimate at a given moment. A productivity loss model was used for the data analysis to determine how microclimate conditions in buildings included in the study affect mental work and performance. The study calculated a relative improvement in productivity in the room with fresh air inflow, moreover four ventilation speed scenarios were modelled. The method of ventilation productivity has been used to perform the economic impact and cost-benefit analysis of changes in the performance.

Publication 5. (L. Asere and A. Blumberga. Does energy efficiency – indoor air quality dilemma have impact on the gross domestic product? (2020) Journal of Environmental Management, 262. ISSN: 03014797.) A system dynamics model that analyses the impact of energy efficiency – indoor air quality dilemma, on gross domestic product was developed in the study. The model simulates students' academic performance, study and work pathway, and its impact on the share of wages in gross domestic product. The study uses data on the Latvian education system. The different modelling scenarios create an understanding of the impact of introduction of energy efficiency measures and the impact of running ventilation systems on greenhouse gas reductions, as well as the development of the total wage share in gross domestic product.

Hypothesis 4

1. Analysis of scientific literature and regulatory acts.
2. Analysis of the most economically feasible solution for the transition of an educational institution building to a prosumer.

The research methods and the obtained results are described in the following publication.

Publication 6. (L. Asere and A. Blumberga. Energy Efficiency – Indoor Air Quality Dilemma in Educational Buildings: A Possible Solution. (2020) Environmental and Climate Technologies, 24(1), 357–367) The study carried out for one typical school building in Latvia allows analysing scenarios for the transition of educational institution's building to a prosumer and the possible solution of energy efficiency and indoor air quality dilemma of buildings. The study has developed various solar panel and wood pellet boiler solutions to find the best and most economically viable solution for the transition of educational institution's building to a prosumer.

Scientific Novelty of the Work

Indoor air quality and climate measurements have been carried out in real education institutions that have introduced energy efficiency measures in order to assess the energy efficiency – indoor air quality dilemma, and provide insight into causal links of the problem. Based on these measurements, as well as interviews between visitors and operators of the premises, a system dynamics model has been developed within the framework of the work. The model includes a number of modules to assess the energy efficiency – indoor air quality dilemma in educational institutions along with its impact on the achievement of the country's climate objectives and the country's long-term prosperity. So far, no publications on such modelling tools have been found in the scientific periodicals. The developed simulation model allows for a causal analysis of the behaviour generated by the complex, nonlinear system with delays. The model structure includes four different public sector building funds, the market for construction companies and its interaction with energy efficiency measures through insulation costs, different types of ventilation systems, levels of education systems from pre-school to university, student performance, wage formation in the labour market depending on the school or university evaluation, the gross domestic product, and greenhouse gases. The structure of the model is complemented by various policy instruments that make it possible to change the behaviour of the model. The simulation model developed is versatile and can be used in other countries and regions of the world to analyse the dilemma. The cost-benefit analysis for the prosumer was done in the work while finding the solution for the dilemma. It provides an insight into what conditions have to be fulfilled in order for a prosumer to become a solution to the dilemma while reducing the impact on the climate and without compromising the country's well-being.

Practical Application of the Work

The results of the measurements and interviews obtained in this study are essential for policy-makers, not only at the state but also at the municipal level. The study shows how closely the policies of different sectors intertwine and interact with each other, including climate, finance, social, educational, and health sector policies, thus, leaving not only short-term but also long-term consequences for the whole population. The model developed within the framework of the paper is a practical tool for policy planners to assess the impact of various policy instruments on different aspects of state and local policy. This allows owners and managers of the buildings to assess the potential for the use of environmentally friendly technologies in both the environmental and financial aspect.

Approbation of the Scientific Work

Scientific publications on the topic

1. L. Asere and A. Blumberga. Energy efficiency – indoor air quality dilemma in educational buildings: a possible solution. (2020) *Environment and Climate Technologies*, 24(1), 357–367.
2. L. Asere and A. Blumberga. Does energy efficiency – indoor air quality dilemma have impact on the gross domestic product? (2020) *Journal of Environmental Management*, 262. ISSN: 03014797.
3. L. Asere and A. Blumberga. Energy efficiency – indoor air quality dilemma in public buildings (2018) *Energy Procedia*, 147, 445–451.
4. L. Asere, T. Mols and A. Blumberga. Assessment of energy efficiency measures on indoor air quality and microclimate in buildings of Liepāja municipality (2016) *Energy Procedia*, 95, 37–42.
5. L. Asere, T. Mols and A. Blumberga. Assessment of indoor air quality in renovated buildings of Liepāja municipality (2016) *Energy Procedia*, 91, 907–915
6. L. Asere and A. Blumberga. Government and municipality owned building energy efficiency system dynamics modelling (2015) *Energy Procedia*, 72,180–187.

The results of the Thesis were presented at six international scientific conferences

1. International Scientific Conference on Environment and Climate Technologies, CONECT, 2020, Riga, Latvia.
2. International Scientific Conference on Environment and Climate Technologies, CONECT, 2019, Riga, Latvia.
3. International Scientific Conference on Environment and Climate Technologies, CONECT, 2018, Riga, Latvia.
4. International Scientific Conference on Environment and Climate Technologies, CONECT, 2015, Riga, Latvia.
5. International Scientific Conference "The Solar Heating and Cooling for Buildings and Industry conference", 2015, Istanbul, Turkey.
6. International Scientific Conference on Environment and Climate Technologies, CONECT, 2014, Riga, Latvia.

Structure of the Work

The Thesis is based on six thematically joint scientific publications (see Page 5). These publications were presented and the results of the studies were validated at a number of international conferences. The corresponding papers are also available in the scientific information repositories and are included in international databases.

The Thesis is written in Latvian, its structure is shown in Fig. 1. The study is based on four main topics.

1. Energy performance of buildings.
   While the introduction of energy efficiency measures in buildings owned by the public sector help to reduce heat consumption and contribute to the achievement of national climate policy objectives, it nevertheless calls for the introduction and operation of mechanical ventilation, which is the cause of the dilemma of energy efficiency – indoor air quality. Studies on the implementation of energy efficiency in the buildings of government and municipal authorities are presented in Publications 1 and 4.
2. Indoor air quality and thermal comfort in energy-efficient buildings.
   An assessment of indoor air quality and thermal comfort was carried out in buildings where energy efficiency measures had been introduced. This was accomplished by using indoor measurements and interviewing visitors at the premises. This research topic describes the detection of energy efficiency – indoor air quality dilemma that is reflected in Publications 2 and 3.
3. National gross domestic product.
   The following topic describes how the energy efficiency – indoor air quality dilemma affects the country's gross domestic product in the long term. The impact of indoor air quality on human performance in education institutions is discussed in Publication 3, while Publication 5 presents different scenarios for the impact of indoor air quality on the gross domestic product.
4. Prosumers.
   Rebuilding educational institutions' buildings as prosumers can reduce greenhouse gas emissions, ensure the consumption of renewable energy sources, and promote energy efficiency in a way that ensures high indoor air quality at the same time. The study is presented in Publication 6.

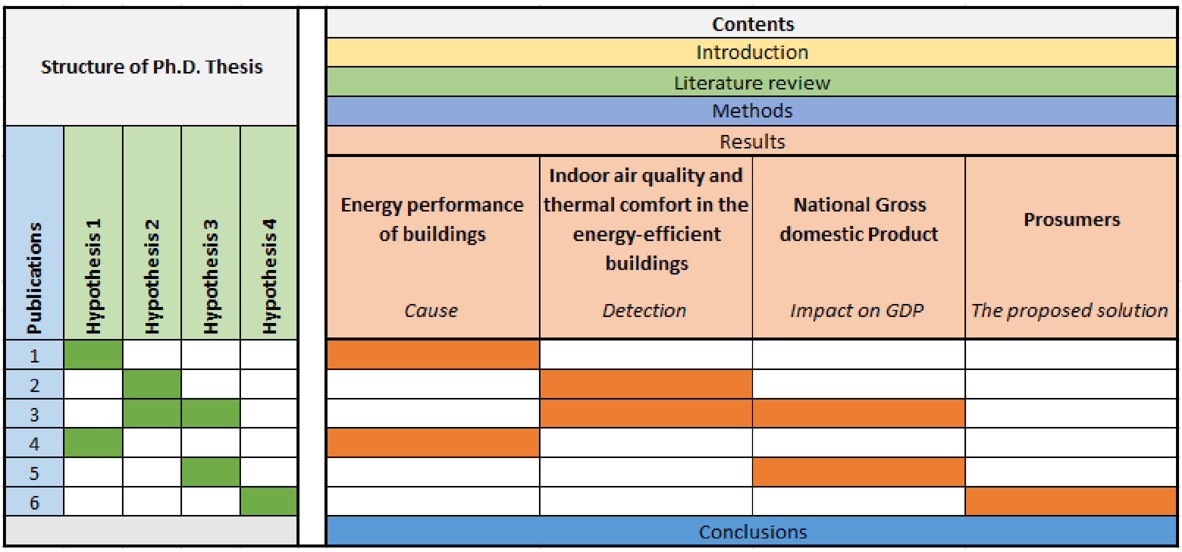


Fig. 1. Structure of the Doctoral Thesis.

The Thesis includes an introduction, three chapters, conclusions, and bibliography. The introduction of the Thesis sets out the aim of the study and the tasks to be performed for its implementation as well as describes the scientific and practical implications of the study. Chapter 1 provides a literature review of the themes. Chapter 2 presents the study methods related to the root cause of building energy efficiency – indoor air quality dilemma, its detection, impact on gross domestic product, and analysis of the economic rationale for the solution. Chapter 3 examines the results of the studies. At the end of the Thesis, the findings are summarised according to the hypotheses. The bibliography contains 95 reference titles.

1. LITERATURE REVIEW

1.1. Energy Efficiency – Indoor Air Quality Dilemma

The building sector has the largest energy efficiency potential in the world, which currently accounts for almost 40 % of the energy balance in the European Union (EU). Most buildings were built at a time when energy savings were not topical, given the comparatively low prices of energy sources and traditional construction methods. Most of these buildings will continue to be operated for a considerable period of time, since the evaluated energy strategy period is unlikely to consider intensive replacing existing buildings with new ones [5]. The gradual restoration of these buildings is now one of the most important energy efficiency policy areas. According to the Latvian Energy Development Guidelines from 2007 to 2016, the total reduction target for energy consumption by 2016 in the public sector was 408 GWh and until 2020–657 GWh, which is the second-largest target after the household sector [6]. Worldwide, maximizing the energy efficiency of buildings is one of the main approaches to achieve sustainability in the building sector while using sufficiently low resources.

Energy efficiency measures in either a large or small municipality provide the opportunity to address technical, economic, socio-economic, environmental, and climate issues. Implementing such an activity benefits all parties involved:

- the state budget – fewer money outflows from the country due to less energy sources imported;
- municipal budgets – by paying less for the energy, more financial resources remain for the municipality's development;
- society – sustainable development of the energy sector provides an orderly environment;
- environment – less pollution in the environment from emissions into the air, water, and soil;
- each energy user separately – the reduction in energy consumption enables the energy consumer to use the funds saved elsewhere;
- the global climate change reduction by burning fewer fossil fuels in the boiler house furnaces.

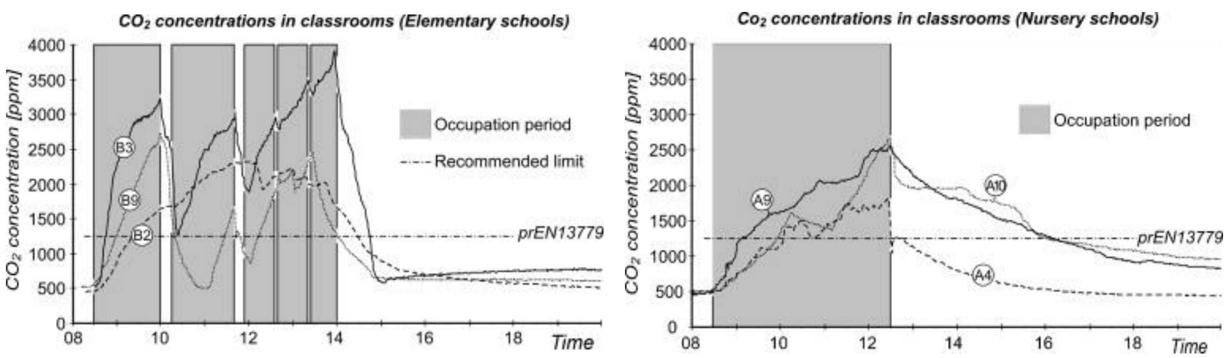
One of the European Union's priorities is to mitigate climate change, which is why the member states have been promoting the introduction of energy efficiency measures and the use of renewable energy sources and reduced use of primary energy resources. The national energy guidelines foresaw a reduction of specific thermal energy consumption of up to 195 kWh/m^2 per year from 2007 to 2016. Moreover, by continuing the energy efficiency improvement measures it was expected to reach 150 kWh/m^2 per year in 2020. The National Energy and Climate Plan 2021–2030 intends to reduce this amount to 120 kWh/m^2 per year in 2030.

State and municipal buildings need to set an example for households and promote energy efficiency measures under the EU Directive on the Energy Performance of Buildings. The directive has set the target for EU countries to make energy-efficient renovations annually in at least 3 % of buildings owned and occupied by central governments.

Indoor air quality and thermal comfort are important factors in designing high-quality buildings, planning and renovating existing buildings. Kamendere et. al. [7] have carried out a study on energy efficiency in two residential buildings illustrating the problem of ventilation systems in the aspect of indoor air quality. Commonly the desire to provide optimum, comfortable indoor air climate conditions is contradictory to the objective of reducing energy consumption. It is more challenging to ensure good indoor climate conditions in educational institutions and office buildings compared to residential buildings, due to higher human density on their premises. Pupils spend around 25 % of their daily lives in educational institutions, resulting in a large part of their youth in such circumstances. It is particularly important that rooms are provided with conditions that will not affect the comfort, health, mental faculties and opportunities of pupils and workers. Therefore, buildings in educational establishments are obliged to ensure optimum conditions for thermal comfort and air quality [8]–[10].

In energy-efficient buildings using only natural ventilation, it is very rarely possible to ensure decent air exchange in order to have adequate air quality and thermal comfort conditions on the premises. These buildings require ventilation units with heating and cooling elements. During the warm period of the year, it is necessary to discharge the heat caused by the sun radiation and internal sources. When the outside temperature is above the required room temperature, cooling systems must be used, whereas if the temperatures are lower, thermal comfort conditions are relatively easier to reach. The heating system must be able to react to the heat produced by the internal heat sources in order to regulate the amount of energy necessary to heat the room. The heat losses are higher in buildings where ventilation is regulated manually. During the heating season, careful control is required to reduce energy losses [9].

For example, a study in Greek cold climate zones in early childhood education institutions and primary schools points out similar energy efficiency and indoor air quality challenges, for instance, air exchange is provided by opening windows, air exchange equipment is often run manually and lacks controlled management, which leads to a high level of CO_2 (Fig. 1.1) [10]–[12]. People who stay for prolonged periods of time on these premises complain about the indoor climate [10].



a) b)

Fig. 1.1. CO_2 concentration in a) primary schools during classes and b) kindergartens [10].

Thermal comfort, indoor air quality and energy efficiency in buildings are considered to create a dilemma because energy efficiency, thermal comfort, and indoor air quality can lead to positive solutions. For example, a research in northern Italy shows that if the building facade is insulated and windows replaced, but no mechanical ventilation is implemented, savings are made, however, comfortable conditions still cannot be achieved. Large capital costs as well as funds are needed to cover operating costs [13].

1.2. Indoor Air Quality and Thermal Comfort in Energy-Efficient Buildings

A large part of the Latvian educational institution buildings built from 1940 to 1992 was constructed according to the building codes of the former Soviet Union. During this period, the supply of fresh air was used in natural ventilation through the gaps of the building windows and leaks in the ventilation slots. Between lessons, the windows were opened when necessary to ventilate the rooms, which ensured air exchange and was considered to be sufficient.

When performing the simplest energy efficiency measures in the buildings, the building envelope was insulated and the building windows were changed to plastic, which significantly reduced the supply of fresh air. This situation poses a risk to air quality and can be a cause for indoor microclimate problems [14].

Indoor air quality

Human breath contains carbon dioxide, consequently, the concentration of CO_2 indoors is greater than outdoors. For this reason, buildings must be equipped with ventilation systems to remove undesirable substances and odours, as well as to supply a fresh air. Ventilation capacity must be proportionate to the pollutants of the space. Air quality may be expressed at the desired ventilation level or level of CO_2 concentration.

As the CO_2 concentration increases, it may affect human well-being. A person starts to feel drowsy at a level where the concentration is between 1000 ppm and 2500 ppm. If it is in the range of 2500 ppm to 5000 ppm, it will start to have adverse health effects – increased heart and respiratory acceleration, signs of intoxication. At significantly higher CO_2 concentration values, i.e., 30 000 ppm, severe headache and nausea have been observed. At 50 000 ppm the person loses consciousness, and in the 100 000 PPM environment the outcome can even be fatal. The ASHRAE guidelines indicate that a human friendly indoor environment is one where CO_2 concentration is from 600 ppm to 1000 ppm [15].

Fisk's overview of air exchange and carbon dioxide concentrations in schools around the world [16] confirms the statement that CO_2 concentrations are not-conformant to the requirements. These measurements and study data indicate a widespread distribution of inability to provide the minimum amount of ventilation for classes as defined in standards. The concentration of CO_2, which often exceeds 1000 ppm, indicates that the air exchange in most cases is much lower than that prescribed in the building regulations. These results coincide with a number of studies (outlined in Publication 5) of excessive CO_2 levels in the schools. It can be concluded that public sector management is geared towards minimizing short-term expenses rather than providing a favourable environment [17].

Thermal comfort

Work or school environment in which a person spends his time has the ability to impact a person's well-being, improve work capacity or, conversely, create dismay and discomfort. The individual and environmental characteristics of the person determine the thermal comfort of a person [18].

The predicted mean vote (PMV) is the average value of a large group of people voting on a seven-point scale – the Fangler model. The PMV index can be calculated for different variations of activity levels, clothing, air temperature, average radiation temperature, airspeed, and humidity. This index is more often used for stable conditions, but it is also functional in dynamic conditions if the other measurement parameters are known at the given time.

The percentage of dissatisfaction or PPD index indicates the thermally dissatisfied part at a particular PMV value. Dissatisfaction can be caused by certain body parts' warming or cooling, commonly known as local discomfort. Daily and well-known types of local discomfort is the pull or draughts that create unpleasant sensations and health problems. Another example is the difference in vertical temperature between the upper and lower parts of the body, which can be caused by excessively cold floor or thermal radiation. People performing low intensity activities, such as carrying out physically light work, react more rapidly to local discomfort due to their body being close to the thermal balance [19]–[21].

Humans want to stay in a comfortable environment, thus, they have been working in order to create such an environment. It can be seen in the construction traditions around the world from the past up till now. One of the biggest challenges in building construction and renovation is the search for balance between energy consumption, indoor air quality, and thermal comfort. The main task of heating and ventilation systems is to give people satisfaction of their surroundings [22].

1.3. Feeling, performance, and Impact on Future Prosperity

The impact of air quality and thermal comfort on performance

The impact of CO_2 on human decision-making capability was addressed in an experiment in which the participants were located in an office in similar circumstances and were exposed to three CO_2 levels – 600 ppm, 1000 ppm, and 2500 ppm. The groups of people were under each of the air quality conditions for 2.5 hours, afterwards taking a computerized decision-making test and completing surveys of self-feeling. The concentration of CO_2 in the room was not disclosed to the participants. The results consist of nine categories – basic activity, applied activity, focused activity, task orientation, initiative, information orientation, information utilization, breadth of approach, and basic strategy [23].

In six categories, a much weaker ability is observed at CO_2 concentrations of 2500 ppm and a small improvement is visible for the focused activity (Fig. 1.2).

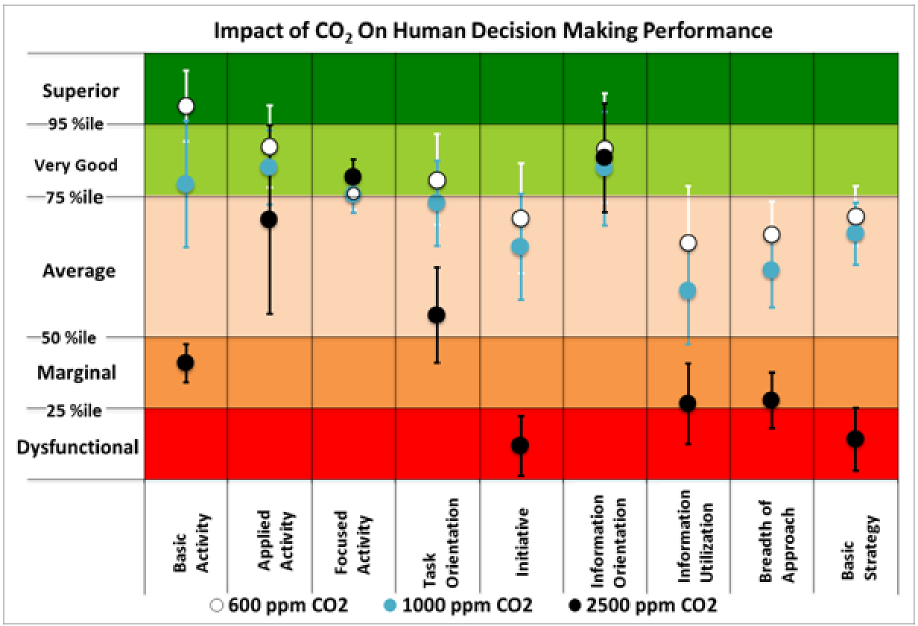


Fig. 1.2. The impact of CO_2 on human decision-making capabilities [23].

A model is created to predict human performance changes at various ventilation levels. It can be used for various occasions with high human density, such as schools and kindergartens. The performance dependency on the fresh air supply is represented in Fig. 1.3 [24].

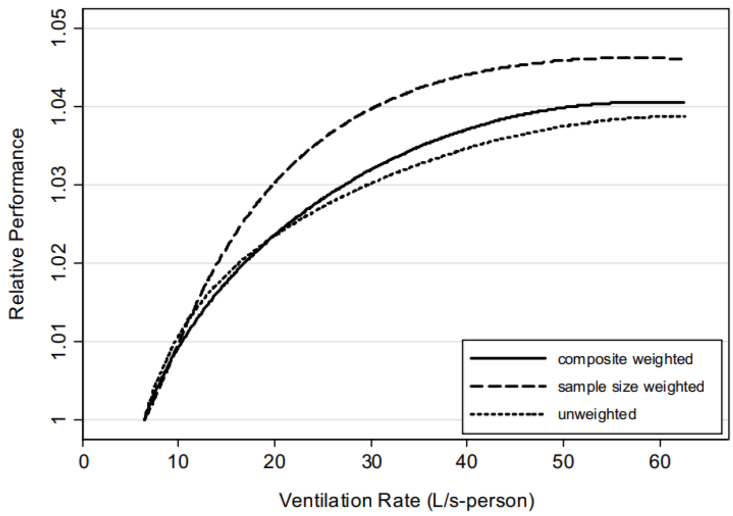


Fig. 1.3. The performance dependency on fresh air supply.

An improvement in performance can be observed with fresh air supply increasing to 45 L/s. At a certain amount of supply air, it is no longer possible to improve the quality of air in space, as the air received also has a certain concentration of pollution, thus achieving the optimum level of CO_2 (Fig. 1.3) [24].

Science and industry are continually offering new and innovative solutions for air conditioning, ventilation, and other indoor climate control. These products help to provide a better environment for people, which can have a positive effect on human health, safety, and productivity. However, the desire to ensure optimal and comfortable climatic conditions is contrary to the objective of reducing energy consumption [25].

Impact on national well-being

Academic performance during studies correlates with the income level after graduation. The study in the United Kingdom points out that it is important from a political perspective to understand the impact of qualifications in the labour market. The results show that 1 % of pupils who leave school at age 16 without any qualifications do so at a high economic cost to themselves and society in terms of lost output. Another conclusion is that even modest improvements in General Certificates of Secondary Education deliver larger returns so there is a strong economic imperative that all children fulfil their educational potential [26]. Italian scientists conclude that employees with tertiary education have steeper experience and earnings increase than employees with upper secondary or lower education. Research showed that education offers not only a preliminary labour market advantage but also a permanent advantage that increases with time in the labour market [27]. OECD report about Baltic countries shows a better earnings increase for more educated employees [28]. Academic performance in high school is important for short term goals, such as college admission, but the study in the USA clearly demonstrates a link between high school GPA and labour market earnings many years later. An increase of one point in high school GPA raises annual earnings in adulthood by around 12 % for men and 14 % for women. The findings show that people with better grades were more likely to keep studying after high school. The results of the study show that high school GPA is a significant predictor of educational attainment and earnings in adulthood [29].

The income of educated persons and added value that they create to the national economy has an impact on the Gross Domestic Product (GDP), thus, every country has to pay attention to the quality of all levels of the education system. The Human Capital Index by the World Bank measures the consequences of neglecting investments in human capital in terms of the next generation's lost productivity. The analysis suggests that the workforce of the future in countries with the lowest human capital investments will only be one-third to one-half as productive as it could be if people had good health and received a high-quality education [30].

1.4. Prosumers

Ventilation and conditioning systems can use the energy provided by solar radiation, thereby increasing the use of renewable resources and compensate costs. Shipkov et al. have indicated that solar energy can be used to reduce the required amount of energy for cooling in Latvian climatic conditions as well [31]. The experimental results from Aguilar et al. in Spain indicate that, during the summer months, the benefits of solar panels are approximately 65 % [32]. Air conditioning is important for optimal maintenance of indoor microclimate, enabling solar energy to be used to ensure optimal conditions not only in offices but also in educational institutions.

Energy transition has three main objectives: to increase energy efficiency, to deploy renewable energy, and most importantly to reduce GHG emissions. Prosumers [33], [34] can be the main players of a more decentralised sustainable energy system by fulfilling part of their energy needs through self-produced energy with renewables.

Worldwide PV prosumers form a significant part of the total installed solar PV capacity and the trend is rising. Interest around solar photovoltaics had been growing everywhere, since product innovation and performance improvements give consumers a greater choice. It is also beneficial that the costs for these systems continuously decrease. The PV prosumers might be one of the main players in energy transition because they consume most of the generated electricity and the grid is fed less by additional electricity. PV prosumer systems must include electricity and heat storage technologies in addition to heat pumps to accomplish the highest possible self-consumption shares [35].

2. THE METHODOLOGY USED IN THE STUDY

This chapter describes the methods used in the study. They are presented in detail in publications in scientific journals and at international conferences. References to the publications (see list of publications on page 5) are used throughout the chapter. The study uses a variety of research methods, including mathematical modelling by system dynamics method, measurement, and interviews in real sites, as well as cost-benefit method.

2.1. Indoor Air Quality and Thermal Comfort in Energy-Efficient Buildings

The assessment of indoor air quality and thermal comfort in energy-efficient buildings was carried out using indoor measurements and interviewing users of the premises. Measurements were taken in buildings administrated by Liepāja – three pre-school education institution buildings, two school buildings, municipal police building, administrative building and museum building. The study is presented in Publications 2 and 3.

Indoor air quality and microclimate measurements

The interviews with building managers or relevant responsible persons were done in order to get an overview of the buildings and to obtain the data necessary for later calculations. In all buildings except buildings F and G, two rooms were selected in which the measurements were performed. Each building was assigned a single letter identifier, whereas the rooms were marked with numbers. In order to understand the overall state of the building, rooms were chosen following the ventilation system design, in such a way predicting potentially good or bad climatic conditions, in which the measurements were taken for 7 days. After surveying the buildings in person, renovation works as well as usage habits of ventilation systems were assessed. Windows have been changed in all buildings and in the majority, the envelope has been insulated and ventilation systems have been installed. In only one of the buildings (educational institution D) the ventilation system operates on a scheduled scale, the other buildings are operated manually after a subjective assessment. These systems consume electricity, thus resulting in operating expenses. For this reason, the equipment is operated less frequently than expected. Building managers try not to operate ventilation units during the winter period.

Measurements in all objects were made in a unified framework to obtain uniform, reliable, and comparable parameters of the thermal environment. When assessing the indoor climate, the operating environment is specified – 0.5 m from the walls and 1 m from the windows [36], [37]. The area of activity in institutions and office buildings is defined in the height of 0.1 m to 1.1 m from the floor [37]

In Publication 2 for the fixation of indoor climate measurements, Delta Ohm HD 32.1 was used in the framework of the study. The device was operated in A mode. The following measurements were obtained with the probe mounted on the rack [38]:

- globe temperature t_g,°C;

- wet bulb temperature t_{nw},°C;
- air temperature t_a,°C;
- atmospheric pressure p_r, hPa;
- relative air humidity, *RH*, %;
- air speed v_a, m/s.

The parameters were recorded every 5 minutes.

Tracer gas technique

In Publication 2, a tracer gas technique was used to determine the air exchange rate. This method allows determining the location and extent of leakage, the efficiency of ventilation and the air exchange rate. For the measurement sulphur hexafluoride SF_6 and the device LumaSense Technologies INNOVA 1303 were used for the determination of the gas concentration. A concentration reduction method was used in the study to determine the air exchange rate [39], [40]. During the study, a small amount of sulphur SF_6 was injected into the room and a steady mixing was ensured in the air. The tracer gas supply was discontinued and measurements of the gas concentration level were made for 30 to 40 minutes at one-minute intervals. During the test, there were no humans in the premises and the ventilation system was not working in order to illustrate the real air exchange rate indoors when not mechanically ventilated. The exponential reduction in the concentration of the tracer gas and the air exchange was determined as stated in Publication 2.

Concentration of CO_2 in the rooms of educational buildings

The concentration of carbon dioxide in the air was chosen as an indicator of indoor air quality in Publication 2. Measurements in each room were taken for one week to determine the dynamics of the parameter. In order to determine the concentration, *Telaire 7001 CO_2 Sensor* device was used and data logger *HOBO U12* was used for recording the measurement results. The concentration of CO_2 was stated every five minutes.

Blower door test

The blower door test was performed and is described in Publication 2, which is a commonly used method that helps to detect leakage in small buildings or parts of them. To carry out the test, the pressure in the room was increased to 70 Pa and further, adjusting the fan speed by 5 to 10 in successive decrements. In the calculations, the density of the concerned space and its need for mechanical ventilation operation was determined.

The predicted mean vote

In all the premises considered in Publication 3, a survey was carried out at the time of measurement to ascertain the subjective views of people about the microclimate of the room. Each participant had to evaluate the comfort level by *Fanger* scale from –3 to +3. All air parameters were recorded at a given time so that further calculations could be made. The level of performed activity and the thermal resistance of clothing was also assessed for subsequent calculations [41]. The predicted mean vote (PMV) values were calculated using the air parameters fixed during the survey.

Impact of thermal comfort on people productivity

The productivity loss model of Kosonen was used in Publication 3 in order to determine the impact of the building's microclimate on human performance [42]. It should be taken into account that the model is based on experimental data and, thus, has practical limitations. The model can be used under the same conditions as obtained – PMV value is in the range from –0.21 to +1.28. The author points out that if the PMV value is lower than the model use range, a linear relationship is observed between the PPD percentage and the performance loss. That means that human performance in performing thought tasks deteriorates by a percentage equivalent to PPD. In contrast, the percentage of writing performance loss is equal to twice the PPD value [42].

Impact of ventilation capacity on people productivity

A lot of studies confirm the impact of ventilation rate and air quality on people's well-being and performance. Seppänen has created a model for predicting human performance changes at various ventilation levels [43]. The model is built on the basis of aggregated results from several studies. It was used in Publication 3 to determine the expected person's performance at a variety of fresh air supply volumes.

Each room has suitable four ventilation capacity scenarios to determine the effect on human performance in Publication 3:

- Scenario 1. Fresh air supply is 5 L/s per person. It defines the requirement for an air supply rate of 15 m^3/h for a person, or 4.17 L/s, specified in Cabinet Regulation No 310.
- Scenario 2. Fresh air supply of 10 L/s per person. It defines the ventilation rate that is a bit higher than specified in ASHRAE guidelines at human educational establishments.
- Scenario 3. Fresh air supply 15 L/s per person.
- Scenario 4. Fresh air supply for 30 L/s per person.

Economic benefit analysis of ventilation productivity gains

During the study (Publication 3), ventilation systems had been already installed in all buildings (except building C). Only one of the rooms had a local exhaust in building F, so the installation of a new ventilation system was included in the calculations.

There are shorter or longer periods during the summer in educational institutions in which ventilation units do not need to be operated. In the case of schools (buildings D and E) and pre-school education institutions (buildings A and B), on average, the work is going on for 186 working days per year and in building C – 230 days. In other municipal buildings the work goes on for 250 days a year. The working time of ventilation units is an important factor to estimate power consumption [44]. The study used the teaching costs approved by the municipality [45], [46].

In consultation with the designer of the practising ventilation system [47], the cost of introducing new equipment was determined where needed. A KOMFOVENT VERSO programme [48] was used to apply air exchange unit equipment.

Cost-benefit analysis

By reconstructing the buildings of educational establishments making them prosumers it is possible to reduce greenhouse gas emissions, ensure renewable energy consumption, and promote energy efficiency so that a high level of indoor air quality is ensured at the same time. The cost-benefit analysis was done for a typical Latvian educational building in Publication 6. Various photovoltaics and wood pellet boilers were proposed to find the best scenario for educational building's transformation from consumer to prosumer.

The assessment of the electricity produced is described in Publication 6. Electricity will be fed into the grid on weekends (the produced electricity that covers around 6 days per month) and variable part was calculated from overall monthly production.

The average monthly electricity bill was calculated before and after installing the solar panels of various power. The electricity tariff is made by the sum of electricity price, fixed distribution tariff, variable distribution tariff, fixed mandatory procurement component (MPC) tariff, variable MPC tariff, and value-added tax. The values used for the calculations are given in Publication 6. Grid-connected electricity producers (over 11 kW) are considered as a single power plant connection so it can sell electricity by feeding it in the grid and afterwards receive it back from the distribution system by buying it. In calculations, the electricity price is considered constant for selling and buying operations. The variable MPC tariff is considered only for the amount of electricity that is taken from the grid. The capital and maintenance costs are provided in Publication 6.

For the energy-efficient school building of 5140 m^2, the proposed solution for heating and hot water supply is a wood pellet boiler (400 kW η =0.92) with pellet container and auger for automatic supply of pellets from the container to the burner. Wood pellet (4.8 kWh/kg) consumption per year is estimated to be around 75 tons. The capital and maintenance costs are provided in Publication 6.

The calculation of CO_2 emission reduction is made by using CO_2 emission intensity in Latvia and data from potential amounts of electricity production in 25 years.

2.2. System Dynamics Modelling

The study used system dynamics modelling. This method of mathematical modelling was developed by Forester in 1961 [49]. It is used to analyse cause-and-effect interactions in complex and dynamic systems with delays, feedback and variables linking non-linear relationships. This mathematical modelling approach is used to study complex system dynamics with feedback, nonlinearities, and delays. Stocks and flows are key elements of the model. Stocks are filled or emptied over time by incoming and outgoing flows. The structure of a system stocks and flows helps to carry out a quantitative analysis. Analysis of causal loops helps to understand the structure of the system feedback and explain the causes of dynamics, the mental patterns of their creators and determine the feedback that is responsible for the problem. *Powersim Studio 10* has been used as a software tool to simulate building stock and flow structure and system behaviour. As part of the work, a system dynamics model was created the original version of which was supplemented with additional modules in the course of the work. The main modules of the model are shown in Fig. 2.1.

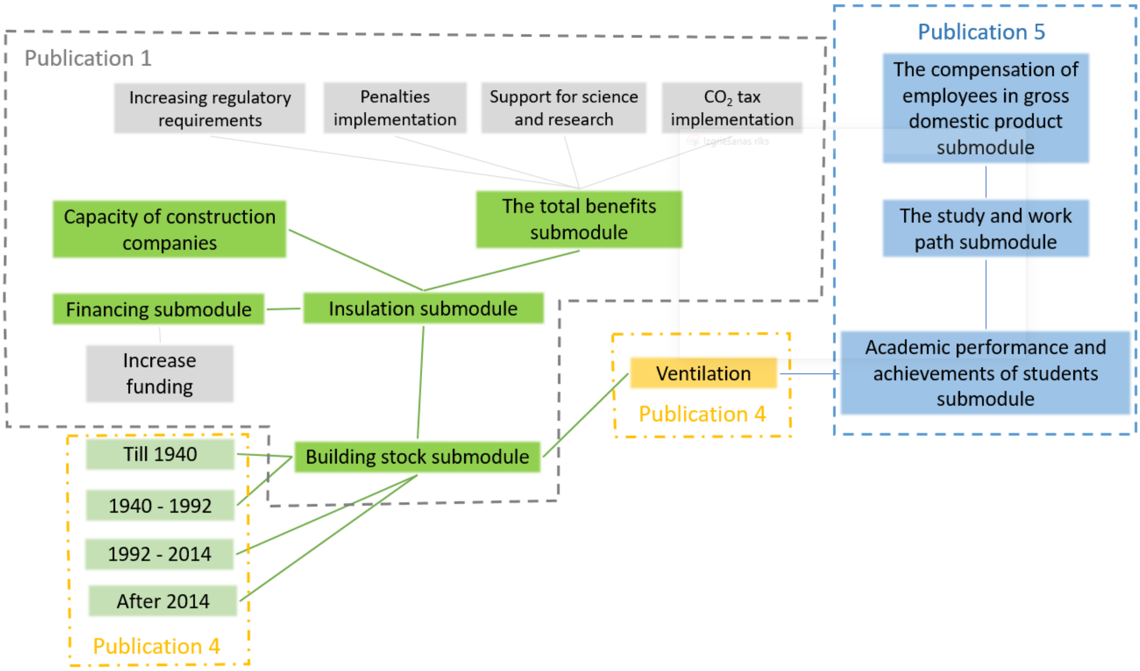


Fig. 2.1. Main parts of the model.

Introduction of energy performance in government and municipalities owned buildings is described in Publication 1, showing the main submodules of the model and their interaction. Energy efficiency – indoor air quality dilemma in buildings is described in Publication 4, dividing the building stock by construction period and introducing ventilation after implementing energy efficiency measures. Educational institutions' building system dynamics model is described in Publication 5 reflecting the impact of energy efficiency – indoor air quality dilemma, in buildings on gross domestic product. The representation of submodules is in Section 2.2 of the Doctoral Thesis.

The model dynamics and behaviour are explained by a causal loop diagram. Three main causal loops are the base of the model – one reinforcing and two balancing loops (Fig. 2.2). Reinforcing loop R starts to work if financing for energy efficiency measures is provided. This, in turn, will increase the energy performance of buildings and GHG reduction rate. The higher the energy performance of buildings (in the case when energy efficiency of the building envelope is improved), the higher the airtightness of buildings and the higher is the need for mechanical ventilation. Operation of ventilation systems will provide higher indoor air quality, thus, having a positive impact on students' academic performance and achievements. It will reduce the fraction of low skilled workers in the population and increase the amount of high skilled worker salaries that constitute a part of the GDP. The higher the GDP, the higher is the financing rate allocated for energy efficiency measures in public buildings.

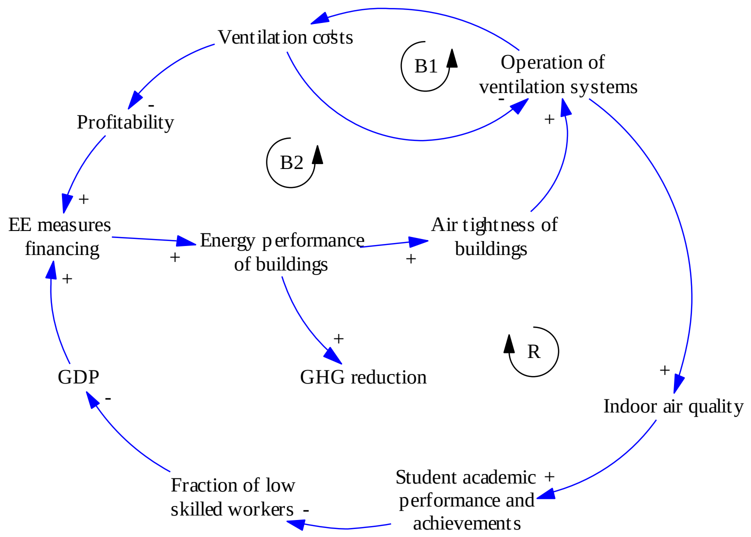


Fig. 2.2. Causal loop diagram.

The behaviour generated by reinforcing causal loop is balanced out with balancing loops B1 and B2. B1 loop shows that if the operation of ventilation systems increases, the energy and operation and maintenance costs also will increase. The costs are high, which leads to reduced working hours of ventilation systems; therefore, lowering of indoor air quality leads to decreased students' academic performance and achievements. The decreased academic performance and achievements, in turn, increase the fraction of low skilled workers in the population and reduce the amount of 'wages' that constitute a part of GDP. The lower the GDP, the lower is the financing rate allocated for energy efficiency measures in public buildings.

The second balancing loop B2 is affected by the growth rate generated by the R loop. The higher the ventilation costs, the lower is the profitability of energy efficiency measures and the the financing rate. Low funding limits building energy performance improvement and GHG reduction, therefore, lowering the need to operate mechanical ventilation systems and cover its costs.

Model validation

The main problem of many modelling studies is the availability and quality of the data. The data generated by the model shows only the trend and does not represent accurate figures, as a result there are no models that perfectly represent the system being studied. The availability of data is not essential to create a good system dynamics model, as Barlas has already explained [50], while Sterman argues that full model testing and validation is not possible [51]. Models are simplified versions of the real-world, and they differ infinitely from reality in a larger or smaller way. Purely analytical assertions and proposals derived from a closed logical system are the only statements that can be confirmed or proved to be true [51].

An important part of the research is testing and validation of the model. All parameter units, their connections and input formulas have been tested. Verification tests, sensitivity testing, parameter verification testing, extreme policies, and extreme condition tests were also carried out [50].

Structural and behavioural testing was carried out throughout the modelling process using statistics and literature data. To build confidence in the model, a historical behavioural validation test was used for study and work pathways, including the salary part of GDP.

Implementing energy efficiency measures in government and municipality owned buildings

The study of the market dynamics of the energy efficiency of state and municipal buildings has been carried out in Publication 1. The system dynamics model of introducing energy performance in government and municipality-owned buildings consists of four submodules: insulation process, total benefits, financing, and capacity of construction companies.

Policy instruments are representatives of the planned action, which entail a change in the functioning of the common system. Five policy instruments were developed to create an impact on the pace of thermal energy efficiency of government and municipality-owned buildings. By investing in science and research, building improvement materials have become more energy-efficient and their life span is longer, hence energy consumption and cost savings can be achieved. This makes a change to the functioning of the system, where additional funding for scientific and research development is foreseen, with a 15 % increase in total energy cost savings. With a CO_2 tax increase of heat tariff, the benefits of energy efficiency measures will be increased and the rate of insulation affected. The improvement of regulatory requirements is involved as an achievable indicator of energy consumption after taking energy efficiency measures. The sanction system implies that, without achieving the long-term objectives of the strategy for improving the energy efficiency of government and municipality-owned buildings, it is required to pay a fine for each m^2 of heated area. The funds obtained may be combined into a common fund intended to improve the energy performance of buildings. The additional funding from external funds aims to increase the resources available to create a faster pace of deployment of energy efficiency measures in buildings.

Energy efficiency – indoor air quality dilemma in buildings

Energy efficiency – indoor air quality dilemma in buildings was analysed in Publication 4. It is based on the system dynamics model that is made complementing the model described in Section 2.2 of the Doctoral Thesis (Publication 1). The total building stock was divided into four parts based on the construction periods. The first part included historic buildings built before 1940. Most of these buildings have heritage value, and a limited set of energy efficiency measures can be used. For example, since exterior wall insulation is not possible, internal thermal insulation should be used. The second part is buildings built between 1940 and 1992. They are built according to the building codes of the former Soviet Union. The third part includes buildings built between 1992 and 2014. The last group of buildings, built after 2014, is intended to be low energy consumption buildings [52].

It is assumed that only natural ventilation with an air exchange rate of 0.7 h^{-1} was performed before the introduction of energy efficiency measures. After carrying out energy efficiency measures, the average air exchange rate of 4 h^{-1} generated by mechanical ventilation is used for simulation. For Latvia’s climate, the specific energy consumption after the introduction of energy efficiency measures is 9 kWh/m^2 per year for air supply and 4 kWh/m^2 per year for electricity with a heat recovery efficiency of 80 % and a specific fan capacity of 1.25 kW/(m^3/s) operating for 12 hours on weekdays.

The model is complemented with the profitability ratio. Profitability also affects the performance of the model: the higher the likely profitability, the greater is the share of funding allocated to this group of buildings. Funding is granted to different submodules of groups of buildings based on profitability ratio that shows the energy saved during the lifetime of energy efficiency measures per euro invested. Logit function is used to split funding.

Model of system dynamics in educational institutions

Publication 5 investigated the energy efficiency – indoor air quality dilemma impact on gross domestic product. This study was based on the model described in Section 2.2 of the Doctoral Thesis (Publications 1 and 4). It is complemented with three submodules: student academic performance and achievements, study and work path, compensation of employees in gross domestic product.

The structure of the general submodule for students' academic performance and achievements is shown in Publication 5. This structure is used for different education levels and different grades. The number of students at a particular education level is accumulated in stocks by the average results. Stock 'Students that begin with grade *X*' either can stay in the same stock for all duration of education in particular education level or can move to stock 'Students that end with grade *X* + 1'. The first stock is regulated by one inflow and two outflows. The inflow 'Entrance rate' is the number of students entering a certain education level every year. The outflow 'Graduation rate with grade *X*' is the number of students who graduate annually with grade *X*. The outflow 'Rate of students who changed grades' is also the inflow for the second stock and depends on the ventilation supply air rate, which has an impact on the academic performance of students. Two ventilation regimes are used in the simulation (3 m^3/h per person using natural ventilation and 36 m^3/h per person with mechanical ventilation). The academic performance increases by 2.7 % for every L/s per person based on [53]. If the current grade is *X* and ventilation is poor and does not increase until a certain level, the student will graduate with grade *X*. If ventilation rate increases more, the student moves from the stock with grade *X* to the stock with grade *X* + 1 and the student will graduate with grade *X* + 1.

This study and work path submodule include an ageing chain of life path from birth through pre-school, elementary school, secondary school, university, work, and, finally, retirement. The stock and flow structure for this submodule is shown in Publication 5. People enter the system via birth rate and accumulate in preschool stock. After that, they move to elementary school. Elementary school graduates may decide to discontinue studies and enter the labour market as low-skilled labour or to continue studies in secondary schools or professional schools. After graduation from secondary vocational education, they can enter the labour market as medium-skilled employees or continue their studies at university.

University graduates enter the labour market as qualified labour. Both secondary school graduates and university graduates are split into subcategories based on their grades.

The gross domestic product (GDP) is measured by the income approach. Total GDP value is calculated as the sum of compensation of employees, gross operating surplus, gross mixed income, taxes minus subsidies on production and imports. In this study, compensation of employees and its impact on GDP is modelled. Compensation of employees includes total remuneration to employees for work done such as wages, salaries, and employer contributions to social security.

Generic submodule of compensation of employees in the gross domestic product is presented in Publication 5. Annual income (salary plus employer contributions to social security) of different labour groups described in the study and work path submodule is changing by the net rate of annual income change. The net rate of annual income change is annual income of particular labour group times fractional annual income change rate (statistic data input is 3 %). Annual income is multiplied by the number of people in the particular labour stock. All groups are summed up to produce the total compensation of employees, which is part of total GDP value. The input data for the model is described in Publication 5.

Simulation scenarios

Six scenarios were simulated (Table 2.1) in which differences were defined for the air change rate and financial resources available for energy efficiency projects. If a building only has a natural ventilation system or it has a mechanical ventilation system that is not operated due to high energy costs, the air change rate is assumed to be 0.5 h^{-1}. If a building has a mechanical ventilation system and it is operated during working hours, the air change rate is assumed to be 6 h^{-1}.

Table 2.1

Simulation Scenarios

	Air change rate in buildings without energy efficiency improvements, h^{-1}	**Air change rate in buildings with energy efficiency improvements, h^{-1}**	**Investments in energy efficiency measures**
Scenario 0 (base scenario)	0.5	0.5	National energy efficiency programs available until 2022*. No further funding available
Scenario 1	0.5	6.0	National energy efficiency programs available until 2022*. No further funding available
Scenario 2	0.5	0.5	National energy efficiency programs available until 2022*. After that 2 million EUR per year funding available
Scenario 3	0.5	6.0	National energy efficiency programs available until 2022*. After that 2 million EUR per year funding available
Scenario 4	0.5	0.5	Additional 130 million EUR per year from national and municipal financing sources
Scenario 5	0.5	6.0	Additional 130 million EUR per year from national and municipal financing sources

*National funding scheme allocated for energy efficiency improvements in state-owned buildings from 2016 to 2022 with a total amount of 115.1 million EUR.

3. RESULTS

3.1. Indoor Air Quality and Thermal Comfort in Energy-Efficient Buildings

The measurement results of indoor air parameters are summarised and described in Publications 2 and 3. They confirm that the ventilation equipment of most studied buildings is operated only as necessary.

The air is noticeably warmer in classrooms with more pupils and that are located on the sun side. Taking into account the level of activity, the ambient temperature must be between 19 °C and 25 °C, following Cabinet Regulations No. 359 [54]. Temperature measurements carried out on the premises of educational institutions showed that in most cases it does not fit within the specified temperature range (Fig. 3.1), approximately in half of the rooms it periodically tends to fall below the minimum value, and in one room, the temperature is markedly higher.

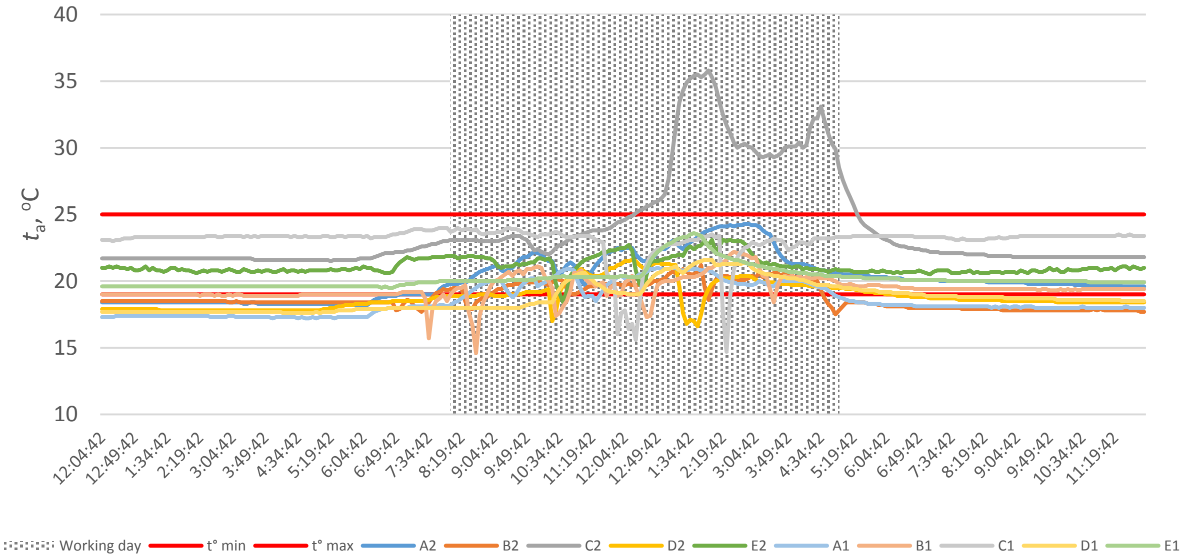


Fig. 3.1. Temperature changes t_a in the education institution rooms during the day.

In one of the studied rooms, at the beginning of the day the temperature was below the optimum and only after the first few hours, when the premises were occupied by people, it reached the norm. In another room, the temperature was too high and the ventilation regime by opening windows a few times a day created only a temporary effect, thus not providing optimum air exchange. This refers to improper use of the building as energy efficiency measures reduced natural air exchange, which cannot be manually compensated.

Measurements of relative humidity in buildings showed that in most cases they are between 30 % and 70 %. Two rooms are exceptions, wherein in one room humidity tends to rise above the norm, and in the other falls below the minimum level.

The study also measured the air movement speed and the results show that they are low, therefore have a small impact on the perceived air quality and thermal comfort (Fig. 3.2). The exception is Room 1 of building B, the air movement speed exceeds the permissible value many times a day.

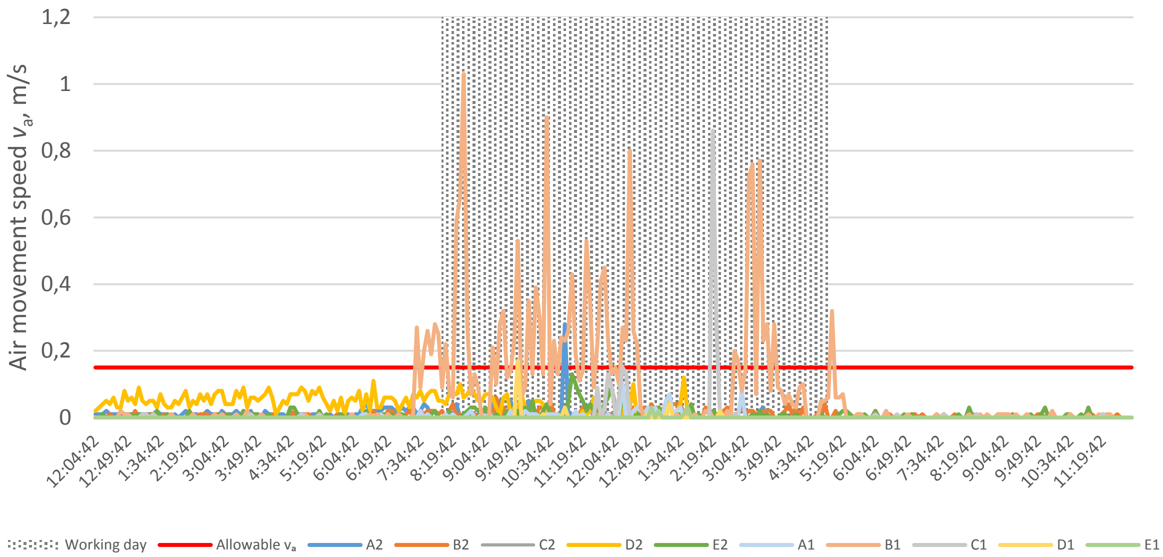


Fig. 3.2. Air movement speed v_a in the educational institution rooms during the day.

Given the temperature drops observed in Fig. 3.1, it can be concluded that rooms are frequently ventilated by opening the windows. The study did not reveal long-term, high values in other rooms, leading to the conclusion that the ventilation systems were operated intermittently or not at all.

According to the ASHRAE guidelines [15], the level of CO_2 concentration in the range of 600 ppm to 1000 ppm is considered to be safe indoor air. Also, after the EN 13779:2007 [36] CO_2 mark up to 1000 ppm is considered optimal.

Measurements in buildings (Fig. 3.3.) showed that all buildings, for a shorter or longer period of time, have elevated CO_2 levels. Both employees and learners may experience drowsiness and fatigue if they stay for prolonged periods of time in such conditions of increased CO_2 concentration, which can have a negative impact on the quality of the studies.

In most cases, CO_2 concentration does not match good air quality during working hours and only decreases at the end of the day and falls into the optimum level of CO_2 concentration (below 1000 ppm). The observed short-term and sharp decreases in CO_2 concentrations, after which concentrations increase rapidly, indicate that the rooms are ventilated by opening the windows. Thus, the exchange of warm room air and cold air with lower CO_2 concentrations is carried out. It requires additional heat to warm the outdoor air. The ventilation scenarios for opening the windows indicate the short-term effect. Study rooms are of insufficient air quality and independent ventilation is required to ensure satisfactory air quality parameters in the premises.

Most of the ventilation units are operated only as necessary, as identified by interviewing employees and confirmed by the subsequent measurement results presented in Publications 2 and 3.

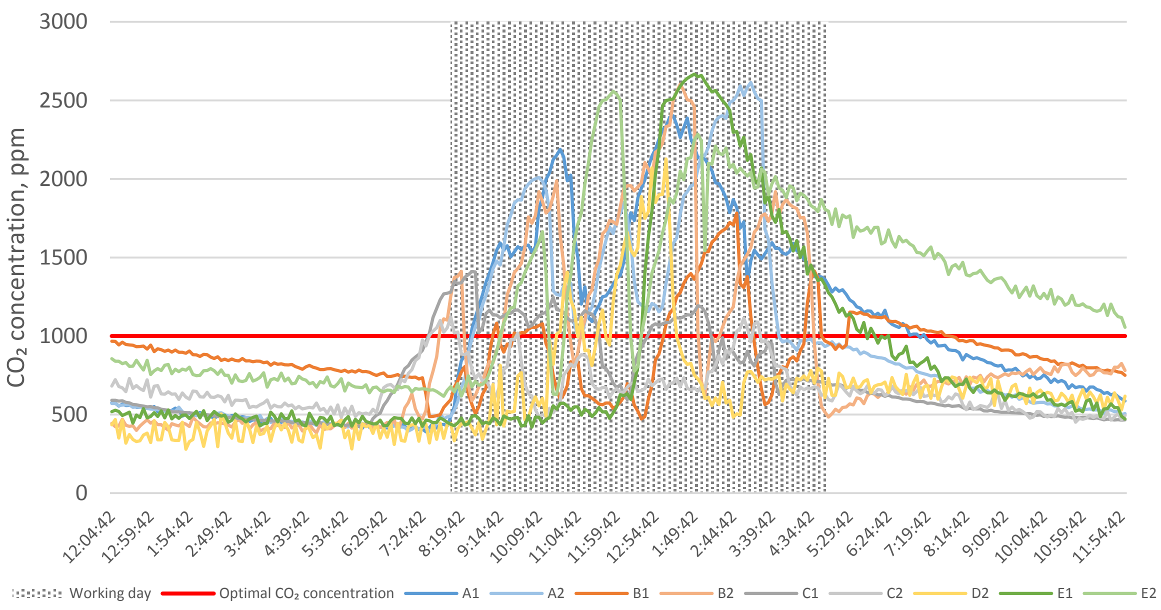


Fig. 3.3. Changes in the level of CO_2 concentration in educational institution rooms during the day.

Air exchange rate and air supply

Tracer gas concentration in pre-school educational institution A, Room 1 in 20 minutes decreased by only about 15 ppm. In this room the air exchange rate was 0.32 h^{-1}, so the air changed in the room only about once in three hours.

The estimated air exchange rates for each room are shown in Fig. 3.4. In high school buildings (D and E) the figures are the lowest in one of the rooms – 0.19 h^{-1} and 0.22 h^{-1}, respectively. Rates are slightly higher in pre-school educational buildings – at least 0.27 h^{-1}. The best air exchange is in buildings G and H, where only 1 to 3 people are present. The results correlate with the above measurements of CO_2 concentrations – the concentration at the end of the day decreases very slowly.

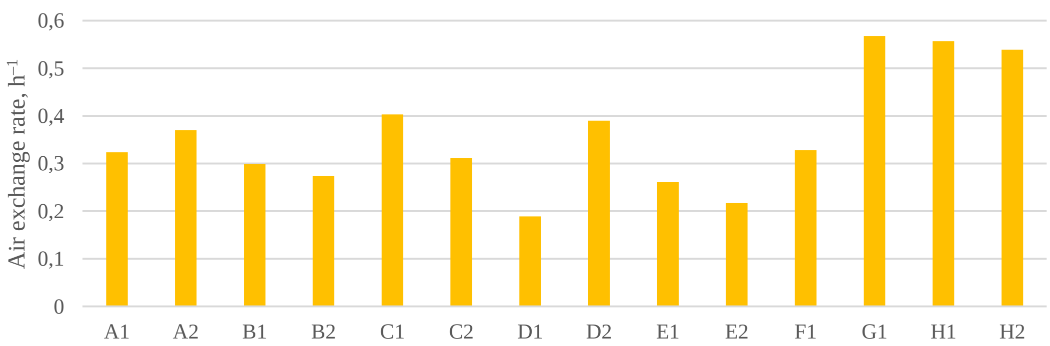


Fig. 3.4. The results of an air exchange rate calculations.

Using the results obtained from the measurement of the tracer gas, the amount of fresh air supply per person was calculated (Fig. 3.5). The values obtained in all educational institutions do not meet the requirements of Cabinet Regulation No. 310 [55]. In other municipal institutions, the amount of fresh air supply is somewhat higher, but the sufficient air supply is only in the legal entity in which it is used.

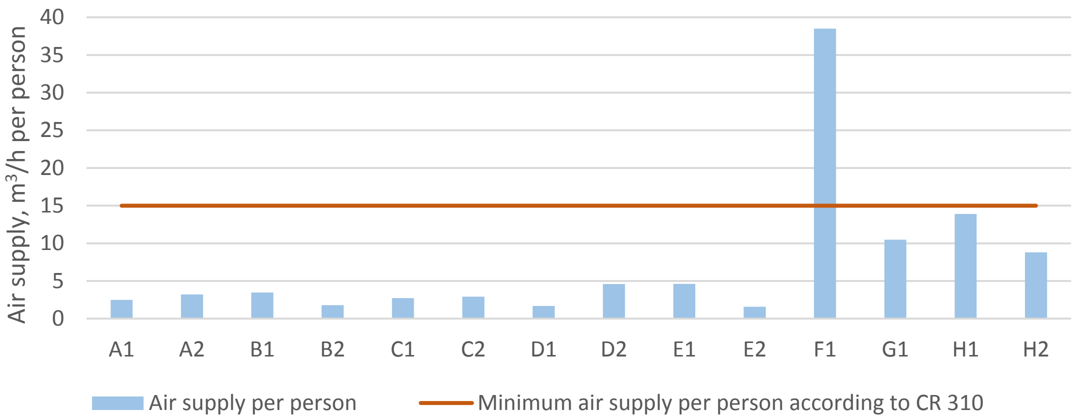


Fig. 3.5. Air supply per person.

The amount of fresh air in the room indicates a critically low performance confirming the observed carbon dioxide results that regular fresh air supply is not provided indoors.

Air leakage

During the blower door test, the airflow readings were recorded. To determine the air exchange rate for the room at 50 Pa and 4 Pa differential pressure the resultant airflow is used. This data allows to analyse the density of the premises concerned and gives an understanding of the tightness of the building. Given the guidelines for the use of the test device and the interpretation of results [56], most educational establishments are assessed as medium-dense and may require mechanical ventilation.

The predicted mean vote

Using the fixed air parameters in the survey, PMV values were obtained by the Fangler model. The dispersion of the average subjective and estimated PMV values is illustrated in Fig. 3.6.

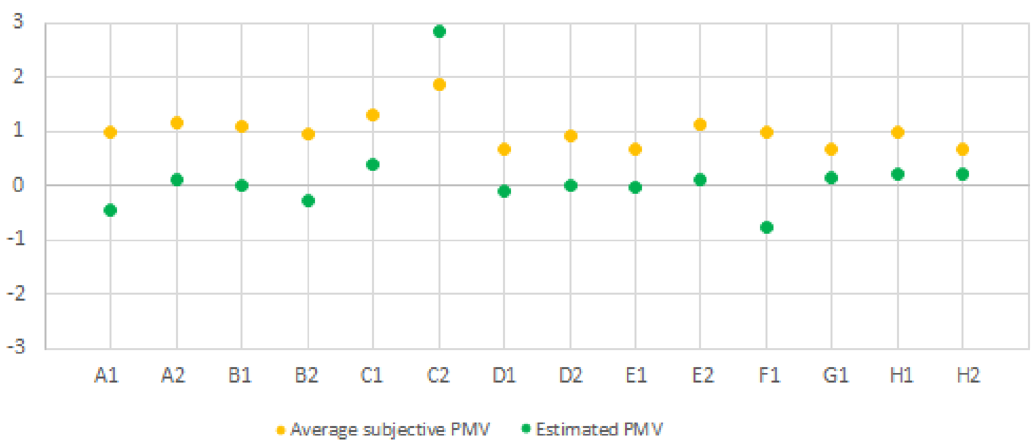


Fig. 3.6. Average subjective and estimated PMV.

In almost all cases, the assessment of human surveys is higher than estimated. People in a particular room feel warmer than the model has estimated. The subjective assessment of Room 2 in building C is somewhat lower than that of the model, although both results are characterised by the hot and unsatisfactory environment.

According to the EN 15251:2007 standard the renovated buildings should provide the level of air quality in category II. For this to be realised, the predicted mean vote should be between –0.5 and +0.5. The estimated PMV values are appropriate in most cases [57].

Impact of thermal comfort on human performance

The calculation of potential performance losses is summarised in Table 3.1. In Room 2 of building C according to the model chosen the numerical value of performance loss could not be obtained, since the PMV index was too high – 2.86. However, it is possible to assume that the losses of thinking and writing exercises would range from 30 % to 35 %, since the effect on human performance becomes constant after the PMV value of 1.28. The results of the first rooms of buildings B, D, and E, which have been studied, provide the best conditions for carrying out work with little physical exertion [42]. The results were based on thermal conditions at specific times in the rooms concerned and the level of activity, although air quality and factors influencing it were not taken into account. The results obtained have an illustrative significance.

Table 3.1

The Effect of Thermal Comfort on Performance Loss

Room	Calculated PMV	PPD, %	Thinking exercises performance losses Y_d, %	Writing exercises performance losses Y_r, %
A1	–0.46	9.4	9.4	18.8
A2	0.13	5.4	3.9	9.9
B1	0.01	5/0	2.0	5.2
B2	–0.28	6.6	6.6	13.2
C1	0.41	8.5	9.9	22.8
C2	2.86	98.3	–	–
D1	–0.10	5.2	0.7	2.2
D2	0.02	5.0	2.2	5.6
E1	–0.02	5.0	1.6	4.3
E2	0.12	5.3	3.7	9.4
F1	–0.77	17.5	17.5	35.1
G1	0.14	5.4	4.1	10.3
H1	0.22	6.0	5.6	14.0
H2	0.21	5.9	5.4	13.5

Impact of ventilation productivity on human performance

After the tracer gas measurements in Publication 2, the air exchange and the supply of fresh air to a person in each of the rooms was clarified. In Publication 3 calculations were made to determine how the expected person’s performance in different volumes of air supply changes. It is visualized in Fig. 3.7.

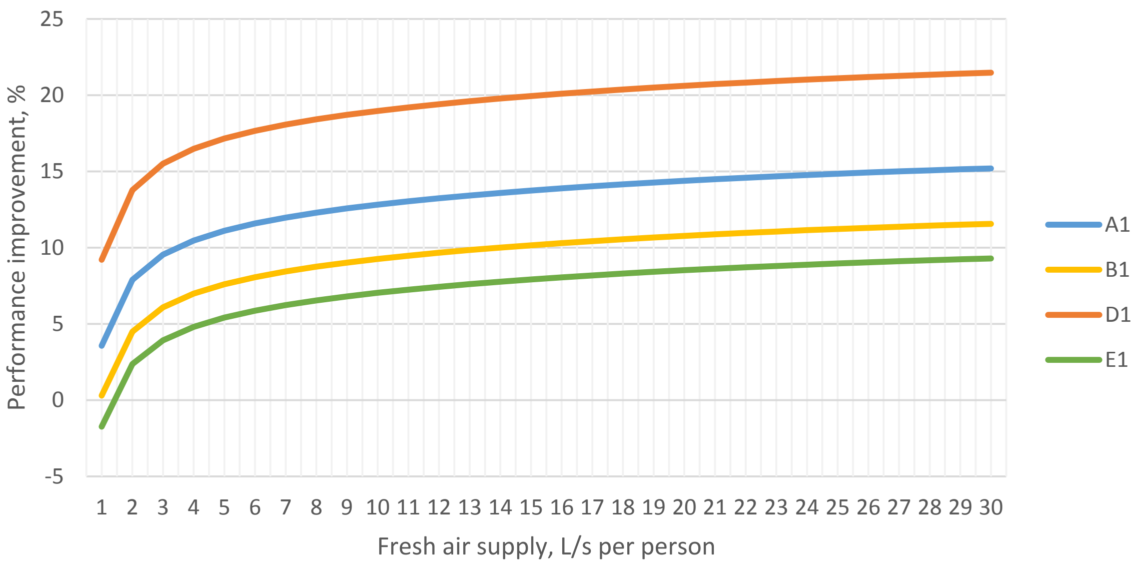


Fig. 3.7. Performance improvement depending on the supply of fresh air to the human.

Human performance is most influenced by the supply of fresh air when it is raised from the lowest value. The improvement in mental working capacity in four of the buildings included in the study is shown in Fig. 3.7. The fastest change is observed by changing the amount of fresh air supply from 1 L/s to 5 L/s per person. From 5 L/s to 10 L/s per person, changes are becoming less pronounced and in the remainder of the range leads to increasingly lower impacts. The biggest impact is in Room 1 of building D, and in Room 1 of building E it is the smallest. The originally calculated amount of air supply on these premises was 0.47 L/s and 1.28 L/s per person, respectively. In Room 1 of building E, 1 L/s to a person leads to a reduction in air exchange, which also results in a negative result.

The economic impact of performance changes

The Scenario 1 (5 L/s per person) can be realized in almost all buildings using existing air exchange units. While the cost of electricity will be increased, greater economic gains will be achieved so that the implementation of a slightly larger influx of fresh air, as specified in Cabinet Regulation No. 310 [55], has been a positive economic benefit in all educational institution buildings (buildings A–E) already in the first year. For administrative buildings with a low human density (buildings F–H) it is close to zero or negative. For Scenario 2, the necessary investments in the first year will not be yet outstanding. The Scenarios 3 and 4 with existing equipment are only feasible in building H.

The economic benefits of the scenario for the second year of implementation are illustrated in Fig. 3.8. All educational buildings have a positive impact in all scenarios because the economic benefits of performance improvements are significantly higher than operating costs. In a building, 5 L/s for a person may produce a greater positive effect than 30 L/s per person, so existing equipment must be used.

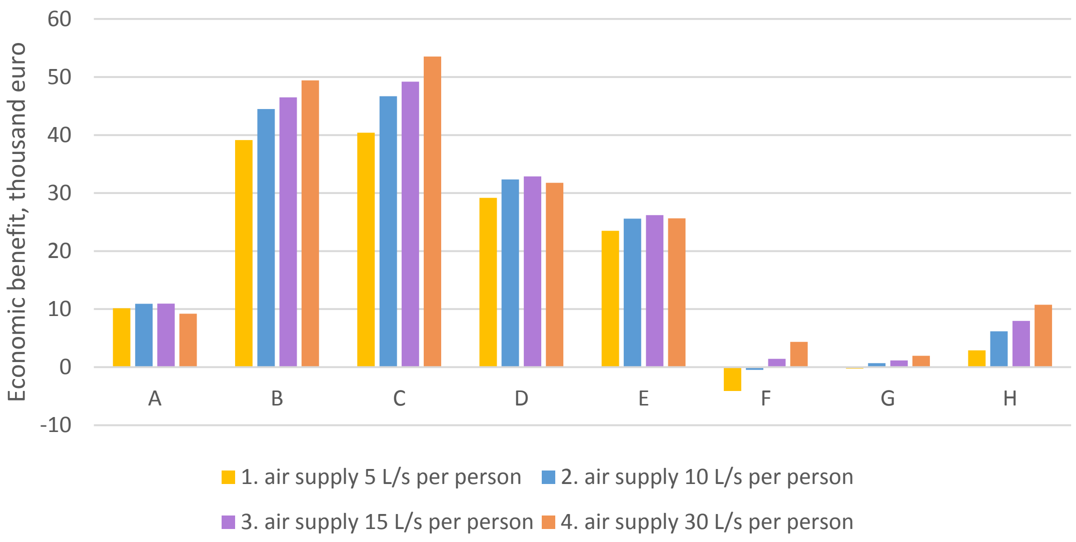


Fig. 3.8. Economic advantage from implementation of four ventilation scenarios in the second year.

The calculation of economic benefits includes student training costs and the average wage of employees. If students improve their performance, less time would be needed to reacquire the learning material, additional lessons, and other aspects that may reduce the overall spending on students' schooling. It is also possible for office staff to reduce expenditure by making the work faster and more qualitative [58].

3.2. Implementing Energy Efficiency Measures in Government and Municipality-Owned Buildings

The simulation of energy savings was carried out by involving several policy instruments and forecasts were made for two deadlines: 2016 and 2020. The results published in Publications 1 and 4 show that by 2016, the 408 GWh savings planned in the national policy documents will not be achieved without implementation of the policies, while savings of 657 GWh can be achieved by 2020. The best results are achieved by implementation of the CO_2 tax policy. If this policy measure is implemented, there is an opportunity to achieve the 88 % target by 2016, which is the closest possible saving to energy consumption to the target set, while by 2020 the value of the parameter may exceed the target of around 80 %. The changes in floor area for buildings with energy efficiency improvements, distributed over different building age groups are indicated in Fig. 3.9. The highest increase is observed in buildings built between 1940 and 1992. Negligible changes occur in buildings built from 1993 to 2014.

Every policy instrument affects both the pace of energy performance implementation and the overall energy consumption, thereby making a positive impact on energy efficiency and, consequently, on the climate as a whole.

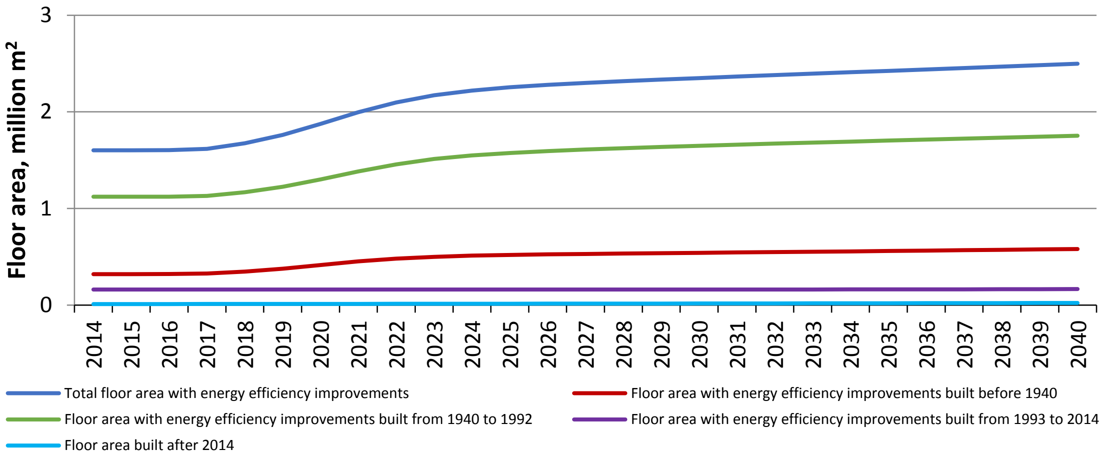


Fig. 3.9. Floor area of public buildings with implemented energy efficiency measures.

Currently, Latvia can achieve its objectives by 2020 if it is only viewed from the point of view of the energy efficiency of buildings, but at the end of the available funding from the Climate Change Financial Instrument and the European Union Structural Funds, the desire of government and local authorities to insulate buildings from its own means will diminish rapidly. Given that the targets will be further set at a higher pace and the construction of low energy consumption buildings need to be promoted, it is necessary to consider in a timely fashion the possible policy engagement and actions that will be implemented to ensure that state and municipal buildings meet the criteria set and to help generate the planned energy savings.

The impact of natural and mechanical ventilation on total energy consumption

The simulation done in Publication 4 show the total energy consumption in public buildings both with and without the operation of mechanical ventilation systems. The result is shown in Fig. 3.10.

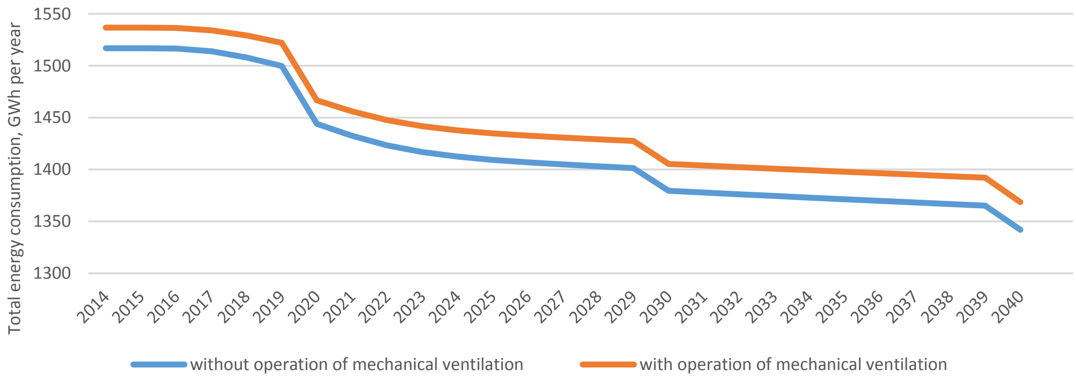


Fig. 3.10. Total energy consumption in public buildings with and without operation of mechanical ventilation after implementation of energy efficiency measures.

In both cases total energy consumption decreases. In the beginning, the difference between both alternatives is 1.3 % and increases by time and reaches 2 % by 2040 or CO_2 emissions 7050 t per year. By 2040, in 667 thousand m^2 energy efficiency measures will be carried out, and this represents only 10 % of the total floor area of those buildings built before 2014. If energy efficiency measures are implemented at a higher rate, the difference in energy consumption between two alternatives increases by 2040.

Profitability of insulation in buildings constructed in different periods

The difference in the growth rate of building floor area with energy efficiency measures is explained by the profitability ratio. The highest ratio is for buildings built from 1940 to 1992, as they have the highest energy efficiency potential, followed by the historic building stock, which has lower energy efficiency potential due to technical limitations and heritage value (Fig. 3.11). The lowest profitability ratio is for buildings built between 1993 and 2014. They have the lowest energy saving potential compared to the costs of construction.

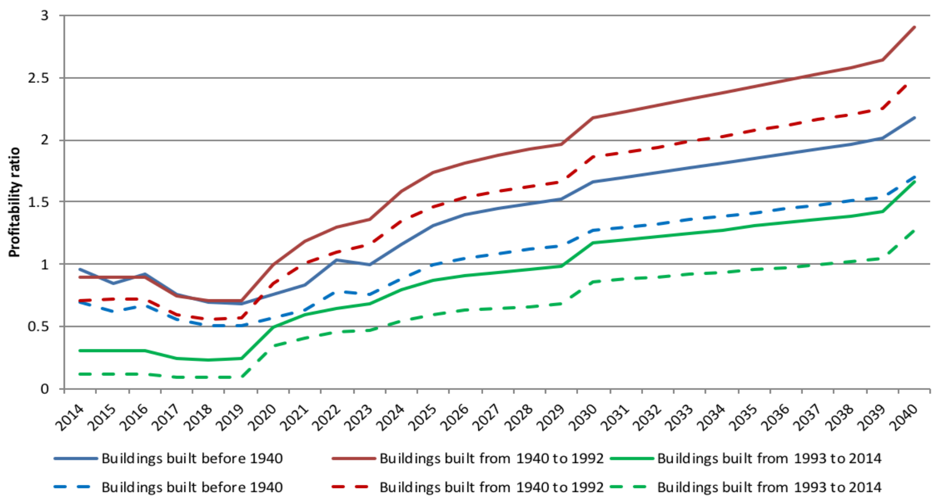


Fig. 3.11. Profitability ratio of energy efficiency measures in public buildings with (dotted lines) and without (full lines) operation of mechanical ventilation after implementation of energy efficiency measures.

Profitability ratio presented in Fig. 3.12 shows dynamic behaviour over time. Changes are caused by feedbacks, non-linearity, and delays built within the system. Supply and demand for energy efficiency measures are illustrated in Fig. 3.12. When no funding is available, demand and supply of energy efficiency measures are low and prices are low as well. As soon as funding enters the market, demand rises as does supply. However, it takes time to build up the capacity of construction companies. In these circumstances, prices rapidly increase due to the gap between supply and demand. When supply and demand are in equilibrium, prices start to fall. When funding is removed, demand falls, followed by supply and in short order prices fall as well. This process where large amounts of funding suddenly flow into the market causes a decrease in profitability as can be seen in Fig. 3.11; and fewer buildings can be renovated due to very high prices compared to conditions before funding.

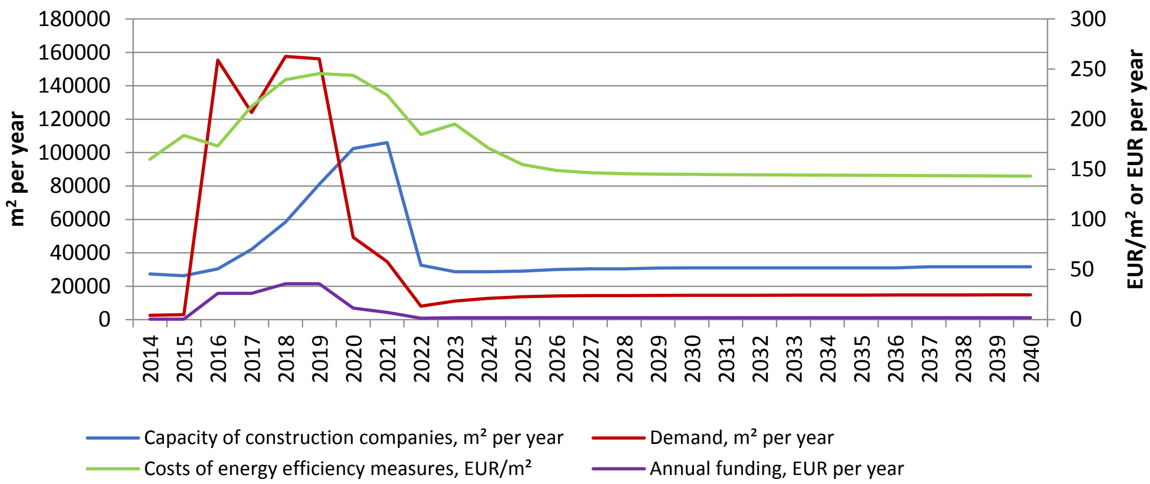


Fig. 3.12. Supply, demand, costs, and funding of energy efficiency measures in public buildings.

3.3. The Impact of Energy Efficiency – Indoor Air Quality Dilemma on GDP

GHG emissions from different scenarios are shown in Fig. 3.13. The lowest GHG reduction is achieved through Scenario 1, followed by Scenario 0. In both scenarios, the implementation of energy efficiency measures is very slow due to a lack of finance after 2022. The difference between these two scenarios is caused by the air exchange round, the higher the rate, the higher is the energy consumption and the corresponding GHG emissions. In Scenario 2 and 3, a higher reduction in GHG emissions is shown. This is due to the additional funding allocated to energy efficiency projects. Similar to Scenarios 0 and 1, the operation of ventilation systems is a difference. Scenario 4 and 5 show a significant GHG reduction, as most buildings have improved energy efficiency. The difference between the mechanical and natural ventilation buildings in 2050 will reach 80 kt.

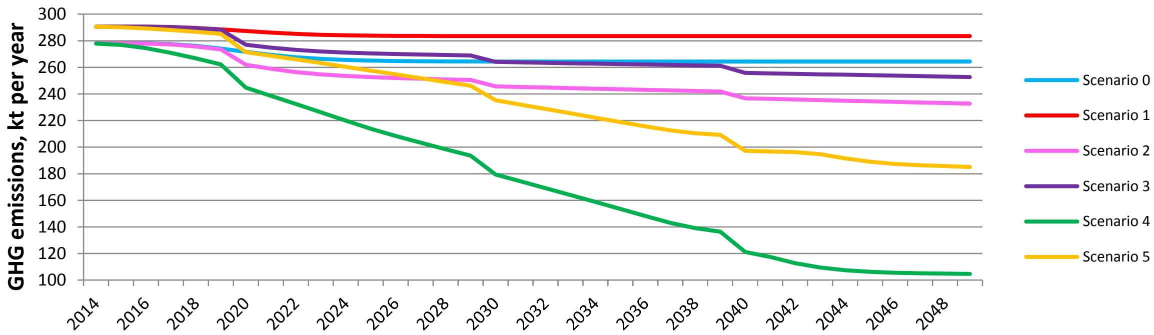


Fig. 3.13. Greenhouse gas emissions for different scenarios.

Fig. 3.14 presents a comparison of different scenarios. GHG emission reduction and GDP income gain are used as indicators. Scenarios are compared in pairs, as the main difference among the scenarios is air change rate (0.5 h^{-1} or 6 h^{-1}): Scenarios 0 and 1, Scenarios 2 and 3, and Scenarios 4 and 5. The comparison between scenarios helps to assess the impact of indoor quality on both GDP and GHG emissions. Each scenario from 1 to 5 is also compared to the base scenario (Scenario 0). Fig. 3.14 indicates the behaviour of two parameters over time – GDP generated by income and GHG emissions. Results show that with sufficient financing and operation of mechanical ventilation (Scenario 5), the GDP has the highest growth rate and reaches a value of 36 million EUR per year higher compared to Scenario 0. At the same time, Scenario 5 shows the second-highest GHG emission reduction rate compared to Scenario 0. While Scenario 4 has a major GHG reduction rate, it has almost no change in GDP. This scenario shows that if energy efficiency measures are implemented without having good indoor air quality, the climate change goals can be met while the GDP only has a marginal growth rate. A minimal GDP growth rate can be observed in Scenario 2 compared to the base scenario although the former scenario does provide GHG emission reduction. In Scenario 1, mechanical ventilation in buildings with improved energy efficiency is used and it results in higher GHG emissions than Scenario 0. On the other hand, Scenario 1 has a significant increase in GDP due to better indoor air quality.

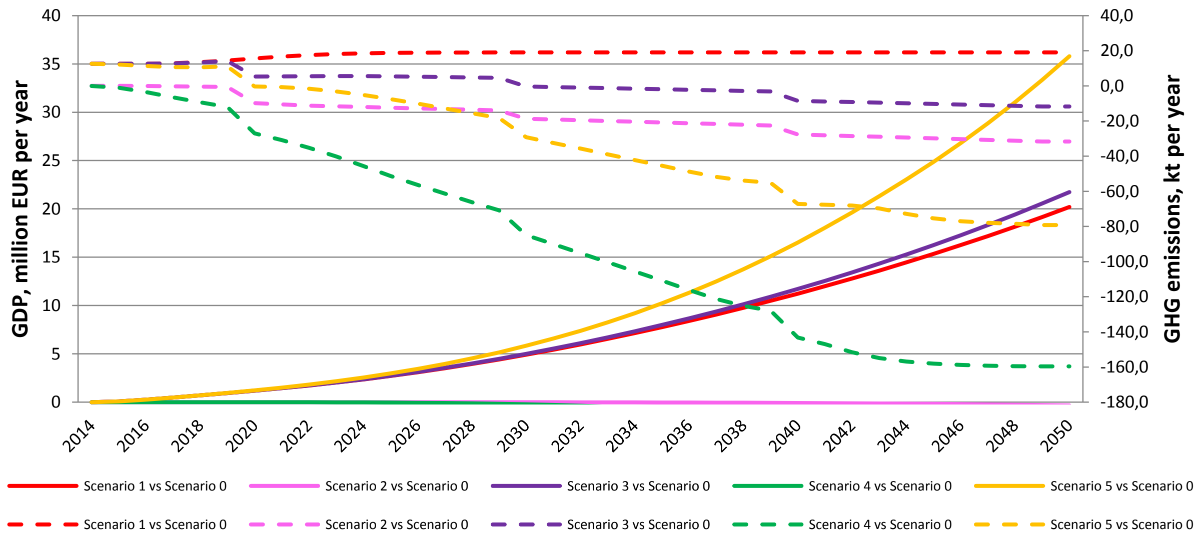


Fig. 3.14. Comparison of Scenarios 1–5 according to pairs and with the base scenario (full lines are GDP income gains; dashed lines are GHG emission reduction).

The optimal scenario (Scenario 6) was created during the research by using the optimisation tool in *Powersim Studio*. An additional 74.66 million EUR per year from national and municipal funding sources and a 4.05 h^{-1} air change rate were used as input data in the optimal scenario.

Fig. 3.15 shows the dynamics of the qualified labour force in different sub-groups for Scenarios 0, 1 and 5. If indoor air quality is improved, the numbers of less paid sub-groups decrease as higher-paid sub-group numbers increase. This is due to higher achievements during the education process if indoor air quality is improved. The same tendency is observed in the sub-groups of medium-skilled labour.

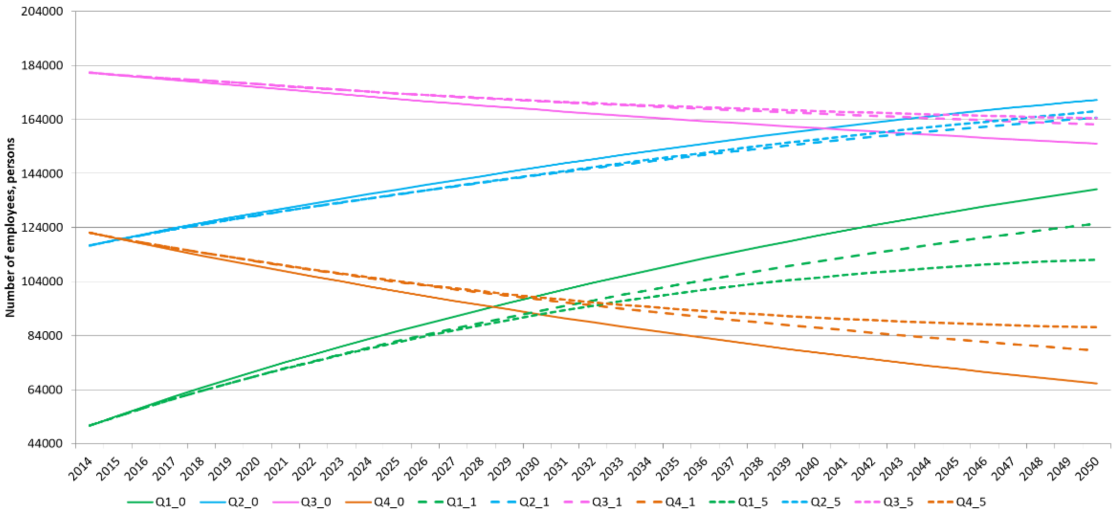


Fig. 3.15. Dynamics of the qualified labour force in different sub-groups (Q1 – low-income labour; Q2 – medium low-income labour; Q3 – medium high-income labour; Q4 – high-income labour) for Scenarios 0, 1 and 5.

3.4. Educational Institution as a Prosumer

The cost-benefit calculations described in Publication 6 show that annual electricity from solar panels will be approximately 963 kWh/kWp. The educational building that produces electricity (even partly) have decreased electricity tariff. The average electricity tariff per month varies between scenarios (Fig. 3.16) and the best one is for the scenario with 30 kW installed power, although almost half of the energy flows into the grid. The generated amount of electricity in the first year will not be the same after 25 years because the PV panel producers guarantee 80 % of efficiency at the end of the PV modules lifetime so the investment payback time should be as short as possible to get the best profit.

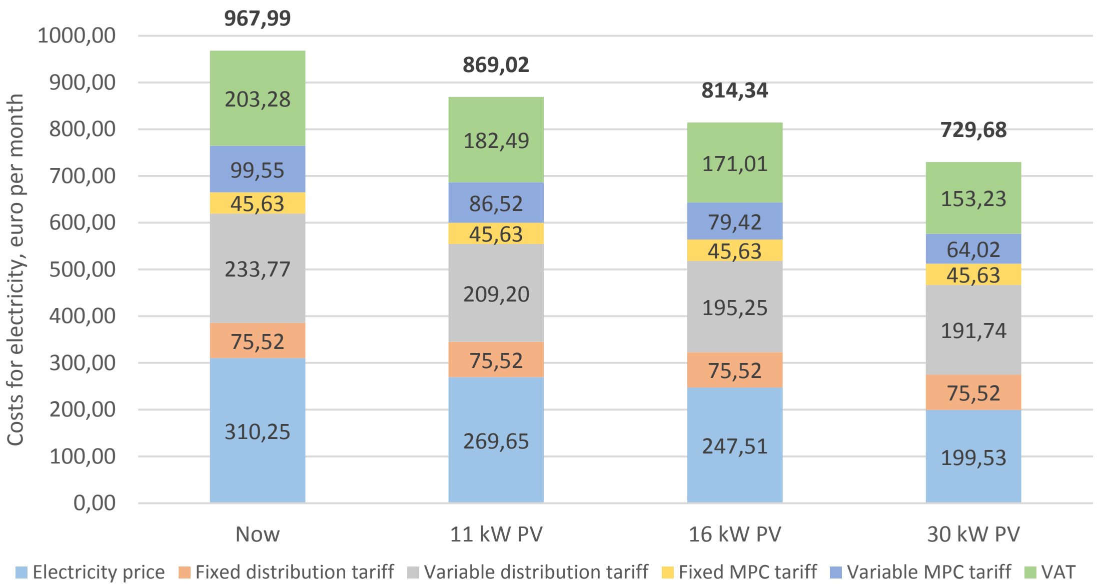


Fig. 3.16. The average monthly electricity bill before and after installation of solar panels.

The cost of capital of the solar panel system and the payback time for its investments are shown in Publication 6. The payback time for the system (16 kW) is less than 11 kW and 30 kW, however, the period of almost 10 years is not satisfactory. The payback period may be reduced by half if subsidies cover 50 % of capital investment. The installation payback time for the biomass boiler is approximately 4.2 years. Since heating costs will be lower, these savings could be as a “subsidy” for the solar panel system. This scenario would help reduce the payback time for PV panels to around 6 years (Fig. 3.17).

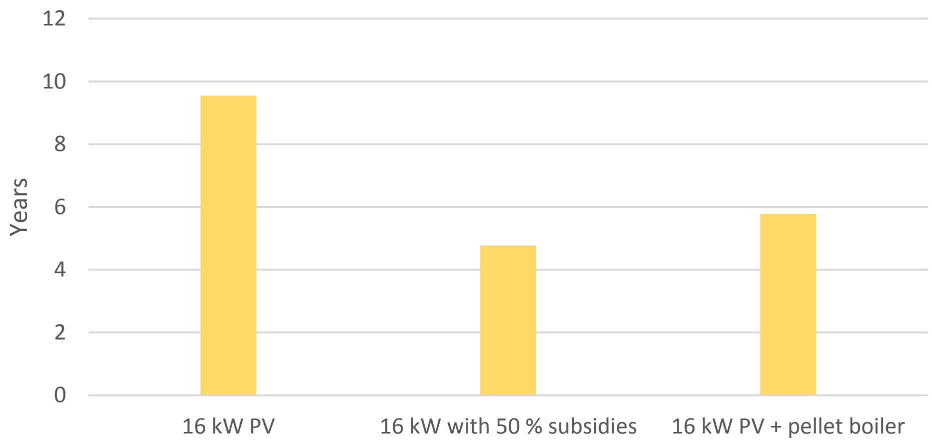


Fig. 3.17. Investment payback time.

Decrease of CO_2 emissions by partly using solar energy instead of taking all electricity from the grid is visualized in Fig. 3.18. The photovoltaic system of 16 kW can reduce around 36 tons of CO_2 in its lifetime. The more power is generated by PV, the larger is the decrease of CO_2 emissions, however, the school building electricity consumption demand specifics show that systems over 16 kW feed into the grid more than 25 % of generated energy.

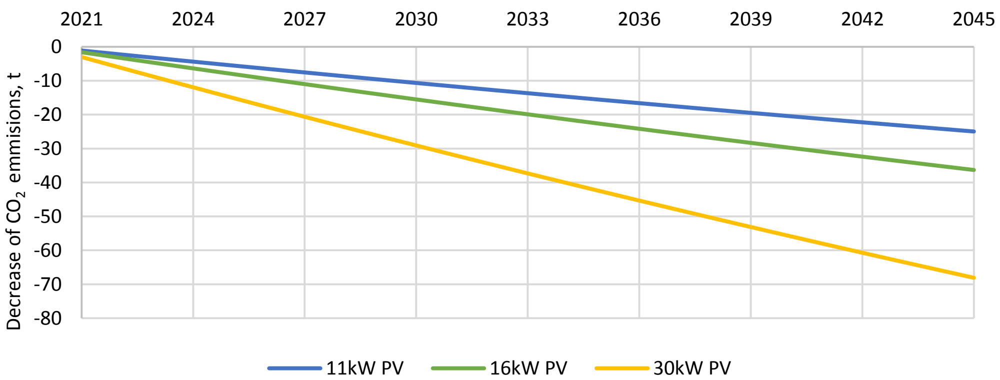


Fig. 3.18. Decrease of CO_2 emissions.

CONCLUSIONS

Hypothesis 1. Introduction of energy efficiency measures in buildings owned by government and municipalities ensures that the national climate policy objectives are achieved.

The first hypothesis was studied in Publications 1 and 4 by using the devised energy efficiency system dynamics model of the government and municipalities owned buildings. This was validated using the available data of the Latvian public sector energy consumption, the heat tariff and its changes, construction costs, and other influencing parameters. Also, the model was validated using the data from Liepāja municipality.

The hypothesis was confirmed because the results reported in Publication 1 showed that Latvia can achieve the objectives set in the national policy documents by 2020 solely regarding from the standpoint of buildings performance. Following the full expenditure of CCFI and the EU Structural Funds, the desire of the state and local authorities to insulate buildings from their own means will diminish rapidly. The economic benefits are one of the most important criteria in the decision-making process for insulation of buildings. Therefore, in order to facilitate any course of action by the national and local authorities in the field of energy efficiency, the budgetary impact of the energy efficiency measures needs to be demonstrated. Both the envelope insulation and window replacement of state and local governments and the restoration of the heating system to renewable energy sources should be promoted, thus reducing the share of the total consumption of fossil resources. Publication 4 showed that the introduction of energy efficiency measures in public buildings has a major impact on indoor air quality, leading to the dilemma of energy efficiency and indoor air quality. The simulation results show that if the ventilation was operated according to the National building standards, the total energy consumption in the public building sector would rise from 1.3 % in 2014 to 2 % in 2040 (or CO_2 emissions 7050 t per year) compared to a situation where there is no mechanical ventilation.

Hypothesis 2. Following the introduction of energy efficiency measures, energy efficiency – indoor air quality dilemma is forming in educational institutions.

The hypothesis was studied in Publications 2 and 3, by performing indoor climate measurements, determining air exchange rates and the supply of fresh air into the premises via building tightness tests, as well as by conducting surveys in educational establishments and estimating the predicted mean vote.

The hypothesis was confirmed because of the presence of sustained, elevated levels of carbon dioxide in the educational buildings studied in Publication 2, which in some cases significantly exceeded the regulatory values. In buildings occupied by a large number of people, it was observed that the episodic airing of the space by opening the window causes temporary effects and the concentration of CO_2 is rapidly reverted to elevated levels. Following the introduction of energy efficiency measures, the buildings have become more airtight. The blower door tests carried out indicated that most of the educational buildings should be considered as moderately dense, which require mechanical ventilation. The measurements in the study show that mechanical ventilation systems operate poorly. The test results demonstrate that the air exchange rate is low in most buildings and the supply of fresh air must be increased at least to the national normative – 15 m^3/h per person [55]. The ventilation systems in studied buildings are being operated incorrectly. The questionnaires of studied rooms' users in Publication 3 show a subjective assessment of +0.67 to +1.86, which indicates that students and staff evaluate the indoor environment as warm and unsatisfactory.

Hypothesis 3. Energy efficiency – indoor air quality dilemma has a long-term impact on the country's gross domestic product.

The hypothesis was studied in Publications 3 and 5 using performance enhancement calculations and system dynamics modelling.

The hypothesis was confirmed in Publication 3. The study carried out indicates that by following a scenario of an increased air supply up to 30 l/s per person, one can achieve up to 19 % improvement in mental work capacity. It is concluded that the extent of the performance improvement depends on the initial air exchange rate. Providing fresh air 5 L/s per person, in the pursuit of one of the scenarios, in most educational buildings can be done without additional capital investment, making it economically advantageous already in the first year. The results of the simulation (Publication 5) show that even if all educational buildings have improved energy efficiency indicators and a significant reduction of CO_2 level is obtained outdoors, the CO_2 level indoors will be very high if mechanical ventilation is not used. The best solution is to increase energy efficiency while ensuring good indoor air quality by operating mechanical ventilation, since GDP growth provides financial sources for future energy efficiency measures. The results indicate that the air exchange rounds used in ASHRAE and EN 15251 provide the most optimal reduction in greenhouse gases and an increase in gross domestic product. The structure of the model established in this study is universal and can be used in different countries with different education systems, wages, and other factors.

Hypothesis 4. Energy efficiency – indoor air quality dilemma can be solved by buildings becoming prosumers using renewable energy.

The fourth hypothesis was studied in Publication 6, analysing the most economically justified solution for the transition of an educational institution's building to a prosumer.

The fourth hypothesis was partially confirmed because the educational institutions studied in Publication 6 could reduce the electricity costs by 16 % if a 16 kW solar panel system was installed. This system has a payback time of about 10 years. The payback period may be reduced by half if a 50 % subsidy of capital investment is received. The investment payback time for the biomass boiler is approximately 4.2 years. Since heating costs will be lower, these savings could be seen as a "subsidy" for the solar panel system. This scenario would help reduce the payback time for PV panels to around 6 years. The scenario of a non-networked consumer was also analysed, but the specific energy consumption profile of the educational institution and the costs of energy accumulators make this scenario non-profitable. The use of solar panels for partial production of electricity allowed to reduce average electricity costs, which is usually the main drawback of regular operation of mechanical ventilation systems. Such system usage in educational buildings is a possible solution for the energy efficiency and indoor air quality dilemma.

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