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Master's thesis

**Design and Performance Evaluation of a Nearly Zero-Energy Office
Building in a Cold Climate**

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Declaration

I hereby declare that this thesis is my own work, that I have not presented it elsewhere for examination purposes and that I have not used any sources or aids other than those stated. I have marked verbatim and indirect quotations as such.

Ingolstadt, 12.12.2023



Igor Baluev

Abstract

Energy independence of commercial buildings is a critical aspect of modern construction. In the context of a planned office building project in Ekibastuz, Kazakhstan, located in an extreme climate with unstable coal energy tariffs, it is necessary to determine the energy needs and understand how to cover them. This thesis focuses on determining the level of efficiency in the use of electricity, reducing dependence on local energy suppliers, and integrating alternative sources. The energy assessment was carried out using software tools such as Autodesk Revit and DesignBuilder, which allow the integration of building information modeling (BIM), building energy modeling (BEM) and energy supply modeling (ESM) to optimize the energy design.

The results of commercial projects aimed at achieving nearly zero-energy building (nZEB) standards have informed the development of two energy concepts, both aiming to decrease dependency on district heating networks. These concepts encompass electrical and thermal concepts. In the electrical concept, the air-water heat pump (AWHP) and electric boiler demonstrated better energy efficiency compared to the thermal concept, which utilized a biomass boiler in conjunction with solar thermal collectors (STC) to mitigate the impact of coal-fired electricity. In addition to reducing energy dependence in the air handling unit (AHU), it is proposed to introduce a ground water-to-water heat pump (GWWHP), which is connected to the surface exchanger to capture heat leaks from central heating networks. A comparative analysis of installations without and with heating recovery unit (HRU) shows a fivefold reduction in electricity consumption for heating supply air. Solar technologies, including STC and photovoltaic (PV) panels, are integrated into each concept, but the limited use of STC makes a PV system the preferred option. The decisions made during the modeling process resulted in a fourfold reduction in the office building's average annual consumption compared to government requirements. Selection of energy efficient equipment and modeling led to nZEB classification for both concepts, achieving renewable energy system (RES) penetration rate from 16% to 33% of total consumption.

Economic analysis using the annuity method highlights the cost-effectiveness of rooftop PV systems compared to façade PV systems. In addition, wood pellets and solar heat help reduce costs in the thermal concept. The environmental analysis shows the significant reduction in carbon dioxide emissions achieved by the thermal concept, highlighting the importance of alternative energy sources for sustainable urban development.

Keywords: office building, near-zero energy building standards, energy independence, Autodesk Revit, DesignBuilder, HVAC, biomass, heat recovery, surface ground exchanger, solar thermal collectors, photovoltaic panels, annuity method, carbon impact

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Abbreviations

AHU – Air Handling Unit
ASHRAE – American Society of Heating, Refrigerating and Air-Conditioning Engineers
AWHP – Air-Water Heat Pump
BEM – Building Energy Modeling
BIM – Building Information Modeling
BTES – Borehole Thermal Energy Storage
CAV – Constant Air Volume
CDH – Cooling Degree Hours
CO₂ – Carbon Dioxide
DHW – District Hot Water
DGCS – Direct Ground Cooling System
ESM – Energy Supply Modeling
GWHP – Ground Water-Water Heat Pump
HDH – Heating Degree Hours
HVAC – Heating, Ventilation, and Air Conditioning
HRU – Heat Recovery Unit
IEA – International Energy Agency
LCOC – Levelized Cost of Cooling
LCOE – Levelized Cost of Electricity
LCOH – Levelized Cost of Heating
MIID – Ministry of Industry and Infrastructure Development the Republic of Kazakhstan
MVHR – Mechanical Ventilation with Heat Recovery
nZEB – Nearly Zero Energy Buildings
PV – Photovoltaic
PVT – Hybrid Photovoltaic-Thermal System
PUR – Polyurethane Rigid foam
QTF – Quadratic Transfer Function
RES – Renewable Energy System
SC – Shading Coefficient
SNiP RK – Construction norms and rules the Republic of Kazakhstan
SPF – Seasonal Performance Factor
USSR – The Union of Soviet Socialist Republics
VAV – Variable Air Volume
VIP – Vacuum Insulation Panel
VLS – Visible Light Spectrum
WWR – Window Wall Ratio
XPS – Extruded Polystyrene insulation
ZSW – Centre for Solar Energy and Hydrogen Research

1 Introduction

1.1 Background

Despite all the efforts of the leading economies during the period of energy market instability, the reduction in the use of fossil fuels as an energy source is belated, deviating from the outlook of world agencies. The global situation in the energy sector of buildings (IEA, 2021) remains at about the same level and represent about 30-35% of total world consumption. Emerging commodity economies are a big contributor to carbon pollution, including Kazakhstan, which is ranked 7th among all countries and produces 1200 tons of CO₂ equivalent (Shulenbaeva, 2021). The Government of Kazakhstan does not leave attempts to turn things, where the situation is fundamentally different from the world and Housing and Public Utilities sector represent about 43% of all energy consumption (Syzdykbaev, 2022). The current situation requires a different approach in the process of implementing a new technology that exists today, namely zero-energy building, passive house, and other energy efficient standards.

Since 1992, Kazakhstan begins a new history of a market economy and imports without the creation of safety mechanisms, which led to the country's first crises, forced to build a completely new economic model. Kazakhstan remained a raw materials appendage of the former USSR and the main supplier of natural resources for manufacturing enterprises. In the period of 2000, the country entered a new stage of socio-economic development and a period of rapid industrial growth. Soviet building regulations governed the application of building codes until 2017, while the Ministry of Industry and Infrastructure Development (2020) made the first attempts at an integrated transition by proposing the first amendments to the rational use of natural resources:

- rational use of energy is considered at an early stage, considering the future climatic location of the building,
- the orientation of the building ensures natural heat retention,
- implementation of modern air exchange systems, in view the complete thermal insulation of the building,
- environmental friendliness is determined by the reasonable consumption of natural resources and the reuse of building materials,
- improving the microclimate inside the building through the introduction of passive and alternative systems at the initial stages,
- energy-saving lighting and introduction of automatic control and monitoring systems.

Existing building standards regulate their strict observance to achieve environmental friendliness, safety and create comfortable conditions in the building. Thus, all changes in the construction code of Kazakhstan (SNiP RK № 31) are aimed primarily at reducing energy consumption, which leads to a decrease in environmental impact. The regulation

of technical requirements for the main elements of the building envelope (walls, roof, and floor) is carried out by the standard (SNIIP RK № 406, 2016), which suggests that modern thermal insulation standards will change the energy balance by recognizing the importance of energy conservation measures inside buildings. Depending on the climatic zone in the Republic of Kazakhstan, the following minimum insulation resistance properties of building elements are established and are given in Table 1.

Table 1: Minimum thermal resistance

Building elements	warm zone	cold zone
	minimum R-value, (m ² ·K)/W	
roof	3.5	4.5
wall	1.8	2.5
floor	2	1.5

The minimum thickness and thermal performance requirements for various types of insulation materials are determined by SNIIP RK № 31, which is necessary to protect building structures from overheating and damage, ultimately increasing the longevity of buildings. Kazakhstan companies such as TechnoNICOL, KazRockwool, Knauf Insulation and KazTermoStroy suggest various types of insulation materials: mineral wool, extruded polystyrene foam (XPS), polyurethane foam (PUF), and others. Each manufacturer has its advantages and disadvantages, as well as different prices for its products which can be found on local online markets such as Mtc-sg. Table 2 shows the dependence on the type of insulation, where the following minimum thermal conductivity properties, their prices and the insulation thickness are established.

Table 2: Minimum thermal conductivity, insulation thickness and prices

type of insulation	k-value, W/(m·K)	frame	masonry	prices (m ²), euro
		walls	walls	
thickness, mm				
Mineral wool	0.044	50	60	2.5
XPS	0.034	40	50	6.2
PUF	0.022	25	30	3.9

The inability to provide energy efficient energy delivery is due to problems of obsolete equipment's and the destruction (Popova, 2022) of central heating networks, which leads to significant losses: up to 20% of all losses in transmission networks, and up to 80% in distribution networks. The government fixed the maximum consumption rate by the SNIIP RK № 15-10313 for zones:

- warm climate no more than 150 kW·h/m²·year,

- cold climate no more than 250 kW·h/m²·year.

Despite energy laws is Kazakhstan, the leader among countries (Zhampiisov et al., 2014) in terms of building heat consumption according to Figure 1, which needs on average three times more energy per unit area than the Nordic countries.

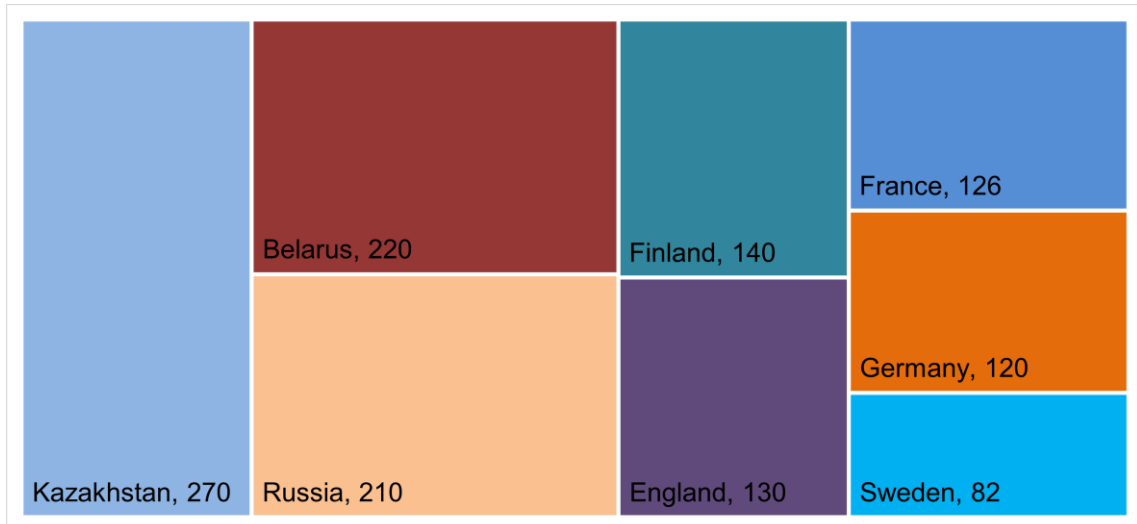


Figure 1: Annual building heat usage in kWh per square meter by country

Climate change requires a reconsideration of the approach to the design and construction of buildings, considering new energy-efficient technologies, primarily in the field of renewable energy sources especially in Kazakhstan. Depending on the building needs during the heating or cooling period, the supply of energy must occur without interruption and with minimal losses, which will lead to efficient use of energy. The choice of the optimal option among various promising technologies depends on the climate and local conditions at the planned construction site. With respect to commercial buildings, the exploitation of solar and thermal energy in combination with high-efficient materials will avoid additional losses for the business.

There are various solutions today to integrate alternative energy sources in different climatic regions to provide a whole building with enough energy. Researchers (ZSW, 2021) determined that it is enough to cover 25% of the office facade and use only a third of its the roof area by PV (photovoltaic) to meet electricity demand of the five-storey building model. In another investigation (Braun et al., 2020), a hybrid photovoltaic-thermal (PVT) system in different climatic zones for non-residential buildings was established that it is theoretically possible to cover the needs, also from an economic point of view with a payback within 3-10 years. Minimization of energy consumption (Yin et al., 2017) is possible by using a hybrid system consisting of an air source heat pump and a water tank in addition to a solar collector, which will reduce electricity consumption by a third with an optimal operating strategy. The aim of the following study (Nord and Wall, 2013) was to select the HVAC (heating, ventilation, and air conditioning) strategy

for the office with passive building standards in a cold climate, resulting in a choice between a solar collector with a geothermal pump and an electric boiler, where in favor of the traditional use of electricity was the fastest payback. Modeling of office with active cooling ceiling (Arghand et al., 2021) in a cold climate, based on an experimental DGCS installation, showed that ground temperatures of different depths and the developed floating control system were sufficient to achieve the thermal comfort. As a result of experimental hybridization (P.Sanmamede et al., 2020) of the system using heat pumps, solar PVT panels and geothermal wells with the theoretical possibility of storing underground thermal energy, where the final operating temperature was less than 50 °C, a significant reduction in heat and electricity consumption was confirmed.

An important stage in the building design is the choice of energy-efficient construction materials, without which it is impossible to effectively use the generated energy. Ensuring a sufficient level of the building insulation overall (Aditya et al., 2017) is the correct choice of insulation materials for external walls, roofs and ceilings, where the main goal is to select the optimal insulation thickness with the highest possible economic and energy benefits (20-55%) depending on the natural and/or new technology materials. In search of the optimal scenario (Atmaca et al., 2021) for building transparency and thermal comfort using dimming and enclosing structures, where various ways to reduce energy costs were considered, the following provisions were highlighted: excessive building transparency (75%) both helps to heat rooms and can become a source of thermal bridge, it is recommended to use roller shutters and windows with triple glazing; enclosing walls structures with an increased thickness of the heat-insulating material reduced the heat load of the building with 50% of transparency by a third; it was possible to achieve minimal energy consumption and losses with a decrease in the transparency of the building to 25%, although it was necessary to increase the consumption of thermal energy instead of solar. The shape and orientation of the building also contributes to the overall energy efficiency, as it was modeled (Hamzaa et al., 2022) that the East-West building orientation reduces electricity consumption and increases the generation of electricity, and the closed building with a square and compact shape had the maximum energy saving potential. The high building standard (González et al., 2021), which maintains a balance between energy consumption and its local renewable production, despite uneven demand, allows this building type to be designated as nearly zero-energy (nZEB). The detailed nZEB reports in Table 3 by Erhorn and Erhorn-Kluttig and in Table 4 by Garde and Donn made it possible to identify various characteristics of commercial buildings and understand the final energy consumption and production methods, which will be used as a reference point for creating the projected office building.

Table 3: Technical characteristic of the new office nZEB examples

Office case studies	Main material description					
	construction		U-value, W/(m ² ·K)	energy system	energy use, kWh/m ² ·year	
KBC Gooik Zero	concrete structure,	ground	0.18	concrete core activation,	HVAC	55.0
Energy Office,	stone façade,	wall	0.20	BTES with a heat pump,	lighting	33.2
Area = 265 m²,	PUR and XPS insulation,	window	0.87	PV rooftop	PV generated	89.7
30% of RES	triple glazing	roof	0.13		Grid electricity	291.0
Rakvere Smart	prefabricated concrete,	ground	0.14	low-temperature CHP,	HVAC	56.7
Building,	PUR insulation, hollow-core	wall	0.07	CAV and VAV systems,	lighting	10.5
Area = 2170 m²,	slab roof, triple glazing	window	0.8	ground heat rejection,	PV generated	13.3
23% of RES		roof	0.08	PV rooftop	Grid electricity	97.9
Horizont-Building	concrete structure,	ground	0.19	concrete core activation,	HVAC	45.5
Strassen,	mineral wool insulation,	wall	0.13	pellet and gas boiler,	lighting	23.4
Area = 3200 m²,	triple glazing	window	0.82	scroll compressor,	PV generated	37.6
84% of RES		roof	0.11-0.18	PV rooftop	heat boiler	1.8+10.7
					Grid electricity	105.9
Miljøhuset GK,	concrete structure, EPS and	ground	0.07	automatic solar shading,	HVAC	31.9
Area = 13619 m²,	mineral wool insulation,	wall	0.14	AWHP, electric heat system,	lighting	12.5
24% of RES	triple-paned windows	window	0.78	MVHR, PV and STC rooftop	PV generated	-
		roof	0.10		solar collector	-
		thermal bridge	0.03		Grid electricity	-

Table 4: Technical characteristic of the new office nZEB examples

Office case studies	Main material description					
	construction		U-value, W/(m ² ·K)	energy system	energy use, kWh/m ² ·year	
Alpine Refuge	prefabricated elements,	ground	0.19	MVHR 85% efficiency, latent	electricity demand	70
Schiestlhaus,	air-tight vapour barrier,	wall	0.13	energy storage with STC, PV	PV generated	15
Area = 550 m²	extremely high insulation	window	0.7	façade, biomass CHP	CHP generated	72
	levels, passive windows	roof	0.12			
Villach Offices &	prefabricated wood,	ground	0.11	MVHR plate type 75%	electricity demand	96
Apartment,	PUR and mineral wool	wall	0.14	efficiency, GWWHP, roof PV,	PV generated	207
Area = 292 m²	insulation, triple glazing	window	0.94	CHP	CHP biofuel	76
		roof	0.09			
Day Care Centre "Die	Polyurethane and mineral	ground	0.16	MVHR 85% efficiency,	electricity demand	132
Sprösslinge",	fibre insulation, triple-glazed,	wall	0.1	radiant heating and cooling,	PV generated	43
Area = 969 m²	thermally separated glazing	window	0.8	STC with gas boiler,		
		roof	0.12	GWWHP (SPF 4.59)		
Marché Kempthal,	mineral wool insulation, triple	ground	0.11	MVHR with up to 75%	electricity demand	78
Area = 1550 m²	glazing	wall	0.12	efficiency, PV, GWWHP	PV generated	63
		window	0.73			
		roof	0.09			

The projects under consideration are primarily situated in cold climates, and an alternative approach to reducing dependence on fossil fuels allows these projects to be designated as nZEB category. When choosing building structures, preference is given to energy-efficient technologies: concrete and metal structures, natural or synthetic insulation, triple-glazed windows. The choice of materials is guided by the goal of achieving an optimal heat transfer coefficient (U-value) for the building envelope or individual structures. So, for example, the optimal U-value of walls can be considered 0.1-0.15, and the roof structure should reach values of 0.15-0.2, but the main source of heat loss will be windows.

The choice of energy systems includes a wide range of different types of devices that can reduce consumption and increase the efficiency of nZEB. The foremost preference is given to thermally active technologies such as radiant floor heating or cooled ceilings, which can connect to an underground heat source for energy storage. To increase the adoption rate of alternative sources, there is a noticeable trend towards the frequent utilization of biofuel or natural gas boilers, while mechanical ventilation with heat recovery (MVHR) clearly allows reducing the electricity consumption for supplying cold fresh air. Energy generation systems such as STC (solar thermal collector) or PV make it possible to reach about 30 percent of the total balance of consumption of buildings. It is important to note that a portion of the electricity is allocated to non-HVAC needs, including office equipment or lighting.

Possibility in the process of building information modeling (BIM) is creating set of systems (Accasoftware, 2022) that considers all the parameters of the model, from materials and planning to a complete analysis of all processes inside and outside the construction. A priority would be to evaluate the impact and energy potential of a BIM model, which requires exporting data for building energy model (BEM), but this process presents several challenges, which in turn involves a comprehensive validation of parameters for a more accurate performance analysis in the initial building phases. An experimental comparison of various structures (Lee and Ham, 2016) of the office building with respect to the values of changes in thermal resistance R showed that the “wall” component is more sensitive to changes in resistance than the “roof” component in cold conditions, but at the same time the “window” component has the least effect on the model energy state regardless of weather conditions. In another study by Durdyev et al. recommended changing the approach to the design and construction at the inventory stage of BIM, which helps to evaluate, and as a result, reduce energy consumption and increase the energy efficiency of buildings by about 10%.

The combined use of BIM and BEM (Allothman et al., 2021) allows to reach the recommended parameters and evaluate which change in the building structure contributed the most energy efficiency (HVAC and wall), and which parameters affected the least (orientation and roof). The study Boafao et al. found that modeling the situation

at the initial stages will predict the heat transfer coefficient change, the implementation of effective solutions in the field of insulation (VIP panels) of buildings carries additional risks of the appearance of the thermal bridge effect due to heterogeneity and the wrong choice of material layer. The success of the BEM modeling process (Mehta et al., 2020) depends on the parameters initially set (e.g., cold climate or insulation materials) which consequently ensures that the results of the energy simulation are covered through the energy supply model (ESM).

1.2 Scope

This thesis suggests different ways of solving the provision of alternative energy for an office building, which is planned to be built in Ekibastuz, Pavlodar Region, the Republic of Kazakhstan as illustrated in Figure 2. Passive building and energy technologies should determine all important priorities in this project. First and foremost, it is the energy efficiency and energy independence of a building built in an area with 100% production from coal. The profitability of a project depends on the amount of energy generated and saved, and therefore on the amount of savings, which can be determined using the simulation of energy processes implemented in the initial stages of construction. The office building modeled in Autodesk Revit will allow data to be imported into DesignBuilder. The assessment of the possibility to cover energy and heat needs will be carried out in detailed analysis using DesignBuilder.



Figure 2: Future construction plan of the office building

Based on the obtained values of energy demand, it is necessary to select the optimal option for heating and cooling, considering energy-efficient technologies. Subsequent energy concept options require economic and environmental analysis to determine the most suitable solution.

1.3 Current situation

The transition period of the economy is determined by the growth of the required investments in the energy sector. Observers note (Kapital, 2019) that the gap between energy consumption and production is growing by 2030. The foundation (more than 53%) of the energy industry is made up of equipment from the 1960s-1980s, the shutdown and repair of which leaves the population and the economy without energy. The implementation and development of energy systems (Samruk Energy, 2022) is slow, but within the limits set by the government as shown in Figure 3.

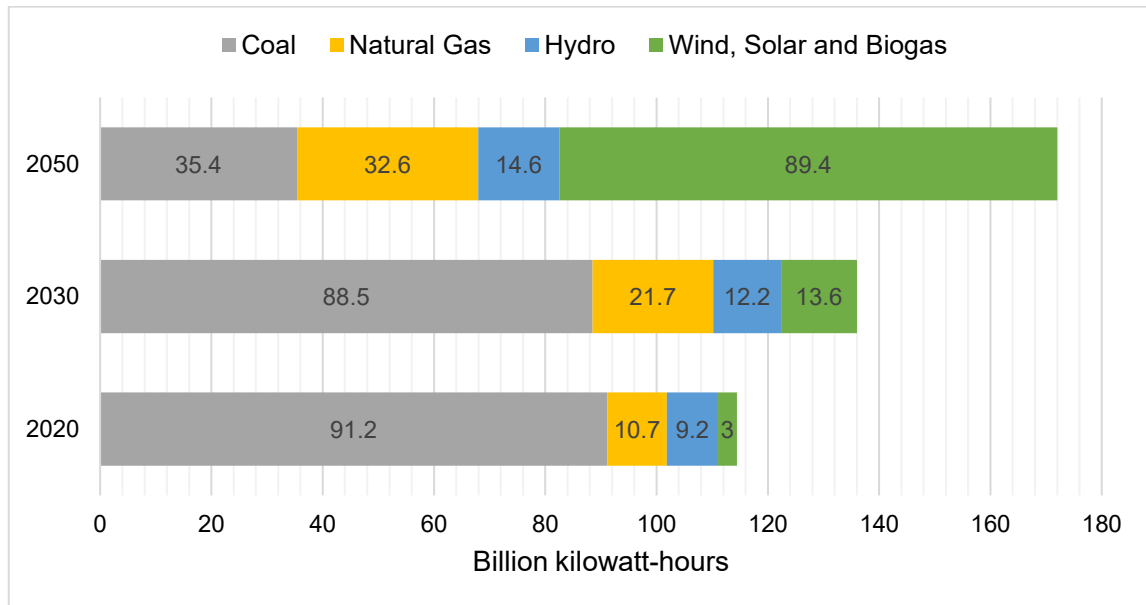


Figure 3: The Republic of Kazakhstan energy demand projected to 2050

In the near future, no one plans to abandon coal either, where its share in the energy balance will only grow until at least 2050, so it is incorrect to talk about the decline of the era of coal, and especially in Kazakhstan. So, by 2020 it was possible to bring up to 3% in the country's total energy system, and by 2030 it is planned to achieve a 10% balance between alternative and fossil sources. It is worth noting that the government has not made enough efforts to support the energy transition of the small business sector, focusing on large projects, providing tax incentives only to large companies with up to 50% investments.

One of the main sources of electricity in the Republic of Kazakhstan (Kubekov, 2014) is Ekibastuz with its coal-fired power plant, where a production capacity of 4000 MW covers 17% of the country's total energy consumption. Despite the city's importance as a major source of energy, the current state of mid-century equipment calls into question the security and independence of the planned office building. At the same time, the heating tariff for business (Pavlodarenergo, 2022) and the population is the highest in the country. Amid unrest and popular discontent due to rising prices, the government of Kazakhstan (Tengrinews, 2022), in turn, is engaged in the regulation and containment

of utility tariffs, or rather it introduces a moratorium, forcing energy companies to deplete their production capacities. Insufficient level of management by the regional government is another sore point that leads to losses, blackouts and unreasonably high electricity tariffs (Pavlodarenergo, 2022) which cannot be said about other types of energy from biomass (RBC, 2020) and district heating, as can be seen in Figure 4.

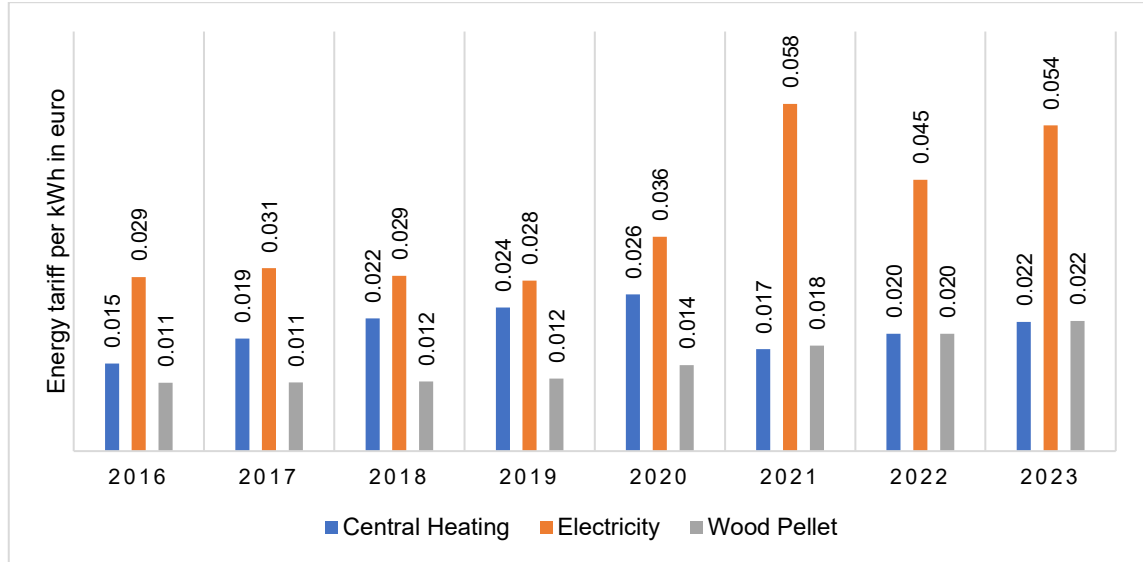


Figure 4: Energy prices in euros for business in Ekibastuz

Ensuring a warm building is a high priority in cold climates, but current heating conditions make this problem either impossible or costly. More than 36,000 news (Pavon, 2022) were analyzed to confirm this situation. As a result of studying, it was found that the Pavlodar region, including Ekibastuz, was left without centralized heating or hot water supply more than 120 times over the past 10 years, as can be seen in Figure 5.

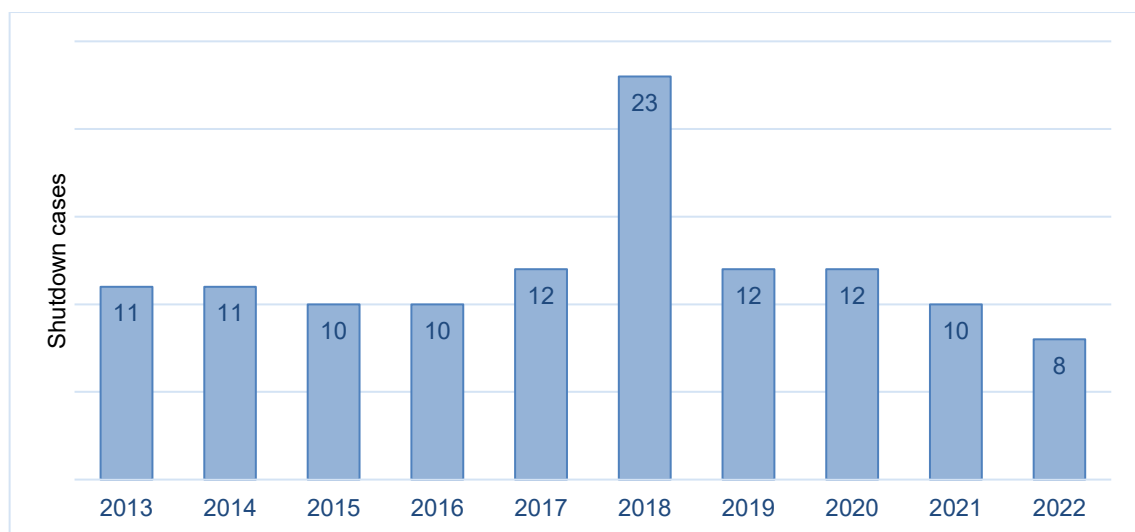


Figure 5: Shutdown cases of heat supply in Pavlodar region

Dependence on district heating, based on inefficient technologies, forces energy companies to invest in the modernization of heat networks, which only slows down the irreversible process, which can be stopped only with a 10-fold increase in the amount of work. The main cause of emergencies can be considered the actions or inaction of city's utilities, when the process of testing heating networks before preparing the cold season, as a result, puts the entire system out of operation as shown in Figure 6.

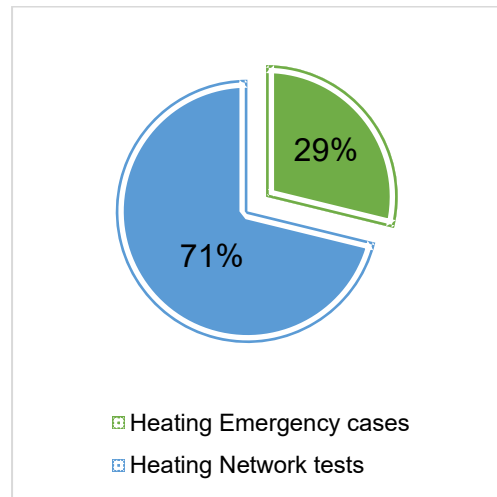


Figure 6: Summarize of heat shutdown cases in Pavlodar region

The heat supply is carried out by a separate thermal boiler plant, which requires more than 400 wagons of coal daily from the largest "Bogatyr" deposit near Ekibastuz. The energy monopolist (Popova, 2022), despite the opportunities and availability of coal, has lost 7.5 million euros over the past three years, where additional heating costs account for more than 70%. The next heating season remains in doubt because it is unprofitable for the company, transferring responsibility to the government. For example, there have already been such situations (Caravan, 2019) when the company refused to work at a loss, then decided to turn off the hot water supply to the entire Ekibastuz for the summer, explaining this by excessive losses in the last heating season. The situation (Volkova, 2021) is aggravated by the inability to modernize equipment and heating networks, the wear of which is more than 84%, all this leads to losses of more than 600,000 GCal per year only in Ekibastuz. However, without infrastructure for the use of urban heating networks, businesses (Pavon, 2018) are encouraged to independently create conditions for connection, the cost of which exceeds more than 200,000 euros with a lengthy bureaucratic process.

The current situation (Gorodpavlodar, 2020) with power grid is quite stable compared to heating system, depreciation and amortization of which has reached 60%. The nature of outage cases is usually temporary with fast local recovery. Energy companies can cover only 20% of the required tariff, meaning more blackouts. Only in Pavlodar region (include Ekibastuz) for 2018-2019 more than 500 MW of electricity was lost, which is shown in Figure 7.

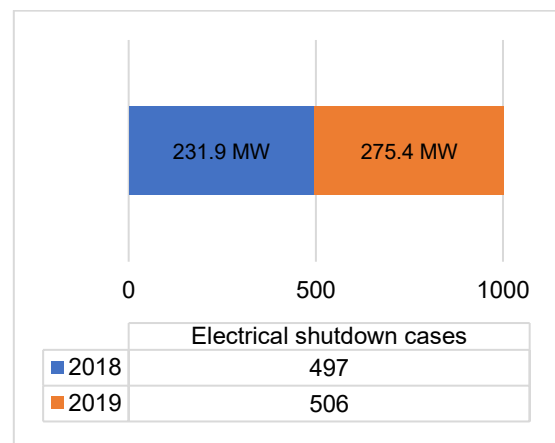


Figure 7: Summarize of electrical shutdown cases in Pavlodar region

Although the construction of new industries (Zakon, 2015) worsens the already poor environmental situation around Ekibastuz, the government did not leave the attempts to make the most environmentally unfriendly city in Kazakhstan, where each inhabitant was accounted for more than a ton of harmful emissions annually. The world's tallest CHP chimney (420 meters) was built in Ekibastuz in order to mitigate the environmental impact on the population, where now, according to satellite images (Novikov, 2021), the spread is far beyond the city borders: smoke – 65 km, nitrogen oxide – 270 km, sulfur oxide – more than 1000 km.

1.4 Problem and question

The rational use of energy is essential in achieving sustainable development goals and generating clean energy, which is especially important in mining areas. The energy state of Ekibastuz is highly dependent on industry and is a by-product that cannot guarantee the independence and continuity of electricity and heat for the office building. The relevance of the study lies in the search for optimal opportunities to meet the needs of the building through the introduction of promising technologies in the field of construction and decentralized production by alternative sources. Energy efficiency improvements are assessed by considering various scenarios through computer simulations of the proposed technologies, where the options will be evaluated both economically and environmentally. These requirements for the optimization model determine the key research question: is it possible to determine an economically viable and energy independence option optimized for the climatic conditions of a given region, considering possible ways to obtain neutral types of energy?

1.5 Thesis outline

In search of the optimal building model, from the standpoint of energy efficiency and energy independence, considering the lowest technology costs, the following thesis outline can be formulated:

- section 1 reports the experience of implemented non-volatile buildings, provides insights into how energy efficiency is enhanced with modern technologies and materials, also explains the future goals of the office building, which should ensure the transition to alternative goals, describes the current status of heating, energy supply, and ecological problems, while identifying prevalent issues and questions for further research.
- section 2 provides a general description of Kazakhstan, consider weather conditions, includes an examination of the geothermal aspects of the construction plan, visualizes the future building with planned characteristics, draws up possible energy concepts and considers the implementation of alternative technologies.

- section 3 offers an overview of simulation programs used in the thesis, facilitates the transformation of information models with problems and solutions, provides identification of building components, identifies the identification of specific building components and the determination of energy requirements based on various building activities, summarizes results of renewable and energy studies.
- section 4 determines the optimal financial solution for each concept according to investment and cost analysis, finds cost-effective solutions and their ecologic impact on environmental.
- section 5 and section 6 make a conclusion of work performed, provides a platform for discussing future avenues of research and development in this field.

2 Methodology

2.1 Overview

The Republic of Kazakhstan is located in Central Asia and covers an area of 2 million 724.9 thousand square kilometers, where more than 19 million people. More than 3/4 of the territory of Kazakhstan is occupied by plains, where deserts and semi-deserts represent 58%, steppes occupy 26%, while forests cover only 6%. The main branches of industrial production are mining, ferrous metallurgy and petrochemistry. The level of the material and technical base is assessed as inferior to advanced economies, where the problem lies with the loading of production capacities and heterogeneity of electricity consumption in some parts of country. Ekibastuz is in the coal basin area, which accounted for 35% of the total country volume and produces a fifth of all electricity from this coal as illustrated in Figure 8 which based on Dreamstime, Solargis and Assembayeva.



Figure 8: Global energy map of Kazakhstan

Sustainable development is impossible without the conservation of natural resources and further pressure on the environment, where increasing emissions and backwardness in low-waste technologies will increase the already high level of climate impact. The potential for the development of renewable energy in Kazakhstan is quite high, hydropower, wind, and solar energy deal with the growing challenge energy shortage. Industrial cities such as Ekibastuz, whose economy is based on the extraction of minerals, cannot boast of the possibility to develop alternative energy. The gradual introduction of small decentralized systems or large wind, solar or hydro plants will help to turn the tide and eliminate dependence on burning minerals.

2.2 Climate conditions

2.2.1 Temperature

The extreme continental climate of Kazakhstan is influenced by its distance from the world's oceans. The change in climatic zones from south to north is determined by the average temperature from 0 to -20 °C in January and from +19 to +26 °C in July. The Pavlodar region is placed in a humid climate, where the length of the winter period is 7-8 months a year with high level of snowfall, after that the population suffers from insufferable heat with the onset of the summer period. Over the entire observation period, the minimum temperature in Ekibastuz dropped to 47 °C, while the average temperature (Meteonorm, 2017) in January is usually -16 °C, when in July the average temperature can be considered 21 °C according to Figure 9.

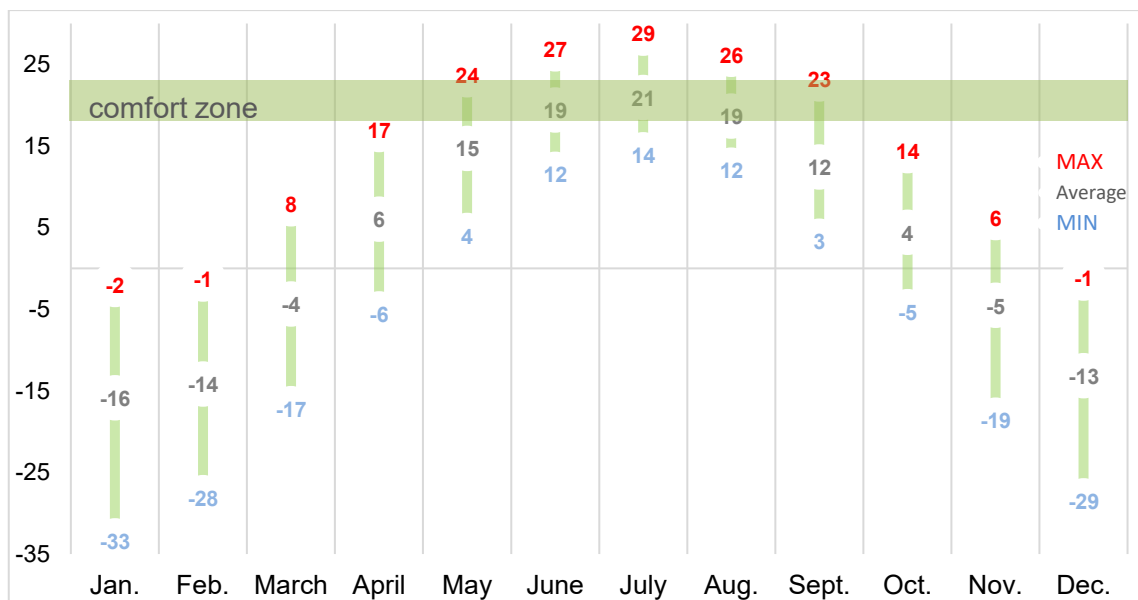


Figure 9: Monthly maximum, averages, minimum temperature data in Ekibastuz

Figure 10 shows a comparison of outside temperature data that directly affects the final energy profile of the office building. During the period when the average temperature falls below the limit for office workers' comfort (18 °C), the heating needs of the building must be covered. The small amount of comfort hours is common in these weather conditions. The unequal ratio between the degree-hours required to cool (24 °C) the office building is the goal in reaching the comfort zone.

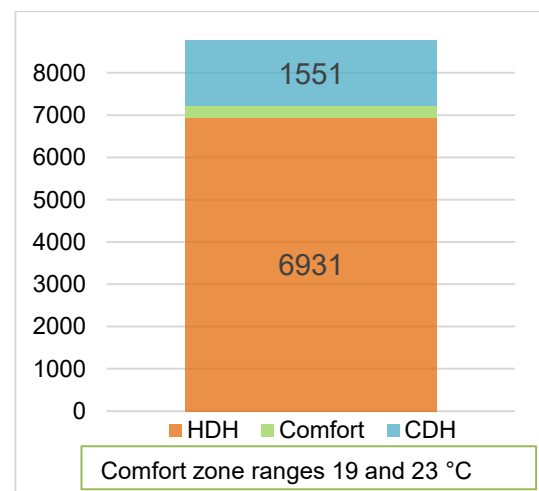


Figure 10: Heating and cooling degree hours in Ekibastuz

2.2.2 Solar energy

Total energy generation from the sun in Kazakhstan is negligible, despite the annual duration of sunshine from 2000 to 3000 hours. A big feature of Kazakhstan and its location is that in the warm season the number of cloudy days does not exceed 60 in the north and 10 in the south. The difference of level total irradiation (Meteonorm, 2017) between the summer and winter period is usually 3-4 times according to a day length and the sun angle as shown in Figure 11.

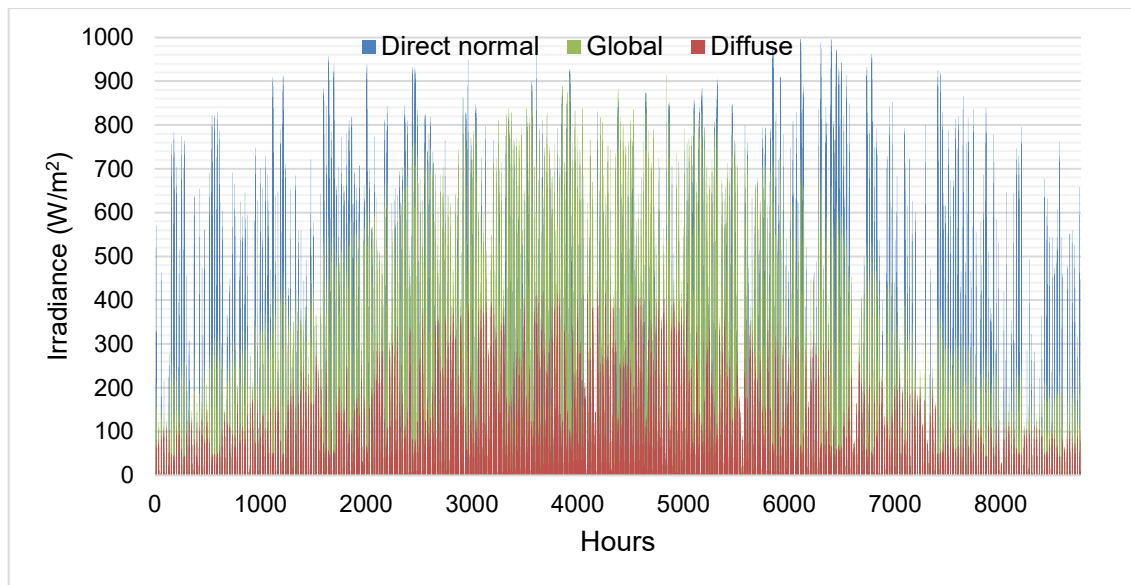


Figure 11: Direct normal, global, and diffuse horizontal irradiance in Ekibastuz

The calculation of the annual global irradiance in Ekibastuz totaled 1313 kWh/m². Subsequent analysis of solar radiation showed the difference between the intensity of the average peak hour during the year. So, the maximum average value of energy production per square meter during the year can be considered 6 kWh according to Figure 12.

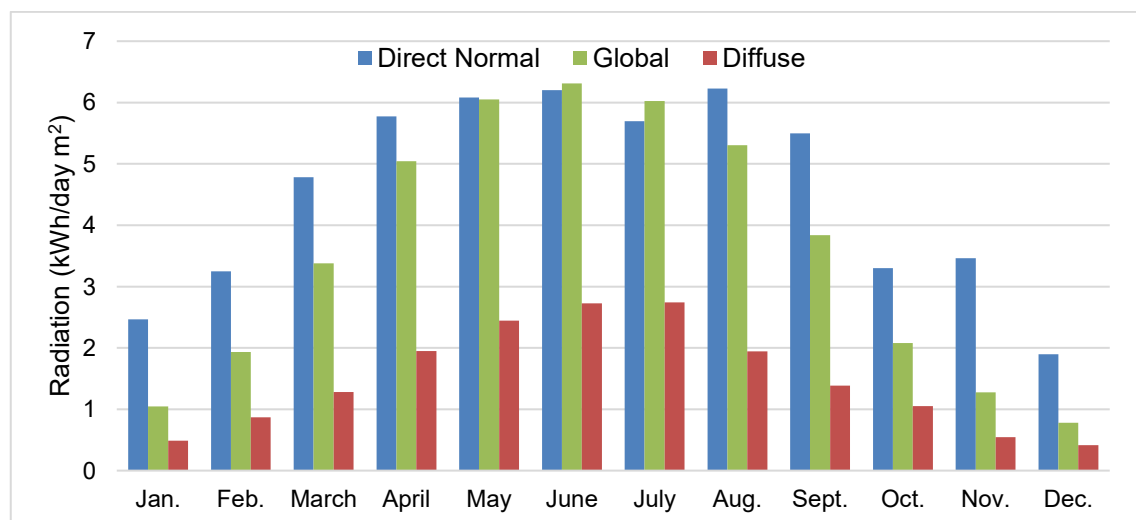


Figure 12: Monthly average daily solar radiation in Ekibastuz

The difference between winter and summer solar activity affects the size of the system and the way radiation is used as an energy source, especially a solar collector. The location of the office building allows to use solar energy throughout the year, both as a source of natural light and PV panels or STC, depending on the azimuth position, as presented in Figure 12 which based on Reimlex.

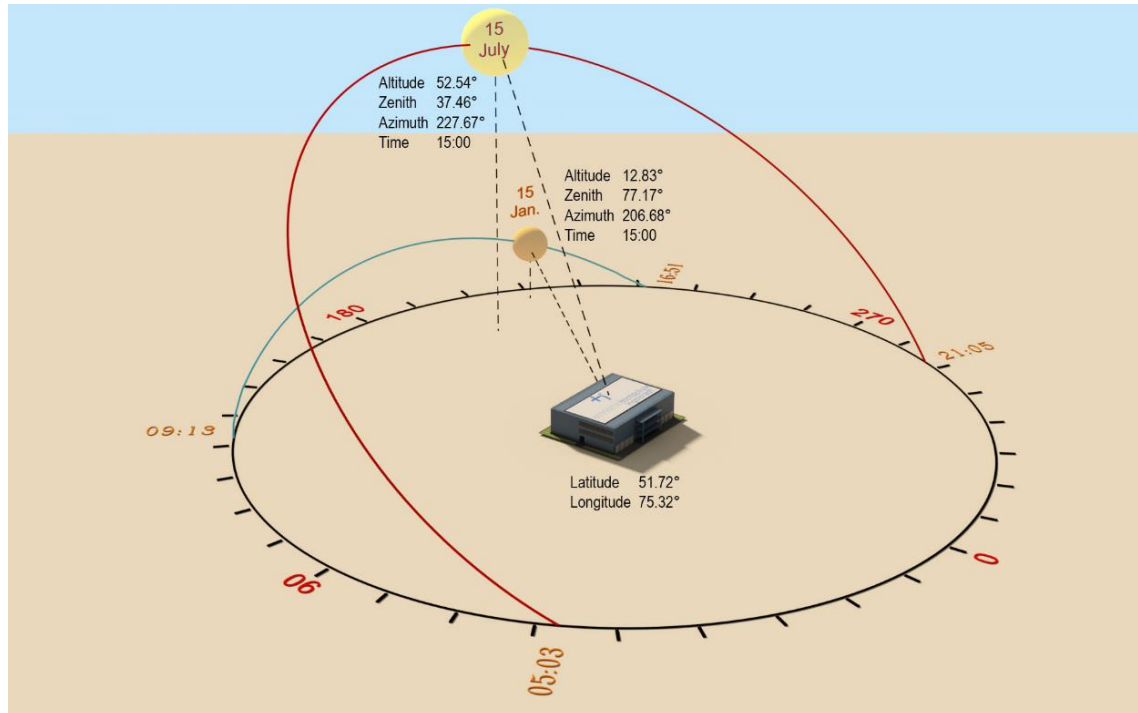


Figure 13: Render of sun path diagram for summer and winter time

The optimal tilt angle was determined by researchers Jacobson and Jadhav as 42° for flat plate solar collectors and PV panels to achieve the highest energy yield for office rooftop installation in Ekibastuz. This statement will be verified by simulation in the following sections.

2.3 Geothermal opportunities

The geological survey can be considered a preparatory stage before the construction of the office building, which reflects the current hydrogeological conditions along with the physical and mechanical soil properties. Sampling by drilling (Kazakhstanproject, 2013) was carried out at a depth of up to 17 meters, after that the samples were subjected to various studies in the laboratory, based on the results of which the following conclusions can be drawn:

- the depth of seasonal soil freezing is 2.2 meters.
- the geological structure of the area is composed of three genetic complexes: a bulk layer of 0.3-1.4 meters, consisting of loam and construction debris; hard and semi-hard sandy and clay deposits, with various layers at a depth of 1.4-3.5

- meters; deposits of clay and loam with interlayers of sedimentary rock and gravel formed an unstructured eluvium deposit at a depth of 7.8-10.9 meters.
- surface water-bearing soil is exposed in layers and pockets of clay at a depth of 1.4-1.7 meters with a possible seasonal water rise to a level of 0.3-0.5 meters, where the main source is atmospheric precipitation and water leakage from city's utilities.
 - weak water saturation of clay reduces soil deformation, while a middle aggressive effect of water on reinforced concrete structures is noted.

Currently, while more modern heat supply schemes are emerging and being introduced, coal heating remains the only source of heat energy in the northern cities of Kazakhstan. The process of converting energy from coal to steam carries large losses at every stage. All consumers in Ekibastuz are provided with heat centrally through heating networks in the winter period, and in the summer periods hot water is delivered through these pipes. Further distribution of hot water through heating networks is also associated with frequent accidents and shutdowns, especially in winter.

As noted previously, the current state of heating networks has been deemed structurally deficient, where the level of depreciation reached almost 90%. Considering the heating network as an extended and branched pipeline system designed to transport heat, it is necessary to assume the inadmissibility of using this type of energy as the main source of heat supply. In the case of the project under consideration, the laying of an underground pipeline is carried out close to the future construction site along Abay Avenue in Ekibastuz.

As is well known, the performance of central heating depends on the coolant, the temperature of which is 130-150 °C for 8 months a year, during the warm season the temperature drops to 70 °C. So that a relatively high temperature, it becomes possible to utilize the thermal field of the heat pipeline, which is lost through the insulation and the air channel, heating surrounding ground area. Ideal conditions (Golyak, 2005) have shown that the temperature fields propagating along are capable of heating and maintaining the surface temperature of more than 30 °C. Moving away from the heating point gradually lowers the gradient of temperature fields, the isotherms of which extend 10-15 meters in different directions. A long-term experimental observation (Kashperuk and Pyatkin, 2017) in one of the largest cities with central heating showed approximately the same effect on the formation and distribution of temperature fields in the zone of active influence of engineering structures. The difference between the temperature data and borehole measurements allows specifying the maximum temperature amplitudes of the soil surface, for example the annual summer value was 32 °C, and above 7 °C in winter. However, it is important to note that this study did not indicate the impact on the increase in ground temperature due to damage and leakage from heating networks because the overall condition of urban communications (Pavon, 2021) is not as

deplorable as in Pavlodar region. In addition, accidental leaks, even short-term, recorded (Zabolotnik, 2015) in the coldest city in the world, lead to temperature increases up to 50°C and 15 meters of depth, and when the accident is eliminated, the subsequent recovery of the temperature soil field takes more than 2 years. Regarding the current project, it is impossible to accurately determine the temperature of thermal fields and their distribution without detailed annual measurements, but the low water saturation of the soil suggests that the process of heating the soil thickness occurs approximately in the same way as in the considered articles. Parametric analysis of the problem allows to assume Figure 14 and the possibilities for further use in this project.

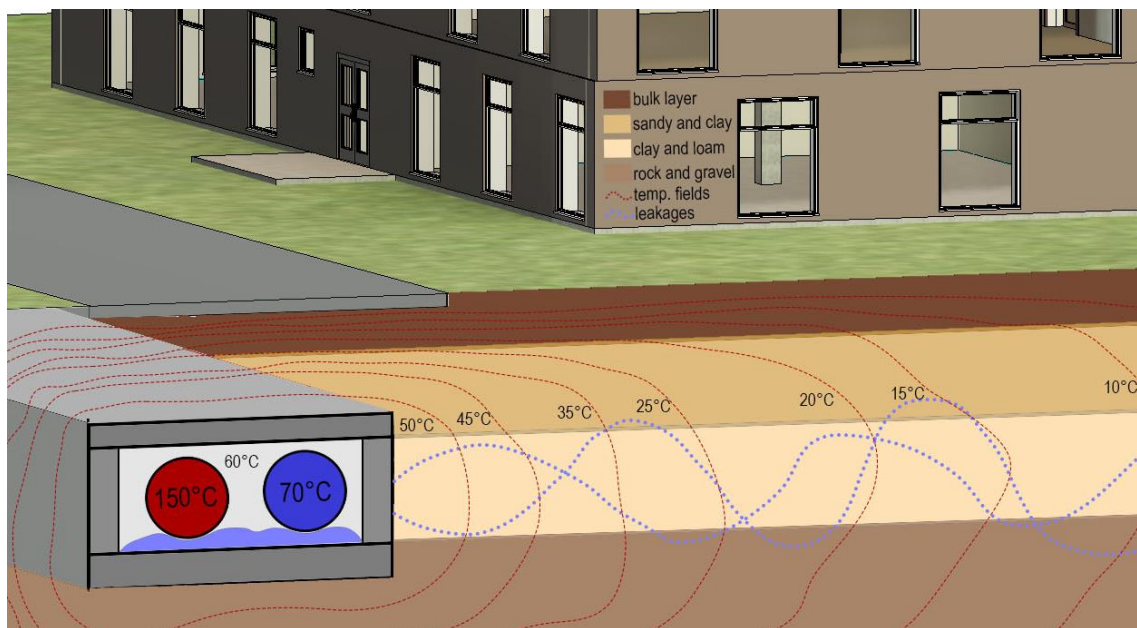


Figure 14: Formation and distribution of temperature fields

Extreme operating conditions and aggressive environments lead to damage and subsequent heat leakage, which allows the use of central city heating as a passive source of heat energy. It is possible to use temperature fields for heating and cooling with an adjacent location of the building site and pipelines, for example, using underground heat pumps in the range of 12-18 °C at a depth of 1.5-2 meters.

2.4 Office BIM description

The location of the construction site of the future office building and its orientation makes it possible to characterize options for the efficient use of solar energy in the center of the industrial city. It is planned that the building will consist of three floors with a total height of 8.7 meters, the width of the building will be 31 meters and a depth of 27 meters. The total area of the office building will be about 2300 square meters. The floor plan of the building implies an open and compact common office space, which also ensures good air conditioning, daylight distribution and air circulation. For example, on the first floor, besides the two office spaces, are a canteen and a warehouse, which can be seen in

Figure 15. The second and third floors will have the same planning and will be divided into four large office spaces of 150 square meters, which will be used as coworking.

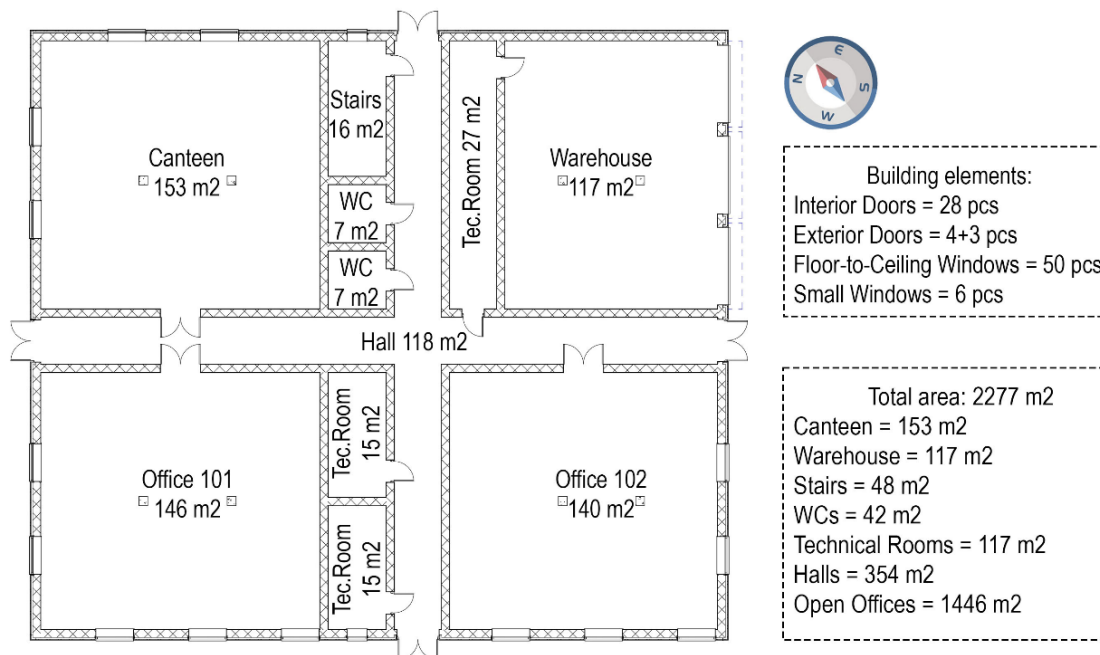


Figure 15: First floor plan of the office building

Preliminary creation (Stamenov et al., 2016) of the project using BIM programs is carried out to make a forecast and the general profile of the building thermal and electrical load, which allows timely assessment of the strengths and weaknesses of the project, especially when the initial information is not enough. Based on many assumptions, the following decisions are made:

- follow the given dimensions of the building, considering the possibilities and ergonomics of the open office space,
- the West-East orientation of the building relative to the construction site is assumed, additional shading from nearby building is considered,
- the choice building materials and thickness of the insulating structures must comply with the weather conditions and the building standards of Kazakhstan,
- consider the general requirements for heating, cooling, and ventilation to create a comfortable environment based on the rational use of energy resources.

The process of creating BIM (Stamenov et al., 2016) can be thought of as an intellectual process, but together with Autodesk Revit, modeling turns into a process of adaptation of the initial idea, where the visualization takes the form of work on errors. The convenience of the Revit tool (Autodesk, 2022) lies in the fact that the creation of a model is carried out through the erection of walls and their connection to the finished building, which allows to work with data and be imported into BEM for clarifications and deeper energy analysis.

Recommended materials as well as possible measures for ensuring energy efficiency in cold climates are considered, which will subsequently require clarification in next sections with BEM. The visualization of the project was based on owner sketches in Autodesk Revit as shown in Figure 16.

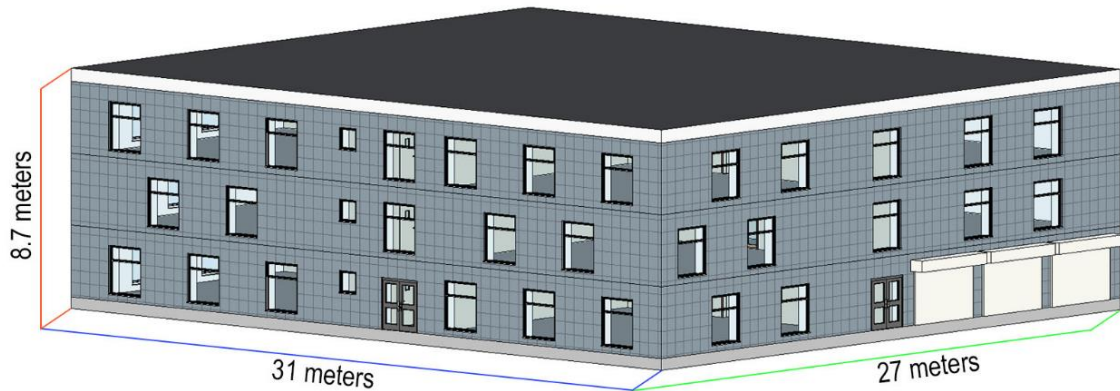


Figure 16: BIM of the office building

An important element in a building is the window, which has a great influence on the natural influx of solar energy. The distribution of vertical panoramic windows throughout space will increase the daylight flow, which in consequence will reduce the consumption of electricity for lighting. It should also be considered that the excessive use of transparent structures carries the risk of affecting the decrease in the heat transfer coefficient, since the window is a thermal bridge with significant losses in cold weather.

In the case of the current project, it was decided to use a percentage ratio of 30% between the windows and the walls of the building, as the most effective according to section 1.1. Incorporating Low-E windows (Stanekwindows, 2017) with low emissivity triple glazing into the model will allow sunlight to pass through but reflect internal heat energy back inward, thus significantly preventing the office building from losing energy efficiency.

The introduction of efficient building technologies in combination with HVAC systems will save energy in comfortable conditions, especially when the climate is subject to global changes. The study (Jacobs, 2007) confirmed that a building where the main building material is concrete which more adaptable in both warm and cold environments, also further reduces energy consumption. Kah et al. also recommended the use of cement in the construction of building structures, the main thing is to consider the level of thermal insulation that prevents the appearance of cold bridges and excess moisture.

In the design of the office building, it is approved to apply:

- monolithic foundation with a continuous insulating layer, where the thickness of the cement layer is approximately equal to the rigid insulating material layer, the polyethylene air barrier provides a gap between the concrete slab and the insulation, the membrane layer reduces the risk of condensation, the granular backfill layer eliminates pressure on the structure,
- external walls, where the laying of concrete blocks helps to seal the outside with a lighter layer of insulation along with metal siding, and inside a heavier one to stabilize comfortable conditions,
- flat roof with double insulation between the concrete part, the roofing felt avoids heat loss.

Figure 17 shows the structural properties of the building envelope.

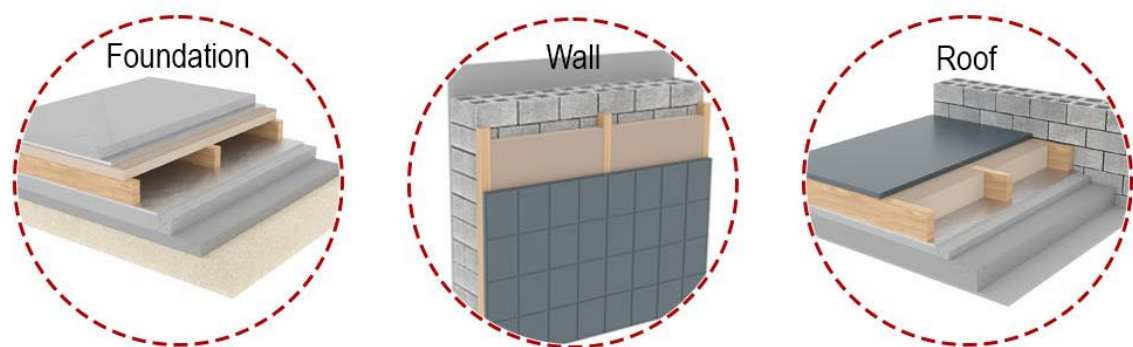


Figure 17: Render of building structures and materials

Overall energy efficiency depends on properly selected components that are interconnected in an envelope. The composition of these components and materials is required to provide a complex relationship between their resistance and heat transfer in search of optimal thermal comfort. The development of sustainable construction is impossible without the correct selection of insulation materials and construction technologies.

According to the selected building materials, there will be a further transition between BIM and BEM, but already at this step it is possible to estimate the approximate thermal characteristics of the building components. When choosing an insulation layer or building thickness, it is important to monitor the optimal level of thermal properties, such as R-value and U-value, so as not to overload the overall building structure. Synergy between HVAC technologies and the correct selection of building materials is essential to positively contribute to a project's environmental sustainability. The tight connection between the structural design and the chosen materials creates an accurate representation of the model's energy future as can be found in Table 5.

Table 5: Building material properties from Revit before exporting to DesignBuilder

Building component	Description		Thermal properties	
Floor-to-Ceiling Windows: Area = 170 m²	Low-E triple glazing with aluminum frame		R-value	0.687 (m ² ·K)/W
			U-value	1.45 W/(m ² ·K)
			SC	0.5
			VLS	0.64
Foundation: Area = 876.3 m²	Concrete,	70+180 mm	R-value	10.44 (m ² ·K)/W
	membrane,	5+5 mm	U-value	0.096 W/(m ² ·K)
	air barrier,	150 mm		
	PUR foam,	80 mm		
	sand cement	300 mm		
Exterior Walls: Area = 791.4 m²	Masonry,	350 mm	R-value	9.65 (m ² ·K)/W
	fiberglass insulation	120 mm	U-value	0.103 W/(m ² ·K)
Flat Roof: Area = 876.3 m²	Concrete,	50+150 mm	R-value	10.32 (m ² ·K)/W
	membrane,	5+5 mm	U-value	0.093 W/(m ² ·K)
	PUR foam,	250 mm		
	roofing felt	20 mm		

These thermal properties and material descriptions have a crucial role for the energy design and analysis of heating and cooling in DesignBuilder. Ensure that this information is accurately transferred to the DesignBuilder software to achieve reliable and effective building performance simulations and energy analyses.

2.5 Energy concepts

The construction of the office building is planned in an area with only one source of heat energy. Central coal heating leads to wasteful production (Bely, 2021) of thermal energy, where 2.5 times more resources has to be spent for each square meter compared to international standards and practices. In a cold climate and with a lack of access to the gas network, the only way out is the reasonable use of "coal" electricity. Decentralization of alternative energy sources reduces dependence on city utilities, improves resource management efficiency and creates a comfortable environment in the office building.

It is assumed that in the current conditions, when it is required mainly for heating, two concepts for project development are possible: electrical and thermal. The first concept involves rational consumption of electricity from the grid in addition to solar and the earth energy. The second concept involves using as many alternative independent heat sources as possible from the energy of the sun, the earth and biomass. Restrictions in

the office building design do not allow the use of underfloor heating, so the only available way to distribute heat is through a radiators network.

Electrical Concept (Figure 18) is based on the production of electricity utilizing solar PV panels on the roof and facade of the building. In this case the main consumers will be an electric boiler, an air-water heat pump (AWHP) and a ground water-water heat pump (GWWHP), which is capable of heating and cooling office space. The AWHP will act as a main source of heat supply, which will be assisted by the electric boiler during particularly cold periods. The city's power grid will become the main source in the event of PV electricity production shortage.

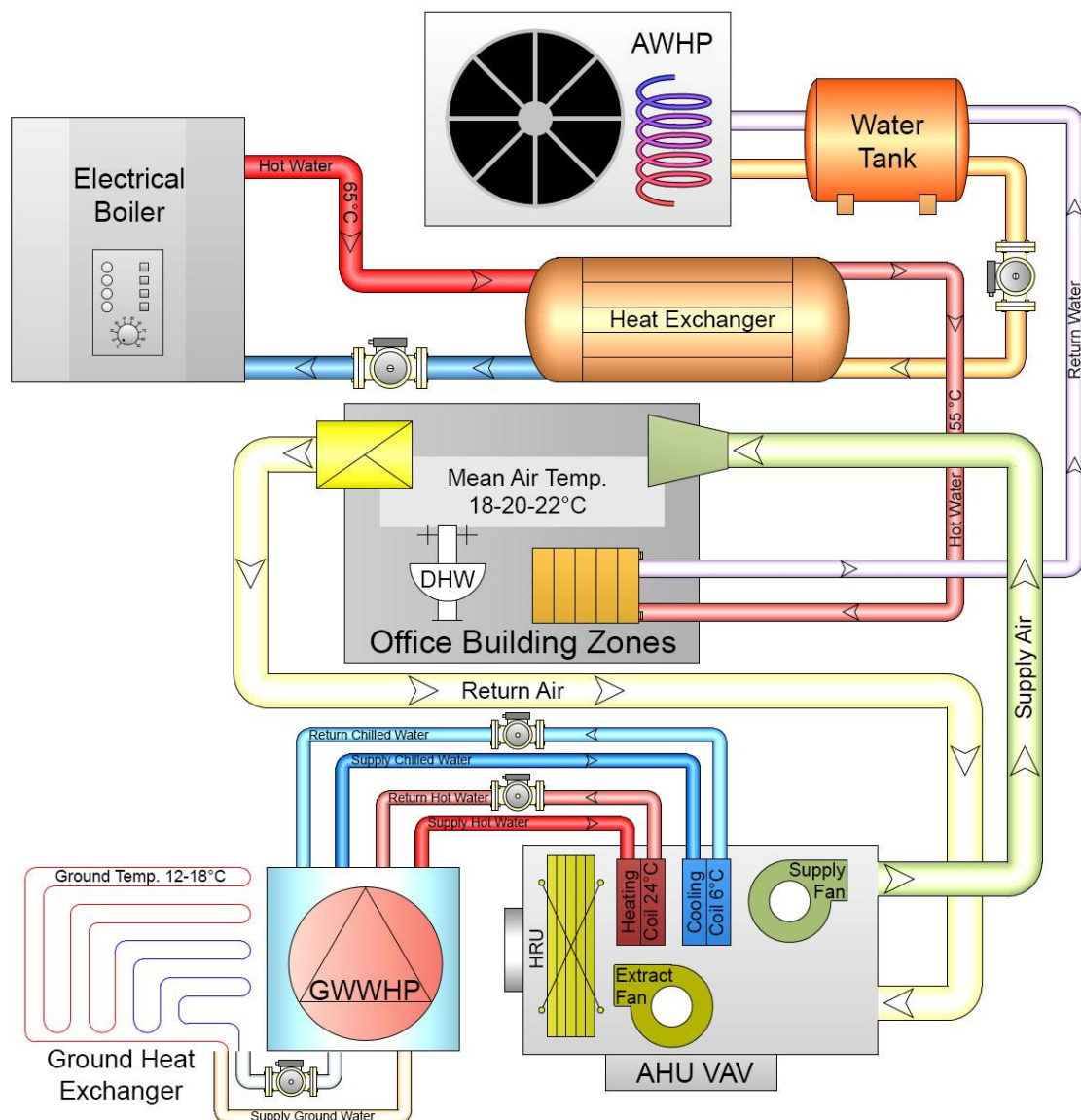


Figure 18: Electrical concept

Thermal concept (Figure 19) assumes that vacuum STC installed on the roof will be the main source of energy. In especially cold periods and during low solar activity, it is possible to apply a wood pellet boiler to set a comfortable temperature or cover the entire

load of the building. Removal of excess thermal energy from the system is possible through the cooling coil and GWWHP.

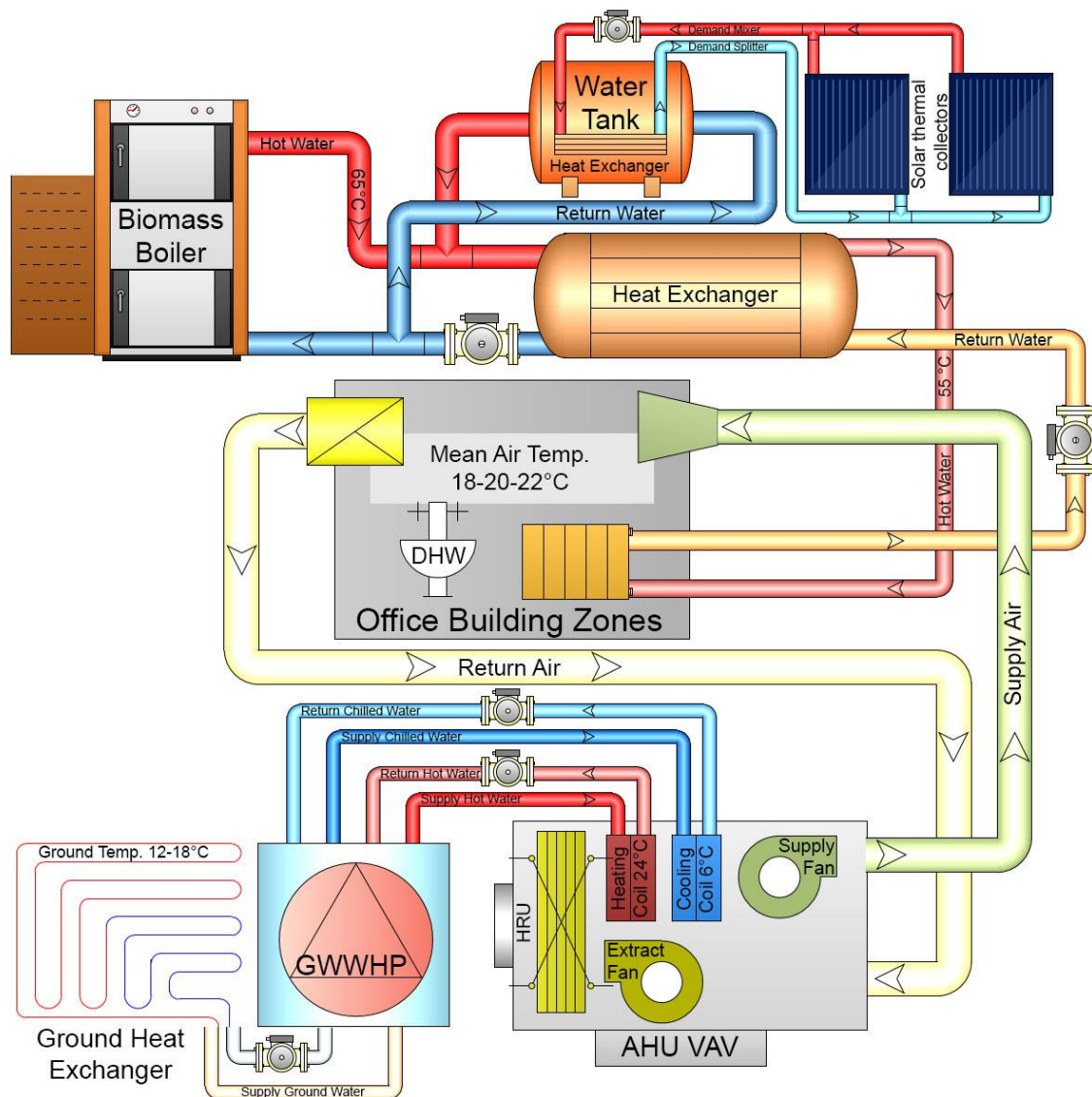


Figure 19: Thermal concept

In both concepts, energy distribution and conservation are facilitated by a ventilation system and a network of pipes connected to radiators. To ensure optimal performance, fresh air supplied to the ventilation system should be preheated during winter and cooled in summer. It is possible to reduce energy consumption with the help of a heat recovery unit (HRU), which can minimize ventilation losses through heat exchange between the exhaust air and the outside air.

2.6 Model pre-processing

Any building modeling process (Lack and Butler, 2019) is based on inputs such as location and weather conditions, project objectives and special requirements that must be considered from the start. Integrating BEM and ESM into every phase of information

modeling enables energy efficient decisions to be made before construction even begins as can be found in Figure 20.

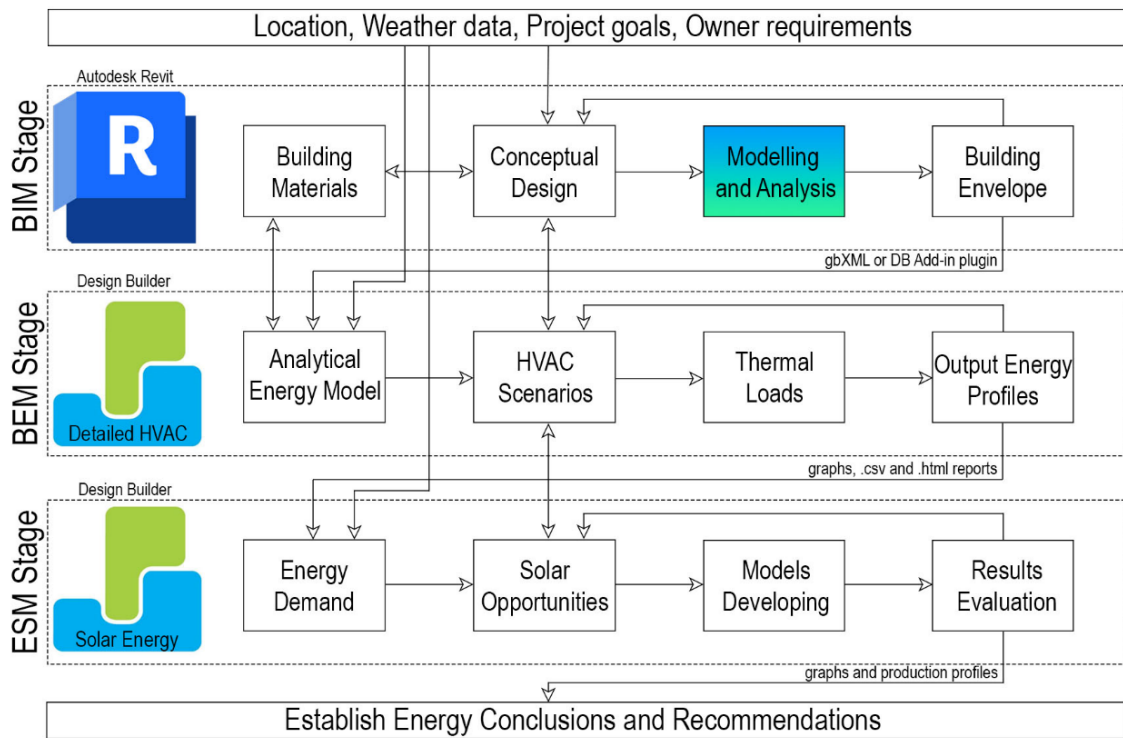


Figure 20: Data exchange between BIM, BEM and ESM stages

When moving from one module to another, it is required to check and compare the resulting values to prevent errors and reduce them quantitatively, including between different types of simulation. As a result, it is necessary to supplement the modeling scenario to achieve the maximum energy efficiency of the building, which will not allow achieving pre-conceived goals without the use of passive and active technologies.

3 Energy Modelling and Simulation

3.1 Detailed energy methods

The energy characterization of the building and its elements is based on detailed energy methods such as the Finite difference method (FDM), Finite element method (FEM), Computational fluid dynamics method (CFDM) and Radiant heat transfer method (RHTM). These methods are the basis for accurately predicting the process of heat transfer between system components, while existing modeling tools simplify this process. Process modeling takes place in programs where detailed methods allow to optimize HVAC systems and implement energy efficient solutions in building structures. Energy analysis of buildings (Reinhart, 2018) is not possible without programs such as eQuest, Open Studio or DesignBuilder, which provide an objective view of the performance throughout its entire life cycle. The easy-to-use DesignBuilder program, built on the EnergyPlus engine, was chosen as the main tool for analyzing the distribution of alternative and traditional energy in the office building as shown on Figure 21.

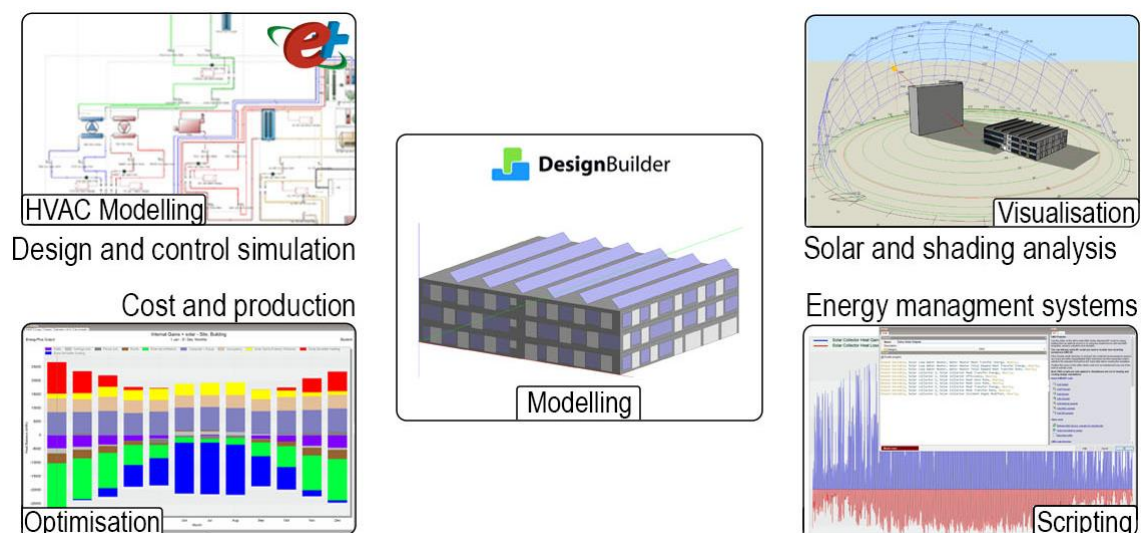


Figure 21: DesignBuilder modelling

The office building will be implemented using the DesignBuilder program, which provides all the possibilities for a correct analysis, for example:

- creation, transfer and editing of 3D models,
- visualization of solar activity, determination of the shading effect from neighboring buildings, production of solar and thermal energy,
- detailed optimization of the building envelope and HVAC systems, the performance of which is directly dependent on weather conditions, occupancy, non-energy efficient equipment and other factors,
- repeating simulation as many times as necessary to find the weaknesses of the model.

The process of HVAC detailed modeling in DesignBuilder occurs through several functions built into the program. A library of various schemes and components, among which climate equipment can be distinguished, makes it possible to configure the HVAC system according to the required comfort conditions. Creating own equipment control strategies improves the energy efficiency of a building and helps determine the effect of implemented systems, such as CO₂ effect or control of alternative heating system. The program provides a detailed report of energy consumption not only for the entire building, but also for each of its zones or specific equipment, which allows to evaluate losses and identify those areas of the building that need replacement or improvement. As a result, this affects thermal comfort, for which there are also tools for evaluating, optimizing, and ensuring the comfort of office visitors.

Building performance modeling capabilities by DesignBuilder are widely used to create detailed simulations of HVAC systems. The software tools enable to predict the optimal equipment for extreme climate, low solar activity, and varying office building occupancy. The building's heating and cooling processes are modeled while considering potential losses through the building zones and gains from external influences during the day. The software also enables control over the ventilation and air ducts, allowing the adjustment of fresh air supply according to sanitary and epidemiological requirements. Providing comfortable temperature and humidity is possible with the help of control systems, which are also used to achieve the efficient operation of the entire HVAC system.

The entire process of managing building operations is carried out either through the scheduling and occupancy of spaces or by using a setpoint manager. The setpoint manager is responsible for monitoring and maintaining comfort parameters, such as temperature and humidity. By achieving the desired levels of these parameters, it ensures optimal performance for each HVAC source in the office building. To promote efficient resource utilization and prevent damage to the structure due to extreme temperatures, it is essential to set limitations on equipment availability.

Implementing alternative solar systems can further reduce consumption of biomass fuel or electricity from urban networks. The integration of solar collectors and PV panels into the model is achieved using the "surface" tool, where each component has its own defined properties. Thermal energy transfer from the surface of solar collectors takes place through a pump, which then delivers it directly to the heating system. The energy generated by PV facade and roof system is processed by inverters, the excess of which is supplied to the city's electrical networks.

3.2 BIM-to-BEM model transformation

Properly prepared conditions (Rathnasiri et al., 2020) for transferring an analytical model from one environment to another directly affect the intermediate result of information modeling. The Revit model contains a lot of information that is not required for energy

analysis but limits the simulation results. First, it is necessary to check (DesignBuilder, 2018) the properties and values of the elements, on the basis of which the building characteristics are identified on Figure 22.

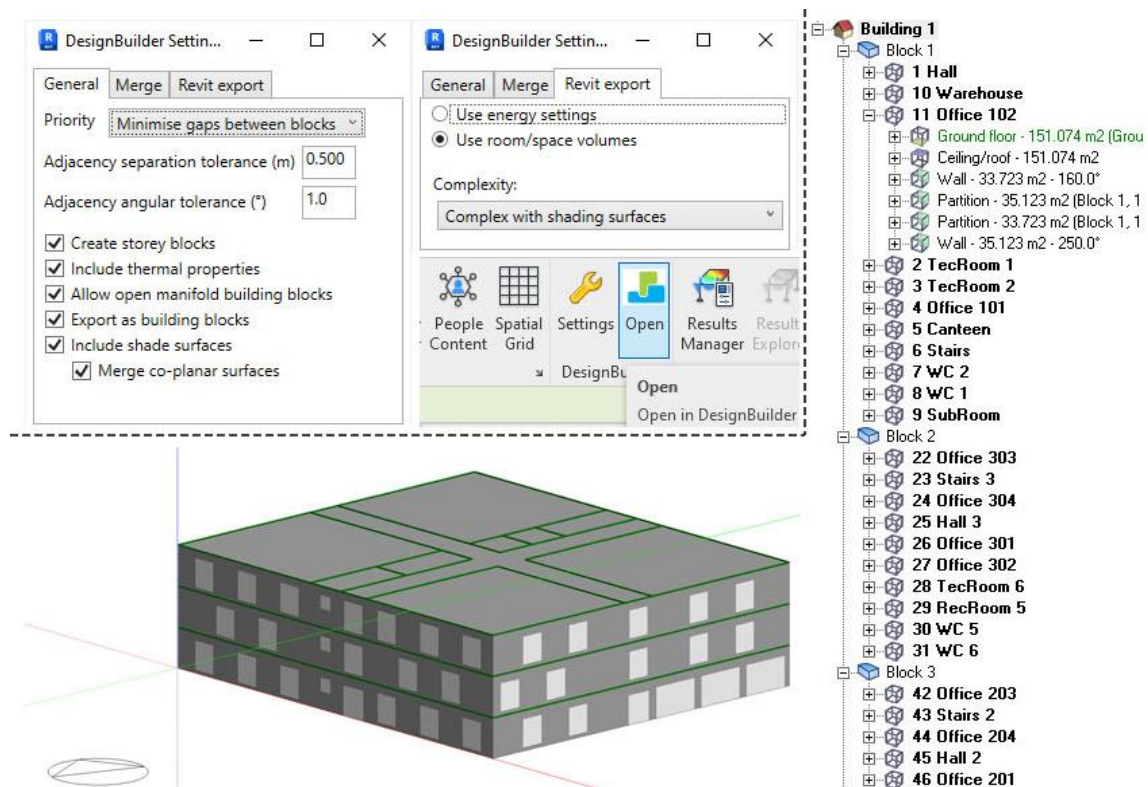


Figure 22: Information transition between Revit and DesignBuilder via Add-In plugin

There were a series of attempts to transform BIM to BEM which revealed differences in building design and materials, and it is also worth noting that it was possible to create the original view only with a "complex" transition. In other cases, the size of the windows and their location were distorted, but even with this approach, a structure of the second floor occurred, where the North part of the building was divided into 2 blocks. This problem with incorrect data transfer is confirmed by Porsani et al., who recommend checking the design for: missing materials library, changing the model size, errors of floors and walls recognition. The only solution suggested by the researchers is to change the model structure in DesignBuilder, which still saves time compared to creating a new model in BEM. Thus, the correct division of space using limiting elements (walls, floors, and ceilings) guarantees the correct identification of the room volume. Some elements (columns) must be disabled via the "Room Bounding" parameter, because it distorts the room model. In case the model is exported using Add-In plugin from DesignBuilder, it is necessary to check "Settings", where each parameter has its own important function for a successful transformation from BIM to BEM. So, the accuracy of detailing depends on the "thermal properties" parameter, which is responsible for modifying the model and building materials. It is necessary to choose what information will be exported – "Energy settings" or "Room volumes". Complexity as a parameter is responsible for the level of

detail, where a “simple” analysis is sufficient, but a “complex” exports all information without losing properties.

The office building model is composed of "zone groups" with parameters determined by their thermal properties. This model optimization process involves grouping similar rooms with identical structures. The "zone" configurations maintain the consistency of the HVAC systems, enabling the identification of problematic areas within the model. Additionally, the performance of these systems is influenced by the unique busy schedules associated with each "zone" type. The interaction between the model elements and DesignBuilder occurs through the method of energy balance, which is used by EnergyPlus to achieve real energy results. The main step of setting up of HVAC simulation begins with the selection of general information regarding the construction site: geographic location, climate zone, weather conditions. Table 6 shows properties for subsequent HVAC modeling between BIM and BEM, as well as insulation and construction characteristics, which required clarification.

Table 6: Building properties of BEM

Occupied area	2314 m ²	
Conditioned volume	6031 m ³	
Construction materials	block (masonry) and aerated concrete	
Insulation materials	PUR foam, fiberglass	
U-value	ground floor	0.098 W/(m ² ·K)
	below grade walls	0.154 W/(m ² ·K)
	external walls	0.169 W/(m ² ·K)
	flat roof	0.166 W/(m ² ·K)
WWR	30%	
Glazing type	Trp LoE (e2=e5=.1) Clr 3mm/6mm Air	
Shading devices	None	
Envelope Infiltration	0.3 ac/h	
Natural ventilation	off	
Annual ground temp.	12-18 °C	

Before running an HVAC simulation by DesignBuilder is required to ensure that the building structure and its elements are specified exactly as the original BIM model, considering thermal properties and structural layers. The blocks of the model are divided into rooms, the functions of which are strictly determined by the parameters of the surface. To ensure that all transformation operations were successful, it should be verified how the model displays the transferred internal and external surfaces.

The subsequent setup refers to the building and its preparation for the HVAC simulation. It is required to choose which occupancy profile is more suitable for the office building to achieve real results, which determine the daily occupancy on weekdays and weekends. Regarding the building, it is planned that most of the office space will be used as co-working with permanent occupancy. Another important factor influencing the final consumption is the lighting and equipment that will be used by the occupants. Balancing the extraction of exhaust air and the introduction of fresh air also demands significant electricity usage. However, adopting an appropriate ventilation approach can mitigate this energy consumption. The night mode of supply and exhaust fan operation provides a constant value of the air change rate (Axair fans, 2021) according to the type of building. Simultaneously, it is required to start supplying fresh air in advance (Lestinen et al., 2021) to cultivate a comfortable workspace environment for office personnel. Table 7 will display the main parameters before starting the HVAC simulations.

Table 7: Parameters of the office activities, lighting and HVAC set-points

Occupancy density	8 m ² /person	
Occupied schedule	Mon-Sat	Sunday
	7:00 – 18:00	off
Comfort temp.	Office zones	Rest.
	20-22 °C	18-20 °C
How water consumption	0.1 liter/(m ² -day)	
Office equipment power density	11.77 W/m ²	
Lighting template	Open plan, 8.72 W/m ² at 100 lux	
HVAC zone setpoints	Heating	Cooling
	12-22 °C	24-28 °C
Mechanical ventilation	5:00 – 18:00	
	10 l/s per person	3 ac/h
Mechanical ventilation: without and with HRU	Air Handling Unit: Variable Air Volume	
	Only Recirculation	Recirculation
		Economizer (12 – 25 °C)
		Frost control
Heating recovery (plate type, 75% eff.)		

Further possible ways to obtain the results of office building requirements in DesignBuilder: simple and detailed HVAC analysis. The main difference between detailed and simple modelling is the ability to obtain more accurate results that are close to real conditions. The optimal control strategy will make it possible to determine the system's operating schedule, including during the worst periods of the year. Optimizing HVAC parameters improves the energy efficiency of equipment and reduces its energy consumption. The project involves the use of different sources of energy generation,

which will allow for scaling the size of the systems, including initially considering the maximum implementation of alternative systems.

Heating and cooling equipment are the primary energy consumers in the model. By creating detailed simulations of systems such as boilers, chillers, heat pumps, and fans, an optimal balance of energy sources can be achieved. “Autosizing” function determines the power of each type of equipment, which facilitates the selection of the appropriate system size based on the maximum power consumption. Boilers generate and distribute thermal energy (e.g., through a pipe system) especially during cold periods, which primarily use electricity or biofuel. Secondary heat sources may include heat pumps that utilize air and ground heat. In warmer periods, heat pumps are necessary to remove heat and reduce room temperatures. A comprehensive ventilation system helps distribute both cool and warm air to enhance overall comfort.

The obtained results of several simulations will allow for establishing the optimal balance between internal conditions and energy efficiency, which will significantly increase the environmental friendliness and efficiency of the building. By analyzing the final report on energy consumption, users can identify the system's weak points, leading to the optimization of individual components or a modification of the project's initial concepts. Overall, an integrated approach to creating an HVAC system model can contribute to partial energy independence from external conditions.

3.3 Model's energy needs

In addition to heating and cooling sources, it's essential to model the behavior of the office building's envelope to identify its energy losses and weaknesses. The appropriate selection of building materials and insulation is crucial for controlling heat leakage during cold periods and retaining cool air during particularly hot periods. Equation 1 presents the general energy demand (Q_D) method (Borodinecs, 2014) of the relationship between losses and gains during heating or cooling period in view of correction (η_L) and utilization (η_G) factors, which can be analyzed to identify potential areas for improvement and energy-saving measures.

$$Q_D = \eta_L \cdot (Q_{tr} + Q_{ve}) - \eta_G \cdot (Q_{sol} + Q_{int}) \quad (1)$$

The building envelope transmission losses (Q_{tr}) consists of several components that ultimately determine the overall energy efficiency and performance of the model. In this context, each component is classified as a vertical (walls), horizontal (floors and ceilings), or movable barrier (windows and doors), all of which meet the specific characteristics previously defined in the BIM and BEM models. Despite the high level of insulation for each component, there is a difference between losses and heat transfer of the office

building model. The thermal performance simulation (Figure 23) by DesignBuilder provides insights into the building's energy efficiency and behavior throughout the year.

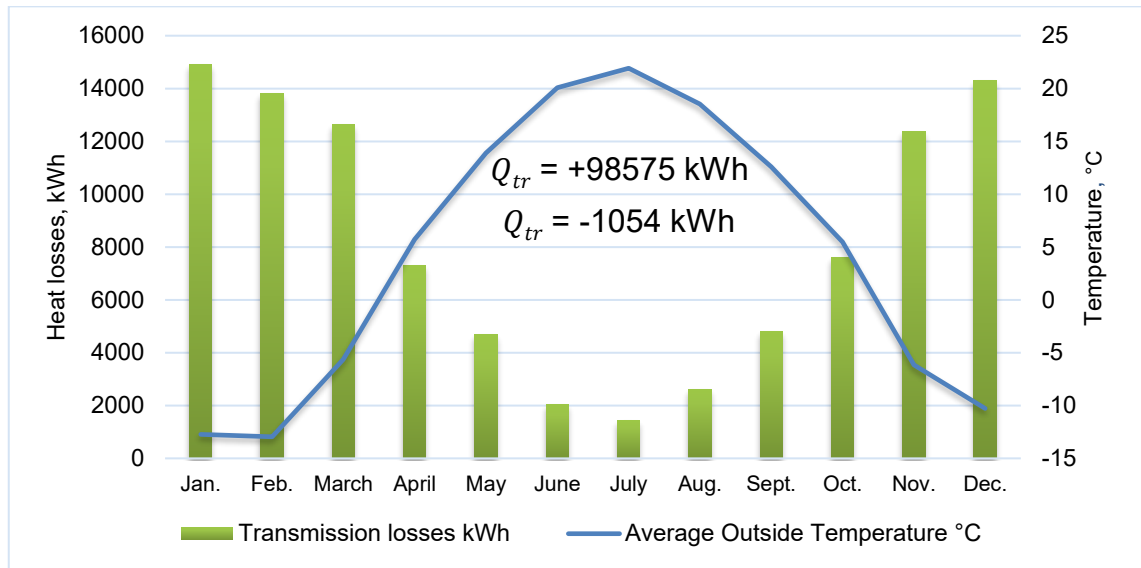


Figure 23: Monthly heat losses of the building envelope

The coldest months exhibit the greatest heat loss through walls and roofs, impacting the overall energy demand of the building. Conversely, during summer, substantial heat flow occurs through the components and their insulation. The main reasons for this imbalance may include insufficient thermal insulation, extreme climate, shading from residential buildings, or low solar activity.

The next factor (Borodinecs, 2014) influencing the efficiency of the office building is mechanical ventilation, through which losses (Q_{ve}) have the greatest impact on energy needs. The first thing to determine is the volume of air required (V), relative to which the microclimate in the building is maintained. The second is how often the air (n) is changed through the ventilation system to achieve optimal air quality. Constants such as specific heat capacity of air (c_p) and air density (ρ) also need to be considered. Equation 2 shows the relationship between losses in different temperature periods (Δt).

$$Q_{ve} = V \cdot n \cdot c_p \cdot \rho \cdot \Delta t \quad (2)$$

According to the characteristics of the BEM model, the selected comfortable conditions, and the established average temperatures inside and outside the building, the following expression was obtained by mathematical calculation.

$$Q_{ve} = 6031 \text{ m}^3 \cdot 3 \frac{\text{ac}}{\text{h}} \cdot 0.279 \frac{\text{Wh}}{\text{kgK}} \cdot 1.2 \frac{\text{kg}}{\text{m}^3} \cdot (t_{indoor} - t_{outdoor}).$$

Air quality is determined by the timely removal of exhaust air to avoid a negative impact on the health and comfort of people. Losses in mechanical ventilation result in wasted energy when heating or cooling incoming air, which requires a constant zone temperature of 18-22°C. When implementing energy-saving strategies with ventilation equipment to maintain the desired temperature, it is essential to consider the office building's fresh air requirements. During periods of reduced demand, when the building is unoccupied, temporarily halting the supply of fresh air can conserve heat energy indoors. This approach helps optimize energy usage and promotes a more efficient HVAC system operation. Figure 24 shows the weekly ventilation loss calculation as a function of the outdoor temperature when fresh air is taken in.

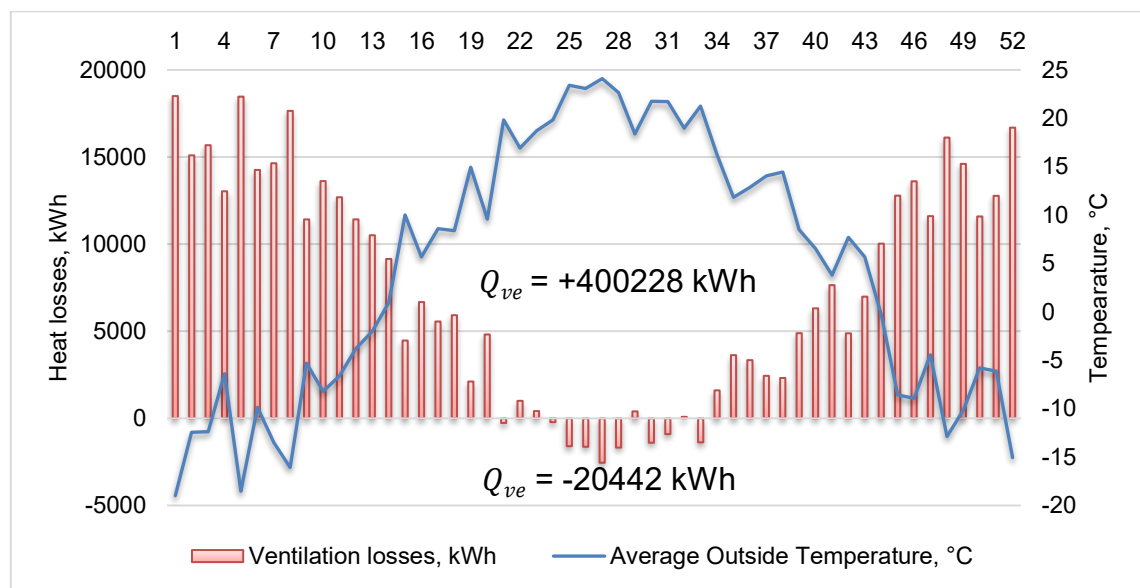


Figure 24: Weekly heat losses of the building ventilation

The significant ventilation losses point to a notable contrast between the intended comfort temperature within the office building and the external outdoor temperature. Such a large amount of heat loss is caused primarily by the given conditions from Table 7, according to these parameters of mechanical ventilation and the comfortable conditions (Axair fans, 2021) of office buildings, it is necessary to refresh the air three times per hour. Also, a minimum of 10 liters of fresh air per second is required for each visitor. By combining the HRU and smart controls, it becomes feasible to prevent the release of warm air, which can be recycled for heating the incoming air.

In addition to the energy sourced from the HVAC system's heating elements, there are also internal inputs (Q_{int}) from people and equipment, along with inputs from the sun (Q_{sol}). Therefore, it is important to consider their impact on the model energy demand. Figure 25 illustrates the annual variation of heat gain from DesignBuilder results such as LED lighting (Q_{Light}), occupancy (Q_{Oc}), office equipment (Q_{OE}) which include web servers, personal PCs, and canteen equipment which use by a schedule.

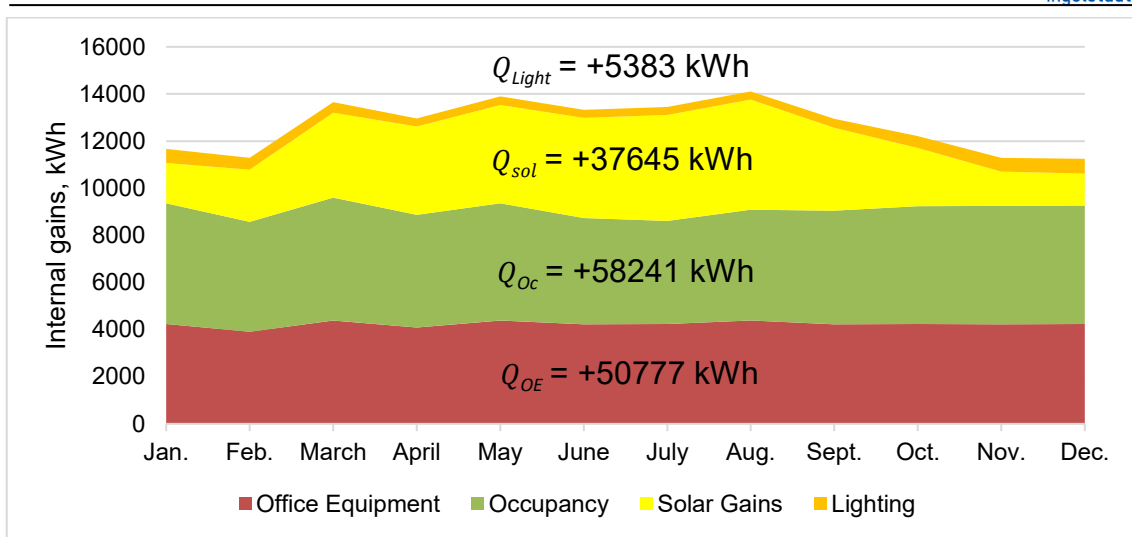


Figure 25: Monthly internal gains of the office building

These processes contribute to the overall energy state and thermal comfort of the office building. Assume that (ASHRAE Fundamentals Handbook, 2001, pp. 630–634) the office equipment as an additional heat source, with nearly 50% (Duška et al., 2007; Polosin, 2013) of the electricity it uses being converted into heat. Similarly, lighting, along with its convective fraction accounting for 10% (DB template), also converts (Sourbron and Helsen, 2011, p. 429) the consumed electricity into a certain level of heat energy. Additionally, occupancy six days a week influences energy gains and the overall energy profile of the office building. Solar energy entering through windows can decrease heating demand in winter or increase cooling demand in summer.

Maintaining the desired temperature in the building's spaces is a primary requirement for the entire project's operation. Analyzing changes in heating or cooling demand helps identify suitable HVAC systems for thermal comfort while seeking energy-efficient solutions. The energy building demand calculation varies according to weather conditions and internal gains as illustrated in Figure 26.

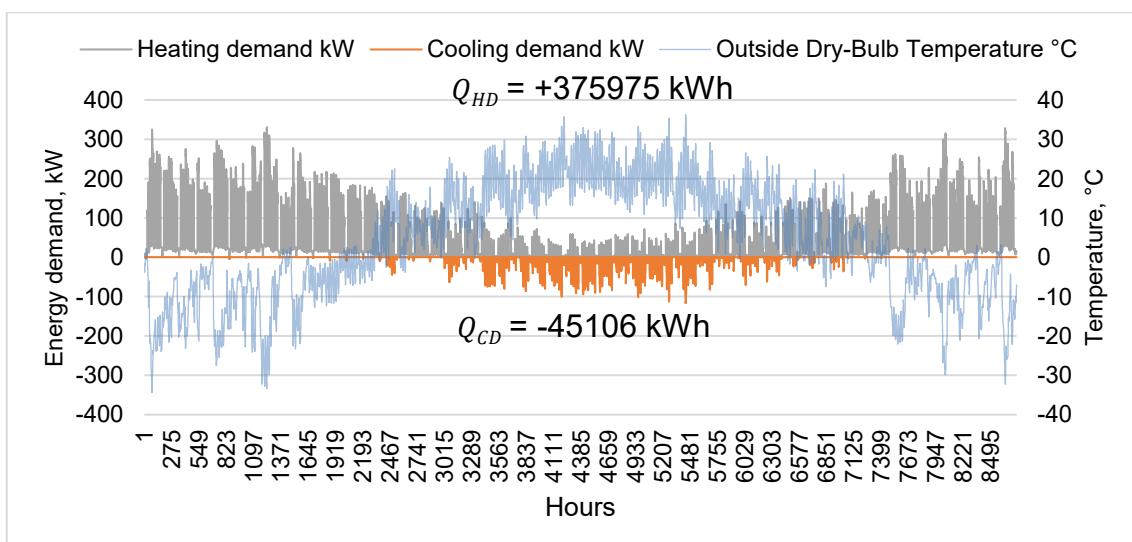


Figure 26: Hourly energy heating and cooling demand

Comparing the annual fluctuations in heating and cooling loads for the zones, it is important to note a significant difference between the loads. In comparison to zone heating and cooling, the next parameters provide insights into the amount of energy required by the HVAC system to maintain a comfortable temperature through ventilation and radiators. It is necessary to examine the changes in the primary parameters of the building's energy performance by DesignBuilder and its HVAC system, including Radiant and Convective Heating, AHU heating, and Total Cooling. To reduce the load, the HRU with plate type heat exchanger can utilize waste heat to preheat the incoming air, thereby lowering heating consumption. The inclusion of the HRU in the overall HVAC system will have a significant impact to cover the heating demand. By preheating fresh air through an exhaust air heat exchanger, the consumption for both radiant and convective heating, as well as AHU heating, will be reduced, especially during the colder months. During the warm season, the HRU system does not effectively recover cold air and does not contribute to cover the cooling demand of the office building.

3.4 ESM of solar sources

The main source of energy for the office building is the urban electrical networks. According to the objectives of this project, the implementation of alternative solar systems on the facades and roof of the office building should be provided, depending on the proposed concept. The purpose of their use is primarily aimed at covering the needs for heating during the cold period using roof area (more than 850 m²). It is required to choose the optimal parameters for solar PV panels and STC to maximize the energy production.

The differences and advantages between solar systems allow to choose the most efficient option during the design stage. Both types of systems convert sunlight into energy, but the design difference between PV panel and STC forces to choose the most efficient and optimal way. Despite being more challenging to maintain, solar collectors produce more energy than PV panels, especially in cold climates and low solar activity. Integrating PV panels with a city's power grid permits the sale of excess energy, which cannot be done with thermal energy from solar collectors. Ultimately, there is a choice of which energy production is preferable for this project.

Many parameters are already set in the model, such as the orientation of the office building, solar activity, and climatic conditions, but it is required to add data from local manufacturers to the DesignBuilder library: PV panels from AstanaSolar (Table 8) and STC from Kuntech (Table 9). All the detailed parameters can be stored in the library of solar systems in DesignBuilder, which are necessary for a series of simulations in search of the optimal tilt angle and distance between panels.

Table 8: Parameters of AstanaSolar KZ PV 270 M72

Cell type	Crystalline Silicon
Efficiency	0.16
Cells in series	72
Area (m²)	1.95
Active area (m²)	1.75
Transmittance absorptance product	0.9
Semiconductor bandgap (eV)	1.12
Reference insolation (W/m²)	1000
Module heat loss coefficient (W/m²-K)	30
Rated electric power output per module (W)	280
Short circuit current (A)	8.2
Module current at max power (A)	7.9
Open circuit voltage (V)	44.2
Module voltage at max power (V)	35.4

Table 9: Parameters of Kuntech KT400

Type	Vacuum insulated
Surface area (m²)	2.03
Absorber area (m²)	1.75
Efficiency	0.81
1st Order heat loss coefficient (W/m²·K)	-3.04
2nd Order heat loss coefficient (W/m²·K²)	-0.0324
Work fluid and ratio (%)	Glycol-to-water, 50%
Working temperature (°C)	above 100
Maximum temperature (°C)	224

Efficient use of rooftop space requires to determine how the neighboring 27-meter building will affect the spread of solar radiation. It is important to determine the impact of partial shading on office building systems during the modeling phase. To avoid the impact of degrading solar system performance as well as their cost-effectiveness is possible to use the pre-planning DesignBuilder visualization tool. It was found that during the period of heating season from October to March, there is almost no direct solar radiation entering the office building until 12:00 as can be seen on Figure 27 (a).

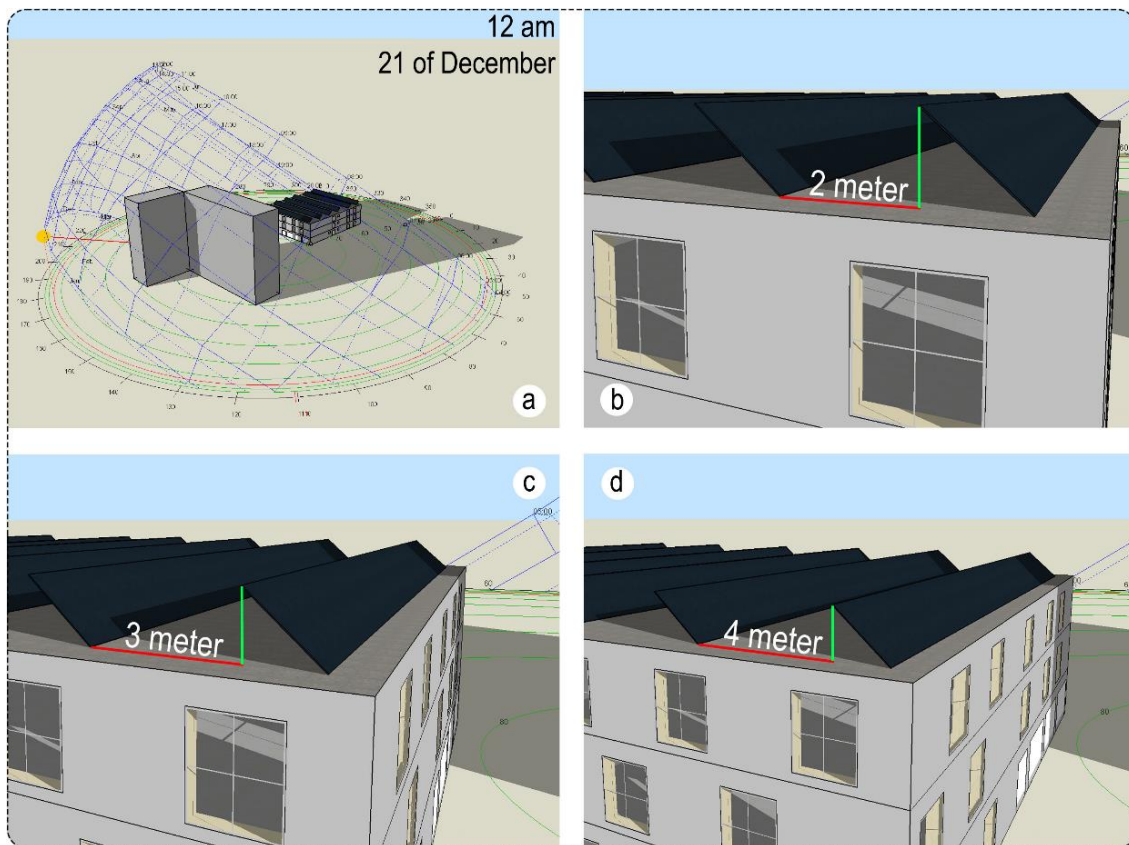


Figure 27: Sun shading effect and optimal solar panel row

Based on section 2.2, an optimal tilt angle of 42° can be considered. According to that angle, the impact of shading between panel lines can be determined visually and its approximate effect on efficiency can be simulated in worst-case scenario. The impact of a neighboring building cannot be reduced; however, maintaining an appropriate distance between rows of solar panels enables efficient use of solar systems, fulfilling the energy requirements. As depicted in Figure 27 (b, c, d), the efficiency decreases by approximately 20-30% when the distance between panel rows is 2-3 meters. A 4-meter distance is regarded as optimal in terms of maintaining efficiency.

The next step is to compare the annual performance of PV and STC systems that will be installed on the roof. Theoretically, the most productive angle for solar systems is already known, but the main condition of this project is to cover the energy demand during the heating period. Therefore, it is necessary to check this statement with the optimal angle, and to find out which angle is the most productive in the cold period. Additionally, when selecting the most efficient angle for the solar panels, it is essential to consider the possibility of snow accumulation on the panels. An appropriate angle should facilitate snow sliding off the panels and reduce the load on the supporting structures. Depending on the chosen concept, in DesignBuilder it is possible to compare the generated energy and choose the most suitable one that covers more needs.

The electrical concept assumes that the main alternative source will be six rows of 156 PV panels, the total active area of which is 273 square meters. The installation PV

system was tested regarding various tilts over a year with 98 inverter efficiency, the results of which can be seen in Figure 28.

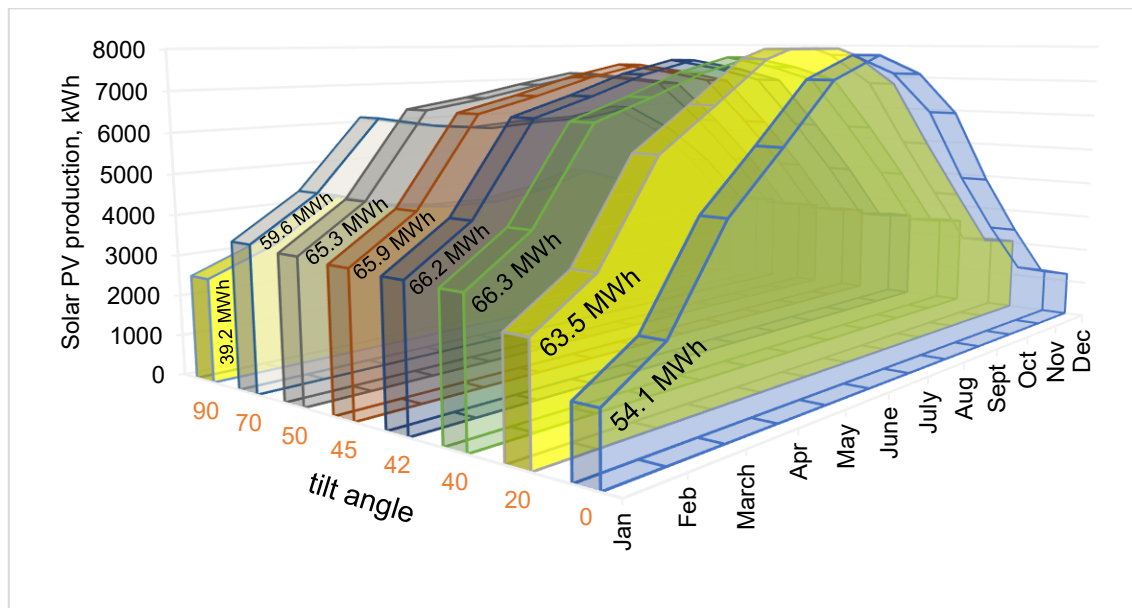


Figure 28: Tilt angles and annual production of PV rooftop installation

The simulation results indicate the existence of performance differences among solar panels at different tilt angles (ranging from 0 to 90 degrees) to examine each period to identify the optimal installation angle of the panels. The maximum annual generation of solar electric energy by PV panels, totaling 66.3 MWh, is achieved at an angle of 40 degrees. During winter (December to February), when the angle between the horizon and the sun is at a minimum, the optimal angle is 70 degrees, which results in a 5% increase in energy production compared to an angle of 40 degrees. The period from May to July (23.8 MWh) sees the highest system performance, with an optimal angle of 20 degrees.

The thermal concept, as opposed to the electrical approach, utilizes an alternative form of energy. It features six rows of 156 vacuum STC with a total active area of 300 square meters. The availability of the system is regulated by a pump and depends on solar activity. In summer, when heating is not required, the thermal collector system should be completely turned off to prevent overheating. The water heated by the sun enters the water tank (10 m³) through a heat exchanger. Following this, the heated water is introduced into the central boiler system. The dimensions of this thermal installation have been tested at various tilt angles during the heating season using Scripting mode (bigladdersoftware, 2023) with “Solar Collector Heat Gain Rate” output. The outcomes of these tests can be observed in Figure 29.

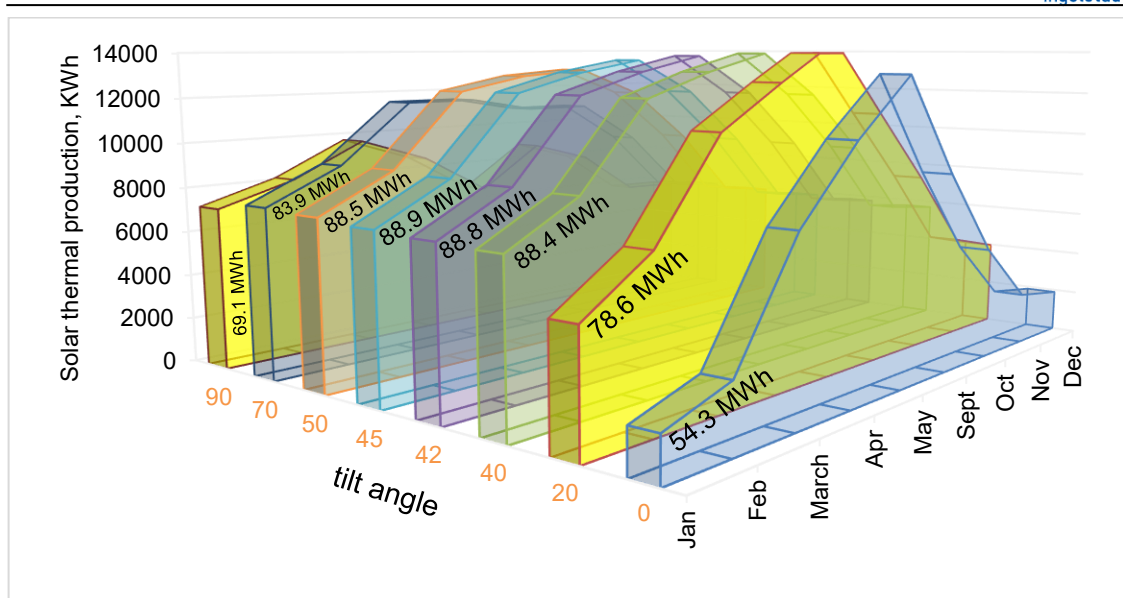


Figure 29: Tilt angles and heating production of STC rooftop installation

In a study conducted to determine the effective tilt angle for thermal solar collectors, it was discovered that variations between different periods need to be adapted the entire system to achieve maximum energy output during the heating season. Unlike PV panel systems, STC reaches peak heat production at a tilt angle of 45 degrees, generating 88.9 MWh. The coldest months of the year (December to February) require maximum performance to minimize biomass consumption, making it more effective to use angles between 60 and 70 degrees.

Upon identifying the most effective tilt angles for each month, it is necessary to consider how much the performance of solar systems will change if the angle is adjusted monthly. Utilizing an adjustable mount enables the optimal use of solar energy throughout the year, as illustrated in Figure 30.

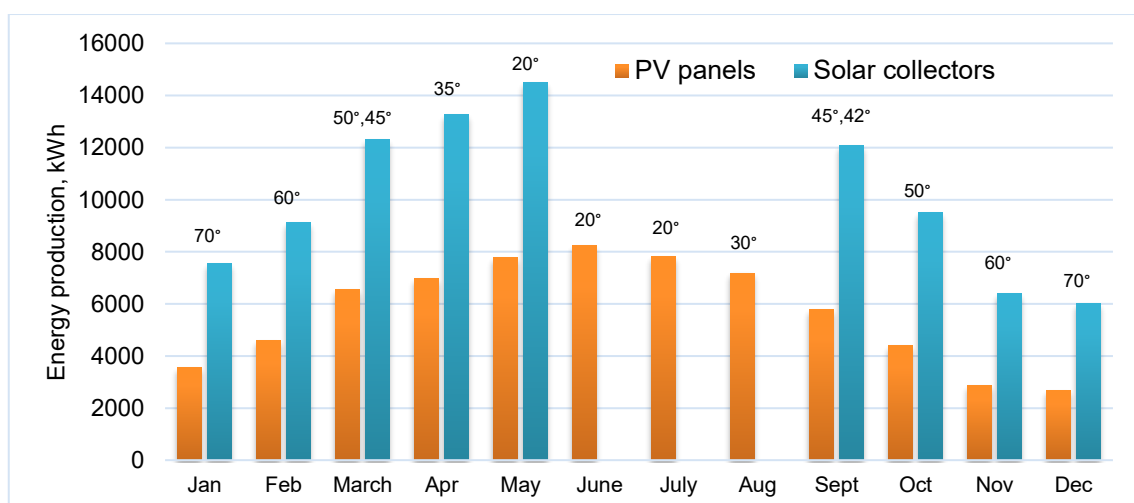


Figure 30: Manual angle adjustments in search of peak performance

As previously mentioned, a steeper angle (60-70 degrees) in winter captures more energy, while a smaller angle (20-30 degrees) is more effective in summer. By manually

adjusting the angle, the overall electricity production for PV systems will increase from 66.3 to 68.4 MWh, and heat energy production by solar thermal collectors will rise from 88.9 to 90.7 MWh.

Achieving energy independence and increasing the adoption of alternative energy sources is possible by the use of façade PV panels. The arrangement of PV panels is contingent upon the available surface area on the building's exterior, considering that windows account for a quarter of the envelope. When integrated into the exterior of an office building, these panels can also serve as an additional layer of insulation, reducing heat loss through the façade. However, the efficiency of such systems may be lower compared to rooftop installations, as the fixed vertical position of the PV panels receives less sunlight. This assertion will undergo validation through simulations. The energy production of 139 PV panels will be examined for the west, south, and east sides of the office building. The analysis will be conducted monthly throughout the year, as depicted in Figure 31.

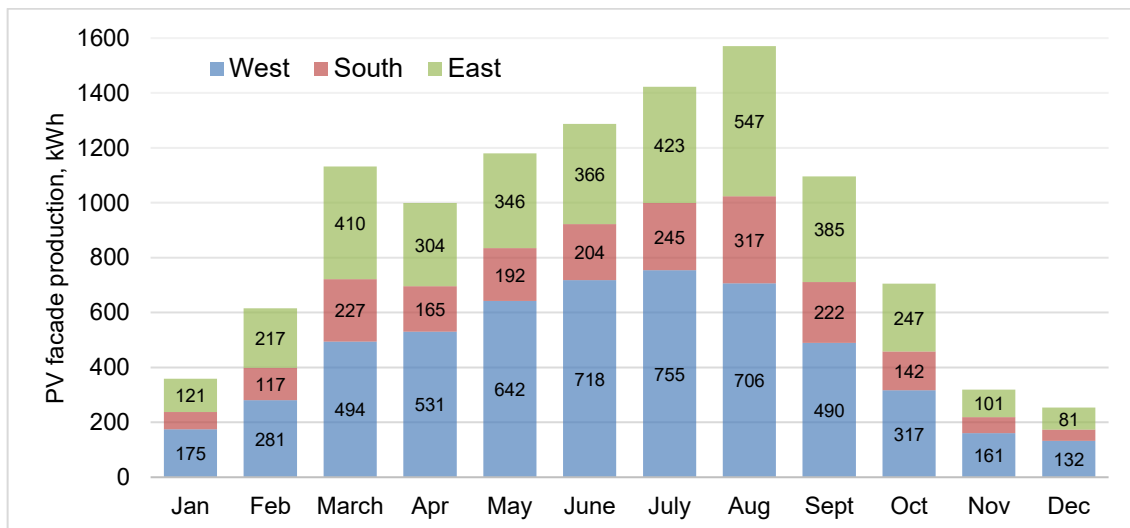


Figure 31: Monthly production of façade PV panels

The entire facade PV system generates an annual output of 10.9 MWh, with the West (41 panels) part contributing half of the total electricity production. This raises concerns about the economic viability of East (61 panels) and, in particular, South (37 panels) system, as their efficiency is negatively impacted by shading.

The effectiveness of solar system implementation depends on how much of the generated energy will eventually be used. Based on the findings, the production of thermal energy surpasses the solar PV electricity generated. However, an issue arises when production outpaces consumption. Surplus PV electricity can be sold back to the power grid, fetching a price nearly equivalent to the cost of grid electricity. If the design doesn't incorporate thermal storage, excessive energy simply dissipates within the system, yielding minimal practical advantage.

3.5 HVAC Modelling

3.5.1 Heating

In Section 2.5, two different heating concepts are assumed with heat distribution through radiators and AHU. In both methods, an underground heat pump is utilized by AHU with and without HRU to warm the incoming ventilation air. The electrical concept is based on the reasonable consumption of electricity by AWHP during the period when the air temperature is above -15 °C, in other side the electric boiler must stabilize the internal temperature. Conversely, the thermal concept aims to minimize reliance on electricity by exclusively employing the pellet boiler as the main heat source.

The electric concept's operating principle is centered on the efficient utilization of "dirty" coal-fired electricity from a local thermal power plant. By effectively using HVAC equipment, the environmental impact is minimized. Combining multiple electrical sources enables the development of an optimal HVAC scheme. During particularly cold periods, the primary heating source is the electric boiler. Its gentle operation mode maintains a working temperature of 65 °C. Heat is transferred to the heating system through a heat exchanger. AWHP serves as an additional heating source, with its operation limited by outdoor temperatures above -15 °C. Heated water also enters the heating system via the heat exchanger, providing both heating and DHW. The combined operation of this heating system allows for efficient electricity usage and consistent heat circulation through radiators. The stability of air heating can be ensured by utilizing GWWHP, which can harness heat from central city heating systems, maintaining a consistent ground temperature of approximately 18 °C year-round. The overall comfort of this concept is achieved when all components function in the appropriate mode, including HRU.

The thermal concept aims to minimize electricity consumption for heating purposes. By using biofuels and solar collectors, an eco-HVAC system can be constructed with minimal environmental impact. Along with heat sources, the system also incorporates ventilation sources similar to the electric concept. The biomass boiler serves as the primary heat source throughout the cold heating period. During periods of high sun activity, the solar collector system helps reduce biofuel consumption. The solar system is linked to the water tank where heat transfer between solar vacuum collectors occurs via the internal heat exchanger. The heated water is mixed with biomass water until reaching an operating temperature of approximately 65°C. Radiators are the sole means of distributing thermal energy, with the exchanger connection.

The next stage explores strategies for heat distribution within the office building and demonstrates how these approaches can be utilized to fulfill the necessary energy requirements for meeting heating demands. To provide a clearer understanding, a comparative energy analysis of the office building will be conducted, comparing two heat distribution systems with the "Autosizing" function: AHU (Q_{AHU}) and radiant and

convective ($Q_{Rad.Conv}$) heating on Equation 3, and the same system incorporating the HRU (Q_{HR}) on Equation 4.

$$Q_{HD} = Q_{AHU} + Q_{Rad.Conv} \quad (3)$$

$$Q_{HD.HR} = Q_{AHU} + Q_{Rad.Conv} + Q_{HR} \quad (4)$$

The GWWHP system is connected to an underground surface heat exchanger positioned at a depth of 1.5-2 meters, running parallel to the central heating networks, utilizing their surplus heat. This ground exchanger model (DesignBuilder Help) operates without the need for complex controls or flow rate adjustments and based on Quadratic Transfer Function (QTF), enabling the extraction and transfer of heat within the range of 14-18 °C from September to May. The fundamental specifications of the surface heat exchanger are outlined in Table 10.

Table 10: Underground hydronic system configuration

Parameter	Value
Hydronic tubing inside diameter (m)	0.2
Number of tubing circuits (m)	10
Hydronic tube spacing (m)	0.3
Surface length and width (m)	30×10

The underground heat exchanger's dimensions and layout should align with both the heating and cooling demands. To achieve this, various system dimensions were evaluated for their impact on energy consumption. This process facilitated the identification of the most efficient surface heat exchanger configuration. The selected system enables the retrieval of surplus heat from central heating, eliminating the need for extra expenses related to earth excavation. The accumulated heat will remain heated or cooled to the desired temperature using GWWHP, which offers greater advantages compared to alternative air preheating systems.

The stipulated temperature requirement brings about specific responsibilities for thermal comfort. Consequently, achieving a particular energy demand becomes a goal for both concepts, which provide energy to the heating systems through radiators and ventilation coils. Following the completion of hourly simulations from the highest to lowest outcomes, an assessment will be made regarding the sum of energy distribution and this evaluation will be visually presented in Figure 32, illustrating the annual energy recovery potential with the utilization of the HRU.

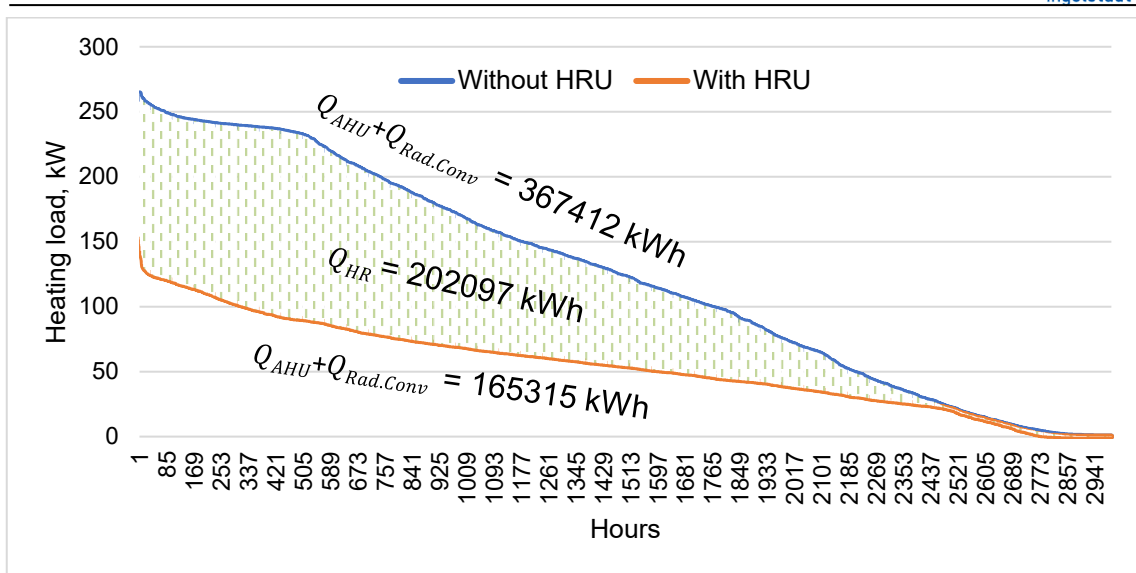


Figure 32: Heat recovery impact on heating needs

When comparing a simple AHU system with a system with HRU, it becomes evident that there is a significant rise in energy consumption related to ventilation. Based on the simulation results, the implementation of the HRU is designed to result in a total energy reduction of less than 55%. The obtained results were analyzed and compared with findings from other studies (Zhao and Du, 2019, p. 16; Ghaderi et al., 2023, p. 17; C. O' Donovan et al., 2021, p. 9; Kassai et al., 2018, p. 12) that similarly observed a significant decrease in the requirement for supplementary energy when employing HRU. In this scenario, it's essential to assess the HRU's impact on the AHU and the power necessary to regulate the temperature of the incoming air stream. Optimizing the fresh air heating system will result in more energy efficient GWWHP use.

As previously stated, both concepts utilize three heat sources to achieve stability once the desired energy level is attained. Boilers as the foundation for both concepts play a pivotal role, where the electric boiler (E_{EB}) shows a higher efficiency (η) compared to the biomass boiler (E_{BB}) due to its effective electricity utilization. The energy efficiency of heat pumps (E_{AWHP} and E_{GWWHP}) can be assessed by employing the seasonal performance factor (SPF), which provides a comprehensive measure of its efficiency across an entire heating season. The following can be assumed that Equation 5 and Equation 6 show how each source contributes a portion of the energy, either through electricity consumption or the combination of biofuels and solar energy.

$$Q_{AHU} + Q_{Rad.Conv} = SPF \cdot E_{GWWHP} + \eta \cdot E_{EB} + SPF \cdot E_{AWHP} \quad (5)$$

$$Q_{AHU} + Q_{Rad.Conv} = SPF \cdot E_{GWWHP} + \eta \cdot E_{BB} + E_{STC} \quad (6)$$

Achieving the efficient use of underground heat is possible with the help of GWWHP, which, together with the HRU, has the capacity to curtail the energy consumption of the AHU. The selection of an AHU option significantly influences the outdoor air heating

requirements, leading to lowered equipment and energy costs. Conversely, the integration of HRU brings challenges in the maintenance and management of air heating systems. Refer to Table 11 for a comprehensive overview of the key attributes of the GWWHP for both ventilation concepts.

Table 11: GWWHP characteristics for air heating

	Without HRU	With HRU
Electricity HP consumption (kWh)	104649	17769
SPF	2.48	3.27
Manufacture	Insolar	Insolar
Model	H-WCh3000	H-WCh1200
Power consumption (kW)	83	32,5
Heating capacity (kW)	355	138
COP	4.28	4.25

Before starting on a comparison of radiator-connected heating systems, it is necessary to establish the proportion between energy generated by solar collectors and the portion that can be effectively employed in conjunction with a biomass boiler. Unlike the electric concept where PV-generated electricity can serve other building needs and surplus can be sold to the grid. At the same time the thermal concept experiences an energy surplus from solar collectors during relatively warmer periods. Figure 33 shows the weekly energy inflow from the biomass boiler and solar collectors into the heating system and how much energy from solar collector can be used.

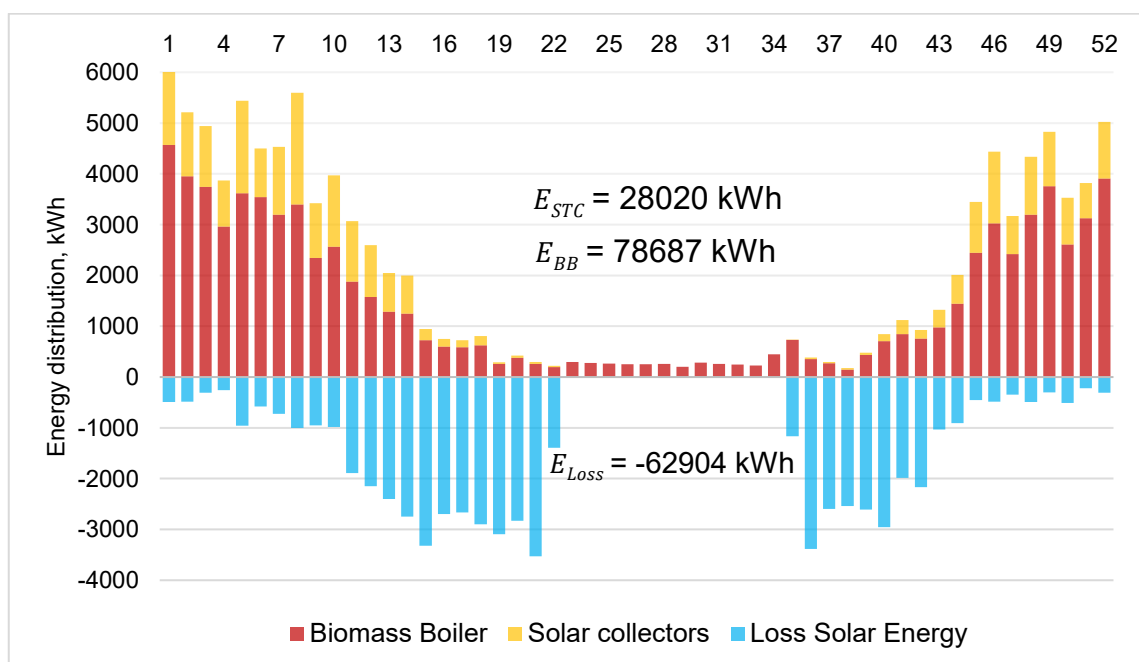


Figure 33: Weekly energy inflow analysis between STC and biomass boiler

In accordance with section 3.4, STC exhibits the capacity to generate approximately 89 MWh of energy. Regrettably, a significant portion of this energy remains unused during the heating season. An annual comparison of the two systems indicates that the highest demand for heat occurs in winter. This becomes problematic as solar collectors do not generate sufficient energy during this period. Most of the heating need arises during times of reduced solar activity, like in the mornings. It is noted that only a quarter of the energy between the incoming STC and the consumed biofuel is ultimately used in the system. Consequently, only a third of the solar energy becomes viable for integration into the heating system, while the remainder dissipates into the atmosphere due to the absence of heat storage. On the other hand, there's the electric concept that combines the electric boiler and the AWHP to effectively utilize the generated PV electricity. The aim of Figure 34 is to conduct a comparative analysis to identify the most suitable choice.

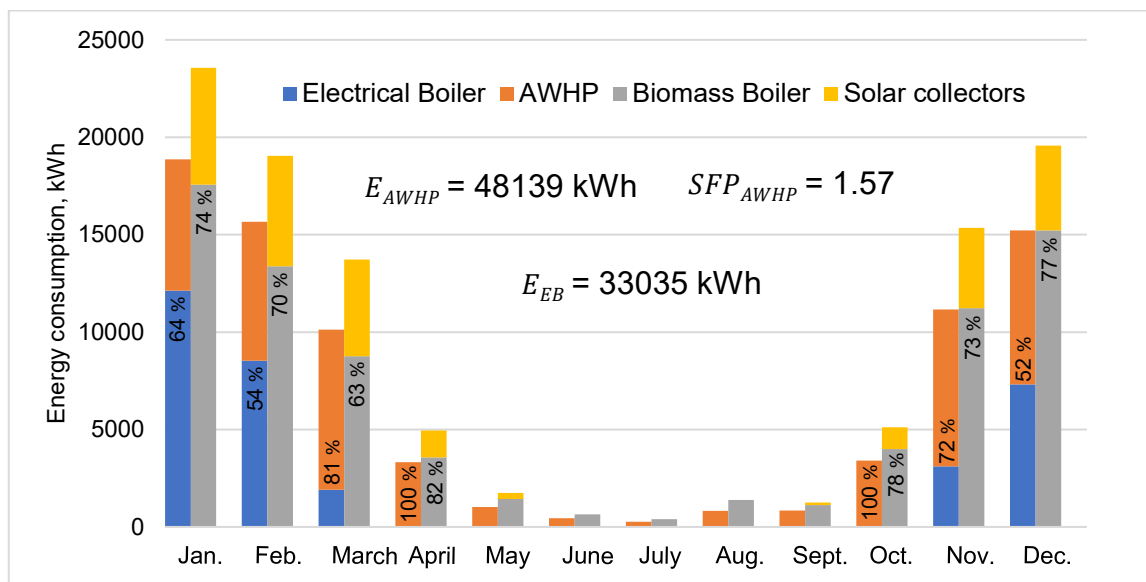


Figure 34: Comparative analysis for radiators heating and DHW end energy use

Comparing the energy analysis of both systems provides insight into the differences in energy production approaches, while also emphasizing the importance of efficiently utilizing electrical or renewable resources. When examining these approaches, it becomes evident that the electric boiler and AWHP collaborate most effectively throughout the year. During colder periods, the requirement for an electricity- or biofuel-powered boiler to maintain comfortable conditions within the office building is apparent. On the other hand, when temperatures rise above -15 °C, the AWHP becomes more significant, demonstrating better efficiency compared to the electric boiler by generating one and a half times more energy than it consumes. Significantly, as a quarter of the total consumption is derived from solar energy, highlighting the need for greater use of wood pellets as the main source of fuel for the thermal system. The main characteristics and selected simulation outputs are presented in Table 12.

Table 12: AWHP, Electrical and Biomass boiler characteristics

	AWHP	Electrical Boiler	Biomass Boiler
Peak Capacity (kW)	55.3	185.4	185.4
Manufacture	Atmoterm	Nevsky	FACI
Model	PW600	200B	208P
Power consumption	62	200	208
Fuel type	Electricity	Electricity	Pellet
Fuel consumption (kg/h)	-	-	20
COP	3.49	-	-
Efficiency	-	0.98	0.92
Storage (kg)	-	-	400

Thus, the selected equipment once again emphasizes how important it is to ensure stable operation of heating, whether through radiators or ventilation. The challenges posed by harsh external conditions complicate the integration of alternative energy sources, the solution of which is possible only with energy-efficient equipment. Fresh air is essential and heating it requires a lot of energy, a demand that can be mitigated through the utilization of the HRU. The electrical concept is devised to intelligently manage power consumption, further supplemented by electricity generation through PV panels. Simultaneously, the thermal concept obligates consistent upkeep of the biomass boiler, involving the loading of pellets, and addresses potential issues within the solar collector system. The decision between these systems primarily depends on the priority of the project, either autonomy with excessive consumption of electricity and expensive equipment, or savings with operating costs.

3.5.2 Cooling

Creating comfortable conditions during the summer months relies heavily on efficient cooling systems that function works similarly to incoming air heating systems. In order to effectively cool the fresh ventilation air, the installation of a cooling coil within the AHU is essential. This cooling coil's loop is interconnected with the GWWHP. Equation 7 can be employed to assess the system's performance in addressing cooling requirements and to understand the influence of the HRU on energy consumption. Similarly, Equation 8 can be utilized to ascertain the efficiency of electricity utilization for the cooling process.

$$Q_{CD} = Q_{AHU} + Q_{HR} \quad (7)$$

$$Q_{AHU} = SFP \cdot E_{GWWHP} \quad (8)$$

Anticipated for the summer season, the ground temperature is expected to decline to a range of 12-14°C. Consequently, a reduced amount of electricity would be required to decrease the working fluid's temperature to 6°C. Simultaneously, the impact of the HRU on the cooling process (Figure 35) is not as great as during the heating period and occurs only when the external temperature exceeds the set parameters by the internal air temperature.

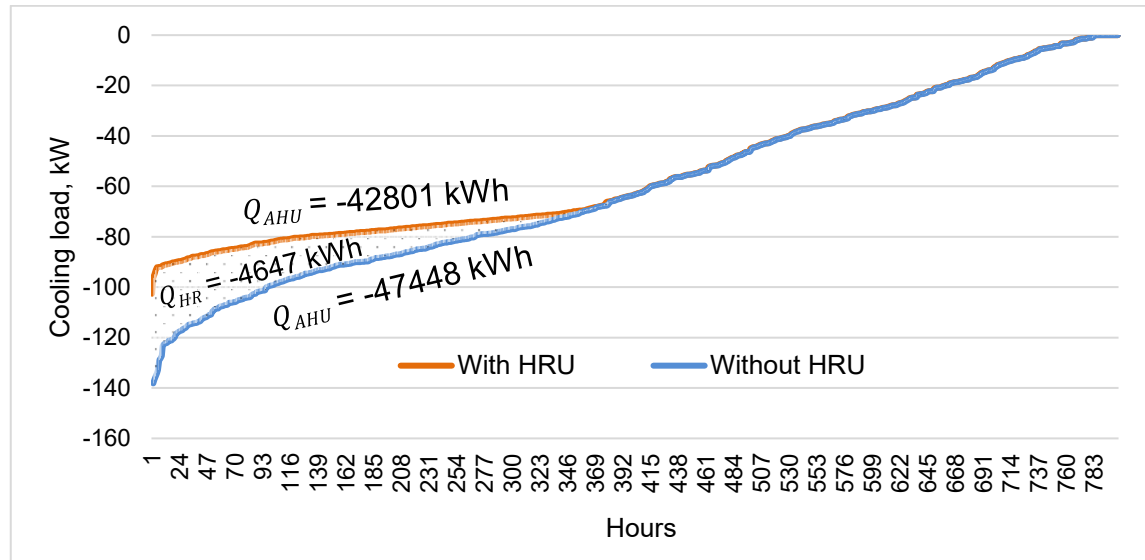


Figure 35: Heat recovery impact on cooling needs

The obtained cooling load results align well with both previously chosen GWWHPs. Moreover, there is no potential for HRU freezing, which sometimes happens in colder seasons, leading to reduced maintenance requirements. Table 13 provides a comprehensive understanding of the key GWWHP attributes related to both ventilation concepts, where simulation outcomes are presented.

Table 13: GWWHP characteristics for air cooling

	Without HRU	With HRU
Electricity HP consumption (kWh)	11109	8364
SPF	4.27	5.11
Manufacture	Insolar	Insolar
Model	H-WCh3000	H-WCh1200
Power consumption (kW)	62	24
Cooling capacity (kW)	305	118
EER	4.95	4.92

Creating comfortable cooling is possible only when several systems are involved in this process at once, each of which consists of energy-efficient equipment. Integration between underground and air systems plays an important role in maintaining the set parameters. Reducing electricity consumption for air cooling by a quarter is possible when using the concept with the HRU.

3.5.3 Ventilation

The source of fresh air is the AHU. Previously, two possible ways of arranging ventilation were considered. The difference between the two systems lies in the plate heat exchanger, which is the main component of the HRU. Instead of expelling exhaust air into the atmosphere via an exhaust fan, it now imparts its heat to the incoming fresh air. Air streams pass through the plates of the exchanger without mixing with each other, where heat exchange takes place for the further supply of warm room air. Figure 36 shows how the mechanical ventilation with heat recovery (MVHR) of the office building is arranged.

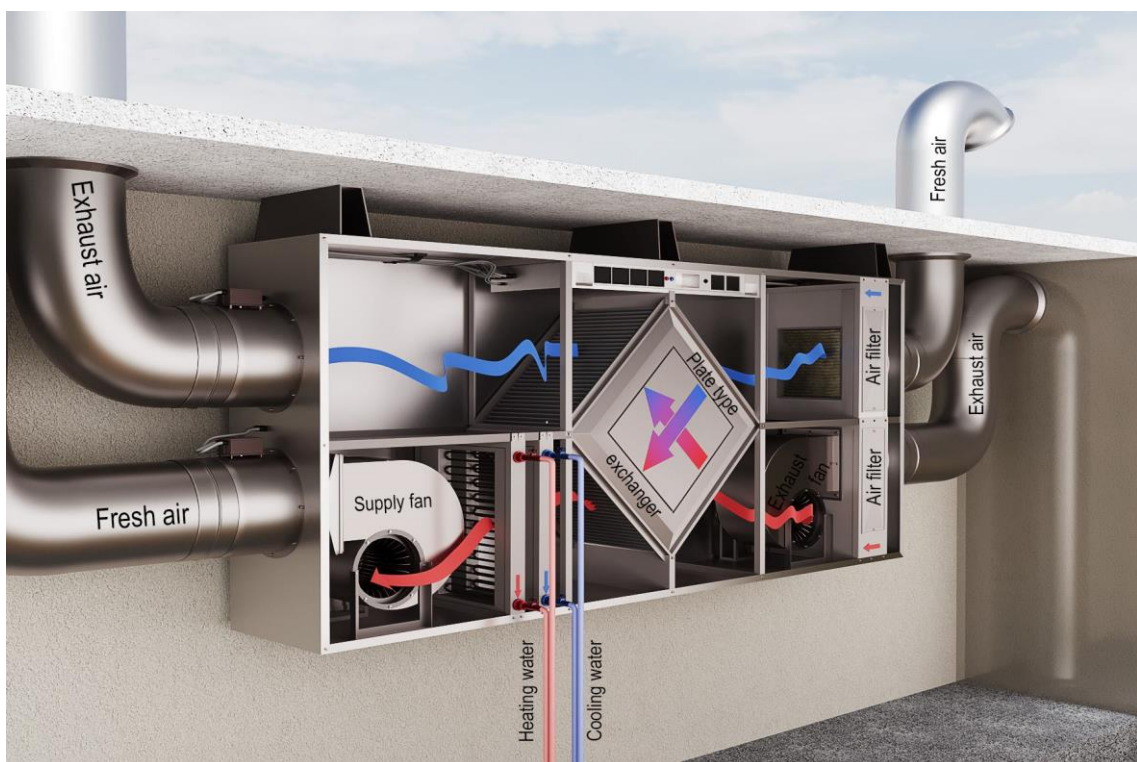


Figure 36: Render of MVHR

The main function of ventilation is to supply fresh air into enclosed spaces through the supply and expulsion of used air, equalizing the internal and external air pressure. Key components may include supply and exhaust fans, as well as filter devices that make it easier to clean the intake and exhaust air. In a broader context, it includes several components such as heating and cooling coils, anti-freeze coil, air intake dampers and various control modules. A special system ensures the accumulation and removal of condensate formed in the heat exchanger due to temperature differences. Monitoring

CO₂ and humidity levels remains key, especially in locations such as office buildings with varying levels of occupancy. The thermostat-controlled automatic temperature control mechanism maintains a comfortable indoor environment by adapting to daily cycles and individual preferences. Efficient air exchange, designed for three cycles per hour, is provided by a complex network of air ducts, providing a standardized parameter of 10 liters of air per person per second. Combining these diverse components together aims to improve indoor air quality and overall comfort according to occupied schedule. According to the selected model settings, the following results are obtained in Table 14, which can help to choose appropriate fans.

Table 14: Simulation results of the AHU

Parameter	Value
Maximum outdoor air flow rate (m³/s)	7.84
Minimum outdoor air flow rate (m³/s)	4.86
Supply fan maximum air mass flow rate (kg/s)	9.22
Fan efficiency	0.7
Rated electricity rate of fans (W)	6721

These results provide valuable insights into AHU performance, aiding informed equipment selection. Values of air flow and electricity rate provide guidance on how to configure for specific system requirements such as fans or ducts. The connection of simulation results and qualitative factors shows the balance between engineering precision and occupant comfort. The system design precises temperature control, and comprehensive monitoring, aligns with optimizing indoor air quality. Integration of diverse components transforms the ventilation system into a holistic solution for enhanced comfort, productivity, and efficiency, contributing to a healthier indoor environment.

3.6 Results evaluation

Ekibastuz stands as the primary energy hub in Kazakhstan, supplying a significant 17% of the nation's overall energy demand. The targeted office building predominantly relies on coal extracted from the Ekibastuz coal mines to meet its electricity needs. The primary objective is to diminish reliance on this energy source. For every 1 kWh of electricity generated (fceland) at the city's thermal power plant, approximately 0.45 kg of coal from the Ekibastuz coal basin is consumed. When factoring in electricity distribution losses (Ministry of Energy of the Republic of Kazakhstan, 2022), averaging around 14%, the total energy efficiency is affected. Addressing both consumption and distribution losses becomes crucial. A viable solution lies in the implementation of decentralized solar energy production, offering the potential to curtail both dependencies and losses.

Furthermore, substituting biofuels for coal in electricity generation presents an opportunity to not only mitigate dependency but also alleviate the environmental impact associated with the office building's energy consumption. The main consumers of electricity, in addition to HVAC equipment, should be considered lighting and equipment, which includes office computers, web servers and canteen equipment. Figure 37 illustrates the correlation between various independence strategies and energy consumption for each concept.

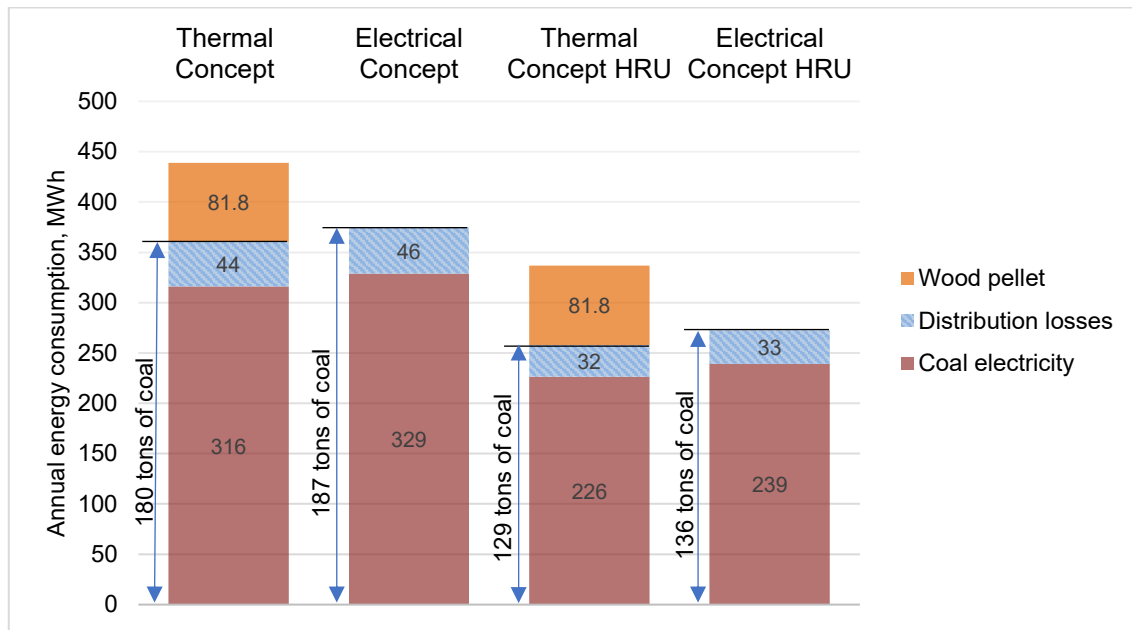


Figure 37: Annual electricity and wood pellet consumption

The obtained results of the energy consumption by BEM model based on DesignBuilder made it possible to evaluate various strategies to creating the energy independence of the office building. The optimization of HVAC concepts is aimed, on the one hand, at covering the energy needs of the building, and on the other hand, at creating a balance between efficiency, environmental, and comfort levels.

Each decision taken in conceptual development and the selection of thermal and ventilation systems required verification in search of the most suitable options for the prevailing climatic conditions. For example, the inclusion of the heat exchanger in the system contributes to additional energy savings which does not simplify the overall design, but at the same time reduces energy costs by using the exhaust air heat. To this should be added that the appropriate integration of alternative energy sources is able to achieve the independence of concepts fully or partially from traditional sources. Reducing the total electricity consumption is possible in all cases due to the generation of PV panels. Considering the introduction of alternative energy sources and overall HVAC consumption, a classification (Osborne, 2020) of each concept can be made. The findings illustrated in Figure 38 emphasize the importance of finding the optimal combination of components to maximize the use of the energy received.

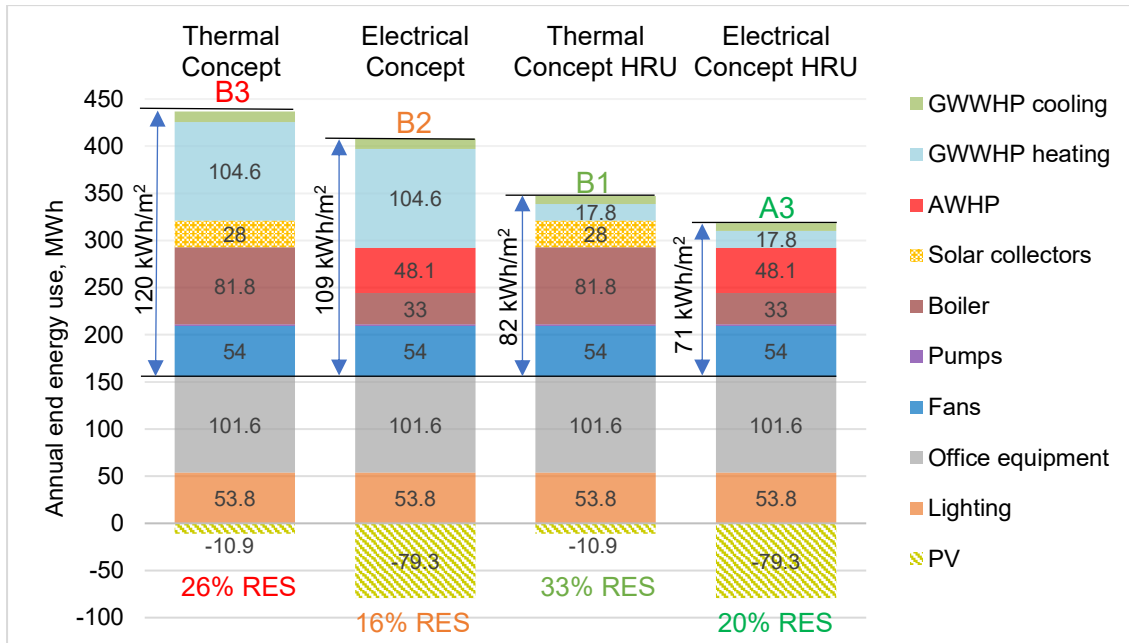


Figure 38: Annual base load and HVAC end energy use with PV generation

The final results of end energy use include the yearly energy consumption of HVAC components across all considered design concepts, the foundation of which is office equipment (43.9 kWh/m²·year) and lighting (23.2 kWh/m²·year). All concepts include PV installations with partially integrated into the façade, which also impacting on final electricity demand. Comparing heat supply through heating radiators, the electric concept demonstrates lower consumption due to the remarkable efficiency of the AWHP. This difference would be greater if it were not a ground heat exchanger with the GWWHP loop for cooling and heating incoming air. However, if the goal is to reduce electricity consumption, then it is necessary to turn to the incorporation of biomass boilers and STC. On other side, Figure 39 helps in determining the practical useful energy utilization based on the efficiency and SPF of the equipment.

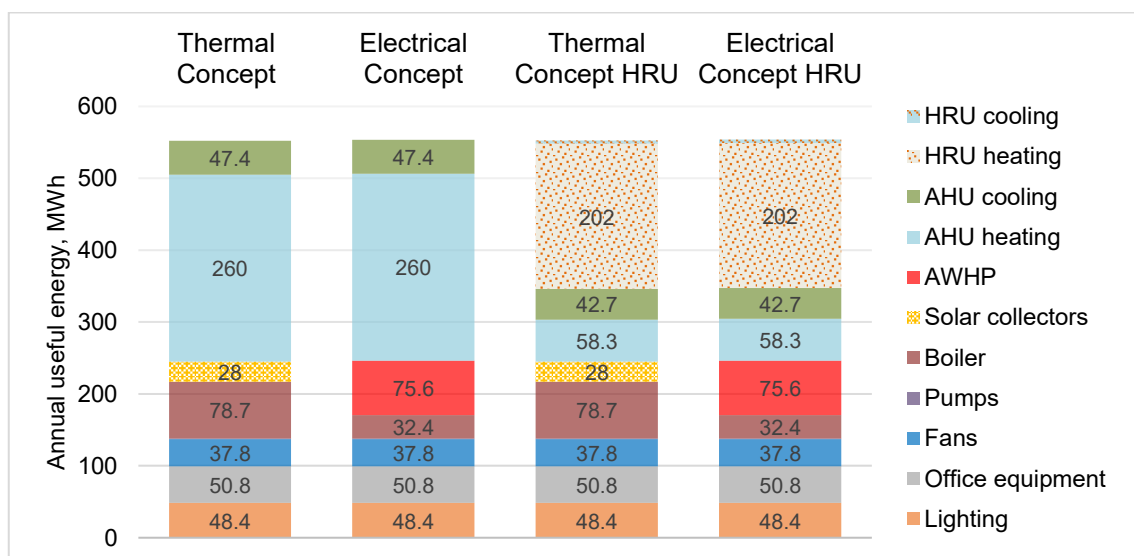


Figure 39: Annual useful energy

The transition analysis between end use energy and useful energy has shown the importance of choosing the right equipment that provides the required energy efficiency. Losses associated with the HVAC equipment are a key aspect for determining wasted or dissipated energy. The desired result of converting end energy into useful energy ultimately depends on how efficiently the chosen concept can use energy to provide the required comfort. This is where the importance of technologies such as the HRU comes into play, which can reduce energy losses while increasing system efficiency.

Research into strategies for achieving energy independence for a coal-dependent office building reveals promising optimization paths. The analysis highlights the importance of addressing issues related to sustainable consumption in the search for sustainable alternatives. The evaluation demonstrates the tangible benefits of implementing alternative energy sources and optimizing HVAC concepts. The results obtained highlight the importance of finding the optimal combination of components to maximize the use of energy generated. The comparison of heating and ventilation with heat recovery and the use of ground heat exchangers contributes to a comprehensive understanding of the dynamics affecting energy consumption. The results show that a smart combination of technologies, including the AWHP, boilers and solar collectors, can have a significant impact on energy consumption and contribute to a more sustainable and energy-independent future for office building.

4 Economic and environmental analysis

4.1 Investment analysis

In search of identifying the optimal solution (Harbach, 2015, pp. 61–62), it becomes to determine the profitability and final cost associated with each HVAC concept, as these factors significantly influence the overall project payback. Economic analysis for owner-occupants (BMW, 2015, p. 58; Beringer, 2022, pp. 47–51) requires considering various investments, including energy and systems costs, all to ultimately determine the financial impacts with Annuity method. The main provisions of the energy costs are built according to the procedure CEN/TC 228 N565 and Simón-Martín et al., enabling to provide an accurate projection of the Levelized Cost of Electricity (LCOE) for PV generation, Levelized Cost of Heating (LCOH) for radiators and ventilation, and Levelized Cost of Cooling (LCOC) for ventilation.

Assume that for the office building as a commercial facility (EN 15459:2013), the lifespan (τ) of the HVAC system is approximately 20 years. Regarding this period, the following parameters (Beringer, 2022, pp. 47–51; Tautenhahn, 2021, pp. 21–24) of Annuity method (A_N) should be considered on Equation 9 to evaluate the investment involving fixed annual costs, making them compatible for direct comparison with annual benefits and savings.

$$A_N = A_{N,I} + (A_{N,MO} + A_{N,F}), [\text{€}] \quad (9)$$

Where:

- investment annuity ($A_{N,I}$) for the purchase, delivery, and installation of each HVAC element,
- maintenance and operational annuities ($A_{N,MO}$) of HVAC systems,
- fuel annuity of total costs for the purchase ($A_{N,F}$) electricity and wood pellets.

None of the concepts being explored involve the sale of energy, except for the surplus PV electricity generated when the office building is unoccupied, accounting for only 7% of the total. The cost of generated electricity is equal (Bukeeva, 2017) to the cost that is purchased from the distribution company without any subsidies from government for selling renewable energy.

The annuity factor (a) plays a crucial role in calculating by Annuity method for the entire operational period. At the same time, according to Equation 10, the value of this factor depends on the level of risk associated with investments within the country. In the case of Kazakhstan (Damodaran, 2023), the discount factor (q) is 7.89% or 1.0789.

$$a = \frac{q^\tau \cdot (q-1)}{q^\tau - 1} = \frac{q-1}{1-q^{-\tau}} \quad (10)$$

In the future, the price of spare parts may change, or the cost of service may increase. Therefore, to ensure the fair value of the annuity for each type of cost, it is necessary to additionally determine the price dynamics (b) coefficient with change price (r_x) coefficient which equal 3% or 1.03 for the entire period of operation of the concept according to Equation 11.

$$b = \frac{1 - \left(\frac{r_x}{q}\right)^\tau}{q - r} \quad (11)$$

Equation 12 of investment annuity ($A_{N,I}$) includes all purchases, delivery, and installation according to first year from the start (I_0) without considering residual value (RW), since all the items do not require replacement during the entire period.

$$A_{N,I} = a \cdot (A_0 + A_1 + \dots + A_n - RW), [\text{€}] \quad (12)$$

The next Equation 13 is used to calculate the maintenance and operational annuities ($A_{N,MO}$) which based on initial investment I_0 , average salary, and factor f_m .

$$A_{N,MO} = I_0 \cdot f_m \cdot b \cdot a, [\text{€}] \quad (13)$$

The cost ($A_{N,F}$) of purchasing (p) pellets and electricity, depending on the energy consumed (E_{fuel}) by each concept and its cost, can be determined using Equation 14.

$$A_{N,F} = E_{fuel} \cdot p \cdot b \cdot a, [\text{€}] \quad (14)$$

In the previous sections, the selection of the main HVAC equipment and solar systems was made. The choice was primarily in favor of local manufacturers or companies with affiliations to Russian supplies. This decision simplifies the import procedure, involving only the payment of VAT in Kazakhstan. According to the Standard Practice for Inspection and Maintenance 180-2018 and practical results by Bloomquist, it is possible to roughly estimate the price level and maintenance procedure for all HVAC systems, which depends primarily on the entire area and ranges from 1 to 4 euros per square meter, depending on the HVAC component. As for the cost of energy, it was determined earlier in Figure 4, and if there is an excess of electricity generated by PV, it will be possible to sell it to the network at the purchase price from the sales company. Table 15 provides the costs for purchasing, transporting, and installing of the HVAC equipment according to obtained results from Equation 9-14. Calculations based on these equations yielded the annuity factor is 0.101 and the price dynamics coefficient is 12.4.

Table 15: Cost analysis of HVAC investment in euro

Equipment	Electrical concept		Thermal concept	
AHU	25000	31250	25000	31250
GWHP	30537	10529	30537	10529
Ground exchanger	43365		43365	
Boiler	6811		7692	
AWHP	21995		-	
Heat exchanger	2825		2825	
STC	-		82541	
Roof PV	37951		-	
Façade PV	34681		34681	
Delivery Charge (10%)	20317	18941	22608	21288
Installation (30%)	60950	56822	67823	63865
Total	284432	265170	316507	298036

All prices have been sourced from manufacturers or distributors in Kazakhstan and Russia, providing a comprehensive reflection of the costs associated with goods and services in the energy market. The difference between ventilation equipment is the inclusion of a plate exchanger within the system. Efficient air heating or cooling is not possible without GWHP, the cost of which is approximately three times greater when comparing systems with or without the HRU. The cost of a surface underground heat exchanger includes the cost of the system (pipes, pump, glycol) and the earthwork required for its installation. Excavating one cubic meter of earth typically costs around 50 euros, with an estimated requirement of 600 m³ of soil.

Biomass boilers and electric boilers are roughly equivalent in terms of pricing. However, introducing the AWHP or solar collectors into the heating system substantially elevates the overall cost of a radiator-based heating system. Looking ahead, it is imperative to assess the viability of incorporating PV panels onto the façade of the office building. It's worth noting that the cost of two solar systems for façade installation tends to be roughly equivalent to one roof-mounted system. It is assumed that the cost of equipment delivery is approximately one-tenth of the total system cost since it is not possible to reliably determine the location of the equipment. A similar situation (Rekuperation, 2023) arises during the equipment installation and commissioning process. As a result, approximate total investments were determined for all considered concepts of this project, which can be revised both higher and lower.

Maintenance costs for these systems vary depending on the sophistication of the HVAC equipment. The thermal concept requires pellet loading and more frequent maintenance of the collector system compared to PV panels, which increases operating costs for these systems. When it comes to energy purchasing, it is necessary to order wood pellets or electricity to provide the required amount of energy as can be found in Table 16.

Table 16: Cost analysis of service investment in euro

Service	Electrical concept		Thermal concept	
Annual Maintenance	7225	7225	8670	8670
Annual Operate	16845	16845	16845	16845
Annual Purchase Electricity	17035	10999	11566	5530
Annual Pellet purchase	-	-	1986	1986

After that it is necessary to calculate LCOE, LCOH and LCOC to make a comparison between energy tariffs. The obtained values (Simón-Martín et al., 2022) reflect the cost of one kW of energy for each method of generating PV energy, as well as distributing thermal energy through radiators and ventilation. The first thing to do is to compare the LCOE of PV systems on the roof and facade of the office building separately over the entire operating period (τ), considering degradation (Deg) using Equation 15.

$$LCOE_{PV} = \frac{A_{N,PV}}{E_{PVpanels} \cdot \tau \cdot Deg}, [\text{€/kWh}] \quad (15)$$

The next step involves assigning the LCOH for each heat propagation method. Depending on the method used to heat the air, it is essential to determine a different tariff that encompasses all associated costs by employing Equation 16. Similarly, the LCOC is determined following the principles outlined in Equation 17.

$$LCOH = \frac{A_{N,Heat}}{Q_{HD} \cdot \tau}, [\text{€/kWh}] \quad (16)$$

$$LCOC = \frac{A_{N,Cool}}{Q_{CD} \cdot \tau}, [\text{€/kWh}] \quad (17)$$

In search of cost-effective solutions, it is necessary to conduct a comparison analysis regarding the resulting final costs for each system, considering all the factors of the Annuity method. As a result, the final tariff for each energy generation or distribution method will reflect the economic feasibility for each selected concept. Table 17 shows the obtained results of LCOE, LCOH and LCOC.

Table 17: LCOE, LCOH и LCOC for concepts in euro per kWh

LCOE	Roof-mounted PV	Façade PV
	0.109	0.66
LCOH radiators	Thermal concept	Electrical concept
	0.123	0.106
LCOH AHU	Without HRU	With HRU
	0.071	0.048
LCOC AHU	Without HRU	With HRU
	0.176	0.167

The energy cost results show significant differences between various energy production methods and heating/cooling systems. This raises doubts about the viability of generating PV electricity through facade systems due to high tariffs and low efficiency. On the other hand, rooftop solar PV systems demonstrate reasonable performance when compared to similar projects.

Additionally, the STC system is included in the radiator heating tariff. To provide a more accurate comparison between these concepts, it was decided to analyze heating methods separately. When focusing solely on radiator heating, there's a 10% difference between the concepts. The electric concept has lower equipment costs but higher energy expenses. In contrast, thermal energy from pellets is approximately 2.5 times cheaper than electricity. However, the cost of STC cancels out these savings due to their relatively low production of useful energy.

Introducing heat recovery through the AHU system reduces the heating fresh air tariff by about a third, despite the increased electricity consumption. In the long term, the HRU system justifies the higher initial investment in equipment and maintenance, including cooling, even though the difference is nearly negligible.

4.2 Carbon impact analysis

Ekibastuz is an industrial center for the extraction of coal and the production of electricity from this coal, which together makes it a center for emissions (Zakon, 2015) of hazardous substances. The level of environmental impact is unusually high, which leads to a general deterioration of the city's ecology. Creating efficient heating and cooling systems in a new office building will correct the situation, although the changes will not greatly affect the overall background, but in any case, it is necessary to start. A comprehensive examination of emissions throughout the lifespan of HVAC systems will offer a comprehensive assessment of the long-term environmental repercussions associated with these energy concepts.

At every stage, whether it involves coal mining, combustion, or the installation of energy-efficient equipment, a distinct carbon footprint is left behind. To embark on the path of sustainability, one must begin by assessing their contribution to energy resource utilization, comparing wood pellets and coal-generated electricity. Coal mining is carried out within Ekibastuz, which reduces the level of emissions for delivery, but the industrial approach aggravates the environmental city situation. It's worth noting that wood pellets cannot be considered entirely climate-neutral, as the CO₂ emissions during combustion are nearly twice as high as those generated by coal at CHPs. Additionally, the initial contribution to pellet preparation, including drying, must be considered. But at the same time, it is necessary to consider the fact that the pellets were originally made from trees, which previously absorbed a sufficient level of CO₂, which contributes to the environmental friendliness of this type of fuel. Regarding this, assume that (Zheng et al., 2022, p. 7) emits about 0.421 kgCO₂ per kW of coal electricity, and renewable pellets will contribute about 0.281 kgCO₂ per kW of thermal energy. The exact environmental footprint of HVAC equipment remains elusive, but researcher (Nutter, 2011, pp. 6–11) recommend considering an approximate value of 2-4% of total CO₂ emissions over the entire consumption period.

In Kazakhstan, the production of solar collectors and PV panels relies on coal energy. Assume that (Müller et al., 2021) the total environmental contribution to produce PV panels includes not only the electricity costs to produce modules, but also delivery and installation. Similarly, the production (Menzies and Roderick, 2010, pp. 4–8) of STC, which includes the panels, tubes, heightened insulation, and additional equipment such as a water tank, incurs an environmental cost. This resulted in the following values: 320 kgCO₂ for each PV panel and 380 kgCO₂ for each solar collector along with additional systems. Figure 40 shows the total CO₂ emissions for each concept.

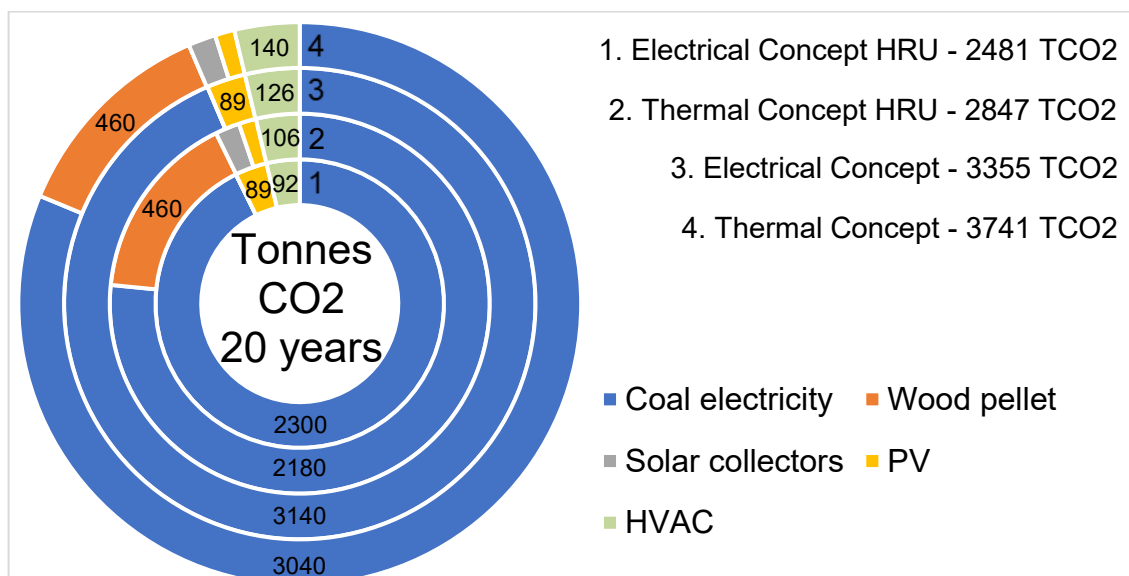


Figure 40: CO₂ emissions in next 20 years

The emissions analysis presented offers insight into the cumulative emissions expected over the next two decades, factoring in electricity consumption with distribution losses, pellet usage, and the installation of all equipment. Traditional energy sources remain the primary contributors to CO₂ emissions across all scenarios. The integration of boilers powered by renewable pellets or efficiently harnessed electrical sources facilitates a decrease in energy emissions. This can be seen as a favorable outcome when juxtaposed with the conventional generation of heat using coal. Achieving a significant reduction in the carbon footprint requires special attention to alternative forms of energy such as PV electricity production, the exploitation of which will accelerate the sustainable development of the city's environment in the long term.

5 Conclusion

Energy independence plays a crucial role in the life of any building, especially in situations where ensuring a stable energy supply during extreme weather conditions is challenging. The planned office building project in Ekibastuz, located in the Pavlodar region of the Republic of Kazakhstan can be connected to city utilities, but frequent accidents of central heating networks called for planning other methods of heat supply. The government's energy pricing policies with public concerns lead to frequent fluctuations and noticeable increases in energy tariffs. The primary focus is on efficiently utilizing energy sources to reduce purchase costs and the environmental impact of the city, which is entirely dependent on coal. This is where the considered concepts emerge based on reasonable energy consumption with maximizing the production of alternative methods of solar and thermal energy.

Properly assessing energy requirements is essential for predicting changes in the microclimate within the office building. Factors such as weather fluctuations, solar or visitors' activity can introduce variability and affect comfort levels. Maintaining a consistent temperature balance between the internal and external environment is critical to energy needs. This may include ventilation and envelope losses, as well as internal and external energy gains. It is possible to plan these processes using integration between different types of modeling even before the start of construction. Software programs like Autodesk Revit and DesignBuilder have greatly simplified the information analysis of all processes for further decisions based on the data obtained. Creating a BIM model of the office building in Autodesk Revit, considering all building structures and insulation materials, allowed for the precise determination of final values, which were then integrated into BEM using DesignBuilder.

Commercial building projects that aimed for nZEB offered insights and potential solutions for the office building model. Their further comprehensive analysis of BEM led to the presentation of four sets of solutions designed to achieve independence from district heating networks. The electric concept prioritized rational coal electricity consumption via the electric boiler during extreme periods, with the AWHP handling the workload during relatively warmer periods. In contrast, the thermal concept was to reduce dependency by introducing STC and the pellet boiler. Energy-efficient equipment was utilized to distribute heat through radiators, although other solutions like heated floors could decrease energy dependent but were not feasible due to building design limitations. The mechanical ventilation system required a different approach in creating additional heating of the incoming fresh air, considering the surface heat exchanger, which should capture heat from the central heating networks. At the same time, the main losses and electricity consumption of GWWHP occur precisely in ventilation, if the concept does not involve a heat recuperator.

Solar systems, including STC and PV arrays on the roof, as well as a facade PV system, were integrated to each concept. Modeling factored in sun shading from neighboring residential buildings, which significantly impacted solar energy production. To increase energy production, it was decided to consider changing the tilt angle of the roof structures monthly to increase the capture of direct solar radiation. This solution made it possible to increase productivity by 2 MWh in both concepts when angles ranged between 20 and 70 degrees throughout the year. Comparing the overall performance of both systems, the STC produced 30 MWh more energy than the PV, but the thermal concept does not include thermal storage, so during warm periods two thirds of the energy produced is lost to the atmosphere. Therefore, given the choice between STC or PV systems, PV emerged as the better option. The size of the facade PV system, which produces 6 times less electricity, is approximately the same. Production is affected by the lack of solar activity due to the neighboring building, so most of the electricity is produced only from the western side.

Energy solutions implemented in DesignBuilder made it possible to find the optimal solution for both the electrical and thermal concepts. Based on heating and cooling needs, energy-efficient equipment was selected, leading to simulations that determined energy consumption levels and energy categories for each concept. Both concepts incorporating MVHR were classified as nZEB buildings due to their low consumption and effective utilization of alternative energy sources. Energy costs without heat recovery greatly exceed consumption for air heating, but in the end, the results for final consumption are still lower than the values established by the government of Kazakhstan. Addressing concepts without the HRU, a viable strategy for mitigating extensive electricity consumption in heating fresh air involves decreasing the frequency of air renewal. This approach may compromise overall comfort. The attainability of these favorable heat recovery outcomes depends on a fully sealed office building envelope, eliminating natural ventilation pathways. Cooling of the incoming air is also carried out through the GWWHP, with the inclusion of the HRU also influencing the results between the concepts.

Economic analysis, employing the Annuity method, provided insight into initial project investments, leading to the reliable determination of energy distribution costs for each method. Notably, the LCOE for roof-mounted PV was only 40% higher than the electricity tariff from the distribution company, with an expectation of further increases. At the same time, the LCOE for facade PV is too high due to low output and high cost, which leads to the conclusion that it is unreasonable to include this system in the overall concept. The LCOH tariff for radiators was approximately the same for both concepts. In the electric concept, increased electricity costs prevailed, while the reduced AWHP consumption offered some compensation. In the thermal concept, high STC costs were balanced by relatively lower costs of wood pellets and solar heat. Achieving a low LCOH required the

use of the AHU equipped with a surface heat exchanger alongside the GWWHP, resulting in a 30% difference in tariffs between systems with and without HRU. However, there was a minimal variation in LCOC AHU.

Efforts to improve the situation through energy efficient HVAC systems are necessary, although their impact on the overall environmental background of Ekibastuz may be limited. A comparison of the carbon footprint of energy sources based on electricity consumption and wood pellets shows the potential benefits of electrical concept with smart and reasonable consumption, which has significantly lower overall CO₂ emissions. Moreover, the analysis highlights the importance of introducing alternative energy sources and HVAC technologies where emissions can be reduced and promoting sustainable urban development over the next two decades.

In the context of Ekibastuz's heavy dependence on coal for energy production, this master thesis not only highlights the importance of energy diversification, but also highlights the potential for innovative solutions that align with global sustainable development goals. By addressing the energy needs of the office building through a variety of approaches, including passive building design, energy-efficient technologies, and rigorous economic and environmental analysis, this master thesis contributes to the broader discourse on sustainable urban development and provides valuable guidance for the future. Ultimately, the success of this project lies in its ability to demonstrate that energy independence and sustainability can be achieved even in regions heavily dependent on traditional energy sources.

6 Discussion and future work

The analysis conducted, based on the selected strategies and solutions, has enabled to make significant progress towards achieving energy independence and sustainability within the framework of planned office building project. However, it is not possible to implement all possible solutions during the review process, but some should be considered further as key discussions and directions for future efforts.

First and foremost, the priority should be optimizing energy systems. The use of both STC and PV panels for solar energy generation has proven effective in reducing electricity and pellet costs. The focus should now shift towards enhancing solar energy generation efficiency, eliminating the need for lithium-ion storage, as nearly all PV-generated electricity is consumed within the office building. Additionally, the integration of PV panels into the building's façade makes the most sense for East or West-facing structures, although significant energy gains may be limited under such conditions. Furthermore, addressing the issue of heat loss during transitional seasons, where excess warmth is not utilized during mild periods, renders thermal storage facilities less practical due to their high costs and prolonged payback periods. There was also a decision not to use STC at all in the summer, if only a small part of the system for DHW needs. A proposal has emerged to incorporate an absorption chiller, which can operate on hot water from STC, potentially reducing system payback times. Nevertheless, given the efficient cooling systems already in place, it may be worth considering a hybrid approach, combining roof systems, with partial STC utilization for DHW purposes or introducing a hybrid PVT. Furthermore, exploring heat storage to supply the GWWHP for heating incoming ventilation air could enhance overall system efficiency. For heating fresh air, which is crucial for occupant comfort, both coil and recuperator systems should be maintained and sealed, and a second stage of heat recovery may be beneficial or include a heat wheel instead of a plate exchanger, pushing heat recovery rates closer to 80-90%.

The second crucial aspect to consider is the integration of smart building technologies capable of adapting to office activity levels, thereby ensuring the energy efficiency of HVAC and lighting systems meets nZEB standards. Explore the incorporation of solar shading devices for windows to mitigate cooling requirements during the summer season. Post-project launch, continuous monitoring of energy consumption and performance will be essential to sustaining optimal energy efficiency. This requires regular assessments and adjustments based on real-world data.

The third point to reevaluate is that the economic and environmental analyzes showed relatively different results, with some methods being more cost-effective than others. Ongoing evaluations must be conducted to determine the long-term viability of selected energy solutions in an evolving energy market. Given Ekibastuz's heavy dependence on

coal, there is a need to increase public awareness of the benefits of alternative energy sources, which is not possible without enhanced propaganda and government policies.

The discussion concludes by highlighting the multifaceted nature of achieving energy independence and sustainability in the Ekibastuz office building project. Future work should focus on refining and implementing the identified strategies, as well as exploring new technologies and sustainability practices to further enhance the environmental and economic benefits of the project. This project serves as a beacon of opportunity for regions heavily reliant on traditional energy sources, demonstrating that innovative solutions can pave the way to a more resilient and sustainable future.

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