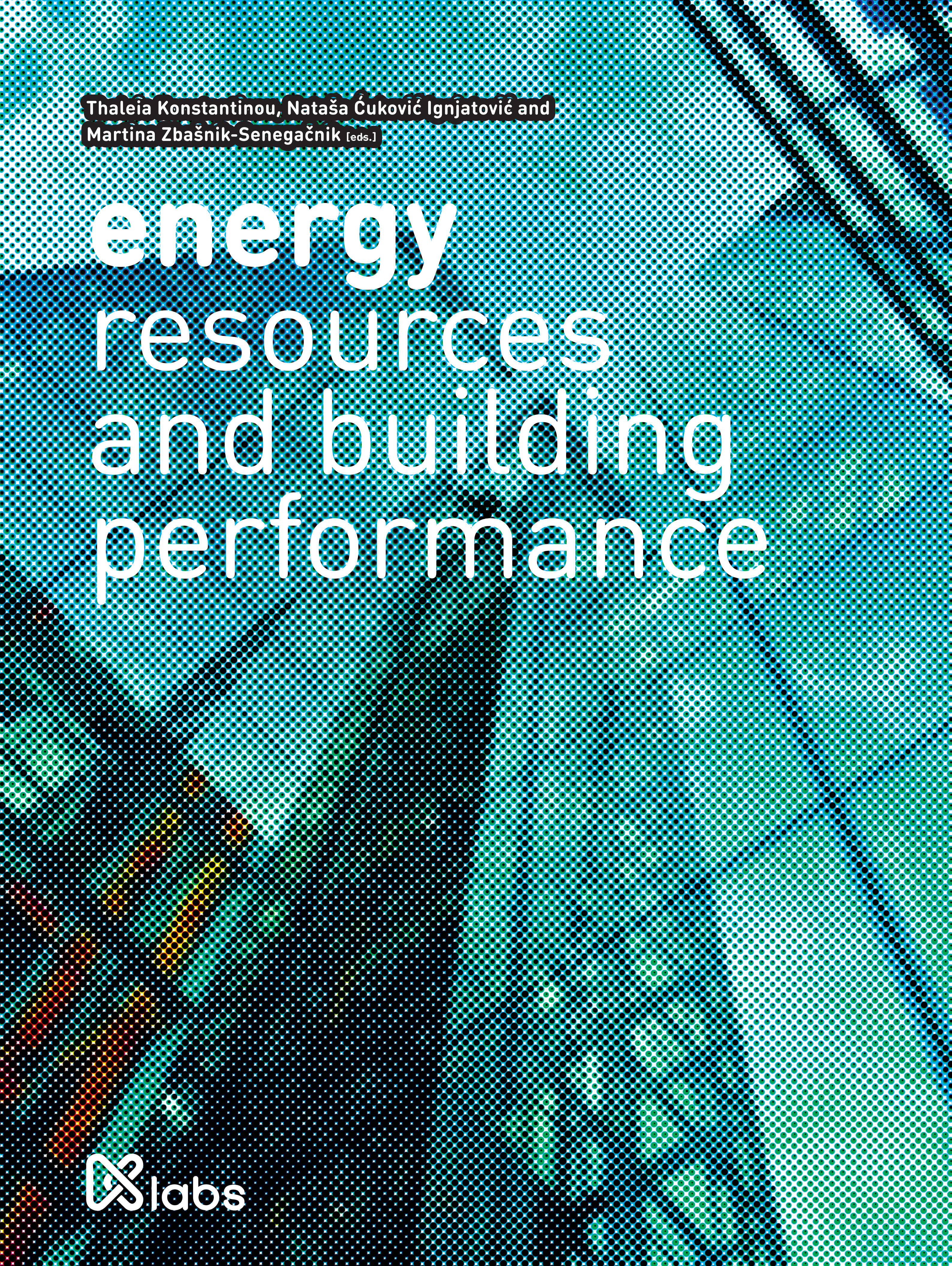
Energy
resources and building performance

Konstantinou, Thaleia; Ćuković Ignjatović, Nataša; Zbašnik-Senegačnik, Martina



Thaleia Konstantinou, Nataša Ćuković Ignjatović and
Martina Zbašnik-Senegačnik [eds.]

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labs

BOOK SERIES

reviews of sustainability and resilience of the built environment for education, research and design

Saja Kosanović, Alenka Fikfak, Nevena Novaković and Tillmann Klein **[eds.]**

This thematic book series is a result of the Erasmus+ project, *Creating the Network of Knowledge Labs for Sustainable and Resilient Environments (KLABS)*. The books are dedicated to establishing a comprehensive educational platform within the second cycle of higher education across the Western Balkan region. The series comprises five volumes in the English language:

Sustainability and Resilience _ Socio-Spatial Perspective
Realms of Urban Design _ Mapping Sustainability
Integrated Urban Planning _ Directions, Resources and Territories
Energy _ Resources and Building Performance
Sustainable and Resilient Building Design _ Approaches, Methods and Tools

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FOR SUSTAINABLE & RESILIENT ENVIRONMENTS

Creating the Network of Knowledge Labs for Sustainable and Resilient Environments – KLABS

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Energy
Resources and Building Performance

Editors
Thaleia Konstantinou, Nataša Ćuković Ignjatović and Martina Zbašnik-Senegačnik

Reviewers
Steve Lo, Dionysia - Denia Kolokotsa

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Thaleia Konstantinou, Nataša Ćuković Ignjatović and Martina Zbašnik-Senegačnik [eds.]

Preface

Saja Kosanović, Alenka Fikfak, Nevena Novaković and Tillmann Klein

The continuous evolution of the notion of a sustainable and resilient built environment demands repeated examination. For this reason, the state-of-the-art thematic series *Reviews of Sustainability and Resilience of the Built Environment for Education, Research and Design* contributes to the comprehensive understanding of the two approaches and their interrelations in the built environment by retrospectively investigating their development, addressing current issues, and speculating on possible futures. The series represents one of the results of the Erasmus+ project, Creating the Network of Knowledge Labs for Sustainable and Resilient Environments – KLABS, dedicated to establishing a comprehensive educational platform within the second cycle of higher education across the Western Balkan Region.

The sustainable and resilient built environment is a multi-layered and multi-disciplinary construct. To successfully tackle the intricacy of the points in question, the series of books comprises five thematic volumes that initially approach sustainability and resilience from the socio-spatial perspective, subsequently address sustainable and resilient urban planning and urban design, and then focus on individual buildings and a range of approaches, methods, and tools for sustainable and resilient design, placing particular emphasis on energy issues. By addressing different levels of the built environment and different aspects of sustainability and resilience in a systemic way, 83 academics from 12 different countries gave 54 contributions in the form of narrative or best evidence articles with the main objectives of informing the development of specialised knowledge, building critical awareness of interdisciplinary and transdisciplinary knowledge issues, and connecting university education with the domain of scientific research. The broad aim is to develop the collection of reviews of sustainability and resilience of the built environment that are useful for students, educators, professionals, and researchers, all of whom are dealing with these two important subjects internationally.

We express our gratitude to all authors, editors, reviewers, and members of the publication board for investing significant efforts in the development of the book series in the framework of the Erasmus+ project, KLABS.

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Steve Lo and Dionysia - Denia Kolokotsa

I

This book should provide a sound foundation for graduates and practitioners commencing their journey along a path towards resource efficiency and lifetime building performance design, specification, and analysis.

The generic foundations of renewable and non-renewable energy sources present a basic knowledge from which to develop an understanding of the inter-related causes and effects of material selection on operational energy consumption.

The relative impact of the embodied energy of typical construction materials on the lifetime embodied energy becomes more important as the operational primary energy of the building is reduced through energy efficiency measures. Energy and carbon payback is a useful tool for commercial justification when planning lower carbon refurbishment and improvements.

The resilience of renewable energy systems is a more thought-provoking approach that results in a useful resilience index rating. This can be used to inform the balance between the increased cost of additional passive/active measures to reduce base and peak loads, and, the economic viability of more optimally sized renewable solutions.

A clear chronology of the development of the thermal performance of buildings shows how it evolved from being fabric-focussed to focusing on improved total user comfort, resulting in useful parametric guidelines for building envelope design. The fundamentals of heat and mass transfer through the fabric are also presented in an easy to digest manner that clearly evaluates the importance, and relative significance, of each layer of the building envelope. A well-considered selection of relevant local case studies over the ages, and the resulting key envelope constructions, will be a useful reference point for the design and construction of future built exemplars. The indicators of achieved comfort will also help students to develop their understanding of the often conflicting inter-relationship between thermal, air, visual, and acoustic comfort. Their final design choices will show that optimal solutions often result from minor compromises of each parameter. This future generation of more informed energy conscious designers and users can advance towards more holistic comfort-based wellness indices.

A clear background to the simulation landscape and building description input processes will be most useful after some hands-on experience with the software. Researchers should strive for design and simulation environments based on rule of thumb guidance at the early stages, to more detailed dynamic modelling environments at later stages, to allow contiguous simulation matched with available building information as the design progresses. This would result in a more seamless transition from early basic location and site information, to more detailed data, such as occupancy, towards the end of the design process. Any performance gaps between designed and operational energy performance could then be supported by a rigorous programme of ongoing POE.

A concise but informative narrative clearly justified the benefits of climate-appropriate external shading solutions using local case study buildings, to produce informative and accessible outputs that can be developed into Useful Daylighting Illuminance (UDI) guidelines. The passive and active measures considered are a sound starting point to reduce base and peak energy loads before deploying renewable energy technologies, and can be used to improve initial simulation studies through parametric analysis.

The PH concept is well suited to the Balkan climate and the outputs have produced some useful lifetime energy comparisons between construction, renovation, and operational energy use and emissions. The inclusion of the five key indicators of building valuation provides very useful guidance for practitioners.

Life cycle analysis over a defined service life allows meaningful bench-marked comparisons to be made that can inform low-carbon improvement solutions. The calculation of payback periods by options that consider the realities of sensitivity analysis will prove invaluable to practitioners and academics alike.

This book provides a basic foundation for interested undergraduate students and fledgling practitioners to make more informed choices whilst remaining aware of the initial and lifetime energy/carbon impact of their solutions.

The outputs, tools, and guidelines presented are, in general, accessible and will assist greatly in their decision-making processes.

Dr. Steve Lo
Bath, United Kingdom, March 2018

II

The book entitled "Energy: Resources and Building Performance" provides an exciting and refreshing perspective on the energy aspects of the built environment.

The book starts by introducing the reader to the energy flows, the energy requirements on a global level, and the role of the built environment in the general energy context. Insights into the role of renewable energy in energy systems' resilience are presented. The introductory section includes all necessary definitions and terminology supporting the reader with the necessary background information and knowledge. Simultaneously, this introductory section is an excellent starting point for students interested in going deeper into the specific research area. The second part is devoted to the assessment of the energy performance of buildings and the understanding of indoor environmental quality. The simulation techniques and the role of design are investigated in this section. The reader is guided smoothly through the calculation and simulation procedures and tools before entering the most important part of the book, which is the analysis of energy conservation strategies and the role of the design process. Advanced shading devices for solar control are discussed. Different variants of passive heating and cooling strategies are presented and analysed. The book then incorporates the critical subject of embodied energy and operational energy in buildings' lifetime by pinpointing the necessity of life cycle analysis.

By providing different perspectives of the energy efficiency technologies, ranging from an integrated overview of the energy sector to the role of renewables to the passive design, while simultaneously highlighting the importance of buildings as energy consumers, the book is a knowledge booster. It is an enjoyable piece of reading with illustrations and examples that can keep the readers engaged.

Edited and authored by well-recognised experts in the fields of energy and environment, energy efficiency, renewables and energy and climate, the book provides hands-on knowledge that is extremely useful for students and researchers in the design, building sciences, energy, and engineering fields. The book supports the readers in understanding, applying, and testing different design strategies to achieve their energy and environmental benefits.

Moreover, the book is a sweeping and comprehensive document that can serve as a one-stop reference for understanding, applying, and evaluating different energy efficiency measures in the West Balkan area as well as worldwide.

I consider this book to be a valuable addition to library shelves for students, research institutions, and organisations, as it provides a different perspective in the integrated energy and environmental design of buildings and other urban structures.

Dr. Dionysia - Denia Kolokotsa
Chania, Greece, March 2018

Introduction

Thaleia Konstantinou, Nataša Ćuković Ignjatović and Martina Zbašnik-Senegačnik

Today, humankind is completely dependent on energy. Energy is indispensable for growth and life on Earth, and it is also of key importance for living comfortably – for heating, lighting, cooling, ventilation, operation of machines and appliances, for transport, etc. The major energy-generating source is the sun, sending the energy to Earth and making life on our planet possible. This energy is free of charge and without negative effects. However, we only know how to use and convert a small part of the solar energy reaching the Earth into other forms of energy necessary to improve the conditions for life and the human comfort.

The production of energy that drives our civilisation still depends heavily on the use of non-renewable fossil reserves. The dependence on coal, oil, and natural gas is a major problem faced by the humankind. Buildings need energy throughout their life cycle, which consists of six stages – extraction of raw materials, production of materials and components, transport, sale, construction, operation and, finally, demolition. Measures aimed at reducing the dependence of a building on energy throughout its life cycle may be implemented on at least two levels. The first important decision is to locate a building in the environment in a manner such that it will help improve the living conditions in the building by making use of the natural features of the site:

- by proper orientation of the building to facilitate heating and lighting by means of solar energy;
- by using the wind to facilitate natural ventilation;
- by including vegetation in the external and internal environment to improve the quality of air; and
- by observing the relevant distance from the adjacent buildings to prevent the shading effect.

The second important decision in the building design process refers to the selection of materials and building technology. Every stage of the building's life cycle calls for a choice that will contribute to the lower energy consumption of the building:

- extraction of raw materials – choice of raw materials (timber, stone, earth), as they are not energy-intensive;
- production of materials and components – choice of materials whose production requires little energy;
- sale of materials and components – choice of materials and components that are produced locally near the construction site and not subject to great transport distances;

- construction of the building – choice of building technologies that do not require much energy;
- use or operation of the building – the building should be designed in such a manner as to require little energy for heating, cooling, lighting, and ventilation;
- demolition – the building should be designed in a manner that permits the structure to be disassembled into the basic elements that can be sorted by specific materials and, if possible, reused or recycled.

The use of energy in buildings is thus a complex problem, but it can be reduced and alleviated by making appropriate decisions. Therefore, architects face a major and responsible task of designing the built environment in such a way that its energy dependence will be reduced to a minimum, while at the same time being able to provide comfortable living conditions. Today, architects have many tools at their disposal, facilitating the design process and simultaneously ensuring proper assessment in the early stages of building design.

This book attempts to highlight the problem of energy use in buildings and propose certain solutions. It consists of nine chapters, organised in three parts. The gathering of chapters into parts serves to identify the different themes that the designer needs to consider, namely energy resources, energy use and comfort, and energy efficiency.

Part 1, entitled "Sustainable and Resilient Energy Resources," sets off by informing the reader about the basic principles of energy sources, production, and use. The chapters give an overview about all forms of energies and energy cycle from resources to end users, and evaluate the resilience of renewable energy systems. This information is essential to realise that the building, as an energy consumer, is part of a greater system and the decisions can be made in different levels.

Part 2, entitled "Energy and Comfort in the Built Environment", explain the relationship between energy use and thermal comfort in buildings and how it is predicted. Buildings consume energy to meet the users' needs and to provide comfort. The appropriate selection of materials has a direct impact on the thermal properties of a building. Moreover, comfort is affected by parameters such as temperature, humidity, air movement, air quality, lighting, and noise. Furthermore, the relation between operational energy, embodied energy and CO_2 emissions is discussed. Understanding, calculating and evaluating those relations are valuable skills for the designers.

After the basics of energy use in buildings have been explained, Part 3, entitled "Energy Saving Strategies" aims to provide information and tools that enable an energy- and environmentally-conscious design. This part is the most extensive as it aims to cover different design aspects. Firstly, passive and active measures that the building design needs to include are explained. Those measures are seen through the perspective of heat flow and generation. The Passive House concept, which is explained in the second chapter of Part 3, is a design approach that successfully incorporates such measures, resulting in low energy use by the building. Other considerations that the following chapters cover are solar control, and finally economic evaluation. The energy saving strategies explained in this book, despite not being exhaustive, provide basic knowledge that the designer can use and build upon during the design of new buildings and existing building upgrades.

In the context of sustainability and resilience of the built environment, the reduction of energy demand is crucial. This book aims to provide a basic understanding of the energy flows in buildings and the subsequent impact for the building's operation and its occupants. Most importantly, it covers the principles that need to be taken into account in energy efficient building design and demonstrates their effectiveness.

Designers are shaping the built environment and it is their task to make energy-conscious and informed decisions that result in comfortable and resilient buildings.

PART 1

Sustainable and Resilient Energy Resources

Energy Flows and Energy Cycle _
From Resources to End Users

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ABSTRACT **Energy resources are classified as renewable and non-renewable. Renewable energy sources include wind, solar, and hydro energy; while Non-renewable energies include nuclear fission materials and fossil fuels. Renewable and Non-renewable energies are regarded as primary energy sources that supply energy straight from raw fuels. The increasing price of oil constantly reminds us of the fact that all resources, except renewable ones, are depleting. Prices of energy will constantly increase, while energy reserves will weaken. It is well known that the efficient use of energy and resources is a fast and painless way of reducing energy costs and decreasing adverse impacts on the environment. There is huge pressure from the public and governments to act in a socially responsible way and to use resources efficiently. Special attention should be paid to energy use in buildings, keeping in mind that these man-made structures are one of the biggest energy consumers. The building sector uses 40% of all primary energy worldwide. Because of that, and the emphasis on efficient energy use there must be changes in this energy sector, by implementation of various energy efficiency strategies. This paper, basically divided in two parts, gives an overview about all forms of energies based on level of transformation, energy cycle from resources to end users, and basics of the energy balance of buildings.**

KEYWORDS resources, energy flow, transformation, energy balance of buildings

1 Introduction

The introduction gives an overview of forms of energies based on the level of transformation and the definitions, with the aim to better understand the whole process of energy flow from resources to end users.

Energy, as generally understood, is a system's capacity to work. Energies exist in various forms like heat, motion, or light. All of these forms of energy can be divided in two categories: kinetic energy or energy of motion, and potential energy or energy stored in mass.

Energy holds the capacity of changing from one form to another. Potential energy has the ability to transform into energy of motion or kinetic energy, while kinetic energy goes to sound or sonic energy.

All of these energy transformations are necessary to create commercial energy.

In order to explain the forms of transformation, we consider a coal-fired power plant. Chemical energy is stored in the coal, which is transformed into heat energy by combustion. Heat transforms water into steam and creates energy of motion. Flowing steam spins a generator's turbine, which changes mechanical into electrical energy. The power system transforms energy to useful work. Some of the energy is wasted during the process. With regard to energy efficiency, the value goes from 0% to 100%. Besides the useful energy, part of the energy that is supplied to a used system is lost: this is non-useful energy (Fanchi, 2011).

An overview of mentioned energies and their hierarchy is given in the diagram below.

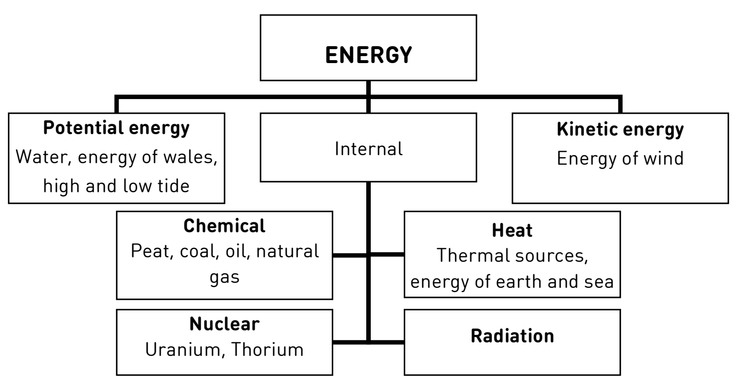

FIG. 1.1 Energies *(Todorovic, 2014)* *(Image by Authors)*

Embodied energy, generally referred to by the term primary energy, represents all of the energy needed to produce a product, which may or may not include the feedstock energy, as heat of burning of raw material inputs to a system. "Operating energy is the energy used in buildings during their operational phase, as for: heating, cooling, ventilation, hot water, lighting and other electrical appliances. It might be expressed either in terms of end-use or primary energy" (Sartori & Hestnes, 2007, p.249). Total energy is represented as the sum of all of the energy that a building use in its lifetime, which means the sum of embodied and operating energy, multiplied by lifecycle. Different user groups like households or industries are using various energy products. That final, useful energy is the energy that consumers are buying for their activities. Industry as well as households uses final energy for heat, lighting, cooling or transport.

In the aim of understanding the life cycle of energy there is a need to define energy flow. The term "energy flow refers to the production, import, export, bunkering, stock changes, transformation, and energy use by energy industries, losses during the transformation, and final consumption of energy products" (IRES, 2016, p.68). When the energy is produced transformed products can be exported, stored for later use, consumed by industries or delivered for final consumption, to different users for heating, cooling, transportation or electricity.

2 Energies Based on Level of Transformation

Two types of energy production exist; primary and secondary. Primary energy sources are "sources found in their natural state" (IRES, 2016, p.21). Primary energy is the energy from renewable and non-renewable sources that has not undergone any transformation process. Secondary energy is obtained from primary energy through transformation process and represents primary energy reduced due to conversion losses (e.g. electrical energy produced in thermal power plants by fuel combustion) (Stojiljkovic, 2014).

Basically, all energy sources can be divided in two categories as renewable and non-renewable. Non-renewable energy sources are fossil fuels and nuclear fission materials; these are sources which are not replenishing like renewable energies, like solar or wind energy, sources that are constantly renewing (Fanchi, 2013).

An overview of forms of energies based on the level of transformation is shown in Fig. 2.1.

The constant increase of energy consumption in all its forms, and the level of transformation, from primary to final energy, raised concern about energy supply, exhaustion of its resources, and the unavoidable environmental impacts like ozone layer depletion, climate change or global warming.

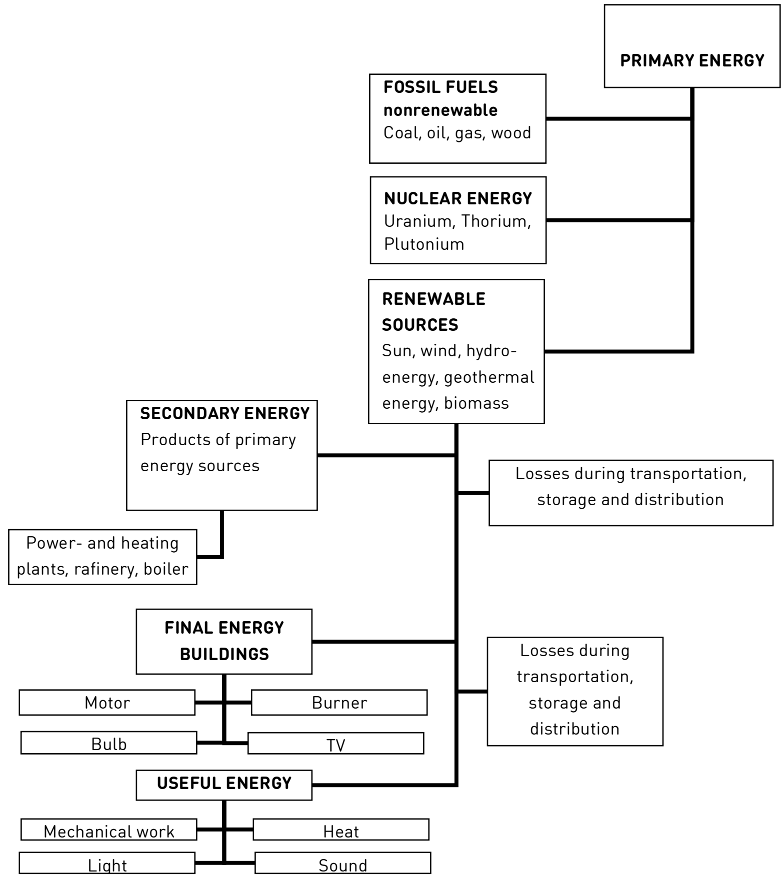

FIG. 2.1 Energy from resources to end users, based on lecturing of professor Milos Banjac, Mechanical Faculty, Belgrade *(Image by Authors)*

The International Energy Agency (IEA) is gathering data about energy consumption worldwide. The observed trend is quite frightening and shows that in the period from 1984 to 2000 primary energy grew by almost 50% and CO_2 emissions by 45%, with an increase of 2% per year respectively. Current predictions show that this trend will continue growing. Basic indicators of the mentioned trend are shown in Table 1.1.

PARAMETER	1973	2004	RATIO %
Population (millions)	3938	6352	61,3
Primary Energy (Mtoe)	6034	11059	83,3
Final energy (Mtoe)	4606	7644	66,0
Electrical energy (Mtoe)	525	1374	161,8

TABLE 2.1 Evaluation of global energy growth from 1973 up to the end of the twentieth century (Lombard, Ortiz, & Pout, 2008)

The primary energy unit is 'toe' (tonnes of oil equivalent). Based on conversion factor 'toe' can be turned into 1 toe= 41868MJ= 11630kWh= 11,63MWh

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Primary energy consumption grows at a higher level than population growth. It is noticeable that electricity consumption has drastically risen, more than two and a half times with 18% by 2000 in the final energy consumption (Lombard, Ortiz & Pout, 2008).

Primary energy

As mentioned, primary energy sources are sources found in their natural state and can be divided in two categories: Non-renewable and renewable.

Non-renewable energy sources

Non-renewable energy sources supply almost 85% of the total energy demand. They include fossil fuels, coal and peat, natural gas, and petroleum (US EIA, 2012).

Fossil energy- coal and peat

Coal is a solid fossil fuel that can be created by algae, phytoplankton, and zooplankton in the process of coalification. It can be also formed by plants and animals. Coal is classified by ranking, which presents the degree of coalification of carbonaceous material. The lowest rank is lignite, followed by bituminous coal, anthracite and graphite (Fanchi, 2013).

There exist two categories of primary coal: hard coal and brown coal. The table shows coal categories, subcategories, and their utilisation.

FOSSIL FUEL- COAL				
Hard coal (GCV less 24MJ/kg, Rr greater than 0.6)			**Brown coal** (GCV less 24MJ/kg, Rr less than 0.6)	
Anthracite Can be used for industrial and household heat boost	**Bituminous coal** industrial coking household heat raising		**Sub bituminous coal** used primarily as fuel for steam-electric power generation.	**Lignite** used exclusively as a fuel for steam-electric power generation
	Coking coal the production of a coke for support a blast furnace charge.	**Steam coal**		

TABLE 2.2 Coal categories and utilisation *(IRES, 2016)*

GCV Gross Caloric Value / Rr Vitrinite mean Random Reflectance per cent

Consumption of coal as primary energy by sector and source is presented in the figure below.

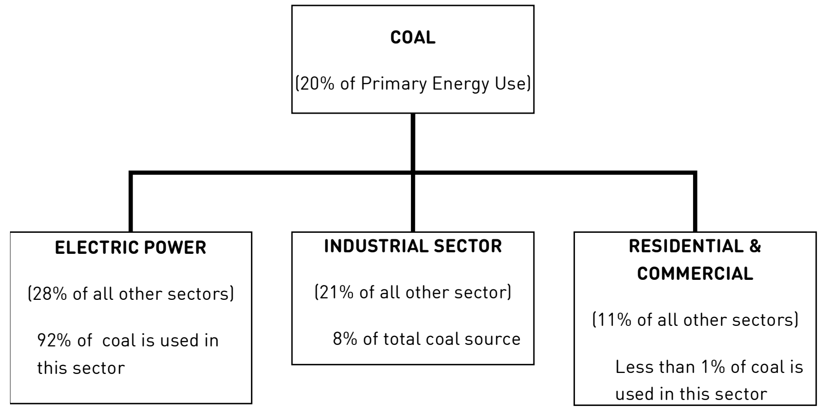

FIG. 2.2 Primary Energy Consumption: Coal, by Source and Sector, 2011, based on data retrieved from https://www.eia.gov/totalenergy/data/annual/pdf/sec2_3.pdf *(Image by Authors)*

Partial decomposition of dead vegetation in high humidity, at the early stage of coalification creates a solid form of peat. The reason why peat is not considered as a renewable source is that its regeneration period is very long. Milled peat and sod peat are two forms of peat available to be used as a fuel.Milled peat can be used in power stations and for manufacture of briquette (IRES, 2016).

Fossil energy- oil and gas
"Oil and gas are terms that refer to mixtures of hydrocarbon molecules in the liquid phase and gas phase, respectively. Crude oil is a mixture of hydrocarbons that exists in liquid phase in natural underground reservoirs and remains liquid at atmospheric pressure after passing through facilities on the surface that separate gas and liquid" (Fanchi, 2013, p. 49).

Crude oil, after refining, is used in the transportation sector as fuel for generation of electric power, and as a fuel in the commercial, industrial, and residential sectors. There are conventional and unconventional oils and gas. Unconventional oil refers to hydrocarbon production from shale oil and tar sands, while unconventional gas refers to coal gas, tight gas, and shale gas. The main difference between the two is the ability of the fluid to flow through rock (US EIA, 2012).

Oil shale or oil sand is a sedimentary rock that contains kerogen, waxy hydrocarbon material regarded as a predecessor to petroleum. Petroleum is a naturally occurring mixture that consists of hydrocarbons in the gaseous, liquid, or solid phase (UNECE, 2004).

An overview of petroleum use in different sectors is given in the diagram below with the remark that this primary energy source, as accounted for in the statistical energy balance, is given before any transformation to secondary or tertiary forms of energy.

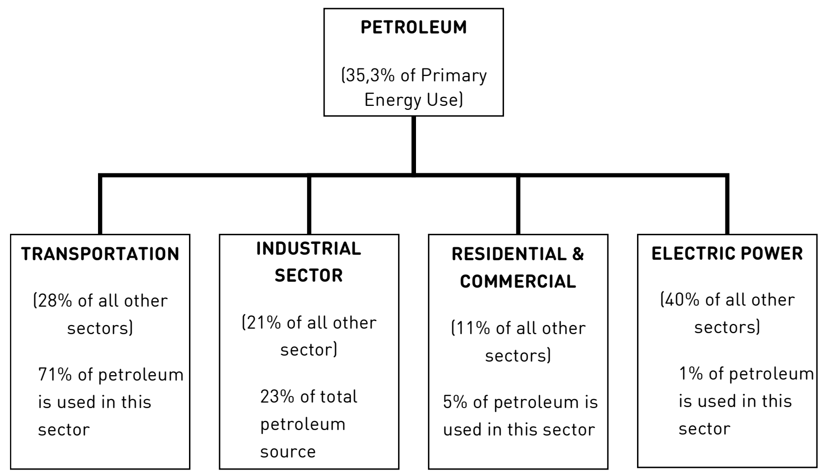

FIG. 2.3 Primary Energy Consumption: Petroleum, by Source and Sector, 2011, based on data retrieved from https://www.eia.gov/totalenergy/data/annual/pdf/sec2_3.pdf *(Image by Authors)*

Natural gas represents a mixture of gaseous hydrocarbons; methane, ethane, propane and nitrogen and carbon dioxide as non-combustible gases (IRES, 2016).

Conventional crude oil, in liquid phase, exists under normal surface pressure and temperature and usually flows to the surface under pressure from the natural reservoir.

An overview of the use of natural gas in different sectors is given in the diagram below.

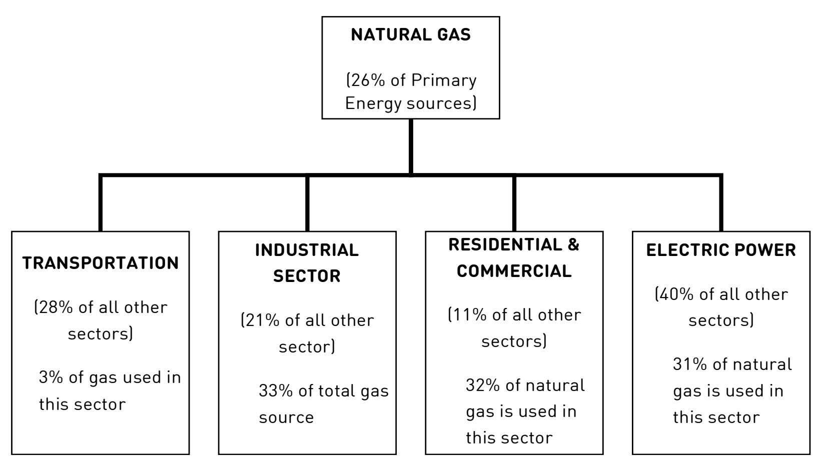

FIG. 2.4 Primary Energy Consumption: Natural Gas, by Source and Sector, 2011, based on data retrieved from US EIA 2011, https://www.eia.gov/totalenergy/data/annual/pdf/sec2_3.pdf *(Image by Authors)*

Nuclear energy

The dominant energy source in the 20^{th} century was fossil fuels. Considering the fact that the supply of fossil fuels is limited, and the fact that the combustion of these fuels is creating greenhouse gases, there is a motive to search for and use other sources of energy. The energy source that is interesting for researchers in this context is nuclear fission energy. Energy is obtained from two types of reaction: fission and fusion.[1] Nuclear fusion is considered to be the technology of the future.

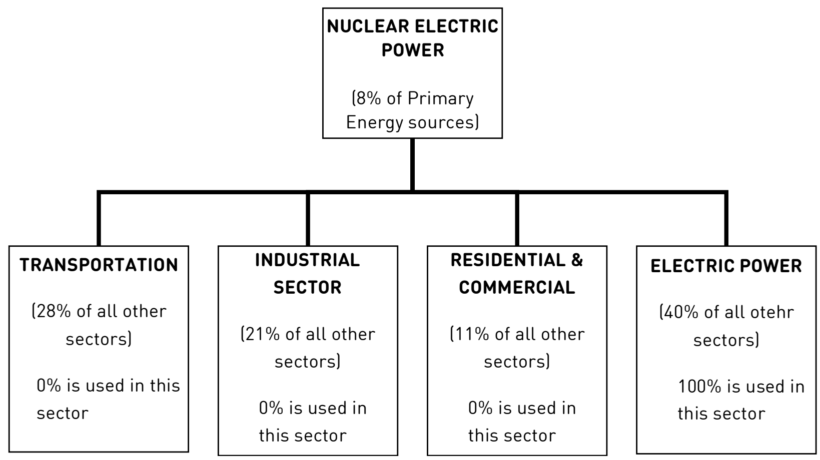

FIG. 2.5 Primary Energy Consumption: Nuclear Energy, by Source and Sector, 2011, based on data retrieved from US EIA, 2011, https://www.eia.gov/totalenergy/data/annual/pdf/sec2_3.pdf *(Image by Authors)*

Uranium is the most plentiful fuel for nuclear fission. In the earth it exists as mineral uraninite or uranium oxide (U_3O_8), that can be found in sedimentary rocks. Uranium is obtained from the mineral uraninite in the mining process. Uranium is considered as a non-renewable energy resource as it exists in a limited volume in the earth. Other fuels that can be used are plutonium and thorium. All three can be used in nuclear reactors, as sources to produce heat and electricity (Fanchi, 2013).

Nuclear energy consumption by source and sectors is shown in Fig. 2.5.

1 Fission is the splitting of one large nucleus into two smaller nuclei; fusion is the joining of two small nuclei into one larger nucleus.

Renewable energy sources (RES)

Renewable energy sources (RES) supply almost 14% of total energy demand. RES includes hydropower, geothermal, biomass, solar, wind, and marine energies. "Renewable energy sources are those resources which can be used to produce energy again and again, e.g. solar energy, wind energy, biomass energy, geothermal energy, etc. and are also often called alternative sources of energy. Renewable energy sources that meet domestic energy requirements have the potential to provide energy services with zero or almost zero emissions of both air pollutants and greenhouse gases." (Panwar, Kaushik, & Kothari, 2011, p.1514.)

An overview of RES use by sectors is given in the diagram below.

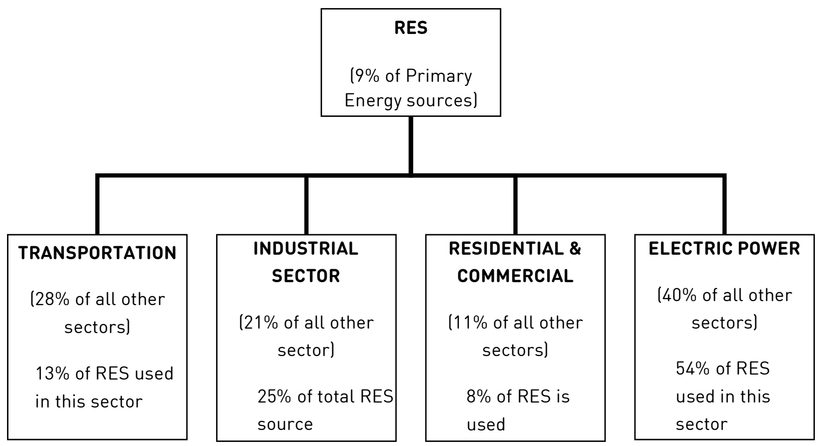

FIG. 2.6 Primary Energy Consumption, RES, by Source and Sector, 2011, based on data retrieved from US EIA 2011, https://www.eia.gov/totalenergy/data/annual/pdf/sec2_3.pdf *(Image by Authors)*

Solar energy

"Renewable is a misnomer when talking about solar energy. Solar energy is provided by the Sun from nuclear fusion reaction. The nuclear fusion process in the Sun consumes isotopes of hydrogen to form helium and release energy" (Fanchi, 2013, p.133). In some time, the fuel for nuclear fusion will be exhausted. However, the remaining time of the Sun is expected to be billions of years and therefore many people consider solar energy to be inexhaustible. The fact is that solar energy is limited but available for many future generations. In spite of the nature of solar energy, without the Sun there is no life on Earth and that is why the general comprehension is that solar energy is renewable.

Around 35% of the light from the Sun doesn't reach Earth because of the clouds, atmosphere and reflection from the Earth's surface.

Whilst fossil and nuclear energy provide energy on demand, RES, like wind and solar, are considered as intermittent energy sources because of their availability. Solar energy relies on access to sunlight, which is not always available and never available during the night, just as wind energy also depends on weather conditions.

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FIG. 2.7 Solar power plant *(Photograph by MTI, retrieved from https://dailynewshungary.com/hungary-solar-power-capacity-reach-2100-mw-end-2018/*

FIG. 2.8 Wind turbine *(Image retrieved from https://cleantechnica.com/2014/04/21/real-innovation-wind-energy/)*

Solar power plants
Solar power plants are designed to provide electrical power in the same way as plants that rely on nuclear or fossil fuel. They use reflective materials like mirrors to concentrate solar energy.

Wind energy
Air motion, wind, is caused by a difference in air pressure. The kinetic energy of moving air is considered to be renewable. Wind turbines convert the mechanical energy of rotating blades into electrical energy with a generator. Converted energy is transmitted through a line that connects the wind turbines to the electric grid with a generator that produces electricity directed to an electric grid.

Energy from water
Water as a renewable energy source makes an important contribution to worldwide energy consumption. "The water cycle is a global cycle of moving water. Water evaporates from lakes and oceans and rises into the atmosphere, where it coalesces into clouds. Clouds can move over all parts of the earth until atmospheric pressure and temperature changes lead to water precipitation in the form of rain or snow. Some of the precipitated water seeps into the earth as groundwater, and some flows along rivers and streams back to lakes and oceans, where the water cycle begins again. The hydrosphere includes groundwater and water found in oceans, glaciers, surface waters such as rivers and lakes, and atmospheric moisture" (Fanchi, 2013, p.183).

Hydroelectric power is an example of the creation of energy from moving water. The movement of water and its temperature gradients are used for providing energy.

A scheme of work of a hydroelectric power plant is presented in Fig 2.9.

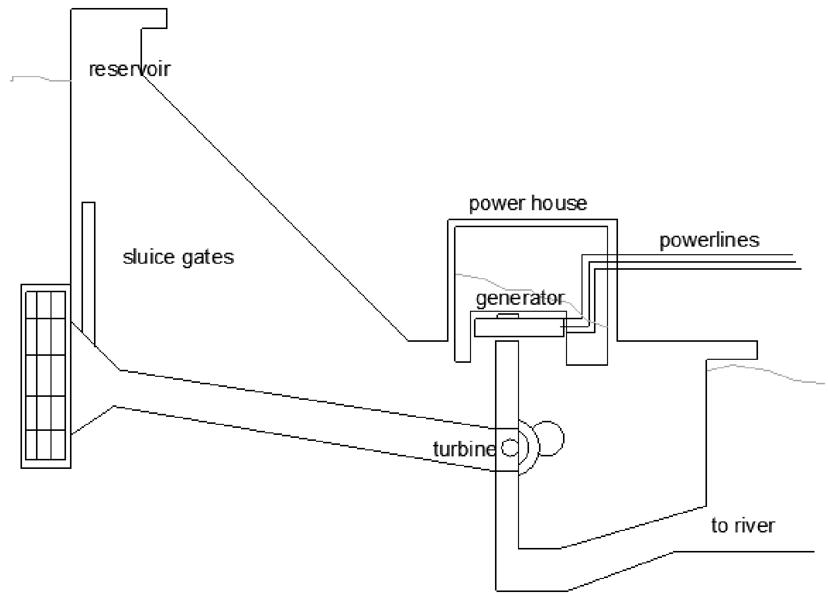

FIG. 2.9 Hydroelectric power plant, based on data retrieved from http://www.tutorvista.com/content/science/science-ii/sources-energy/hydro-electric-power.php *(Image by Authors)*

Energy from waves and tides

While renewable energy research is focused on the development of solar, wind, and biomass sources, it is important to keep in mind the massive energy stored in oceans. The benefit of the creation of a system of energy consumption from the waves or tides derives from the fact that much of the infrastructure already exists due to the role of the oil industry. The process of energy transformation in the oceans is as follows: "Ocean thermal energy conversion produces electricity from the natural thermal gradient of the ocean, using the heat stored in warm surface water to create steam to drive a turbine, while pumping cold, deep water to the surface to re-condense the steam. In closed-cycle warm seawater heats a working fluid with a low boiling point, such as ammonia, and the ammonia vapor turns a turbine, which drives a generator" (Pelc & Fujita, 2002, p. 473.).

In total, it is estimated that about 10 TW (10 trillion W or 10 billion kW) of power, can be provided by the conversion of ocean thermal energy without affecting the thermal structure of the ocean (Pelc & Fujita, 2002).

Bioenergy and synfuels

Biomass includes wood and other plants or animal substances, that can be burned directly or converted to fuels. During combustion, biomass is transformed into useful energy. There are technologies that convert animal dung, plant garbage, and municipal solid waste into natural gas. An example of energy conversion from biomass is the production of gas from organic waste in landfills.

Biofuels are derived directly from biomass. The table shows the current categories and utilisation of biofuels.

BIOFUELS				
Solid biofuels				
Wood- fuel Wood pellets used as fuel	**Bagasse** From fibre after juice extraction	**Animal waste** When dry used directly as a fuel	**Black liquor** For pulping process	**Charcoal** As fuel for transport, electricity or stationary engines
Liquid biofuels				
Bio gasoline Blended with petroleum and used directly in engines		**Biodiesels** Used for diesel engines		**Biojet kerosene** Replacing jet kerosene
Bio gasses				
From anaerobic fermentation To be processed to remove carbon dioxide		**From thermal processes** Produce substitute natural gas		

TABLE 2.3 Biofuels and their uses, based on IRES, 2016*(Image by Authors)*

Geothermal energy

Heat from the earth is geothermal energy. Sources of geothermal energy can be from shallow ground to hot rock and water found miles under the Earth's surface and even deeper to magma (molten rock). Hot dry rock resources occur at the depth of 3 to 5 miles beneath the Earth's surface. Shallow ground maintains a constant temperature of 10°C to 16°C. Geothermal pumps can tap into the source to heat and cool buildings. "A geothermal heat pump system consists of a heat pump, an air delivery system (ductwork), and a heat exchanger- a system of pipes buried in the shallow ground near the building. In the winter, the heat pump removes heat from the heat exchanger and pumps it into the indoor air delivery system. In the summer, the process is reversed, and the heat pump moves heat from the indoor air into the heat exchanger. The heat removed from the indoor air during the summer can also be used to provide a free source of hot water" (Geothermal Energy Association, 2016).

Geothermal electricity production that generates electricity from the Earth's heat is one of the existing geothermal energy technologies. Besides this, there is geothermal direct use, which takes heat directly from the hot water in the earth. A final existing geothermal energy technology is the geothermal heat pump that uses heat from shallow ground for heating and cooling buildings.

2.1 Secondary Energy

The first law of thermodynamics states that "Energy can neither be created nor destroyed." In other words, it just changes from one form to another.

"Energy transformation is any process of transforming energy. Energy of fossil fuels, solar radiation, or nuclear fuels, which are all primary, can be converted into other energy forms such as electricity and heat that are more useful to us. All energy that has been subjected to human-made transformation is secondary energy" (Overgaard, 2008, p.5.).

The classification of primary energies and their conversion into secondary energies is provided in Table 2.4.

	Primary	Secondary
NON-RENEWABLE	– Hard coal – Brown coal	– Coal products
	– Peat	– Peat products
	– Oil shale – Natural gas	– Manufactured solid fuels and gases
	– Conventional crude oil – NGL – Additives and oxygenates	– Refinery feedstock – Petroleum products
	– Industrial and municipal waste – Nuclear and Heat from chemical processes	– Electricity and heat from combusted fuels of fossil origin – Electricity from nuclear heat, chemical processes – Any other product derived from primary/secondary non-renewable products
RENEWABLE	– Biofuels (except charcoal) – Municipal waste – Heat from renewable sources, except from combusted biofuels – Electricity from renewable sources, but not from geothermal, solar thermal or combusted biofuels	– Charcoal – Electricity and heat from combusted biofuels – Electricity from geothermal and solar thermal

TABLE 2.4 Classification of energy products, primary energy and their conversion in secondary energy *(IRES, 2016, p.178)*

Coal products

Coal products are derived either directly or indirectly from different classes of coal, through carbonisation or pyrolysis processes. All of the coal products and their uses are given in Table 2.5.

	Coal product	Products of the product	Use
COAL PRODUCTS	**Coal coke**	Coke oven coke	Heat source in Iron and steel industry
		Gas coke	For heating purposes
		Coke breeze	Residue from screening coke
		Semi cokes	Used as heating fuel
	Patent fuel	Hard coal briquettes	Possible substitute for wood fuel
	Brown coal briquette (BKB)		Composition fuel
	Coal Tar, LCD		Medical and industrial
	Coke oven gas		To produce coal coke
	Gas works gas		
	Recovered gas	Blast furnace gas	As fuel and to heat blast air
		Oxygen steel furnace gas	Industry
		Other recovered gases	

TABLE 2.5 Coal products and their use *(IRES, 2016, p.35-38)*

Peat products

Peat products are derived from sod peat and milled peat. Peat products comprise peat briquettes that are used mainly as household fuel and other peat products such as peat pellets.

Oil products

Oil products are obtained from crude oil, gases from oil, or gas fields. Production is done through the refining of crude oil or during separation process of natural gas (IRES, 2016, p. 39-45.).

An overview of oil products and their use is shown in the Table 2.6.

	Oil product	Products of the oil product	Use
OIL PRODUCTS	**Refinery gas**		Mainly use as a fuel in refinery
	Ethane		Feedstock for petrochemical manufacture
	Liquid petroleum gases LPG		Used for heating and as vehicle fuel
	Naphtha		Manufacture of olefins in petrochemical industry
	Gasolines	Aviation	For aviation piston engines
		Motor gasoline	For motors
		Gasoline type jet fuel	Aviation turbine fuel
	Kerosines	Type jet fuel	As jet fuels
	Gas oil	Diesel oil	For diesel engines
		Heavy gas oil	Gas oil and fuel
		Fuel oil	Industrial fuel oil
	Other oil products	Lubricants, paraffin waxes, bitumen...	

TABLE 2.6 Oil products and their use *(IRES, 2016)*

Waste

Waste means material that is no longer required by its holders, and, in general comprises municipal and industrial waste. Industrial waste often consists of used tires or special residues from chemical industry, while municipal waste is collected at facilities for waste disposal with a system of recovery for liquids, gases, or heat.

Nuclear fuels

Nuclear fuels like uranium, thorium, plutonium, and their products, can be used in nuclear reactors for electricity and heat production.

Other than the afore mentioned non-renewable primary energies and their transformation to secondary energies, there also exist renewable primary energy sources whose conversions are given in the following chapter.

Biofuels

Biofuels are derived directly or indirectly from biomass.

	Biofuels	Categories	Subcategories	Use
BIOFUELS	**Solid biofuels**	Wood fuel	Wood pellets	As fuel
			Wood residues and by products	As fuel
		Bagasse		Fuel
		Animal waste		Directly as fuel
		Black liquor		Fuel in pulping process
		Charcoal		Fuel
	Liquid biofuels	Biogasoline	For transport and electricity	
		Biodiesel		
		Biojet kerosine		
	Biogases	Biogases from anaerobic fermentation	As fuel	
		Landfill gas		
		Sewage sludge gas		

TABLE 2.7 Biofuels, products of biomass *(IRES, 2016)*

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There are three categories of biofuels defined based on physical state of the material: solid, liquid biofuels, and biogases. Biofuels are presented in Table 2.7.

2.2 Concept of Energy Flow

The term "energy flow" refers to the production, bunkering, transformation, import, export, use of energy by industries, and losses during the transformation processes, to the final consumption of energy products.

Energy production is of major importance in the energy flow process, and can be primary and secondary. Primary refers to the extraction of energy from natural energy flows whilst secondary refers to the manufacture of energy products through the process of transformation of other energies.

ENERGY INDUSTRY	MANUFACTURE PROCESS
Electricity, CHP and heat plants	Electricity, steam and air conditioning supply
Pumped storage plants	
Coal mines	Coal and lignite
Coke ovens	Coke oven products
Coal liquefaction plants	Refined petroleum products
Patent fuel plants	Refined petroleum products
Brown coal briquette plants	Refined petroleum products
Gas works	Gas, distribution of gaseous fuels
Gas separation plants	Crude petroleum and natural gas
Gas to liquid plants GTL	Refined petroleum products
LNG plants	Support of petroleum and natural gas extraction
Blast furnaces	Of basic iron and steel
Oil and gas extraction	Crude petroleum and natural gas
Oil refineries	Refined petroleum products
Charcoal plants	Manufacture of basic chemicals
Biogas production	Gas
Nuclear fuel extraction and fuel processing	Uranium and thorium ores
Other energy industry	Extraction of peat

TABLE 2.8 Energy industries with their main activities *(IRES, 2016)*

After production, energy, or part of it moves to one or more different energy products (like heavy fuel oil to electricity). The process is called transformation of energy, and is identified by the plants in which it occurs: electricity plants, CHP plants, heat plants, coke ovens etc. Besides transformation, there is a need to define losses as a very important part of the energy flow concept. Losses merge during the distribution, transmission, and transport of fuels, heat, and electricity. The energy that is extracted, produced, transformed and distributed with the losses in the process of the flow results in what is called final consumption, or- useful energy.

Final consumption refers to all fuels and energy that is delivered to the final consumers, or end users.

Energy industries are involved in primary production, distribution, and transformation of energy products. Industries and their basic activities are listed in the Table 2.8.

Electricity and heat

Electricity is defined as "transfer of energy through the physical phenomena involving electric charges and their effects when at rest and in motion" (IRES, 2016, p.49). It can be generated within the generating plants in different processes like conversion of energy of falling water, wind or waves, by combustion of fuels or through photovoltaic process.

There are three types of generating plants:

- Electricity plants that only produce electricity that can be obtained from geothermal, wind, hydro, tidal, solar energy, or from nuclear reactions.
- Combined Heat and Power (CHP) plants that produce heat and electricity.
- Heat plants that produce heat only.

Heat is "energy obtained from the transitional, rotational and vibrational motion of the constituents matter, as well as changes in its physical state. Heat can be produced by different production processes" (IRES, 2016, p. 50).

An overview of the electricity and heat that can be generated through different technologies is given in Table 2.9.

PRODUCTION	
Electricity	
Solar PV electricity	from solar photovoltaics
Solar thermal electricity	from solar heat
Wind electricity	from devices propelled by wind
Hydro electricity	by devices propelled by falling water
Wave electricity	by devises driven by motion of waves
Tidal electricity	by devices driven by tidal motion
Geothermal electricity	Generated from the heat from geothermal sources
Nuclear electricity	Generated from nuclear heat
Heat	
Solar heat	Generation of heat from solar thermal
Geothermal heat	Heat extracted from earth
Nuclear heat	Obtained from the nuclear reactor fluid
Heat from combustible fuels	Combustion of fuels, same for electricity
Heat from chemical processes	Generated in Chemical Industry

TABLE 2.9 Types of technologies for generation of heat and electricity

2.3 Final Energy

The term itself refers to the use of services and goods by individual households in order to satisfy individual and collective needs.

Final energy use is divided into three categories: industry, transport, and other. The *other* category includes agriculture, services, and residential buildings. Services refers to all commercial buildings and energy services within them, including HVAC, and food preparation. Buildings, both domestic and nondomestic, account for up to 40% of the total energy consumption. "Growth in population, enhancement of building services and comfort levels, together with the increment of time spent inside buildings, has raised building energy consumption to the levels of transport and industry." Industry accounted for 39% of total energy use at the end of twentieth century, transport 25%, and other sectors for 36% of total energy use. The situation is different nowadays (Table 2.10.). The growth in population caused an increased demand of services like health, education, culture, and the energy consumption within them, at the rate of 2% per annum worldwide (Lombard, Ortiz, & Pout, 2008, p. 395.).

SECTOR	FINAL ENERGY CONSUMPTION %
Industry	30
Transport	28
Other sectors	42

TABLE 2.10 Final energy consumption by sectors worldwide *(Lombard, Ortiz, & Pout, 2008)*

3 Basics of Energy Balance of Buildings

The building sector is responsible for 16–50% of the energy consumption in the world, compared to the consumption by all other sectors, which averages approximately 40% worldwide (Swan & Ugursal, 2009). Energy consumption in buildings significantly differs based on location, area, and applied structural materials. It consists of thermal energy used for space heating and hot water, and electrical energy for air conditioning, cooling, ventilation, equipment, and lighting.

Conventional buildings are those that are built according to the common practice of a specific country in a specific period. These buildings use 200-300 kWh/m^2 of heating energy while low energy houses consume 40 kWh/m^2 and passive houses 15 kWh/m^2 or less (Sartori & Hestnes, 2007). In developed countries, energy saving is of very high priority. In the process of design and construction, the adaptation of suitable parameters such as building orientation, shape, envelope system, mechanisms of passive heating and cooling, as well as shading and glazing, are vital in energy saving. However, in existing buildings where it is impossible to change the most important parameters, energy efficient retrofitting measures should be highly implemented (Pacheco, Ordonez, & Martinez, 2012).

The focus is placed on the thermal envelope of the buildings where different passive and active features can be applied. The structure's thermal envelope refers to its elements that are in contact with the outside air – these are the elements by which the heated and the unheated spaces are separated: transparent and non-transparent parts. The transparent elements are the windows, patio doors, front doors, and storefronts, while the exterior walls are considered the non-transparent parts of the facade assembly. The transparent elements account for the highest percentage of heat energy losses; 40% of energy is lost through standard façade doors and windows, which, therefore, need to receive special attention (Miletic, 2014).

In one conventional residential house, ventilation and transition losses through transparent parts of the building are up to 51%, internal gains account for 6%, and solar gains 12% while losses through the heating system are 12% (Stojiljkovic, 2014). Such losses show the potentials for energy saving, and for the implementation of energy efficiency measures. It is known that 40% of all primary energy is used for buildings, and in adition, that through architectural retrofitting it is possible to achieve a 60% saving in heating energy (Asif, Muneer, & Kelley, 2007).

Heat losses during the heating period for the conventional residential house are shown in Fig. 3.1.

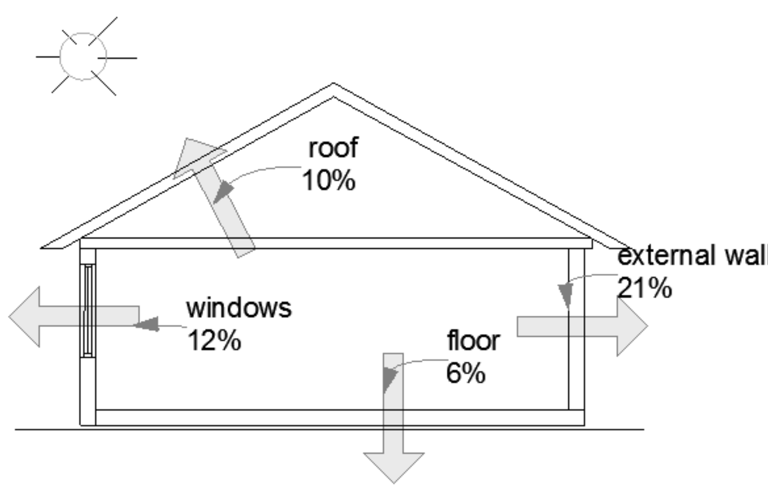

FIG. 3.1 Heat losses during the heating period of residential house *(Image by Authors)*

3.1 Passive Retrofitting Interventions

Some of the technologies that enable the capture of solar energy are passive features. Passive technologies do not use mechanical devices. Simple passive systems are roof overhangs (shades) and thermal insulation. One of the ways of controlling direct solar heating in buildings with transparent sections of the façade is the construction of roof overhangs.

Thermal insulation installed in walls can keep heat out of a structure during the summer and keep heat inside the room during the winter period, thus demonstrating another passive technology. This strategy reduces the demand of total energy use in the observed structure.

This passive measure of energy saving applies of thermal insulation to the non-transparent parts of the thermal envelope. The thermal insulation can be found in different physical forms, such as (Sadineni, Madala, & Boehmn, 2011):

- Mineral fibre blankets (such as fiberglass and rock wool);
- Poured-in with concrete (cellulose, perlite, vermiculite);
- Loose fill, which can be blown-in (fiberglass, rock wool);
- Rigid boards (polyisocyanurate, polystyrene, polyurethane and fiberglass);
- Boards or blocks (vermiculite and perlite);
- Foamed (polyisocyanurate and polyurethane);
- Reflective materials (aluminium foil, ceramic coatings);
- Insulated concrete blocks.

The strategy of initial improvement by passive retrofitting interventions implies the upgrading of thermal insulation, both in fabrics and thickness, which can be applied internally or externally. One of the ultimate achievements should be that the value of thermal transmittance, or U- value (W/m^{2}K) is reached by retrofitting actions on different parts of the thermal envelope thus reducing energy consumption. Values are given by Passive House Regulation (EnerPHit/EnerPHit^{+i} for retrofitting of existing buildings) in the table below.

DESCRIPTION U [W/m^{2}K]		EnerPHit/EnerPHit^{+i} U [W/m^{2}K]
External wall	External insulation	≤ 0,15
	Internal insulation	≤ 0,35
Floor		≤ 0,15/f (f-temperature factor)
Roof		≤ 0,15
Transparent part of facade		≤ 0,85
Air infiltration		max n_{50} ≤ 1,0
ENERGY		*kWh/m^{2}a*
Heating energy		≤ 25
Cooling energy		Defined through Primary energy
Specific Annual Primary Energy		Qp≤ 120+((Qh-15)x1,2)

TABLE 3.1 Maximum U-values and expended energy based on EnerPHit/EnerPHit+ certification *(Passive House Institute, 2016)*

Glass is treated as a special class in the context of materials that are important for the thermal insulation of buildings- because, by its nature it is a poor thermal insulator. One measure of passive retrofitting is the increase of opening sizes and the replacement of existing glazing.

For heat and light energy transfer, glazed surfaces should meet the following requirements (Table 3.2.):

- minimise heat loss (outward heat transfer)
- minimise heat gains (inward heat transfer)
- provide the optimum amount of light (Miletić, 2014).

TYPE OF GLASS	HEAT TRANSFER COEFFICIENT U (W/m² K)	TOTAL SUN ENERGY TRANSFER g	LIGHT PERMEABILITY T
Duplex thermo insulation glass	≥ 1.1	0.55-0.65	0.8
Triplex thermo insulation glass	≥ 0.5	0.5	0.4-0.7
Sun radiation controlling glass	≥ 1.1	0.5-0.65	0.7-0.8

TABLE 3.2 Requirements glass needs to meet, regarding its heat and light energy transfer properties *(Miletić, 2014)*

Besides improvements in the previously mentioned parts of the façade, the roof is considered to be part of the thermal envelope of the building in which increasing the thickness of insulation is one of the verified methods of improvement. As a special intervention, the construction of a green roof is shown to be a successful tool in gaining economic and environmental benefits, reducing energy consumption and costs for end users, and also minimising the environmental impact due to low emissions. “Green roofs could be seen as a design technique which contributes to achieving sustainable development postulates in urban areas. Diverse benefits of green roofs, from environmental, economic and social aspects, have been confirmed by numerous studies worldwide” (Stamenković, Miletić, Kosanović, Vučković, & Glišović, 2017).

3.2 Active Retrofitting Technologies

Active solar energy represents the construction of systems that collect and convert solar energy into other energy forms, like heat and electricity. Solar heat collectors are features of active energy technology.

Solar heat collectors transform radiant energy into heat energy by capturing sunlight. Photovoltaic (PV) systems produce electricity directly from solar radiation. These systems became widespread in domestic buildings, producing lighting and general power (PV installation guide, 2001). A photovoltaic scheme is presented in Fig. 3.2.

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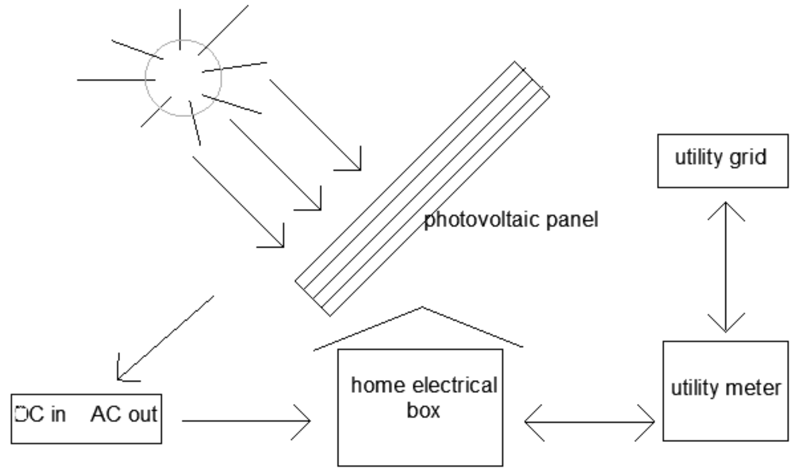

FIG. 3.2 Photovoltic scheme, based on data retrieved from http://www.growbygreen.in/knowledge.php *(Image by Authors)*

3.3 Estimation of Effects of the Implemented Measures

Building energy modelling and dynamic simulations can be used to estimate the energy performance of building, HVAC sizing, lighting requirements, or economic feasibility. All proposed retrofitting measures, and their effects in energy saving, can be evaluated through different software like EnergyPlus, BLAST, DOE-2.1E, ECOTECT, Ener-Win, Energy Express, Energy-10, eQUEST, ESP-r, IDA ICE, Integrated Environmental Solutions IES/VE, HAP, HEED, BSim,DeST, PowerDomus, SUNREL, Tas, TRACE and TRNSYS (Sadineni, Madala, & Boehm, 2011). Basically, these programs have modules to evaluate the application of different individual, or group, energy efficiency measures selected after defining methodology for improvement. These modules can be used by building designers to develop an optimal energy efficient building (Dodoo, Tettey, & Gustavsson, 2017). The accuracy of the building energy simulations depends on user input data such as geographic location, orientation, building geometry, construction details, mechanical equipment, existing parameters of HVAC system, type of building, thermal characteristics etc.

4 Conclusions

The increase of primary energy consumption by almost 50% in the final years of the twentieth century, and the increase of overall CO_2 emissions by 45% with an average increase of 2% per year have raised big concerns for population and governments worldwide.

In the process of energy flow, final consumption refers to the use of fuel, electricity, or heat that is delivered to end users. That final energy use is divided into three categories within different sectors: industry, transport, and a third sector that includes agriculture, and commercial and residential buildings. Industry accounts for 39% of total energy use, transport 25% and other sectors 36%.

Currently, industry uses 8% of total coal resources worldwide, the electrical power sector uses 92%, while other sectors use less than 1%. Transportation uses 71% of the total petroleum sources, while the residential sector 32% of total source of natural gas, and the electric power sector uses 100% of nuclear electric power resources.

A constant increase in energy demand and energy consumption is putting pressure on the finite availability of mentioned fossil fuels.

The trend is moving towards an increase in the use of renewable energy sources, RES, and their systems. At present, the situation is as follows: 13% of total RES is used in the transportation sector, 25% in industrial, 11% in residential and 54% in electric power systems.

One of the predicted scenarios, in the sense of increased use of RES indicates complete replacement of nuclear and fossil fuels with renewable energy only. A very important objective of this scenario is the reduction of greenhouse gas emission to levels that are considered safe. One obstacle to this scenario is that most of the global energy infrastructure is designed to use fossil fuels. A conversion from fossil fuels to forms of renewable energy will require the construction of a completely new infrastructure. An attempt to move too quickly away from fossil energy can disrupt the modern economy, whereas moving too slowly toward energy sustainability can lead to undesirable and irreversible changes to the climate. The transitional rate should be optimised.

Some governments are encouraging or requiring the development of energy saving technologies within the building sector. Energy use in this sector accounts for almost 50% of that consumed by all other sectors, approximately 40% worldwide. Some of the measures to decrease energy consumption and improve energy efficiency are passive and active features that were mentioned earlier. We can expect energy saving to increase in the future as a result of a more widespread adoption of energy efficiency measures and by improvements in energy conversion efficiency. However, we should not expect energy conservation and implementation of the energy saving measures to be enough to satisfy global energy needs. It is essential for the building industry to achieve sustainable development, meaning development with low environmental impact. To achieve this goal, there is a need to adopt a multi-disciplinary approach such as energy saving, energy conservation measures, retrofitting actions, and reuse and recycling of materials with control of greenhouse gas emissions. That should be the overall objective - to start from small actions so as to achieve a remarkable one.

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Resilience of Renewable Energy Systems

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ABSTRACT **Resilience is the ability of a system to resist unwanted influences and effects during its proper operation. The concept of resilience provides a new framework for how to "measure" the vitality/adaptability of systems and analysis systems, which faces many challenges (predictable and/or sudden changes). The resilience index of a defined energy system with the selection of the specific indicators reflects specific constraints, namely the change of individual indicators with other indicators being constant. The paper in the analysis of renewable energy systems (PV-solar and wind-based power plants) takes into consideration the following indicators: change of electricity costs, change of energy consumption of the system, change of the energy costs, change of electricity, change of concentration pollution gases for solar power plant, and change of wind power density, change of efficiency of wind power plant, change of frequency and change of electricity costs for wind power plant.**

KEYWORDS resilience, indicators, renewable energy

1 Introduction

A system is in control if it is able to minimise or eliminate unwanted variability, either in its own performance, in the environment, or in both. In order to be in control, it is necessary to know what has happened, what is happening, and what may happen, as well as knowing what to do and having the required resources to do it. A resilient system must have the ability to anticipate, perceive, and respond (Afgan, 2010). When resilience is lost or significantly decreased, a system is at high risk of shifting into a qualitatively different state. Restoring a system to its previous state can be complex, expensive, and sometimes even impossible.

Resilience provides a new framework for analysing economic, ecological, technological, and social systems in a changing world that faces many uncertainties and challenges. It represents an area of explorative research under rapid development with major policy implications for sustainable development.

Since the beginning of the 1990s, there has been a growing evolution of the principles for organisational resilience and in the understanding of the factors that determine human and organisational performance. The research group uses a different terminology and provides the term engineering resilience for the property resilience and the term ecological resilience for the stability property robustness (Afgan, 2010).

By appreciating the dynamic and cross-scale interplay between abrupt change and sources of resilience, it is obvious that the resilience of complex adaptive systems is not simply about resistance to change and conservation of existing structures. Resilience is defined as the capacity of a system to absorb disturbance and reorganise while undergoing change, so as to still retain the same essential function, structure, identity, and feedbacks (Folkea, 2006).

Resilience is the ability of any system to avoid or minimise, and recover from, the effects of adversity, under all circumstances of use. In addition, resilience can be defined in at least two more ways. The first is a measure of the magnitude of disturbance that can be absorbed before the system changes its structure by changing the variables and processes that control behaviour. The second, a more traditional meaning, is a measure of resistance to the disturbance and the speed of return to the equilibrium state of a system (Afgan, 2010).

The resilience of an energy system is defined as the capacity of an energy system to withstand perturbations from e.g. climatic, economic, technological, and social causes and to rebuild and renew itself afterwards (Kainan, 2006).

The time change of the economic indicators is common to the classical evaluation of a system. Any crises of the economic system are preceded with corresponding changes in the economic indicators of the system. Qualitative measurement of the indicator changes may lead to the forecast of the economic crises, which is only one element of the potential disastrous changes of the system that affects its safety (Afgan & Carvalho, 2008).

The change of social element of complexity of the system is a property of the complex system. The social aspect of the system includes the risk of changes as health hazards and may have to deal with a compounding of complexity at different levels. It is of interest to notice that some of the social changes are inherent characteristics of the system. As an example, we can take any strike, which is the result of the economic changes of the system. A similar example can be seen if there is a sudden change in the environment, which will lead to social disturbances (Afgan, 2010). This paper is devoted to the resilience assessment of renewable energy systems (primarily PV-solar power plant and wind power plant), as a complex problem for the urban community.

2 Renewable Energy

Renewable energy continued to grow against the backdrop of increasing global energy consumption, particularly in developing countries, and a dramatic decline in oil prices during the second half of 2014. 176 countries (increased again) had defined renewable energy targets by 2016 (REN21, 2016, REN21 2017). Globally, there is a growing awareness that increased deployment of renewable energy is critical for addressing climate change, and thereby creating new economic opportunities. Renewables also are an important element of climate change adaptation, improving the resilience of existing energy systems and ensuring delivery of energy services under changing climatic conditions.

Renewable energy (all renewables) provided an estimated 19.3% of global final energy consumption in 2015. The most rapid growth, and the largest increase in capacity, occurred in the power sector, led by wind, solar PV, and hydropower. Growth has been driven by several factors, including renewable energy support policies and the increasing cost-competiveness of energy from renewable sources (REN21, 2017).

The supply of biomass for energy (heat, power, and transport) has been growing at around 2.5% per year since 2010 (REN21, 2017). The geothermal industry (for electricity and thermal energy) continues to face significant project development risk, and various efforts are underway to ameliorate such risks in developed and developing countries (REN21, 2016, REN21 2017). Geothermal energy global output was 78 TWh for power and 79 TWh for heat, in 2016 (REN21 2017). Several EU cities (e.g. Munich, Paris, Bordeaux) are expanding their geothermal district heating network. Ocean energy capacity, mostly tidal power generation, were in some form of pilot or demonstration projects.

Hydropower is still giant among its peers. Global hydropower capacity reached over 1,000 GW (REN21, 2016, REN21 2017). Solar PV is starting to play a substantial role in electricity generation in some countries as rapidly decreasing costs have made unsubsidised solar PV-generated electricity cost-competitive with fossil fuels in an increasing number of locations around the world. The CSP (Concentrating Solar-thermal Power) market remains less established than most other renewable energy markets. Wind power is the cheapest option for new power generation. Wind generated more than 20% of electricity in several countries: Denmark (37%), Ireland, and Portugal. 11 out of the 28 Member States had a wind penetration rate of more than 10% (Nghiem & Mbistrova, 2017).

In recognition of the importance of renewable energy and energy efficiency for sustainable development, the United Nations General Assembly declared 2014 the first year of a decade of Sustainable Energy for All (SE4ALL). SE4ALL aims to double the share of renewable energy in the global energy mix from a baseline share of 18% in 2010 to 36% in 2030 (United Nations Decade of Sustainable Energy for All 2014-2024, 2015; Tracking Progress, 2015; Our Objectives, 2015).

New global investment in renewable power and fuels (not including hydropower >50 MW) was USD 241.6 billion in 2016, as estimated by Bloomberg New Energy Finance (REN21, 2017). Renewables outpaced fossil fuels for the sixth year running in terms of net investment in power capacity additions with 9.8 million jobs in 2016 (REN21 2017).

Stronger position in terms of taking responsibility for climate change by the USA during two mandates of President Obama has resulted in the signing of the Paris Agreement of 2013, which opens new perspectives for RES, especially in developing countries. It remains to be seen what lies ahead of us.

3 Renewable Energy and the Environment

Each renewable energy source has its own particularities (hydropower, biomass, wind energy, solar energy, geothermal energy, tidal energy, wave energy, Ocean Thermal Energy Conversion - OTEC). This also relates to environment and landscapes. The focus here will be on only some specifics on wind energy and PV-solar energy.

3.1 Wind Energy

Wind turbines have some negative as well as positive impacts on the environment. The possible negative impacts of wind turbines are: visual impact, noise, fatal accidents involving birds and bats, shadow effect, and pollution during manufacturing and installing the wind turbines, as well as land use, electromagnetic interference, marine mammals, etc. Each wind energy plant must complete an environmental assessment impact and monitoring measures. A number of studies have concluded that these impacts are minor or easy to avoid.

TYPE	ENERCON E-70	NORDEX N80	REPOWER 5M	VESTAS V90/3 MW
Hub height (m)	57 / 64 / 85 / 98 / 113	60 / 80 / 100; 115 (lattice)	100 / 120 onshore	80 / 105
Rated power (kW)	2300	2500	5000	3000
Tower construction	Concrete, tubular steel	Conical tubular steel, lattice	Conical tubular steel	Conical tubular steel
Tower weight (t)	140 / 232 / 336 / 1171	115 / 193 / 281 / 205		175 / 275
Nacelle weight (t)	66	86	290	70
Cut-in wind speed (m/s)	2,5	4	3,5	4
Cut-out wind speed (m/s)	28-34	25	25	25
Rotor diameter (m)	71	80	126	90
Swept area (m^2)	3959	5026	12 469	6362
Rotor speed (rpm)	6-21,5	10,9-19,1	6,9-12,1	8,6-18,4
Blade weight (kg)	6000	8700	19 000	6600

TABLE 3.1 Characteristics of wind turbines *(Johnsen, Baars, & Ellinghaus, 2007)*

Wind turbines (windmills) have been a feature of the landscape of Europe for more than 800 years. Wind turbines are highly visible elements with rotating blades in the landscape. Table 3.1 shows the main gabarit (dimensions) characteristics of some types of wind turbines that can be found on the market.

In flat areas, wind turbines are often placed in a simple geometrical layout, while in hilly areas the turbines follow the altitude contours of the landscape and therefore they have a better layout. Big wind turbines with low blade rotation speed, and similar size and type, fit better in the surroundings than a greater number of small turbines with higher rotation speed, in terms of their visual effect as an environmental factor. Large wind turbines produce the same amount of energy as large number of wind turbines with decreased power. There may be economic advantages to this, such as lower maintenance costs. In the first half of 2016, approx. 71% of the wind turbines erected in Germany had a hub height of more than 120 m (Ender & Neddermann, 2016).

Large modern wind turbines have become very quiet. Birds do collide with high-voltage power lines, towers, cars, windows of buildings. In Denmark there are several examples of birds nesting in cages mounted on wind turbine towers. Some birds get accustomed to wind turbines very quickly, while others take a somewhat longer time. A number of environmental assessment impact and monitoring measures studies (including offshore wind farms) came up with the conclusion that birds almost always modify their migratory routes. However, migratory routes of birds should be taken into account when siting wind turbines.

Wind turbines cast a shadow on the neighbouring area when the sun is visible. The rotor blades cause a flickering (blinking) effect while the rotor is in motion. In Germany, the judge tolerated 30 hours of shadow flicker per year (Hinweise zur Ermittlung und Beurteilung der optischen Immissionen, 2002). In addition, there are possibilities of computing a shadow map (Zlomusica, 2013).

Wind energy plays an important role in helping nations reach Kyoto Protocol targets. Environmental benefits of wind electricity can be assessed in terms of avoided emissions compared to other alternative electricity generation technologies (CO_2, SO_2 and NOx and other pollutants). Emissions that are avoided by using wind farms to produce electricity instead of coal or natural gas power plants are quantified in Table 3.2, comprising NGCC - Natural Gas Combined Cycle and NMVOC - Nonmethane volatile organic compounds. The CO_2 emissions related to the manufacture, installation, and servicing over the average 20-year life cycle of a wind turbine are offset after a mere three to six months of operation, resulting in net CO_2 savings thereafter (Lago, et al., 2009).

	BENEFITS		
	vs. coal	vs. Lignite	vs. NGCC
CO_2, fossil (g)	828	1051	391
SF_6, fossil (mg)	2546	236	984
NOx (mg)	1278	1010	322
NMVOC (mg)	65	3	123
Particulates (mg)	134	693	-6
SO_2 (mg)	1515	3777	118

TABLE 3.2 Emissions avoided by using wind farms to produce electricity *(Lago, et al., 2009)* / Source: CIEMAT

Wind energy is not only a favourable electricity generation technology that reduces emissions, it also avoids significant amounts of external costs of conventional fossil fuel-based electricity generation.

Wind turbines and access roads in wind parks occupy less than 1% of the area in a typical wind park. Table 3.3 shows land used by some power plants in terms of the power produced per square metre.

	SITE	**DATA**	**LAND USE**
Hydropower	Itaipu (Brasil) Spiez (Swiss)	12 600 MW 23 MW	6 W/m^2 70 W/m^2
Coal (lignite) fired plant	Schkopau (Germany) Buschhaus (Germany)	1000 MW 380 MW	8 W/m^2 31 W/m^2
Wind park	Germany	4.5 – 6 m/s	50-120 W/m^2 (rotor area). Foundation area is 10 times less

TABLE 3.3 Power per square metre land used *(Gasch & Twele, 2002)*

The average installed power of an onshore wind turbine reached 2.84 MW in Germany in the first part of 2016. The share of wind turbines with installed power 3.0 – 3.49 MW was 56.6% (Ender & Neddermann, 2016).

The average annual electricity consumption in households in Federation of Bosnia and Herzegovina is 4.483 kWh per year. The average number of occupants in a household is 3.2 (The Institute for Statistics of FB&H, 2016).

An example: The output of a wind turbine depends mainly on the turbine's size and the wind's speed at the location of the wind park. An average wind turbine (onshore) with a capacity of 3 MW can produce more than 6 million kWh per year for Bosnian wind conditions. It is enough to supply 1,338 average Bosnian households or 4,282 members of households with electricity.

3.2 PV - Solar Energy

PV-solar cells can be classified into three type of generation cells. The first generation is made of crystalline silicon (polycrystalline and monocrystalline silicon) and this is a dominant PV technology. The monocrystalline solar panels have the advantage of having the highest efficiency rates (15-20%). Most installed solar panels are monocrystalline panels. The main disadvantage of monocrystalline solar panels is their price. The process used to make polycrystalline silicon is simpler and not expensive. The efficiency of polycrystalline solar panels is about 13-16%.

Second generation or thin-film PV panels have about 12% efficiency rates. The different types of thin-film solar cells can be categorised by which photovoltaic material is deposited onto the substrate:

- Amorphous silicon (a-Si)
- Cadmium telluride (CdTe)
- Copper indium gallium selenide (CIS/CIGS)
- Organic photovoltaic cells (OPC)

Solar panels based on amorphous silicon, cadmium telluride, and copper indium gallium selenide are currently the thin-film technologies that are commercially available on the market. Their mass-production is simple, and they are cheaper, but they require a lot of space in comparison with e.g. monocrystalline.

The third generation of solar cells includes a number of thin-film technologies often described as emerging photovoltaics. Most of them are still in the research or development phase.

For those with limited space, crystalline-based solar panels are the best choice, but if you want the lowest investment costs per rated power then it is advisable to investigate the thin-film solar panels. Different computer programs (calculators) have been developed to calculate the size and costs of PV systems for certain locations and conditions (e.g. PVGIS, see more at: http://photovoltaic-software.com/pvgis.php or HOMER, see more at: http://www.homerenergy.com/pro-faq.html).

A PV-plant doesn’t emit gaseous and pollutants, but in the case of fire CIS and CdTe modules, there is a risk of emitting of highly toxic substances into environment.

Building-integrated PV modules can be in facades, roofs, windows, walls (e.g. noise barriers alongside highways) which do not require additional land. It will be visible to neighbours, and it can be attractive or not.

Multi-megawatt PV-plants are installed on land specially designated for that purpose and this will have visual impact. The total land required, at a rough estimate, for a 1 MW power plant setup is around 1.5-2 hectares for crystalline technology and around 2.5-3 hectares for thin-film technology, and this may vary based on type of technology, efficiency of panels, and the location of the solar plant.

4 The Resilience Concept

The sudden change of the indicator and its return to the primary state is the measurement of the capacity of the respective system to withstand the changes of the system. There are several potential changes of every system that may result in the eventual catastrophic event. It is important to visualise the characteristic behaviour of the sudden change of the indicator. The integral value of the indicator in the time scale, until it reaches the steady state, is the measuring parameter of the resiliency index (Afgan, 2010; Afgan & Cvetinović, 2011; Holling, 1973; Kainan, 2006). It is possible to use the Sustainability Index as the resilience metric parameter.

It is assumed that the Sustainability Index (Afgan, 2010; Afgan & Carvalho, 2008; Zlomušica & Afgan, 2010) is a linear agglomeration function of products between specific indicators and corresponding weighting coefficients. It will be adapted so that each of the specific indicators is weighted by the respective weighting coefficient. The sum of a specific indicator multiplied by the corresponding weighting coefficient will lead to the Sustainability Index, $Q(t)$, with the following mathematical formulation:

$$Q(t) = \sum_{i=1}^{i=k} w_i q_i(t)$$

Where are:
w_i - weighting coefficient for the i-th specific indicator;
q_i - i-th criterion for sustainability assessment.

The evaluation of the energy system as the complex system is the prestigious goal of the modern approach to the validation of the energy system. In this context, the notion of the Resilience Index is introduced as the agglomerated indicator for the measurement of the energy system quality (Afgan, 2013). The Resilience Index presented in Fig. 4.1 is a graphical presentation of the sudden Sustainability Index change in time and its recovery to the initial state of the system.

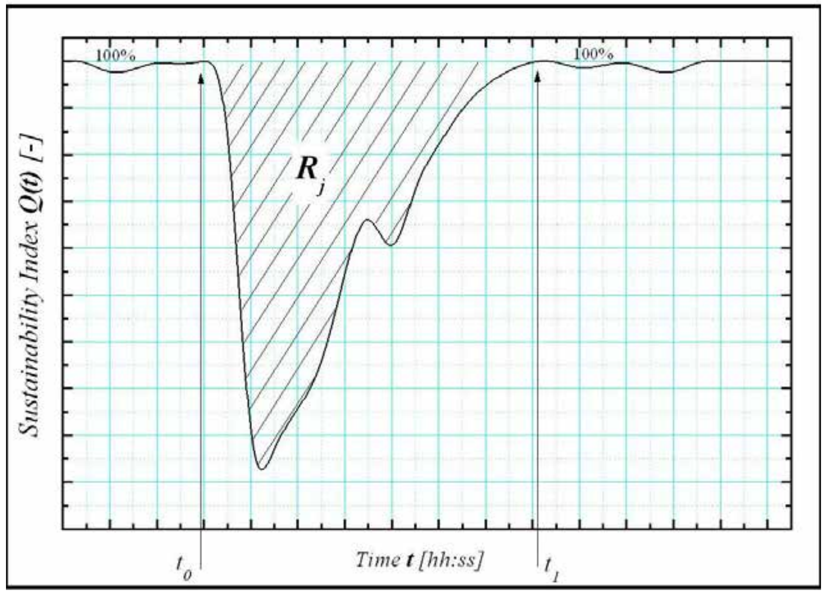

FIG. 4.1 Graphical presentation of Resilience Index *(Afgan, 2013)*

The Resilience Index is integral to the Sustainability Index between time of sudden change in the respective indicator and the time when it resumes a steady state value (Afgan, 2013; Afgan, 2010; Afgan & Cvetinović, 2010). The Resilience Index for an energy system is composed of the following elements: economic, environmental, technological, and social indicators. The Resilience Index is expressed with following mathematical formulation:

$$R_j = \sum_{i=1}^{i=k} w_i \int_{t=t_o}^{t=t_1} [100 - q_i]\, dt$$

Where *j* stands for resilience indicator.

In this definition it is anticipated that the time is an independent constant for every indicator. The sudden change of the specific indicator from the initial value will be recovered within the time period Δt. Under the assumption that the sudden indicator change represents a linear function of time, then it can be written as:

$$R_j = \frac{1}{2}\, w_i(\Delta q_i \Delta t_i)$$

Where are:
Δq_i - indicator change;
Δt_i - time change.

If it is assumed that the time interval for resuming starting state is equal for all indicators and then the Resilience Index for the individual case is:

$$R_j = \frac{\Delta t_0}{2}\, w_i \Delta q_i$$

The total Resilience Index is an additive function of all Resilience Indexes is:

$$R_{tot} = \sum_{n} R_j$$

Where are:
Rtot – total Resilience Index;
Ri – specific change.

5 Selection of the Resilience Index Indicators

In analysis of the Resilience Index of an energy system, the following indicators can be taken into consideration: economic, environment, and social indicators.

Change of energy (power) consumption of the system indicator and the Investment Cost indicator are used as the economic indicators, as shown in Fig. 5.1. The recent problem of global warming has introduced the need for the assessment of man-made pollution with the substitution of new energy sources in order to prevent further pollution problems. It is very common that the change of environment in the vicinity of an energy system is change of concentration pollution gases. The Social Indicators, the elements of resilience at the community level, can be observed through: employment, crime rates, tourism, education, health care, city infrastructure, demographic factors, or other culturally defined variables. But at the individual level, choices in livelihoods and social investments are more likely to be observed through income and other variables such as migration, which indicate stability at the household level. Fig. 5.1 presents an example of an agglomeration scheme of the Resilience Index of energy system.

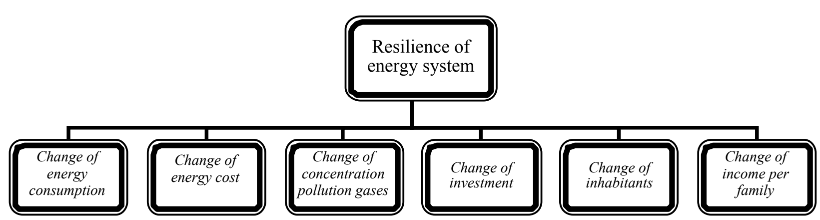

FIG. 5.1 Agglomeration scheme of the Resilience Index

Change of energy (power) consumption of the system (kWh/cap)
The change of energy consumption is an imminent problem for any energy system. There is possibility to have sudden increase of the power demand in some urban regions leading to the potential critical state of the energy system. It is important to emphasize that the change in power consumption and its maximum value may result in the catastrophic event.

Change of energy costs

The energy costs indicator is one of the economic indicators that is subject to sudden changes due to market fluctuation. It is usually expressed in the c€/kWh reflecting the market change of the economic environment. Analysis shows that the maximum change of energy cost indicator value is e.g. 30% of the standard energy costs while its minimal value is zero, meaning that there is no change of this indicator under this condition.

Change of the investment costs

The Investment Cost indicator comprises the investment (material, manpower, and capital costs) needed to recover damage caused to the hardware elements induced in the potential change of system structure. These changes are followed by the expenses expressed in EUR (€). The maximum value of this indicator is e.g. 10%, while the minimum value is 0.

Change of concentration pollution gases

It is very common that the change of environment in the vicinity of an energy system is manifested by the change of concentration pollution gases. In some evaluations, changes in CO_2 can be taken into a consideration, meaning the increase of concentration of CO_2 in exhaust gases. CO_2 emissions are the sum of the CO_2 emissions per unit of electricity produced expressed in kg/MWh. In the assessment of the potential changes of this indicator, it is anticipated, for example, that the maximum value of this indicator is 400 g/kWh while its minimum value is zero.

Change of the income per family

If a sudden change of income per family is introduced with other indicator changes this option will correspond to potential social impacts to the Resilience Index. As was defined for other options, if the sudden change of income per family leads to an unexpected change of the Resilience Index, then even the catastrophic can be expected. Otherwise, this situation can lead to social events that may be difficult to control. Analysis shows that the sudden changes can lead to no salary, discount salary, or full salary.

Change of the inhabitants

Mobility and migration are important indicators of resilience. However, resilience or changes in resilience cannot simply be inferred from the presence or absence of migration in any given community, the degree of labour mobility, or an increase/decrease in total population over time (as in the Western Balkans). Significant population movement may be evidence of instability, or could be a component of enhanced stability and resilience, depending on the type of migration. Migration may be caused by an adverse state of affairs in the local community or state level and often has negative impacts on social infrastructure on both sides of the migration. The maximum value of this indicator may be, for example, 5% in next 10 years.

Indicators, as shown in this section, can have multiple sub-indicators. In the following simplified examples, only some indicators were used.

6 Demonstration of Photo-Voltaic Power Plant Resilience

The quality of the photo-voltaic (PV) plant can be defined by the sustainability index, including economic, environment, and social indicators. The economic indicator includes electricity costs and electricity production. The electricity production indicator reflects total energy production by the PV plant. The environment indicator comprises reduced CO_2 emission; it is anticipated that 1 GW coal fired power plant produces 6 Mt CO_2 /year. The social indicator includes maintenance costs which arise from the need for cleaning PV modules. Indicators analysed in this example are: electricity costs, electricity production, and CO_2 emission, with maximum, minimum, and mean values of the specific indicator. See Table 6.1.

ELECTRICITY COSTS (EC) EUR/kWh	ELECTRICITY PRODUCTION (EP) kWh/DAY	CO_2 EMISSION (ENI) g/kWh
0.23	40	0
0.115	80	100
0	0	220

TABLE 6.1 Sustainability indicators *(Afgan, 2010)*

The Sustainability Index based on the indicators as shown can be defined by following expression:

$$Q = w_1 q_1 + w_2 q_2 + w_3 q_3$$

Where are:
w_1 - weighting coefficient for electricity costs indicator;
w_2 - weighting coefficient for electricity production indicator;
w_3 - weighting coefficient for CO_2 emission reduction indicator;
q_1 - electricity costs indicator- EUR/kWh;
q_2 - electricity production indicator – kWh/day;
q_3 - CO_2 emission reduction indicator – g/kWh.

The first step in the Sustainability Index determination is the normalisation of the indicators. This means that the special procedure is adapted for the formulation of the Sustainability Index as the aggregation function of the indicators. The next step is to define the constraints for the weighting coefficient. In this analysis it has used following cases of constraints:

- Case 1 - Electricity Costs > Electricity Production = Environment Indicator
- Case 2 - Electricity Production > Electricity Costs = Environment Indicator
- Case 3 - Environment Indicator > Electricity Costs = Energy Production

The resilience of the PV power plant is the capacity of the plant to withstand sudden changes of the indicators. The Resilience Index will be determined as the sum of all indicators of sudden change multiplied by time period needed for their recovery. The Resilience Index rating for each case will be obtained in numerical form, corresponding to the constraints as specified for each case. For each case, the maximum value Resilience Index will be determined and presented as the rating among the analysed cases. This approach will give us the possibility to validate the change of indicators in terms of safety of the energy system under a specific constraint. The Resilience Index for PV plant is defined by formula:

$$R = (w_1 \Delta q_1 + w_2 \Delta q_2 + w_3 \Delta q_3)\Delta t$$

Where are:
Δq_1 - change of electricity costs;
Δq_2 - change of electricity production;
Δq_3 - change CO_2 emission.

In order to determine the specific value of the Resilience Index for the individual cases, the following options are taken into a consideration. The option design is based on the priority given to the change of individual indicators. Each option is defined using a maximum change of specific indicator and the changes to which other indicators are introduced, as specified in Table 6.2. The following options of PV plant resilience were taken into consideration:

- Option A is based on the assumption of an Environmental indicator change (EnI) of 0 g/kWh, with an Electricity production indicator (EP) of 4 kWh/day and Electricity costs (EC) of 0.023 EUR/kWh.
- Option B represents a maximum of Electricity production indicator change (EP) of 8 kWh/day, while other indicators have some mean values.
- Option C represents an Electricity cost indicator change of 0 and the other indicators change as shown in row Option C in Table 6.2.

OPTIONS	ELECTRICITY COSTS (EC) CHANGE ΔEUR/kWh	ELECTRICITY PRODUCTION CHANGE (EP) ΔkWh/DAY	CO_2 EMISSION (ENI) CHANGE Δg/kWh
Option A	0.023	4	0
Option B	0.0115	8	10
Option C	0	0	20

TABLE 6.2 Resilience indicators for PV power plant *(Afgan, 2010)*

The total Resilience Index is determined for the following cases, where priority is given to the criteria in a specific case, while other indicators have the same value:

- Case 1 - Electricity Costs Change > Energy Production = Environment Indicator
- Case 2 - Electricity Production >Electricity Costs Change = Environment Indicator
- Case 3 - Environment Indicator > Electricity Costs Change = Energy Production

7 Demonstration of Wind Power Plant Resilience

In this case, it will be assumed that every indicator is measured in the time interval *Δt*. In addition, it is assumed that the air temperature and air pressure are constant. The following indicators are taken into consideration:

- Change of wind power density
- Change of efficiency of wind power plant
- Change of frequency
- Change of electricity costs

Nominal values and sudden changes of indicators are given in Table 7.1

OPTIONS	WIND POWER DENSITY (WPD) Δm/s	EFFICIENCY OF WIND PARK (EWP) Δ%	POWER FREQUENCY (PF) Δ AMPERE	ELECTRICITY COSTS (EC) EUR/kWh
Options 1	4/20	2.5	1.25	0
Options 2	2	5/100	2.5	1.25
Options 3	1	1.25	5/50	2.5
Options 4	0	0	0	5/20

TABLE 7.1 Resilience indicators for wind power plant *(Afgan, 2010; Afgan & Cvetinović, 2010)*

In the design of the analysed objects, it is assumed that the sudden change of indicators is triggered at the same moment for all indicators. Additionally, the changes of indicators are normalised and the maximum change for each of the indicators is expressed in a normalised value. Each object is defined as the composition that simulates sudden changes in all indicators, as shown on Table 7.1. The total Resilience Index is determined for the following cases:

- Case 1 - WPD > EWP = PF = EC
- Case 2 - EWP > WPD = PF =EC
- Case 3 - PF > WPE = EWP = EC
- Case 4 - EC > WPPD = EWP = PF

The results obtained for these cases are shown in Table 7.2.

In terms of the wind power plant analysis, it is proven that, in the most stable case, the sudden change of the indicators is in Case 2, when the priority of the indicators is given to the Efficiency Wind Power plant.

CASE	RESILIENCE INDEX
Case 1	0.755
Case 2	0.866
Case 3	0.612
Case 4	0.647

TABLE 7.2 Rating list *(Afgan, 2010; Afgan & Cvetinović, 2010)*

8 Conclusions

The Resilience Index is a stability parameter of any system and it can be used as the measuring parameter for the assessment of potential hazard events.

The sustainability change in time is defined as the resilience of the system. It describes the safety capacity of the system. With the monitoring of the sustainability change of the system in time, it can be used as the diagnostic parameter of the system's safety.

There are a number of the indicators that can be used for the assessment of the stability of the system. The selection of appropriate indicators is a primary goal in the design of the system stability. It reflects the quality of the system measured by the appropriate changes of the indicators.

The Resilience Index will be determined as the sum of all sudden change indicators multiplied by the time period for their recovery. The Resilience Index rating for each case will be obtained in the numerical form, corresponding to constraints as specified for each case. For each case, the maximum value for the Resilience Index will be determined and presented as the rating among the analysed cases.

As a conclusion it is important to mention that the Resilience Index is the parameter of the system that can be used as the diagnostic tool in the assessment of the potential hazard event of the system, as is clearly shown in this paper.

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PART 2
Energy and Comfort in the Built Environment

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Material Aspect of Energy Performance and Thermal Comfort in Buildings

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ABSTRACT **Modern design and construction strives to establish an appropriate relationship between three characteristic poles: man – the user, the building, and the environment. This chapter seeks to highlight this problem by considering the relevant characteristics of the building's thermal envelope, i.e. the impact that the choice of materials has on the behaviour of the building as a whole. Today, we are intrigued by the behaviour of a building as a system, mostly through the prism of the amount of energy it consumes during its existence. On the one hand, this leads us to the need for adequate knowledge of the basic principles of building physics, and on the other, to the awareness of the relevant properties of the materials that we use in the construction process, in order to meet the comfort requirements of the user. Although this chapter emphasises the problem of meeting the thermal comfort requirements, in the example of the review and analysis of characteristic types of residential buildings in the Belgrade area, the scope of meeting the overall comfort requirements has been considered, as well as the interdependence that exists between different types of comfort (thermal, indoor air, sound, and light).**

KEYWORDS parameters and comfort conditions, buildings' behaviour, heat and mass flow, thermal insulation and thermal mass, vapour permeability

1 Introduction - Contemporary Attitude Towards the Issue of Thermal Protection of Buildings

Modern society requires a large amount of energy for its operation. As that energy has largely come from non-renewable sources, the question of energy consumption has become one of the most important problems that modern society has faced since the energy crisis of the 1970s. Given that buildings have been proven to be the largest consumers of energy, this problem refers directly to their design and structure.

At first, attention and care were primarily directed towards the need for more rational energy use, contributing to the development of regulations in the field of thermal protection of buildings. Nowadays, however, the attitude towards the environment is understood in a much broader way, known as the sustainable development doctrine, which, from the viewpoint of energy, would mean that the original approach regarding the need for energy conservation has evolved over time into a holistic concept of energy efficient buildings. The problem of the energy efficiency of buildings is, in general, related to the need to control operational energy consumption. However, it could be expected that, in time, with the increase of energy efficiency, the problem of energy use will shift towards a problem of so-called embodied energy of materials and components, giving more importance to the issue of material selection in achieving overall energy efficiency (Zöld & Szalay, 2007).

The energy performance of energy efficient buildings and their energy consumption undoubtedly depends, to a great extent, on the achieved thermal characteristics, but also on other factors that play an increasingly important role, such as heating and air-conditioning installations, the application of energy from renewable sources, passive heating and cooling elements, shading, indoor air-quality, adequate natural light, and the design of the building (The European Parliament and the Council of the European Union, 2010). It should be stressed that such buildings should be designed and constructed in such a way that they consume a minimal amount of energy, but with the simultaneous provision of maximal living comfort. Such an integrative approach to the architectural design process has three equal poles of interest – man, building, and technology, and is often understood as climate design (Hauslanden, de Saldanha, Liedl, & Sager, 2005).

The appropriate selection of materials has a direct impact on the achievement of the required thermal properties of a building. However, comfort is affected by many parameters, such as temperature, humidity, air movement, air quality, lighting, noise, etc. (Sassi, 2006), which are also dependent on the material properties or the fabric of the house. Therefore, this chapter will analyse the complex correlation between a contemporary building's thermal requirements and the material aspect of the building, bearing in mind the expressed need for the creation of a comfortable environment.

The discussion of the problem in this chapter is divided into several parts that explain:

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- basic aspects and parameters of comfort in buildings;
- relevant elements of building behaviour through the basic principles of building physics, taking into account the hygrothermal properties of building materials and those elements relevant for the adequate thermal behaviour of a building envelope and a building as a whole.

In the last part of the chapter, the interconnection between the choices of materials, the behaviour of the building, and the resulting comfort level is analysed and presented in the form of case studies. As a result of a previous study that focused on the rate of achievement of overall living comfort of Belgrade building stock (Đukanović, 2015), and as a model for this particular investigation, several representative buildings were chosen. Since Belgrade is a capital city, and the largest in Serbia, the study indicates the wider picture and refers to the quality of living comfort in the whole country. Bearing in mind the location of the selected model, the achievement of living comfort was evaluated with respect to the relevant Serbian regulations.

2 User Requirements – Achievement of Comfort in Buildings

It could be said that one of the principles and goals of contemporary design is the achievement of the so-called user's requirements. Although, in general, the user could be either a human or any living being, or a thing for which the building is designed and built, in most cases man is the focus of a design interest. The level of the fulfilment of the user's set of requirements or, in other words, the overall impression of the quality of the space is, on one hand, individual, and a result of the perception of our senses, but on the other hand, it is also related to the compliance with standards that define limiting measurable values of representative parameters. In both cases, the impression is based on the achieved comfort of the place. The term comfort could be understood as everything that makes life more comfortable, or it could be defined as "a state of physical ease" (Sassi, 2006).

Although the terms comfortable and healthy are not synonyms, the comfort of a place is closely related to the notion of a healthy place. Hence, the modern desire for designing for comfort could be understood as a prerequisite for the achievement of a healthy environment (Sassi, 2006). Accordingly, nowadays research and practices strive to define relevant health and comfort indicators (Bluyssen, 2010).

Meeting the physical aspect of the comfort level means to provide:

- adequate indoor temperature relative to outside temperature;
- adequate relative humidity level and its impact on temperature;
- ample natural light and good quality lighting without glare;
- adequate sound separation between buildings – from the outside and within a building; etc.

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These aspects could be understood as specific types of comfort: thermal, visual or lighting and acoustic or sound. Bearing in mind that creating a healthy environment requires the provision of adequate quality of air which is free from toxic substances, we could also discuss indoor air comfort, which could be referred to as air comfort.

The built environment affects us through our sensory organs (Szokolay, 2004), and our experience of comfort depends, to a large extent, on the sensitivity of our senses, which is an individual category. However, there are also various building-related parameters that affect all types of comfort. The relationship that exists between different types of comfort, our senses with which we perceive them, and physical parameters by which we describe, explain, and measure these types of comfort is shown in Table 2.1.

TYPE OF COMFORT	THERMAL	AIR	VISUAL	ACOUSTIC
Sense	skin	nose, mouth	eye	ear
				
Related physical parameters	temperature	O_2:CO_2 ratio	illuminance	loudness
	humidity		glare	sound level
	air movement	ventilation rate	colour temperature	noise
	mean radiant temperature	presence of pollutants	daylight factor	

TABLE 2.1 Type of comfort sense-parameter relation

Although thermal comfort is just one type of comfort, it is considered the type of comfort that is linked with a sensation of complete physical well-being (Harris & Borer, 2005).

Thermal comfort is understood as "the condition of mind that expresses satisfaction with the thermal environment" (Szokolay, 2004). It could be also explained as a thermally neutral environment in which there is no feeling of discomfort, and the regulatory mechanisms of the organism are burdened minimally, that is, where thermal equilibrium of the body is achieved (Jovanović Popović, 1991). The metabolism of a human body continuously produces heat by its processes and, depending on the environmental thermal conditions, different thermal adjustment mechanisms might be activated (such as: vasoconstriction, vasodilatation, evaporation and shivering) in order to maintain the thermal balance of the organism. Both the rate of heat dissipation from the body, as well as the type of mechanism that might be activated depend on several groups of variables, presented in Table 2.2. The groups of variables could be named as either environmental, personal or contributing factors (Szokolay, 2004), or as objective or subjective parameters (Jovanović Popović, 1991).

GROUP OF VARIABLES (AFTER SZOKOLAY, 2004)		
ENVIRONMENTAL	PERSONAL	CONTRIBUTING FACTORS
Temperature	Metabolic rate (activity)	Food and drink
Humidity	Clothing	Body shape
Air movement	State of health	Subcutaneous fat
Mean radiant temperature	Acclimatisation	Age and gender
OBJECTIVE	SUBJECTIVE	
PARAMETERS (AFTER JOVANOVIĆ POPOVIĆ, 1991)		

TABLE 2.2 Type of variables, i.e. parameters related to the perception of thermal comfort

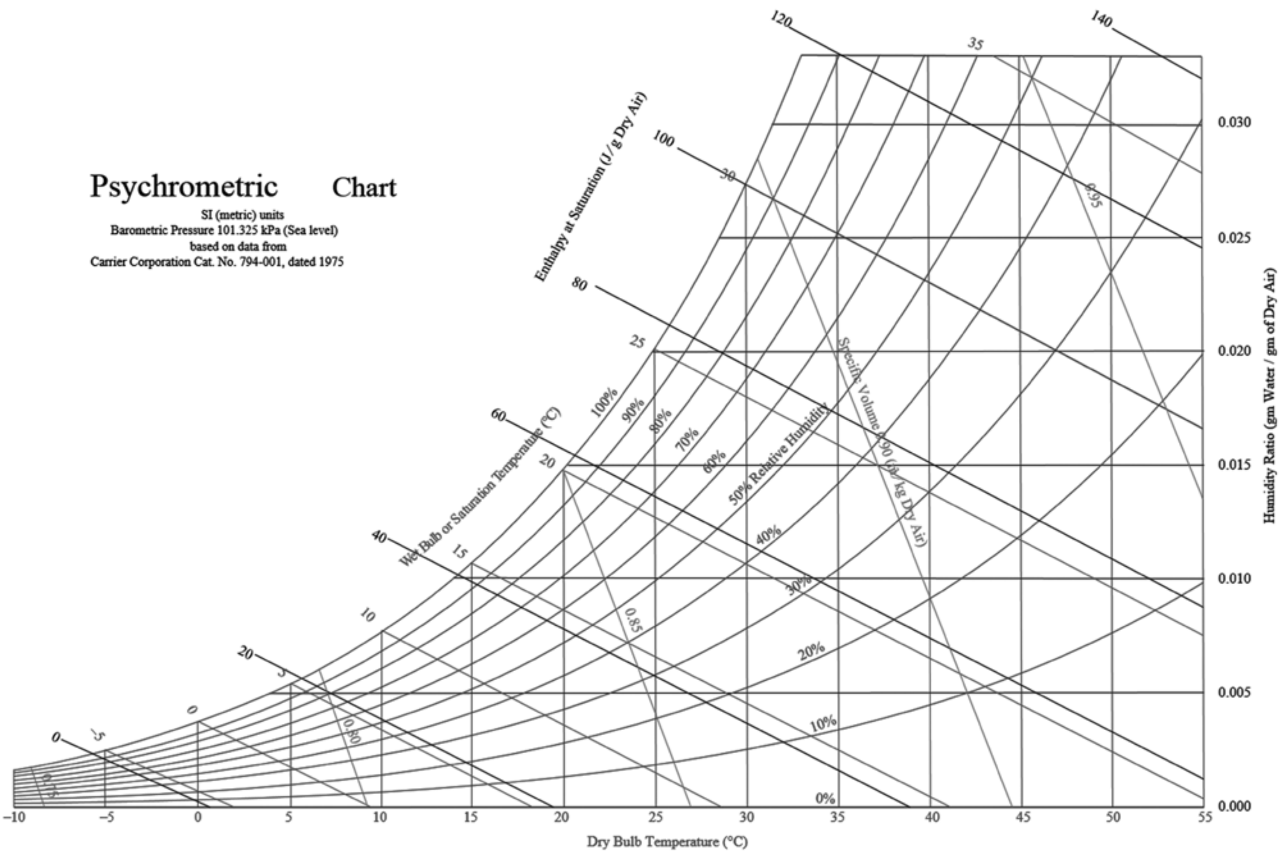

FIG. 2.1 Psychrometric chart
(©-2009-Creative Commons; retrieved from: https://commons.wikimedia.org/wiki/File:PsychrometricChart.SeaLevel.SI.svg)

In general, a good understanding of thermal comfort requires different types of representation of various combinations of simultaneous actions of thermal parameters. Based on a correlation between the temperature and humidity of the air, which is important for a perception of a thermal environment, a psychrometric chart could be understood as the most commonly used way of displaying the limits of comfort (Fig. 2.1).

An individual perception of the thermal environment, as well as not only the fact that "a person is different to other person, but he or she changes over time" (Hauslanden et al., 2005), influences the fact that today, the analytical determination and interpretation of thermal comfort is usually based on the calculation of the PMV and PPD

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indices that indicate the rate of thermal discomfort (EN ISO 7730, 2005; EN 15251, 2007).

Nowadays, efforts to reduce the use of resources in general, in the context of achievement of sustainability, result in the notion of sustainable thermal comfort. Although there is no simple answer to the question of what exactly sustainable thermal comfort is, the provision of thermal comfort is closely related to the problem of the heating and cooling of a building, i.e. of its energy consumption. In that sense, it could be assumed that suggestions and measures for good housekeeping contribute to the reduction of energy use. Bearing in mind that there are many combinations of relevant parameters that result in the achievement of thermal comfort, different rates of clothing and/or activity in combination with lower environmental temperatures and other objective thermal parameters could still result in an adequate level of thermal comfort which is, certainly, more sustainable in terms of energy consumption (Parsons, 2010).

3 Mechanisms of Behaviour of a Thermal Envelope in the Service of Thermal Comfort

The thermal envelope of a building is an element that separates the external from the conditioned, heated, or cooled internal environment and predetermines the quality of achieved comfort. It could be also considered as an interface between the exterior and the user inside the building (Hauslanden et al., 2005). Combined with the spatial design of a building, the design of a building fabric has a direct impact on the building's energy consumption. Hence, a proper envelope design is considered one of the passive design measures that should be applied in order to achieve energy conservation (Oral, Yener, & Bayazit, 2004; Sassi, 2006). Research on today's principles of building envelope design, conducted by Oral et al. (2004), determines that there are several types of parameters that affect the behaviour of a building envelope. They are primarily grouped as those related to the outdoor (external) environment, and those related to the indoor or built environment (Table 3.1).

The parameters related to the outdoors are a result of climate conditions and, therefore, are understood as natural factors that should be considered with their given values. On the other hand, those that relate to the indoor environment are the result of a designer's decision and include problems and decisions on different scales: immediate surroundings, a building, a room, or an element.

Accordingly, modern regulations in the field of thermal protection anticipate the verification of the energy performance of the building on two levels: 1) the individual building construction and 2) the whole building. With respect to this, in the case of Serbian thermal regulations (Ministarstvo za zaštitu životne sredine, rudarstvo i prostorno planiranje Republike Srbije (Ministry of Environmental Protection, Mining and

Spatial Planning of the Republic of Serbia), 2011), the required verification is defined in the following way:

- on the level of the individual building construction by means of the identification of the U-value, i.e. the coefficient of heat transmission or thermal transmittance, by checking the mechanism of water vapour diffusion that occurs through the construction and by checking the so-called mass effect in the summer period;
- on the level of the whole building by means of the heat transmission loss coefficient $H_{T,}$ which considers the effects of thermal bridges, ventilation loss coefficient H_V, specific heat transmission loss H'_T and total volume heat losses q_V;

POS.	OUTDOOR	INDOOR				
scale		surroundings	building	room	element	
					opaque	transparent
parameters	***air temperature***	***dimensions and orientation of external obstacles***	***orientation***	***position within building***	***thickness of materials***	***dimensions of transparent components***
	solar radiation	***solar radiation reflectivity of surrounding surfaces***	position relative to the noise source	***dimensions and shape factor***	***density of material***	***number of layers of glazing***
	humidity	light reflectivity of surrounding surfaces	position relative to other buildings and the noise source	***orientation***	***specific heat of the materials***	***heat transmission coefficient of glazing***
	wind velocity	***soil cover and the nature of the ground***	***form***	***absorption coefficient for solar radiation entering through the transparent component***	***heat conduction coefficients of the materials***	***absorption, reflection and transmission coefficient of glazing (solar)***
	illumination level			sound absorption coefficient of the internal surfaces	light absorption and reflection coefficients of the surfaces	transmission coefficient of glazing for diffuse sunlight
	sound level			total sound absorption coefficient	sound transmission coefficient	transmission coefficient of glazing for direct sunlight
				light reflection coefficients of the internal surfaces	porosity and roughness of the surface	transmission coefficient of glazing for sound
					sound absorption coefficient of the surface	***type of frame***
					construction of the surface	maintenance factor of glazing
					layered structure	
					depth of the cavity between the layers	
					thickness and sound absorption of the insulating material inside the cavity	
					type and number of connections between layers	

TABLE 3.1 Parameters that influence the envelope design* *(after Oral et al., 2004)*

**italicised text represents parameters that have a direct impact on thermal comfort*

In general, the verification of the thermal characteristics of a building is carried out on the elements of its thermal envelope, i.e. all of the building elements that separate either the unheated from the heated parts of the building, or that separate parts of the building that have different comfort conditions.

3.1 Heat and Mass Transport Through a Building's Fabric

A building's fabric is a mediator through which heat and mass transport occur as a result of typical mechanisms of action. Acting on certain mechanisms of heat and mass transfer through the envelope contributes to the reduction of the energy requirements of the building (Sassi, 2006). These actions could be defined as the need for:

- minimising heat loss through appropriate insulation and making a building airtight;
- minimising unwanted heat gains with solar shading, insulation and reflective finishes;
- considering the use of thermal mass in order to moderate daily temperature variations or as heat storage.

Thus, the heat flow through the building's fabric could be explained by the mechanisms of heat reflection, heat transmission resistance that depends on the mechanisms of conduction and convection of the heat on its way through the element of the envelope (Fig. 3.1), and heat capacity, which can have significant effects on heat transfer (Hall & Allison, 2010). Conduction, as a mechanism for transmitting heat, is a result of direct contact. It is characteristic of solid bodies and stationary fluids and is transferred from one molecule to another or, in the case of metals, by the movement of free electrons. On the other hand, convection is characteristic of fluids (liquids and gases) and is achieved by the movement of the fluid's molecules. The third method of heat transfer - radiation, occurs when the heat of the radiation source is transmitted by the transformation of the internal heat into energy in the form of electromagnetic radiation (infrared radiation), which can be reflected or absorbed by a solid body. Each of the heat transfer modes is a complex function of the size, shape, composition (types of materials) and the orientation of the construction component.

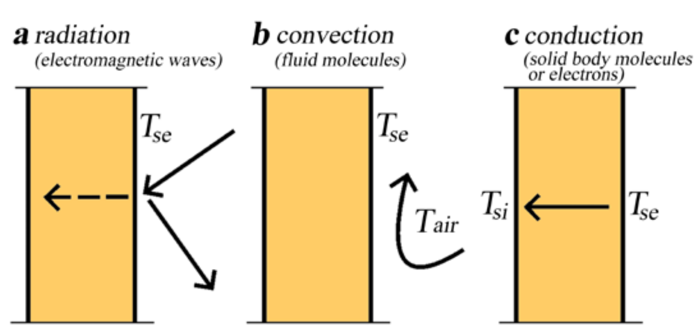

FIG. 3.1 Methods of heat transfer

When it comes to heat flow through architectural objects, the important issue is the transfer of heat from a fluid to a solid body, i.e. from the air to the building and vice versa, due to a temperature difference, as well as the transfer of heat through the construction itself. It is determined on the basis of thermal resistance (R value), which includes resistance to heat transfer at the boundary surface between the structure and the air (R_{si} and R_{se}), as well as resistance to heat conduction through the structure (R_T), which is dependent on the thermal conductivity (λ) and thickness (d) of each layer of material within the structure in question. The overall thermal transmittance (U value) of a building's fabric, which is the subject of thermal regulation, represents the reciprocal of the thermal resistance:

$$U = \frac{1}{R_{si} + R_T + R_{se}} = \frac{1}{R_{se} + \sum_n \frac{d_n}{\lambda_n} + R_{se}} = \left[\frac{W}{m^2 K}\right]$$

The building structures that are commonly used today can be very complex, consisting of homogeneous or inhomogeneous layers, containing different types of air layers, air spaces etc. Such circumstances might additionally complicate the calculation of their thermal performance (EN ISO 6946, 2007; Vilems, Šild, & Dinter, 2008; Medved, 2011), as well as the determination of the mechanism of heat transfer through them.

However, the mass flow through a building's fabric refers to a mechanism of diffusion wetting, i.e. the transport of water vapour. This natural process of water vapour transmission should be carried out in such a way that two requirements are met: 1) there is no surface condensation on the inner surface of the thermal envelope of the construction; and 2) during the diffusion transfer of water vapour in the construction structure, there is no condensation of water vapour, to the extent that the increase in humidity affects the durability and bearing capacity of the building constructions (Medved, 2011).

Generally speaking, both heat and mass transport are results of the imbalance that exists in the environment with regard to temperature and relative humidity. In the case of heat transfer, it is explained as the transport of energy that results from temperature difference, while mass transport is a result of the difference in the concentration of matter (Hall & Allison, 2010). The directions of heat and thermal mass movement are generally synonymous but, under specific conditions, may be different (Vilems et al., 2008). Depending on the specific direction – towards the exterior or the interior of the occupied space, we can discuss the heat losses or heat gains, both of which could be either desirable or undesirable, depending on the particular situation. Therefore, it is important to properly understand the mechanisms of the transport, as well as the methods of quantification (Hall & Allison, 2010; Künzel & Karagiozis, 2010).

Certain assumptions are adopted when calculating the thermal characteristics of the thermal envelope, such as a stationary method of heat transfer a one-dimensional heat transfer, that is, the assumption that the heat flux is perpendicular to the observed barrier, as well as the postulation that all the relevant physical properties of the material are constant (Todorović, Bogner, & Denić, 2012). Bearing in mind the complexity of the problem of heat transfer, such assumptions and simplifications are justified and the calculated values are, in the majority of cases, sufficiently accurate. However, we should be aware of the fact that in reality there is a constant variability of certain parameters such as temperature and relative humidity; hence, instead of a steady state environment and stationary heat transfer, they are moisture-dependent and time variable (Hall & Allison, 2010). This fact affects both the characteristics of the material within the thermal envelope and, consequently, the mechanism of heat transfer.

3.2 Relevant Characteristics of Building Materials and Principles of Structuring a Building's Fabric

On their way through the thermal envelope, both heat and moisture might be stored or transmitted, depending on the hygrothermal properties of the applied building materials. In principle, the control of heat flow through a material or construction is based on three characteristic mechanisms of action: first, heat reflection, which is a characteristic of metals, i.e. the material in which the radiation prevails as a way of transferring heat. The principle is related to the correct installation of metal foils within the structure; the resistance of heat transmission, which is the principle of operation of thermal insulation materials; and the storage or accumulation of heat as a characteristic of solid constructions, which is time variable (Hall & Allison, 2010) and significant for the adequate thermal stability of the structure. The way in which the natural process of water vapour diffusion through the envelope takes place is directly related to the permeability of a building material, and porous building materials are especially sensitive to any change in moisture content. Consequently, the measured values of the thermal conductivity of a built-in porous material and its design values can vary to a certain extent, so this fact should be taken into consideration when designing an element of a thermal envelope (Hall & Allison, 2010).

Depending on the dominance of relevant hygrothermal properties, materials can be classified into several particular groups. Regarding their basic thermal properties, one can distinguish the following types of materials:

- those having good thermal accumulation and bad insulating properties, like the so-called structural materials;
- those having bad thermal accumulation and good insulating properties, such as thermal insulation;

- glass as a unique building material that is specific for its transparency and exhibits specific behaviour in relation to different electromagnetic/solar radiation ranges - visible, ultraviolet and infrared; and
- innovative insulating materials which could be understood as a new generation of building materials that are the result of the increasing need for better energy efficiency in buildings;

On the other hand, regarding their vapour permeability and the role in the structure, there are two specific types of materials:

- those that act as an impermeable film or a vapour barrier that retards vapour movement but does not totally prevent its transmission; and
- vapour permeable foils, i.e. layers of thin material that allow the passage of water vapour in one direction, but prevent it in the other;

The proper functioning of the physical process of water vapour diffusion, the accomplishment of which is important, depends on the climatic conditions, the type and properties of the applied materials, the thickness and vapour permeability of the individual layers of the material, as well as their order in the assembly. Otherwise, an undesired increase in the humidity of a material within a thermal envelope may occur as a result of an uncontrolled diffusion flow, which, over time, can cause changes in its thermal, mechanical and other properties, that is, various forms of construction damage and the premature aging of materials and constructions (Künzel & Karagiozis, 2010).

Contemporary thermal requirements impose specific problems in building practice due to the increased thickness of conventional building materials. Therefore, there is a need for a more efficient use of building materials and structures, due to an increased awareness of their relevant properties and rules of behaviour. The provision of comfort and efficiency in a building construction in terms of energy can be achieved when several aspects are taken into account simultaneously: the insulation properties of materials and constructions, their behaviour regarding the water vapour diffusion that is dependent on a material's permeability, and adequate application of thermal inertia that is relevant for better thermal storage and enables thermal phase or time lag. In that sense, the basic principles to be respected are as follows:

- In the case of layered constructions, the resistance to heat transfer of all layers should increase from the inside out, and at the same time, their water vapour diffusion resistance should decrease from the inside to the outside;

- In order to take advantage of the thermal inertia of walls, thermal insulation should be on the outside of the construction - exceptions are rooms that are occasionally heated in which rapid warming of the air in the room is needed (theatre and concert halls, sports halls, etc.);

- When creating the concept of a building and structuring the assemblies one should strive for an adequate combination of thermal inertia and good thermal insulation;

– Ventilated air layers can contribute to better characteristics of structures in relation to the diffusion of water vapour through the structure (by omitting a vapour barrier), as well as to the summer stability of the structure (by increasing the temperature oscillation damping factor).

4 Comfort in Buildings and the Interdependence of Comfort Requirements – Case Studies

In practical terms, the achieved comfort in buildings is a direct result of the way we build buildings; specifically, the applied materials, the design and construction rules that change over time as a result of technical and technological innovation, the development of building regulations, social, economic, and other circumstances. An estimation of the achieved living comfort might be a starting point for understanding the quality of the building stock, as well as its potential for further energy improvements.

Bearing this in mind, the housing stock of Belgrade was analysed from the perspective of thermal comfort but with a reflection on its effects on other types of comfort (Đukanović, 2015). The assumption was made that the erected buildings, through their structure, volumetrics, and shaping, create the most important preconditions for achieving thermal comfort, in which a decisive role is played by the façade envelope, as the boundary between the most expressive temperature differences. In both thermal conditions to which the façade is exposed (winter and summer), the structure of the envelope (exterior walls, windows, roofs, etc.) is crucial for the achievement of thermal comfort, while in the summer, additional protection at the window level together with natural ventilation also play an important role and contribution.

As part of the conducted research, constitutive structures of thermal envelopes of typical residential buildings were determined and used as a basis for the creation of representative models of the residential architecture of Belgrade. These models were the subject of further analyses, conducted according to the determined comfort parameters, in order to examine the overall quality of the analysed housing stock.

4.1 Determination and Characteristics of Representative Models

Three theoretical models that reflect different periods of construction of the housing stock are selected and analysed: 1) the oldest buildings (built before the First World War); 2) those built during the mass housing construction of the sixties and seventies; and 3) buildings built in the 1990s (Table 4.1). Regarding the existence of regulations in the field of thermal protection (Radivojević, 2003; Radivojević & Jovanović Popović, 2013), the selected construction periods correspond with the following times: 1) before the adoption of the first regulations in this area; 2) the time that corresponds to the first regulations on thermal protection in Serbia; and 3) the period preceding the adoption of the

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Rulebook on energy efficiency of buildings (Ministarstvo za zaštitu životne sredine, rudarstvo i prostorno planiranje Republike Srbije (Ministry of Environmental Protection, Mining and Spatial Planning of the Republic of Serbia), 2011), which introduced an obligation in Serbia to build energy efficient buildings. The analysis of the three selected models focuses on the façade envelope and the effects it has on the realisation of thermal, air, acoustic, and visual comfort.

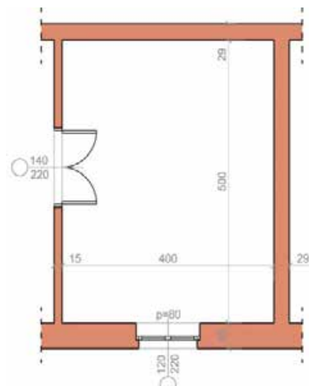
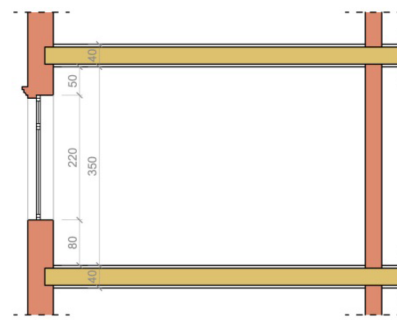
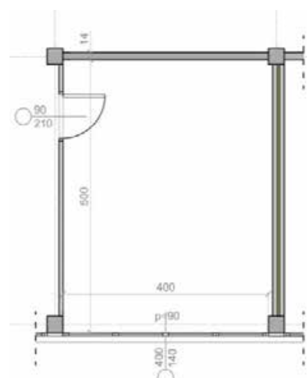
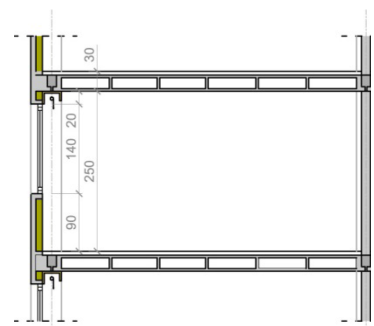
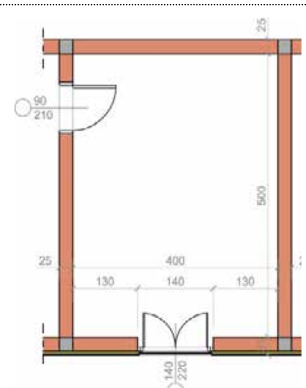
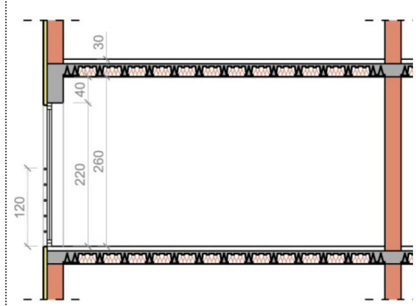
	TYPICAL HOUSE / ROLE MODEL	FLOOR PLAN	CROSS SECTION
Model 1 (before 1919)			
Model 2 (1960-1975)			
Model 3 (post 1990)			

TABLE 4.1 Basic characteristics of the analysed theoretical models

The models were created with all the relevant elements that represent a typical living room from the analysed period. The living room is selected as a place where daily activities take place. Therefore, it can be considered relevant for assessing the extent to which housing comfort was achieved. The analysis of the Belgrade housing stock indicated that the length and width of the room might be the same for all models (5 x 4 m), corresponding to a constructive and functional grid found both in massive and skeletal systems. However, the height of the room is variable depending on the period that the model represents. The analysed room occupies a central position in the organisational scheme, having peripheral walls that are determined as follows: one wall of the room is defined as a façade wall, another is a barrier to the neighbouring apartment, and the other two as partition walls between the other rooms of the apartment. Viewed vertically, the spatial unit is installed in the central part of the building, so that above and below there is a neighbouring residential area. This is the most common position in multi-storey residential buildings. A southern orientation of the room was adopted, which is a desirable position for this spatial purpose.

Peripheral structures of analysed models (walls, floor structures and windows), as well as the applied structural system (massive or skeletal) correspond to those typical for the observed construction period. The window dimensions, their position, number, height of the parapet, applied frame material and structure, glazing, as well as the type of window protection, vary depending on the current modes of construction and architectural styles. The influence of window features is perceived in all forms of housing comfort (visual comfort), and in some it plays a decisive role.

For model 1, which represents the oldest buildings in Belgrade, massive, brick masonry is the characteristic basic material of construction. The earliest construction period was marked by the use of wooden windows with a double frame and a single glazed sash, which were built into a brick wall (Đukanović, Radivojević & Rajčić, 2016). According to the set criteria, in accordance with the standards and architectural volumetrics of the time, high individual windows were installed.

Model 2 represents objects formed during the period when prefabricated systems, based on reinforced concrete, were applied. The model was created in the skeletal, IMS system, which prevailed in the residential construction of Belgrade at the time, with a parapet structured from a combination of regular and foam concrete. In accordance with the recognisable form of facades of multi-storey residential buildings of the time, the model has strips of horizontal windows and parapet-shaped panels of a multi-layered structure. Due to the reduced thickness of the parapet walls and the propagated savings in construction, single frame, wooden windows with a connected double sash and single glazing were used. Therefore, an assembly with a canvas roller blind was adopted in model 2.

Model 3 reflects the period after 1990, which is characterised by the abandonment of prefabricated reinforced concrete systems and the return to traditional building methods. The load-bearing walls were most often made of cavity clay blocks, which became the dominant material in the construction of residential buildings, replacing bricks in constructive positions. Façade walls are coated with plastered insulation material (usually polystyrene). During the 1990s, the production of PVC windows started, which eventually suppressed the use of wooden ones, primarily because of simple maintenance, good thermal properties and low prices (Table 4.1).

4.2 Indicators of Achieved Thermal Comfort

In accordance with the requirements derived from the relevant regulations in Serbia, the selected parameters for evaluating thermal comfort are: heat transfer coefficient (U), water vapour diffusion parameters - condensation check, summer thermal stability check by calculating the temperature oscillation damping factor (ν) and the temperature oscillation delay (η), as well as transmission losses through the façade elements. In Table 4.2, the structure of the façade envelope is shown for each model: the percentage distribution of the surfaces of opaque and transparent parts, as well as the ratio of transmission losses through the window and façade wall on the observed segment. This approach is a consequence of the way in which the research model is formed, where the dimensions of the windows are variable and reflect the characteristics of the selected construction period. In this sense, a model has been designed so that its thermal envelope consists only of a façade wall with a window. Thus, changes in the dimensions of windows and the height of the storey would be seen independent of other influences.

In the case of the non-transparent parts of the façade, heat transfer coefficients of exterior walls do not meet current regulations in any of the models, which, according to Serbian regulations, for existing buildings should be less than 0.4 W/m^2K (Ministarstvo za zaštitu životne sredine, rudarstvo i prostorno planiranje Republike Srbije (Ministry of Environmental Protection, Mining and Spatial Planning of the Republic of Serbia), 2011). By comparing the results shown in Table 4.2, the worst results for the heat transfer coefficient are for the concrete prefabricated wall (model 2), which is due to the poor thermal characteristics of reinforced concrete as the basic material in the assembly. Summer thermal stability parameters do not meet the prescribed values for this particular façade wall, which can result in a variation of air temperature in the interior of the room, depending on the temperature of the outside space. In the layers of the façade walls in models 2 and 3, condensation occurs, which dries within the allowed time limit. However, the drying time for model 2 is significantly longer, indicating the more unfavourable characteristics of this wall as it relates to water vapour diffusion.

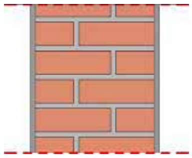
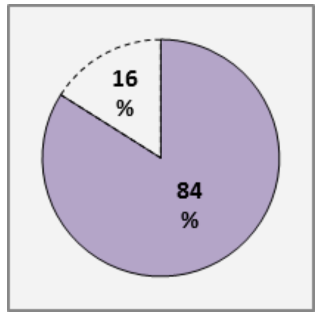
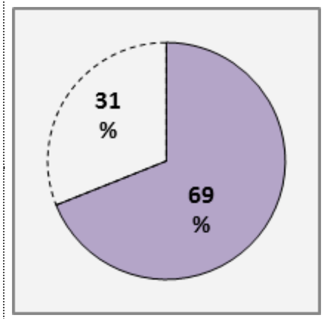
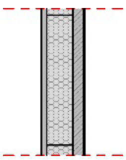
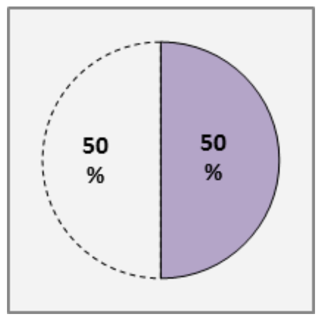
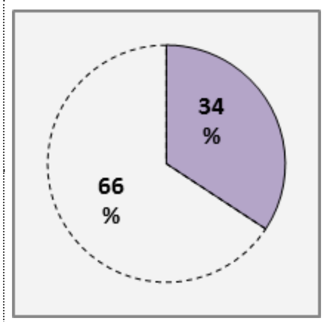
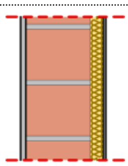
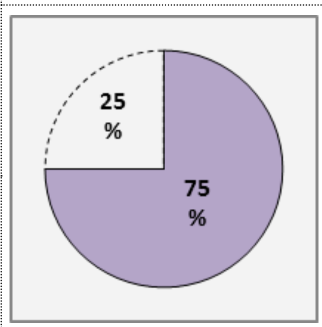
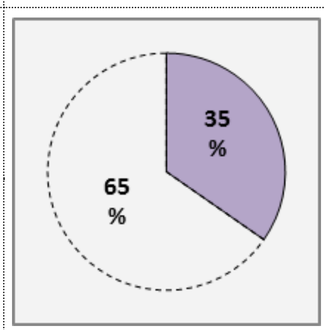
MODEL 1 FAÇADE ENVELOPE			
Façade wall	**Window**	**Opaque/transparent representation**	**Transmission losses**
			
brick wall 45cm, both sides plastered	wooden, double frame, double sash (wide box); single glazed interior curtains		
U=1.1 W/m²K $U > U_{max}$	**U= 2.6 W/m²K,** $U > U_{max}$	**surface of façade envelope: 16.46** m^2	**total transmission losses of the façade envelope: 22.08 W/K**
$v=131.0 > v_{min} = 15$			
$\eta=16.8 > \eta_{min} = 7$		façade wall: 13.82 m^2	façade wall: 15.22 W/K
condensation: none		window: 2.64 m^2	window: 6.86 W/K
MODEL 2 FAÇADE ENVELOPE			
Façade wall	**Window**	**Opaque/transparent representation**	**Transmission losses**
			
parapet element with a combination of regular concrete and foam concrete	wooden, double frame, connected sash; single glazed canvas roller blind		
U=1.46 W/m²K $U > U_{max}$	**U= 2.8 W/m²K** $U > U_{max}$	**surface of façade envelope: 11.76** m^2	**total transmission losses of the façade envelope: 25.04 W/K**
$v=10.4 < v_{min} = 15$			
$\eta=5.9 < \eta_{min} = 7$		façade wall: 5.88 m^2	façade wall: 8.58 W/K
condensation: in layer 2; 25.6 days drying time		window: 5.88 m^2	window: 16.46 W/K
MODEL 3 FAÇADE ENVELOPE			
Façade wall	**Window**	**Opaque/transparent representation**	**Transmission losses**
			
cavity clay block wall with plastered thermal insulation	single three-chamber plastic window, double glazed external roller blind		
U=0.53 W/m²K $U > U_{max}$	**U= 3.0 W/m²K** $U > U_{max}$	**surface of façade envelope: 12.33** m^2	**total transmission losses of the façade envelope: 14.15 W/K**
$v=109.7 > v_{min} = 15$			
$\eta=9.3 > \eta_{min} = 7$		façade wall: 9.25 m^2	façade wall: 4.91 W/K
condensation: in layer 3; 1.5 days drying time		window: 3.08 m^2	window: 9.24 W/K

TABLE 4.2 Indicators of thermal comfort of analysed models

Different windows are built into the models, resulting in differences in heat transfer coefficients. The best features are seen in the wooden double window with a wide box, and the worst in the single three-chamber plastic window with double thermal insulating glass. For model 1, the transparent parts are less represented in relation to the façade wall (16%), but due to the poorer thermal characteristics ofthe window compared to the wall, the redistribution of transmission losses through the envelope changes.

The graph representing the transparent and non-transparent façade parts in model 3 shows a slightly higher window presence (25%) compared to model 1, but the ratio of transmission losses through the façade elements is completely different, due to the large differences in heat transfer coefficients between the two elements of the thermal envelope. Although in model 3, the façade wall contains thermal insulation so the value of the coefficient of heat transfer through the wall is more favourable than in the case of model 1, thermal characteristics of the window are assessed as the worst among the three model buildings, resulting with a high percentage representation in total transmission losses of this model.

The specificity of model 2 in relation to the other examples is the structure of the envelope, in which the surface of the façade wall is equal to the surface of the window, which is informed by the design characteristics of the first prefabricated buildings in Belgrade. Alternating horizontal window and concrete parapet elements is a feature of this construction period, and demonstrates certain specificities in the results of the thermal calculation. The unfavourable heat transfer coefficient of the applied window, combined with a 50% representation of the window surface in the façade envelope, contributes to the high value of heat losses through the window. The heat loss through the window consists of 66% of the total generated heat, which represents the largest share taken by any window in the conducted research. At the same time, among the analysed models, transmission losses through the façade have the highest value in the case of model 2.

4.3 Indicators of Achieved Air Comfort

For the assessment of air comfort, ventilation through infiltration is important, and is determined by the applied façade materials, the type and quality of the joinery, and the way it is incorporated. Since energy efficient architecture aims to achieve energy savings and reduce heat losses, minimising uncontrolled infiltration by sealing the fissures and couplings is a way to achieve large energy savings for heating and cooling. However, doing this may create spaces in which air quality is not at a satisfactory level.

The infiltration of air through the façade wall is of low intensity and, in most cases, it cannot provide a minimum number of air changes to achieve the hygienic minimum. Air infiltration through façade joinery is several times more intense than the flow through the exterior walls, which contributes to the focus of the analysis of the air comfort of existing residential buildings in Belgrade on this parameter which, on the one hand, contributes to the quality of indoor air, and on the other, increases the ventilation losses and the energy needed for heating. The amount of air infiltrated through the joints of the window is calculated according to a general formula, which includes the length of the coupling, the permeability of the joints and the pressure difference.

The air flow by infiltration through the couplings has been calculated for the analysed models and the obtained results are shown in Table 4.4. For model 1, double wooden windows with a spaced double sash were applied, in which the elements of the frame and sash were made with folds, and without any means of sealing. The doubled window frames and sashes, the formation of ridges in the bricks on which the window bears, and the buffer layer of air between the outer and inner elements, all contributed to the better insulating properties of this type of window. The windows are divided into two-pieces in width and height, which increases the length of the couplings that are relevant for the airflow calculation and, with a pressure difference of 25Pa, the hygienic minimum is reached, i.e. the half-volume flow of the total volume of the room achieved for one hour, according to the standard EN 12831 (2003).

On model 2, wooden windows with a connected double sash were applied, which correspond to the concept of thin walls comprising reinforced concrete, typical of the multi-family buildings of the analysed period. The couplings between the window elements are formed with folds and without seals, and since the window frame is single, this set shows higher air permeability than a double window with a spaced double sash. The windows are continuous, forming horizontal strips that extend along the entire length of the façade, which significantly increases the length of the overlap and additionally contributes to a higher air flow. In Table 4.3, it can be seen that at a minimum pressure difference of 5 Pa, a hygienic minimum is achieved, while in the case where the difference between the external and internal pressure is 50 Pa, achieved only by infiltration through the joints, i.e. without opening the window, almost three changes of air are performed per hour.

	WINDOW TYPE	VOLUME OF THE SPACE [m^3]	LENGTH OF THE OVERLAP L [m]	PERMEABILITY a [$m^3/hmPa^{2/3}$]	AIR FLOW [m^3/h] $V=\Sigma a_i \cdot l_i \cdot \Delta p_{E-I}^N$									
					Δp_{E-I}									
					5	**10**	**15**	**20**	**25**	**30**	**35**	**40**	**45**	**50**
Model 1	double wooden with a spaced double sash	70	11.4	0.4	13	21	28	34	39	44	49	53	58	62
Model 2	wooden with a connected double sash	50	16.4	0.6	29	46	60	73	84	95	105	115	125	134
Model 3	PVC single with a double glazed unit	52	11.2	0.2	7	10	14	17	19	22	24	26	28	30

TABLE 4.3 Air flow through window couplings on analysed models

Favourable thermal and sound performance, affordable price, and easy maintenance, have all contributed to the fact that plastic windows have become the most commonly used in domestic housing construction since the 1990s, as was adopted in model 3. The results show that the best air tightness is achieved in this model due to the low coefficient of permeability and a coupling length approximately equal to model 1 and significantly shorter than model 2. The minimum airflow through the window couplings by the mechanism of infiltration is achieved at a pressure difference of 40 Pa, as shown in Table 4.3.

4.4 Indicators of Achieved Sound Comfort

The consideration of the façade barrier in the context of sound comfort is largely conditioned by the window opening, which represents the weakest segment in the overall façade wall assembly and the potential place where sound impulses are transferred. As various window assemblies applied on the façades of residential buildings in Belgrade are analysed in this study, one should bear in mind the fact that the insulating properties of the applied window (Fasold & Sonntag, 1971 and database in the software *Ursa Fragmat Akustika RS*) greatly contribute to the total sound insulation of the barrier (Table 4.4).

The new system of standards in the field of sound protection has introduced significant changes in the method of calculating the acoustic properties of the premises. Unlike the previous calculation method in which the partitions are viewed as individual, separated elements, the current method of calculating involves a complex view of all the surrounding structures and their interconnections, which directly affect the isolation power of the observed partition. In this way, the overall complexity of sound transmission through the construction is considered.

	TYPE OF WINDOW	WINDOW SOUND INSULATION	FAÇADE WALL ASSEMBLY	SOUND INSULATION $D_{2m,nT}$
Model 1	double wooden with a spaced double sash (12cm)	39 dB	massive brick masonry	45 dB
Model 2	wooden with a connected double sash	31 dB	concrete prefabricated parapets	31 dB
Model 3	PVC single with a double glazed unit	31 dB	massive block masonry	34 dB

TABLE 4.4 Sound insulation properties of façade wall assemblies

The sound insulation ($D_{2m,nT}$) of a façade wall is defined as the difference in the sound levels between the two spaces separated by the façade partition and, as such, is determined by the limit values of noise in the open space and indoors. Depending on the location of the object in relation to the acoustic zones, the sound insulation values were determined, and for the purposes of this study a minimum value of $D_{2m,nT}$=20 dB was adopted. All the analysed façade walls satisfy these conditions, but the best results were achieved with model 1, because the sound insulation of the barrier is in direct proportion to its surface mass, and the application of a solid brickwork structure shows its good insulation characteristics (Table 4.4). On the other hand, the use of wide-box windows, which have a high level of insulation properties compared to other types of windows applied, affects the insulation of the façade far beyond the prescribed minimum values.

4.5 Indicators of Achieved Visual Comfort

The research of light comfort, for natural lighting conditions, resets the focus to the façade wall and its role in the realisation of this form of comfort. The achievement of the given conditions by using daylight provides incomparable health benefits to the users of the space and at the same time contributes to the rational use of energy and the improvement of the overall energy efficiency of the building. The maximum use of natural light in order to achieve optimal conditions of light comfort, while reducing the use of artificial light, is a recommendation of all standards that deal with this issue.

The research of light comfort of the Belgrade housing stock was done for daylight conditions. The selected models illustrated the typical ways of forming transparent parts of the envelope in Belgrade residential buildings. In addition to the dimensions of the window opening, other elements of the envelope structure that affect the level of illumination of the room are the dimensions of the illuminated room (width, depth, and clear height), the height of the parapet, and the existence and depth of a terrace or a loggia.

In order to examine the established models, identical environmental conditions (location, orientation, and conditions of the sky) are set. A southern orientation is selected, which is recommended for the living space, although in the summer months it may be unfavourable due to the occurrence of glare. In the middle of a room, a table was placed to monitor the brightness and flash in the work area. The parameters on which the assessment of the quality of lighting of residential buildings was carried out are the ratio of daylight and glare. The analysis of the light comfort of the analysed models was done using a computer tool, which allows a simple, spatial view of the parameters of light comfort (Velux Daylight Visualizer 2).

In the case of Model 1, the use of windows that were taller than usual in relation to the width is characteristic, with the ratio of their dimensions being approximately 1:2 (w/h). The average daily illumination ratio is 1.89% (Table 4.5), which fits into the average requirements that are prescribed for living rooms (1.6-3%), though it is close to the lower limit. In the central part of the room, where daily activities are performed most frequently, the daily illumination ratio is about 1.5%, which is between the median and low requirements according to the current domestic regulations (SRPS U.C9.100, 1963; Jugoslovenski komitet za osvetljenje (Yugoslav Committee for Lighting), 1974).

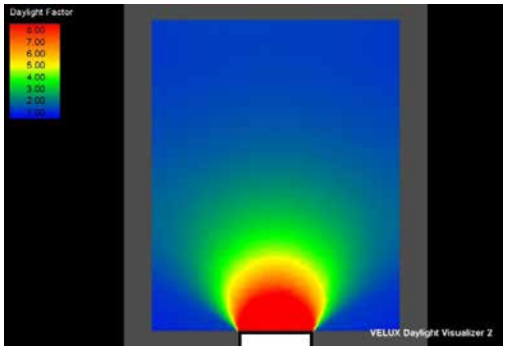
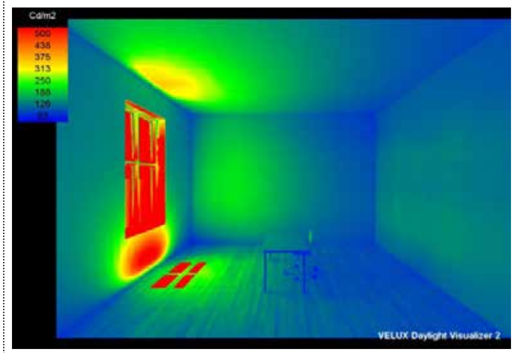
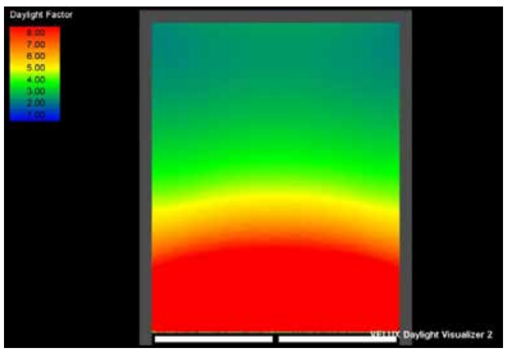
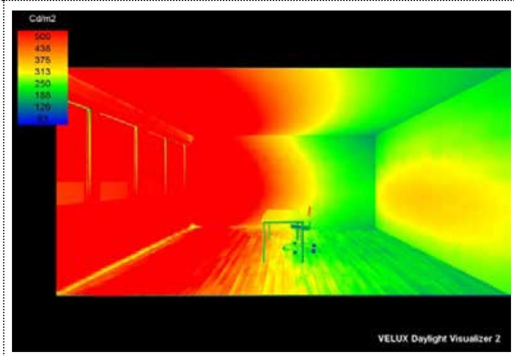
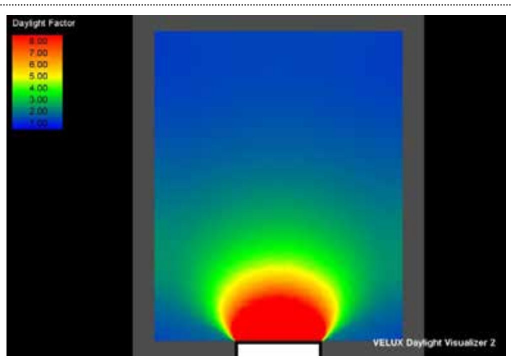
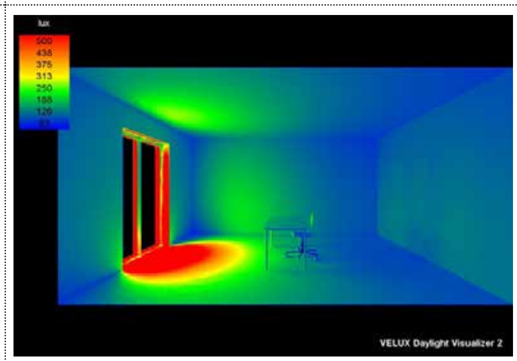
	DAILY ILLUMINATION RATIO [%]	GLARE [cd/m2]
Model 1: window 120/220cm	average value: 1.89	
		
Model 2: window 400/140cm	average value : 5.17	
		
Model 3: window 140/220cm	average value : 2.05%	
		

TABLE 4.5 The representation and values of the parameters of light comfort as a result of the use of Velux Daylight Visualizer 2

The accentuated height of the window opening allows the penetration of light deep into the room, but its insufficient width results in poorly illuminated parts in the corners of the room next to the façade wall, resulting in an unevenly illuminated space. Glare appears on a small surface next to the façade wall, and the brightness of the wall and ceiling surfaces is, with minor deviations, at optimum limits. However, the brightness of the visible task on the set work table is 100 cd/m^2, which is on the lower scale of the recommended values (100- 300 cd/m^2).

For model 2, the daily illumination ratio is 5.17% and this value is in the category of large requirements prescribed for the living room, in which tasks such as reading and studying are envisaged. The value of this parameter varies from 1.74 to 16.99% and ranges from the level of medium requirements to extremely large (over 12%). A uniform distribution of light in the room is evident as a result of the installation of window strips along the entire length of the façade wall. It is equally distributed across the width of the room with uniform attenuation in the depth of the room.

The walls have a surface gloss of more than 200 cd/m^2 and in the zone next to the window it increases to 1000 cd/m^2, which is a multiple of the recommended value. The brightness of the ceiling also exceeds the optimal values (250-1000 cd/m^2). In addition, in the first third of the depth of the room, a glare phenomenon with values exceeding 6.000 cd/m^2 is recorded. In order to achieve optimum levels of illumination and prevent the appearance of glare, the obtained results suggest that protection in the form of curtains or blinds in the summer months is necessary.

On the facades of residential buildings built after 1990, represented by model 3, there are elongated window openings with or without a low parapet, and with one-leaf or two-leaf doors with an outer railing of an appropriate height (a so-called French balcony). The average daily illumination ratio is 2.3%, which fits into the category of median requirements prescribed for living rooms (1.6-3%). In the central part of the room, the daily illumination ratio is approximately 2%.

The walls of the room have a surface gloss of greater than 100 cd/m^2, and the glare phenomenon is registered in the lower zone around the façade opening. The brightness of the ceiling surface is largely within the recommended limits (100-300 cd/m^2), while the glare phenomenon is registered only in the area of the floor or work surfaces that are placed directly next to the door opening.

It has been shown that the similarities in the design of the window openings in models 1 and 3 have affected the results of the study of the illumination of the living room, showing only slight differences. On the other hand, model 2 is specific and completely different, so that the parameters of visual comfort show diametric differences in relation to the other two models, both in terms of the means of distribution of light in the room, and in relation to the values of the parameters of illumination that determine the extent of the achieved light comfort.

5 Conclusions

There are different reasons and methods in which the choice of materials affects both the living comfort and energy efficiency of a building. As has been explained, this refers especially to the design and structure of a building envelope, which is the main interface between man and his environment, on one hand, and the most relevant factor for the achievement of living comfort and simultaneous energy consumption of a building on the other. Our knowledge of the behaviour and role of materials in a construction enables us to predict the behaviour of a building as a whole and to understand the effects of a design on the building's operation and function.

The presented analyses of selected models of Belgrade housing stock have pointed out how different structures of building fabric, building techniques and technologies, together with the applied design principles that were typical for the time represented by a model, affected the achievement of comfort conditions and energy consumption. It is characteristic that the various parameters and their combination, which relate primarily to the characteristics of the façade envelope (such as the wall and window structure and the wall to window ratio), influence the realisation of the various types of comfort:

- **thermal comfort** is dependent on a combination of the characteristics of the wall structure and the quality and structure of the window but, due to the significant difference in transmission losses of these elements, it is also highly dependent on the wall to window ratio;
- achievement of **air comfort** is, to a great extent, a result of the air tightness of the façade, as a consequence of the quality and size of the window, but also from the junction of the window with the wall;
- **sound comfort** depends on the surface mass of the wall and on the properties of the window frame and glazing structure; while
- quality of **visual comfort** is, to a large extent, conditioned by the wall to window ratio.

Although the models represented situations that were in accordance with the standards of the time, from today's perspective, regarding the majority of the analysed parameters, certain enhancements are needed in order to adjust to current demands (Đukanović et al., 2016), which confirms the evolution of our understanding of living comfort.

The emphasised need to reduce energy use is imperative today, putting into focus the issue of thermal comfort, although other forms of comfort are monitored simultaneously. The high demand for minimal energy consumption in buildings, among other things, imposes the need for the use of thicker insulating materials, which often jeopardises the feasibility of such complex and often bulky constructions. On the one hand, solutions for such problems are sought in the application of new types of advanced materials that will be more adaptable to the set requirements, and on the other hand, there is the question of the need to re-examine the high demands of thermal comfort in so-called sustainable comfort. However, it is certain that, in time, in the light of sustainable development, besides the problem of energy, other issues will be included in current doctrines of design and construction, bringing a new perspective to the selection and use of building materials.

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Embodied and Operational Primary Energy Content and CO_2 Emissions_

Optimising the Efficiency of the Building Envelope

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ABSTRACT **Buildings are major energy consumers. The embodied energy and operational energy account for the largest share of the total energy use. Increased energy efficiency of the buildings, which results in reduced operational energy, entails an increase in embodied energy. For this reason, when improving the energy efficiency of buildings, the decisions and measures to be taken need to be properly balanced.**

Embodied and operational energy and their environmental impact are evaluated with the environmental parameters $PEC_{n.r.}$ (non-renewable primary energy content), GWP_{100} (global warming potential in 100 years), and *AP* (acidification potential). The energy-environmental impact of the built-in energy is shown. The values of the above three environmental parameters, according to their thermal conductance coefficient λ, are presented for specific structural sections of the building envelope (walls, roof, floor to ground, windows). The most common construction sets for building envelope, composed of different materials - brick, wood, and aerated concrete, with added thermal insulation of synthetic, mineral, and natural origin, were analysed. The analysis of the building envelope structure also includes windows with different frames.

The advisability of thermal insulation improvement depends on the payback period. For the energy efficiency improvement measures of each individual construction set, the expected payback period is presented. The improvement of thermal insulation is achieved by additional thermal insulation, resulting in increased cost of investment.

KEYWORDS primary energy content, embodied energy, operational energy, passive house, low-energy house

1 Introduction

The built environment largely depends on energy. 30 - 40% of all primary energy is used for buildings, which are held responsible for 40 - 50% of greenhouse gas emissions (Asif, Muneer, & Kelley, 2007). The data on the primary energy use also present useful indicators on greenhouse gas emissions and the resulting impacts on the environment.

Buildings demand energy throughout their life cycle, which consists of the following phases: the production of raw materials, production of building materials and components, integration of materials and components and, finally, demolition of the building. The results show that 80 – 90% of energy is required in the operational phase (operational energy), and 10 – 20% of energy in the construction phase (embodied energy) of a building. At the end of a building's service life, energy is required to demolish the building and transport the waste material to landfill sites or recycling plants. Data indicate that the share of energy required for the demolition of a building accounts for approx. 1% of the total energy use (Adalberth, 1997). Energy savings from recycling or reusing the demolished building materials are not considered in the above calculation.

The analysis of life cycle energy savings identifies and mostly targets the phases that have the largest primary energy use, i.e. the operational and embodied energy.

Embodied energy is the energy used during the manufacturing phase of the building. It is associated with the production of raw materials, production and transport of materials and technical equipment, and the construction and renovation of the building. In the analyses, the operational phase of a building is limited to 60 years, with intermittent rehabilitation of technical installations and those materials that have a shorter life span than other materials. In addition to this, buildings require regular annual maintenance, which also demands energy.

Operational energy is the energy required for maintaining the optimal comfort conditions and day-to-day maintenance of the buildings. It is the energy for HVAC (heating, ventilation, and air conditioning), domestic hot water, lighting, and powering appliances.

Activities to achieve reduction in primary energy use over the building's life cycle are focused mainly on reducing the operational energy demand of the buildings. This is implemented by applying passive and active technologies, such as the provision of a thicker layer of thermal insulation on the shell of the building, using gas filled triple pane windows with low emissivity coatings, ventilation air heat recovery from exhaust air, heat pumps coupled with air or ground/water heat sources, solar thermal collectors, and building integrated solar photovoltaic panels. However, reduced demand for operational energy results in an increased share of embodied energy of the building due to the use of energy intensive materials, installations, and equipment. Although the embodied energy constitutes only a 10 – 20% share in comparison to life cycle energy, the use of low energy materials should be encouraged. Venkatarama and Jagadish (2003) state that, in this way, the embodied energy may be reduced by 30 – 40%. Thormark (2000) also notes that the reuse of materials and components in a building may save 55% of embodied energy.

Increasing the energy efficiency of a building is an important measure to reduce the demand for operational energy. A number of energy efficient building types based on different concepts have been developed, such as very low-energy houses, passive houses, zero-energy houses, self-sufficient houses, etc. The analyses show that passive houses are the optimal energy-efficient houses in terms of the energy used over the building's entire life cycle (Feist, 1996). However, measures may also be counterproductive if the increase in embodied energy is excessive. Currently, self-sufficient houses that are entirely independent from external energy sources (zero operating energy) have a higher energy demand in the life cycle context than low energy houses (Ramesh, Prakash, & Shukla, 2010). For this reason, when improving the energy efficiency of buildings, the decisions and measures to be taken need to be balanced properly.

A building's negative impact on the environment is defined by the energy and environmental indicators, which serve to assess these impacts. The $PEC_{n.r.}$ energy indicator refers to the non-renewable primary energy content required for the production of building materials, elements, and components. The environmental indicators GWP_{100} (global warming potential, 100 years) and *AP* (acidification potential) are used to assess the burdening of the environment during the phase of production of building materials and components with substances causing a greenhouse effect. The *OI*3 indicator provides combined assessment of all three indicators and comprehensive information about the combined effect of building materials, elements, or components on the environment. The study presents different variants of building envelope structural components made of different building materials and using different construction technologies through the perspective of energy and environmental indicators, and the expected payback period of different measures applied to improve their energy efficiency.

2 Energy and Environmental Indicators of Thermal Envelope Structural Elements

When deciding on energy efficient building, it is therefore essential to study the negative potential over the total life cycle of the building, which consists of the following four phases:

- production of raw materials, building materials and components for the building;
- sale and integration of building materials and components;
- use of the building as the longest phase of its life cycle;
- demolition of the building and its components.

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In the environmental analysis, which is limited to the period extending to the completed production of structural elements, four indicators that apply to thermal envelope structural components are comparatively examined:

- the first is the $PEC_{n.r.}$ energy indicator, assessing the primary non-renewable energy content, used per unit area of the structural component (indicator unit kWh/m^2);
- the next two indicators are the environmental indicators GWP_{100}, assessing the global warming potential of the product (in 100 years), and *AP*, assessing the environment acidification potential of the product, measured per unit area of the structural component (indicator units kg_{CO2equ}/m^2 and kg_{SO2equ}/m^2);
- the last environmental indicator is the *OI3* indicator (IBO, 2017), providing more comprehensive information about the combined effect of the three preceding indicators through a dimensionless score system. The three indicators are equally weighted (in thirds) according to the following equation (Eq. 2.1):

$$\Delta OI3 = \frac{1}{3}\times\left[\frac{1}{10}\times PEC_{n.r.} + \frac{1}{2}\times GWP_{100} + \frac{100}{0{,}25}\times AP\right] \quad [points]$$

2.1 Building Materials and Their Impact on the Environment

The energy efficiency of a building depends on the thermal envelope composition, i.e. on the wall and roof structure, the structure of floors in contact with the ground or floors exposed to unheated parts of the building, and joinery. The impact of the materials incorporated in the thermal envelope on the environment varies over the life cycle of a building. A proper selection of materials improves the heat insulating properties and the values of environmental parameters. The study focuses on the comparison of environmental impacts of different building envelope structures. For the evaluation of environmental parameters, the most frequently used load-bearing building materials and thermal insulation have been selected:

- materials used for solid masonry structure
- materials used for light timber structure
- synthetic thermal insulation materials
- mineral thermal insulation materials
- natural (biological) thermal insulation materials.

Materials utilised for load-bearing structure and thermal protection vary in terms of their thermal conductance coefficient, which, according to the manufacturers (Baubook, 2017), falls in the range of $\lambda \leq 0.05$ W/(m • K) for thermal insulation materials. The impacts of materials on the environment (also depending on their thermal conductance) are assessed using the environmental parameters $PEC_{n.r.}$, GWP_{100}

and *AP*, with the data obtained from different databases, including from Baubook (2017).

No significant trends are observed in the non-renewable *primary energy* ($PEC_{n.r.}$) content, required for the production of all five selected groups of materials (Fig. 2.1), which means that the use of materials in a thermal envelope should be considered on a case-by-case basis for each separate structure. Materials utilised for solid masonry structure have values between e.g. 250 – 500 kWh/m^3. Thermal insulation materials of natural origin have the lowest values in the group, materials of mineral origin record higher values, and materials of synthetic origin have the highest values. The differences between the values are in the range of 0 – 1,200 kWh/m^3.

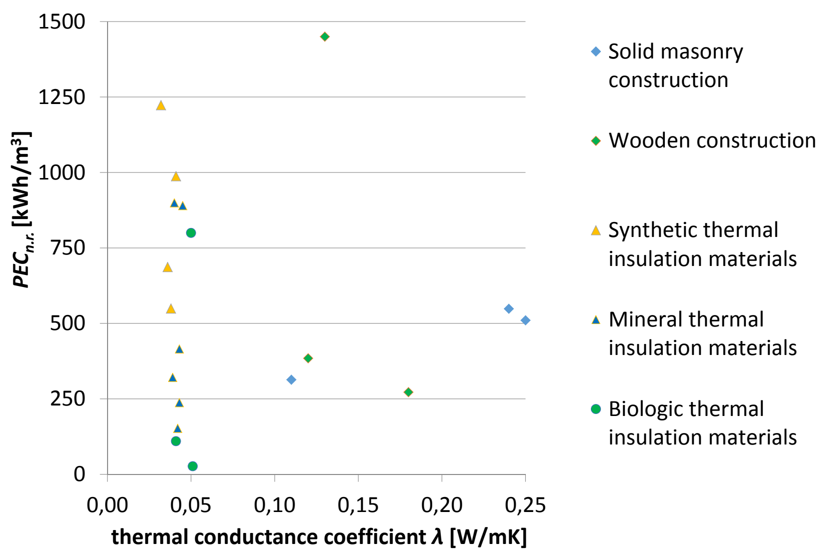

FIG. 2.1 Primary energy ($PEC_{n.r.}$) content required for the production of different groups of building materials depending on their thermal conductance

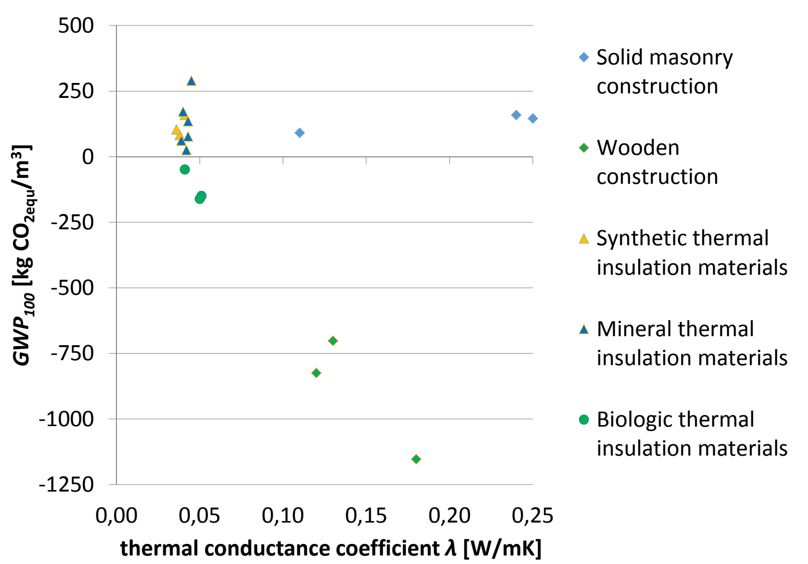

FIG. 2.2 Global warming potential (GWP_{100}) depending on thermal conductance of building materials

The values of *global warming potential* (GWP_{100}) indicate positive aspects of using load-bearing construction and thermal insulation materials of natural origin, such as, for example, wood and wood products (Fig. 2.2).

These materials, due to the CO_2 accumulated or tied in at the growth stage, have negative GWP_{100} values, which range up to -200 kg CO_{2equ}/m^3 for thermal insulation materials, and from -700 – -1,200 kg CO_{2equ}/m^3 for load-bearing construction materials. The GWP_{100} values of all other materials fall within the positive range from 0 – 300 kg CO_{2equ}/m^3.

The values of *environment acidification potential (AP)* do not depend on the structure in which the material is incorporated. The results fluctuate between the values of 0.1 – 1.1 kg SO_{2equ}/m^3 (Fig. 2.3).

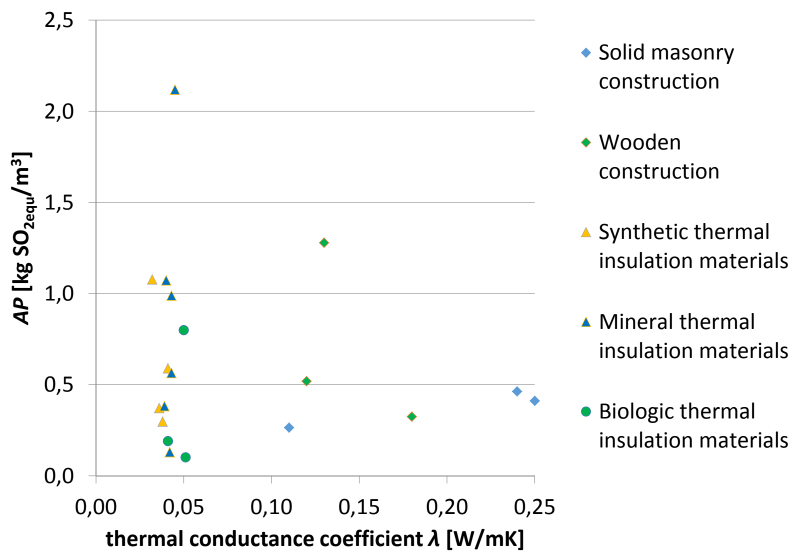

FIG. 2.3 Environment acidification potential (*AP*) depending on thermal conductance of building materials

2.2 Variants of Building Envelope Structural Components

For further analysis, descriptions of the structural components of the building envelope that are most frequently used in new construction are given for:

- **solid masonry walls** (SW) and **lightweight timber walls** (LW);
- **pitched roofs** (PR) and **flat roofs** (FR), and
- **ground floor** (GF) and **floor to unhea;ed parts** of the building (FU).

The components are identified by codes for the purpose of analysis presentation. They are presented below, together with the objectives and decisions that influenced their selection.

2.2.1 Solid Wall

Nine structural components have been selected for the exterior solid walls, and are described in Table 2.1:

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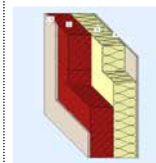
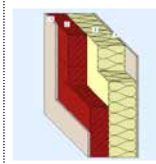
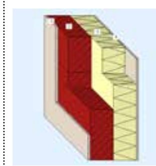
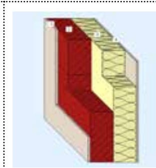
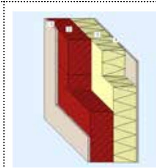
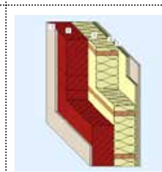
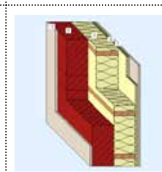
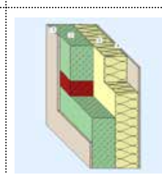
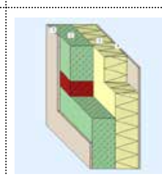
SW1	30 cm brick wall, mineral wool thermal insulation	
SW2	Derived from SW1, 20 cm brick wall, mineral wool thermal insulation	
SW3	Derived from SW1, 30 cm brick wall, thermal insulation made of expanded polystyrene (EPS)	
SW4	Derived from SW1, 30 cm brick wall**,** mineral wool thermal insulation of lesser density (for ventilated façade)	
SW5	Derived from SW1, 30 cm brick wall, thermal insulation from extruded polystyrene (XPS) (for brick walls below ground level)	
SW6	Derived from SW1, 30 cm brick wall, mineral wool of lesser density installed in a timber substructure, finished on the exterior with a wood fibreboard (assessing the impact of wood in the solid wall component)	
SW7	Derived from SW6, 30 cm brick wall, thermal insulation from cellulose flakes blown into the timber substructure, finished on the exterior with a wood fibreboard (assessing the impact of materials of biological origin)	
SW8	Derived from SW1, 30 cm wall made of aerated concrete blocks (instead of reinforced concrete), thermal insulation from mineral wool (assessing the impact of the load-bearing building material)	
SW9	Derived from SW8, 30 cm wall made of aerated concrete blocks, thermal insulation from EPS (instead of mineral wool).	

TABLE 2.1 Structural components for the exterior solid walls *(Baubook, 2017)*

2.2.2 Light Timber Wall

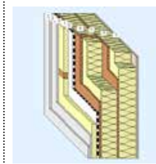
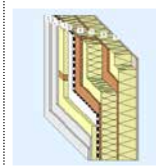
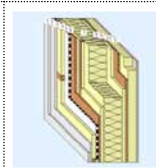
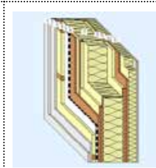
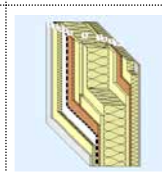
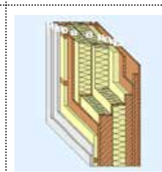
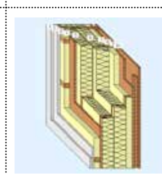
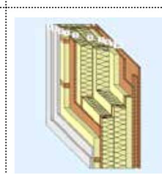
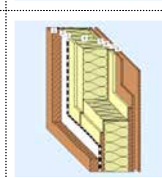
LW1	16 cm thick timber structure filled with mineral wool insulation; a layer of mineral wool insulation on the exterior surface (with plaster); installation frame filled with mineral wool on the interior surface	
LW2	Derived from LW1, thermal insulation from EPS on the exterior surface (assessing the effect of synthetic insulation)	
LW3	Structure from timber I-beams, with mineral wool of lesser density filled in-between; mineral wool of lesser thickness and a thin-layer of plaster on the exterior surface; installation frame filled with mineral wool on the interior surface	
LW4	Derived from LW3, EPS on the exterior surface (assessing the effect of synthetic façade insulation)	
LW5	Derived from LW3, natural thermal insulation is used – cellulose flakes filled between I-beams, wood fibre boards on the exterior and interior surfaces	
LW6	Framework structure (built in-situ): mineral wool insulation filled in-between; wood fibre thermal insulation on the exterior surface, ventilated façade.	
LW7	Derived from LW6; cellulose flakes are blown into the timber structure spaces.	
LW8	Derived from LW6; straw bales are fitted in-between the timber load-bearing structure	
LW9	Wall from solid glued wood; substructure made of I-beams on the exterior surface, thermal insulation from cellulose flakes blown in-between; wood fibre board on the exterior surface.	

TABLE 2.2 Structural components for the exterior lightweight timber walls *(Baubook, 2017)*

A lightweight timber structure is the preferred structural component of energy-efficient buildings. There are two main implementation methods: the building envelope structure can be prefabricated, or put together at the construction site. Nine structural components for the exterior lightweight timber walls were selected for the analysis, and are described in Table 2.2:

2.2.3 Flat and Pitched Roofs

Different structural components for pitched roofs and flat roofs, with wood and reinforced concrete structures, have been selected for analysis. Pitched roofs are described in Tab. 2.3, and flat roofs in Tab. 2.4.

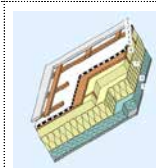
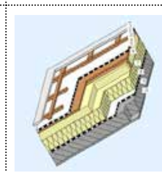
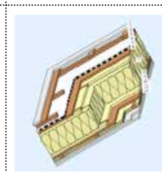
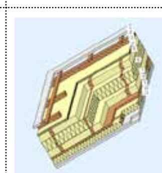
PR1	Mineral wool of lesser density between rafters; mineral wool of lesser density under the rafters between the spaces of the timber substructure	
PR2	Rafters over a reinforced concrete slab, mineral wool between and under the rafters (assessing the impact of the concrete)	
PR3	Derived from PR2, aerated concrete slab instead of a reinforced concrete slab	
PR4	Structure from timber I-beams, thermal insulation made of cellulose flakes	
PR5	Derived from PR4, straw bales instead of cellulose flakes	

TABLE 2.3 Structural components for pitched roofs *(Baubook, 2017)*

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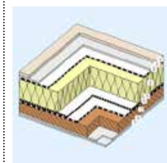
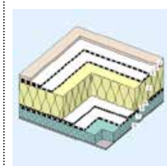
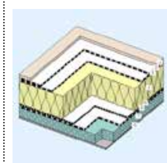
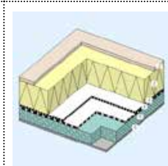
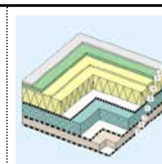
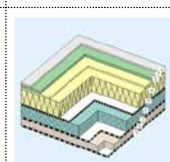
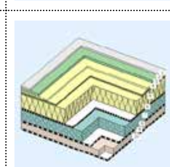
FR1	Glued wood slab, mineral wool on the exterior surface	
FR2	Reinforced concrete slab; EPS on the exterior surface	
FR3	Derived from FR2; reinforced concrete slab; mineral wool on the exterior surface	
FR4	Reinforced concrete slab; XPS on the exterior surface	

TABLE 2.4 Structural components for flat roofs *(Baubook, 2017)*

2.2.4 Ground Floor and Floor to Unheated Basements

Structural components for solid floors in contact with the ground, and structural components for solid and lightweight timber floor structures that are exposed to unheated parts of the building, have been selected for the analysis, and are described in Tab. 2.5 and Tab.2.6:

GF1	Reinforced concrete slab; EPS on the exterior surface	
GF2	Derived from GF1; mineral wool on the exterior surface (assessing the impact of selecting different thermal insulation)	
GF3	Derived from GF1; perlite on the exterior surface (assessing the impact of thermal insulation with different environmental parameters)	

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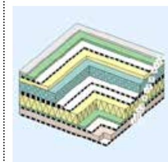
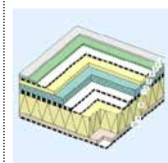
GF4	Reinforced concrete slab; mineral wool on the exterior surface and XPS on the interior surface	
GF5	Derived from GF4, foamed glass insulation on the interior surface (assessing the effect of exclusively mineral thermal insulation materials)	

TABLE 2.5 Structural components for ground floors *(Baubook, 2017)*

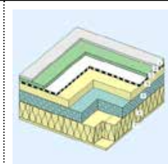
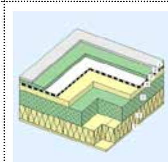
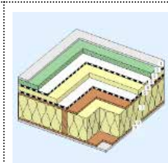
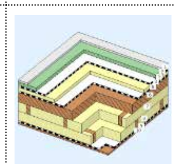
FU1	Reinforced concrete slab; mineral wool on the exterior surface; suspended ceiling with mineral wool on the interior surface	
FU2	Derived from FU1; aerated concrete slab	
FU3	Ceiling made of timber joists with mineral wool in-between; mineral wool on the exterior surface	
FU4	Glued wood slab; mineral wool on the exterior surface; mineral wool fitted in-between timber beams on the interior surface	

TABLE 2.6 Structural components for floors exposed to unheated parts of buildings *(Baubook, 2017)*

2.2.5 Windows

Windows have a major impact on the energy balance. On the one hand, they impact the reduction of heat losses, and on the other hand, they provide for solar gain. However, energy efficiency and impact on the environment are not measured only in terms of the effects that the windows have on the building's thermal balance during the building use phase, but throughout its life cycle. Selection of the most appropriate windows is based on various criteria, e.g. the window frame material, protection against external influences, the glass used, and the construction and physical characteristics such as thermal transmittance of the window frame and glass, and solar energy transmittance of the glass.

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For the purpose of further analysis of energy and environmental parameter trends, six groups of window frames with different composition and thermal transmittance U_f have been selected:

- a frame made of larch, external layer made of aluminium (wood-alu, larch)
- a frame made of spruce, external layer made of aluminium (wood-alu, spruce)
- a frame made of spruce (wood, spruce)
- a frame made of larch (wood, larch)
- a frame made of PVC
- a frame made of PVC, external layer made of aluminium (PVC-alu).

Glazing also has an impact on the thermal transmittance of windows. Triple glazing with different thermal transmittance (U_g) has been selected for analysis. Double glazing has only been used in the comparative part of the analysis.

3 Analysis of Energy and Environmental Indicators in the Structural Components of the Selected Building Envelope

For the aforementioned structural components of the building envelope, the analysis of energy and environmental indicators associated with their production has been carried out.

The first part of the analysis compares the trends in key parameters in terms of the target, i.e. operational energy efficiency, reflected through the achieved thermal transmittance, for different structural components.

The second part of the analysis shows the trends in environmental indicators according to the different primary energy inputs required for achieving a better thermal insulation performance of a structural component. At the same time, the payback period of such primary energy inputs in terms of subsequent operational savings is analysed. The overall payback time of primary energy input for different thermal protection levels achieved in the components is compared with that obtained under the reference thermal transmittance U, e.g. the maximum permitted thermal transmittance.

The third part of the analysis examines the cumulative environmental indicators over the life cycle of a building through a comparison between the reference and energy-efficient solutions for buildings.

3.1 Primary Energy Content, Global Warming Potential, and Environment Acidification Potential, and *OI3* Indicator for Building Envelope Structural Components

The values of the four targeted indicators for previously described structural components have been obtained by using online tools (Baubook, 2017).

3.1.1 Solid Walls

The trends in solid wall indicators are shown in Fig. 3.1 – 3.4. Since thermal protection of masonry components is modified by varying the thickness of thermal insulation, the trends in the observed indicators are continuous as expected. The monitoring of parameters is focused on thermal insulation and the recorded values range between the low thermal transmittance of structural components adhering to the passive house standard (*U* = 0.10 - 0.15 W/(m² • K)) and the reference values, i.e. the maximum values (*U* = 0.28 W/(m² • K)) permitted by the Slovenian legislation for the exterior walls during the study period (Uradni list RS, No. 52/2010).

$PEC_{n.r.}$

The findings in terms of the $PEC_{n.r.}$ indicator trend are as follows (Fig. 3.1):

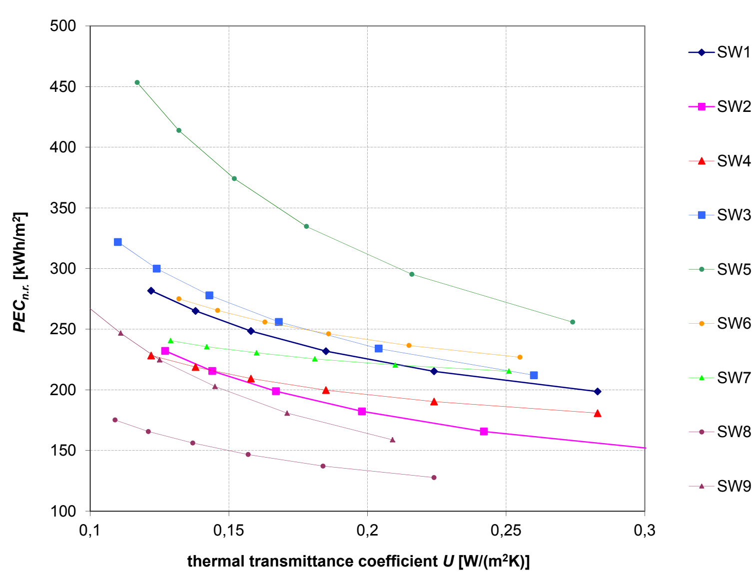


FIG. 3.1 The $PEC_{n.r.}$ indicator of primary energy content for exterior solid walls

– The primary energy used for the execution of the basic masonry component SW1 ranges from 200 – 300 kWh/m², and the relevant U-values of the component range from 0.28 – 0.10 W/(m² • K). The execution of a SW1 structural component with high thermal insulation performance requires 50% more primary energy content due to a thicker mineral wool layer.

- The primary energy content required for the execution of the SW2 solid wall component is reduced due to a lower proportion of bricks used, as follows: in the variant with thermal transmittance U = 0.28 W/(m^2 • K), it is reduced by approximately one quarter, and in the passive house variant by only one sixth. Due to a lower proportion of brick material, the same embodied energy content is used to produce a structural component with thermal transmittance U_{SW2} = 0.10 W/(m^2 • K) or U_{SW1} = 0.15 W/(m^2 • K).

- If EPS thermal insulation is used, the embodied energy content in the SW3 structural component is slightly increased, e.g. by 10% compared to the basic SW1, at thermal transmittance U = 0.15 W/(m^2 • K). Thus, a change in the façade system, which consists of replacing the mineral wool thermal insulation with a cheaper synthetic one, does not have a significant effect on the analysed parameter.

- By replacing mineral wool of a higher density with that of a lower density (the SW4 variant), the primary energy savings are 20% lower than those associated with the SW1 variant, at thermal transmittance U = 0.15 W/(m^2 • K). This difference indicates that the replacement of thermal insulation (change in the façade system) in solid masonry walls already has a more significant effect on the energy indicator.

- XPS is usually used when other materials cannot be applied. Compared to the analysed variants, the embodied primary energy content is highest in the SW5 variant (250 – 500 kWh/m^2). In terms of embodied primary energy content, the variant with the maximum permitted thermal transmittance exceeds the SW1 by one quarter, and the passive house variant by two thirds, due to an increased use of insulation material.

- The SW6 structural component with mineral wool insulation in a timber substructure is not significantly at variance with the SW1 variant. By increasing the thickness of thermal insulation, the embodied primary energy content in this component has turned out to be equal or lower at U_{SW6} = 0.12 W/(m^2 • K), due to a larger quantity of wood and mineral wool of lesser density used.

- The difference in the embodied primary energy content grows even more significant when only natural materials are used for insulation. In the SW7 variant, the embodied primary energy content becomes equal to that of the SW1 variant at U = 0.20 W/(m^2 • K), whereas at U = 0.10 W/(m^2 • K), the embodied primary energy content is lower by as much as one sixth. Opting for wooden façade cladding on solid walls is thus preferable in terms of primary energy use only when combined with natural thermal insulation.

- The variant involving solid walls made of aerated concrete blocks and insulated with mineral wool has yielded the best results among the variants. The SW8 structural component has 45% less embodied primary energy content compared to the SW1 variant, which highlights the great advantage of constructing the buildings with aerated concrete blocks.

- The SW9 variant with EPS thermal insulation applied to walls made of aerated concrete blocks still reflects the positive effects of aerated concrete use. Compared to the SW1 variant, the primary energy use is lower by 20% to 30%, according to reduced *U*-values.

GWP_{100}

The findings in terms of the GWP_{100} environmental indicator for exterior walls are as follows (Fig.3.2):

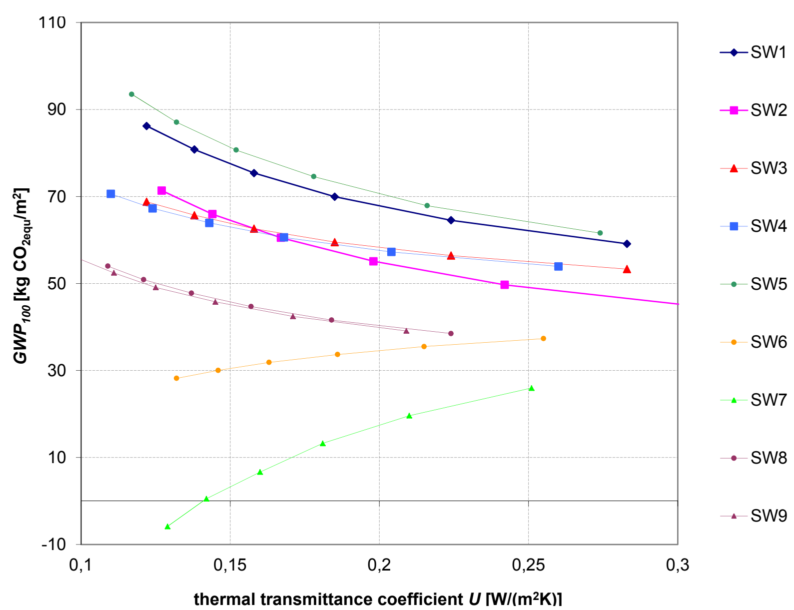


FIG. 3.2 The GWP_{100} environmental indicator of impacts on the global warming potential for exterior solid walls

- The basic SW1 structural component demonstrates high values in the range of 60 – 90 kg CO_{2equ}/m^2, which indicates a high level of environmental burden in terms of this parameter compared to the other analysed structural components. The variant with a thinner brick solid wall shows a reduced indicator value by approximately 15% when the thermal insulation system is left unchanged. The use of EPS thermal insulation in the SW3 variant and the use of mineral wool of lesser density in the SW4 variant show identical results. Compared to the SW1 variant, the parameter values of walls in a low-energy house with $U = 0.15$ W/(m^2 • K) are lower by approximately 15 – 20%.

– Thermal insulation made of XPS has proved to be the most environmentally burdensome, including in terms of this analysed indicator. The values of the SW5 variant are higher by 5% compared to the SW1 variant.

– The brick wall component using timber structure shows the positive effects of the use of wood, since the values of this indicator are decreasing with the increasing thermal protection level. In the SW6 variant, insulated with mineral wool, the parameter at $U = 0.20$ W/(m^2 • K) decreases by 50% if the thermal protection level is increased, compared to the SW1 variant. When using thermal insulation made of cellulose flakes, negative values of this environmental parameter are already achieved when the *U*-values of the wall are low.

– The exterior walls made of aerated concrete in the SW8 and SW9 variants have values that are lower by approximately 45% throughout the thermal transmittance *U* range, compared to the SW1 brick structural component.

AP

The findings in terms of the *AP* environmental indicator for exterior solid walls are as follows (Fig. 3.3):

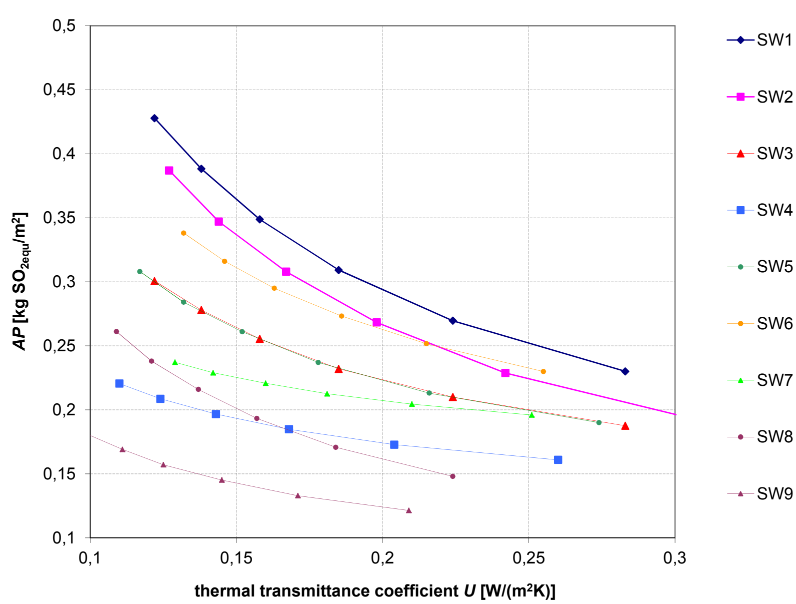


FIG. 3.3 The *AP* environmental indicator of impacts on the environment acidification potential for exterior solid walls

- An identical trend in the *AP* values is recorded in all variants. The SW1 basic component has the highest values ranging from 0.23 – 0.50 SO_{2equ}/m^2, depending on thermal transmittance.
- Considering the level of environmental burden in terms of this parameter, the variants are ranked in the following order: SW2 and SW6, SW4 and SW5, SW7, SW3, and SW8 and SW9. The variants with aerated concrete thus demonstrate the lowest values.

OI3

The best results scored by the variants for exterior solid walls (Fig. 3.4), in terms of the combined impact of the *OI*3 indicator, were recorded in the SW8 and SW9 walls, which were made of aerated concrete. On the other hand, the least favourable results were achieved by the SW1 basic wall and the SW5 variant with XPS. The use of polystyrene in the SW3 variant or mineral wool of lesser density in the SW4 variant gives the same results, which fall in the middle of all the compared variants. The score achieved by the use of mineral wool in a timber load-bearing structure in the SW6 is close to the score achieved by the SW1 basic component, and similar to the score of the SW2 variant with a thinner brick wall. The consistent use of wood or thermal insulation from cellulose flakes in the SW7 variant has only slightly variable results over the entire range of thermal transmittance and records a better result at its lowest analysed values than the wall made of aerated concrete.

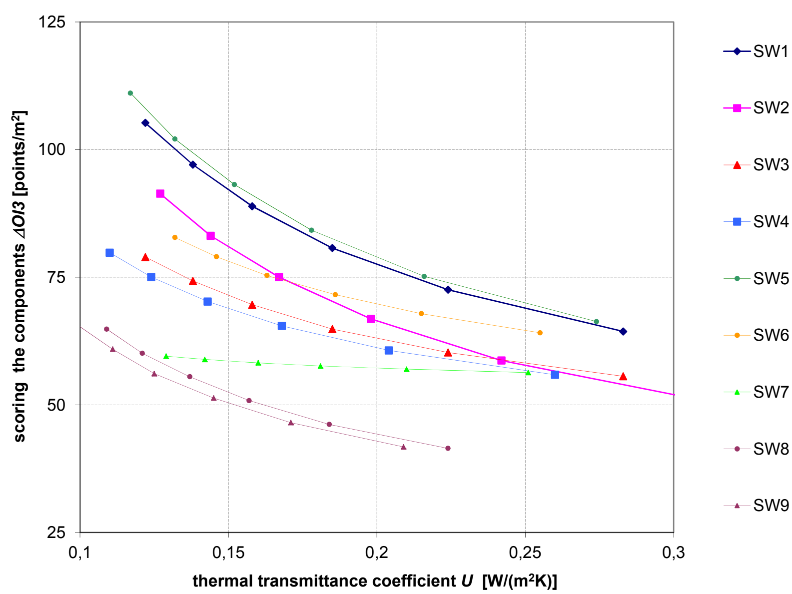


FIG. 3.4 The *OI3* combined environmental indicator for exterior solid walls

3.1.2 Lightweight Timber Walls

The analysed range, which, in the preceding case, included thermal transmittance ranging from the highest permitted value as defined by the legislation to the passive house values, is much more limited in the case of environmental indicators for lightweight timber walls. The reason for this is that better thermal protection of timber components is easier to achieve, and because the approach to increasing or reducing the thermal transmittance of timber components is often discontinuous. Light timber structures for energy efficient new buildings have thermal transmittance $U \leq 0.18$ W/(m² • K). As a result, the environmental indicators may not be compared up to the limit value $U = 0.28$ W/(m² • K), which in this case is consequently reduced to $U = 0.18$ W/(m² • K).

$PEC_{n.r.}$

The findings in terms of the $PEC_{n.r}$ energy indicator for lightweight timber walls, on the basis of the trends described are as follows (Fig. 3.5):

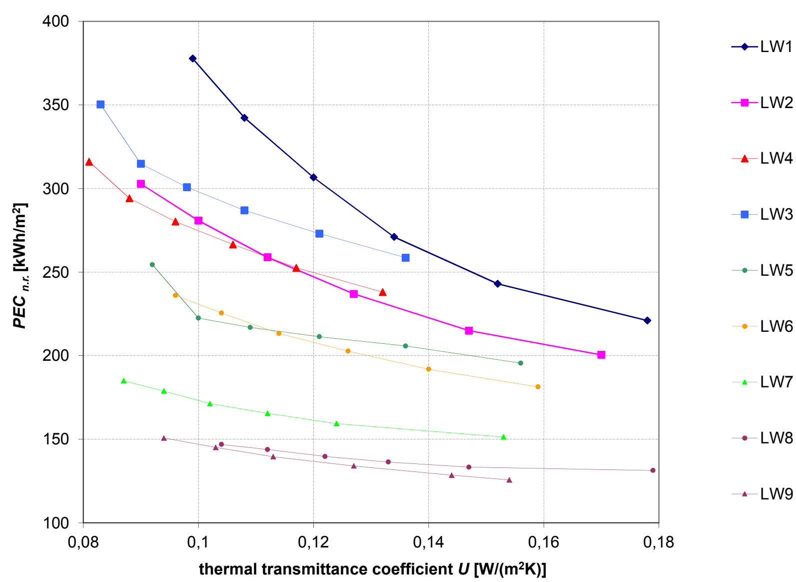


FIG. 3.5 The $PEC_{n.r.}$ indicator of primary energy content for lightweight timber walls

- The execution of the LW1 basic structural component requires 220 kWh/m² - 380 kWh/m² of primary energy at the corresponding thermal transmittance $U = 0.18$ and $U = 0.10$ W/(m² • K). A 50% decrease in thermal transmittance U is reflected in an approximately 80% increase in the primary energy use. This sharp increase in the primary energy use is the result of an increased thickness of façade insulation.
- When using the EPS thermal insulation in the LW2 timber component, the primary energy use is lower, and ranges between 10 and 35% compared to the LW1 basic component

at both limit thermal transmittances. This variant is more acceptable in terms of the analysed parameter.

- A similar characteristic is recorded in the LW3 I-beam variant, which is more efficient than the LW1 basic variant at a high thermal protection level, and has a value below 300 kWh/(m^2 • a) at U = 0.10 W/(m^2 • K). In the case of the EPS thermal insulation used in the LW4 variant, the values are only slightly lower, i.e. by approximately 10 % at a high thermal protection level due to a thinner layer of this material.

- Better values are recorded in the LW5 variant, which has thermal insulation made of cellulose flakes filled between the I-beams, where the values drop to 200 – 220 kWh/m^2. An almost identical result is recorded when the wall is insulated with mineral wool in the LW6 variant. These values indicate that more favourable results are achieved in the components that contain larger quantities of less technologically processed wood.

- A large difference is observed in the use of natural thermal insulation. The values in the LW7 framework structure with blown-in thermal insulation made of cellulose flakes drop to 150 – 180 kWh/m^2 at limit thermal transmittances. When straw bales are used in the LW8 variant, the values are reduced by a further 15%, and are thus almost 50% lower than the LW1 basic component.

- The results for the LW8 and LW9 solid timber walls with thermal insulation made of cellulose flakes indicate virtually the same values, as well as the best results for the analysed parameter among all the solutions provided for timber walls.

GWP_{100}

The findings in terms of the GWP_{100} environmental indicator for light-weight timber walls are as follows (Fig. 3.6):

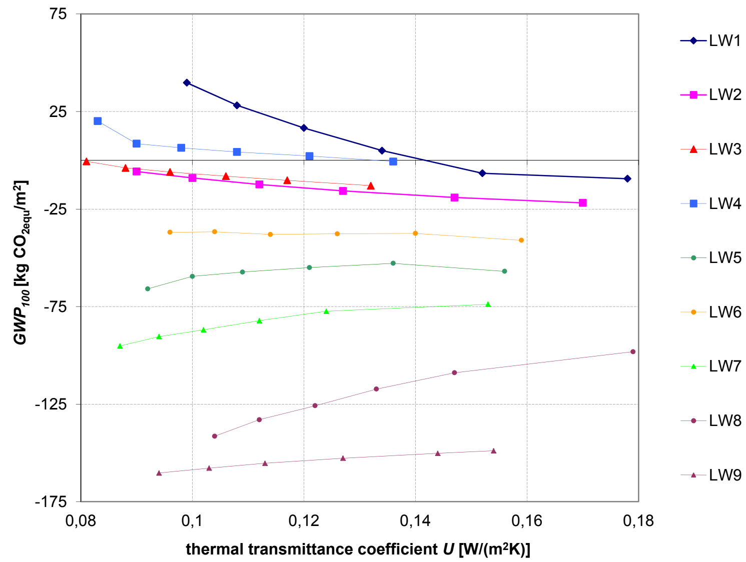


FIG. 3.6 The GWP_{100} indicator of impacts on the global warming potential for lightweight timber walls

- The LW1 basic component has the highest values compared to the remaining analysed components in this case. Due to a large proportion of wood in the component, the values at higher thermal transmittances are slightly negative and achieve 40 kg CO_{2equ}/m^2 only at a high level of thermal protection, which indicates an extremely low environmental burden in terms of this parameter, including in the case of the least thermally insulated exterior wall.

- The LW3 structural component with mineral wool fitted between I-beams has slightly positive values and an extremely low variance regardless of the achieved thermal transmittance.

- The LW2 and LW4 structural components, both with EPS thermal insulation, yield practically identical results that do not reach positive values of the analysed parameter even at a maximum thermal protection level.

- The remaining variants demonstrate a reverse trend in the analysed parameter since its value is declining by increasing the thermal protection level, which is due to a larger quantity of wood used and the natural thermal insulation. The structural components are ranked according to the declining values as follows: the LW5, LW7, and an identical trend for the LW8 and LW9. The structural components with the major part of their load-bearing structure and thermal insulation of natural origin produce the best results in terms of this environmental parameter.

AP

The findings in terms of the last *AP* environmental indicator are as follows (Fig. 3.7):

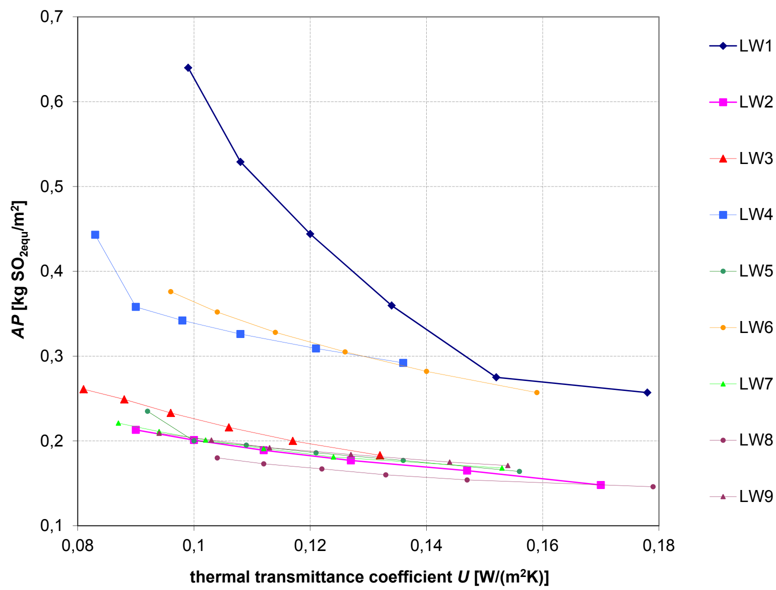


FIG. 3.7 The *AP* environmental indicator of impacts on the environment acidification potential for light wood walls

- The same trend is recorded in the values of all parameters. The LW1 basic structural component has the highest values ranging between 0.25 and 0.65 SO_{2equ}/m^2, depending on thermal transmittances.

- The LW3 and LW6 structural components, both insulated with mineral wool, have the next highest curve of values for this parameter. All the remaining structural components have practically identical values for this parameter in terms of environmental burden, with values ranging from 0.15 to 0.20 SO_{2equ}/m^2, which accounts for only one third of the values achieved at a high thermal protection level of structural components, compared to the basic structural component.

OI3

The least favourable evaluation results, based on the scoring system for the *OI*3 indicator (Fig. 3.8), are obtained by the LW1 basic structural component. Slightly lower values are recorded in the LW3 and LW6 structural components, both insulated with mineral wool. The LW4 and LW2 variants with EPS thermal insulation produce almost identical values. The next-ranked score result is recorded in the LW5 and LW7 variants with thermal insulation made of cellulose flakes. The best combined values are demonstrated by the LW8 light timber wall insulated with straw and the LW9 solid glued wood wall insulated with cellulose flakes.

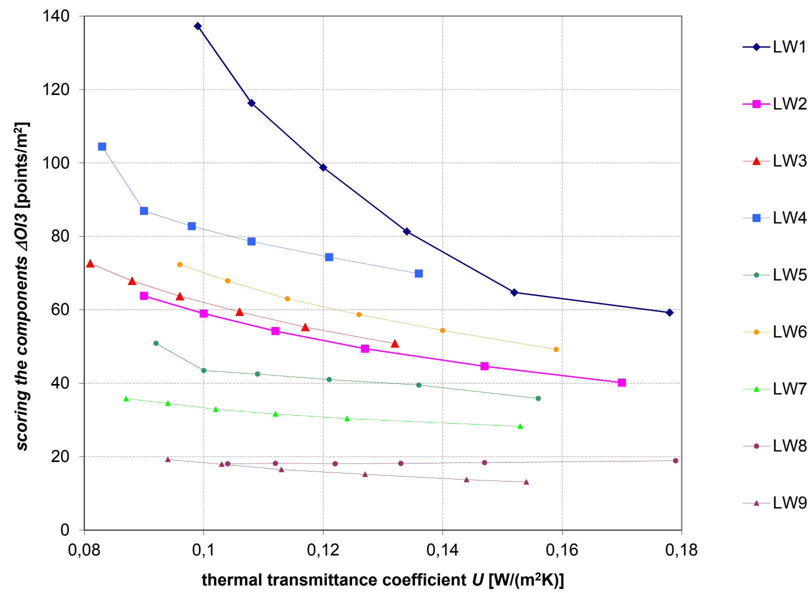


FIG. 3.8 The *OI3* combined environmental indicator for lightweight timber walls

3.1.3 Pitched and Flat Roofs

The analysed indicators for pitched and flat roofs are shown in Fig. 3.9 – 3.12, which simultaneously demonstrate a high thermal insulation performance of these structural components. The highest thermal transmittances do not normally exceed $U \leqslant 0.15$ W/(m^2 • K) and the roof structures for passive houses usually have the values $U \leqslant 0.09$ W/(m^2 • K). The movement of indicators will therefore be monitored within the range of the indicated limit values associated with the normal technological implementation.

***PEC**$_{n.r.}$*

Based on the results obtained, the findings in terms of the $PEC_{n.r.}$ energy indicator are as follows (Fig. 3.9):

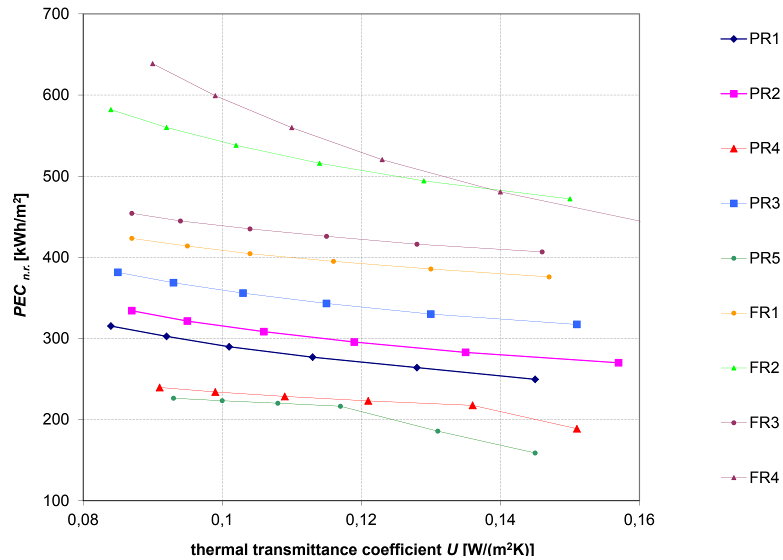


FIG. 3.9 The $PEC_{n.r.}$ indicator of primary energy content for pitched and flat roofs

- The PR1 pitched roof structural component indicates favourable results within the group of the analysed structural components. The embodied primary energy ranges between 250 and 300 kWh/m², pertaining to the thermal transmittances *U* = 0.15– 0.09 W/(m² • K). In order to reduce the thermal transmittance by 50%, the primary energy content in this structural component should be increased by 40%.

- A parallel trend in values is recorded in the PR2 structural component, i.e. a pitched roof with rafters over a reinforced concrete slab. The added solid layer accounts for approximately 10% higher primary energy content. A slightly larger difference in the same direction, and for the same reason, is recorded in the roof structure with an aerated concrete slab pertaining to the PR3 variant, whose value is 25% higher than the PR1 variant.

- The pitched roof made of timber I-beams in the PR4 and PR5 variants, insulated with cellulose flakes and straw, achieves the lowest values in the group of analysed structural components. Even at the highest thermal protection level, the values do not reach 250 kWh/m², which makes them 25% better than the PR1 basic structural component. Ultimately, the results obtained for the pitched roof insulated with straw are slightly better than those obtained for the pitched roof insulated with cellulose flakes.

- The flat roof made of glued wood with mineral wool insulation (FR1) has produced the best results in the group of flat roofs, but has a higher primary energy content than all the pitched roofs. Its embodied primary energy is higher by 120 kWh/m² compared to the PR1 basic structural component, which accounts for approximately 35% upward deviation at a high thermal protection level.

- The FR3 structural component with a reinforced concrete slab and mineral wool insulation has primary energy content that is higher by approximately 10% compared to the FR1 structural component. If foamed polystyrene thermal insulation is used, the values at a lower thermal protection level are higher by approximately 20% compared to those recorded in the FR3 variant. At a higher thermal protection level, however, the FR2 structural component insulated with EPS demonstrates upward deviation of approximately 25% compared to the FR3 structural component, and of almost 45% compared to the structural component insulated with XPS.

GWP_{100}

The findings in terms of the GWP_{100} environmental indicator for pitched roofs and ceilings are as follows (Fig. 3.10):

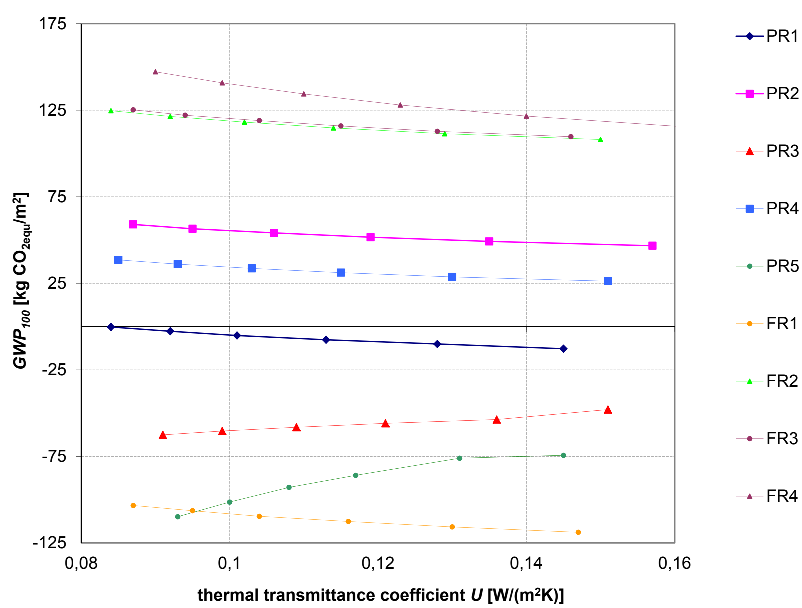


FIG. 3.10 The GWP_{100} environmental indicator of impacts on the global warming potential for pitched and flat roofs

- The PR1 pitched roof basic structural component has negative values, which approach 0 kg CO_{2equ}/m^2 when thermal protection levels are increased, which is typical for timber structures. Even better results among the selected pitched roofs are recorded by the PR4 and PR5 structural components made of I-beams, where the variant with straw insulation demonstrates a sharper decline in values when thermal protection levels are increased. The lowest value is observed in the FR1 flat roof made of glued wood, which, however, is brought to the same level with the value recorded in the

PR5 variant at a high thermal protection level, i.e. the value of -110 kg CO_{2equ}/m^2.

- Positive values of this environmental indicator are achieved in ascending order by the PR3 pitched roof with aerated concrete structure and the PR2 with reinforced concrete slab. An identical high value is recorded in the FR2 and FR3 flat roofs. The highest value is measured in the FR4 variant insulated with XPS, reaching 150 kg CO_{2equ}/m^2 at a high thermal protection level.

AP

The findings in terms of the last *AP* environmental indicator are as follows (Fig. 3.11):

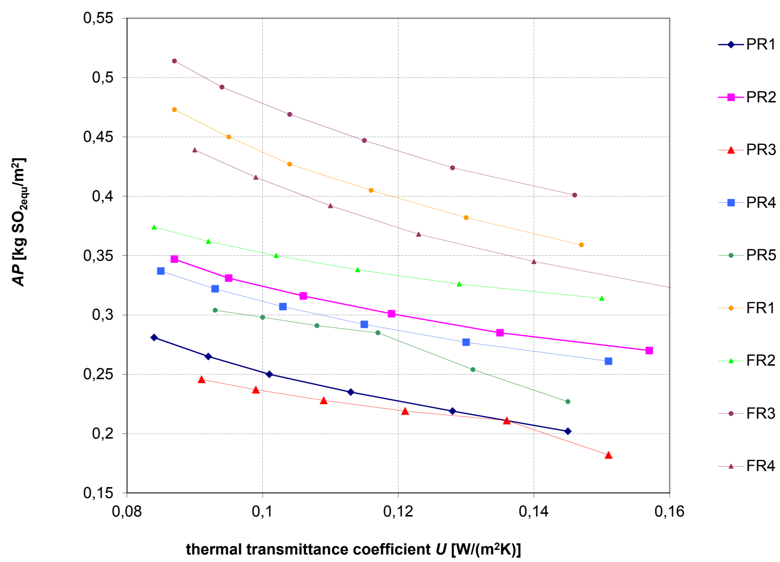


FIG. 3.11 The *AP* environmental indicator of impacts on the acidification potential for pitched and flat roofs

- The values of all variants show an identical trend. The PR1 basic structural component demonstrates favourable low values, which, depending on *U* thermal tranmittances, range between 0.20 and 0.27 SO_{2equ}/m^2. Better values are recorded only in the PR4 variant insulated with cellulose flakes, followed by the PR5 variant insulated with straw. The next ranked are the PR3 structural component with an aerated concrete slab and the PR2 structural component with a reinforced concrete slab which have almost identical values. They are followed by the FR2, FR4, and FR1 variants.

OI3

The best values of the total score results achieved for the combined effect assessed by the *OI3* indicator are measured in the PR4 and PR5 structural components (Fig. 3.12) with a pitched roof from timber I-beams, with almost no difference between the two thermal insulation materials used. The next-ranked values are recorded in the PR1 structural component. A similar upward deviation in the *OI3* indicator values is observed in the PR2, PR3, and FR1 variants, which produce almost identical results and come next in the ranking order. The least favourable *OI3* combined indicator values are measured in flat roof variants ranked in the following order: FR2, FR3, and FR4.

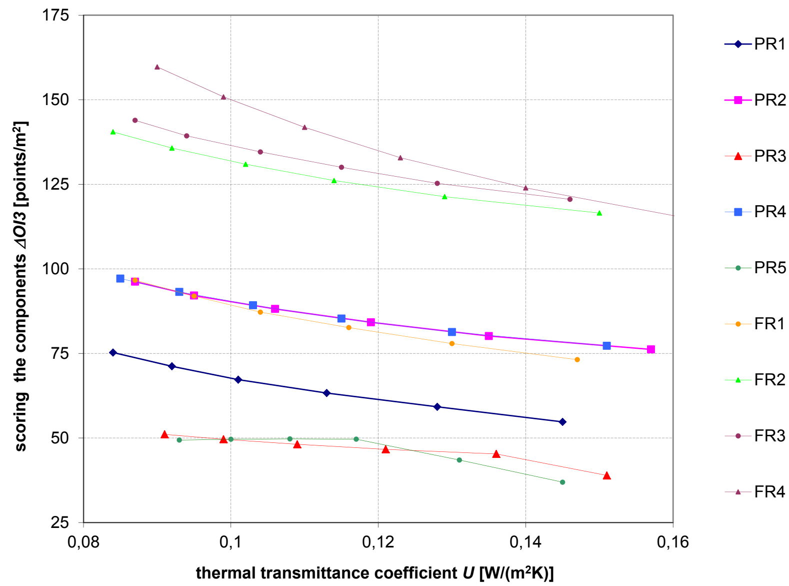


FIG. 3.12 The *OI3* combined environmental indicator for pitched and flat roofs

3.1.4 Ground Floor and Floor to Unheated Basements

Thermal transmittances in ground floor structural components normally range between $U = 0.10$ and 0.25 W/(m^2 • K) according to a higher degree of homogeneity in layers, and a continuous increase in thermal protection, which also represents the limits within which the fluctuation of environmental indicators is monitored.

$PEC_{n.r.}$

Based on the results obtained, the findings in terms of the $PEC_{n.r.}$ energy indicator are as follows (Fig. 3.13):

TOC

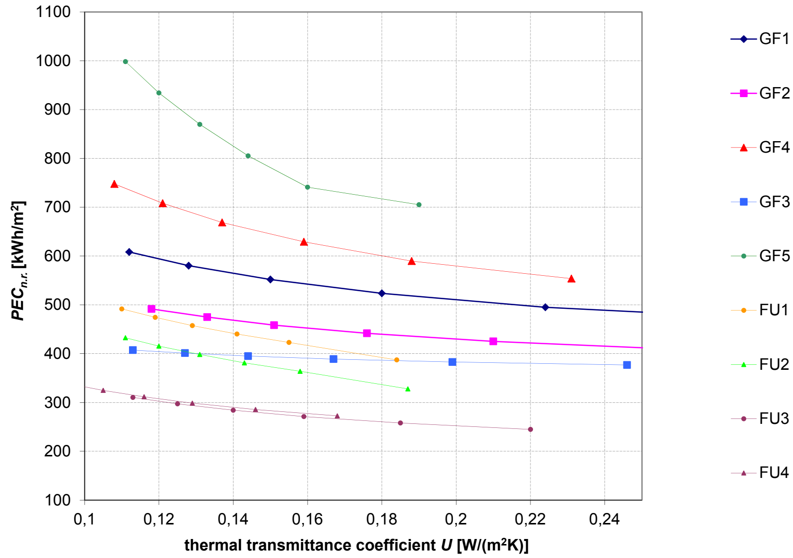


FIG. 3.13 The $PEC_{n.r.}$ energy indicator for ground floor and floor to unheated parts of a building

- The GF1 basic structural component for ground floor with EPS thermal insulation has the mean values among the variants. The primary energy content is from 500 to 650 kWh/m² for thermal transmittances U = 0.10 – 0.25 W/(m² • K). In order to reduce thermal transmittance by 50%, this structural component requires 25% more embodied primary energy, which indicates that a higher embodied energy content is inherent in those layers that do not make up the thermal protection of the component.

- The primary energy content in the GF2 structural component with mineral wool thermal insulation is lower by an average of 15%. The GF3 structural component insulated with perlite produces results that vary only slightly when thermal protection levels are increased by values not exceeding 400 kWh/m², which makes them as much as 35% lower than those recorded in the GF1 basic structural component at a high thermal protection level.

- The GF4 structural component with XPS thermal insulation on the interior surface of the reinforced concrete slab shows a 20% higher primary energy content than the GF1 basic structural component. The difference in the primary energy content measured in the GF5 structural component with thermal insulation made of foamed glass, however, is major, and exceeds the results recorded in the GF1 variant by almost 100% at a high thermal protection level.

- The FU1 structural component for floor to unheated parts of a building demonstrates an average of 20% lower values compared to the GF1 variant. The primary energy use in the

FU2 variant where the reinforced concrete ceiling is replaced by an aerated concrete ceiling, is reduced by an additional 10%.

- The FU3 and FU4 timber ceiling structural components have practically identical values of primary energy content, which are the lowest within the analysed group of variants. The values trend is parallel to that in the GF1 variant with a 250 kWh/m² variance, accounting for a 50% share at a high thermal insulation level.

GWP_{100}

The findings in terms of the GWP_{100} environmental indicator for ground floor structural components are as follows (Fig. 3.14):

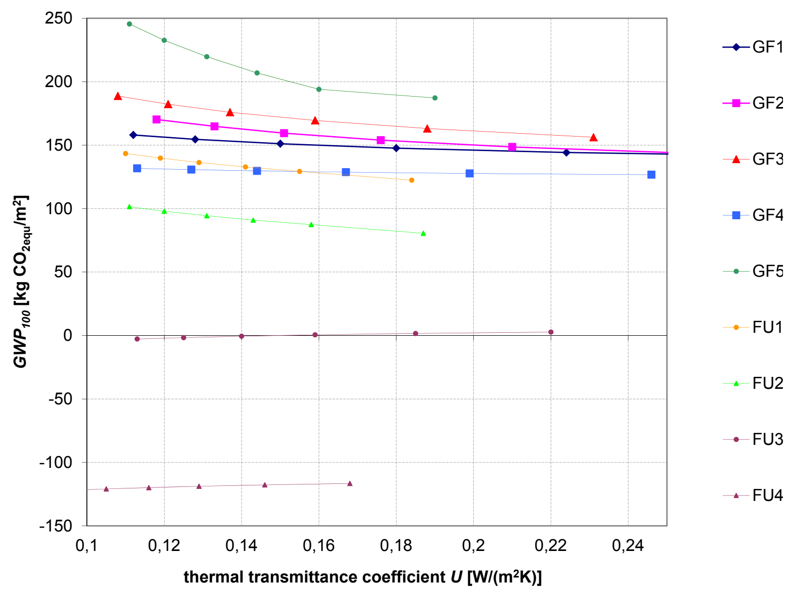


FIG. 3.14 The GWP_{100} environmental indicator of impacts on the global warming potential for ground floor and floors to unheated parts of a building

- The GF1 structural component records high values which vary very slightly when thermal protection levels are increased, and amount to 150 kg CO_{2equ}/m², which again indicates a very strong impact of the construction part of this variant. The use of mineral wool as thermal insulation in the GF2 variant increases the values indicated above by 10% at high thermal protection levels. When thermal insulation made of perlite is used (the GF3 variant), these values are almost 20% lower than the ones measured in the GF1 variant.

- The two structural components with thermal insulation under the foundation slab again indicate the highest values among the variants compared. The GF4 structural component insulated with XPS records 20% higher values compared to the GFI basic variant. At a high thermal insulation level, the structural component with foamed glass insulation indicates a more than 70% higher value, exceeding 250 kg CO_{2equ}/m^2, compared to the parameter value measured in the GF1 variant.

- The parameter values in floor to unheated basement structural components are better than in the previously analysed structural components for ground floor. The value obtained in the FU1 variant is 20% lower than the GF1 variant, whereas the value measured in the FU2 variant is lower by an average of 40%.

- Structural components with timber elements again produce good results, as expected. The values measured in the FU3 variant are around 0 kg CO_{2equ}/m^2 owing to a smaller proportion of wood. The lowest values, however, are recorded in the FU4 variant with a solid glued wood slab, and oscillate around -120 kg CO_{2equ}/m^2.

AP

The findings in terms of the *AP* environmental indicator are as follows (Fig. 3.15):

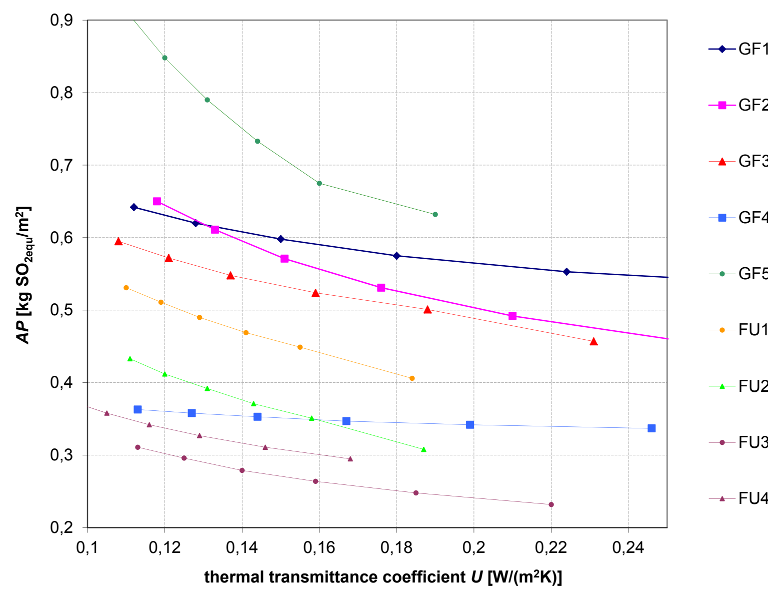


FIG. 3.15 The environmental indicator *AP* of impacts on the acidification potential for ground floor and floor to unheated parts of a building

- The same trend is recorded in all structural components. The GF1 basic structural component has high values compared to the remaining variants in the group, which range from 0.55 to 0.65 SO_{2equ}/m^2, depending on thermal transmittance *U*. The values measured in the GF2 structural component, with thermal insulation made of mineral wool, are more favourable when the thermal protection level is poor, whereas they are brought to the same level when the thermal protection level is high. The parameter value observed in the GF3 variant, insulated with perlite, is, again, little influenced by the thermal protection level and the results at a high thermal protection level reach almost half the value of those recorded in the GF1 basic structural component.

- The GF4 variant with thermal insulation made of XPS has lower values by approximately 10%. Here again, the GF5 structural component demonstrates the highest values of this parameter within the group, which exceed 0.9 SO_{2equ}/m^2 at a high thermal protection level.

- The floor to unheated basement structural components again produce lower parameter values compared to the GF1 basic variant: in the FU1 variant, they are lower by an average of 25% and in the FU2 by an average of 40%.

- The values for timber floor to the basement are the lowest in the group, including for this parameter. The FU4 structural component made of glued wood has a slightly lower value than the FU3 structural component, whose values range from 0.22 to 0.33 SO_{2equ}/m^2.

OI3

The best values in the group in terms of the combined effect of the *OI3* indicator are achieved by the FU3 and FU4 timber structural components (Fig. 3.16), in which the solid structural component imposes the lowest burden on the environment. The FU2 structural component for floor to unheated basement made of aerated concrete and the FU1 structural component made of reinforced concrete demonstrate the next best-ranked values (almost double points), with the aerated concrete variant having a lower impact on the environment than the reinforced concrete variant. The lowest combined environmental impact among the ground floor variants is achieved by the GF3 structural component insulated with perlite, followed by the GF2 variant insulated with mineral wool and the GF1 basic variant insulated with EPS. The GF4 ground floor structural component with XPS thermal insulation on the interior surface of the reinforced concrete slab has an identical environmental impact to the GF1 basic variant. The highest burden on the environment is recorded in the GF5 structural component with foamed glass insulation, where the combined environmental effect at a high thermal protection level may even be 50% higher than that in the GF1 basic variant.

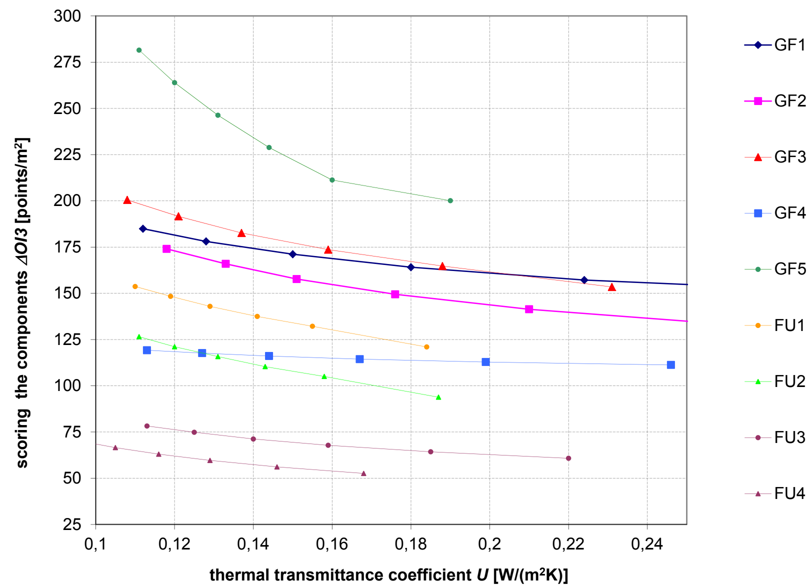


FIG. 3.16 The *OI3* combined environmental indicator for ground floor and floor to unheated basement structural components

3.2 The Primary Energy Content, Global Warming Potential, Acidification Potential, and *OI3* Indicators for Windows

$PEC_{n.r.}$

The $PEC_{n.r.}$ indicator of primary energy content for the production of windows (Fig. 3.17) is shown in terms of its dependence on thermal transmittance *U*, with window frames and glazing shown separately:

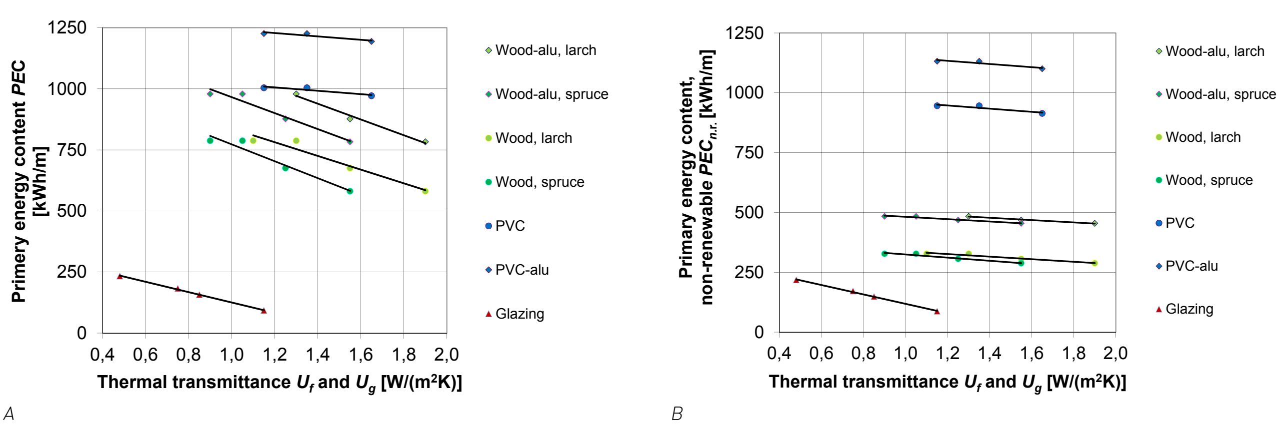


FIG. 3.17 Comparison between the total primary energy content (A) and the non-renewable primary energy content (B) for window frames and glazing in terms of its dependence on thermal transmittance

- Non-renewable primary energy content required for glazing amounts to approximately 90 – 220 kWh/m^2. Double glazing with thermal transmittance U_g = 1.1W/(m^2 • K), selected for further comparative reference, has low primary energy content indicated by the aforementioned bottom limit value. The top limit value, which is more than doubled compared to the previously indicated value, pertains to a triple glazing system with U_g=0.50 W/(m^2 • K), which is most frequently used in passive houses.

- Non-renewable primary energy used for the production of wooden window frames amounts to 290 – 330 kWh/m^2. If spruce wood is used, these values refer to the frame with thermal transmittance U_f = 1.55 – 0.90 W/(m^2 • K), and if larch wood is used, they refer to the frame with thermal transmittance U_f = 1.90 – 1.10 W/(m^2 • K). A timber frame with external layer made of aluminium requires an additional 160 kWh/m^2 of non-renewable primary energy.

- PVC frames require between 910 and 950 kWh/m^2 of non-renewable primary energy, which refers to the frames with thermal transmittance U_f = 1.1 – 1.65 W/(m^2 • K). In this case, the addition of an external aluminium layer made for the protection of the frame requires an additional 180 kWh/m^2 of non-renewable primary energy.

- The added primary energy content required to reduce the thermal transmittances U_f of window frames accounts for less than 15 % in timber frames and only up to 5 % in PVC frames. It may thus be concluded that in the case of window frames with identical energy efficiency, a PVC frame requires approximately three times as much primary energy as a timber frame.

- It may also be concluded that the specific primary energy used for glazing is lower than that required for window frames; however, the actual surface ratio between the glass and frame should also be taken into account. The frame surface area in a standard window (1.23 m x 1.48 m) (DIN EN 14351-1:2006-07) measuring 1.82 m^2 thus accounts for 32 % of the total window surface area. Consequently, the proportion between the primary energy used for glazing and the primary energy used for frames is usually equivalent, or the glazing may account for a 40 to 50% share of the total primary energy used for the production of the complete window.

- The renewable primary energy content in glazing is approximately 10 % and in timber frames up to 50 – 60%; if an exterior aluminium layer is added for frame protection, then this figure is 10% less than the values indicated. In PVC window frames, this share accounts for 5 – 10%, with the lower values pertaining to the frames with an exterior aluminium layer.

GWP$_{100}$ and *AP*

The findings in terms of the impact of different window variants on the *GWP*$_{100}$ and *AP* environmental indicators are the following (Fig. 3.18):

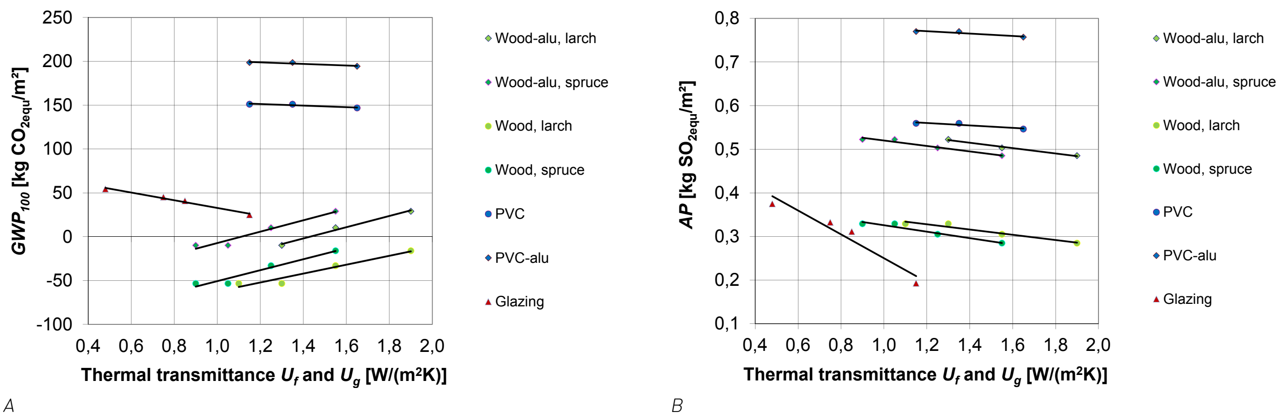


FIG. 3.18 The *GWP*$_{100}$ (A) environmental indicator of impacts on the global warming potential and the *AP* (B) environmental indicator of impacts on the acidification potential for window frames and glazing in terms of their dependence on thermal transmittance

– The PVC window frames, with the option of an additional external layer of aluminium protection, have values of 150 kg CO_{2equ}/m^2 or 200 kg CO_{2equ}/m^2, respectively. When thermal protection levels are increased through glazing, the increase in this parameter is more significant and achieves values between 25 and 50 CO_{2equ}/m^2. As expected, timber frames have declining values when thermal transmittance is reduced, achieving 15 to -50 CO_{2equ}/m^2. If an additional external layer of aluminium protection is added, the values rise to -10 to +30 CO_{2equ}/m^2.

– The values recorded for the second environmental parameter increase in the same direction for all the compared elements in parallel with the decreasing thermal transmittance. The most significant difference is observed in glazing where the value of the indicator is doubled when thermal transmittance is decreased, i.e. it rises from 0.2 SO_{2equ}/m^2 to 0.4 SO_{2equ}/m^2. In wooden window frames, the values oscillate by around 0.3 SO_{2equ}/m^2 on average and increase by 60 to 70%, i.e. to 0.5 SO_{2equ}/m^2, when the external layer of aluminium protection is added. PVC window frames have higher values compared to those recorded in wooden window frames and range above 0.55 SO_{2equ}/m^2 on average, increasing to 0.75 SO_{2equ}/m^2 when the external layer of aluminium protection is added.

OI3

The weighted environmental effect of the three previously described indicators (Fig. 3.19) is also presented through an environmental score system set up for the elements of a standard dimension window. The results show that, in this respect, the environmental burden caused by PVC window frames is two to three times higher than that caused by wooden window frames.

When analysing the combined impact of the glass and the frame of standard dimensions, it is also observed that the impact of glass considerably increases with a larger glazed window surface. Windows with dimensions exceeding the reference ones are frequently found in energy efficient new buildings. Considering this fact, the environmental impact of glazing becomes even more considerable.

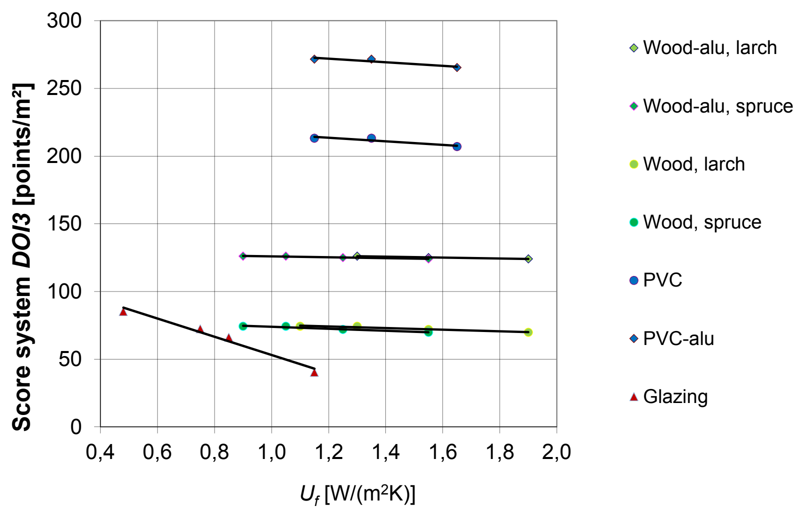
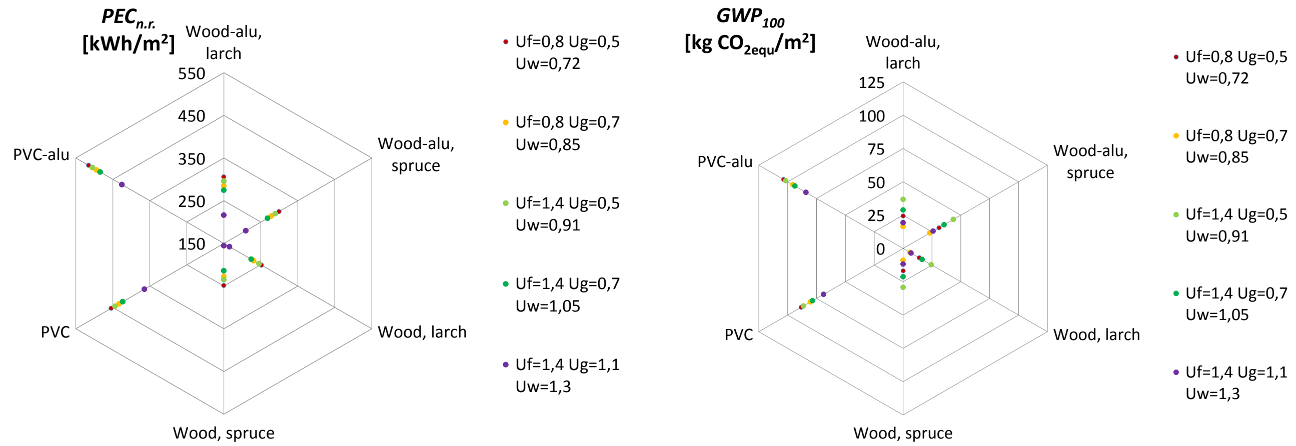


FIG. 3.19 The *OI3* combined environmental indicator for window frames and glazing according to its dependence on thermal transmittance

The changing of the two key parameters $PEC_{n.r.}$ and GWP_{100} is not analysed only for individual components (glass, frame), but also for their combinations, which result in different joint thermal transmittances of the window U_w. For the purpose of comparison, the basic combination with the reference value U_w = 1.3W/(m^2 • K), which is the highest thermal transmittance permitted by the legislation, has been defined. The variants with thermal transmittances between the reference values U_w = 1.3W/(m^2 • K) and U_w = 0.7W/(m^2 • K) have been designed through various combinations of more efficient glazing and frames (Fig. 3.20). The results obtained are as follows:



A *B*

FIG. 3.20 Changing the $PEC_{n.r}$ (A) and GWP_{100} (B) indicators for joinery with different efficiency

- The primary energy content in wooden windows with thermal transmittance from U_w = 1.3 to 0.7 W/(m² • K) ranges between 170 and 250 kWh/m², with the difference between the reference and high energy efficiency values amounting to 45%. If the exterior aluminium layer for the protection of the frame is added, the primary energy content increases to 210 – 300 kWh/m², i.e. 20% higher than the previous values. The primary energy content in PVC window frames ranges between 360 and 450 kWh/m², which accounts for a 25% difference between the reference and high efficiency values. If the exterior aluminium protection layer is added, the embodied primary energy is increased to 430 – 510 kWh/m², which is again up to a 20 % rise compared to the window without the frame protection. When comparing energy efficient wooden windows and PVC windows with the U_w = 0.7 W/(m² • K), the results indicate an 80% higher primary energy content in PVC windows.

- The data for the GWP_{100} environmental parameter indicate positive changes in wooden window frames, which result from a larger proportion of wood used as the material for the production of windows. In windows with low thermal transmittance, a larger proportion of wood used brings the joint value of the parameter (15 – 30 kg CO_{2equ}/m²) closer to the results achieved by the windows with reference thermal transmittance U_w = 1.3W/(m² • K) (10 – 20 kg CO_{2equ}/m²). In windows with a PVC frame, however, the increase of the GWP_{100} parameter value is not affected by decreasing thermal transmittance U_w of the window, and ranges between 90 and 100 kg CO_{2equ}/m² in highly energy efficient windows, and between 70 and 80 kg CO_{2equ}/m² at the reference thermal transmittance.

TOC

4 The Expected Payback Period of the Measures Applied to Improve the Energy Efficiency of the Building Envelope Structural Components

When improving the energy efficiency of the thermal envelope structural components, larger quantities of non-renewable primary energy are embodied in a new building, burdening the environment with CO_2, which has been embodied in the products during their production phase. The values of both indicators obtained during the construction process (the primary energy content and CO_2 content) are compensated by the savings in the energy used for heating the building. The building envelope with a higher thermal protection level has lower transmission heat losses. This difference in the building's energy balance may be evaluated in terms of less energy needed to heat the premises. The heat generated for this purpose may also be evaluated in terms of the corresponding primary energy content and CO_2 emissions.

The calculation of the expected payback period of the primary energy and CO_2 embodied in the structural components is based on the following assumptions:

- Since the majority of energy efficient residential buildings are supplied with heat through heat pumps, the consumption of electrical energy with a specific emission of 0.53 kg CO_2/kWh and a primary energy conversion factor of 2.5 have been applied for estimation purposes. Both values have been determined (MOP, 2010) for use in cases when the supply structure of the energy product used is not defined in detail or is unknown.

- To determine transmission heat losses, the temperature deficit of 3,000°day/year has been taken into account, being the most frequent or characteristic value in the territory of Slovenia.

4.1 Exterior Solid Walls

The payback period of the embodied primary energy through operational savings is rapid in *exterior solid walls*, considering the long life cycle of masonry elements. The results shown enable the comparison between the reference construction with thermal transmittance U = 0.28 W/(m^2 • K) and a highly efficient construction with thermal transmittance up to 0.10 W/(m^2 • K) (Fig. 4.1).

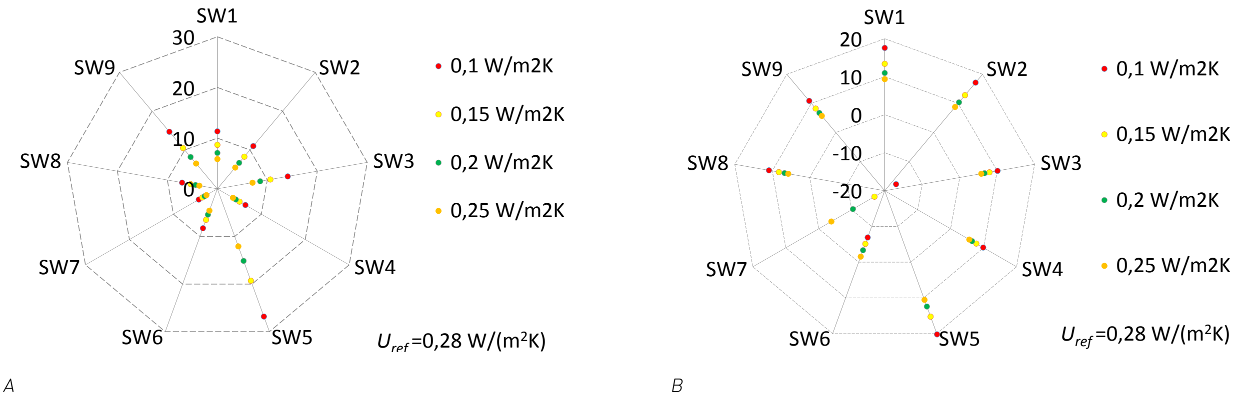


FIG. 4.1 Payback period of embodied primary energy (A) and embodied CO_2 (B) through savings for solid masonry walls

In most cases, the expected payback period of additional embodied primary energy to achieve the thermal transmittance of the element U = 0.15 W/(m^2 • K) is less than 10 years, and not more than 15 years at the thermal transmittance U = 0.10 W/(m^2 • K). A notable exception is the SW5 structural component with thermal insulation made of XPS, which has a payback period of almost 30 years. The lowest values are measured in the SW4, SW7, and SW8 variants, where mineral wool of lesser density fitted to a brick wall, cellulose flakes blown into the timber framework, or mineral wool fitted to an aerated concrete wall are used for thermal protection.

The payback period of embodied CO_2 in structural components with the highest thermal protection level U = 0.10 W/(m^2 • K) is typically between 10 and 20 years. The exceptions are the SW6 and SW7 variants, where the payback period is decreasing in parallel with an increasing proportion of wood used in a structural component.

4.2 Lightweight Timber Walls

In *lightweight timber walls*, a simple comparison with the high reference thermal transmittance, as has been made in the preceding case, is not possible due to technological reasons. These structural components usually achieve thermal transmittances $U \leqslant$ 0.18 W/(m^2 • K), therefore the reference value U = 0.28 W/(m^2 • K) applied in the preceding case may not be used. However, the findings (Fig. 4.2) within the range of the results for e.g. U = 0.10 and U = 0.18 W/(m^2 • K) may be interpreted in terms of a transition from the structural components of a low-energy house envelope with poorer thermal protection performance to more energy efficient structural components of a passive house envelope.

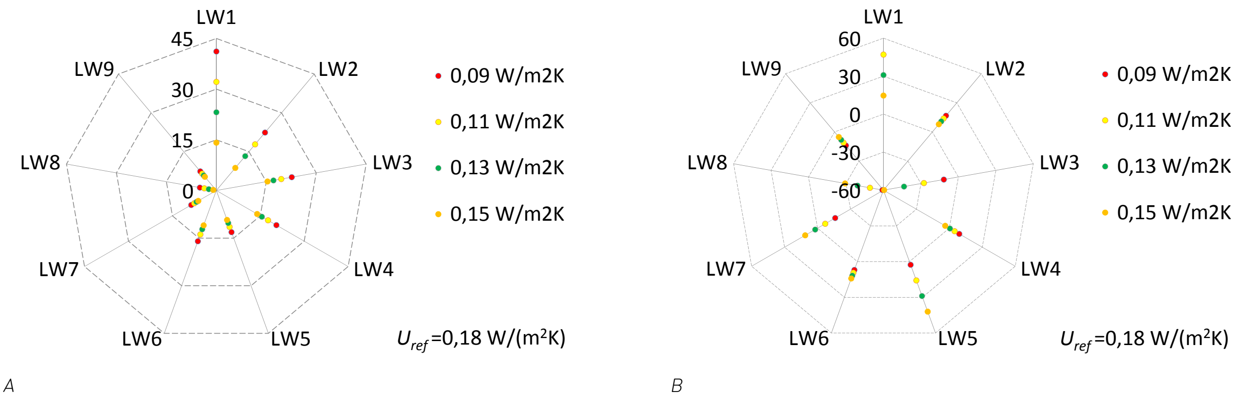


FIG. 4.2 Payback period of embodied primary energy (A) and embodied CO_2 (B) through savings for lightweight timber walls

The expected payback period of added embodied primary energy in most frequently used variants of lightweight timber walls is 20 years. The payback period for the walls insulated with natural thermal insulation materials, however, is less than 10 years. The two results are thus very stimulating, particularly in comparison to the low thermal transmittance *U* of the reference structural component.

The payback period of embodied CO_2 in light timber structures is usually less than 20 years. When natural thermal insulation materials are used, the payback period declines sharply in parallel with the increasing thermal protection level, dropping below 0 value. Such a favourable result means that the added embodied CO_2 in improved structural components exceeds the emissions during operation.

4.3 Pitched and Flat Roofs

In the case of *pitched and flat roofs*, the comparison (Fig. 4.3) of energy efficient structural components is made according to the reference structural component (U = 0.20 W/(m² • K)).

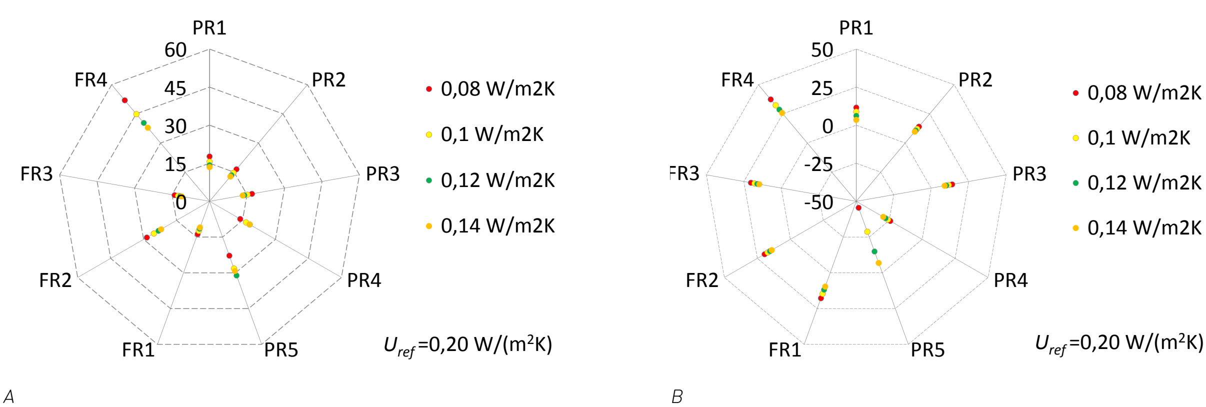


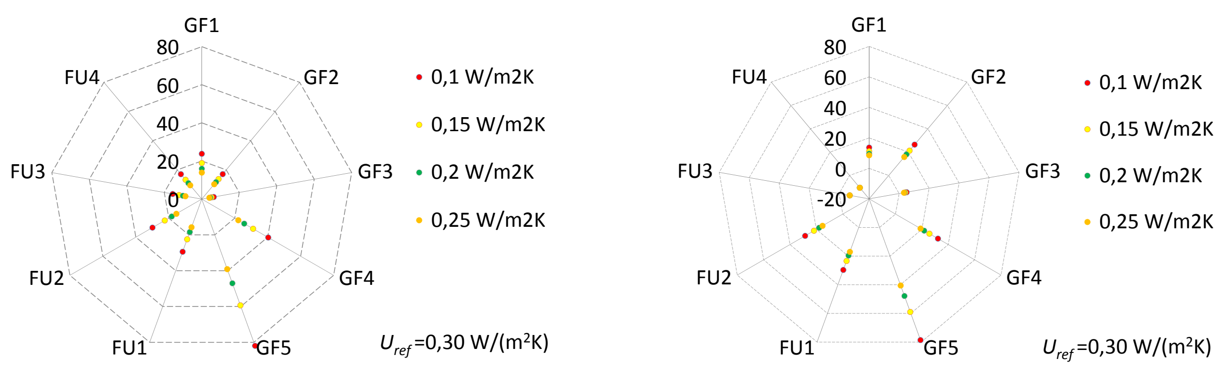
FIG. 4.3 Payback period of embodied primary energy (A) and embodied CO_2 (B) through savings for pitched and flat roofs

The payback period of added embodied primary energy for structural components with a high thermal protection level is between 15 and 20 years due to increased thickness of thermal insulation. The two exceptions are the flat roof structural components with EPS and XPS thermal insulation, where the payback period is 30 or 45 years, respectively.

The payback period of embodied CO_2 in pitched roofs through savings is less than 20 years. When thermal insulation made of natural material is used in pitched roofs, the values drop below 0. The payback period for flat roofs is 25 years, except the structural components insulated with XPS, which record a 35-year payback period.

4.4 Ground Floor and Floor to Unheated Basement

Energy efficient *ground floor and floor to unheated basement* (Fig. 4.4) structural components are compared with those having the reference thermal transmittance *U* = 0.30 W/(m² • K).



A *B*

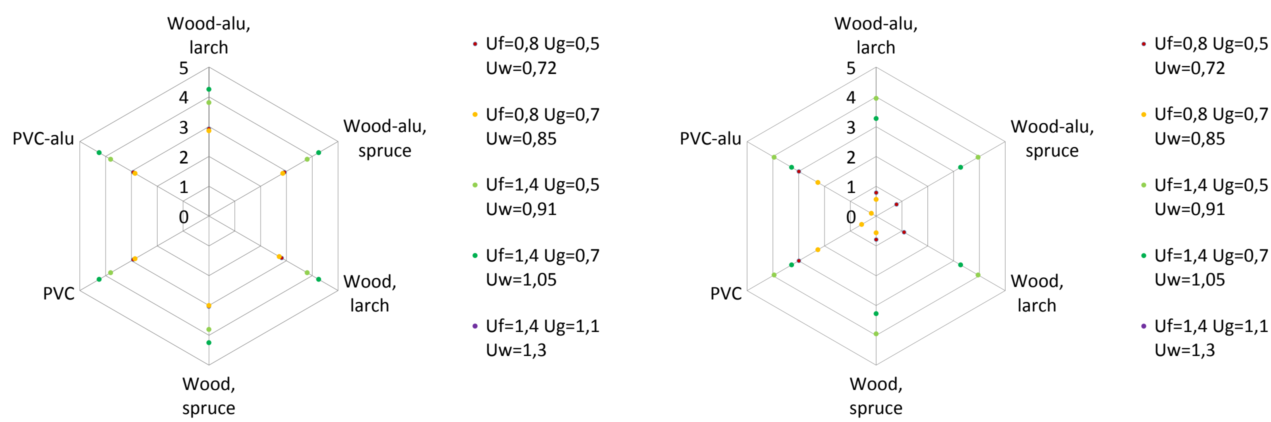
FIG. 4.4 Payback period of embodied primary energy (A) and embodied CO2 (B) through savings for ground floor and floor to unheated basement

The payback period of additional primary energy content is 20 to 30 years. One exception is the structural component insulated with perlite, which has a payback period of less than 10 years. The payback period for the variants with thermal insulation on the interior surface of the reinforced concrete slab is 40 years if XPS is used for insulation, and as many as 80 years if foamed glass is used as insulation.

The payback period of embodied CO_2 in ground floor structural components is normally 30 years. The exceptions are solid structural components insulated with perlite, and timber structural components insulated with mineral wool, where the payback period is reduced to mere months. An upward deviation value is again recorded in the structural component insulated with foamed glass (i.e. 80 years).

4.5 Windows

In *windows*, the achieved thermal transmittance *U* of the elements, when compared to the previously obtained data, typically decreases at a relatively low added primary energy, which applies to both wooden frame windows and PVC frame windows. When the thermal insulation performance of a window is increased, its thermal transmittance decreases more significantly than in opaque thermal envelope structural components. Consequently, transmission heat losses decrease more significantly, thus providing higher primary energy savings during operation. The expected payback period of added embodied primary energy in the windows with lower thermal transmittances *U* is 3 to 4.5 years (Fig. 4.5). The low payback period is obtained from the comparison between the reference and most energy efficient windows U_w = 1.3 W/(m^2 • K) and U_w = 0.7 W/(m^2 • K), and the higher payback period from the comparison between the two variants with U_w = 1.3 W/(m^2 • K) and U_w = 1.1 W/(m^2 • K).



A *B*

FIG. 4.5 Payback period of embodied primary energy (A) and embodied CO_2 (B) through savings for joinery

Similar favourable results are observed in the payback period of embodied CO_2 for windows through savings in CO_2 emissions during the operation of the building. The payback period for PVC windows is 2 to 4 years, depending on the thermal transmittance U_w of the windows. The payback period of the analysed windows with U_w = 0.7 W/(m^2 • K) is 3 years. The payback period of wooden frame windows is 0 to 4 years; the windows with low thermal transmittance U_w have a payback period of one year.

5 Conclusions

The analyses described above present various options for selection, and outline the key rules of incorporating and combining the materials that the planners should take into account when designing thermal envelope structural components. When planning a building, the selected construction technologies and the resulting environmental impacts produced even before the start of operation of the new building should be given equivalent consideration as the energy and environmental efficiency of the building during its operation. The results of the analyses enhance the proper understanding of the impact that the construction phase has on a more comprehensive evaluation of the impacts of buildings over their entire life cycle.

In the final part of the study, it is necessary to highlight the following basic guidelines, constituting the conclusions of the analyses presented above:

- Materials used for construction and thermal insulation have a lower impact on the environment when used in their original, natural form, and when environmentally less burdensome processes are used for their production, as well as smaller quantities of input raw materials. Thus, for example, in terms of the indicators analysed previously, the use of natural wood in construction is preferable to the use of similar products made of processed wood. Aerated concrete blocks are more suitable than bricks and thermal insulation made from straw is better than the blown cellulose insulation. Similar results are obtained when comparing the mineral wool of higher and lesser density, and EPS and XPS.

- The results of the combined environmental evaluation on the basis of three parameters (the *OI3* indicator) for solid masonry walls are less favourable than for the lightweight timber walls. The most common variants of solid masonry wall thermal protection in low-energy and passive buildings produce higher, e.g. environmentally more burdensome, results. The highest values obtained in timber construction systems are still below the lowest *OI3* values obtained in solid masonry construction systems. Even more divergent values are recorded for pitched and flat roofs. The difference between the final environmental burden values recorded in various groups of light timber and solid masonry structures may be up to 50%.

- Increasing the thermal insulation performance of the structural components of the building envelope results in enhanced energy efficiency of the building's further operation. In most structural components, this also results in increased environmental burden during the construction phase, i.e. before the start of the building's operation. The structural components with a high proportion of incorporated natural materials are exceptions to this rule. They are subject to an opposite conclusion: by increasing the use of these materials, the thermal insulation performance of the envelope is increased, while the environmental burden during the construction phase is reduced.

- Reducing the thermal transmittance of structural components requires a higher primary energy content. If, for example, thermal transmittance is reduced to half the reference values, 50% more primary energy is usually required for the production of a structural component. This points to rather high energy inputs in thermal protection systems and highlights the importance of a proper selection of combinations of materials in these systems. When thermal protection levels are increased, these relations are modified in the structural components where the construction part of the component has a major role. In this case, higher primary energy content is dictated by the structure itself, whereas thermal protection systems increase the primary energy content to a lesser extent.

– The added primary energy content, non-renewable, and the CO_2 produced during the construction phase have payback periods of 10 - 20 years in energy efficient new buildings, which is less than one third of the thermal protection system life span. When higher initial inputs in construction parts of the components are made, the payback period may be extended to 20 – 30 years of the operational period. The most favourable results in this respect are observed in windows where higher initial environmental inputs are paid back in less than 5 years.

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Building Simulations and Modelling: Energy

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ABSTRACT **The quest to achieve high standards in energy efficiency has resulted in the development of complex simulation tools that aim for a precise calculation of energy performance, thus supporting building design as well as the management process.**

Common questions regarding the simulation of performance address several issues: during what stage is simulation being conducted (preliminary design, main design, dimensioning of the systems, certification), how complex is the procedure, what resources are needed (data and computational) etc.

In everyday practice we are confronted with a variety of available software options, each of which is advertised as the right choice for building energy performance simulation. With regard to the approach towards modelling, complexity, and simulation processes, we can distinguish several application levels, each having certain advantages and disadvantages.

The starting point for an adequate simulation procedure relies on the available legislation and professional standards, calculation procedures, and computational logic. Depending on the desired outcome or goal of the process, an adequate simulation strategy must be applied.

A comparison between the two most commonly used pieces of simulation software in Serbia, *KnaufTerm2* and *Ecotect*, has been conducted, illustrating the differences in procedure and the results gained.

KEYWORDS simulation, modelling, energy performance

1 Introduction – Building Simulations and Modelling

To address the expected performance of buildings, whether in terms of occupancy comfort or energy consumption issues, it is necessary to make some predictions as they relate to more or less accurate assumptions. Since the energy performance of buildings depends on many factors, our assumptions rest on many limitations and generalisations. This is the case especially when addressing the complex issue of occupancy behaviour, which significantly influences energy consumption. When dealing only with energy demand, the greatest field of assumptions are found in the choice of elements within the complex nature of heat transfer taken into account.

The definition of the *thermal simulation* of a building, as given by Bahar, Pere, Landrieu, and Nicolle (2013), represents a dynamic analysis of building's energy performance by using computer models and simulation tools. Bahar et al. (2013), state that there are currently over 400 applications that can be used for analysing building energy and thermal simulation. Among these, we vary simulation tools with visual communication (so called *frontend*), such as *DesignBuilder*, *Ecotect,* and *IES Virtual*, where, through creation of a 3D building model and assigning relevant properties to modelled elements, all relevant parameters are defined, and simulation-calculation tools, where all necessary data are entered in textual/numerical format (simulation tools such as *EnergyPlus*, *DOE*, *HTB*, etc.). For the latter, this means that all preceding analyses of geometry and thermal zoning are done using some other modelling software, or frontend simulation software. The interoperation of both types of simulation tools with existing 3D modelling programs (such as *ArhiCAD*, *Revit*, *SketchUp,* etc.) represents a developing field, with the purpose of integrating energy modelling with the design process as early as possible in the design development. Standardising the format of the necessary data extracted from the modelling software for the easier input and recognition by the simulation tools is also a developing issue (*Green Building Studio - gbXML* file format is an example).

Gado and Mohamed (n.d.) claim that the benefits of simulation in predicting the performance of the design at both early and detailed design stages outweigh the cost of simulation in the majority of cases. They also indicate the practice of widespread use of software like Ecotect or IES in architectural firms, for checking the performance of their designs even before consulting specialised engineering consultants in this field.

It should be emphasised that most of the software that is widely used for whole building energy modelling is not designed for specific uses, such as the dimensioning of HVAC systems, or identifying problems that occur in the thermal envelope of a building (moisture content, thermal bridging etc.). Specific software exists for each of these uses, such as numerous software types dealing with thermal bridging, as stated by Tilmans and Orshoven (2010). The main use of energy modelling is the comparison of several design options in terms of energy performance, and the certification of a particular design when compared to a determined base case model. In addition, thermal simulations can be used for various research and practical purposes. The authors, Rajčić, Radivojević, and Elezović (2015), used thermal simulations (IES software) in a study to test the thermal influence of unconditioned staircases to heated zones, in order to determine more precise parameters used in energy performance calculations.

Depending on the specific purpose of thermal simulation (certification, comparisons between designs, research, examination of building components etc.) different tools can be used. This chapter aims not only to give an overview of possible uses and adequate tools, but also to illustrate differences that can occur when using two different simulation tools for the same purpose. Further discussion of the results clarifies the details of the tools used, which influence the results and thus their adequate use.

2 Simulation and Modelling

There are two basic principles for heat transfer simulation in the quantitative analysis of building energy performance through calculation of energy demand:

- quasi-stationary method, where heat transfer is determined for a longer time period (monthly or seasonally) and in which the dynamic effects of heat transfer are taken into account through the empirically determined utilisation factors of heat gains and the influence of heat loss;
- dynamic method, in which heat transfer is determined for shorter periods of time (hourly) and which takes into account the heat that is stored and released through the thermal mass of the building.

International standard EN ISO 13790 defines three different approaches to the methodology of calculation of energy need for heating and cooling in buildings:

- a fully prescribed monthly quasi-steady-state calculation method (or, optionally, a seasonal method)
- a fully prescribed simple hourly dynamic calculation method,
- calculation procedures for detailed (e.g. hourly) dynamic simulation methods.

In the quasi-steady-state methods, the dynamic effects are taken into account by introducing correlation factors (utilisation factors for gains and losses).

A dynamic method models thermal transmission characteristics, heat flow by ventilation, thermal storage, and internal and solar heat gains for every defined building zone. The EN ISO 13790 standard gives full specification for a three-node hourly method. A monthly calculation method gives adequate results on a yearly level, but values for specific months near the beginning or the end of the heating season might significantly differ from the real ones. The hourly method is introduced to include the influence of different regimes in the calculations. In addition, the hourly method takes into account the influence of insolation in a much more precise way, which is more significant for the assessment of energy need for cooling than monthly/seasonal methods. The dynamic model gives the most precise results, but also requires a large set of input data and parameters that significantly influence the results if not addressed properly.

One of the aspects that significantly influences the results of the dynamic simulation is the modelling of occupant behaviour. This may not be a crucial issue when comparing several designs based on the same occupancy behaviour pattern, but it may be very significant if we are trying to predict future energy consumption or comparing the model and the real building, in the case of refurbishment of the existing buildings. The influence of occupant behaviour on energy consumption is an elaborately studied field, and authors, such as Gram-Hanssen (2013), conclude that identical buildings can differ in terms of energy consumption for heating by up to 2-3 times, depending on occupancy behaviour. The behaviour of building users is taken into consideration during a computer simulation by specifying properties such as the number of occupants, their clothing level, metabolic rate, the appliances on/off patterns, and even the open/close patterns of windows and doors. It is possible to set these levels in the model that are similar to the values used in calculation procedures, but it is not so easy because a thermal model consists of multiple *thermal zones* and these values need to be set for each zone, rather than for the entire building.

Thermal zoning is also the reason why it is impossible to directly use a 3D model of the building used for the purpose of visualisations, or generated through BIM software. Zoning of the model is a specific principle in building energy simulation, where every part of the building that has different thermal comfort bands, occupancy profiles, orientation and influence of adjoining components, needs to be defined as a different thermal zone. This type of information is specific for thermal modelling and this is why it is very difficult to integrate thermal modelling into regular BIM models used in design and construction purposes.

Another crucial set of data is the climate data for thermal simulations. These are provided through a *weather file*, with statistically weighed climate data for a chosen location. These files differ, based on the source, since the relevant data for a typical meteorological year are usually not publicly available.

An overview of the most commonly used tools is given in literature by Bahar et al. (2013), with the emphasis on its interoperability through the BIM Platforms. Crawley, Jon, Kummert and Griffith (2008) conducted a comprehensive comparative survey of twenty major building energy simulation programs based on 14 categories. These categories depict the complexity of the thermal simulation issues:

- Zone Loads;
- Building Envelope and Daylighting;
- Infiltration, Ventilation and Multi zone Airflow;
- Renewable Energy Systems, Electrical Systems and Equipment;
- HVAC Systems;
- HVAC Equipment;
- Environmental Emissions; and
- Economic Evaluation.

The most complex tools can address all of the listed issues, while others deal only with the first three.

3 Simulation in the National Context

Methods of energy performance calculations and simulations are introduced into international and national legislation for the purpose of building design verification and certification based on energy performance level. Thus, all methods that are prescribed as part of legislation must be fully defined, in terms of parameters and procedures, and can be considered as *verification methods*. Since they are used for rating and comparing different building designs, their actual accuracy is not of utmost importance, but rather the straightforwardness and clarity of the prescribed procedures, in order to avoid different interpretations, is imperative. Defined in this way, verification methods are usually characterised with more limitations than simulation methods. Also, simulation methods are not related to any specific regulation, but are free to be used internationally.

Verification tools are mostly used for checking the achieved performance of the whole building at the end of the design process, while simulation tools are more often used for optimising design decisions during the design process. While some parameters, such as U-values of components, shading coefficients etc., can also be altered during the calculations to see how they affect the overall energy performance, there is usually a missing link to building geometry that prevents calculation methods being used more as energy performance oriented design development tools.

In Serbia, the national standard for calculation and certification of building energy performance is regulated by the Rulebook on energy efficiency in buildings (2011). This rulebook is entirely in line with EN ISO 13790, and the calculation procedure is based on the fully prescribed monthly quasi-steady-state calculation method. Currently, the calculation of energy need is based on the energy requirement for heating, which is also used for expressing a building energy level. It is planned to include all other energy uses (cooling, ventilation, lighting, appliances), as well as energy from renewable sources in the calculations, upon the adoption of a national software for this purpose. The energy need for heating is determined for a defined heating season for several locations in Serbia based on a heating degree day method.

Climate data used in calculations consist of the number of heating days and outside temperatures determined for representative locations in Serbia. Solar radiation is addressed based on the average values for the entire territory of Serbia.

A comprehensive overview of the methodology for energy performance calculations in Serbia, based on current legislation, is given by Rajčić and Ignjatović (2012) in the case study of one typical multifamily housing building. Several commercial tools have been developed in the market for calculation and certification of energy performance of buildings, mostly by companies that produce thermal insulation materials (*Ursa*, *Knauf Insulation*, etc.).

Energy modelling in the context of national standards is sometimes necessary in order to achieve certain incentives targeted at improving energy efficiency. Ignjatović, Jovanović Popović, and Kavran (2015) used thermal simulation to validate the energy savings achieved by applying sunspaces in the design of a residential building in Belgrade. This kind of validation was needed for obtaining fiscal incentives for the developer, since the area of the sunspace can be excluded for the calculation of the net useful area upon which the tax is paid, but only if the energy savings achieved by a sunspace are validated through energy modelling software. In this way, the benefits of energy modelling outweigh its cost.

4 Simple vs. Complex Simulation

In order to illustrate the differences between various calculation and simulation tools, a case study is presented, on a typical single family, single storey house. The calculation tool in use is *KnaufTerm2 pro V27* and the simulation tool used is *Ecotect Analysis.*

The method of calculation is actually a verification method based on the national legislation, and uses the fully prescribed monthly quasi-steady-state calculation method using the degree-day method, while the simulation tool uses the simplified dynamic simulation on an hourly basis using the admission method.

4.1 Calculation Tool: KnaufTerm pro V27

KnaufTerm is one of the most widely used calculation tools in Serbian practice for the verification of the energy performance of buildings. The author of the software is Dr Aleksandar Rajčić. The software is available for free use with registration on the website of KnaufInsulation company. The version of the software used in this case study is *KnaufTerm2Sv27.13*.

The method of calculation is based on the determination of the annual energy requirement for heating, through energy balance calculation, which includes transmission and ventilation heat losses, and solar and internal energy gains. The influence of thermal mass is taken into account through the *dimensionless gain utilisation factor for heating* ($h_{H, gn}$).

The procedure for calculation in the software starts with the input of data about the building's geometry: net heated area, gross heated volume, surface area of all the elements of thermal envelope, net ventilated volume etc. Then details about the structural characteristics of the thermal envelope are filled in, together with all the relevant parameters that are set according to the current legislation (Rulebook, 2011). The data on the building geometry can be taken from the technical drawings by measurement, but it is recommended that a 3D CAD model is built, as illustrated in the example given by Rajčić and Ignjatović (2012). The work environment in the software illustration is presented in Fig. 4.1.

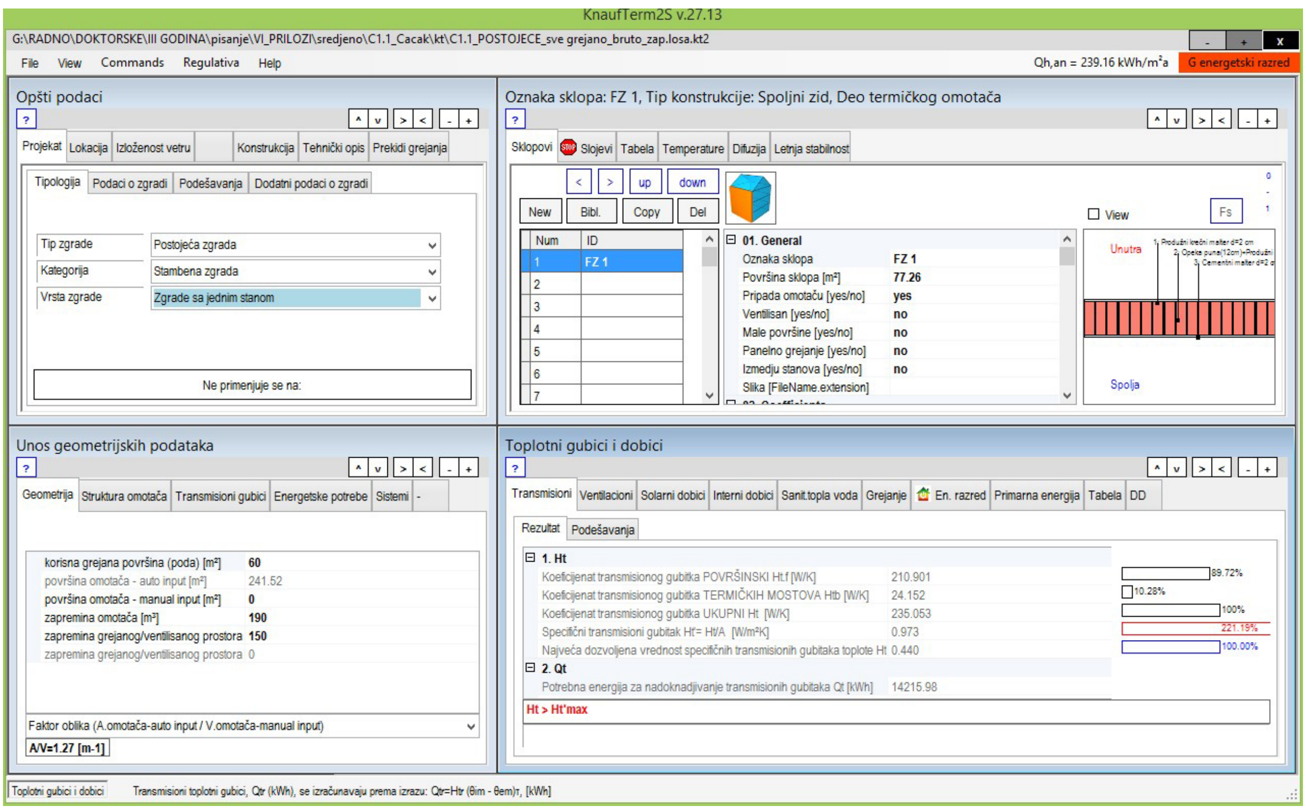

FIG. 4.1 Working environment in the *KnaufTerm2* software

The method defined in standard EN ISO 13370 is used for the calculation of floors and walls in contact with ground, and it takes into account the geometry of the floor, through the value of the characteristic floor dimension (B' [m]) and equivalent floor thickness, as well as the thermal properties of the soil. By using this method, the floors on the ground of the same structural composition can have significantly different U-values, depending on their shape and size.

Besides the widespread use of verification of energy performance of buildings in domestic practice as a part of the documentation for obtaining a building permit, *KnaufTerm2* was excessively used in the research field. All calculations of energy need for heating and improvement levels in the *National typology of Residential Buildings of Serbia* by the group of authors: Jovanović-Popović, Ignjatović, Radivojević, Rajčić, Ćuković Ignjatović, Đukanović and Nedić (2013), were performed using this software. Also, it was used for the assessment of the energy efficiency improvement of the traditional housing type by the authors Radivojević, Roter-Blagojević, and Rajčić (2012). It was also used in the case study of possibilities for energy rehabilitation of a typical single-family house in Belgrade by application of some complex improvement measures by the authors: Ćuković Ignjatović, Ignjatović, and Stanković (2016).

4.2 Simulation Tool: Ecotect Analysis

Ecotect Analysis is one of the most widely used programs for the simulation of building energy performance as stated by Crawley, Jon, and Griffith (2008). Its greatest advantage in comparison to other simulation software is its user-friendly interface for model building and its possibility to perform different types of analysis (solar gains, shadows, daylight, energy performance, acoustic performance) in the early phases of the project. Because of this ease of use, many architectural offices are using it as a tool in the design phase, as stated by Gado and Mohamed (n.d.). The program was developed by Dr. Andrew Marsh and *Square One Research Ltd.* in 1996, and in 2008 it was taken over by *Autodesk*. Within *Autodesk* three more standalone versions were developed (2009, 2010, and 2011), and since March 2015, the functionalities of this software were merged with *Autodesk Revit*. Since then, it works as a plug-in in this widespread BIM tool, and is being developed together with Green Building Studio simulation tool known as *Project Vasari*. The version of the software used in this case study is the stand-alone version *Autodesk EcotectAnalysis2011*. The work environment in the software illustration is presented in Fig. 4.2.

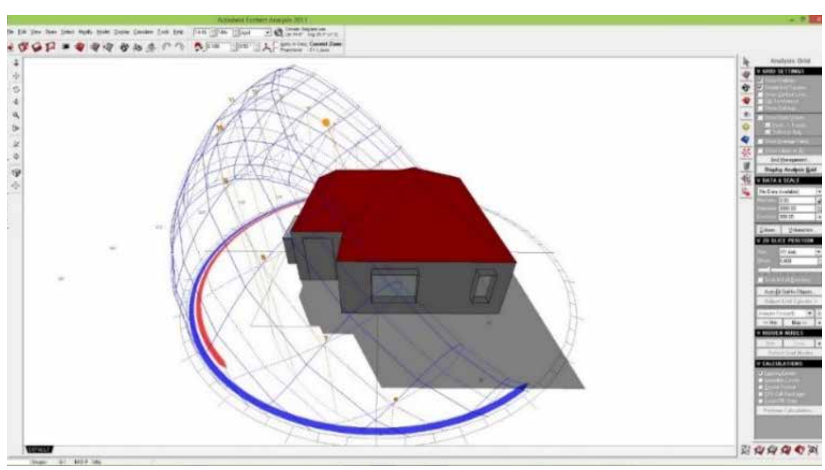

FIG. 4.2 Working environment in the *Ecotect* software and model appearance

The greatest advantage of simulations in *Ecotect,* in comparison to the calculation made using the monthly method, lies in the accurate calculation of solar heat gains, through real sun tracing and mapping of solar radiation on the building facades, taking into account real shadow geometry, instead of median sums of solar radiation and correction factors for shading used in calculations according to standards.

The greatest difference between simulations and quasi-steady-state calculations is the method of taking into account the dynamic effects of heat transfer. The way a simulation program treats this problem depends on its *simulation engine*, which is essentially a calculation tool based on sets of thermodynamic equations. *Ecotect* software uses a dynamic method known as *CIBSE Admittance Method.* This method was developed in the '50s, driven by the need to address the problem of overheating in buildings that had a high percentage of glazing, and calculate maximum temperatures in natural and mechanically ventilated buildings. Rees, Davies, Spitler, and Haves (2000) explain that, unlike ASHRAE, whose methods were directed towards the creation of a constant internal temperature, so that the internal mass had only a second order effect, CIBSE's primary aim was to demonstrate the role of internal mass in modifying room temperature. This method is defined in CIBSE (Chartered Institute of Building Services Engineers) *Guide A - Environmental design* (CIBSE 1999), by using methods for calculation of temperature profiles defined by Steve Szokolay in his seminal book *The Thermal Design of Buildings* (1987). CIBSE differentiates two types of dynamic simulations: *cyclic* and *transient*. Cyclic simulations are those in which it is supposed that boundary conditions (temperature, solar radiation) affect the construction in regular sinusoidal cycles during a 24-hour period, while in transient models, boundary conditions are more sensitive to external and internal influences. Cyclic models, like the admission method, are adequate for the assessment of thermal characteristics and related energy performance in cases of constant usage regimes and exterior conditions, and are less accurate in intermittent heating or cooling, large thermal inertia, or sudden changes in outside temperature or internal gains (CIBSE, 2006).

Using this method, the energy requirement for compensation of energy gains/losses is determined similarly to the quasi-steady-state calculations, through the difference in outside and inside temperatures multiplied by the heat gains/losses. The data on median outside temperatures are generated from the weather file. The determination of internal temperatures that define the comfort band is where differences between methods occur. Comfort temperature (Tc) is defined as the temperature that depends on the set point air temperature in the room (Ta), and environmental room temperature (Te), which depends on the temperature of all room surfaces, in the following ratio:

Tc=0.25Ta + 0.75Te (Rees et al., 2000).

When calculating transmission heat losses/gains, set point internal air temperatures are weighed against a daily level, depending on the internal surfaces temperatures, which are determined based on the structure's admission value. Admittance value (Y), in contrast to transmittance, describes the capacity of the material to exchange heat with its surroundings in cyclic temperature swings. As explained by Hall and Allinson (2008), it is this non-steady-state parameter that positively indicates the ability of the fabric to absorb (and store) heat energy from the environmental node, i.e. fabric energy storage, or thermal mass. Three additional parameters need to be defined for each structure in order to determine this ability, which define the non-stationary heat flow: admittance value [W/m^{2}K], degree of roughness and thermal decrement (f). The values of admission and thermal decrement are calculated using characteristics of thermal conductivity, thickness, density, and specific heat of the material and its position in the thermal envelope. The values for time dependency (v, or f - time lag [h]) are determined based on tabular values, given in literature by De Saulles (2009).

In this way, the factor of thermal inertia of a building (its thermal mass) is taken into account. Evangelisti, Battista, Guattari, Basilicata, and de Lieto Vollaro (2014) found that these factors significantly deviate from values that are taken into account in stationary calculations through gain utilisation factors. Detailed explanation of the calculation procedure, with the following set of matrix equations is given in the CIBSE manual, as well as throughout literature, for example, in studies by Hall and Allinson (2008), and Rees, Spitler, Davies, and Haves (2000).

This method proved to be accurate in assessing the influence of passive design measures on building energy performance. Stoios, Bougiatioti, and Oikonomou (2006) proved the adequacy of this software application in the case of sunspace influence assessment on winter and summer comfort, by comparison of modelled and measured temperature profiles. The author of the software, Dr Marsh (2005), also recommends it as a fine tool for comparative analysis of different designs, but for obtaining precise data recommends the data output to some other simulation engine based on more detailed dynamic simulations.

4.3 Case Study

The case study of comparative calculation and simulation is conducted for a typical Serbian single family house, built during the period 1950-1970. The model of the building is seen in Fig. 4.2.

Three models were tested through the calculation and simulation method:

- M0 – the original state of the house;
- M1 – first level of refurbishment;
- M2 – second level of refurbishment.

Relevant parameters for calculations in *KnaufTerm2* software, for all three models, are given in Table 4.1.

BUILDING GEOMETRY		M0	M1	M2
Net heated area [m^2]		60		
Gross heated volume [m^3]		190		
Net heated volume [m^3]		150		
Gross area of thermal envelope [m^2]		241.5		
Shape factor [m^{-1}]		1.27		
Envelope characteristics				
Mean U value [W/m^{2}K]		1.02	0.40	0.25
Specific transmission heat loss - **H$_t$**, [W/m^{2}K]		0.957	0.414	0.283
Maximum allowed transmission heat loss **H$_t$**, **max** [W/m^{2}K]		0.44		
Windows	**U** [W/m^{2}K]	3.5	1.5	0.8
	g [%]	0.8	0.6	0.4
Air tightness – air changes per hour (**n**) [h^{-1}]		1	0.6	0.5
Location				
Wind exposure		Moderately shielded		
Sun exposure (Shade factor)		Unshielded position (0.9)		
Location		Belgrade		
Heating days (HD)		175		
Heating degree days (HDD)		2520		
Internal set point temperature		20°C		
Hours of operation		Non stop		

TABLE 4.1 Relevant parameters for calculations in *KnaufTerm2* software for all three models

For simulations in *Ecotect* software climate, the data for Belgrade were used, from the *EnergyPlus Weather Data* file (Energy Plus, n.d.). Thermal model was created in the software, with two defined thermal zones, one conditioned (the entire ground floor, without subdivision into rooms, matches with the net heated area from *KnaufTerm2*) and one unconditioned, thermal buffer attic zone. The basic parameters for creation of the model are given in Table 4.2 and zone management area with these settings is shown in Fig. 4.3.

WIND EXPOSURE	MODERATELY SHIELDED
Terrain	Suburban
Air tightness – air changes per hour (**n**) [h^{-1}]	**M0:** n = 1 h^{-1} for conditioned thermal zone, and n = 2 h^{-1} for unconditioned attic zone
	M1: n = 0.6 h^{-1} for conditioned thermal zone, and n = 2 h^{-1} for unconditioned attic zone
	M2: n = 0.5 h^{-1} for conditioned thermal zone, and n = 1 h^{-1} for unconditioned attic zone
Location	Belgrade
Lower Thermostat Band	20°C
Upper Thermostat Band	26°C
Hours of operation	Non stop
Type of HVAC system	Full Air Conditioning

TABLE 4.2 Relevant parameters for simulations in *Ecotect* software

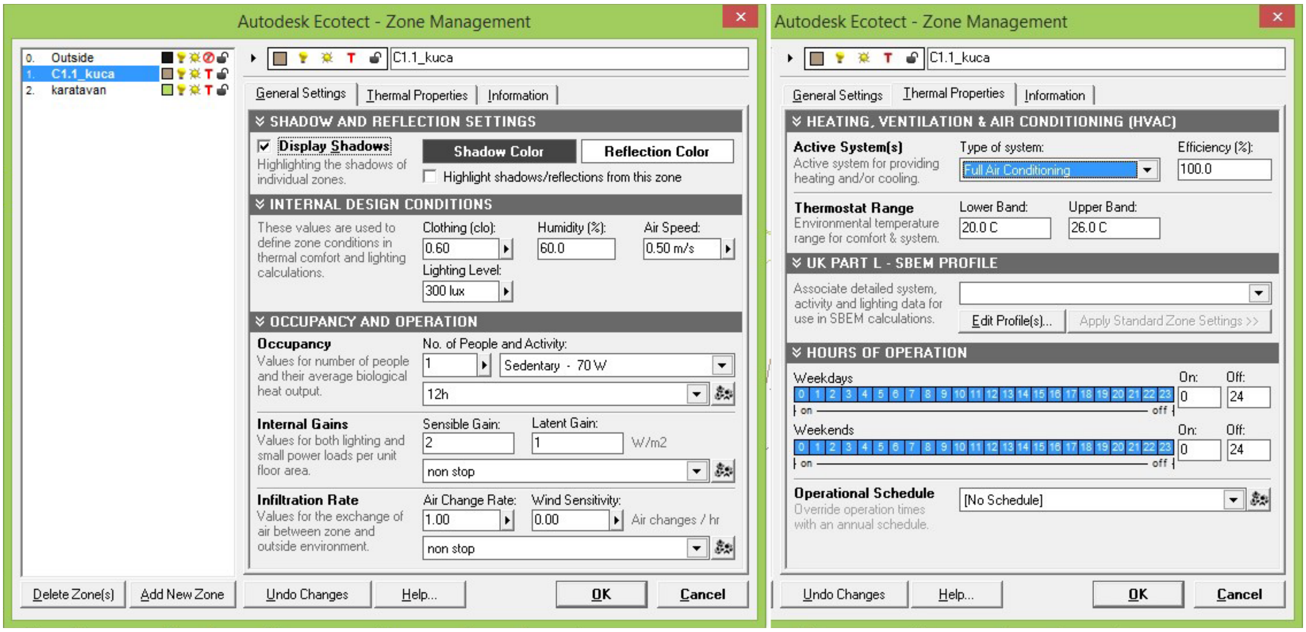

FIG. 4.3 Zone management area in *Ecotect* software

4.4 Results and Discussion

Since the simulation method gives the values of energy need for heating and cooling on a daily basis, irrespective of the heating season (Fig. 4.4.), in order to compare these values with the calculated ones, we need to limit them to the defined heating season, not taking into account any heating needs that usually occur in the transient months.

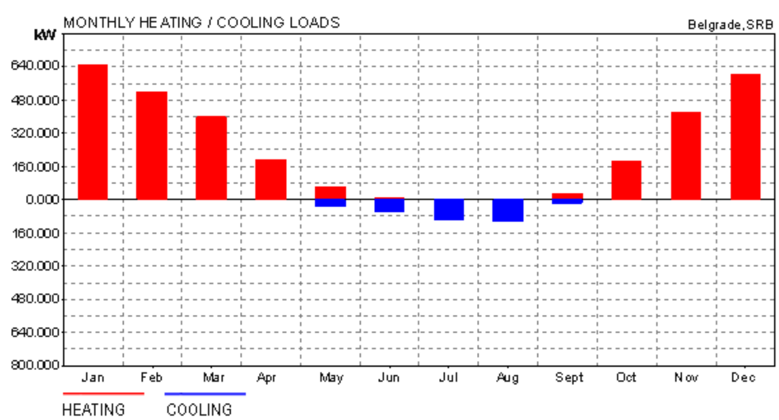

FIG. 4.4 Monthly heating/cooling loads distribution, M0

The overall comparison between the obtained energy performances in terms of energy need for heating shows similar results in all three models using methods of calculation and simulation (Fig. 4.5.). Calculation results show higher values of energy need for heating in the present state (M0), possibly because no thermal mass effect is taken into account, and the analysed building shows a high level of thermal inertia (massive brick walls).

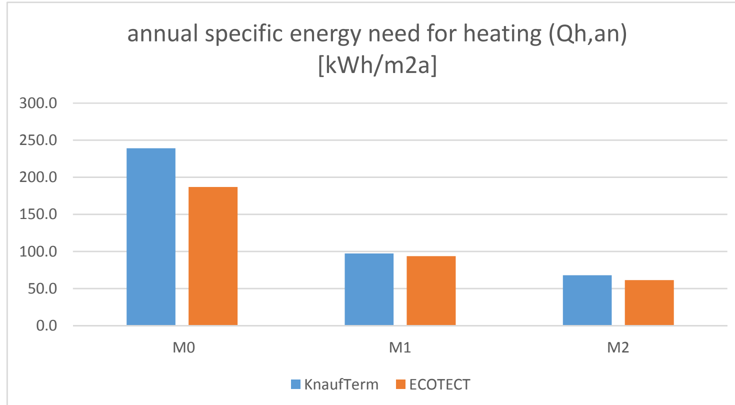

FIG. 4.5 Comparison between obtained values of energy need for heating for three analyses models by calculation in *KnaufTerm2* software and simulation in *Ecotect* software

The ratio between transmission and ventilation losses shows that transmission losses in all models have values up to 5 times higher than the ventilation losses (Fig. 4.6.).

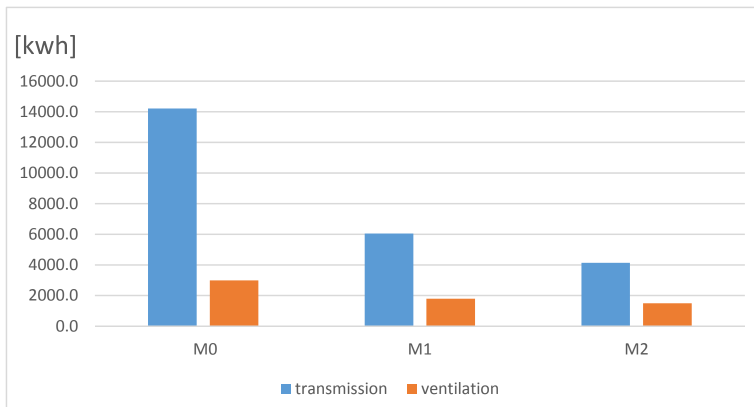

FIG. 4.6 Ratio between transmission and ventilation heat losses obtained by calculations in *KnaufTerm2* software for three case models

However, the gains/loads breakdown obtained through simulation results (Fig. 4.7.) shows that ventilation loads (marked in green) are more significant than the conduction ones (marked red). Additionally, in the gains section, significant sol-air (indirect) gains appear, mostly due to the overheating in the unconditioned attic zone.

These results are in line with the data found in literature, about the over emphasis on ventilation loads in Ecotect software simulations, especially when the infiltration levels are set high, as given in Hensen (2004), due to the calculation method which also takes into account wind speed from the weather file and the orientation, and not just the infiltration level. Other simulation software also shows less significant influence of transmission loads in the thermal loads structure compared to stationary calculation methods, as stated in a study by Dobrosavljević (2016).

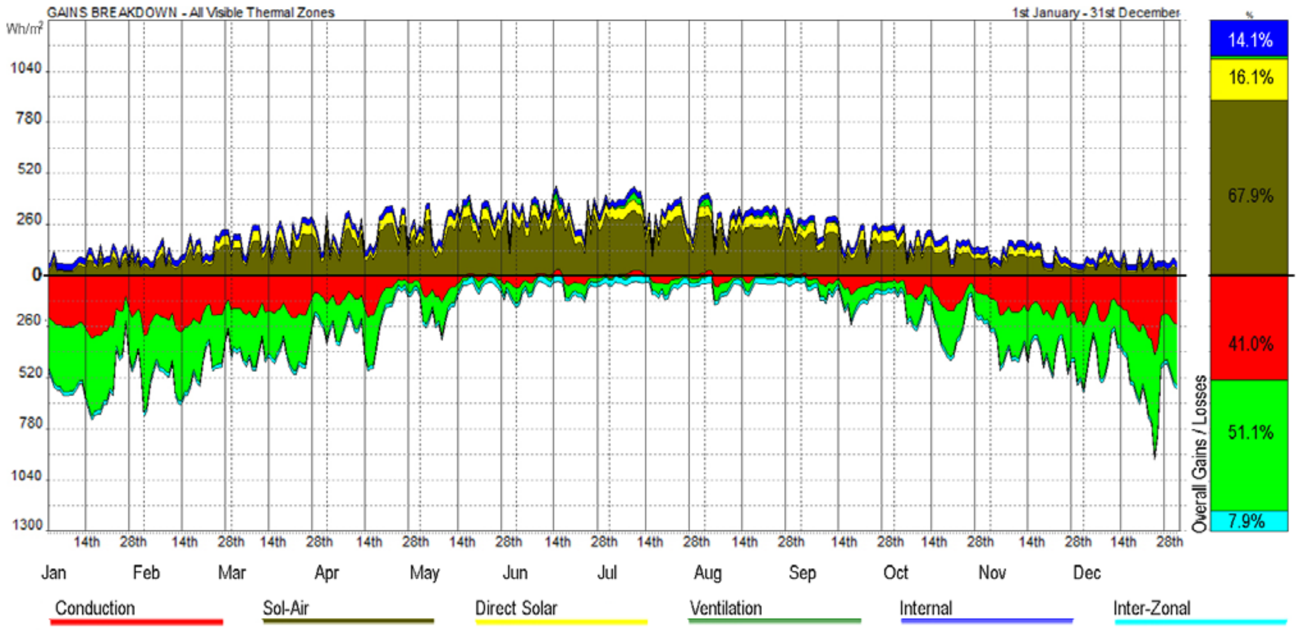

FIG. 4.7 Gains/loads breakdown obtained by thermal simulation for M0 model

Very low cooling loads in all three investigated models can be explained by a low glazing percentage and low solar gains, as well as the influence of thermal inertia. In addition, low cooling needs can also come from the imprecision of the thermal simulation engine and related calculations; literature-based data were found that support these claims, such as De Saulles (2009) and Hensen (2004).

5 Conclusions

Building energy performance can be assessed at various stages of the building design process and with more or less precise methods. Among numerous tools and methods for addressing the energy performance of buildings, calculations are mostly used for the verification of achieved performance and certification according to regulations, while whole building thermal simulations can be used for numerous purposes, depending on the simulation software.

As a representative verification tool, *KnaufTerm2* is presented, a widely used tool in Serbia for the certification of buildings based on domestic regulations, in line with EN ISO 13790 standard. *Ecotect* is presented as a representative of the simulation tools, used widely as a design assistance tool for simple dynamic simulations of energy performance.

The energy performance of the three test case models were assessed by calculation and simulation. The first model is a present, unrefurbished state of a typical single family house in Serbia, while the other two models are two variations of its improvement. The differences between overall energy performance assessed by methods of calculation, by stationary method, and simple dynamic simulation are about 20% for the present state model, and less than 2% for the refurbished models. By comparing the structure of the thermal loads and gains, as well as the influence of the energy need for heating in the overall energy balance, some data found in literature have been confirmed, which testifies for the limitations of the applied calculation method and the simulation tool.

However, despite the differences that exist in results of calculations and simulations using different tools, it is strongly suggested that simulation tools are used early in the design stage, because the greatest advantage of their use is optimisation of design. When used in later stages, usually a very robust model is created, in which the manipulation of design options is complicated, and although results are trustworthy, their applicability is questionable.

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PART 3
Energy Saving Strategies

Environmental Design Principles for the Building Envelope and More _

Passive and Active Measures

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ABSTRACT **Given the need to reduce building sector related energy consumption and greenhouse gases (GHG), passive and sustainable buildings are a focal point. Simple methods and techniques, which use appropriate building design, material and systems selection, and reflect consideration of the local environmental elements, such as air and sun, provide thermal and visual comfort with less non-renewable energy sources. These techniques are referred to as environmental or bioclimatic design. There are two types of measures to be taken: passive and active. Passive principles exploit the design and properties of the building envelope to minimise or maximise the heat losses and heat gains respectively, to reduce the energy demand. In addition to passive, active measures such as heating systems and solar power technologies are used to produce and distribute the energy needed to achieve comfort of the occupants.**

The present chapter aims at giving an overview of design principles that result in more comfortable and energy efficient buildings. Passive and active design principles are in line with the environmental design concepts. The environmental design principles can be beneficial to the building performance, whether the design ambition is to have a comfortable and functional building with reasonable energy demand or goes as far as achieving sustainable standards such as zero-energy or passive house.

KEYWORDS environmental, bioclimatic design, passive, active

1 Introduction

Due to the need to reduce the energy demand and the related GHG, passive and sustainable buildings that use less non-renewable energy sources is a focal point. To achieve this, we can apply simple methods and techniques, starting with an appropriate building design, and material and systems selection, which make use of environmental elements such as the air and the sun, to provide thermal and visual comfort to occupants. These techniques are often referred to as environmental or bioclimatic design. Such ideas have existed since man first sought for shelter. As a term, however, bioclimatic design was identified and developed in the 1960s. Bioclimatic issues, including occupants' thermal comfort and passive, low-energy architecture have been a starting point for designing new buildings and refurbishment projects.

There are two courses of measures to be taken: passive and active. On the one hand, passive measures are principles that exploit the design and properties of the building envelope to reduce the energy demand, by maximising or minimising heat losses and heat gains. On the other hand, active systems are used to produce and distribute the energy needed to achieve comfort of the occupants. The use of waste energy should also be considered on a building or neighbourhood scale.

The present chapter aims at giving an overview of passive and active design principles that can be applied to the design of the building envelope and the system selection, resulting in more comfortable and energy efficient buildings. Firstly, general guidelines and possible classification of these strategies are discussed, focusing on hierarchical models to assist in the design process. A hierarchical approach to sustainability suggests, firstly, the prevention of energy use; then, renewable energy sources use as widely as possible; and finally, efficient use of fossil fuels. Subsequently, it is explained which passive and active design principles are in line with the environmental design concepts and how they are implemented. The chapter concludes with an explanation of how the application of such measures can be evaluated based on climate characteristics.

2 A Hierarchical Approach to Sustainable Design

Several authors have discussed the implementation of energy-saving strategies, organising them according to several parameters. Lechner proposed a three-tier design approach for sustainable buildings in 1991 (Lechner, 2014). The first tier deals with basic building design strategies such as orientation, insulation, and the use of exterior shading. If this is insufficient to meet the requirements, which is often the case in warm climates, then the second tier of passive or hybrid systems should follow. This second level is based on natural energies and considers the use of evaporative cooling, earth coupling, or diurnal/nocturnal ventilation. Lastly, mechanical equipment could be incorporated into the building in the third tier, if needed, within an already passively optimised building design.

Similarly, Herzog, Krippner, and Lang (2004) defined two sequential sets of strategies to cope with the regulatory functions of the façade. As a first resource, the authors considered the application of measures such as thermal insulation, sun shading or even vegetation; they then suggested the use of supplementary building services such as artificial lighting and air conditioning, only if needed. The authors also considered the use of thermal collectors or PV panels for energy generation, which relates to the hybrid use of natural energies expressed by Lechner as an alternative to the use of fossil fuels.

"Trias Energetica" as a concept was introduced by Lysen in 1996 (AgentschapNL, 2013) and is based on Duijvestein's (1993) three-step scheme, which ranked sustainable measures for the building industry. The scheme was as follows: firstly, prevent the use of energy (prevention); then, use renewable energy sources as extensively as possible (renewable); finally, if still needed, use fossil fuels as efficiently as possible (efficiency). The Trias Energetica was adopted internationally, starting in 2001 by the former president of the 'International Solar Energy Society' (Entrop & Brouwers, 2010). For zero-energy buildings and homes in particular, the third step suggests using finite energy sources very efficiently and compensating them with 100% renewable energy (AgentschapNL, 2013).

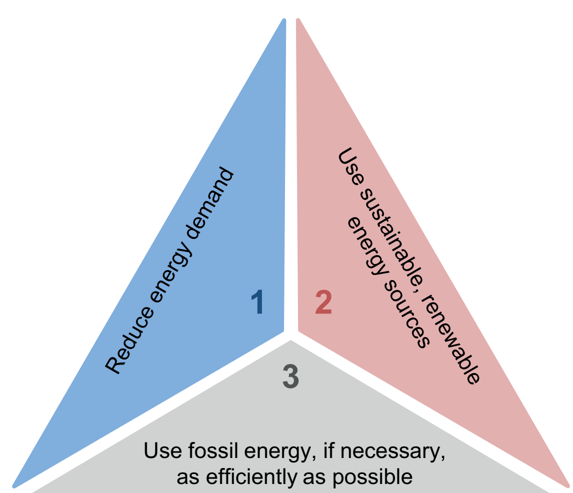


FIG. 2.1 The "Trias Energetica" principle

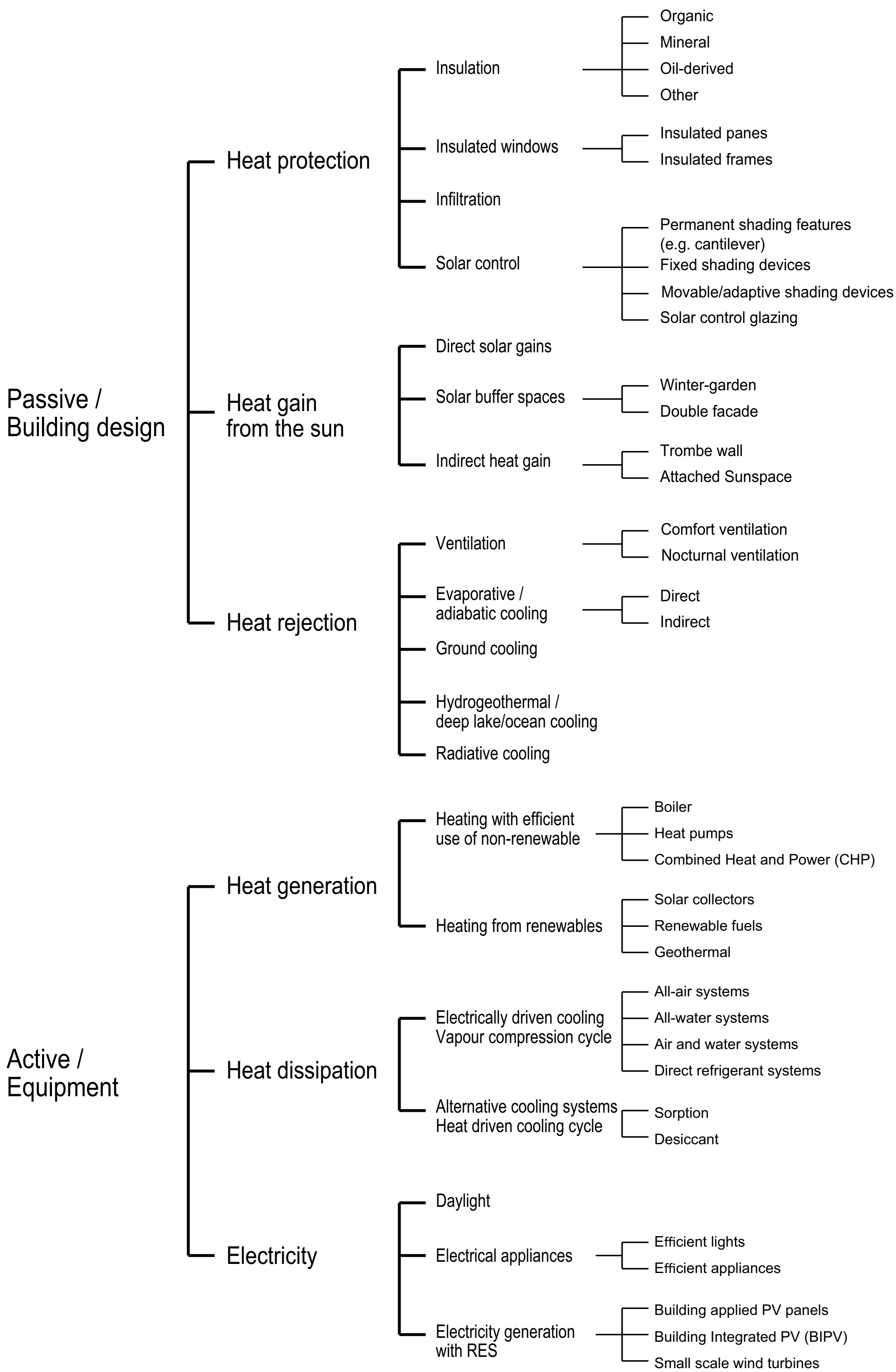


FIG. 2.2 Overview of the passive and active measures and their objective, within the scope of environmental design

More recently, the New Stepped Strategy (NSS) has substituted the Trias Energetica. This strategy adds a significant step between minimising the demand and the use of renewable sources, and it incorporates a waste stream strategy inspired by the Cradle-to-Cradle principle.

The previous last step, which implied accepting the use of fossil fuels, becomes obsolete (van den Dobbelsteen, 2008).

Whatever the approach, the common thread is that the measures that need to be considered during environmental design can, generally, be characterised as passive or active. Passive measures are related to the building design and the properties and function of the building envelope, while active measures include the use of mechanical equipment. The objective for both passive and active measures is to enhance the heat flow in and out the occupied spaces, towards the ultimate goal of achieving thermal comfort. Fig. 2.2 provides an overview of the measures and their objective. The next sections of this chapter explain the principles, following the proposed classification of passive and active measures.

3 Passive/ Building Design Strategies

Passive design principles aim at minimising the energy demand of the building. Proper consideration of the local climate and environmental elements, building layout, and material properties make the energy demand reduction possible. Passive principles can be classified in the following basic functions: heat protection, solar heat gain, and heat rejection.

3.1 Heat Protection

In order to reduce the energy demand, the building envelope should prevent, or at least minimise, heat flow due to the temperature differences. In winter, the flow goes from the inside to the outside, and vice versa during summer, when outside temperatures are higher than the interior temperature. A low thermal transmittance of the components is, thus, essential during all seasons. Increasing the airtightness and thermal resistance of the building envelope with the use of insulating materials for opaque elements of the envelope and insulated windows for the openings is the main strategy for heat protection.

3.1.1 Insulation

A material with a high thermal resistance that opposes heat transfer between areas with temperature differences is considered an insulator (McMullan, 2002, p. 37). Such materials, mostly used on the opaque building components, can improve the thermal and sound insulation of the building. They reduce transmission heat losses and produce higher surface temperatures (Hausladen, Saldanha, & Liedl, 2008).

	INSULATION MATERIAL	DENSITY ρ (kg/m^3)	THERMAL CONDUCTIVITY λ (W/(mK))	WATER VAPOUR DIFFUSION RESISTANCE INDEX μ	FIRE RESISTANCE CLASS EUROCLASS	FORMS AVAILABLE	APPLICATIONS	INSULATION THICKNESS FOR U-VALUE 0.2 W/(m^2K)	EMBODIED ENERGY MJ/kg
ORGANIC	Flax	20-50	0.038-0.045	1-2	E	Batts, blown material, loose fill	exterior wall, cavity, ETICS, floor, loft, roof	18-20 cm	11-30
	Hemp	20-50	0.038-0.045	1-2	E	Batts, blown material, loose fill	exterior wall, cavity, ETICS, floor, loft, roof	18-36 cm	10.5-33
	Wood fibres	150-250	0.040-0.081	2-5	E	Boards, blown material	exterior wall, cavity, ETICS, floor, loft, roof	18-36 cm	17
	Wood-wool boards	60-600	0.080-0.100	2-5	E	Boards	exterior wall, cavity, ETICS, floor, loft, roof	40-45cm	10.8
	Cork	100-120	0.038-0.050	10-18	E	Granulate, board	exterior wall, cavity, ETICS, floor, loft, roof	18-25	26
	Reed	155	0.040-0.065	2	E	Batts	exterior wall, floor, loft, roof	20-29	
	Sheep's wool	20-50	0.040-0.044	1-2	E	Batts, blown material	exterior wall, cavity, ETICS, floor, loft, roof	18-20	20.9
	Cellulose	25-66	0.040-0.045	1-2	E	Loose fill, blown material	exterior wall, cavity, ETICS, floor, loft, roof	18-20	7,6
MINERAL	Rock wool	20-40	0.031-0.040	1-2	A1	Batts, blown material, boards	exterior wall, cavity, ETICS, floor, loft, roof	16-22	16,8
	Glass wool	16-25	0.031-0.040	1-2	A1	Batts, blown material, boards	exterior wall, cavity, ETICS, floor, loft, roof	16-22	49,6
	Mineral foam	70	0.035-0.051	3-5	A1	Board	exterior wall, ETICS, floor, loft, roof	16-20	
	Perlite	60-160	0.040-0.060	5-25	A1	Loose fill	exterior wall, cavity, floor, loft	25	
	Cellular or foam glass	10-120	0.040-0.055	∞	A1	Loose fill, board	exterior wall, cavity, ETICS, floor, loft, roof	18-25	26
	Aerogel	180	0,013	∞	A	Batts, granulate, monolithic	exterior wall, loft, roof	6,5	53
OIL-DERIVED	Expanded polystyrene (EPS)	15-30	0.035-0.040	20-100	D to F	Board	exterior wall, ETICS, loft, roof	16-18	108
	Extruded polystyrene (XPS)	20-50	0.030-0.040	5-23	E	Board	exterior wall, ETICS, floor, roof	13-18	95
	Polyurethane	30-40	0.025-0.040	30-100	C (B for Metal faced sandwich panels)	Board (PUR/PIR), in situ foam	exterior wall, cavity, ETICS, floor, loft, roof	11-18	101
OTHER	Vacuum insulation panels (VIP)	150-180	0.07–0.10 W/(m K)	∞	A (for VIP core)	Panels	exterior wall, floor, loft	3-4	81.9
	Transparent insulation			5-26		Board	exterior wall		

TABLE 3.1 Typical insulation materials *(Konstantinou, 2014, Table 4.3)*

The insulating effect is the result of the low thermal conductivity of air that is enclosed in the porous material. There is a bewildering range of insulating materials, from the familiar polystyrene and mineral wool to alternative materials that are gradually establishing themselves in the market such as sheep's wool and hemp. Table 3.1 presents typical insulation materials organised firstly according to the origin of the raw material, and then classified into organic, inorganic/mineral, or oil-derived types. Moreover, insulation technologies can be artificially manufactured, such as vacuum insulation panels. Additional information about specifications, form, and applications for the different materials is also provided (AEA, 2010; Giebeler, 2009; greenspec, 2013; Lyons, 2010; Papadopoulos, 2005).

Besides thermal and moisture related properties, other parameters that determine the final choice of insulation material are fire resistance, sound insulation and mechanical properties, cost, suitability and ease of installation, environmental properties and pollutants content, and production process and chemical composition.

Depending on their form, they are subdivided into fibre, foamed, and granulate or loose fill insulation (Hausladen et al., 2008). The adequacy of the various insulation material depends on the application. Loose materials can be inserted between wooden posts and beams or, more generally, in structurally hollow spaces. Insulating panels or matting are cut to size and can then be installed accurately. Rigid foam insulation boards are appropriate for external applications, due to higher impact strength.

3.1.2 Insulated Windows

Openings are an integral part of the building envelope, serving view, daylight and ventilation. These openings are usually operable and made of transparent material, mostly glass, to fulfil their functions. One of the shortcomings of glass are its relatively poor thermal properties. Nevertheless, technology provides the opportunity to use insulated windows, consisting of panes and frames with lower thermal conductivity.

Over the last decades, multiple panes of glass separated by air spaces have replaced single glazed window panes, resulting in significant improvement of the window insulation value. Additionally, if the cavity between the panes is filled with a less conductive, slow-moving gas, such as argon or krypton, the conductance of the cavity is even further reduced, which improves the thermal performance of glazing units.

Moreover, low-emissivity coatings, called Low-E for short, are used to reduce the surface emissivity of glass. Such coatings consist of a microscopically thin metal oxide or semiconductor film, and they are applied on the faces between the panes, facing the cavity. They are mainly transparent across the visible wavelengths of light but reduce the long-wave infrared thermal radiation that is absorbed and emitted by the glass pane. This reduces heat loss because the re-emission is directed to the interior of the building if the coating is on the outside face, as is advised for cold climates. In a hot climate, the coating should be placed on the inside face, so that the solar radiation is reflected to the environment (Fig. 3.1).

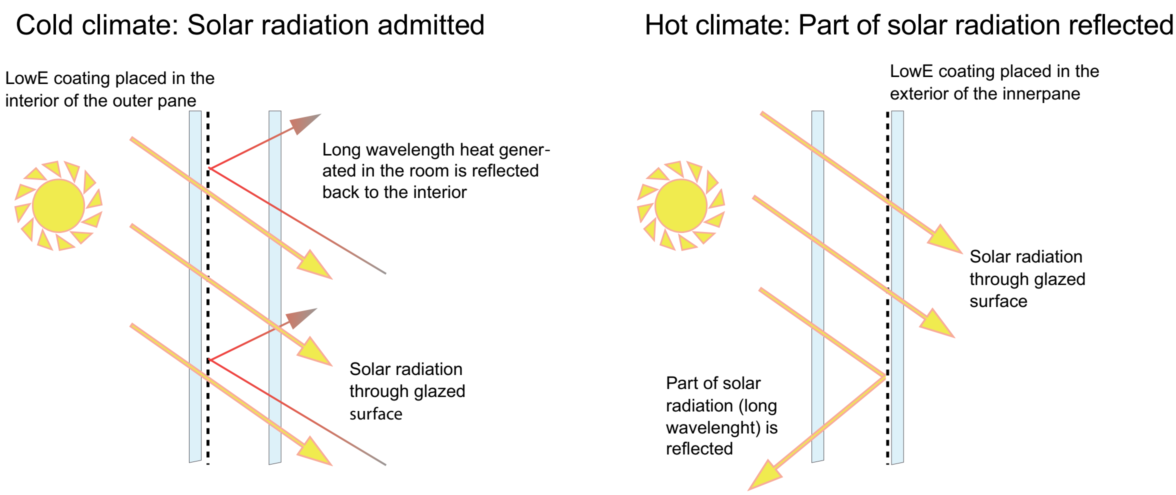


FIG. 3.1 Scheme of coating placement

Thermal transmittance coefficient or *U-value* is typically used to evaluate the window pane performance. The overall thermal conductivity depends on the number of panes, the depth of the cavity, the gas infill, and the coating. Table 3.2 compares glazing types with different characteristics. The values given in the table may vary for specific products. However, they aim at indicating the thermal performance of the glazing according to its specifications.

GLAZING	NUMBER OF PANES	GAS INFILL	DIMENSIONS (mm)	U-VALUE (W/(m²K))
Single glazing	1	n/a	4	5.6
Double glazing	2	Air	4-6-4	3.3
Double glazing	2	Air	4-12-4	2.8
Triple glazing	3	Air	4-6-4-6-4	2.3
Triple glazing	3	Air	4-12-4-12-4	1.9
Double glazing with Low E coating	2	Air	4-6-4	2.5
Double glazing with Low E coating	2	Air	4-12-4	1.7
Triple glazing with 2Low E coatings	3	Air	4-6-4-6-4	1.6
Triple glazing with 2Low E coatings	3	Air	4-12-4-12-4	1.0
Double glazing with Low E coatings and Argon	2	Argon	4-6-4	2.1
Double glazing with Low E coatings and Argon	2	Argon	4-12-4	1.3
Triple glazing with 2Low E coatings and Argon	3	Argon	4-6-4-6-4	1.2
Triple glazing with 2Low E coatings 2 and Argon	3	Argon	4-12-4-12-4	0.8

TABLE 3.2 Comparison of typical heat transfer through different glazing options *(source: ISO10077-1, 2006, p. 18, table C.2)*

As glazing and wall thermal performance improves, the window frame can create thermal bridging problems. To overcome this issue and reach requirements for higher efficiency of the building envelope, thermal breaks within the window frame profile are introduced. Some of the materials used are ABS (acrylonitrile butadiene styrene), polyethylene HD, polyamide (nylon), PVC-U (polyvinylchloride), polypropylene, and polyurethane (ISO10077-2, 2006). A definition of the thermal transmittance of the frame section *Uf* considers the thickness of the frame material, the thermal break material, the glazing, and the sealant.

Window frames are made of different materials, as shown in Table 3.3. Most commonly, window frames consist of timber, aluminium, steel, or plastic. The choice of the frame type depends on the properties and cost of the material, as well as the desired architectural expression.

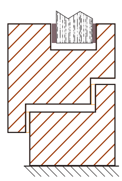
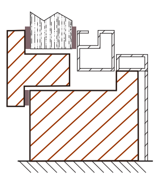
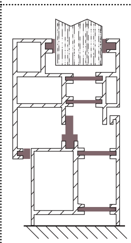
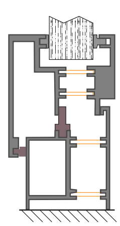
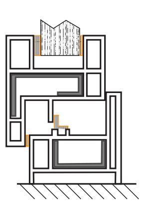
MATERIAL	SCHEMATIC SECTION *	PROPERTIES	LIMITATIONS	THERMAL CONDUCTIVITY, λ W/(mK)*
Timber		Psychological/aesthetic effect as a "warm" material Low embodied energy Good thermal behaviour	Need regular maintenance Special considerations against water penetration, mould and insect infestation	0.13
Timber/ aluminium		Aluminium cladding covering the entire exterior of the frame Weather protection Psychological/aesthetical effect as a "warm" material in the interior	Need regular maintenance Special considerations against water penetration, mould and insect infestation	See thermal conductivity for timber and aluminium
Aluminium		Extruded profiles Structural integrity Precise and airtight construction Easy maintenance	High thermal conductivity. Thermal break needed. High initial cost High embodied energy	160
Steel		Profiles made of folding sheet metal High bending and torsion strength Good fire protection properties	Thermal break required High cost Corrosion protection needed	50
Plastic (uPVC)		Extruded profiles Impact and scratch resistance Low cost Easy installation and maintenance Resistant to water and corrosion	Prone to heat deformation Not fire resistant Limited structural strength	0.17

TABLE 3.3 Window frame types *(Konstantinou, 2014, Table 4.5)*
*adapted from ISO10077-2 (2006)

3.1.3 Infiltration

Infiltration, or air leakage, is the movement of air through leaks, cracks, or other adventitious openings in the building envelope (Sherman & Chan, 2004). Air-tightness is the fundamental building property that affects infiltration. From the energy perspective, air leakage is one of the leading causes of heating energy loss, as it allows heated air to escape the conditioned spaces. Even with current standards for air-tightness, envelope leakage can increase the heating needs by 5-20 kWh/(m^2a) in a moderate climate (BPIE, 2011, p. 51). Moreover, it degrades the effectiveness of the insulation and allows potentially damaging moisture to penetrate the building envelope. Air leakage occurs at joints of the building fabric, around doors and windows, cracks in masonry walls etc., as well as where pipes and cables pass through the building (Hall, 2008a, p. 49). Nevertheless, the quest for air-tightness must be coupled with an appropriate ventilation system to introduce fresh air in a controlled manner, preserving adequate indoor air quality levels.

The values can be defined in standards and regulations as n (vol.h) or air flow/outer envelope or air flow/floor area, for a pressure difference of 50 Pa or 10 Pa or 4 Pa. Another unit to measure infiltration and ventilation is air change per hour (ACH), which refers to how many times the air is replaced within a defined space, e.g. a room. High air-tightness requirements for energy-efficient buildings indicate around 1.2 ACH at 50Pa (EN15242, 2007) and 0.6 ACH for the passive house standard. In existing buildings, values up to 16 ACH at 50Pa have been measured (Stephen, 2010), suggesting that the building stock's airtightness should significantly improve.

Careful implementation of strategies throughout the design and construction phases achieve adequate air-tightness. The materials and their application depend on the type of leakage. Air-barrier membranes and sealants, such as expanded foam, gun-applied sealants, tapes, and fillers, should be applied to prevent uncontrolled air and water flow.

With regard to windows, air leakage occurs around the window frame, at the wall connections, and between the operable parts of the frame. Leakage at the wall-frame connection may account for as much as 14% of the total leakage. This source of air leakage can be tackled by applying casing tape, poly-return, poly-wrap and foamed-in-place urethane, and other sealing methods (Sherman & Chan, 2004). Some materials used for weather stripping and sealing the edge of the windows are indicated in ISO10077-2 (2006).

3.1.4 Solar Control

Even though solar radiation is welcome during winter, as will be explained in Section 3.2, it should be excluded during summer to avoid overheating of the occupied spaces. The best solar control is proper external sunshade, intercepting direct solar radiation before it strikes the window of a given wall. Shading systems can vary significantly in design, size, and placement, ranging from simple Venetian blinds to more advanced and complicated systems, which ultimately determine the entire building architecture, such as the example in Figure 3.2.The choice depends on the desired performance, functional and aesthetic result. For instance, external shading is more efficient than internal shading, even though it requires higher maintenance.

Shading systems are commonly classified according to their control possibilities, thus separated in movable and fixed systems. The first system offers the user more options but incurs high maintenance costs, while the second are thought to be more efficient (if well designed) but consider no possibility of control from the user and can exhibit varying performance during the day. The movable systems are often referred to as adaptive because they adapt to the changing internal or external conditions.

Orientation is a major factor in determining the shading type. Horizontal screening louvres exclude direct sunlight on the south side with little visual interference. Permanent building elements such as cantilevers function as seasonal solar screening. They block the high angle sun rays in the summer, while they enable solar heating during the winter by allowing lower angle sun rays to penetrate the room. On east and west façades, movable vertical louvres are preferable because the sun strikes at low altitudes. By setting the angle of the louvres accordingly, sunlight can be blocked while retaining some of the view (Hausladen et al., 2008).

FIG. 3.2 Al-Bahr Towers, Abu Dhabi. The Mashrabiya as seen from the inside – Sky garden open space *(Photograph by Abdulmajid Karanouh, Ramboll (Karanouh & Kerber, 2015))*

A

B

FIG. 3.3 A+B: Reflective glazing in office buildings. Chicago, USA

Moreover, avoiding the admittance of excess solar radiation can be achieved with the use of special glazing, such as tinted, coated or switchable glazing. Glazing can become tinted with small additions of metal oxides to the float or rolled glass composition, which would colour the glass bronze, green, blue or grey but would not affect its basic properties, except changes in the solar energy transmittance.

Chromogenics is a technology of switchable glazing. It refers to glazing in which transmission properties can be regulated by a reversible change of the glass from darker to lighter, or transparent to translucent. Such technologies include photochromic glass that encompasses coatings of silver halide, which changes from clear to dark depending on incident sunlight, while thermochromic glass has a coating of vanadium oxides which exhibit a reversible semiconductor-to-metallic phase transition when the temperature rises (Soltani, Chaker, Haddad, & Kruzelecky, 2008). Electrochromic glazing is a technology of switchable glazing, which is more controllable, as it is coated with tungsten trioxide that changes from clear to dark when electrical current is applied. The effect is that the glazing switches between a clear and a transparent blue-tinted state with no degradation in view, as is shown in Fig. 3.4. Typical EC windows have an upper visible transmittance range of 0.50-0.70 and a lower range of 0.02-0.25.

Finally, another technology of switchable glazing that is gaining popularity is the Liquid Crystal Window. When an electrical current is applied to the thin layer of liquid crystals placed between the panes, the crystals are being rearranged and, as a result, the transmission of the window changes from bright to dark, while maintaining its transparency, as shown in Fig. 3.5. The windows can switch to all intermediate states in-between bright and dark. The *g-value* of the windows ranges between 0.45-0.09.

A

B

FIG. 3.4 A+B Example of chromogenic glazing *(photo courtesy of SAGE Electrochromics, Inc., Copyright Eric Sahlin Photography)*

FIG. 3.5 Example of Liquid Crystal Window technology *(photo courtesy of Merck Window Technologies B.V.)*

3.2 Heat Gain From the Sun

Passive solar heating is essential during winter when energy for heating is needed for a thermally comfortable indoor environment. It employs transparent elements of the building envelope to collect, store and distribute solar energy without or with the minimum use of mechanical equipment (Hyde, 2008). During summer, when the heating effect is not needed, the glazed parts should be open or protected with adequate shading.

Passive solar heating primarily occurs in the south part of the building – or north for the southern hemisphere. On a dwelling level, this is usually not a big problem, as heat gains can be distributed in short distances and reduce the overall heating loads. In larger buildings, however, it is possible to require zoning in the energy use for different orientations (Hall, 2008b). Moreover, since the windows are one of the primary sources of fabric heat losses, the heat gains through the windows must outweigh the heat losses.

TOC

3.2.1 Direct Solar Gains

In buildings, sunlight is directly collected through the glazed areas of the façade, especially the equator-facing surfaces. The specific physical properties of glass allow for using solar radiation to heat the interior space. The heating effect is based on the principle that glass is permeable for short-wave radiation (ultraviolet radiation) from the sun but impermeable for the long-wave heat radiation, which is emitted by the materials. The orientation, the positioning and size of the transparent areas, as well as the interior layout for thermal zoning determine the effectiveness of the direct solar heating (Hegger, Fuchs, Stark, & Zeumer, 2008).

3.2.2 Solar Buffer Spaces

Solar buffer space is an intermediate space between the occupied, interior space and the exterior. This space is unconditioned and heated exclusively by solar irradiation. As the temperature in the buffer space is higher than the external temperature, the transmission heat losses of the interior are reduced. In dwellings, such spaces are also referred to as winter-gardens, because the temperature in the buffer space can be within comfort levels for a larger percentage of the year, due to solar heat gains. In this way, the usable area increases.

FIG. 3.6 The winter-garden of Pret-a-loger, TU Delft Campus, NL

Double façade constructions can also create a buffer space. Double façades include an exterior façade layer, which is separated from the (interior) façade elements that enclose the occupied space. The distance between the interior and exterior façade layers can vary. Depending on the method used to conduct air in the space between the two façades, double-skin façades can be grouped into four main categories (Knaack, Klein, Bilow, & Auer, 2007):

- box-window façade, where the air only circulates within one façade element,
- shaft-box façade, where the air rises in vertical shafts,
- corridor façade, where the air circulates within the gap between the façades horizontally across one storey, and
- second-skin façade, where the air can flow across the entire, unrestricted gap cavity.

Apart from the thermal buffer effect, a double façade has additional functions regarding ventilation (see also section 3.3.1), noise, and wind protection.

A

B

FIG. 3.7 Double façade examples. Post tower, Bonn (A). Stadttor Düsseldorf, Düsseldorf (B)

3.2.3 Indirect Heat Gain

Indirect solar heat gain occurs in the form of heat storage in components with high thermal mass, for example when using transparent outer layer and a heat-absorbing element between the incident solar radiation and the space to be heated. Solar energy transmitted through the transparent layer is absorbed by the outer surface of the wall and conducted to the inner surface several hours later, or is conveyed flowing through the air between glazing and wall. Such methods can be of great benefit, especially when combined with air circulation measures, in areas that receive inconsistent solar radiation (Smith, 2005). Well-

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known technologies of indirect solar heating are the Trombe wall and the attached sunspaces. Apart from the advantage in energy efficiency, such constructions can have the benefit of enlarging the living space.

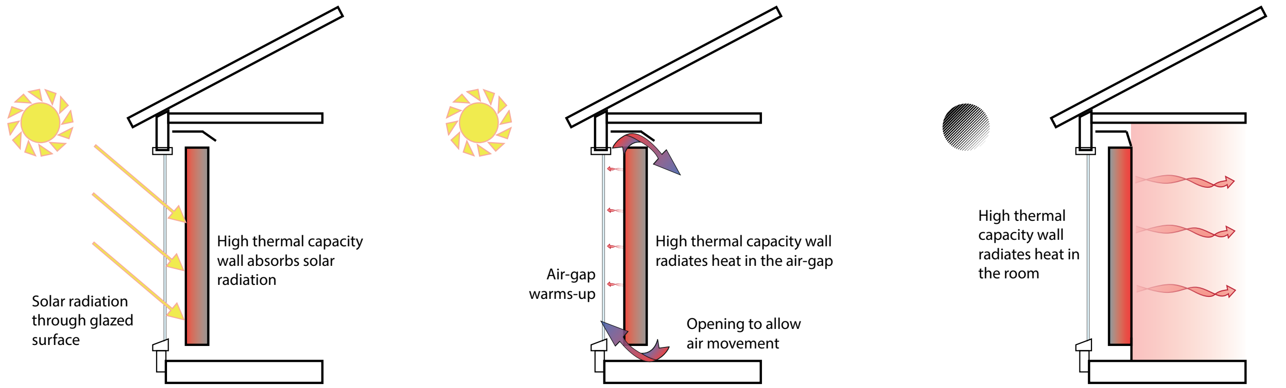

FIG. 3.8 Principle of Trombe wall and attached sunspaces

3.3 Heat Rejection

As previously stated, the use of solar control strategies is a highly effective method of preventing heat from entering the building, minimising the occurrence of overheating, and thus, reducing overall cooling demands. However, the presence of internal heat gains and unwanted solar gains, even using optimised shading systems (due to diffuse solar radiation), mean that heat prevention strategies alone are not usually enough to lower indoor temperatures to comfort levels, particularly during summer season. Hence, it is important to consider passive strategies aimed at dissipating heat generated or stored indoors to the external environment (Givoni, 1994; Santamouris & Asimakopoulos, 1996).

Heat rejection or heat dissipation strategies seek to remove indoor heat, releasing it into a natural reservoir (air, water, ground). Passive heat dissipation strategies accomplish this without energy consumption, while their efficiency may benefit from the use of additional equipment such as pumps and fans in so-called hybrid or low-exergy heat rejection systems (Ala-Juusela, 2003; Kalz & Pfafferott, 2014). Moreover, the efficiency of these strategies increases when they work together with heat modulation methods, such as the use of thermal mass for heat storage, to be dissipated to an external heat sink at a more suitable moment, such as night time (Hegger et al., 2008, p. 98). Heavyweight construction, such as concrete, terracotta, and limestone, can provide sufficient thermal mass. Nevertheless, for the thermal mass to be effective, the components need a direct link to the interior. Internal linings and suspended ceilings prevent the heat flow between the air temperature and the building thermal mass. Alternatively, Phase Change Materials (PCM) may be used instead of massive constructive elements for heat storage purposes.

Heat dissipation strategies may be classified according to the heat sinks they employ as base for their cooling principle (Samuel, Nagendra, &

Maiya, 2013). Hence, the use of the ground, air, and water in proximity to the building, and outer sky as heat sinks defines specific heat dissipation possibilities, as shown in Fig. 3.9. As mentioned above, in most cases, an efficient application of these strategies relies on the use of auxiliary mechanical equipment. Therefore, the subsequent description will focus on the passive cooling principles behind each strategy, without detailing further use of active components, such as pumps and fans, for their application in the built environment. Nevertheless, ventilation strategies will be explored in detail, due to their energy savings potential and simplicity of implementation under purely passive operation.

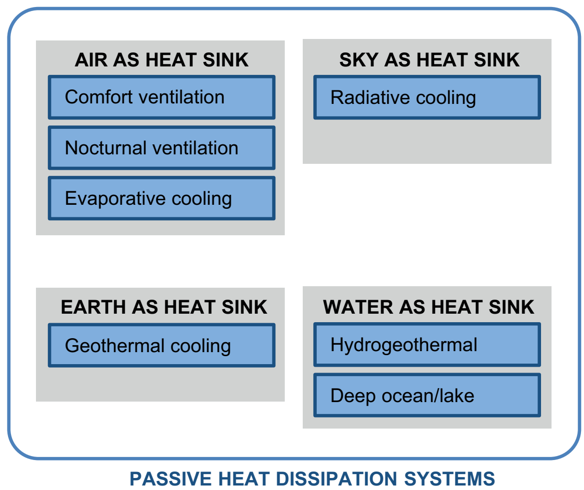

FIG. 3.9 Passive/low-ex heat dissipation strategies according to the heat sinks used for their cooling principle

3.3.1 Ventilation

Ventilation is the most common heat dissipation strategy, using external air as a heat reservoir to lower indoor temperatures. Two main strategies are distinguished based on the principle: comfort or diurnal ventilation, and nocturnal or night-flush ventilation. The former acts during peak demands, improving users' perceived comfort, while the latter operates at night time, rejecting stored heat to cool down the building for the next day. High temperatures during daytime may be counterproductive for the application of comfort ventilation, but research has shown that building occupants are willing to accept higher indoor temperatures if they have access to natural ventilation, promoting its use under adaptive comfort control models (Nicol, Humphreys, & Roaf, 2012). Fig. 3.10 shows the different ventilation strategies.

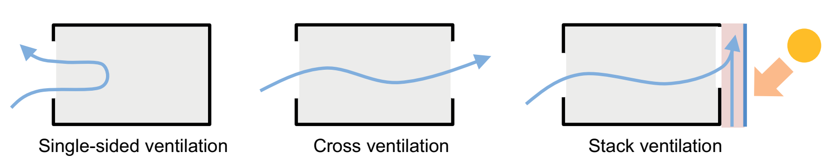

FIG. 3.10 Ventilation strategies: single-sided, cross, and stack ventilation

Nocturnal ventilation has been regarded as an efficient cooling method for buildings and has been consistently researched as a particular topic of interest over the last 20 years (Prieto, Knaack, Klein, & Auer, 2017). Some early experiences dealt with the evaluation of these strategies via on-site measurements, while others have used simulations to assess the energy saving potential of their application, discussing possibilities for implementation in different climate contexts (Artmann, Manz, & Heiselberg, 2007; Geros, 1999). Several research experiences have shown potential for cooling demand savings, ranging from 40% to 80%,depending on flow rates, climate context, and particularities of the building (Ferrari & Zanotto, 2012; Roach, Bruno, & Belusko, 2013). Nocturnal ventilation strategies perform better in climates with high thermal oscillation between day and night (more than 10°C), taking advantage of lower night temperatures to release heat stored during the day.

A *B* *C*

FIG. 3.11 A+B+C: Ventilated double façade and air inlets for cross-ventilation in the GSW building, Berlin

Nocturnal ventilation has been regarded as an efficient cooling method for buildings and has been consistently researched as a particular topic of interest over the last 20 years (Prieto, Knaack, Klein, & Auer, 2017). Some early experiences dealt with the evaluation of these strategies via on-site measurements, while others have used simulations to assess the energy saving potential of their application, discussing possibilities for implementation in different climate contexts (Artmann, Manz, & Heiselberg, 2007; Geros, 1999). Several research experiences have shown potential for cooling demand savings, ranging from 40% to 80%,depending on flow rates, climate context, and particularities of the building (Ferrari & Zanotto, 2012; Roach, Bruno, & Belusko, 2013). Nocturnal ventilation strategies perform better in climates with high thermal oscillation between day and night (more than 10°C), taking advantage of lower night temperatures to release heat stored during the day.

Natural ventilation (air currents without the use of fans), occurs under two basic principles: wind driven ventilation, and stack or buoyancy driven ventilation. The former relies on wind-induced pressure differentials and air inlets in the building facade, while the latter results from convective flows originated by vertical temperature gradients. The application of different ventilation principles implies design decisions at the early stages of a building project. Room orientations, building layouts, and window size and position are factors to consider to allow for single-sided or cross-ventilation, while architectural elements such as atriums, solar chimneys, and multi-layered facades have been conceived to promote buoyancy driven ventilation specifically.

3.3.2 Evaporative / Adiabatic Cooling

Evaporative cooling provides a cooling effect through the evaporation of water. Thus, internal heat gains are used as latent heat for the phase change from water to vapour in the humidity content of indoor air. The effectiveness of the strategy relies on the circulation of air before it reaches humidity saturation levels, releasing warm and humid air to the external environment. These techniques have mostly been researched for hot-arid climate applications, considering them along with ventilation strategies to bring pre-cooled fresh air into the buildings, such as in Fig. 3.12. Nonetheless, their efficiency has been analysed in different climate contexts in order to explore the potential for implementation in other regions (Morgado, Melero, Neila, & Acha, 2011).

The implementation of these technologies follows two possibilities: direct and indirect evaporative cooling systems. Direct systems increase the humidity of the room, directly integrating a water source into space, or mixing it with an air current, while indirect systems keep the water in a closed cycle, with the exception of incoming fresh air. The latter is a more complex system, but its application is suitable for cases where indoor humidity levels are a relevant issue. Building application has sparked the exploration of integration possibilities in façade modules or solar chimneys, in combination with ventilation strategies (Abdallahet al., 2013; Abu Khadra & Chalfoun, 2014).

A B C

FIG. 3.12 A+B+C: Adiabatic cooling in courtyards, Morocco

3.3.3 Ground Cooling

Ground or geothermal cooling uses the earth as a heat sink during the summer season, taking advantage of constant temperatures below 6 meters deep throughout the year. Application of these strategies requires the use of earth-to-air heat exchangers with improved effectiveness when coupled with other strategies such as thermal storage, evaporative cooling, or ventilation by use of solar chimneys. This strategy will be further explored in section 4.1.2 when referring to geothermal heating by use of renewable sources.

3.3.4 Hydrogeothermal / Deep Lake / Ocean Cooling

Hydrogeothermal and deep lake/ocean cooling follows the same principle as ground cooling, but uses a large mass of water as heat reservoir instead of the earth. In the first case, underground water is used as a primary source, while the bottom layer of lakes and oceans is used as cooling source for the second one (Samuel et al., 2013). The applicability of these technologies in the built environment is limited, being mostly reserved for large infrastructure or offshore projects. Nonetheless, they are considered in this review for the sake of completeness.

3.3.5 Radiative Cooling

Radiative cooling uses the outer space as a heat sink, rejecting heat in the form of electromagnetic radiation at long waves, from surfaces exposed to the sky during night time (Samuel et al., 2013). Therefore, the roof is regarded as the most important passive radiative cooling element in a building, and design variables such as colour and the use of movable insulation may increase the effectiveness of this strategy (Santamouris & Asimakopoulos, 1996). Radiative cooling strategies achieve higher performances under clear and unpolluted skies, so their use is recommended in hot-dry climate zones.

4 Active/ Equipment

Passive design principles alone cannot eliminate energy demand across all seasons. Even after applying passive measures, the additional energy required is provided by the technical building systems, which are the technical equipment for the heating, cooling, ventilation, hot water, lighting, or for a combination thereof.

4.1 Heat Generation

4.1.1 Heating with Efficient Use of Non-Renewable Energy

Heating system operation has to cope with heating energy demands of any given indoor space for the indoor temperature to reach thermal comfort levels. Hydronics are systems that use hot water for transferring heat from the heat generator to the heat emitters. The most common type of heat generator for hydronic systems is a 'boiler'. Boilers are available in a broad range of types and sizes and operate with different fuels, such as gas, oil, electricity or biomass. Fig. 4.1 shows the mix of energy sources used for heating in various European countries.

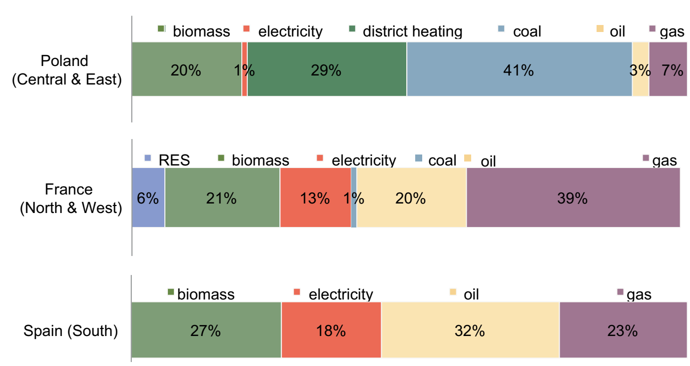

FIG. 4.1 Mix of energy sources used for heating *(source: BPIE, 2011)*

The efficiency of any given boiler indicates how well it transfers the heat generated during combustion (Hall, 2008b). Boiler efficiency has improved markedly over the past two decades, with efficiencies that reach up to 91% (SEDBUK, 2005). This is an important consideration, particularly in the case of retrofitting, as the older buildings most likely have heating systems with efficiency levels lower than current standards.

EPBD suggests that boilers older than 15 years should be inspected and replaced, and new boilers should be inspected every 2-4 years.

Heat pumps can also generate the hot water for hydronic heating systems. They include a vapour compression refrigeration system or a refrigerant/sorbent pair to transfer heat from the source using electrical or thermal energy at a high temperature to the heat sink (EN15316-4-2, 2007). Heat pumps make use of different sources of low-grade heat. Air source systems (ASHP) offer advantages regarding space requirements and ease of installation, but they cannot offer the same year-round efficiency as other sources. Water source heat pumps (WSHP) provide the best coefficient of performance (CoP), but they require a nearby water source. Ground source heat pumps (GSHP) should not be confused with geothermal energy. GSHP pipes are only buried 1 meter below the surface to use the solar energy stored in the ground. Geothermal energy, on the other hand, is heat within the earth in depths of around 30m (Hall, 2008a). The heat pumps widely used for heating are reversible air-to-air units that can also be used for cooling (CISBE, 2005). These systems will be explored in section 4.2.1, discussing the vapour compression refrigeration cycle.

Hydronic systems can work with different heat emitters, such as radiators, convectors or under-floor heating. The efficiency of the heat emitters and circuit, together with the boiler's efficiency, determine the overall efficiency of the heating system.

Warm air, produced by either stand-alone heaters or a central air-handling plant, is a different heating system. In many cases, the same plant is used for summertime cooling/ventilation. The heat output is provided mostly by convection through the warm air. Such systems have a faster response time than hydronic systems.

Combined Heat and Power (CHP) or cogeneration plants provide simultaneous generation in one process of thermal energy and electrical and mechanical energy. The energy efficiency for building-integrated cogeneration installations ranges, depending on the technology, from 75% to 105%, which means that the energy output can be higher than the input (EN15316-4-4, 2007). CHP schemes may be useful for dense group of properties, such as high-rise flats, or even applied on a community level (Emmanuel & Baker, 2012).

District heating is an efficient way to provide heat, particularly when combined with CHP units. The heat is generated in a central source and delivered in the form of hot water on demand to a group of buildings (Hall, 2008b). Similarly, the same principle may be used during summer, in the opposite direction. However, district cooling applications are scarcer.

4.1.2 Heating from Renewables

Heat can be generated from renewable sources, for example through active solar systems or biomass. An active solar thermal system (e.g. from evacuated solar heating panels) combined with large hot water storage to supply domestic hot water (DHW) and heating, is an efficient solution, particularly in the summer. Solar collectors convert direct solar radiation into other forms of energy, i.e. they preheat water using a closed-circuit clarifier. The different types of solar collectors depend on the system construction. Evacuated solar heating panels are more efficient than conventional flat plate type collectors and perform better in cold, cloudy, and windy conditions. The higher efficiency of evacuated solar heating tubes means less surface area is needed on the roof.

Moreover, there are heating systems that use renewable fuels, such as biomass. Biomass is organic substance. In the energy context, biomass is considered a renewable raw material that provides energy without producing additional amounts of CO2 within its life cycle, as the amount of CO2 released has already been absorbed by the plants during growth. Therefore, it is considered a CO2 neutral source and the primary energy factor of biomass is lower compared to other fuels (Hegger et al., 2008). Modern biomass heating systems are an alternative to fossil fuel systems, and they are as efficient and easy to use as conventional systems. There can be various renewable sources used as fuel in modern heating systems, predominantly wood (in the form of pellets or wood chips, such as the ones shown in Figure 4.2), but also vegetable oil or biogas. The characteristics of the biomass fuel determine how the system performs.

A *B* *C*

FIG. 4.2 Biomass boiler (A), wood pellet (B) and wood chips (C) *(Image source courtesy 3N e.V.)*

Geothermal heating is based on the principle that the temperature in the ground is constant at a deeper depth, and beyond approximately 30m it corresponds to the average air temperature (Hegger et al., 2008). Water that is pumped down a borehole into the ground and back to the surface transfers the heat by simple conduction from the ground to the water, which is then used to heat the building.

4.2 Heat Dissipation – Ventilation and Cooling

If the use of passive cooling strategies does not suffice to guarantee comfortable temperatures during the summer season, the use of building services should include complementary mechanical cooling system. The use of such systems is common in warm climates, and particularly necessary in commercial buildings, due to high internal heat gains because of occupation, lighting, and office equipment. Studies have shown that refrigeration and air-conditioning are responsible for about 15% of the total electricity consumption in the world (CICA, 2002), and their consumption share in office buildings may reach up to 50% of the total energy demands in hot and humid environments (Qi, 2006). It is important to understand their functioning principles and basic components to appropriately consider them in terms of building design, preventing oversizing, and extra energy expenditure.

4.2.1 Electrically Driven Cooling: Vapour Compression Cycle

A mechanical cooling system comprehends five elements/stages: the room to be conditioned, heat transfer equipment, the refrigeration machine, heat rejection equipment, and the external heat sink. Cooling generation is based on thermodynamic cycles. The most frequently used system is the vapour compression cycle, which represents over 90% of all installed systems. The working principle is based on the compression and subsequent expansion of a circulating liquid refrigerant in a closed cycle. The expanded refrigerant evaporates in contact with indoor air, absorbing ambient heat. After being compressed, releasing the latent heat into the environment, the heat later condenses outdoors, to restart the cycle (Fig. 4.3).

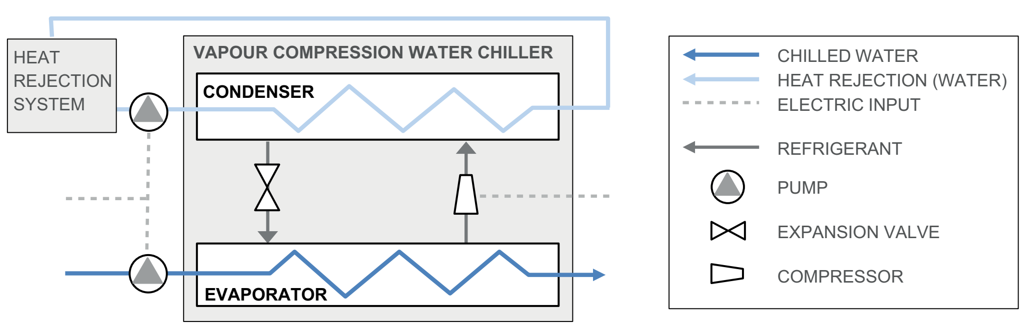

FIG. 4.3 Functioning scheme of a conventional vapour compression air-conditioning system

There are several technologies based on vapour compression; these are categorised into four basic types of air conditioning systems according to their heat transfer medium: all-air systems, all-water systems, air and water systems, and direct refrigerant systems (Daniels, 2003; Lechner, 2014). In all-air systems, air is directly cooled and delivered by ducts, while in all-water systems, water (or another liquid such as glycol) is chilled and then delivered through pipes. Air and water systems refer to the combined use of both systems in order to fulfil cooling requirements, usually relying on an all-water system to handle the bulk of the cooling. Finally, direct refrigerant systems consist of refrigeration machines and two fans to deliver cool air indoors and to reject heat to the external environment. In practical terms, direct refrigerant systems use air as the transfer medium, but they deliver cooling directly, without the use of ducts from a centralised refrigeration machine. In that respect, they could be regarded as all-air systems as well, with the only difference being that they are de-central systems. Typical systems for building applications derived from each technology are shown in Table 4.1.

HEAT TRANSFER MEDIUM		AIR	WATER
Cooling generation	Central application	- Direct expansion systems (rooftop units)	- Chilled water systems (chillers)
	Decentral application	- Window units - Split systems	-
Cooling distribution		Air ducts / Fans	Hydronic systems /Pumps
Cooling delivery	Air cooling	- Diffusers	- Fan-coil units - Induction units
	Surface cooling	-	- Embedded pipes (thermally activated building systems) - Mounted pipes (chilled ceilings) - Capillary tubes

TABLE 4.1 Common technologies based on vapour compression air-conditioning

4.2.2 Alternative Cooling Systems: Heat-Driven Cooling Cycles

Alternative systems for space cooling can potentially replace vapour compression technologies, lowering energy consumption while eliminating the need for harmful substances used as refrigerants. Some explored alternatives are sorption, desiccant, magnetic, thermo-acoustic, thermoelectric, and transcritical CO2 cooling (Brown & Domanski, 2014). All these technologies consider specific components and could be promising alternatives in the future based on further development; however, this review will focus on two of the most mature ones, with current application possibilities in the built environment: sorption and desiccant cooling.

These technologies use heat as the main driver of distinct refrigeration cycles, only requiring electricity for minor auxiliary equipment such as pumps and fans. The potential use of heat, a low-grade energy, as the main driver for cooling has attracted researchers' attention over the years, promoting alternatives based on the re-use of waste heat, or solar energy through thermal collectors. Nowadays, solar thermal cooling is a well-established research field that explores solar driven sorption and desiccant technologies with countless research projects, prototypes, and systems developed for commercial application in buildings. Similar to vapour compression systems, sorption cooling is based on the basic refrigeration cycle, which results from the continuous evaporation and condensation of a particular refrigerant. However, in sorption cooling, the mechanical compressor unit is replaced by a 'thermal compressor' unit that drives the cycle using heat from an external source (Henning, 2007). The cooling effect is obtained with a working pair of refrigerant and sorbent. The refrigerant evaporates in the evaporator, extracting indoor heat. It is then mixed with the sorbent and consecutively separated, to end up being condensed again, rejecting the extracted heat outside.

There are two distinct technologies under this basic principle, defined by the type of sorbent used. Absorption heat pumps use a liquid solution as sorbent, while adsorption heat pumps use solid sorption materials. Both technologies commonly use water as the main refrigerant, as well as a heat transfer medium for cooling distribution on a closed cycle (Fig. 4.4). Therefore, complementary distribution and heat rejection components must be considered next to a parallel ventilation system to bring fresh air into the building. Absorption chillers represent a mature technology (OECD/IEA, 2012), commercially available across a wide range of cooling capacities from 4.5 to over 20.500kW. Adsorption systems are less frequently used due to lower efficiencies and intermittent operation. However, they do not rely on moving parts in their working cycle, which simplifies maintenance and offers noiseless operation (Balaras, Grossman, Henning, Infante Ferreira, Podesser et al., 2007)

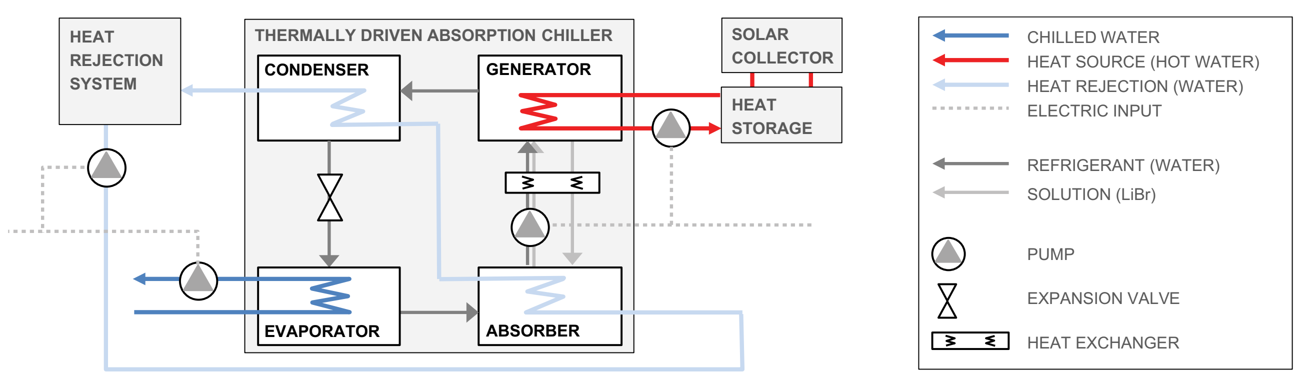

FIG. 4.4 Functioning scheme of a solar driven absorption chiller

Desiccant cooling technologies are also sorption-based, using a working pair of refrigerant and sorbent materials. However, while sorption cooling works in closed systems, desiccant systems provide conditioned air directly into the building, under an open-ended process.

Therefore, internal heat is removed through airflows of conditioned fresh air, providing not only temperature control for indoor spaces but also ventilation (Kohlenbach & Jakob, 2014). The cooling effect is achieved through the combination of dehumidification and adiabatic cooling of the incoming airflow, which is why these technologies are known as desiccant-evaporative cooling systems (DEC). At the beginning of the cycle, external air is dehumidified by direct contact with a desiccant, and then cooled using indirect or direct evaporative coolers. Heat exchangers are commonly used to pre-cool the incoming air to enhance the efficiency of the system, while the heat source is used to regenerate the desiccant material (Fig. 4.5). There are two main technologies following this principle, based on different desiccant types. Solid DEC uses a solid hygroscopic adsorption material, commonly placed on a rotary bed referred to as a 'desiccant wheel'; while liquid DEC uses a hygroscopic solution, which may be applied onto a carrier or directly sprayed into the incoming air stream (Kohlenbach & Jakob, 2014).

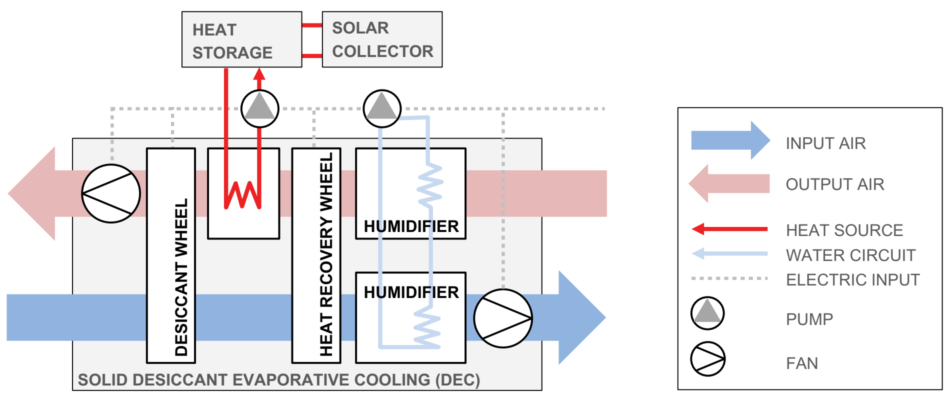

FIG. 4.5 Functioning scheme of a solar driven solid desiccant (DEC) cooling system

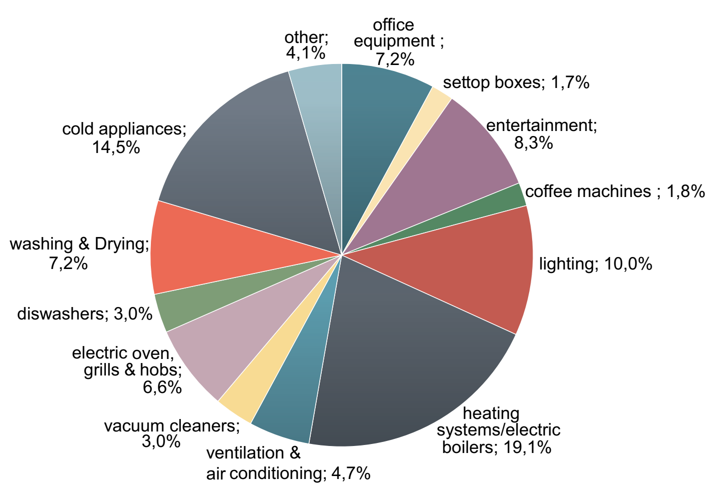

FIG. 4.6 Residential electricity consumption breakdown in the EU-27, 2009 *(source JRC) (adapted from Bertoldi, Hirl, & Labanca, 2012, p. 35, table 31)*

4.3 Electricity

With appliances accounting for 11% of the total energy used in residential buildings and lighting for 10% of electricity consumption (Fig. 4.6), considering this share of energy use during the design phase can have benefits in the overall energy performance of the building.

4.3.1 Artificial Lighting and Appliances

Increasing the efficiency of lighting and appliances is the first step to reduce the energy use. Directives on eco-design (DIRECTIVE, 2009/125/EC) and energy labelling of products (DIRECTIVE, 2010/30/EU) provide the regulatory framework. Apart from the products' efficiency, which is provided by the manufacturer, the usage patterns determine the energy use, which can be improved by better and smarter systems control.

4.3.2 Daylight

Apart from passive heating, the sun can be used for daylight to reduce the need for electric lighting. Daylight is the preferred form of illumination in buildings. The human eye has evolved using it, and its full spectrum output means it delivers better colour rendering properties than any other light source (Hall, 2008b). Most importantly, with the energy use for lighting being 10% of total electricity consumption in dwellings (Bertoldi et al., 2012) and up to 30% in high-rise office buildings (Wood & Salib, 2013), the use of daylight instead of electrical lighting can drastically reduce the energy demand.

The amount of sun radiation used for both passive solar heating and daylight admitted in the space depends primarily on the amount of transparent and translucent areas of the façade. Additionally, the building orientation, shading and reflectance of the surrounding buildings, and weather condition are influential (Hausladen et al., 2008).

4.3.3 Electricity Generation (RES)

In contrast to energy produced from fossil fuel, such as oil or gas, renewable energy is tapping into natural processes, such as sun radiation, wind, water movement etc., processes that are perpetually repeated. Both electricity and heat can be generated by renewable energy sources. Renewable energy production includes geothermal and biomass, which were discussed in previous sections, as well as solar, wind, and hydro power. According to Eurostat (2016), the share of renewables in electricity consumption is growing. In the scope of this chapter, we discuss renewable energy production technologies that

FIG. 4.7 Photovoltaic cells integrated into the glass panels on the roof of Akademy Mont-Cenis in Stadtteilpark Mont-Cenis in Herne, DE

are more commonly used on a building scale, which are photovoltaic panels, also often referred to as Building integrated photovoltaic (BIPV), and small-scale wind turbines.

Photovoltaic (PV) assemblies are technical systems that transform radiation directly into electricity. At the core of the installation, there are solar cells, combined into modules that produce DC voltage (Schittich, 2006). Typical PV cells are mostly composed of crystalline silicon cells, either formed in a single or multi-crystalline structure. The second generation of PV cells consisted of thin-film cells, made from different semiconductor materials; while novel developments such as organic solar cells or polymer cells have been branded as emerging technologies or 'third generation' cells. These refer to technologies which have been developed past the 'proof-of-concept' phase, but further research is needed to allow for widespread commercial application (Munari-Probst & Roecker, 2012). Electricity from photovoltaic modules can be fed to the electricity network, or can cover electricity demand on site.

The annual output of the PV system is also determined by the orientation and the angle of the module surface. For northern Europe, the highest annual radiation is for south-facing systems at an angle of 30°. The performance significantly decreases on vertical surfaces. However, generally speaking, the available building façade area is considerably larger than the roof space of a building. Thus, incorporating PVs in façade design results in more electricity production. R&D experiences have been driven by the evaluation of new concepts such as photovoltaic double-skin façades and PV integrated shading devices, or the exploration of specific attributes such as semi-transparent PV glazing, or colour customisation possibilities for solar modules. The task of integrating the PVs into the building skin is integral. The visual and constructional integration must guarantee that the installation does not conflict, but complements the requirements and characteristics of the building skin.

Wind turbines use the kinetic energy of the air to rotate their blades, which turns a generator, producing electricity. Wind turbines can be freestanding on their tower, or can be attached to buildings. Nevertheless, the latter is still not commonly used, as it can be more advantageous to place them near rather than on buildings (Hall, 2008b). Building-integrated turbines, where buildings are designed with wind energy in mind, are an option for consideration by developers tuned into the change surrounding sustainable living (Bobrova, 2015).

5 Conclusions

This chapter presented passive and active measures that are in line with environmental or bioclimatic design principles, aiming at buildings that provide thermal comfort with minimum or no use of non-renewable energy sources. Within this framework, the main actions come down to preventing/minimising the energy demand for heating and cooling and an efficient use of energy from renewable sources. These actions do not compete but rather interact with and complement each other. Thus, the design should consider them in parallel and should not neglect any step.

The discussed measures have been summarised in Fig. 2.2 and they are linked to how the heat is treated by the building envelope and building systems. Passive measures result in heat protection, heat gain from the sun and heat rejection, while active measures are related to heat dissipation and energy generation.

Ultimately, the energy use in the building is related to the users' wishes and behaviour. The measures described in the present chapter primarily affect the building-related energy demand, such as heating, cooling, and ventilation, with the user's satisfaction naturally being a precondition. User-related energy demand, such as energy used for appliances, lighting, and hot water, is not directly influenced by the building design. However, some of the measures discussed, such as electricity generation or the design for daylight, can contribute to reducing this energy consumption.

The environmental design principles can be beneficial to building performance, whether the design ambition is to have a comfortable and functional building with reasonable energy demand or go as far as achieving sustainable standards such as zero-energy or passive house.

The choice of measures is ultimately a design choice that will affect the architectural quality and expression of the building, as well as its function. The climate and local environmental elements should be considered, but the decision cannot be based on that alone, as every design needs to consider many parameters. The objective of providing the passive and active measure overview is not to give a prescription but provide knowledge to designers.

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The Passive House Concept _
An Energy, Environmental and Economic Optimum

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ABSTRACT **The heating requirements of a passive house are up to 15 kWh/(m²•a) of energy. Due to a good thermal and airtight envelope without thermal bridges, the building shows low transmission heat losses, while ventilation heat losses are reduced through a built-in system of controlled ventilation with heat recovery of the exhaust air. At their maximal load during peak heating season, heat losses do not exceed 10 W/m² and can be compensated with hot air heating. In such buildings, conventional heating systems are no longer required. Increasingly, heat pumps are used as heat generators.**
Such optimal results were made possible with considerable engineering knowledge and implementation experience, as the required rational concept can only be achieved by design optimisation, which must also be reflected in economic and environmental terms. Architectural and technological concepts to be included in the passive house design are presented. Using a model of a two-storey single-family house, five configurations are presented and evaluated with the parameters of energy efficiency (Q_{NH}/A_u), primary energy consumption ($PEC_{n.r.}$), CO_2 emissions (GWP_{100}), cost (*Cost*) and living environment (*LE*).

KEYWORDS passive house, low energy house, energy concept, primary energy, heating requirement

1 Introduction

The passive house concept was developed by Dr. Wolfgang Feist, who, in 1991, in Darmstadt, within the Cepheus project (Cost Efficient Passive Houses as European Standard), erected the first passive house. This prototype's successful performance led to the establishment of the passive house standard and passive houses have been part of the home market since 1998.

The passive house standard can be applied to buildings of all purposes, from passive single-family houses to multi dwelling buildings, office buildings, schools and kindergartens, sports halls, shops, churches, manufacturing plants, hotels, pools, etc. Similarly diverse are the building technologies used in the construction of a passive house. Today, passive houses are built on all continents in hot, temperate, and cold climate conditions. According to the Passivhaus Trust (2017) information, over 65,000 buildings have been built whose performance was certified to the passive house standard requirements. Both long-term experience with indoor living in passive houses as well as numerous studies show high user satisfaction (Keul, 2010). This is due not only to low heating costs and high environmental awareness, but mainly to the high indoor living comfort – the indoor air is fresh at all times and the air temperatures are uniform (Zbašnik-Senegačnik & Senegačnik, 2010).

The passive house's name does not stem from passive use of solar energy, but from the building not requiring a conventional space heating system (Feist, 1998a). A passive house is not a new construction technology. It is merely a very meticulously executed low-energy building, while its construction and function remain traditional. Neither does a passive house require additional design constrictions, as the higher standards are acquired solely through technical improvements of the building's envelope and of its heating and ventilation systems. All passive house demands can be met by installing innovative technical equipment for heating and ventilation, much in the same manner as the construction of a low-energy house.

Proper planning, followed by consistent implementation, is of key importance for achieving the passive house standard. The architectural design should include the optimal orientation, design, and functional arrangement of the building's premises. The thermal envelope with the pertaining joinery is very important for energy efficiency of the building and must be airtight and free of thermal bridges. The building must have mechanical ventilation. The heat demand of such a building is extremely low (Zbašnik-Senegačnik, 2009).

The cost of a passive house is 5 – 15 % higher than that of a conventional house (Galvin, 2014), with savings achieved in the medium and long term by consuming less fuel. Economic viability is difficult to assess accurately, since the future price of fuel and the discount rate are unknown (Galvin, 2010). Energy and environmental benefits are easier to assess because they are calculated directly on the basis of primary energy savings. The living comfort experienced by the users may be measured insofar as it refers to the temperature and humidity levels.

The study presents architectural and technological concepts of the passive house design. Presented below are five energy concept variants of single-family houses pertaining to different energy classes, including the evaluation of energy, environmental, and economy indicators. In an architectural model, all five-concept variants of single-family houses are evaluated with the parameters of energy efficiency (Q_{NH}/A_u), primary energy consumption ($PEC_{n.r.}$), CO_2 emissions (GWP_{100}), cost (*Cost*), and living environment (*LE*). The overall evaluation is carried out according to three methods of weighting: the objective weighting and the weighting from the national or user perspective.

2 The Definition and Concept of a Passive House

In comparison with conventional houses, constructed in accordance with valid regulations, passive houses do not demand additional building physics requirements. The building of passive houses, however, calls for strict observance of requirements regarding its components (Feist, 2015):

- thermal protection: the thermal transmittance coefficient U of all structural elements is below 0.15 W/(m^2•K), with values below 0.10 W/(m^2•K) recommended for free-standing single-family houses;
- thermal bridge free construction (linear thermal transmittance ψ £ 0.01 W/(m•K)
- high airtightness, monitored with a pressure test according to DIN EN 13829 – where the air exchange in both pressurised and depressurised states at 50 Pa pressure difference should be less than n_{50} = 0.6 h^{-1};
- glazing with U_w ≤ 0.8 W/(m^2•K) with high total solar energy permeability (g ≥ 50 % according to DIN 67 507), allowing net heat gains even in winter periods;
- window frames with U_f ≤ 0.8 W/(m^2•K) according to DIN EN 10077;
- the ventilation unit's consumption of electric energy ≤ 0.4 Wh/m^3 of the transported air volume;
- minimal heat losses in the preparation and distribution of hot sanitary water;
- efficient use of electricity in the household (use of A and A+ energy class equipment and household appliances).

A building does not become a passive house by assembling the necessary passive house suitable components. The passive house standard is achieved through an integrative plan that links the individual components into a comprehensive whole.

Typical values of characteristics denoting a passive house are (Feist, 1998):

- specific annual energy consumption for space heating ≤ 15 kWh/(m^2•a)
- total primary energy consumption ≤ 120 kWh/(m^2•a)
- electricity consumption ≤ 18 kWh/(m^2•a)
- heat losses ≤ 10 W/m^2
- airtightness n_{50} < 0.6 h^{-1}

3 Architectural Optimization of Passive House Design

As the building's architectural design impacts on its energy efficiency, it is crucial that the design process of passive house takes into account the building's orientation, shape, and spatial hierarchy (Zbašnik-Senegačnik, 2009).

3.1 Orientation

The integration of solar energy into the building's energy balance and appropriate placement of a building into its surrounding landscape can strongly affect the building's energy efficiency. Favoured plots for passive house buildings are oriented to the south. During cold periods, a south orientation maximises solar energy use and contributes a share of up to 40 % of the building's space heating demand. Thus, the passive use of solar energy positively influences the building's heat balance. Larger glazed areas on south façades are advisable for solar gains. The efficiency of solar irradiation gains is reduced by shading the building with trees or other buildings. The distance between adjacent buildings should be dimensioned according to the low incidence angle of the winter sunlight (Fig. 3.1).

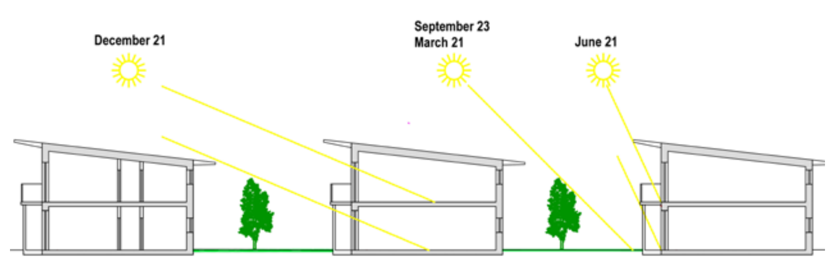

FIG. 3.1 The distance between adjacent buildings is determined by the low incidence angle of the winter sun.

3.2 The Building's Shape

Usually, most heat losses occur through a building's external envelope. Larger exterior envelope surfaces result in larger heat losses. In order to reduce these heat losses, it is imperative that the shape factor, i.e. the ratio between the surface area and volume, is carefully taken into account. Particularly favourable shape factors come with cubic, round, octagonal, and elliptical forms (Fig. 3.2). Typically, a freestanding single-family passive house will have a relatively high proportion of external surfaces relative to its volume (Fig. 3.3). Buildings in densely built clusters or large passive buildings have more favourable shape factors (Fig. 3.4).

FIG. 3.2 A round passive house floorplan resulting in a favourable shape factor

FIG. 3.3 Cubic shaped single-family passive houses with green flat roofs

FIG. 3.4 Compact shaped commercial building, Energy base

3.3 Functional Interior Space Design

Heat losses through walls increase with a growing temperature differential between the interior and exterior surface. To reduce a building's heat losses, rooms with lower temperature demands (i.e. staircase, storage, and other auxiliary spaces) should, ideally, be assigned to its north oriented spaces with the lowest exterior wall temperatures. Due to their larger temperature demand, living areas should be south oriented in order to gain heat from solar irradiation.

FIG. 3.5 A separate entrance into the unheated basement underneath the building (view from the terrace during construction)

FIG. 3.6 External staircase of a multi-unit residential passive house, excluded from the thermal envelope

Unheated areas should not be included within the thermal envelope. In buildings with basements, the whole floor above the basement should be thermally insulated, including the lower walls. The simplest solution is a separate basement entrance (Fig. 3.5). Especially in multifamily houses, where they account for a large part of the building's volume, staircases and halls may be excluded from the thermal envelope (Fig. 3.6).

4 Technological Optimisation of Passive House Design

All construction technologies are applicable for the building of passive houses. Equal results can be achieved in both massive and lightweight construction types, as well as with different building materials. The choice is subject to the investor's personal preference and is, mostly, price dependent.

4.1 Massive Walls

In massive construction types, the load bearing construction is brick, brick filled with perlite, concrete, or aerated concrete brick, and in all cases is clad with an appropriately thick layer of thermal insulation on the outside (Fig. 4.1).

A *B* *C*

FIG. 4.1 A+B+C: A massive wall – brick with external mineral wool and XPS thermal insulation

The thickness of a massive wall depends on its load-bearing requirements, while the façade cladding, as in conventional buildings, may be ventilated or unventilated. The cladding, however, must be mechanically fastened with anchors in such a way as to avoid the formation of thermal bridges.

4.2 Lightweight Walls

There are two basic systems for timber frame passive house construction: the pillars and beams system, and the frame system. In either case, the empty spaces may be filled with mineral wool, sheep wool, linen, or thermal insulation of cellulose or wood flakes. Typically, passive houses have thicker exterior walls than conventional buildings. Thermally insulative materials are installed between the load bearing construction elements. On the outside of the walls, another layer of thermal insulation is added, serving simultaneously as a sublayer for the façade plaster. On the inside, before the vapour barrier, which simultaneously functions as an airtightness layer, the additional thermal insulation is added (Fig. 4.2).

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FIG. 4.2 Passive house wall element, from left to right: Timber-frame with I-joists and cellulose thermal insulation (system Lumar IG); Panel construction system with wood fibre thermal insulation (system Marles hiše Maribor); Panel construction system with mineral wool thermal insulation (system Marles hiše Maribor) *(Image by The Producers Lumar IG and Marles hiše Maribor, 2017. Reprinted with permission)*

4.3 Thermal Insulation

Thermal insulation is the most important element of a wall. Its thickness of 25 – 40 cm depends on both the building material used and the wall structure. Any existing thermal insulation materials may be used in passive houses. In massive construction, the fastening of thermal insulation is carried out by gluing, anchoring, nailing, screwing, or installing with cants. In lightweight construction, some types of thermal insulation, i.e. cellulose and wood flakes, sheep wool, and hemp may be blown into the space between load bearing elements. The fastening of softer types of thermal insulation requires a substructure.

Thermal insulations differ in price and in their ecological components. The passive house concept is, by itself, environmentally friendly. The choice of building materials should consider that they are ecological, produced with a minimum of embodied energy, and that they have no negative impact on humankind and the environment during their total life cycle, the latter spanning from production, installation, and use, to demolition.

4.4 Joinery

The passive house development pointed to the crucial importance of high quality windows in meeting the requirements of the standard. With this in mind, triple glazed windows ($U_g \leq 0.8$ W/(m^2•K)) with a heat transfer U_w at most 0.8 W/(m^2•K) and with an improved frame insulativity ($U_f \leq 0.8$ W/(m^2•K)) (Fig. 4.3) (Feist, 1998b) were developed. Notwithstanding large glazed surfaces, such windows drastically reduce heat losses while simultaneously offering high solar irradiation gains. This contributes positively to the building's energy balance as, in south oriented windows, heat gains exceed heat losses even between December and February, the coldest period in our geographic location, thus resulting in a positive energy balance.

4.5 Prevention of Thermal Bridges

Thermal bridges are locally restricted surfaces on building elements with increased heat flow. They occur on the building's outer envelope as a consequence of improper and deficient design and implementation.

A building may lose copious amounts of heat through improperly protected parts of its façade.

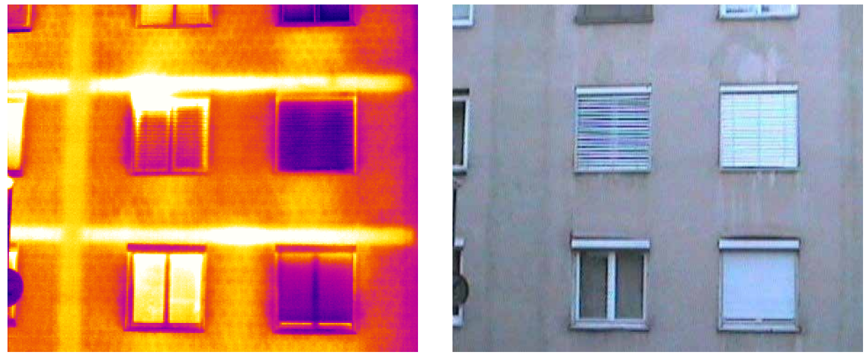


FIG. 4.3 Window frames fit for passive houses *(Source: Marles)*

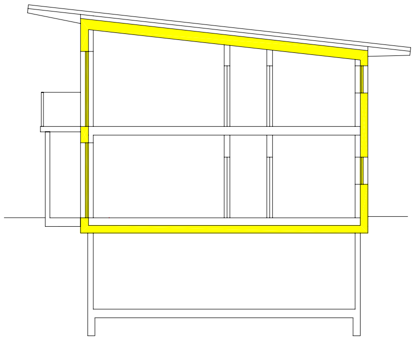
FIG. 4.4 A+B: Thermographic image of a façade – left in the infrared spectrum (7–15 mm) and right in the visible spectrum

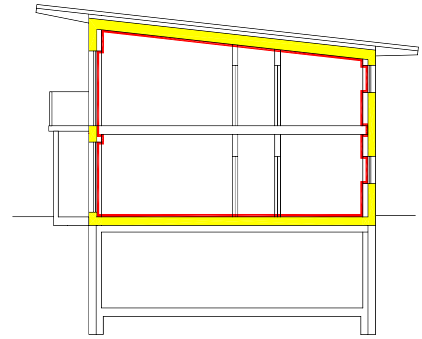
In passive houses, the so-called construction thermal bridges were found to be the most problematic (Feist, 2007). They occur at thermal envelope interruptions (Fig. 4.4). Mostly, they are caused by improperly designed details at openings, overhangs (braces, support beams), joints, ribs, and interrupted thermal insulation. Such mistakes should not happen in a passive house, as they are required to be thermal bridge free.

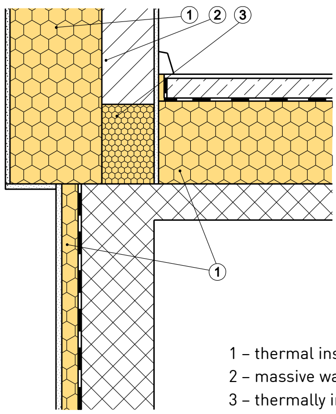
Any possible thermal bridge occurrences in a building should be checked using special two- and three-dimensional calculations. Generally, thermal bridges in a passive house must be avoided, or at least limited to the best of abilities, as even the heat losses from a small thermal bridge may seriously endanger the entire passive house concept. The basic principle of passive house construction is *thermal bridge free* implementation, following the basic rule that the thermally insulative layer must be designed as an uninterrupted envelope (Fig. 4.5).

In a building, thermal bridges occur at different locations: the building's thermal envelope may be interrupted on the plinth towards the foundation or the unheated basement, in the joining of the roof and exterior wall, on balconies and overhangs that are a part of the inner storey construction, or in the installation of windows and doors etc.

Thermal bridge free joints of constructional elements are achieved through carefully planned details, and careful construction (Fig. 4.8, Fig.4.9).







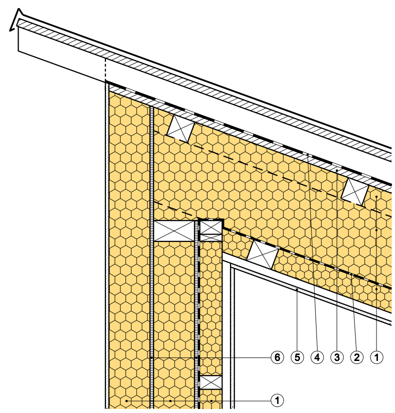


FIG. 4.5 (top left) A building's thermal envelope must not be interrupted (yellow line).

FIG. 4.6 (top middle) Properly fixed window installation into the outer exterior wall plane, and the sealing process

FIG. 4.7 (top right) The airtightness layer in a passive house must continuously encompass the building's heated volume (red line).

FIG. 4.8 (bottom left) Connection detail of the thermal envelope's wall with an unheated basement

FIG. 4.9 (bottom right) Connection detail of the roof construction with a lightweight wall

Special attention should be paid to the window installation. In constructions with massive walls, windows are point fixed into the thermal insulation layer on the exterior wall, and all openings between the wall and windows are carefully sealed. The thermal insulation material must cover as much of the frame as possible to increase thermal protection (Fig. 4.6). Windows installed without such a protective frame cover may result in a 70 % increase of a building's linear heat transfer. The passive house's goal is to reduce linear heat transfer Ψ below 0.01 W/(m•K).

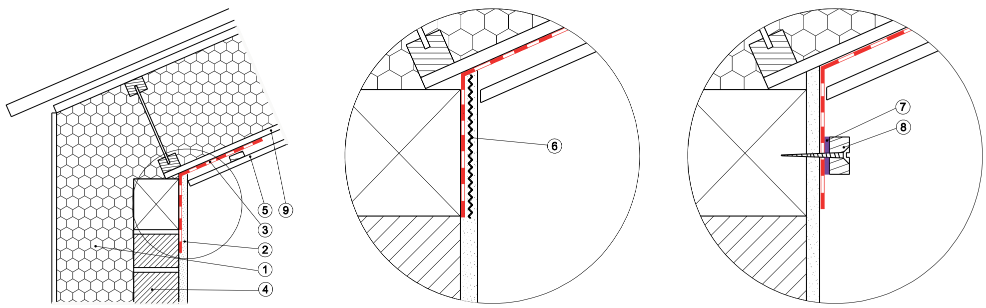
4.6 Airtightness

Airtightness refers to the intensity of the differential pressure-induced uncontrolled air flow through the building's construction, either into the building or out of the building. Uncontrolled air flow occurs through joints, cracks, or other leakages of the building's envelope.

A

B

C

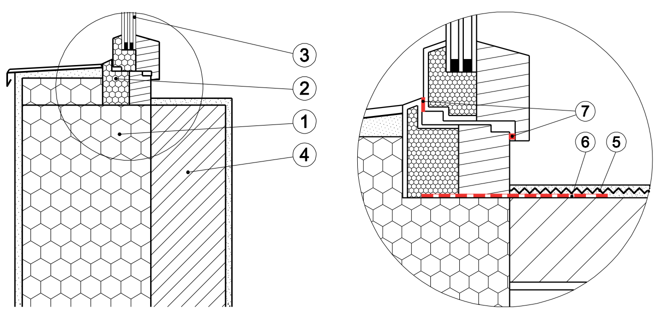


1 – thermal insulation
2 – plaster
3 – sealing tape
4 – masonry wall
5 – ceiling cladding
6 – plaster subsurface
7 – levelling strip
8 – screwed batten
9 – airtight board

FIG. 4.10 A+B+C: Measures to achieve airtightness

FIG. 4.11 Connection detail of a sloped roof and a masonry wall with plastered interior wall

FIG. 4.12 Airtight window installation into masonry wall



1 – thermal insulation
2 – insulative frame
3 – insulative glazing
4 – masonry wall
5 – plaster subsurface
6 – sealing tape

In order to achieve airtightness, all details of the joint datails of building elements must be carefully designed. The building's envelope airtightness, just as its thermal envelope, must be complete and continuous (Fig. 4.6).

Usually, the airtightness layer is located on the inside of the building's envelope and can be achieved using different materials. A massive masonry wall is airtight if the spaces between bricks are carefully filled and the inner plastering is executed continuously from the raw ground (before screed installation) up to the raw ceiling. In lightweight construction, vapour barriers may act as an airtight layer. Different foils or boards (OSB boards, plywood, DWD boards etc.) may be used, depending the producer's warranty. Special features in this respect are the joints between individual elements, where we must also ensure airtightness using different sealants, tapes, expansion tapes, sealing profiles etc. (Fig. 4.10).

The efficiency of the airtightness of the envelope is tested with the Blower Door Test. For passive houses, an upper limit value of $n_{50} \leq 0.6\ h^{-1}$ (Feist, 2005) is set.

Leakages may occur at joints, or seals, between individual elements of the airtightness layer (i.e. joints between foils or boards), at joints between individual elements (i.e. at joints of walls, at joints between the roof and walls, etc.) (Fig. 4.11), and at joinery installation (Fig. 4.12).

4.7 Ventilation

To reduce ventilation heat losses while simultaneously achieving optimal indoor air quality, a ventilation system with a minimum 75% efficient exhaust air heat recovery is mandatory for passive houses (Feist, 1997). This means that the warm exhaust air transfers its heat to the cold incoming air, thus additionally reducing ventilation heat losses. A bonus for allergy sufferers are filters that eliminate pollens and dust.

In passive houses, fresh air is taken from the building's environment through a safety mesh positioned either on the façade or on the roof, and transported through well-insulated ducts to the ventilation unit. Before entering the indoor space, dust particles are eliminated by filters. Fresh air is pre-warmed in the heat exchanger, with the warmth taken from the extract air as it is pumped out of the building. The pre-warmed fresh air leaves the heat exchanger through a duct system and flows into the so-called supply rooms (living room, dining room, bedrooms, and home office). Used air is extracted from wet and odorous spaces (kitchen, sanitary spaces, and possibly utility and auxiliary spaces) and transported through ducts to the ventilation unit. Here, it transfers its heat via the heat exchanger to the fresh intake air, to be extracted through well-insulated ducts into the environment (Fig. 4.13).

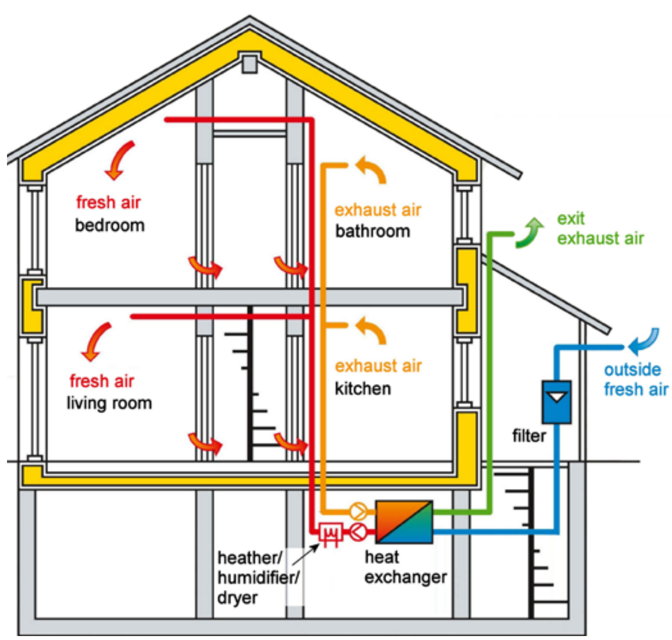


FIG. 4.13 Ventilation system performance in a passive house *(Source: Passive House Institut, in Zbašnik-Senegačnik, 2009, reprinted with permission)*

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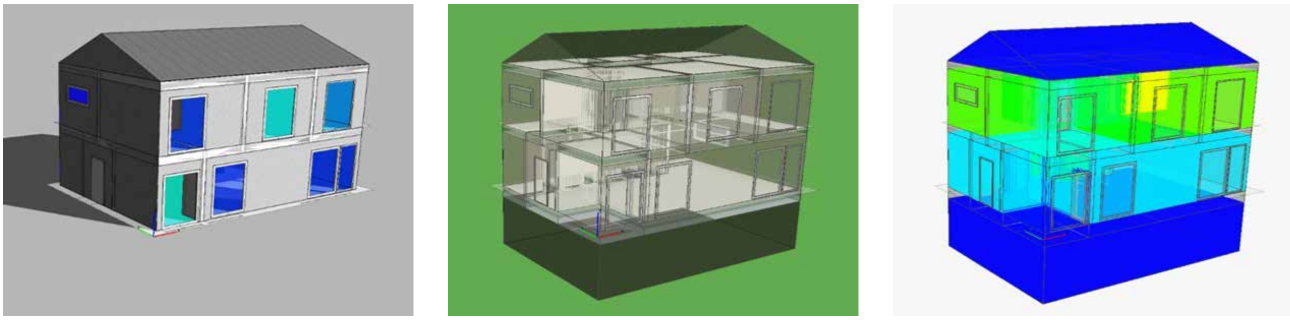
In modern ventilation units, heat exchangers may reach a very high efficiency, and almost completely recover the exhaust air heat (even above 90%). In this way, the greater part of the heat remains within the building while the indoor air is always fresh.

4.8 Heating

The reason for a passive house's minimal heat losses are a high quality and well-designed thermal envelope and a central ventilation system recovering the exhaust air heat. Heat demand, therefore, is low, and conventional heating systems are no longer required (Feist, 2009). Even at winter peaks, both transmission and ventilation specific heat losses can be less than 10 W/(m^2). For such low heat demand, warm-air heating is a suitable choice for space heating. Here, during winter, the air transported into the building is somewhat pre-warmed (Graf, 2000) by heat generators, heat pumps, or any other heat generators that may be used.

5 Comparison of Different Energy Efficiency Variations of Single-Family Houses

The decision to build an energy efficient house is based on certain criteria. Obviously, one of them is environmental concern. Energy efficient buildings are intrinsically environmentally friendly, as they reduce energy consumption in their operational stage. This, however, may be deceiving, as lower operational energy demand usually means higher embodied energy, that is, energy consumed in the production of building materials, energy used for the improvement of the building's thermal envelope, and energy used in the functioning of the equipment. Demand for space heating energy, therefore, cannot be the only criterion supporting the decision. Another high-ranking criterion is indoor living satisfaction – in a passive house, the air is always fresh and appropriately warm, and in winter, the surface temperature of walls and other elements is higher. Cost is another important factor in the form of initial investment in the construction stage, and in the form of rehabilitation cost in the operational stage. Even prestige may be a decision-making factor, although irrational and not easily quantifiable. The design of energy efficient houses considers a hierarchy of environmental, economic, and indoor living comfort indicators, which are, finally, unified into an assessment (Praznik & Zbašnik-Senegačnik, 2016).



A *B* *C*

FIG. 5.1 Presentation of the building's model (A), its energy interpretation (B), and graphic presentation of the result (C)

5.1 Presentation of the Single-Family House and its Energy Efficiency Variants

The valuation of five differing energy efficiency configurations is analysed on a two-storey single-family house model (shown in Fig. 5.1) with the following characteristics: conditioned surface A_u = 137 m^2, thermal envelope area A = 454 m^2, window's surface A_w = 30 m^2, shape factor f_o = 0.68 m^{-1}, average air exchange n_{50} = 0.4 h$^{-1.}$ The climate region has a temperature deficit HDD = 3200 K d a^{-1} (Ljubljana). The building is designed for four persons. The heat characteristics and heat transfer were calculated with a validated method based on methodology to international standards, and relevant to the respective building physics (Feist, 2015; SIST EN 13790, 2008).

Five configurations of the presented model, a timber frame single-family house (variants V1 through V5) were assessed, with different structures of the external envelope, space heating systems, and energy efficiency (from low energy to passive house):

Variant 1 (V1)
The building's heat demand is Q_{NH}/A_u = 50 kWh/(m^2•a); airtightness n_{50} = 1.0 h^{-1}; and mean thermal transmittance coefficient of the envelope U_m = 0.25 W/(m^2•K). Predominant in the thermal envelope is mineral wool, while window frames are PVC. The building uses natural ventilation. Due to higher space heating demand, an economically and environmentally more efficient system is chosen for heat generation – a pellet furnace with fitted solar panels for hot sanitary water preparation. The building uses radiators.

Variant 2 (V2)
This is a more energy efficient building design: Q_{NH}/A_u = 40 kWh/(m^2•a); airtightness n_{50} = 1,0 h^{-1}; mean thermal transmittance coefficient of the envelope U_m = 0.21 W/(m^2•K). Predominant in the thermal envelope is mineral wool, while window frames are PVC. The building uses natural ventilation. To maintain the investment value, a simple, yet, in the long term, both economically and environmentally less efficient heat generating system was chosen. The condensing gas furnace is fitted with solar panels for hot sanitary water preparation. The building uses radiators.

Variant 3 (V3)

This is a very low-energy house: Q_{NH}/A_u = 25 kWh/(m^2•a); airtightness n_{50} = 0.8 h^{-1}; mean thermal transmittance coefficient of the envelope U_m = 0.20 W/(m^2•K). Predominantly, the thermal envelope consists of mineral wool, and has wooden window frames. The building achieves higher energy efficiency using a central ventilation system with an 85% efficient exhaust air heat recovery. Heat for space heating and hot sanitary water preparation is generated with a heat pump that captures heat from a horizontal ground heat exchanger. Floor heating is installed for space heating.

Variant 4 (V4)

This variant is a passive house: Q_{NH}/A_u = 15 kWh/(m^2•a); airtightness n_{50} = 0.6 h^{-1}; mean thermal transmittance coefficient of the envelope U_m = 0.16 W/(m^2•K). In the building envelope, predominantly mineral wool is used, with wooden windows. The ventilation system achieves an even higher heat recovery (90%). Heat for space heating and hot sanitary water preparation is generated with a heat pump that captures heat from a horizontal ground heat exchanger. The space heating system is integrated into the ventilation system, thus reducing initial investment costs into HVAC.

Variant 5 (V5)

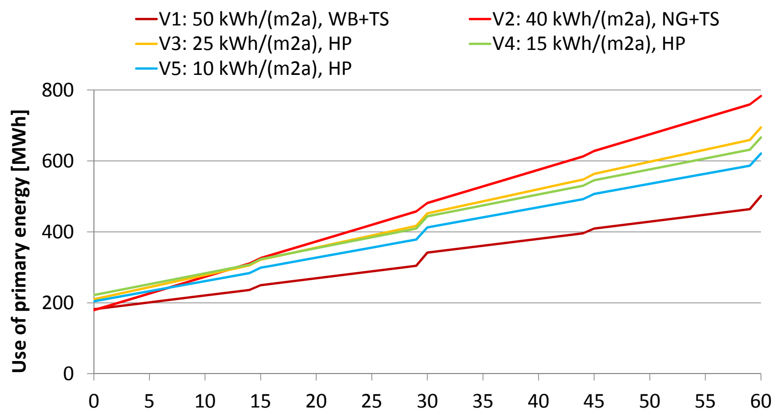
Variant 5 is built in the passive house standard with improvements in terms of energy efficiency and environmental friendliness, with the following values: Q_{NH}/A_u = 10 kWh/(m^2•a); improved mean thermal transmittance coefficient of the envelope U_m = 0.14 W/(m^2•K); airtightness n_{50} = 0.6 h^{-1}. To ensure higher values of environmental indicators, cellulose flakes were chosen for the envelope instead of mineral wool; windows are made of wood. The foundation slab is lined underneath with XPS.

For the comparison of above described building variants (V1 through V5), an operational cycle of 60 years is observed. This period consists of two 30-year cycles of building operation. After each cycle, some worn envelope elements require rehabilitation in the form of limited or small building repair. This 30 year cycled rehabilitation is estimated at 2% of the building's construction cost. In addition, a 15-year cycled rehabilitation period is observed for technical equipment for heat generation and space heating and ventilation. Solar panels, heat storage units for hot sanitary water and similar equipment require a 30-year cycle for replacement with new units.

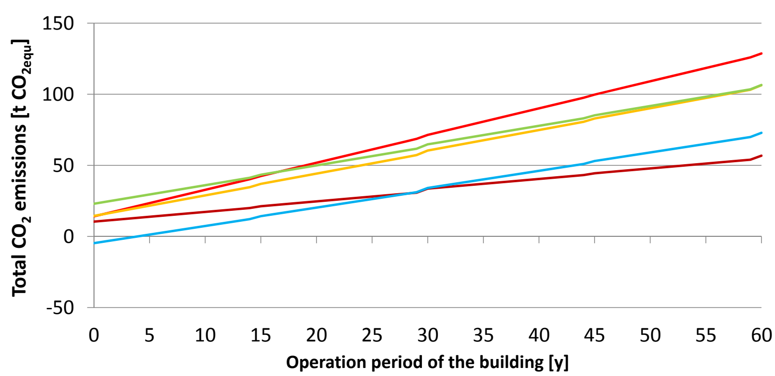
The compared variants V1 through V5 have differing investment costs and, consequently, different financial burdens at every 15 year rehabilitation cycle. Differences also occur with respect to embodied primary energy and CO_2 emissions. The investment costs for the construction stage rely on the prefabricated house producer's calculations, and are supplemented with the authors' estimates with respect to HVAC investment costs. The estimated values of indicators showing the use of primary energy and CO_2 emissions during the construction stage were acquired from publicly accessible databases (Baubook, 2017). The authors' estimates of rehabilitation costs follow the same guidelines.

Even with identical hot sanitary water demand, the buildings' conceptually differing energy efficiency (Q_{HN}/A_u) results in different annual heat demand in the operational stage. Annual energy costs and respective primary energy use, as well as CO_2 emissions, were assessed for all configured heat generation systems. The cumulative cost, primary energy, and CO_2 emissions for the 60-year period of operation and interim building and equipment maintenance costs are shown in Fig. 5.2.

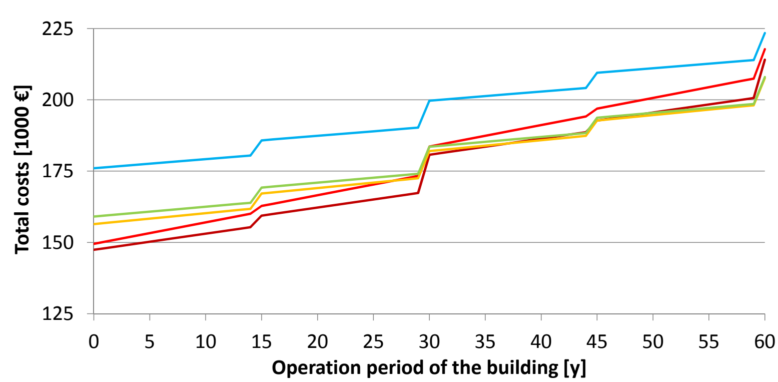
FIG. 5.2



Cumulative values of **energy indicators** of the building during its 60-year operation period



Cumulative values of **environmental indicators** of the building during its 60-year operation period



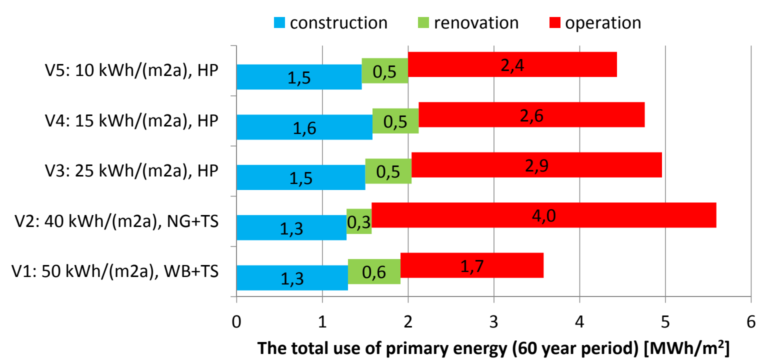
Cumulative values of **financial indicators** of the building during its 60-year operation period

The above diagram indicates why the five variants of new building configurations are a reasonable choice. V1 and V2 were chosen mostly to enable comparison between them, i.e. to show the impact of additional investment into small building envelope improvement, while simultaneously reducing the investment into heat generation systems. V3 and V4 indicate a comparison between very low-energy houses and passive houses, with possible optimisation of heat generator investment and additional investment into the building's envelope. V5 shows the impact of yet additional investment by installing natural building materials with a lesser environmental impact into a passive house.

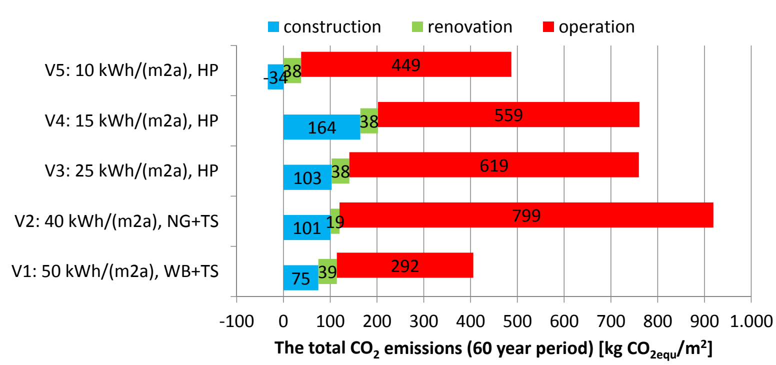
5.2 Valuation of Energy, Environment, and Economic Indicators in the Life Cycle of a Building

The result and findings of comparing all five building variants (V1 through V5) with respect to energy, environmental, and economic indicators are shown below (Fig. 5.3):

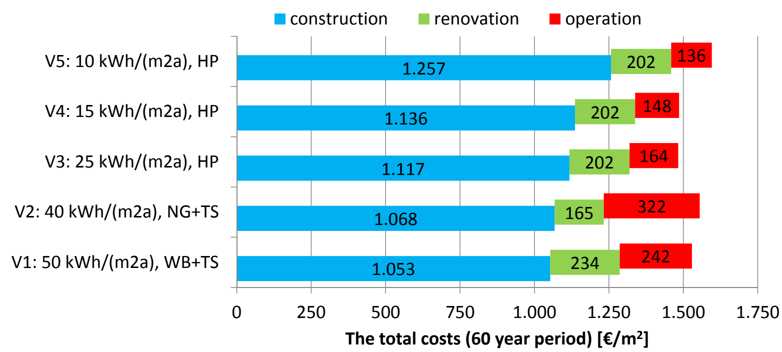
FIG. 5.3



Energy indicators of a building in 60 years of operation



Environment indicators of a building in 60 years of operation



Economic indicators of a building in 60 years of operation aption

– Irrespective of the extreme comparison divergence with regard to energy demand for space heating (Q_{HN}/A_u), the proportion of which, among the shown variants (V1 through V5), is a remarkable 1:5, the difference in the initial investment cost of a new building is relatively low. The difference in investment costs between V1 and V2 amounts to less than 2%. The difference in investment costs between V3 and V4, i.e. between building a very low-energy house and a passive house, also amounts to less than 2%. As shown, the difference in investment costs between the basic V1 and the very low-energy house V3 is 6%, and the investment cost difference between V1 and V4, which is a passive house, is 8%. The most energy efficient variant V5 requires a 19% increase of investment cost from the basic V1. As the investment cost difference between V4 and V5 amounts to approximately 11%, we may conclude that the better part of this differential is a consequence of choosing natural thermal insulation building materials, and not of energy efficiency improvement. Evidently, if accompanied with logical investment optimisation during the construction and installation stages, the leaps in energy efficiency have no meaningful impact on the height of investment cost.

– The rehabilitation investment cost, occurring four times in the observed period, amounts to approximately 15 – 20% of the initial investment cost. The rehabilitation costs are mostly dependent on measures connected with HVAC, as the service life of these components is much shorter than the service life of the building. The most costly rehabilitations of heat generating systems are a consequence of choosing technologies that result in less environmentally burdening indicators during their operation (V1).

– The cost of operational energy amounts to a 10 to 30% share of the initial investment cost. The highest share is attributed to the less energy efficient building, using a relatively lower cost demanding heat generation system (V2). In this case, the operational energy costs are double the rehabilitation costs. With an optimal combination of energy efficiency and heat generator systems cost, operational energy costs are lower than rehabilitation costs. We can conclude that in highly energy efficient buildings (V3 through V5), the majority

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share of the costs within the 60-year period is caused by »avoiding« costs related to energy consumption.

- Notwithstanding the different values and proportions of building, operation, and rehabilitation costs, the final sum total is nearly identical across all five described variants (V1 through V5). V2 differs from V1 by only 2%. The low-energy house and the passive house (V3 and V4, respectively) show an identical final result, 3% lower than the total cost of V1. V5 exceeds V1 by 4%. We may conclude that, irrespective of energy efficiency and heat generation system, the total cost is similar, as the group shows a deviation of less than 5% from the average value. This conclusion, consequently, indirectly confirms the fact that priority in modern building design should be given to the reduction of the buildings' impact on energy consumption and environment. With similar total cost, we should strive for the best values of the buildings' environmental and energy indicators.

- As the economic indicator was predominantly influenced by the initial investment cost, we may conclude that all consequent energy and environment indicators are predominantly influenced by the operational stage and its respective energy consumption.

- In terms of embodied primary energy, the demand of the more energy efficient buildings (V3 through V5) exceeds the basic V1 by 15 to 20%. In the rehabilitation stage, the embodied primary energy demand amounts to an average of one third of the initial investment cost. Relatively lower rehabilitation impacts are typical for solutions with simpler HVAC systems. Due to an appropriately chosen heat generation system, larger proportions of embodied primary energy in the rehabilitation stage result in decidedly lower annual operational primary energy consumption, thus leading to a favourable end result.

- With a complex heat generation system (V1), rehabilitation requires more embodied primary energy. The investment cost sum total in V1, however, is the lowest in the group due to lower primary energy consumption in the operational stage, irrespective of the fact that the building was designed with the lowest energy efficiency. In V2, the sum of primary energy consumption in 60 years is the highest in the group and is larger than the result for V1 by 50 %. In more energy efficient buildings, the primary energy consumption in the operational stage is decreasing, while still exceeding the sum of primary energy consumption in both initial and rehabilitation inputs.

- With regard to these results, it can be concluded that the balance between a building's energy efficiency and its heat generation systems is a key factor in the design of an energy efficient new building. On the contrary, with respect to primary energy consumption, a less energy efficient building- can be optimised by introducing more environmentally acceptable heat generation systems.

- The importance of an appropriate choice of building technology is also clearly shown from the viewpoint of primary energy use. While increasing the thermally protective envelope in a building, eventual additional inputs of primary energy can be reduced by choosing different building materials, both for construction and thermal protection. This is clearly shown in variant V5, where, if compared to the previous variant V4, no primary energy increase in the construction stage was noted. On the contrary, there was a 10% reduction.

- The CO_2 emission environmental indicator shows a continuation of the trend noted in primary energy examination. Its values, however, strongly reflect the impact of energy consumption and transformation in the operational stage. Between 75% and 85% of total CO_2 emissions occur in the operational stage. A larger share of the latter is expected to stem from the environmentally more burdensome heat generation systems. The smaller proportion reflects the use of more CO_2 neutral heat generation systems.

- The construction stage is also important in terms of energy consumption. Increasing a building's energy efficiency may result in the reduction of the environmental indicator value, if, where appropriate, CO_2 neutral systems of construction and heat protection are used. A clear example thereof is, again, the result for V5 in comparison with V4. In all solutions, the rehabilitation stage accounts for 20% to 50% of all CO_2 emissions as compared to the indicators' value in the buildings' construction stage.

5.3 Buildings' Valuation Using Five Key Indicators

The design, i.e. configuration, of a building affects its energy efficiency, primary energy consumption, the amount of CO_2 emissions, the cost, and the level of indoor living comfort. For their assessment, five key indicators were used:

- the Q_{NH}/A_u indicator (annual heat demand for space heating): the lower its value, the higher the building's energy efficiency

- the $PEC_{n.r.}$ indicator (amount of non-renewable primary energy used per unit area of the structural component and operation): a lower $PEC_{n.r.}$ value shows lower environmental impact

- the GWP_{100} indicator (CO_2 emissions during the production of building materials and heat generation for the building's operation): a lower GWP_{100} value denotes higher environmental efficiency

- the *Cost* indicator (costs of construction and costs of energents for heat generation in the operational stage of the building): lower costs imply higher economic efficiency

- the *LE* indicator (living environment): better indoor living conditions reflect a proper building's design with respect to the inhabitant's requirements
  The assessment is based on the respective indicator values, the latter having been acquired both objectively and subjectively.

The Q_{NH}/A_u indicator
This indicator's value was assigned by calculating the building's energy balance using conventional methods (Feist, 2015; SIST EN 13790). A quick approximation of this value is also possible with the following equation (Eq. 5.1) (Praznik, Butala, & Zbašnik-Senegačnik, 2013):

$$Q_{NH}/A_u \approx (78{,}3\times H'_T\times f_d + 64{,}2\times n_v) - \eta_G\times\left(4{,}9\times q_i/A_u + 78{,}7\times ASF/A_u - 2{,}3\right)$$

Included is a smaller number of parameters, which affect the building's energy balance: its shape and intended use, thermal envelope characteristics, and the type of ventilation.

Indicators $PEC_{n.r.}$, GWP_{100} and *Cost*
Both $PEC_{n.r.}$ and GWP_{100} are connected with materials and components installed in the building. Data for primary energy consumption and CO_2 emissions are at the designer's disposal in publicly accessible databases (i.e. Baubook, 2017). The investment cost data for building materials and HVAC machinery are available from sellers. The operation stage is limited to 60 years. The consumption of primary energy, the CO_2 emissions, and the energy costs are calculated using the estimated electricity of fuels for heat generation (Gustavsson & Joelsson, 2010). Also assessed are the rehabilitation costs for the building envelope and heating and ventilation machinery within the 60-year period, as are, consequently, the primary energy, CO_2 emissions, and cost demand.

Indicator *LE*
This indicator's value is assessed with respect to three areas affecting living comfort:

- thermal comfort is a consequence of the building's thermal envelope. A value of 0% is assigned to thermal envelopes of the highest energy efficiency, and 35% to the envelope with the lowest thermal protection and with temperature asymmetries;

- thermal comfort as a consequence of the heating system operation: 0% is assigned to the system with minimal negative impact on living comfort, and 35% to the system which only essentially fulfils its operation requirements;

- providing air quality with the ventilation system: a 0% value is assigned to the ventilation system with minimal negative impact, and 30% to systems with barely acceptable impact on living comfort.

TOC

The complex valuation of different design variants may be achieved in three different ways (Fig. 5.4):

- objective weighting of indicators – in the overall estimate, all indicators are assigned equal weights;
- weighting according to state criteria – both Q_{NH}/A_u and GWP_{100} are assigned double weights;
- weighting according to the user's criteria – both *Cost* and *LE* indicators are assigned double weights.

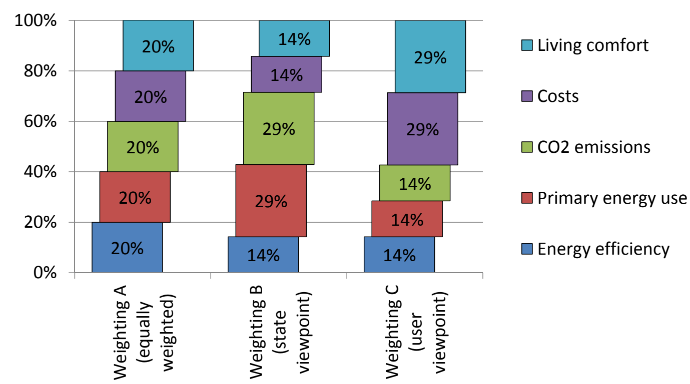


FIG. 5.4 Five key indicators with differently assigned weights – assignation of equal weights and assignation of weighting for both the state and the user point of view

5.4 Valuation of Buildings with the Five Indicators Method

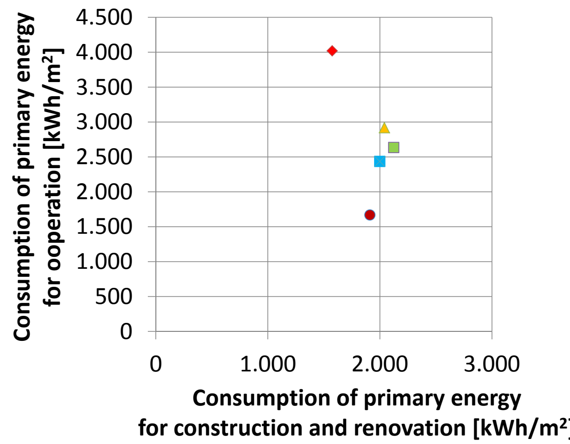
The five building variants with differing energy efficiency (V1 through V5) were evaluated using the five indicators method.

In Fig. 5.5, the data used for value assignment to $PEC_{n.r.}$, GWP_{100} and cost indicators (Fig. 5.3) is shown from the initial cost, rehabilitation cost, and cost of operation point of view.

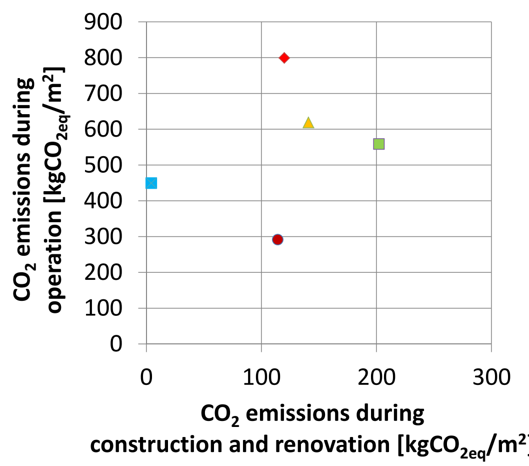
All five indicators are assigned values for every variant V1 through V5. The highest value of 100% for indicators Q_{NH}/A_u, $PEC_{n.r.}$, GWP_{100}, and *Cost* is assigned to the variant with the best cumulative result. The indicator values for other variants are proportionally reduced according to the deviation of their result from the maximum result reached in the comparison group of variants V1 through V5. The *LE* indicator (living environment) is assigned values with regard to three estimated areas. For negative impact on indoor living comfort as a consequence of the building's thermal envelope, values between 0% and 35% are assigned (i.e. 0% should be assigned to the variant with the best performing thermal envelope and 35% to the variant with the barely acceptable thermal protection). Similarly, the negative impacts of the heating system on the temperature comfort are estimated. The third part of the estimation reflects the negative impact of ventilation and the resulting effect of the indoor air quality on the indoor living comfort (a value of 0% is assigned for ventilation with the least impact and 30% for ventilation with acceptable living comfort impact). All assigned indicator values for all variants (V1 through V5) are shown in Fig. 5.6.

FIG. 5.5 Values of primary energy use (A), CO2 emissions (B) and costs (C) for all five variants V1 through V5 in a 60 years period

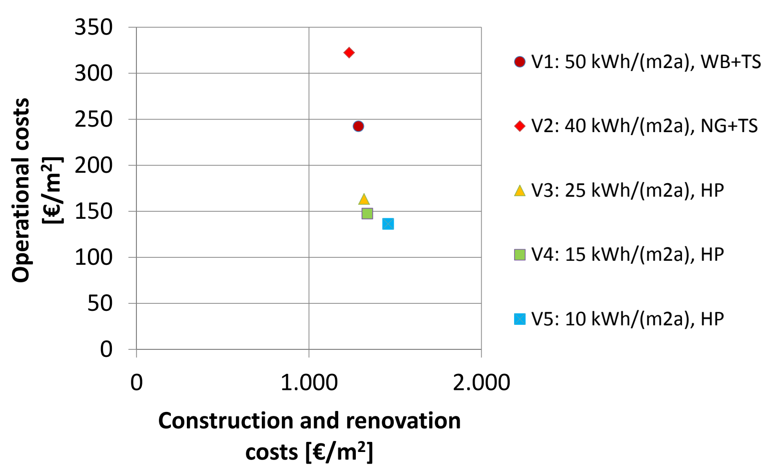
A



B



C



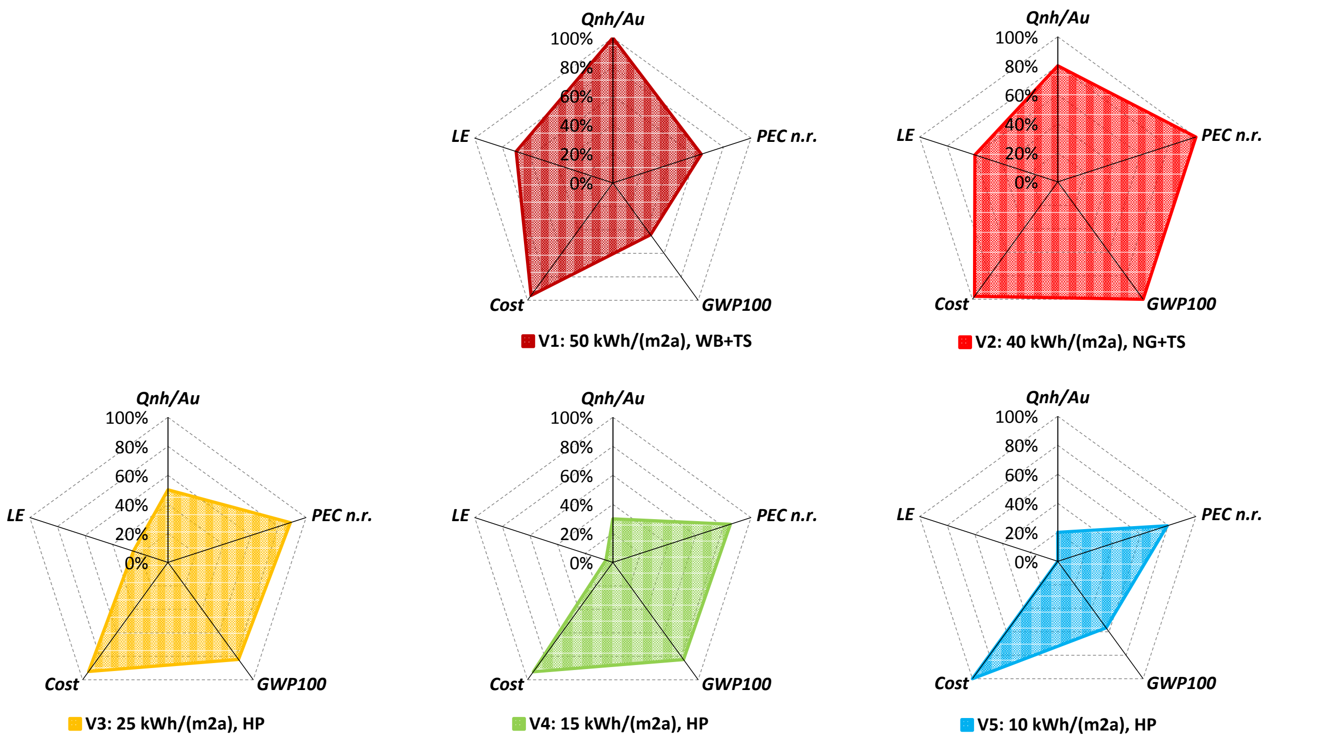


FIG. 5.6 Values of five key indicators for the five variants of building design

The complex valuation is executed using three methods as shown in Fig. 5.7 the objective weighting, and with weight assignment according to the state or users' point of view. The results confirm our premise that an appropriately optimised new building design concept, shown here with the two passive house variants (V4 and V5), achieves the best, i.e. minimal, total assessment score, valid for the objective as well as for both subjective assessment methods. In variant V5, the results vary between 58% and 61%, and in variant V4 between 66% and 73 %. The complex valuation of the design concept for a very low-energy building (variant V3) comes in third place with regard to all three assessment methods, with an estimate between 77% and 80%. The worst complex valuation result of 100% was reached by the less energy efficient design concept (variant V2), where heat is predominantly generated using fossil fuel. This result is shared over all three-weight assignment methods. Also confirmed by the complex valuation is the fact that even the least energy efficient concept of a new building (variant V1) may be improved with appropriately corrected heat generation, based solely on using renewable sources of energy. After the implementation of such measures, variant V1 was reassessed and achieved a result between 76% and 93%.

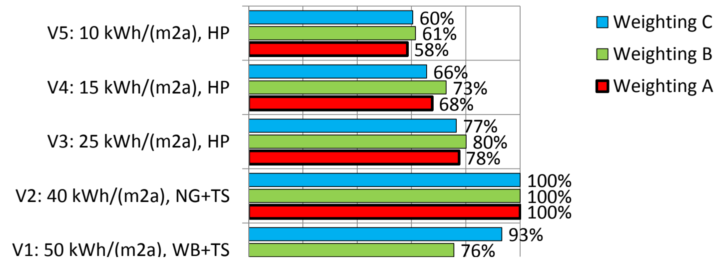


FIG. 5.7 Comparison of the indicator valuation for variants of a new building using differing weight assignment

6 Conclusions

In recent years, increasing attention has been paid to the energy efficiency of buildings. The legislation prescribes a maximum permitted energy use for heating, and in most EU countries, the heating demand is below 50 kWh/(m^2•a). With further improvements to the building envelope and the installation of ventilation system, the energy consumption is reduced accordingly until the passive house standard is achieved, with energy consumption up to 15 kWh/(m^2•a). Improvements and optimisation of passive houses allow the energy consumption to drop even below 10 kWh/(m^2•a). By increasing the energy efficiency of buildings, the living comfort is improved and the space heating demand is reduced but, as a consequence, the negative impacts on the environment and the cost of construction, or investment amount, are increased.

Selecting the energy class of the planned house is a multi-faceted decision and is based on various criteria. Five variants of energy efficient buildings have been displayed using a single-family house model. The variants with the following energy consumption values for heating have been evaluated: V1 up to 50 kWh/(m^2•a), V2 up to 40 kWh/(m^2•a), V3 up to 25 kWh/(m^2•a), the passive house variant V4 up to 15 kWh/(m^2•a), and the improved passive house V5 up to 10 kWh/(m^2•a). The evaluation with the energy efficiency (Q_{NH}/A_u), primary energy consumption ($PEC_{n.r.}$), CO_2 emissions (GWP_{100}), cost (*Cost*), and living environment (*LE*) indicators was carried out.

The evaluation was performed according to three methods of weighting, depending on the perspective of the evaluator. In objective weighting, all five indicators are equally weighted. From the national perspective, the Q_{NH}/A_u and GWP_{100} indicators have double weight, and from the perspective of the users of the building, the *Cost* and *LE* indicators are given double the weight. The results confirm the assumption that the properly optimised concept of the most energy-efficient new building, represented by the two passive house variants V4 and V5, whose energy consumption for heating is up to 15 kWh/(m^2•a) or up to 10 kWh/(m^2•a), respectively, would obtain the best evaluation results under all three weighting methods.

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Methods for Design of Static Solar Shading Devices

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ABSTRACT **The existing condition of energy and environment requires that contemporary architecture pays particular attention to the exact parameters of energy optimisation, persistence, and sustainability of buildings and the built environment. One basic premise of sustainable development in architecture is the fulfilment of the requirement for luminous ambience – visual comfort in internal space, along with the optimisation of energy requirements. It is highlighted that it is important to integrate daylighting studies in the early design phases. Analyses and research have proved a connection between daily illuminance and heat losses/gains by emphasising the significance of the use of shading devices in the reduction of electrical energy consumption. In this way, the building envelope becomes unique and adaptable to climate, since it unifies and combines a myriad of specific patterns and methods of the location itself.**

This work tackles the significance of the usage of daily illuminance in office buildings in Podgorica (capital of Montenegro) and daylight performance, in relation to an overview of the existing norms in this field. The second part of the paper will present basic formal typologies of external static shading devices and distribution of daily luminance and their use in office buildings, through the use of different software tools for the design and modelling of buildings. Conclusions are provided either as guidelines for the design of new projects, as general parameters, or as a verified method of adjustment of existing office buildings. The use of software has verified the respective research via simulations.

KEYWORDS daily illuminance; daylighting methods; shading devices; visual optimisation; energy optimisation

1 Introduction

Daylighting is a visible part of the spectrum of solar radiation, which, after entering the Earth's atmosphere, passes through a series of transformations. There are three essential characteristics of daylight from which the basic influencing factors of daylight are defined: radiation spectrum, variability throughout the day, and light distribution within the atmosphere resulting from the distribution of brightness of the sky. Daylighting varies over time in terms of its intensity, brightness distribution, and light spectrum.

Daylighting factors are divided into two categories, quantitative: conditions of *macro location* (geographical position on Earth, position of the Earth in relation to the Sun during the day and the year, the current sky condition - cloud cover, slope of the terrain, surrounding objects, vegetation, etc.) and *local parameters* (micro location: building orientation, building morphology - layout of the volume of the building itself, geometry of the façade and interior space, size and arrangement of openings, morphology inside the building - materials from which transparent and non-transparent surfaces of the interior and façade are made) (Mudri, 1997), as well as a set of qualitative *parameters* (comfort, pleasantness, dynamics of light, games of light, and shadows, etc.). These parameters are important for the formation of the light ambience of a given space. From the analysis of the listed factors that influence the distribution of natural light and its distribution in the interior of a spatial volume, the conclusion has been made that the assessment of the light ambience is a complex task that is subject to further analysis. By using static shading devices, the aim is to undermine the light and heat comfort and the pleasantness of particular spaces.

The characteristics of natural light in any space can be divided into two other categories: static and dynamic (Veličković, Lenard, Mudri, 2011). *Static characteristics* represent the light ambience of a space at a precisely determined time during the day and the year, for precisely defined weather conditions. *Dynamic performance* describes the light ambience as a variable category that is conditioned: by time, i.e. weather conditions during the year. Before the emergence of computer tools, static characteristics were the only measure of the quality of light ambience, and their estimate was defined using formulas, tables, empirical formulas, and other similar methods. Today, computer tools enable the accurate calculation of the distribution of light in a designed space within a short period of time, based on climate characteristic data of a particular location on Earth. Dynamic characteristics more faithfully show the illumination of a space because they take into account the variability of daylight over time.

Some of the reasons for previous complications relating to the integration of daylight in buildings are outlined in the Report of IEA SHC Task 21 (2000) as well as: lack of data on the benefits of using daylight; lack of methods and computer tools that enable the design of shading design and daylight calculation; unfamiliarity with the strategies for controlling and manipulating daylight into the depth of the room; outdated data or lack of data on the climate characteristics of a particular location.

When analysing the significance of natural light, the risk of discomfort should not be forgotten, such as, for example, glare, unwanted reflections of sunlight, overheating of space, rapid changes in the intensity of light, among others. The instability of the state of natural light (flux) during the day makes its changeability very frequent. Another problem is the decrease in intensity of natural light along with the depth of the room, i.e. moving away from glazed surfaces, which is solved in practice by the introduction of artificial lighting.

A lighting simulation tool provides to architects a range of technical solutions that are applicable in the process of design and planning, providing huge aesthetic potentials. The understanding of the phenomenon of "façade aesthetics" in relation to climate parameters may lead architects and urbanists towards a better contextualisation of the building envelope and built environment, and thus improve visual and energy aspects by correct dimensioning and the optimum disposition of transparent surfaces, as well as by understanding basic terms, functionalities, and technological implementations and optimisations of shading devices. The genesis of such knowledge and skills may become a new idea, manner of work, valorisation of the existing, conceptual experimenting with new materials and technological achievements, in order to achieve a contextualisation of new architecture.

1.1 Local Aspects and Standards

Energy consumption in office buildings represents a significant share of the total electricity consumption. According to the IEA (World Energy Outlook, 2008), buildings are "responsible" for spending about 40% of total energy and 36% of CO_2 emissions in Europe. 25 - 40% of the energy expenditure of buildings is from artificial lighting. Therefore, improving the energy performance of buildings would contribute to significant energy savings, one of the main elements for achieving the climate and energy goal of the European Union by 2020, which plans to reduce gas emissions and save energy by 20% (European Commission Strategies 2010-2020). Over the past decades, daylighting methods have been recognised as a new potential for reducing energy consumption. The objective of the European Commission is to give guidelines for the better utilisation of daylighting in buildings with the aim of reducing electricity consumption. As an alternative to artificial lighting, natural light is the source of light most suited to the human eyes and makes the working environment most pleasant (Webb, 2006).

Unlike thermal performance, which represents binding requirements in the design and adaptation of objects, standards and recommendations related to the quality of interior lighting are only superficially mentioned. Only in the latter half of the 20^{th} century have the basic recommendations related to the quality of interior illumination been given. They recommend that the illumination of workspaces should be "adequate and sufficient" with the note that lighting should be natural, if feasible (The Workplace Regulations, 1992). The basic objectives of calculating the daylight in architecture are designed so that the function of the space is provided with a sufficient level of daylight, and that the proper dimensioning and optimum disposition of the light surfaces, i.e., openings are undertaken.

The U.S. Green Building Council defines a system of grading new and renovated buildings according to LEED™ standards. The LEED certificate recognises the criterion for improving the quality of lighting as a way to save electricity by which points are given: if a minimum DF (daylight factor) of 2% is achieved in at least 75% of the total office space intended for visually demanding tasks. One point is given if it is possible to achieve a view of the environment through a window from 90% of the total useful floor are of the building.

In France, the state institute Certivéa (n.d.) defines the characteristics that must be fulfilled in order for a building to achieve a HQE (High Quality Environment) mark. Depending on available daylighting level inside the offices, a building can get evaluation degrees from basic, to advanced, to highly advanced.

European Union countries prescribe recommendations and certificates for the construction of sustainable, green buildings, in accordance with the Directive (2002/91/EC), dated 19 May 2010 (EUR-lex, n.d.). Currently, there are more than 50 European standards relating to shading devices, and it should be noted that the documents are constantly being updated.

SRPS.C.9 100			**DIN 5035**	**BEL.ST.IES**	**IES CODE**
Serbian			German	American	British
illumination (lx)		daylighting factor (%)	illumination (lx)	illumination (lx)	illumination (lx)
Very low	30 - 50	0.55 - 0.90	60 – 120	300	100
Low	50 - 80	0.90 – 1.50	120 – 260	500	200
Middle	80 – 150	1.50 – 2.70			400
Large	150 – 300	2.70 – 5.50	250 – 500	1000	600
Very large	**300 – 600**	**5.50 – 11.0**	600 - 1000	2000	900 – 1300
Extremely large	over 600	over 11.0			1300 – 2000
Special					2000 - 3000

TABLE 1.1 Comparative analyses of the defined standard requirements for illumination

According to local regulations, pursuant to Article 17 of the Law on Energy Efficiency (Official Gazette of Montenegro, no. 29/10), the Ministry of Economy has adopted the "Instructions on Energy Efficiency Measures and Guidelines for their Implementation". The provision of Article 2 of the Law stipulates the obligation to increase energy efficiency and the use of renewable energy sources through investments in "buildings (building cover, systems of heating, cooling and ventilation, interior lighting systems, domestic hot water supply systems, reduction of energy requirements through the introduction of bioclimatic principles, etc.)". The law also envisages investments that will increase the energy efficiency of the building cover with energy efficiency measures for new objects, according to which it is recommended that "buildings should be designed based on bioclimatic principles (orientation, natural light, natural ventilation for night cooling, passive bioclimatic solar systems)" (Official Gazette of Montenegro, no. 29/10).

2 Interior Luminous Ambience Qualities

High quality daylighting is created through a process of analysis and adequate design, in order to satisfy the required level of comfort, with the aim of increasing productivity at work. Adequate lighting is a relative term because the amount of daylight that is optimal for one type of work may not be adequate for another one. When calculating daylight, it should not be forgotten that spaces intended for different purposes require an appropriate distribution and quality of daylight, and that users of a certain space may perceive the comfort of its ambient light differently.

The term illumination is most often used when considering daylight and has an instantaneously changing value, because it changes from one second to another. Illumination is defined as an indicator of the light intensity that falls on a certain surface and equals the density of the light flux per unit area (E=Ø/S). Daylight factor (DF) represents the relationship between the illumination of a specific point in the interior of the room and the horizontal illumination outside a given object, for the distribution of brightness of the sky corresponding to the standard CIE cloudy sky. It is expressed in percentages (%). It represents the minimum available natural light, because it is counted in the case of the cloudy sky. Recommended minimum values for DF: from 2% to 5% in the least illuminated zones (Rakočević, 1989).

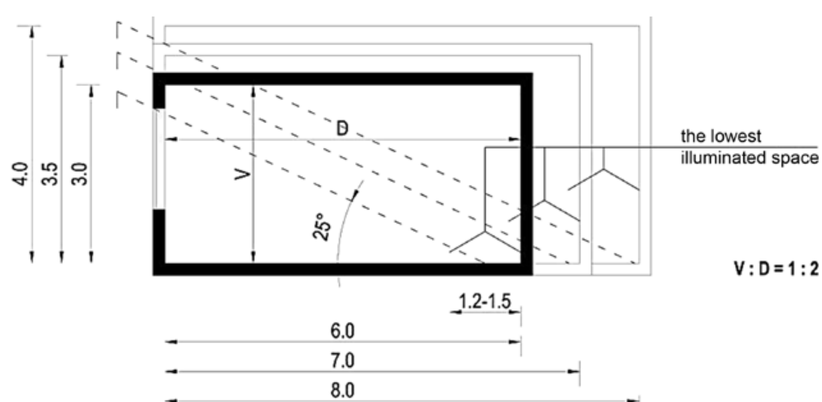

FIG. 2.1 Proportional relationship between the height of the opening and the depth of the office

The basic parameters of the interior that influence the quality of the ambient light are room geometry, index of the room, and internal reflection.

The geometry of the room defines the relationship of the shape, size, and room geometry, respectively the position of the opening concerning the height of the office. The depth of daylight intensity will depend on the orientation, height of the ceiling, and its relationship to the upper edge of the window (Fig.2.1).

The index of the room (i) depends on the height of the room *(Hp)*, the width of the room *(S)*, the length *(L)*, and the height of the working plane at 0.85 meters from the floor height. The index of the room is determined using the empirical pattern: *i=2S+L/6Hv*. The index of the room combines the influence of dimensions of the room and working plane. It represents a part of the light flux that enters the window and the part that falls on the work surface. The degree of utilisation () of the overall lighting depends on the coefficient of reflection of the walls and ceiling and index of the room. It is used to determine the coefficient of attenuation and the degree of use of daylight (Rakočević, 1989).

The reflection factor is indicated in percentages and depends on the colour, the brightness of the material, and the surface of the floor. The largest determining factor in the reflection of natural light is the surface of a ceiling, from which light is reflected and then dropped to the working surface (Rakočević, 1989). The wall that is opposite the opening (the rear wall) also has an important role, followed in importance by the side walls and, finally, the floor surface. The Illuminating Engineering Society (IES) recommends that ceilings need to be finished with a reflection rate greater than 80%, walls 50-70%, floors 20-40%, and furniture only 25-45% (the matt finish of the furniture is recommended in order to achieve good distribution of daylight and the reduction of glare) (O'Connor, Lee, Rubinstein, Selkowitz, 1998).

2.1 External Shading Devices as a Bioclimatic Response to Local Climatic Characteristics

The theme of "utilisation of the Sun" is not new, and has roots in the distant past. In fact, dating back to 2800 BC, solar orientation was one of the basic principles of Egyptian temples. Socrates, in 400 BC, reviewed the solar principles of a house called "Megaron House". This ancient principle, and the research of North African and Arab vernacular architecture, helped architect *Le Corbusier* to build a "pact with nature" and develop *"brise-soleil"* systems (Mohammad, 2013). He introduced ancient principles into a scientific framework, analysing specific climate and geographical parameters by identifying architectural problems associated with tropical climates and seeking an adequate solution. The parameters were divided into three categories: the first took into account natural factors (temperature, humidity etc.), the second was related to factors necessary for achieving comfort in the interior, and thirdly were architectural solutions, i.e. elements that would help achieve inner comfort.

Over the past 60 years, the building envelope, especially of administrative buildings, has been resolved by large glass surfaces (curtain wall).

This complex technological façade system is often used completely uncritically, without any concern for the real needs of the users or for achieving the desired level of visual and thermal comfort.

As early as the 1960s, the World Environment Agenda was evaluated. The reconsideration of the use of natural resources and energy in buildings accelerated the economic crisis of the 1970s. Only at the end of the 20th century, the moral responsibility of such facilities, in relation to the environment, encouraged discussions on the problem of the use of fully glazed façades that are completely opposed to concepts such as beauty, place, ethics, and aesthetics.

From the aspect of thermal comfort, external shading devices are much more effective in blocking the Sun's radiation compared to internal shading systems. Radiation, once introduced to the interior, can hardly be excluded from it. Overhangs are designed as a basic element of façade. Overhangs are designed to represent an integral part of the architectural expression, and do not rely on the secondary elements of the control of daylight distribution. Secondary elements are subsequently applied daylighting systems that can be of the most diverse constructional, material, and design characteristics.

3 Methods of Designing External Static Shading Devices

On the basis of the analysis outlined earlier in this chapter, the possible solutions and proposals of bioclimatic interventions on the façade are considered for the purposes of adapting existing buildings and providing guidelines for the design of new ones, in the territory of Podgorica and beyond. The proposed interventions relate to both the administrative building in its entirety and to the work unit as a characteristic unit of the case study. Interventions are the answer to the observed problems of the existing facilities and they were made with the aim of improving their energy state, in terms of both thermal and visual comfort.

By solving identified problems, models were considered, which can provide a means to a higher standard in terms of comfort. The analysis will be carried out on the use of external static shading devices in the design of façades, using the example of a residential business building UNISTAN - Tower C in Podgorica.

Using the software tools that enable the impact analysis and precise dimensioning and design of external static shading devices, the results of the calculation of various characteristics of natural light are provided, i.e. its visual components - daylighting, their impact on the reduction of electrical energy consumption, the impact of implemented shading devices on the ability to achieve views of the environment, as well as the impact of adjacent objects (built environment) on the observed building (office).

3.1 Computer Simulation as a Tool for Designing of External Shading Devices

Prior to the emergence of software tools, the calculation of illumination was done by mathematical geometric methods of calculating the spatial angle, daily factor, methods of fictitious openings, and so on. This method of calculation required a number of measuring instruments and input data, which were most often not available. Calculations were performed only for premises with a depth exceeding 5 metres, because it assumed that workspaces at such a great distance from the window were too compromised to meet the requirements for the required level of illumination, while it was assumed that if a workspace is within 5 meters of a window it is adequately illuminated. However, it has been shown that this assumption is not always correct. Therefore, the calculation of natural lighting should be done in parallel with the production of other project documentation, because it directly conditions the brightness, height of the room and the size of the opening, the correct fenestration, the orientation of the rooms in relation to the type of work and the required level of daylight, and other parameters of visual and thermal comfort.

Computer tools make it possible, within a short period of time, to calculate the distribution of light in the designed space for a period of one year, based on the climatic characteristics of a particular location on Earth. Models can be directly used in daylight analysis, using Building Information Modelling (BIM), a comprehensive design process that starts with the concept design and ends with the detail project documentation.

This paper has used models for analysis of the daylight factor (DF), which were simulated using computer tools. These simulations indicate how much natural light is available in the interior, and in practice are often used as a *measure of the quality of the natural lighting of the space*. The first data needed for the simulation is *Weather data* from the *Meteonorm27* database, in TMY2 format, which was updated only for Podgorica. Climate data is obtained from local weather stations and generate all the necessary data related to a particular climate area. By introducing local climatic characteristics, the precise simulation of solar radiation, based on latitude and longitude, will be enabled by the precise entering of the date and time for which the calculation is performed. In further work, two software packages from Autodesk were used for energy calculations: *AutoCAD 2011* and *Autodesk Ecotect Analysis 2011* - for Visual and *Energy Plus* with *Open Studio*. Shading models were performed by modelling within the *CAD platform* and then in the .dxf format introduced into the simulation program. The EcoTect program tool is not the standard program that architects use and by retrieving the data from the *Meteonorm27* database we have come up with data that defines the period of the year for which it is necessary to determine the requirement for shading devices (Fig.3.1).

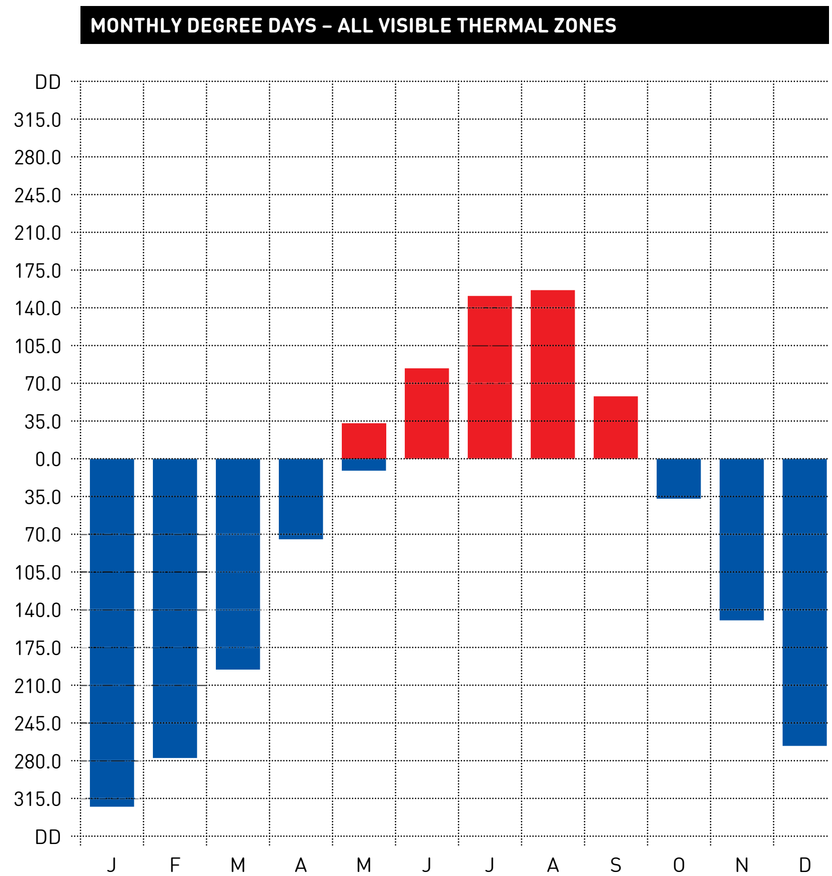

FIG. 3.1 Thermal zones for Podgorica by months in relation to the heating and cooling season

BLUE: for air temperature below 20°C, a heating set point is activated.
RED: for air temperature above 24°C cooling set point is activated. The graph shows that for the period from May 9 to September 21 it is necessary to anticipate shading devices that would prevent the decline of high solar radiation and reduce overheating

By analysing the graph, it is concluded that, for buildings in Podgorica, it is necessary to provide shading devices that block unfavourable solar radiation in the period from May 9 to September 21. This involves adjusting the envelope of the building to prevent overheating, thus reducing the use of electricity in the facility during the summer months. These data are used for dimension calculations of shading devices.

This data is especially important for DF calculation because, on the basis of accurately determined time intervals, the precise position of the Sun (incidental angles) is reached, on the basis of which further modelling and dimensioning of the sun protection system in relation to the orientation of the object is possible. Based on these angles, a proposal was made for the possible rehabilitation and dimensioning of the applied shading devices; the program then showed a distribution of the illumination across the depth of the office, in order to achieve the precise data of each individual solution. An interactive display that represents analytical results directly in the context of the model itself provides reliable information that can be used as a guideline for the dimensioning and use of different elements of architectural design, as well as in defining the exact time interval that results in the overheating of the room and the high values of daylighting factors (DF) for which it is necessary to incorporate shading devices.

As the paper emphasised the importance of understanding the environment and connecting users with the immediate building environment, the program also simulated the presentation of views from the position of the workplace, in relation to the implemented system. Stereographic diagrams show to what degree implemented systems are interfering, and, in relation to the field of vision, in which zones they are interfering, as well as the degree of indeterminacy (the ratio of background and figure) that can be caused in the field of vision.

The model defines all parameters of the interior space and the environment that are important for the calculation. Parameters and reflection of surfaces in the model are defined in accordance with standard DIN 5034-1, for all daylight level simulations, in the following way:

PARAMETERS FOR SIMULATION	
Value	
ab - ambient rejection	5 times
ar - ambient resolution	256 px
at – ambient accuracy	0.10%
Brightness of the material	
Floor	20% of reflection
Walls	50% of reflection
Ceiling	70% of reflection
Transparency of the glass	80% of transparency
Cleanness of glass	90% of transparency
External shading devices	40% of reflection

TABLE 3.1 Parameters and brightness of materials used in the simulation *(details from Ecotect Software)*

4 Case Studies: Office Buildings in Podgorica

This chapter presents a case study of an office building in Podgorica (UNISTAN - Tower C), which aims to provide higher standards in terms of visual and energy characteristics for office buildings.

In order to gain a clearer picture of how the building will behave towards the environment, we must first understand how the environment will behave towards the building under the given circumstances, so the shadow simulation was strategically undertaken for four days of the year: March 21, June 22, September 21, and December 21.

By describing and analysing interventions for a case study on a precise example, through the guidelines and presented standards and norms, numerical indicators of DF will be obtained in relation to the implemented shading systems for the period from 9 May to 21 September, for which it is necessary to predict shading devices on the territory of Podgorica. By definition, the daylight factor is counted only in the case of the *cloudy sky*, which is crucial for understanding the results of the simulations. In the case of cloudy sky, direct light entering the interior of the office is not taken into account so the rotation of the building in a given direction will not significantly change the calculation. In relation to the SRPS.C.9.100 standard (Table 1.1), a very high illumination value of

300-600 lx and a daylight factor (DF) value of 5.5 - 11.5% will be taken as reference values. The system will also be valued in relation to the percentage coverage of the room by DF at a defined interval (5.5 - 11.5% in 80% of the room that has direct contact with the façade).

When introducing a daylighting system on the southern façades, it was considered that they should not be implemented at a height of less than 2.3m (if there was a possibility to do so) in order to minimise the interruption of possibility of linking users with the environment, i.e. understanding the environment.

4.1 Climatic Characteristics for Study Area: Podgorica, Montenegro

Based on temperature measurements, average daily, average monthly, and average mid-year values with basic static indicators are calculated. In this way, it is possible to recognise the thermal characteristics and the climate type of an area.

In Montenegro, the number of sunny hours is over 2,000 hours a year, especially in coastal and central areas, so the country has good preconditions for using natural lighting and justification for the implementation of shading devices as an integral part of the building shell.

Podgorica is located at an altitude of 44.5 meters. Coordinates of 42.26 northern latitude and 19.16 degrees eastern longitude determine the geographical position. Podgorica has a changeable Mediterranean climate with warm, dry summers and cold winters. The temperature exceeds 25 °C for 135 days a year while the mean daily temperature is 16.4 °C (Burić, Micev, Mitrović, 2012).

CITY	AVERAGE VALUE	MAX	MIN
Podgorica	15.3	16.1	14.3

TABLE 4.1 Average annual air temperature in ºC for Podgorica *(Burić et al., 2012)*

CITY	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEPT	OCT	NOV	DEC
Podgorica	4.9	6.7	10.0	14.0	19.0	22.8	26.0	25.5	21.3	16.0	10.5	6.5

TABLE 4.2 Average monthly air temperatures in ºC for Podgorica *(Burić et al., 2012)*

Podgorica is especially known for exceptionally warm summers: temperatures above 40 °C are frequent during July and August. The highest recorded temperature of 45.8 °C was measured on August 16, 2007. The maximum annual number of sunny days in Montenegro, about 157, was recorded in Podgorica – capital of Montenegro (Burić et al., 2012).

CITY	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEPT	OCT	NOV	DEC
Podgorica	19.2	23.6	27.4	30.0	35.4	37.8	40.4	41.4	38.8	31.2	23.8	20.8

TABLE 4.3 Extreme maximum monthly air temperatures in Podgorica in ºC *(Burić et al., 2012)*

4.2 UNISTAN - Tower C

The office building UNISTAN - tower C is located on the corner of a new seven storey residential/ office building, oriented to the south and east, with one smaller part to the north. The 16.5m width of the building was designed in a linear way, with two tracts (the depth of the tract to the south (A) - 6.5m, north (C) - 6.35m and east (B) - 4.6m).

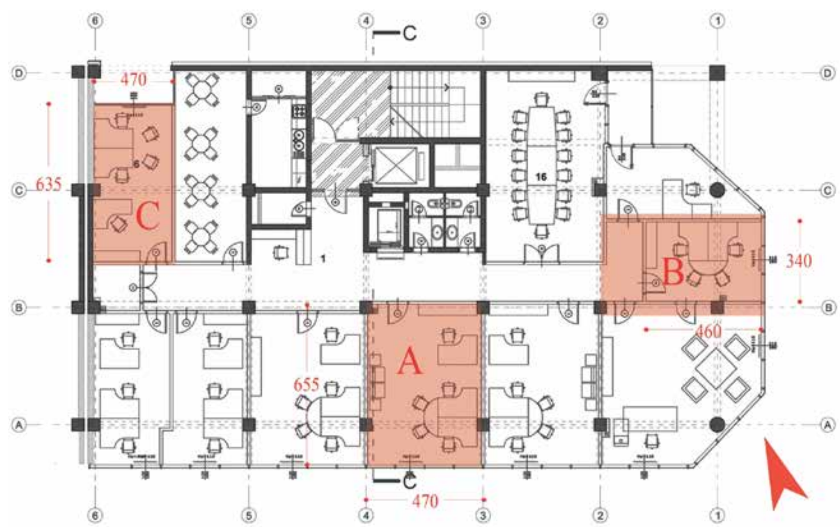

FIG. 4.1 Typical floor plan (north -22º)

From the floor plane it is obvious that most offices are orientated to the south. The north-orientated spaces were used to accommodate vertical circulation areas, and auxiliary and service rooms. The structural façade comprised highly-reflective glass, while on the inside a window parapet was formed at a height of 1.1m. Close to the ceiling level the room height is reduced to the height of the beam, in order to allow the implementation of HVAC. By doing so, the surface of the window opening is reduced, and, at the same time, it is possible to overheat the interior of the volume of the building. Visual quality is enhanced by moving pillars behind the façade. Since the designer did not create a possibility to incorporate external shading devices, the daylighting control intrusion was resolved using the internal shading devices in the form of a roll curtain. Semi-transparent curtains insufficiently block the penetration of solar radiation, resulting in heat accumulation and overheating of offices as well as frequent use of electricity in regulating heat comfort.

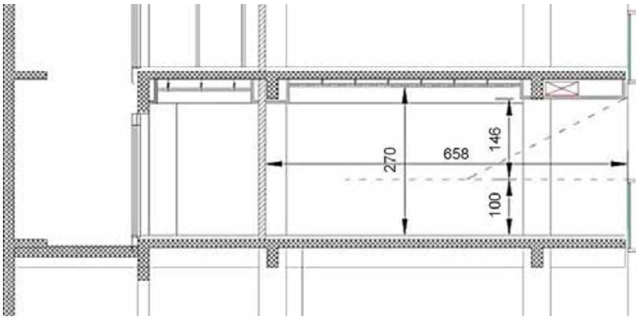

FIG. 4.2 Segment of the southern façade

FIG. 4.3 Photo of the residential and commercial building UNISTAN - Tower C

The inadequate organisation of workplaces contributes to the creation of glare, as direct sunlight falls directly on to working areas and computer monitors. As the employee faces away from the window opening, it is impossible to visually connect with the environment (Fig.4.1). Overheating caused by the lack of adequate daylight monitoring systems should be addressed by: adding control elements to the interior, improving the performance of glazing materials, and introducing external static shading devices. External systems for controlling and distributing daylight and their impact on specific offices, A, B, and C, will be further analysed.

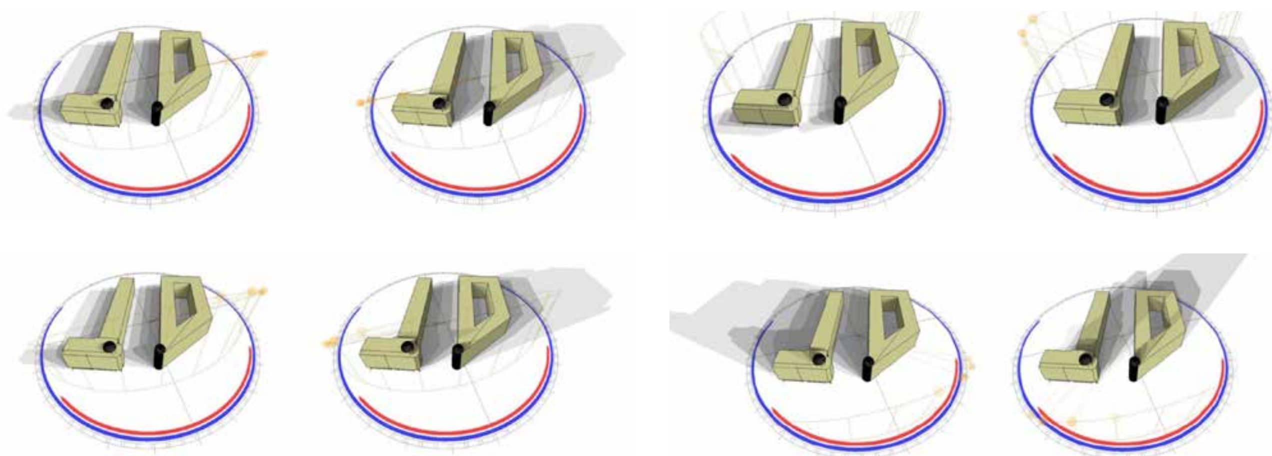

FIG. 4.4 The path of the sun and the position of the shadow, for March 21 from 08.00-12.00 and from 13.00-17.00 hours

FIG. 4.5 Idem, for June 22 from 08.00-12.00 and from 13.00-17.00 hours

FIG. 4.6 Idem, for September 21 from 08.00-12.00 and from 13.00-17.00 hours

FIG. 4.7 Idem, for December 21 from 08.00-12.00 and from 13.00-16.00 hours

Figures 4.4-7 simulate the interaction between the building and the relevant neighbouring object in the specific environment in four typical days of the year (location of the object: latitude 42.442292, longitude 19.244573 degrees).

From Fig.4.4-7, we can conclude that on the southern side it is necessary to implement shading devices, while on the eastern and northern faces it is unnecessary due to the shading created by adjacent objects and the shadow created by the building itself, due to its orientation.

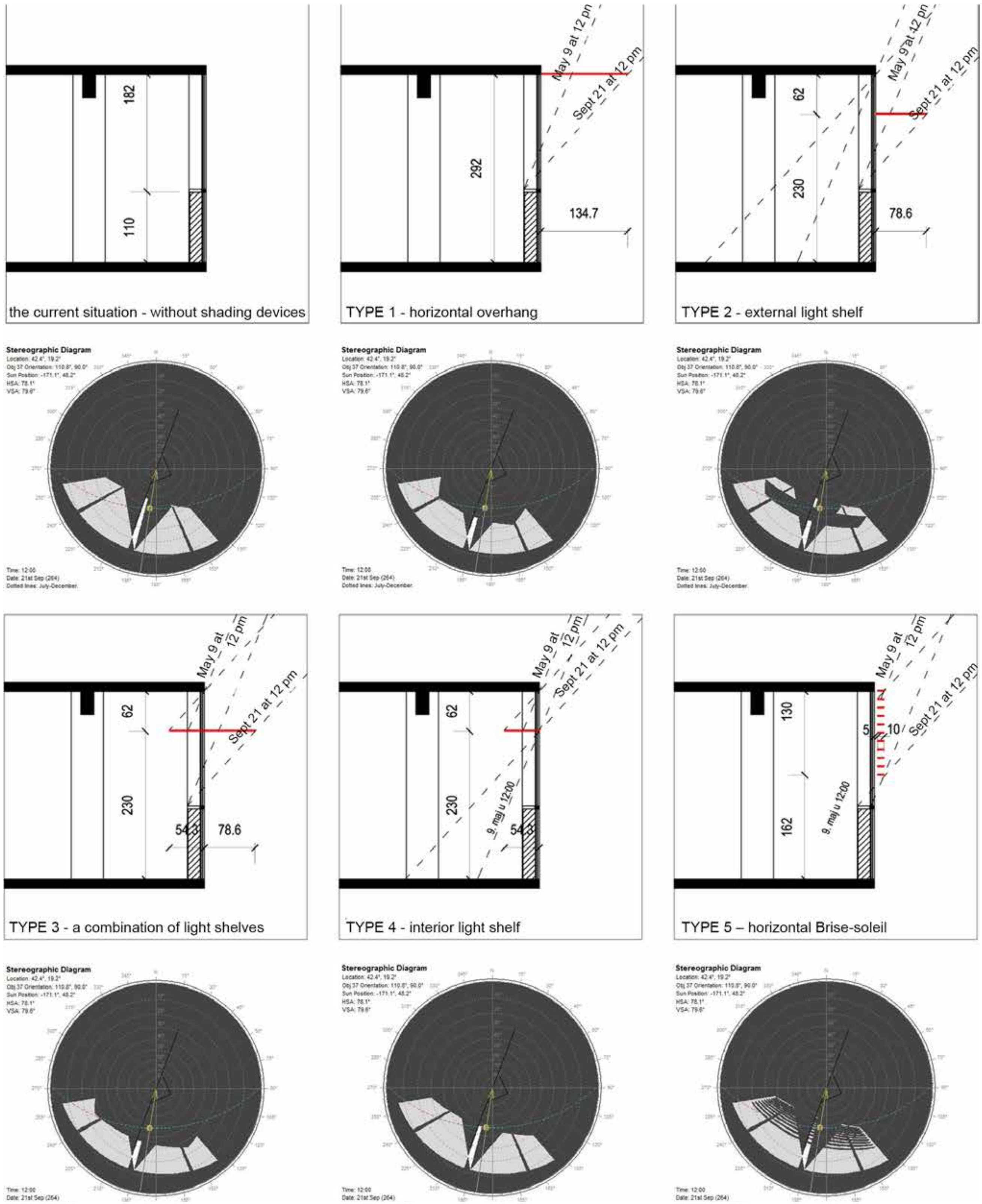

FIG. 4.8 External static horizontal shading devices (May 9 - September 21, 12: 00h), calculated by DF and view towards the environment

The relevant height of the incident angle of daylight was used to determine the systems of protection against unfavourable solar radiation that leads to overheating in internal spaces. This was done as follows: using the sun angle of incidence for May 9 at 12 pm (67.36°) and for September 21 at 12 pm (47.86º) (noon is taken as a reference point due to the fact that it is the time when the Sun is in the zenith), a series of solutions for office A for reducing excessive daylight, and therefore overheating of the room, are given. Subsequently, 6 characteristic cases are defined, namely:

- the current situation - without shading devices;
- TYPE 1 - horizontal overhang;
- TYPE 2 - external light shelf;
- TYPE 3 - a combination of external and internal light shelves;
- TYPE 4 - interior light shelf;
- TYPE 5 – horizontal brise-soleil.

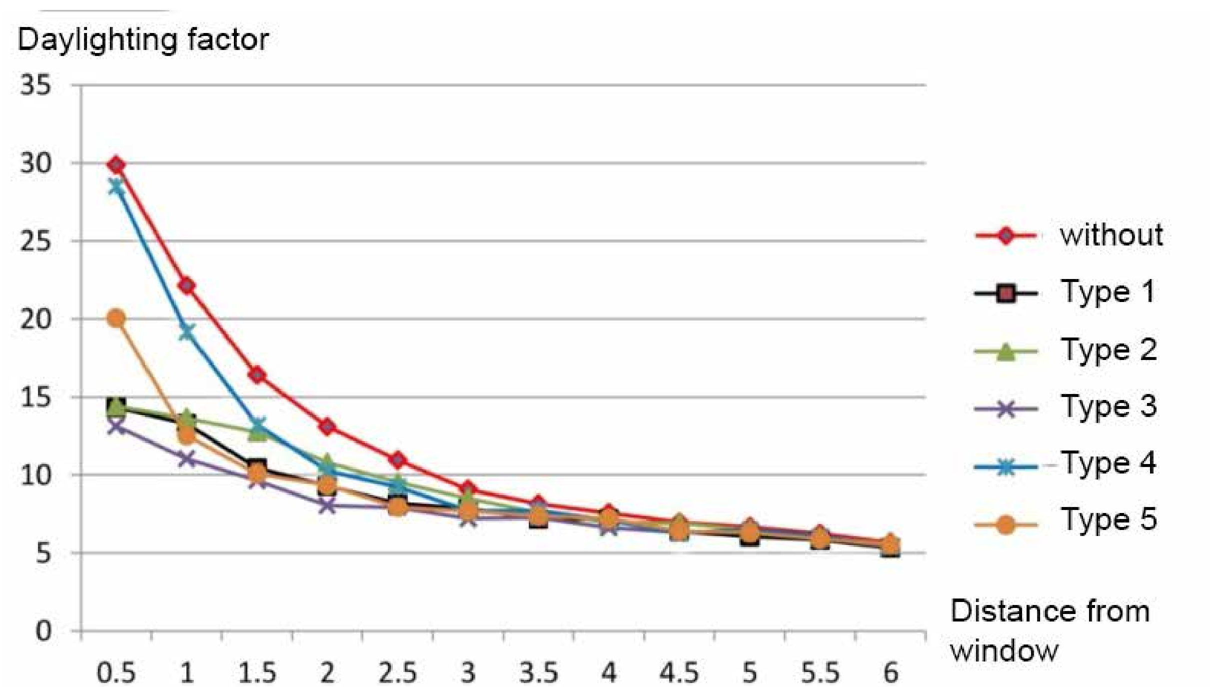

FIG. 4.9 DF value in the observed area

The DF diagram for the observed office varies in relation to the applied shading device. The daylight factor at a distance of 1m from the window ranges from 11.04 using a TYPE 3 shading device to 19.19 using TYPE 4. As TYPES 1, 3, and 5 show similar values of daylight distribution over the depth of the office, the choice of an adequate system depends on aesthetic, and urbanism and technical conditions (TYPE 1 would increase the volume of the building by 1.35m). TYPE 3 and TYPE 5 meet the basic criterion according to which 80% of the room meets the required range of DF values. TYPE 3 proved to be the system with the most regular distribution of daylight. TYPE 5 also meets the required criteria. Brise-soleil are commonly used in the adaptation of buildings because they are most easily incorporated into the existing structure. The disadvantage is that their use disrupts views and contact between the user and the environment.

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[m]	WITHOUT SHADING DEVICE 67 %	TYPE 1 75 %	TYPE 2 75 %	TYPE 3 83 %	TYPE 4 67 %	TYPE 5 83 %
0.5	29.89	14.33	14.41	13.12	28.53	20.04
1	22.14	13.28	13.64	11.04	19.19	12.54
1.5	16.42	10.44	12.74	9.63	13.23	10.07
2	13.1	9.28	10.8	8.02	10.25	9.34
2.5	10.94	8.17	9.52	7.91	9.25	7.92
3	9.06	7.85	8.49	7.2	7.7	7.69
3.5	8.14	7.17	7.58	7.25	7.7	7.35
4	7.54	7.16	6.97	6.61	7.1	7.2
4.5	6.97	6.38	6.91	6.32	6.3	6.39
5	6.67	6.04	6.49	6.4	6.5	6.28
5.5	6.23	5.83	6.05	5.98	6.08	5.89
6	5.66	5.33	5.53	5.41	5.45	5.52

TABLE 4.4 DF of the observed area calculated at 0.5m distance intervals from the window

The energy optimisation check was made in programs for three characteristic cases:

- no shading devices;
- TYPE 1 - horizontal overhang; and
- TYPE 5 - horizontal brise-soleil.

In the simulations the following input parameters were used:

- the office has two distinct working areas;
- electricity consumption is calculated for heating, cooling, ventilation (HVAC), and additional artificial lighting;
- the time of calculation is limited to working hours from 7:00 am to 7:00 pm with a break of 1 hour from 12:00 pm to 1:00 pm;
- data on climate characteristics are downloaded from the *Meteonorm27* database.

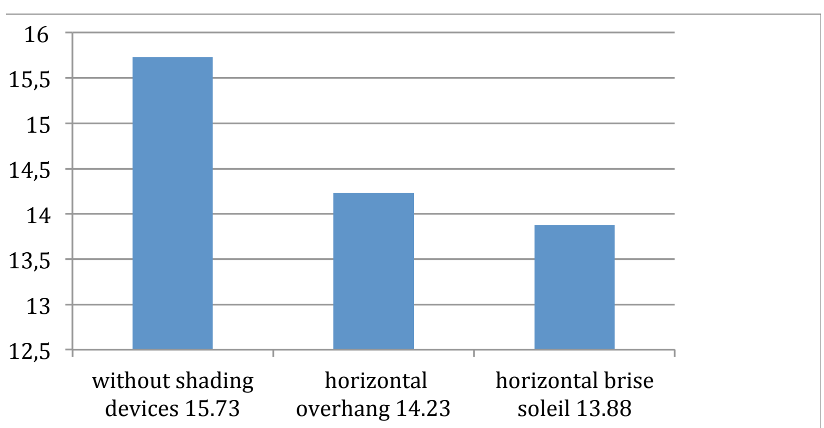

FIG. 4.10 Total energy consumption at the site (GJ)

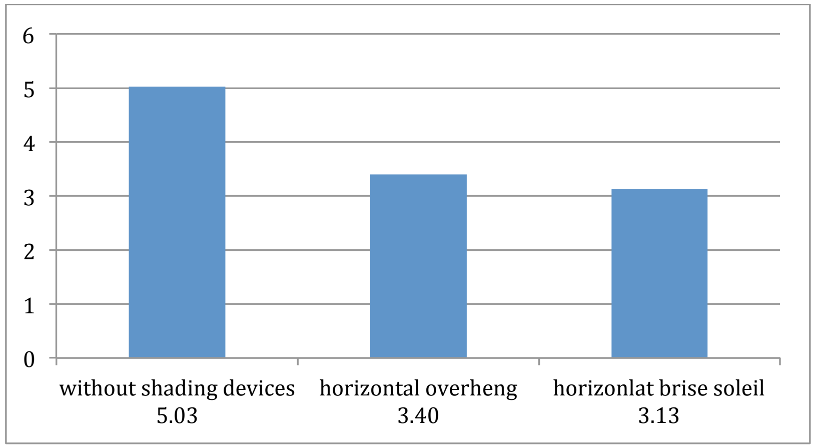

FIG. 4.11 Summary of annual energy consumption for cooling (GJ)

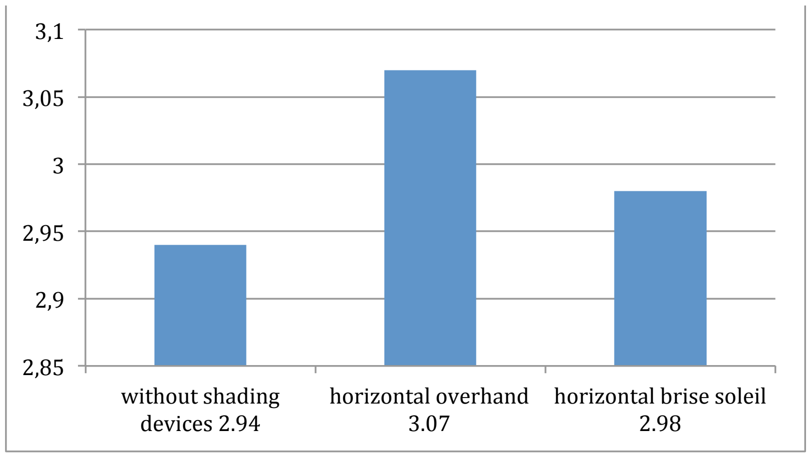

FIG. 4.12 Summary of annual energy consumption for heating (GJ)

The energy state of the object, i.e. office A indicates that by using horizontal brise-soleil (TYPE 5), the consumption of total annual electricity can be reduced to up to 12%. Independently, the parameters of energy consumption for heating and cooling were analysed on an annual basis. It has been proven that the use of horizontal overheads reduces the consumption of cooling energy to 32.41% while this percentage increases with horizontal brise-soleil to 37.78%. The use of shading devices has slightly increased the consumption of heating energy by 1.3 – 4.2%, caused by the constant blocking of harmful and direct sunlight. Through this example it has been proven that the use of static shading devices responds to building design requirements, according to the principles of high energy efficiency, sustainable construction, and energy savings, relying on the maximum utilisation of available natural light.

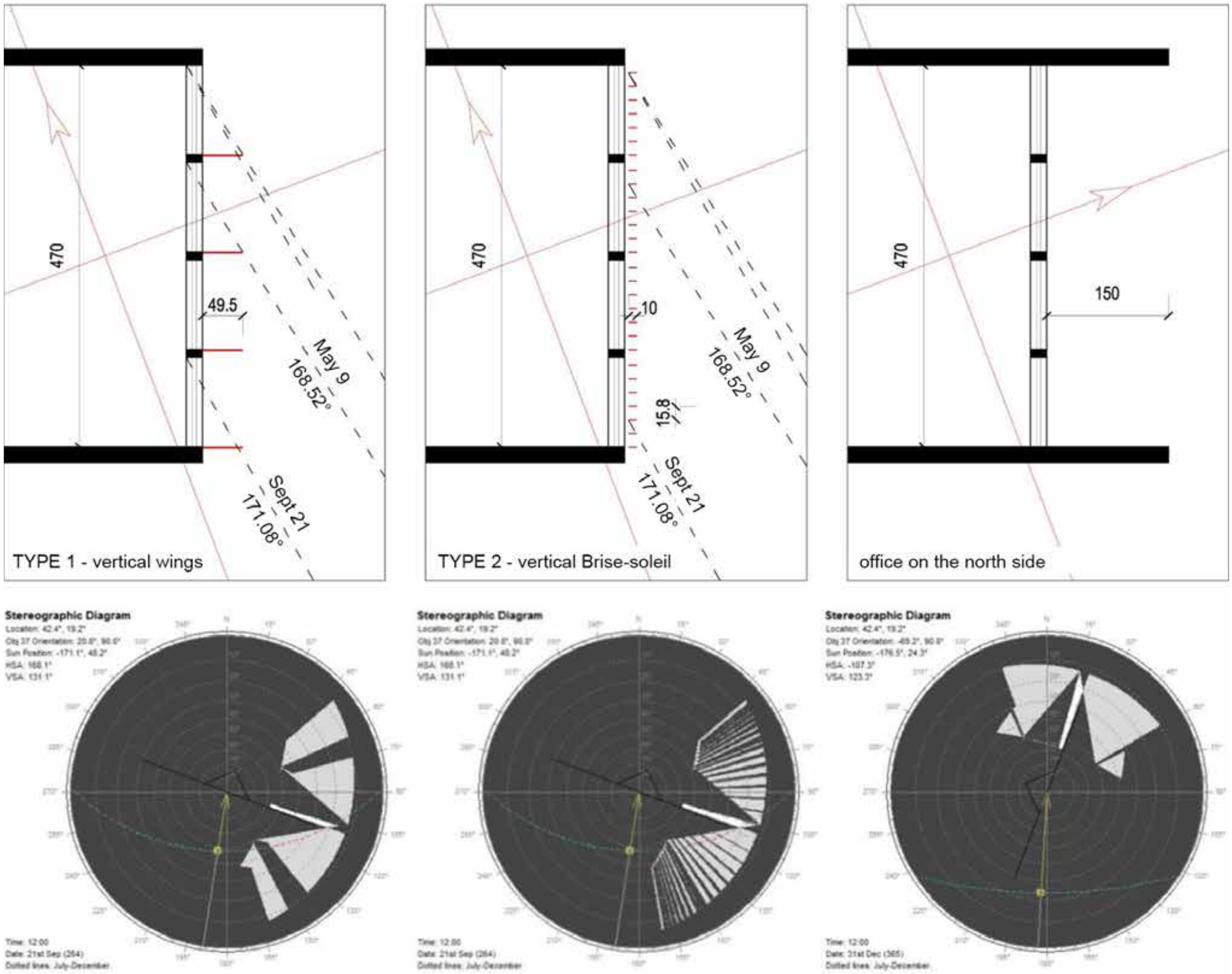

FIG. 4.13 Eastern and northern orientation (May 9 - September 21, 12: 00h) showing calculated DF and view towards the environment

The east façade is shaded by the neighbouring building in the morning, and shading caused by the building itself in the afternoon is noticeable. For the calculation of vertical shading devices on the east façade, the relevant values of the azimuth angle were used (which are for May 9 - 168.52º and for September 21 - 171.08º). A number of scenarios were examined: the east façade with the influence of the adjacent object; the east façade without the influence of the neighbouring object; TYPE 1 - the use of vertical wings associated with divisions of window openings; and TYPE 2 - the use of vertical brise-soleil. The diagram is also associated with DF analysis and a north-facing view for an office that sits 1.5m back from the façade line. The north office was also influenced by the eastern wing of the building during simulations.

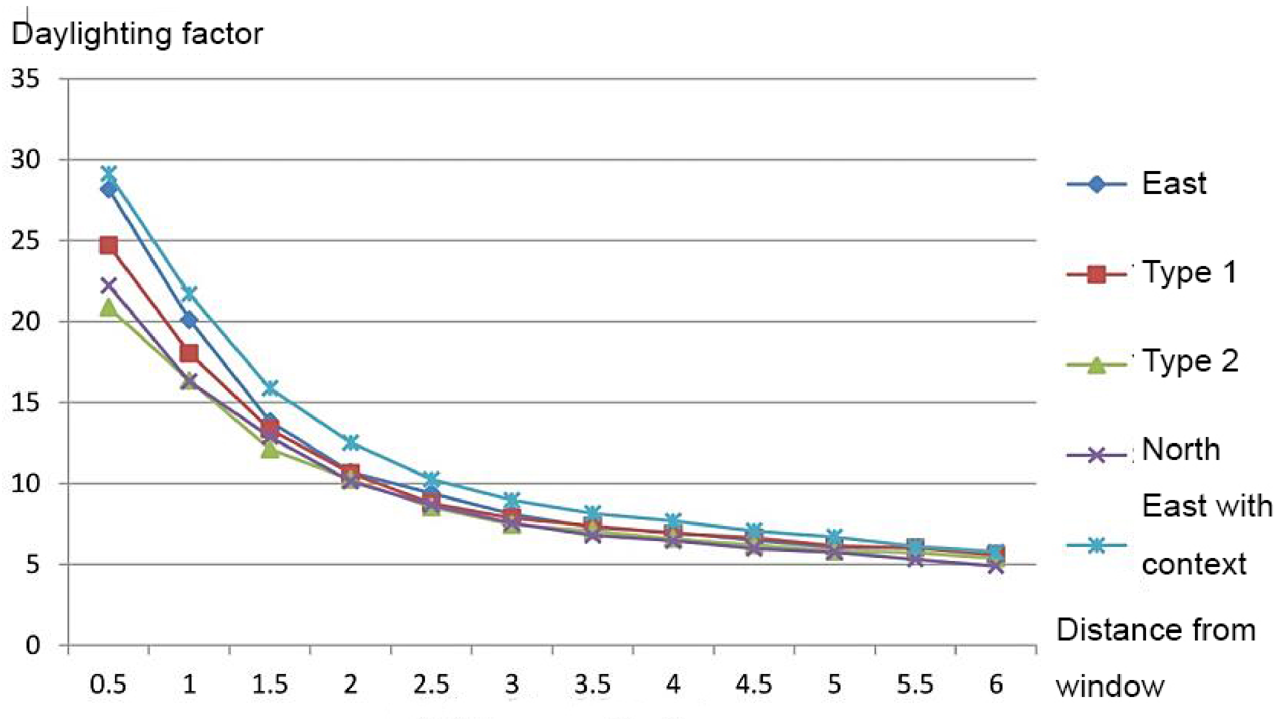

FIG. 4.14 DF in the observed area

The DF diagram for the observed east-facing work unit (office B), compared with the situation of the east façade, without the impact of the context in Table 11 shows that the DF is significantly reduced due to shading caused by the orientation and position of the neighbouring object.

[m]	EAST 75%	TYPE 1 75%	TYPE 2 67%	NORTH 58%	EAST WITHOUT CONTEXT 67%
0.5	28.17	24.71	20.87	22.23	29.13
1	20.1	18.04	16.35	16.29	21.69
1.5	13.82	13.34	12.11	12.88	15.87
2	10.69	10.63	10.23	10.13	12.51
2.5	9.39	8.77	8.54	8.66	10.25
3	8.11	7.87	7.46	7.54	8.96
3.5	7.28	7.38	7.07	6.79	8.15
4	6.97	6.9	6.58	6.46	7.68
4.5	6.49	6.65	6.2	5.98	7.07
5	6.04	6.14	5.81	5.76	6.69
5.5	6.03	6.02	5.73	5.32	6.1
6	5.62	5.6	5.37	4.89	5.77

TABLE 4.5 DF in the observed area is calculated at 0.5m intervals from the window

Adding shading device TYPE 1 would not significantly reduce the curve of daylight distribution. The use of shading device TYPE 2 fully corresponds to the distribution of daylight in the north-facing office. The use of brise-soleil would completely prevent the visual connection between the user and the environment while the north-oriented office (office C) has compromised lateral views towards the environment and

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it is recognised that the distribution of daylight is not adequate across the depth of the office (58% of the space has a satisfactory DF value). The analysis showed that the planned construction and the inclusion of a natural light study in the design phase can significantly influence the improvement of the quality of daylight in the interior.

5 Conclusions

It is important to note that the factors of daylighting shown in the previous chapter do not mean that the level of illumination for different geographic locations is shown by the same DF value; for Podgorica, it is 7754 lux.

The connection between DF and distribution of daily illumination across the depth of the office was analysed in relation to the simulated southern façade - without a shading devices. Also, the impact of adjacent objects was analysed in order to highlight the relationship between the building and the built environment, which must become an important factor in configuring the envelope of a future building. For the south-oriented façade, the total annual energy consumption is simulated for three characteristic cases, in order to prove that the harmonic relationship between the building shell, the climate characteristics of the site, and the daylight can significantly influence the reduction of the consumed electricity for heating, cooling, ventilation, and additional artificial lighting.

The daylight factor in the south-oriented office was tested using a shading device in the form of horizontal projections whose dimension is dependent upon the height of the angle of incidence and deviation from the south position by 20.78º. The DF at a distance of 1m from the window gave a value of 11.04 by using light shelves on both window sides, at a height of 2.3m from the floor, and reached up to 19.19 using the shading device of only the internal light shelf. At 2 metres from the window, the DF is between 8.02 and 10.25, depending on the applied system, and the differences in factor values across the depth of the room oscillate very little. Using light shelves on the outside and the inside, along with horizontal brise-soleil, the best distribution and the smallest oscillations of daytime illumination across the depth of the office were achieved. It was noted that the choice of an adequate system will depend on the aesthetic and urban-technical conditions of the location of the facility. Often the most appropriate intervention in the renovation is adding brise-soleil because it is easiest to incorporate them into the existing structure of the object. The predominant shortcoming of the brise-soleils is that their use disrupts views towards the environment. Analysis and simulations have shown that the distribution of daylight across the depth of the office can be corrected by 16% when using an adequate shading device.

For three characteristic cases: in terms of the consumption of electricity (for the example without shading device, such as horizontal overhang, and horizontal *brise-soleil*), the simulation showed that by using the horizontal *brise-soleil* the total electricity consumption for HVAC and additional artificial lighting can be reduced by up to 12%, while by using a horizontal shading device, the consumption of cooling energy can be reduced by 37.78%. The use of the shading device slightly increased the consumption of heating energy from 1.3 to 4.2% which was caused by the constant blocking of low winter solar radiation.

The DF diagram for the observed east-oriented work unit shows that the DF is significantly reduced due to shading caused by the orientation and position of the neighbouring object. Adding vertical wings would not significantly reduce the curve of daylight distribution, while the use of vertical brise-soleil would not significantly affect the distribution of daylight across the depth of the office.

The paper shows that new space has opened up for additional analysis in terms of thermal characteristics and a more comprehensive analysis of daylighting, which would connect the light and energy components of daylight and show their interdependence. This topic can be a good starting point for future research that can be also complemented by dynamic systems.

The dynamic nature of daylight, both during the day and throughout the year, makes the use of shading devices a complex process, with significant planning challenges. In order to ensure high-quality visual comfort, in designing, particular attention should be paid to the geographical location, orientation, and shape of the building, the area in its surroundings, overhangs, and window surfaces, the reflectivity of the interior space and the position of the workplaces. Specific façade elements, with particular attention given to their influence on the southern orientation of the typical work unit at the location in Podgorica, for 30th April at 10:15 am, are thoroughly analysed.

Despite the fact that the overall results of the study were not completely unexpected, the analysis was made to test the existing objects, the shading device characteristics, and achievement of better energy efficiency, understanding the importance of software support and design verification.

Static shading devices should be designed as an integral part of architectural plastic, an inseparable part of the building shell that affects the distribution of daylight, based on the blocking of negative direct sunlight. The use of these systems is indispensable for objects designed in the Mediterranean climate - such as Podgorica - in order to find a compromise between summer heat and winter energy (heat) losses. As the number of sunny hours in Montenegro exceeds 2,000 hours per year, good preconditions for the use of natural light are set and the implementation of the shading device is justified. Consequently, the applicative guidelines for the correct and innovative approach in planning façade envelopes in the Mediterranean area are given. This way, the envelope of the building becomes a climate-adaptive façade and is treated as a medium that both connects and divides the interior of the building from the environment, creating comfortable working spaces using the external environmental conditions. Each climate-adaptive façade is unique because it unites and combines a variety of specific patterns and methods.

The strategy to naturally illuminate the building can be changed after the completion of its construction, but with significant financial expenses. From the point of view of using renewable energy sources, energy consumption, overheating, environmental pollution, and indirect impact on health, it is important to conduct natural light studies in the early stages of design, while understanding the importance of software support when checking the design of static shading devices as an integral element of architectural design. If a natural light study is not included in the early stages of design, the adaptation and pre-design (redesign) of the façade shell can be an opportunity to significantly improve the visual and thermal comfort within the facility, and correct the shortcomings of the original solution, with the maximum utilization of the location conditions.

Using shading devices in Podgorica, the consumption of total annual energy can be reduced by up to 12% while using horizontal shading devices, and the consumption of cooling energy can be reduced to 37.78%, in the south-oriented façade of the building.

Potential fields of further research:

1. Updating the CIE (International Commission on Illumination) report - getting familiar with relevant CEE standards, technical committees and the application of standards in Montenegro;
2. The relationship between applied shading devices and visual comfort;
3. The relationship between applied shading devices and thermal comfort for the purpose of proper use of energy and sustainability;
4. Technical solutions and methodology for establishing sustainability, durable and functional envelope of the facility;
5. Getting familiar with and working on modern technical solutions for the distribution and reduction of daylight - mobile shading devices as an integral part of envelope of the facility;
6. Building shell and its aesthetic characteristics: a shell as a medium of architectural plastic;
7. The connection between the actual energy state and the actual architectural - design response;
8. Researching daylighting as a balance between energy, visual environmental parameters, and user health without neglecting the design and aesthetic potential of these solutions.

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Economic Evaluation of the Energy Efficiency Improvement Projects

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ABSTRACT **The process of adaptation of the buildings in architectural projects is codified by a set of energy efficiency regulations that are mandatory and which affect designers. To fulfil these requirements certain investments are necessary, which influence the economic performance of the project in construction phase, as well as in the long run over the building's exploitation period. Therefore, an analysis of the economic effectiveness of the project is needed, which would also take into consideration the operation phase of the project, to include the whole life cycle. The methodology of the life cycle costs and savings analysis is presented in the following sections, which would be adjusted to the specific preconditions of the energy efficiency improvement projects, availability and possibility to gather relevant input data, as well as the perspective and understanding of architects as prospective analysis practitioners. The format of the proposed study is created to comprise several steps or phases, and their contents would be further elaborated. The methods that are applied include analytical procedure, comparisons, deduction and elaboration of the existing tools, and techniques and methods in the field of economic analyses in architecture and building construction. The resulting procedure allows for practical and theoretical implementation in actual projects. It is simple and straightforward to conduct, easy to understand, and open for expansion.**

KEYWORDS life cycle, evaluation, energy efficiency, costs and savings

1 Introduction

The adoption of the new energy efficiency regulation in building codes of Serbia in 2011 brought about a new aspect in design practice. Parameters for dimensioning outer envelopes of the object and the adjoining thermal insulation that were previously widely used and proven through professional experience have since been changed. This is also the case in terms of other widely used façade elements, such as windows and doors that are made of wood, plastic, or metal alike. On the other hand, it has been formally acknowledged that the energy available for the normal functioning of the buildings is getting scarce, and the costs associated with it are getting higher. The problems of energy resources, ecological implications, and the quest for sustainable alternatives have all been growing over the last decades. All the interventions on the building that require the issuing of a building permit, including adaptation works, are linked with the obligation to upgrade the energy efficiency category according to the regulatory rulebook. It is therefore implied that the appropriate systems and elements of building envelope have to be designed. At the same time, these requirements have implications on the capital investment for the client, affecting the life cycle costing. Through a well-balanced building intervention and the selection of heating and cooling systems, possibilities emerge to optimally achieve both regulated EPC (energy performance certificate) and the positive investment outcomes for client.

The global aim of the life cycle study would be to achieve a balance between cost and energy efficiency benefit on adaptation projects. To achieve this end, it will be necessary to define and explore which capital investments provide the best results during the life cycle, making savings that prove the investment profitable in the long run. Various methods and techniques of calculating costs and savings during the life cycle can be used in the process, as well as some of the economic performance measurements. It is also necessary to make choices regarding the study period, as well as dealing with the time value of money through the discount rate and currency expression in constant or current terms. However, above all, the analysis is based on the manner and creation of the design cases that would be considered.

Bearing in mind the needs of architects as practitioners, the prevailing types of projects, the availability of relevant information and data, and especially the global aims of the applied life cycle cost analysis, a seven steps model has emerged. These seven steps transform into seven chapters of the life cycle study in a project for building energy efficiency improvement.

2 Project Description

Even though the proposed model can be adjusted to a potentially wide array of projects, the most common form of energy efficiency project is the adaptation of an existing building. According to the regulations, complete design documentation is needed for adaptation, which does not necessarily include the life cycle analysis study. Therefore, there is no code by which to regulate its contents, but it would be recommended that the project and the building information remain within a relevant scope for the life cycle study. This would start with a description of the project under consideration, consisting of three generic parts, which are as follows:

- *Basic information on the project to be analysed.* In the short table format, some information should be given that creates a specific ID of the building: location, function, year of construction, the kind of intervention that is planned, the form of ownership, and the potential financing that is expected (private, public, partnership, etc).

- *Project description summary*. Comprising approximately one written page, the project should be described in terms of function, form, materials, construction, equipment and other relevant features. Such chapters are standard for new projects, and should also be followed in all other projects. This description should encompass both existing buildings and planned interventions.

- *Building illustration.* The life cycle study is not regulated by any code for project documentation. Therefore, it is advised that a reference be made within the life cycle study to the adaptation project documentation under analysis, and that an illustration of the building be added through an appropriate set of photographs and/or drawings. This should not exceed the length of one page.

3 Formulation of Project Options

Life cycle costs are meaningful in terms of decision making only when a project option is compared to a basic or reference case, also known as the zero option. In the case of an existing building, the reference case typically requires no investment. In this case, life cycle costs contain the use costs only, afterwards compared to the combined investment and use costs for other options.

In the case of the life cycle study of a new construction, the reference case is usually set as the one with the lowest investment costs, or the minimal acceptable performance level according to the regulations.

There are three key points to consider when the options are to be selected. The most important one is to bear in mind that a good project decision directly depends on the quality of options chosen for analysis. An analysis based decision cannot be better than the best option considered, no matter how good economic evaluation is. This is all about a creative choice that precedes rigorous analytical procedure.

The second point of interest would be to take into consideration only the options that meet the performance standards. Furthermore, other possible constraints should be considered, such as the availability of energy sources, or the regulation requirements. It is not sensible to perform an economic evaluation on the option that would otherwise be rejected for other reasons.

Finally, in some cases, it is only required that the minimal performance level be met, whereas, in other cases, options that exceed the required threshold and bring additional advantages are favoured. If so, they should be observed, or, if they are of non-monetary nature, the benefits they allow should be noted and included in the documentation text.

3.1 Description of the Reference Case

In cases of the adaptation of existing buildings, the reference case is the zero option, without intervention.

The reference case description principally relates to the systems and elements of the object, which can be broken down in the following way:

- HVAC systems;
- building envelopes and its layers;
- façade, roof, and other elements and products with thermally insulating functions;
- building structure with structural and partition elements.

After the building systems and elements definition, the next step would be to calculate energy losses and establish the energy category for the object.

3.2 Description of the Project Options

Following the reference case, a description of the proposed alternative systems and elements should be made, mainly in the form of text with some illustrations. Then, the calculation of energy losses is carried out and the energy category for the building established. Finally, it should be determined whether the object has achieved an upgrade in its energy efficiency category, which is a legislative prerequisite for building adaptation.

To make the decision based on an analysis meaningful, the fundamental minimum is to have at least two project options that can be compared to the reference case. The more project options we have, and the more elaborate they are in terms of the combined use of systems, materials, and products, the better educated the decision will be. However, it is common for all the analyses and studies to have an optimal level of effort, time, and cost allocated to the work. It is preferable not to surpass nor fall short of this optimal level to any great extent.

4 Input Analysis Parameters

Costs and savings in the project life cycle occur at different times, at different periods, and under the influences of all mechanisms that are associated with the time value of money. From the point of view of the analysis credibility, it is of paramount importance to consistently apply the accepted suppositions concerning money management in time. The accuracy of the suppositions can even be considered to be of lower priority than the uniformity of its application to all the project options.

There are three basic input parameters for the life cycle analysis: the discount rate to be applied, the study period that is suitable for the planning horizon, and the manner of monetary expression of costs and savings incurred.

4.1 Discount Rate

Before summary costs that take place at different times within the study period can be compared, they have to be converted to a common point in time to reflect the time value of money. This conversion procedure is called discounting. It is customary to discount future costs and savings to the present value, so that they could be directly set against the investment cost.

There are several conventions to show money flow that can be adopted when discounting future costs to present value. One-time costs are usually discounted from the actual time of occurrence. Annually recurring costs, which occur once a year at approximately same amount, are typically discounted from the end of the year. Costs that occur at the start of the study period are not discounted because they already take place at present time.

A discount rate that is used to adjust future costs to the present value is, in fact an interest rate at which it is equal for the investor to reclaim his investment at that time or any other. The discount rate reflects an investor's appreciation of time and money, or the return rate of the best option investment. The discount rate is also often referred to as the minimal acceptable rate of return (MARR). It is important to understand that each investor has preferences about money and therefore his own discount rate.

When life cycle cost analysis is carried out, there are three types of future money flows that arise, and each one is associated with a particular type of present value index (Fuller and Boyles, 2000).

– One-time money flow is multiplied by the single present value index (SPV) to obtain the present value. Examples of these sorts of money flows are replacement costs or the residual value at the end of the study period.

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- Annual equal amounts are multiplied by the uniform present value index (UPV) to obtain the present value. Examples for these are annual operation and maintenance costs.

- Annual changing amounts that differ from year to year at the known rate are calculated by multiplying the amount from the base year with the modified uniform present value index (UPV^*) to obtain the present value. An example of this is the energy consumption for which it is estimated that it would remain at the same annual level, but the prices of energy sources would escalate at their own projected rate.

The calculation formulas for corresponding discounting indices are standard compound interest formulas, used on discount rates instead of interest rates, but are conveniently readily available for widespread use in form of discount index tables.

Inflation decreases the buying power of money through time. Money spent in different years, with different buying power, cannot be directly compared to provide a relevant result. When the economic evaluation of capital investments over time is performed, following the discounting procedure, both the changing buying power of money and the real earning power of money have to be taken into consideration.

There are two basic methods of accounting inflation in the economic analysis (Fuller and Boyles, 2000):

- Estimating future costs and benefits in the current currency, and discount them with the nominal discount rate, which means that the discount rate includes inflation rate; or
- Estimating future costs and benefits in the constant currency, and discount them with the real discount rate, which means that the discount rate doesn't include inflation rate.

The methodology of life cycle cost analysis allows money flow to be presented either way. Analyses done in constant or in current currencies result in the same present value, and therefore support the same conclusions. Choosing constant currency is, however, usually more suitable because there is no need to predict future inflation rates. Prices in constant currency are not influenced by general inflation rate.

As mentioned before, prices of particular commodities and products escalate at rates that are not identical to the general inflation rate. These individual escalation rates are especially important for the prices of energy sources, which are known to have considerable deviations from the general inflation rate. This can be noticed from historical data. To deal mathematically with escalation rates, the same rules are applied as for discount rates. The resulting present value will be identical if the costs of the basic year are:

- Escalated to the future value by using current currency and nominal prices escalation rate (E, inflation excluded), or discounted back to the present value using nominal discount rate (D); or

– Escalated to the future value by using constant currency and real prices escalation rate (e, which is differential rate), or discounted back to the present value using real discount rate (d).

If correctly conducted, both procedures finally show the same result.

The price escalation is considered to be constant over the years, as suggested by the basic equations and indices that derive from them. If that rate changes, which is the case in real life, future costs must be calculated with the compound rate. There are sources and publications that provide an estimation of the price escalation of energy sources. Nevertheless, it is clear that the analytical process is constrained by a number of assumptions which, in the long run, diminish its reliability.

For practitioners in the field of energy efficiency in architecture who are not professional economic analysts, it is most appropriate to adopt the real discount rate from which the inflation rate is excluded and to disregard relative escalation rates for individual energy sources. To remedy the setbacks that develop from these simplifications, it is advised to perform some of the risk analysis techniques.

The Directorate-General for regional and urban policy at the European Commission recommends the use of relevant real discount rates in cost-benefit studies for investment projects. Bearing in mind that energy efficiency improvement projects are not developed for investors for whom it would be possible to calculate a weighted average cost of capital (WACC) that would represent the personal discount rate, it is advised to accept the financial discount rate of 4%, for member countries and the whole of the euro zone, as instructed by the Commission Delegated Regulation (EU) No 480/2014 of 3 March 2014. Apart from the financial rate, a social discount rate is set by this publication, within which a wider social view on future costs and benefits is taken into account. To apply the proper social discount rate, countries are differentiated both as member countries of the EU, for which the recommended rate is 3%, and so-called cohesion countries (which include Serbia) for which the rate is 5%, according to the Commission Implementing Regulation (EU) No 1011/2014 of 22 September 2014. The latter rate is therefore suggested for use in the analyses of energy efficiency improvement projects. These recommendations are given for the years 2015-2020.

4.2 Study Period

The study period is the time during which the effects of the decisions are of interest to decision makers. There is no such thing as the correct study period, but it should be long enough to enable the accurate estimation of long term economic performances. The expected lifespan of a system under analysis is often taken as the study period. However, the study period of the maximum of 25 years from the start of operation is limited by specific regulations in the field of energy consumption (European Commission, Directorate General for Regional and Urban Policy, 2015). This constraint is due to growing uncertainties in price

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estimations if the period is longer. In addition, the duration of the study period is limited according to the conditions for the realistic financing arrangements for the project.

Besides the limitation for the maximum duration, some other factors determine the length of the study period, such as:

- All the options should be compared against the same time period. Discounted cash flow diagrams for one period cannot be compared with the ones calculated for longer or shorter periods of time.
- All the measurements of economic evaluation should be calculated for the same study period. If not, they would not be consistent.
- Investor's planning horizon should be taken into consideration. For instance, the study period could be either shorter or longer depending on whether the investor is the building's user or the developer only.
- The analysis should be adjusted to different expected life spans of the systems or the buildings. To fit various life spans into one study period, residual values (i.e. sale, demolition, remaining) are used to level the differences.

Practitioners in the field of energy efficiency in architecture in the region of the western Balkans are advised to adopt a study period of twenty years. Any longer-term financing is not available, and this period may be considered as long enough to examine the relevant effects of costs and savings over the life cycle.

4.3 Monetary Expression

As previously noted, future costs and benefits can be evaluated in the current currency and discounted with the nominal discount rate, which includes the inflation rate, or evaluated in constant currency and discounted with the real discount rate, which doesn't include the inflation rate. Since we have already given the reasons for the acceptance of the social real discount rate offered by the latest recommendation of the European Commission, it is implied that the monetary expression through constant currency in the zero year of the analysis is selected, without counting the individual escalation rates of the energy sources.

5 Cost Analysis

Cost analysis is the key step in a cost study. It consists of the estimation and documentation of the costs, classified by their types, character, frequency, and magnitude. During the cost analysis, one relies on the breakdown, which principally starts from the initial or investment costs versus in-use or life cycle costs.

In energy efficiency improvement projects, investment costs are comprise all the construction or renovation works, as well as the purchase and installation of the systems. For economic analysis

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purposes all of these costs take place in present time and hence the effects of time value of money are not applied. Most of the challenges that generally appear in the use of data sources for cost estimation are applicable for this analysis. The most reliable source is the personal database of the cost analyst, who is best acquainted with the specific condition under which the information is generated. Thus, the analyst can avoid the danger of using the same cost data in different real-life conditions. Aside from the personal archive, the best source of information about purchase and installation costs would come from the local supplier or contractor. Furthermore, it is also possible to use price books, contract information, commercial publications, or information from a third party (Gasic et al, 2012). All methods of information gathering can be beneficial in combination with the experience and skill of the analyst, provided that quite enough resources are assigned to the operation. The obtained data has to be documented by stating the reference, which can range from the publication of any sort, to the quotation of a website or a person (i.e. contractor).

Cost analysis principles for life cycle costs don't differ from the ones that are applied on the analyses of the initial costs. However, the information that can be used for analysis is even less available and less reliable, because the cost occurrence is expected far into the future. During the process, the life cycle cost breakdown must be noted as below (International Standard ISO 15686-5, 2008).

- By the cost carrier:
    - owner of the building;
    - user of the building.
- By the cost origin:
    - ownership costs;
    - use costs.
- By the time of the occurrence of the cost:
    - regular costs;
    - cyclic costs;
    - random costs.
- By the cost magnitude:
    - fixed costs;
    - changeable costs.

The most difficult task is to obtain the data for the life cycle cost analysis concerning the estimation of the maintenance and repair costs. It is possible to get manufacturers recommendations on maintenance, warranty, and service periods for some products and systems, which is a good basis for life cycle cost estimation. However, it is often not possible to find objectively grounded information. In such a case it is necessary to set aside a fund for maintenance and repairs, as a lump sum or as a percentage from the total investment.

In an architectural project for energy efficiency improvement, costs can be divided into four groups, which would form four chapters in the life cycle cost study.

5.1 Analysis of the Energy Sources Prices

Data on the prices of the energy sources are openly available via websites and publications of communal companies. Therefore, this set of information is the simplest for price analysis purposes. Some particularities, however, should be noted. Measurement units for energy sources differ and there are special charge rates in some cases, due to either social policy to protect the poor population, or as a stimulus for economy or specific social groups (i.e. for a branch of industry). In these cases, it is not possible to precisely ascertain which of the tariffs shall be applied, but it can be foreseen with a satisfactory level of accuracy, based on some average consumption values.

It is also useful to gather data on the prices of energy sources from the immediate and more distant surrounding countries, for the purposes of comparison and interpretation of trends. For an economy in transition it is safe to assume that the prices of the energy sources are at least partially undervalued, and that their future trend is comparable to the ones that are in a more advanced phase of transition. Besides, the trends in developed economies provide good indications of the presumed future global evolution.

The prices of the energy sources should then be applied to the expected consumption level during the life cycle, which results in the energy sources cost. These costs fall to the group of the regular costs, as to their time of occurrence, and to the use costs by their origin. For the majority of energy sources, there is the fixed starting charge set, which doesn't depend on the consumption level, although this minimum charge does not move the group into ownership costs.

In the discounting process, the multiple present value index is used, unless the prediction of the relative price escalation for the energy sources is considered for the sake of calculation.

5.2 Analysis of the Systems and Equipment Prices

The purchase and installation of the materials, products, elements, equipment, and systems also fall into the investment costs, which is previously set by the project options. The cost of the associated construction works is also included, such as the addition of the thermal insulation on the building envelope, or replacement of openings, as well as the installation or replacement of the air and water heating, cooling, ventilation, and conditioning systems.

When estimating the systems and equipment costs, it should be observed that the most commonly available price sources indicate the acquisition but not the fitting cost. From the cost analysis point of view, it is necessary to consider so-called built-in prices, together with purchase cost. When certain engineering systems are analysed, manufacturers or suppliers often offer an installation service, which makes the total cost data easily available. This is also the case with façade elements, but it should be noted that the installation service doesn't always include the treatment of surrounding walls, which is needed. In cases of acquisition of thermal insulation for the façade or other envelope elements, it is more common that only the purchase price of material is available. The estimate in this case should include consultation with contractors, or other accessible data sources to derive the price of the full installed element.

While the systems and equipment costs can be considered as investment costs, discounting is not applied on them, since they take place in the present time.

5.3 Maintenance Cost Analysis

Systems and elements need to be maintained in some way over the life cycle. When purchasing, some of the building systems suppliers provide manufacturers' instructions for maintenance, which can be used as a basis for the cost estimation. It is important not to confuse these costs with repair and replacement costs. In most cases, it would be useful to create a fund for elements and systems maintenance, which can be set as a percentage of the buying price, or as a lump sum based on certain presumptions. The data source on the maintenance cost could consist of the manufacturers' catalogues, the price list of the specialised maintenance companies, service providers, etc.

Multiple present value index is used for discounting of the maintenance costs, because it is presumed that the amounts needed for maintenance would be evenly distributed throughout the life cycle, similarly to the energy consumption costs. In reality, of course, maintenance costs rise according to the elements and systems age, but calculating with an average value is more practical and deemed to be sufficiently accurate.

5.4 Analysis of the Repair and Replacement Cost

Unlike maintenance of the built-in elements and systems, repair and replacement cost occur in incidents, as one-time costs. The occurrence of these costs is forecasted based on the presumed lifetime duration and the experience of services. Calculating repair and replacement cost into the life cycle cost analysis requires two types of assessment – the first one is the estimation of the actual repair and replacement cost, and the second one is the estimation of the periods in which they would occur.

To reach this goal, the first step would be to determine the lifespan of the systems and equipment designed based on the project options. In most cases, the lifespan of the built-in systems and equipment exceed the study period. Therefore, it is adequate to consider the residual value at the end of the study period. Building elements that are constructed for the purposes of energy efficiency improvement are not likely to have any residual value that would be applicable to the life cycle study. However, for some systems it would be possible to determine a residual value that could be calculated in the study, with the appropriate amortisation rate taken into account.

The periods of repair and replacement of the systems and equipment can be determined based on the instructions of the manufacturer or the service provider, as well as the duration of the warranty. With insufficient information on the repair and replacement periods it is acceptable to set up a repair and replacement fund, as a lump sum or a certain percentage of the capital investment sum.

Repair and replacement costs are one-time and changeable by nature. Therefore, for life cycle study purposes they can be considered to be regular. For discounting procedure, a multiple present value index should be used instead of a single present value index.

6 Life Cycle Analysis

After certain presumptions considering economic, monetary, and time parameters are adopted, and cost analysis conducted according to the previously set project options, one can proceed to the life cycle analysis. The choice of the type of the analytical procedure depends on the economic indicator that can be considered as primary, with a major influence on the project stake holders and specific project. This indicator, in a mathematical sense, represents the result of the whole life cycle analysis, but essentially it is better described as the basis for the analysis interpretation and decision making, which would consequently follow.

Each of the life cycle analysis procedures is simple to conduct, and sometimes those procedures are no more than a variation of another. In life cycle analysis, the focus is on the costs and savings. When benefits occur in the form of increased income (i.e. from rent) or from an improved level of service (i.e. more net floor area) it is usually referred to as cost-benefit analysis, which aims for selection of the project option with the highest profit (in the private sector) or the highest net benefits (in the public sector). On the other hand, when benefits take place primarily in the form of reduced exploitation cost, with little or no service level change, the life cycle analysis is applied and the case with the lowest life cycle cost is sought. The analyses, linked with the energy preservation, are mostly related to the investment and in-use costs, and therefore the life cycle model is applied (Davis Langdon LLP, 2014).

6.1 Calculation of the Life Cycle Cost by Options

General algebra for a life cycle cost calculation shows that the life cycle cost is the sum of all the project costs, without benefits, over the years of the study period. Both investment and in-use costs are included. Investment costs take place in the present time, while for the other costs principles of money time value are applied. The sum is as follows:

$$LCC = I + Rp - Rs + E + OMR$$

where the abbreviations stand for:
I: present value of investment cost
Rp: present value of replacements cost
Rs: present value of residual value
E: present value of energy consumption cost
OMR: present value of operation, maintenance and repair cost

The mathematical procedure is simple and straightforward after the assumptions on the study period, type and degree of the discount rate, and the cost analysis results are considered, evaluated, and adopted. The rule for decision making certainly means that the project option with the least life cycle cost shows the best economic performances.

6.2 Calculation of Net Savings by Options

Net savings are a measurement of the long-term profitability of an option in comparison to the reference case. The net savings method is a variation of the net benefit method, used when benefits occur primarily in the form of a reduced cost. Net savings result in a sum expressed in present time, which describes how much savings have been made during the study period by the specific option case. It is especially important to note whether the sum of net savings outweighs the sum that would have been achieved through the minimum acceptable rate of return (MARR) which is, in fact, equal to the discount rate.

Net savings can be calculated as an extension of the life cycle cost method to show the difference between the total life cycle cost for the reference case and the total life cycle cost for the option case. Net savings can also be directly calculated from the differences in cashflows between the reference case and the alternatives.

The net savings method can be used to determine the cost effectiveness of a project. If a project is to be considered as cost effective, it means that its net savings are positive. For instance, if there is a positive present value of the net savings for an alternative system of the building, it means that by choosing this system a saving would be achieved during the study period, which would be over and above the savings that would have been made at a minimal acceptable rate of return.

Mathematically explained, net savings equal the difference between the present value of the operating cost savings and the present value of the additional investment cost:

$$NS = (\Delta E + \Delta OMR) - (\Delta I_0 + \Delta Rp - \Delta Rs)$$

where the abbreviations stand for:
ΔE = difference in energy cost in favour of the alternative (reference minus option case)

ΔOMR = difference in the values of the operation, maintenance, and repair costs in favour of the alternative (reference minus option case)
ΔI_0 = difference in the values of the additional investment cost (option minus reference case)
ΔRp = difference in the values of the additional replacement cost (option minus reference case)
ΔRs = difference in the residual values (option minus reference case)

6.3 Calculation of the Savings/ Investment Ratio by Options

Savings/investment ratio (SIR) is an evaluation indicator that describes the relation of the savings versus costs. It is a variation of the cost/benefit index (BCR), used in those cases when benefits take place in the form of a cost reduction.

Savings displayed in the formula relate to those associated with the building use (i.e. energy consumption reduction, and differences in operation, maintenance, and repair costs). A denominator shows the rise of the investment costs (i.e. the rise of the capital investment, differences between the replacement costs and residual values).

Savings/investment ratio as a measurement can be used to determine the cost effectiveness of a project. The index of 1.0 and above generally shows that the project is cost effective. The higher this index is, the higher are the savings for the invested money, and also over and above the sum that would have been saved at the minimal acceptable rate of return. Also, the savings/investment ratio is recommended for setting priorities between the projects when the budget is insufficient to support all the cost-effective options. If the project cost is approximate, which means that the budget cannot be used with great accuracy, the net savings method provides better decision guidelines than the savings/investment ratio. Total net savings can be calculated for the test combinations to find the set of the options that will maximise the total net saving while remaining within the budget framework.

The calculation of the savings/investment ratio (SIR) is conducted by dividing the discounted savings value by the in-use costs, compared with the reference case, and discounted value of the additional investment costs.

6.4 Calculation of the Payback Period by Options

The payback period shows how long it would take the initial investment cost to be recovered by the savings. The measurement is calculated as the number of years between the capital investment and the moment at which the aggregated savings (from which all costs are deducted) have accumulated sufficiently to compensate the investment cost.

The payback period method that is used involves time value of money by discounting cash flows and it is therefore known as the discounted payback period, as opposed to the simple payback period.

Both simple and discounted payback periods as measurements are gravely deficient, due to the fact that all the costs and savings that take place after the achieved balance (or the payback) are neglected. For this reason, it is possible that an option with a shorter payback period turns out to be a worse investment, if entire life span of the project is considered. Where projects for energy efficiency improvement are concerned, it often happens that applied systems need more maintenance and repair as time goes by, and so the in-use costs tend to rise.

The discounted payback period can be used as a supplementary measurement for the following purposes:

– preliminary grading to support the decision to accept or reject;
– assessment of the minimal required life cycle of the project to protect the initial investment funds from uncertainties; and
– determination of cost effectiveness when potential benefits beyond a certain point in time are irrelevant.

A mathematical procedure is conducted by deriving the minimal value of N, for which the following formula is used:

$$\sum_{t=1}^{N} \frac{(S_t - \Delta I_t)}{(1+d)^t} \geq \Delta I_0$$

where symbols stand for
S_t- savings in the use costs that could be attributed to the project option in year t
ΔI_t - additional investment cost in year t, over the initial investment cost
ΔI_0 - additional investment cost for the specific option.

7 Sensitivity Analysis

Risk is defined as the probability of the occurrence of an event or an error, as well as the consequences and the impact of this event or error. Unlike uncertainty, which is characterised by the lack of reliable deterministic values that could be used as the input variables for analysis, risk is subjected to an array of analytical methodologies described and tested in the theory and practice of project management.

Major risks in the life cycle cost study for energy efficiency improvement projects can be identified within the group of adopted input data for the analysis, and from the results of cost analyses. The recommended discount rate results from the various macroeconomic analyses and it is published by the relevant international institution. Of course, this can also be proven wrong under certain circumstances.

Cost analysis is a part of a study in which most of the wrong assumptions can infiltrate, because they are based on estimations that, for numerous reasons, do not necessarily come true. As far as the assumed periods and time of the cost occurrence in the future is concerned, it is more important to consistently apply the assumptions for all options than to predict them with any great precision.

Given that the analyses previously presented are simple from a mathematical point of view, the sensitivity analysis method enables a fast, clear, and understandable way of including the risk factor treatment into the analysis. This method is based on the variation of input data and examination of the changes in results and the consequential conclusions obtained from the life cycle study. Even though it is applicable to all the input data, including the study period and the discount rate, the most interesting domain of its employment would be in the energy sources prices.

By adopting the real social discount rate of 5%, which doesn't include the effects of inflation, it becomes possible not to estimate future costs and benefits, but to use their present time values. The need for complex forecasts and assessments of future events is thereby eliminated. When leaving out the energy sources' respective escalation rates from the calculation, a simplification is made that is unrealistic by nature, but enables the comparison of the options on equal terms. Sensitivity analysis should primarily be directed towards this segment, that is, to alternate energy sources prices in order to observe the consequences that might show up for different economic efficiency indicators of the project options. In the conditions of the transition economy, the obvious approach would be to choose to alternate input data using the energy prices from the closer and more distant surrounding economies. The economies in closer surroundings include countries in a more developed phase of transition, while more distant surrounding countries include developed economies whose overall performances a transition country generally aspires to reach. In this way, it would be possible to observe the trends, presumably reflecting some likely future developments.

The conclusion that follows a sensitivity analysis doesn't have to be straightforward and definite, because the tendencies that are examined through the analyses don't always come true. Whether something will happen or not is influenced by too many factors that cannot be ascertained. However, this procedure gives us the ability to determine which input data can be considered to be more important and more influential in the determination of the results of the final analyse. This can and should be made a part of the concluding considerations of the study.

8 Conclusions

The proposed procedure for the study development is based on an analytical approach on one hand, but also on the adoption of some simplifying assumptions on the other hand. Those assumptions enable us to create a study with an optimal balance of effort, time, and even cost, against accuracy and precision. It would be expedient to make a distinction between the concepts of accuracy and precision. Accuracy describes how well a statement or a data relate to the truth of factual condition, while precision describes how fine is the deviation that is made. The accuracy of an estimate is measured by its closeness to the measurements achieved, whereas its precision relates to the level of refinement, details, and articulation. Obviously, to reach a high level of precision requires a higher level of investment into the study itself, both in terms of money and time. Of course, the ideal achievement would be to have as much accuracy and precision as possible. However, for the sake of the study's credibility, the fact of how true the adopted assumptions are is less important than the consistent usage of all the assumptions and input data for all the project options.

The concluding chapter of the study should provide a summary of the answers to the basic questions that the study was supposed to address:

- Has the higher category of energy efficiency been reached and all the other regulation prerequisites been fulfilled, for all the project options respectively?
- Has the criterion for energy efficiency been fulfilled for all the project options respectively, according to the selected measurements for the particular analysis (costs, net savings, savings/investment ratio, payback period)?
- Do the results of the sensitivity analysis indicate that there is a higher level of risk to question the reliability of the conclusions of the life cycle analysis?
- Recommendation for the selection of the project option.

Even though the results of the study as a whole are measurable and conclusive by nature, their interpretation is still free to some extent, and the analyst can and should present his own criteria and reflections in a certain form. Sometimes, this might be done by adding appendices to the analysis, comprising documentation of various kinds, but in most cases it would be of great use to describe and support in narration what were set as primary criteria, and for what reason have certain measurements been given advantage while the others have been disregarded. Even though we aspire to the automation of the data processing, and inclusion of as many parameters and measurements as possible into analysis, interpretation and decision-making still remain the principle task of the analysts and those who make decisions based on the study results.

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