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Transition towards Positive Energy District: A Case Study from Latvia

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ABSTRACT

The transition from a fossil fuel-based energy system to renewable energy sources has become a crucial consideration in both national-scale planning processes and local-scale energy system planning. Research has been conducted to seek technical solutions for a specific district of a university campus located on the peninsula of Riga to implement a smart energy system with multiple energy sources, storage systems, and energy efficiency measures. The solutions for the transformation toward a positive energy district include power generation by building integrated solar panels with different power storage alternatives, such as thermal storage, batteries, hydrogen, and fuel cells. The simulation also evaluates the potential for heat recovery and waste heat integration from the data centre and cooling systems to cover the heat demand. The interlinkage with energy efficiency improvements through improved building management systems provides an opportunity to increase RES utilization rates and improve overall energy efficiency. To provide a holistic overview of the future development of the urban area, the research also compares the connection to the district heating network.

Results show that the analysed district can achieve up to 80% of the RES self-consumption level as cost-optimal solutions by combining off-site wind turbine, solar PV panels, water source heat pumps, waste heat recovery and adjusted power storage.

Keywords

Energy communities;
Renewable energy systems;
Energy storage systems;
System dynamics modelling

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1. Introduction

Smart cities and communities are at the core of action of the European Strategic Energy Technology Plan aiming to reduce greenhouse gas (GHG) emissions and increase energy independence [1]. Positive Energy Districts (PED) and Energy Positive Neighbourhoods are a particular type of energy community approaching low-carbon society in the cities. Overall, it is expected that PEDs will stimulate the usage of renewable energy sources (RES) and support energy efficiency measures. Thus, through RES usage, the PED goal might be achieved [2]. However, the implementation of carbon-neutral urban energy communities is facing several challenges due to technical limitations, implementation constraints, and social acceptance due to the necessity to share resources [3]. The broader uptake of such systems is still at an early stage [4].

In smart neighbourhoods, the important factor is the ability to optimize energy flow on the low-voltage grid level thus decentralized energy storage systems are a promising means to match the supply and demand of fluctuating renewable energies more effectively [5]. Energy interactions between energy generation units, buildings, vehicles, energy storage systems, and microgrids are under recent investigation to eliminate technical and economic barriers to PEDs [6].

Achieving carbon-neutral status for existing buildings can be challenging, as implementing RES projects on these buildings depends on their type, location, and operating requirements [7]. Some buildings will be able to achieve more cost-effective results than others. Installing

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rooftop photovoltaics (PV) may be infeasible due to inadequate roof size/orientation and issues related to shading. Also, power grids have limited capacities to efficiently use surplus RES power. On the other side of the coin lies energy efficiency improvement and demand side management which is used to change consumption patterns to optimize the use of energy supply [8]. A more active role is expected from energy consumers, e.g. changing energy consumption towards higher efficiency, providing flexibility, or taking their role as prosumers [9].

Currently, energy communities are mainly viewed through the prism of RES electricity generation. Several research examines issues in the cost-effectiveness of installing solar panels, how they will affect the electricity grid, and what the benefits of implementing energy production measures will be [10,11]. An optimization model was developed for a study that looked at the community interaction between a small town and a winery with a solar panel installation [12]. A similar study involving 18 homes and 3 enterprises looked at how the interaction of solar panels, electricity storage technology, and aggregates could help increase electricity self-sufficiency and what the final costs would be. The authors conclude that the larger the electricity storage battery installed, the greater the electricity self-sufficiency, but the investment payback time increases as the total costs increase [13].

It is also necessary to evaluate whether the energy community will use common or distributed electricity storage technology. In a study by Luthander et al [14] several storage options were tested and the results show that the energy produced by solar panels for self-consumption increases when a common, rather than an individual, electricity storage battery is used. Recent research also incorporates the utilization of hydrogen as an energy storage solution for transport [15], however, there is a lack of studies on hydrogen utilization for covering power and heat demand.

Different modelling approaches are used to evaluate the optimal implementation of energy communities and PEDs. Ari et al. [16] have used a rule-based control method by developing an EnFloMatch tool and an optimization method to compare different RES technologies to reach the minimum life cycle cost. Zhou et al. [17] have studied a series of technical solutions, including the integration of plug-in vehicles and grid-responsive control by using a detailed TRANSYS simulation model for a particular urban district with office and hotel buildings. An alternative approach is used by Castillo-Calzadilla et al. [18] which uses an agent-based fuzzy logic methodology to define transition scenarios for an urban area with 3 residential and 3 public buildings. Zhang et al [19] have developed a mixed integer linear programming model under three different spatial scales (building, community, and district level) to optimize multiple energy storage resources. Viesi et al. [20] have coupled the software EnergyPLAN with a multi-objective evolutionary algorithm to seek carbon emission reduction with optimal cost levels for the energy community located in the Alps. Several researchers have focused on the strategic implementation of PEDs through SWOT analyses combined with energy production simulations [21] or social aspects such as energy vulnerability [22] and energy justice [23].

Another approach for modelling complex, dynamic processes is system dynamics (SD). There are two different strands in building energy efficiency modelling – looking at the entire housing stock (top-down approach) [24] and the building level (bottom-up approach) [25]. The top-down approach is considered more appropriate when analysing energy supply solutions on the way to decarbonization, while the bottom-up approach is used when considering the energy demand side.

The previous research shows a wide variety of PED and energy community simulations. However, only a few studies include the potential energy efficiency measures and RES installation by merging both types of potential solutions toward carbon-neutral neighbourhoods. This article provides a detailed analysis of the primary research question: What are the cost-optimal solutions for decarbonizing the university campus district by integrating energy efficiency measures and various RES? The phase-out of fossil fuels for energy production became crucial under steep energy price increases in 2022 therefore, several potential measures for energy consumption reduction have been identified through detailed building auditing. Additionally, this research includes various RES technologies (solar PV panels, vertical and horizontal wind turbines, heat recovery from data centres and cooling units, air-to-water, and water-to-air HPs) merged with several storage technologies for energy production (see Figure 1). However, further research could focus on additional technical solutions for cooling demand coverage and implementation of demand side management measures for additional RES potential utilization.

The research proposes a novel methodology by using a developed SD simulation model to perform multi-objective differential evolution optimization for a wide variety of solutions. Additionally, the developed decentralized solutions are compared with the possibility of connecting to the city`s district heating (DH) system for a holistic evaluation of PED`s feasibility.

2. Methodology

The overall methodology consists of three stages: initial research of case study, development of SD simulation tool, and assessment of alternatives for energy supply transformation through multi-objective optimization (see Figure 2).

The initial study includes an analysis of the current situation, an assessment of the potential for improving energy efficiency, and a feasibility study of the available RES technologies by defining technical and economic

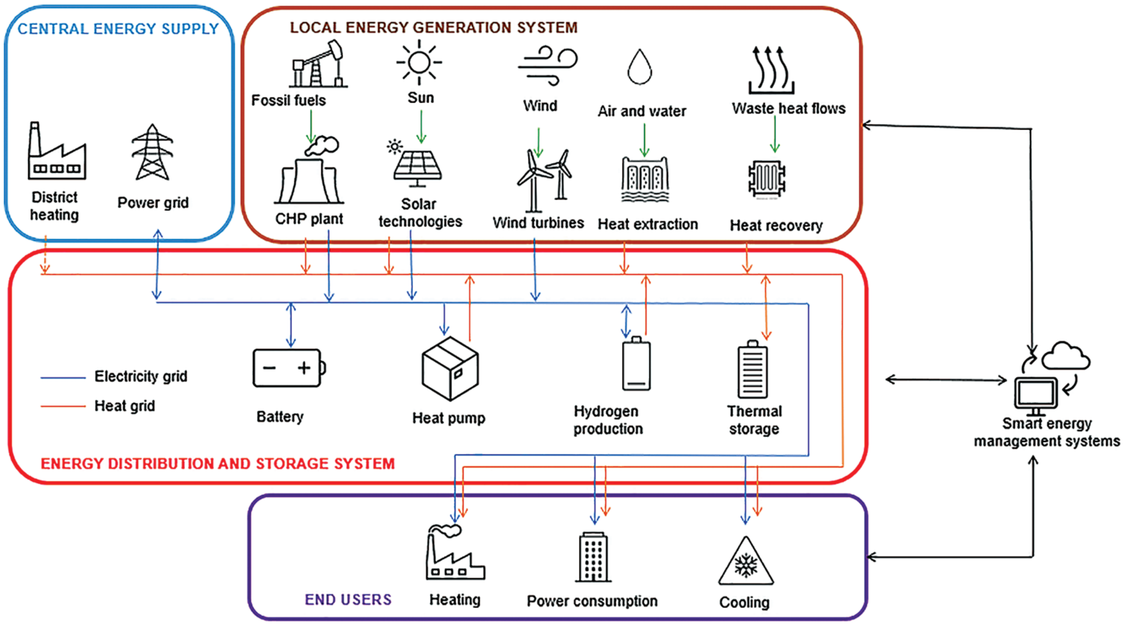


Figure 1: Proposed research boundaries and synergies between energy flows.

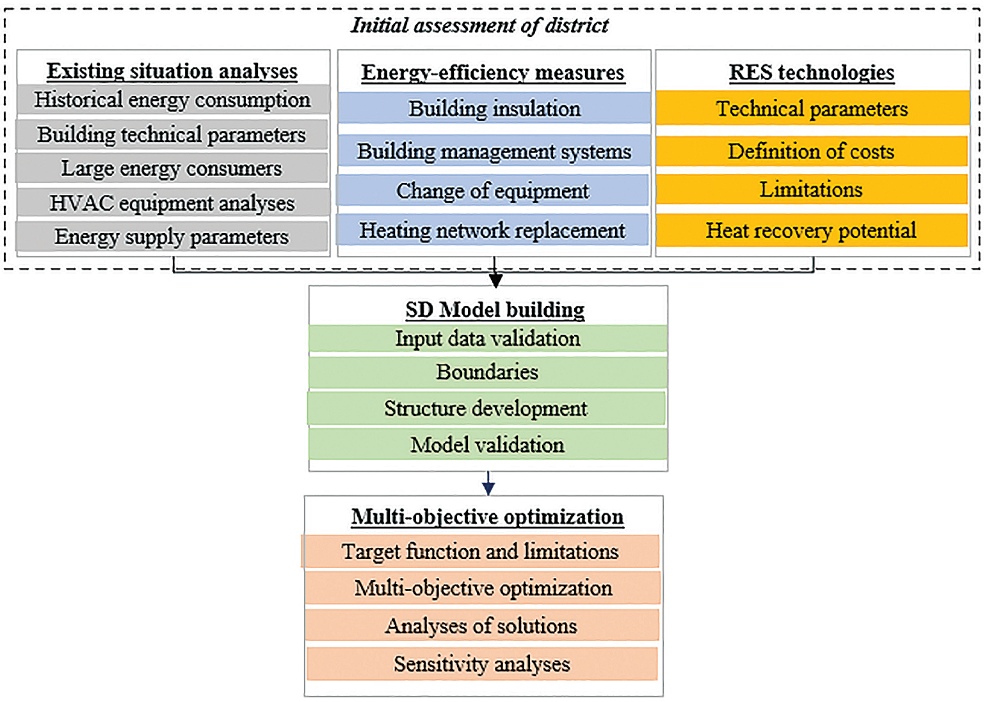


Figure 2: Methodology framework.

parameters and limitations. Further, the gathered data is used to develop a simulation tool based on the SD modelling approach with the help of Stella Architect's software.

Optimization of the power supply system and energy supply transformation alternatives have been further analysed with the created simulation tool to achieve the highest possible share of renewables in an economically justifiable manner. A comparison of alternatives is carried out using economic, technical, and environmental indicators.

2.1. Framework of analysed district

The modelled system includes 15 buildings owned by Riga Technical University (RTU) (see Figure 3 and Table 1) located on the peninsula of Ķīpsala in Riga, Latvia. Those include research buildings, dormitories, and a swimming pool for which detailed information on enclosing structures and engineering systems have been gathered. Most of the buildings have been built recently or renovated within the last decade. The research building No.15 is still in the building phase, however, its potential energy demand has been estimated through building parameters. In several buildings data centres and server rooms are located which are further considered as a potential heat source for HP installations.

Indirectly, the model includes a nearby exhibition hall due to close cooperation with the Campus. Its roof area and the parking lots could be used for solar panel installations. The existing version of the model does not include possible synergy with other buildings located in the explored peninsula (e.g., a shopping centre, private houses, and a hotel) due to a lack of available data. However, it could be further analysed to develop a larger energy community.

The existing energy supply system of the studied district is a natural gas boilers and cogeneration system with around 3 km long heating network. An overview of the installed equipment for heat and power generation

Figure 3: Spatial overview of studied buildings.

Table 1: Parameters of Campus buildings included in the model.

No.	Building type	Construction/renovation year	Area, m^2	Energy supply
1.	Faculty building	2015	8099	Local heating system
2.	Faculty building	2019	7250	Local heating system
3.	Faculty building	2019	859	Local heating system
4.	Dormitories	2012	18595	Local heating system
5.	Pool	2015	8288	Local heating system
6.	Faculty building	2012	10423	Local heating system
7.	Faculty building	2021	14072	Local heating system
8.	Faculty building	2019	9783	Local heating system
9.	Laboratory building	2020	6772	Local heating system
10.	Faculty building	2018	15447	Local heating system
11.	Library	2012	2344	Local heating system
12.	Faculty building	2021	3115	Local heating system
13.	Faculty building	2021	7731	Local heating system
14.	Hangar	2021	382	Local natural gas boiler
15.	Newly built Faculty building	2024	1661	New building, not included in the baseline scenario

is shown in Table 2. In one of the buildings, an individual gas heating boiler with a power of 30 kW is used. The total annual heat consumption of buildings reaches around 9329 MWh, while the total electricity consumption is 5249 MWh per year. The maximum heat load is 4.5 MW, while the maximum electrical load can briefly reach 2 MW in the summer when buildings are intensively cooled.

The research base year is 2022, but an adjustment has been made to the historical energy consumption of buildings due to the remote study process during a pandemic and significant deviations in the energy consumption of buildings over the last three years. The base simulation time of the model is assumed to be one year with hourly resolution.

2.2. Available RES technologies and limitations

The criteria and limits included in the optimization scenario are summarized in Table 3. The model incorporates two technological alternatives for vertical wind turbines on the roofs of buildings with low-power wind turbines (5 kW) and high-power vertical wind turbines (2.8 MW) also defining the relevant investment and construction costs. The model sets a limit that only one wind turbine can be installed on the roof of each building. Additionally, one off-site wind turbine with a capacity of 3 MW could be installed within the rural area owned by the university. It would supply electricity to the building complex, considering the necessary transmission costs for produced power.

For the energy supply transformation, it is possible to choose to install solar panels on the roofs of buildings, parking lots, southern facades of buildings, and the roof of the exhibition hall (up to 1 MW of solar panels). Currently, in the territory of Campus, there are approximately 200 parking, which could be equipped with solar panel sheds (the maximum available area is 2700 m^2). The area of the southern facades suitable for the placement of solar panels is 2500 m^2.

Table 2: Overview of existing local heating installations.

Parameter	Natural gas cogeneration unit	Natural gas boiler	
Heat production efficiency	46 %	93 %	86 %
Electricity production efficiency	39 %		
Electric power, MW	0.356		
Heat capacity, MW	0.464	3.5	6

The main alternative to covering the heat load is the installation of HPs [26]. The model offers four types of HP solutions with different capacity and operation limitations.

- Installation of individual HPs in buildings that use ambient air. There is a restriction that air HPs can only be used up to an ambient temperature above 0 °C.

Table 3: Overview of optimization criteria and added constraints.

Optimization criterion	Limit
Power and number of vertical wind turbines	One wind turbine of 5 kW or 2.8 MW can be placed on the roof of each building
Off-site horizontal wind turbine	It is possible to place one wind turbine (3 MW)
Solar panel placement and power	Available area of roofs, facades, and parking lots
Type and capacity of the HP	Central HP up to 1 MW in the channel; Central HP up to 2 MW in the River; An individual air HP adapted to the heat load of the building
Heat recovery from data centres	Maximum available heat output 424 kW
Arrangement and power of individual electric batteries	Maximum battery capacity in each building 2000 kWh
Installation of a centralized electric battery	Maximum centralized battery capacity 10,000 kWh
Type and size of heat accumulation	Maximum heat storage volume 10,000 m^3
Hydrogen production and storage	500 kWh of electricity supplied for hydrogen production
Connection to DH	Able to cover the entire heat load by considering pipe construction and heat tariff
Renovation of existing heating networks	Maximum reduction of heat loss by 0.2 MW
Energy efficiency measures in pool	Maximum electricity savings of 155 MWh per year
Improvement of building management systems	Adjusted temperature and ventilation modes in each building depending on the existing control system
Lighting replacement	Replacement of lighting in six buildings to more efficient LED, maximum electricity savings of 254 MWh per year

- Placement of an HP in the nearby water channel. The maximum heat output of the HP cannot exceed 1 MW and the HP can be operated to an outdoor air temperature of –5 °C, due to the shallow depth.
- Placement of an HP in the nearby river Daugava. The maximum heat output of the HP cannot exceed 2 MW, but it is assumed that the riverbed has a constant temperature, and it is possible to use the HP throughout the heating season.
- HPs that use waste heat from data centres and cooling systems. The maximum heat output is 424 kW.

Based on a feasibility study of suitable battery solutions, maximum charging capacity limits have been set. The model also incorporates an alternative for heat storage using pit or tank-type heat storage systems with a maximum available volume of 10,000 m^3. Excess electricity can also be used for hydrogen production with a limit on maximum electricity consumption of 500 kWh per year.

In addition to installing RES technologies, several energy efficiency measures can be taken in an optimization scenario at the corresponding costs. For each energy efficiency measure, a maximum possible reduction in energy consumption has been identified (see Table 3).

An alternative carbon neutrality pathway of the Campus could be a connection to the RES-based DH system. The existing heat supply system of Riga has not been fully decarbonized yet, but there could be potential for broader utilization of biomass [27] and HPs [28]. Therefore, to not eliminate the role of DH in the future, it has been considered as a potential solution in the model for heat load coverage in analysed buildings. The connection would require the construction of new pipelines with a total length of 1200 m. There are no restrictions in the model that DH should be used to cover the load completely, part of the heat load can also be covered.

2.3. Model Structure

The developed SD model for transitions to PED consists of several different submodels (see Figure 4). These include heat demand, electricity demand, heat supply and storage, electricity supply and storage, hydrogen production, hydrogen storage, and fuel cell production, heat recovery, energy production and technology costs, energy produced by RES, and the calculation of emissions. In addition, the model uses historical values of parameters such as solar radiation, electricity consumption, the price of electricity, and outdoor air temperature in daily and hourly values.

2.3.1 Energy demand submodel

The heat demand of buildings is divided into the hourly heat demand for heating and hot water preparation. The heat demand submodel calculates the heat consumption based on outdoor air temperature, solar radiation, shading, wall, roof, and basement U-values, thickness of insulation materials, area of rooms, walls, and windows, hot water consumption and specific heat [29]. The high

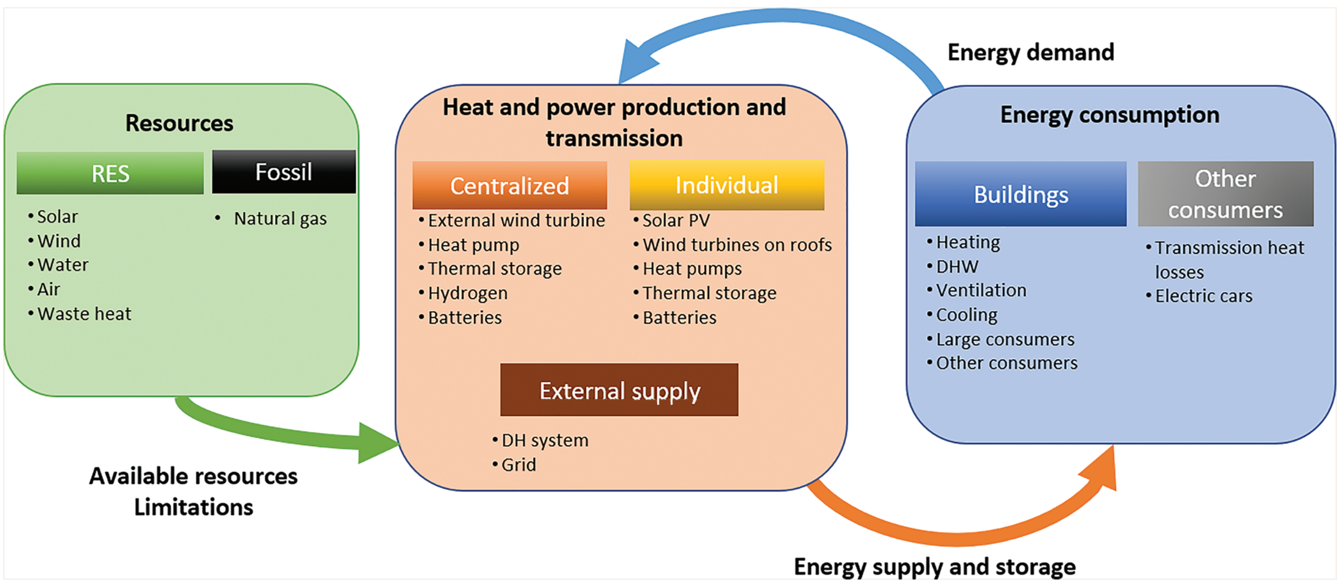


Figure 4: Overview of the structure of the model.

level of details of building configurations allows us to indicate the potential energy efficiency measures corresponding to each building – adjustments of air rates, changes in temperature regimes, improvements to the ventilation system, and reduction of solar heat gains.

The electricity demand submodel uses historical electricity consumption data and information on major electricity consumers: e.g. ventilation, cooling, lighting, data centres, and large electricity consumers. Based on historical consumption, normalized electricity consumption has been determined with defined workday and holiday consumption loads.

University have faced several challenges during the explored period including the online study process in 2020 and 2021 as well as reduced indoor comfort levels due to high energy costs in 2022. Therefore, the gathered energy consumption data are lower and have been normalized according to energy consumption data from 2018 and 2019. However, the incorporated energy consumption patterns could differ under normal operation conditions of buildings.

2.3.2 Energy generation submodel

Solar electricity calculation begins with assessing available installation areas like roofs, facades, and parking sheds. Using panel efficiency and solar radiation data, the model determines solar energy production. The model uses hourly average values from the last three years from the national meteorological database.

The calculation of wind electricity is based on the determined wind speed and wind turbine parameters. The data available in the meteorological database on the average wind speed in Riga are used to determine the electricity produced by wind turbines (1).

$$P_R = \frac{1}{2} \times \rho \times A \times v^3 \times C_p \quad (1)$$

where *PR* – rotor power, W; ρ - air density, kg/m^3; *A* - rotor area, m^2; *v* - speed, m/s; *Cp* – power factor.

The installation of various types of HPs has been considered the main alternative for heat production. Those include air-to-water HPs which use outdoor air or exhaust air from data centres and water-to-water HPs which use nearby channel or river water as a heat source [30]. The model assumes constant values of HP efficiency depending on the type of heat source and the average temperatures. Further research could include dynamic modelling of the coefficient of performance of the HPs. The available waste heat from the data centre is calculated by knowing the power of the installed electrical equipment and the efficiency of the heat exchanger. It has been assumed, that the available waste heat potential is constant throughout the year.

2.3.3 Energy storage submodel

The model integrates several options for direct electricity storage – installation of individual or centralized batteries, hydrogen production, and transfer of electricity to the electricity grid. The model also integrates the power-to-heat solution with the help of HPs, using excess electricity to cover the heat load.

RES electricity is stored at times when the electricity demand is low and consumed based on the electricity demand of buildings. However, it is also possible to transfer electricity to the grid when the power price is high (2).

$$AEE_t = AEE_{(t-DT)} + DT \times \left(SE_t + ET_t - EP_t - ENT_t \right) \quad (2)$$

where *ET* – electricity received from the network, kW; *AEE* – accumulated electricity, kWh; *EP* – electricity consumption, kW; *SE* – electricity produced from RES, kW; *DT* – the smallest unit of time of the model, h; *t* – the instantaneous value of the model time, h; *ENT* – electricity transferred to the network, kW.

Hydrogen production has been considered as another alternative to electricity storage. The amount of hydrogen that can be produced from given excess electricity production is based on the current amount of hydrogen in the storage, hydrogen storage capacity, amount of hydrogen that can be produced per electricity unit, and excess electricity produced (3).

$$RE = MIN\left(ELSS; \frac{HSC - HS}{SHP} \right) \quad (3)$$

where RE – Required electricity, kWh; ELSS – Electricity leftover after supplying campus storage, kWh; HSC – Hydrogen storage capacity, kg; HS – Hydrogen stored in the storage, kg; Specific hydrogen production, kgH_2/kWh.

The hydrogen production inflow and the stock outflow change the value of stock in the next time step (4).

$$HS_t = HS_{(t-DT)} + \left(RE \times SHP - HU \right) \times DT, \quad (4)$$

here t –time, h; DT – Time step, h; HP – Hydrogen production, kg/h; HU – Hydrogen used, kg/h.

The amount of supplied electricity is then used to meet the total electricity supply (5). Further, waste heat resulting from electricity production is delivered to thermal energy storage via heat pumps if the heat pump capacity allows it.

$$HU = MIN\left(ED; \frac{HS}{RHP}\right) \times RHP \quad (5)$$

where ED – Electricity demand left to supply, kW; RHP – Hydrogen required to produce electricity via the fuel cell, kg/kWh.

Several heat flows are available for heat storage – waste heat from the cooling of data centres and buildings, waste heat from electrolysis, and heat generated by the HP if excess electricity from RES is generated [31]. The model incorporates two types of storage systems – pit-type and tank-type storage systems, the storage capacity of which is determined based on the required amount of accumulated thermal energy [32]. The heat generated by the HP, which is transferred to the storage tank, depends on the available solar panel or wind electricity and the efficiency of the HP.

2.3.4 Economic and environmental submodels

The investment decision in ordering and installing a particular technology is determined based on the required amount of energy produced, comparing the investment and operating costs of the available technologies. The cost in the model consists of discounted capital costs, operating and maintenance costs divided into fixed and variable costs, fuel costs, risk costs, as well as other costs [33]. However, additional costs could occur during the installation of technologies, e.g., the necessity to strengthen the building constructions for the installation of solar PV panels and wind turbines.

Net present value (NPV) and internal rate of return (IRR) are used as key indicators to calculate the economic rationale for the measures. The project lifecycle cash flow is calculated under a discount factor of 5% and a life cycle time and loan term of 20 years.

A significant factor affecting the use of RES technologies is the cost of fossil energy resources. Accordingly, the main assumptions in the model are the price of natural gas and the final tariff for electricity. The current version of the model assumes that the price of natural gas is constant at 100 EUR/MWh over the entire modelling period. The heat distribution and sales costs from the existing local heat supply system are 18.2 EUR/MWh. This assumption is made against the background of both the sharp increase in the price of gas in 2022 and the low gas prices in the spring and summer of 2023. To determine the potential savings from the electricity produced by RES, the model uses the average hourly price of *Nordpool* electricity over the last three years. The average annual electricity price is about 80 EUR/MWh. Additionally, the electricity transmission and distribution component is 50 EUR/MWh. In a technical solution when the heat load is covered by connecting to the city's heat supply, the model uses the fixed heat tariff of the DH system of 91.26 EUR/MWh. Economic indicators of the project in the case of other energy prices are determined using sensitivity analysis.

The emissions submodel aggregates emissions from the use of natural gas, DH and electricity taken from the grid. The used CO_2 emission factors are the following: 0.202 tCO_2/MWh for natural gas; 0.264 tCO_2/MWh for DH; and 0.109 tCO_2/MWh for power from the grid.

2.4. Model verification

To assess the behaviour of the developed SD model and its relevance to real conditions, the results of the model are compared with historical building consumption indicators. The main comparable parameters are the amount of heat and electricity consumed. Figure 5 shows the probability of deviations in energy

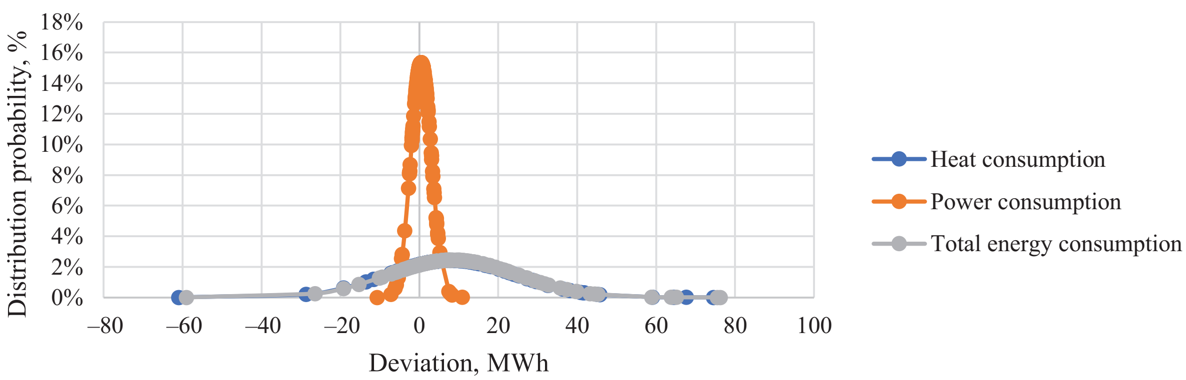


Figure 5: Deviations in energy consumption and distribution of probability.

consumption for thermal, electricity, and total energy consumption. For each building, the total annual energy consumption is forecasted with high accuracy, with a maximum relative deviation of 16%. Deviation of electricity consumption within 10 MWh is possible with a relatively high probability. In turn, the deviation in heat consumption can vary up to 20 MWh per month, but with a very low probability (2 %). The overall accuracy for building energy consumption forecast under various circumstances and technical parameters is relatively high, therefore allowing us to evaluate the impact of different energy efficiency measures which mainly focus on improved building management.

2.5. Optimising transition to carbon-neutral energy community

The main task of optimization is to show which of the combinations of RES technologies and energy efficiency measures can make the greatest economic contribution. The study uses the multi-objective differential evolution (MODE) method which is based on an assessment algorithm used to find the best solutions for several simultaneously optimized goals [34]. Multi-goal optimization uses specific evolutionary operators and customizations to perform evolution and find Pareto's optimal solutions. Therefore, it is widely used in various fields where there are several conflicting goals, for example, in engineering, economics, financial analysis, and other industries [35].

Optimization of Campus energy supply includes two target functions:

1. to achieve the maximum share of renewable self-consumption in the Campus energy supply
2. to achieve the maximum value of the net profit of the RES project (NPV), considering the savings in energy costs and the necessary capital costs.

The model optimizes the energy supply system by considering the limitations described in Section 2.2.

3. Results

The section presents the results of different pathways to move forward to a positive energy district. Considering the assumptions made regarding electricity and heat tariffs, the total cost of heat in the Base scenario is 1.21 million EUR per year, while the cost of electricity is 763 thousand EUR per year. In the baseline scenario, CO_2 emissions from the supply of heat and electricity amount to 8.67 tons per year.

3.1. Optimization results

Optimization for energy system transformation was carried out by seeking the maximum NPV value and the maximum share of RES self-consumption. Figure 6 shows the 50 optimization results obtained after multiple optimizations. Within the specific limits, the maximum share of RES self-consumption is 82%, which can be achieved by different solutions. Three marginal optimization solutions (highlighted with dots in Figure 6) and their energy production solutions have been explored in detail to compare different potential pathways (see Table 4).

In all the optimization solutions identified in Figure 6, the maximum possible capacity of solar panels (3.4 MW) and an off-site wind turbine with a capacity of 3 MW is installed. Also, energy efficiency measures are with high priority in all optimization solutions. For the storage of

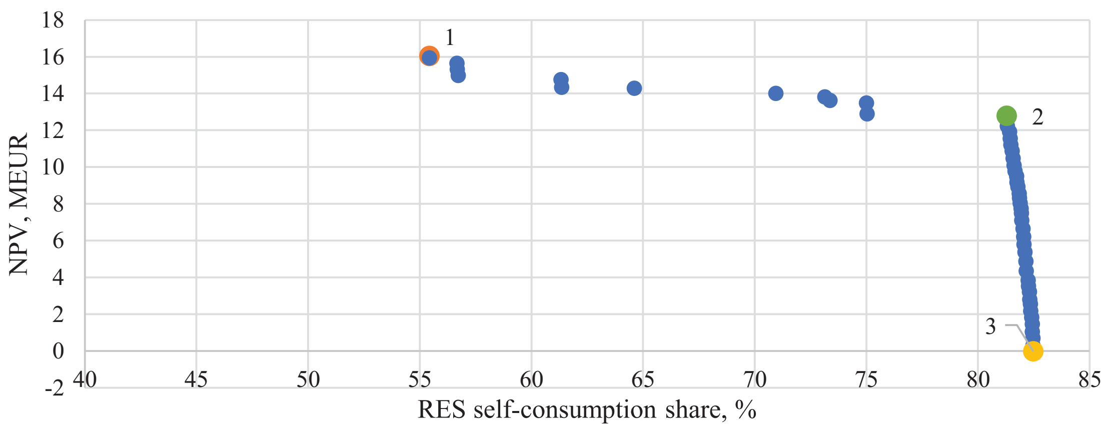


Figure 6: Optimization results – correlation analysis of NPV and RES share.

Table 4: Comparison of key parameters of optimization solutions.

	Option 1	Option 2	Option 3
Share of RES self-consumption, %	55.4	81.3	82.5
NPV, MEUR	16.03	12.78	–0.02
Total investment, MEUR	23.77	25.37	33.47
IRR value, %	8 %	7 %	2 %
Installed power of solar panels, kW	3389	3389	3389
Installed power of wind turbines, kW	3070	3070	3075
HP for the use of waste heat, kW	424	424	424
HP in the channel, kW	440	440	980
HP in the river, kW	40	2000	2000
Heat storage tanks, m^3	190	190	210
Power of individual electric batteries, kWh	10 360	10 340	27 200
The capacity of the central electric battery, kWh	10 000	10 000	10 000
Hydrogen production, kWh$_{el}$	0	0	8475
Energy efficiency measures	Improvement of building management systems, replacement of lighting, energy efficiency measures of the pool, replacement of the heating main		

electricity, a centralized battery with a maximum permissible capacity of 10,000 MWh is installed in all the proposed solutions. The main variable parameters that distinguish the proposed optimization solutions are the installed HP capacities, the number of low-power wind turbines installed on the roofs of buildings, and energy storage technologies (size of heat storage, use of installed individual batteries, and hydrogen production).

In the first optimization solution, the maximum NPV value and the share of 55 % RES in energy self-consumption are achieved. In this solution, a HP is not installed in the river and a small HP in the channel is used. The maximum accumulation of electricity reaches 20.4 MWh, and there is only a small heat storage tank. The second optimization solution achieved an 81% share of RES when installing high-capacity HPs. In the third solution, individual electricity batteries were additionally installed in buildings, reaching a total electricity storage capacity of 37 MWh per year. In this scenario, five wind turbines are additionally installed on the roofs of buildings. The third optimization solution has a slightly larger heat storage tank and, in addition to electric batteries, excess electricity is used to produce hydrogen. This optimization solution has the highest share of RES, while the value of NPV is - 22 kEUR for 20 years.

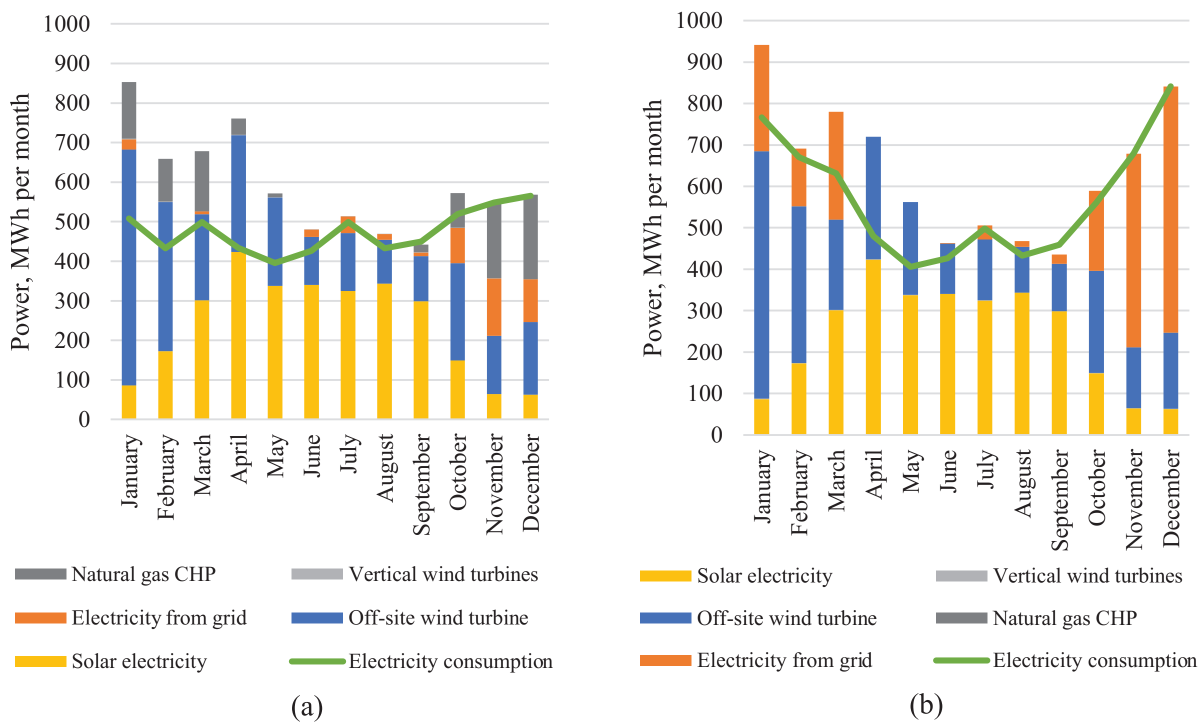
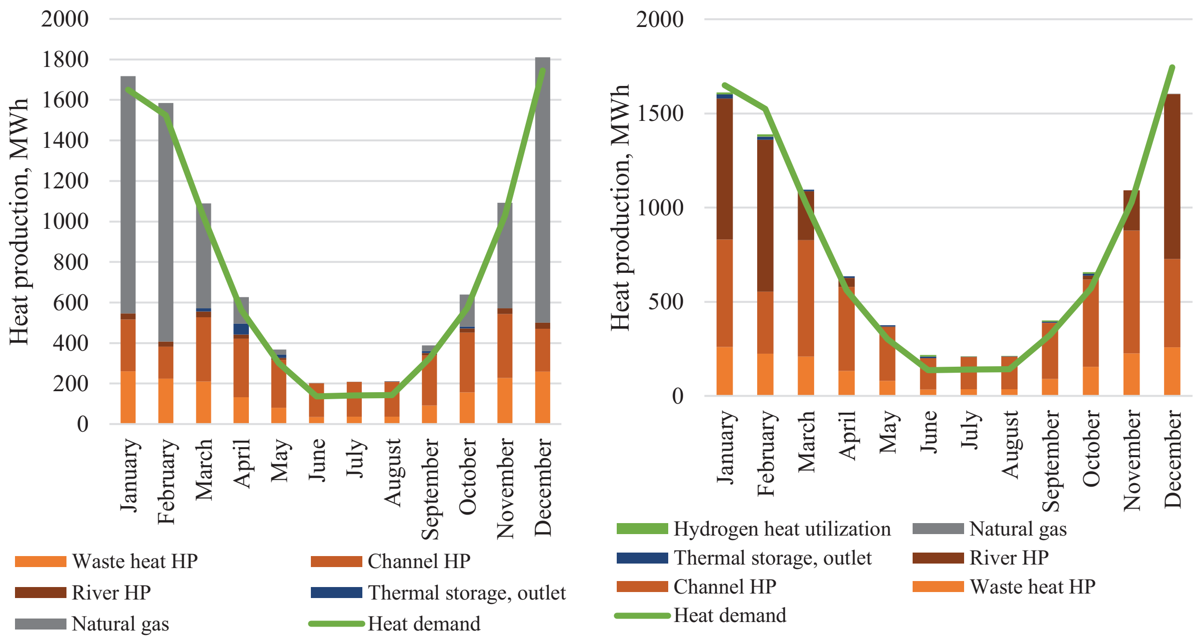


Figure 7: The generated electricity by resource in optimization solution 1 (a) and optimization solution 3 (b).

Figure 7 and Figure 8 show the amount of electricity and heat produced in optimization solution 1 (a) and optimization solution 2 (b) by month. Given that the installed capacities of solar and wind are similar in all three optimization solutions explored, the volumes of energy produced are also similar. The largest amount of available wind electricity is in January and February when there is also higher consumption of electricity and heat. In turn, solar electricity is produced in spring and summer. It should be taken into account that the model incorporates the linkage of heat and electricity consumption through the use of HPs. Accordingly, during periods when a larger amount of RES electricity is available, the amount of heat generated, which is accumulated, increases.

Solar and wind electricity production creates excess electricity during periods when there is a low electricity demand, but a high amount of renewable energy is produced. The model incorporates various alternatives to the use of this excess electricity. The most cost-effective way is to transfer excess electricity to the grid since this does not require additional investments. The model compares the price of hourly electricity with alternative storage systems and their available capacities to decide whether to transfer



(a) (b)

Figure 8: The generated heat by resource in the optimization solution 1 (a) and optimization solution 3 (b).

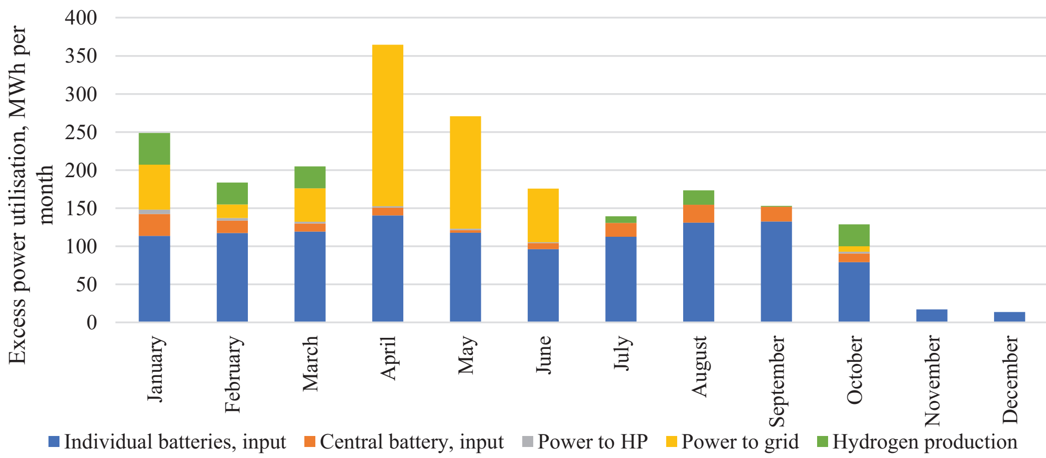


Figure 9: Electricity storage in the optimization solution 3.

electricity to the grid or divert it to storage. Figure 9 shows the use of excess electricity by month in optimization solution 3. Due to the limited capacity of installed batteries, a large part of the electricity is transferred to the grid.

Figure 10 compares the strategy for using excess electricity in the optimization solutions considered. In the second and third solutions, electric batteries are used as the main form of storage. The third solution installs higher battery capacities and additionally produces hydrogen. Hydrogen is used to generate electricity and the waste heat of electrolysis is used to cover the heat load. In optimization solution 3, the consumption of electricity from the network increases to ensure the operation of HPs, therefore the largest electricity deficit is in November and December.

In optimization scenarios, a large part of the electricity produced is transferred to the grid at the relevant hourly exchange price, so the total energy costs are negative, i.e. the electricity sold covers the costs of natural gas and purchased electricity. As a result, the total income from the energy supply system in optimization solution 1 is 838.3 kEUR per year, in optimization solution 2 727.7 kEUR per year, and 411.2 kEUR per year in optimization solution 3. The resulting CO_2 emissions in these scenarios range from 2.59 tons to 2.23 tons of CO_2 emissions per year.

3.2. Sensitivity analysis

A sensitivity analysis was carried out for different levels of energy prices. Figure 11 shows how the value of NPV obtained in optimization solution 1 changes depending on energy prices. The greatest impact on the economic feasibility is the price of electricity. If it rises to 200 EUR/MWh, which was observed in 2022, then the NPV value of the project reaches almost 50 million euros. Changes in natural gas prices and increases or decreases in the electricity distribution tariff have relatively smaller impacts.

In different external conditions, energy prices often increase simultaneously, therefore Table 6 summarizes

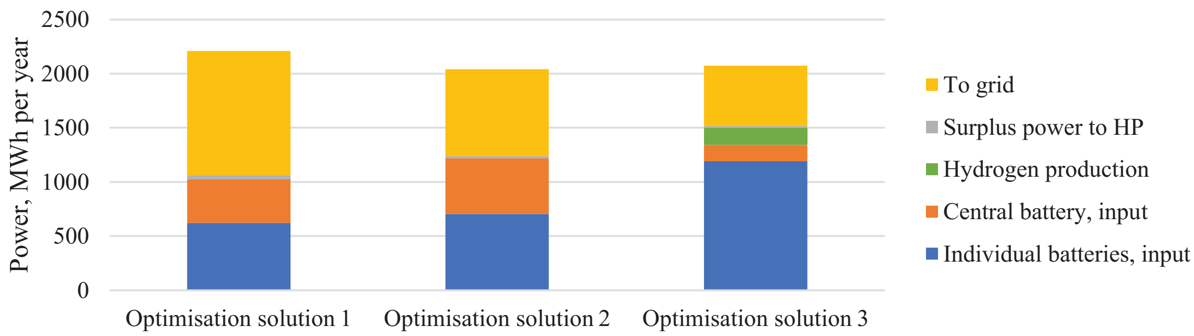


Figure 10: The use of excess electricity from RES in various optimization solutions.

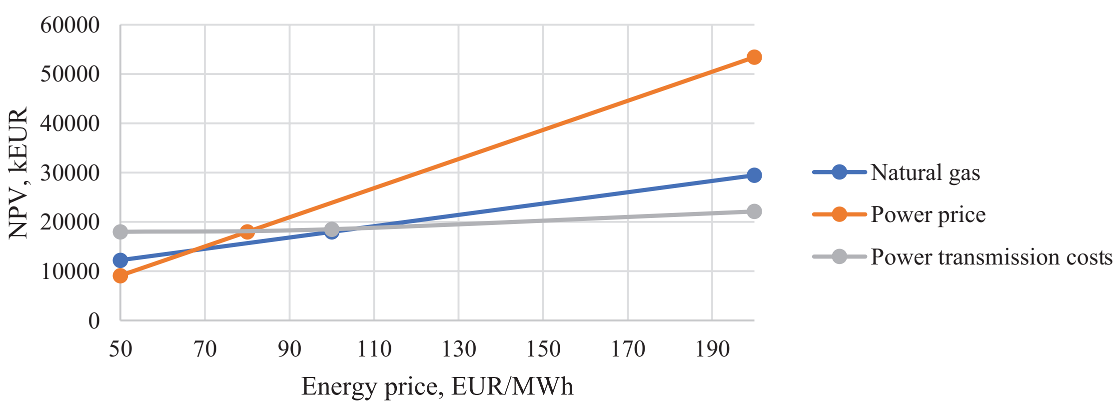


Figure 11: The results of the sensitivity analysis for optimization solution 1 (share of RES 55 %) if other parameters remain unchanged.

Table 6: Sensitivity analysis results for high and low energy prices.

Optimization solution	Parameters of sensitivity analysis			Calculated parameters				
	Nature-gas price	Electro-energy price	Transmission costs	Reduction of energy costs	NPV	IRR	Payback time	Discounted payback time
	EUR/ MWh	EUR/ MWh	EUR/ MWh	Million. EUR per year	Million. EUR	%	Years	Years
Basic prices								
1				2.54	16.0	8 %	9.4	11.2
2	100	80	50	2.43	12.7	7 %	10.5	12.7
3				2.11	–0.02	2 %	15.9	21.8
Low energy prices								
1				1.56	–0.61	3 %	15.3	20.7
2	50	50	50	1.44	–4.03	1 %	17.7	25.6
3				1.20	–15.6	–3 %	27.9	61.6
High energy prices								
1				5.73	61.4	24 %	4.1	4.5
2	200	200	100	5.17	51.5	20 %	4.9	5.4
3				4.48	33.1	12 %	7.5	8.6

the results of optimization solutions for lower and higher energy resources and transmission costs compared to the Baseline scenario. As can be seen, only in the case of low energy prices, a negative NPV and IRR value is achieved in the optimization solution 3. On the other hand, if all energy prices increase significantly, then the discounted payback period of all optimization solutions is less than 10 years.

4. Conclusions and Discussion

The study performed multi-objective differential evolution optimization to identify energy transition solutions for University Campus buildings with the highest share of RES and economic returns. Within the limits included in the optimization of the available area and by considering the energy efficiency potential, it is possible to achieve a share of approximately 80 % of the energy produced by RES, with a net present value of EUR 12 million over 20 years. The optimization solution includes solar panels (total capacity of 3.4 MW) on the roofs, facades, and parking lots of buildings and an off-site wind turbine (capacity of 3 MW). For the storage of electricity, individual batteries, and a centralized battery with a total storage capacity of 20 MWh per year are installed. Thermal energy in buildings would be provided using heat pumps with a total heat capacity of 2.8 MW, which would use the recovered heat from data centres, the water channel, and the river as a heat source. In all optimization solutions, energy efficiency measures are carried out with high priority. The resulting CO_2 emissions in these scenarios range from 2.59 thousand tons to 2.23 thousand tons of CO_2 emissions per year. Therefore, the proposed solutions are close to reaching the positive energy district level.

The investment required for such a solution is more than 25 million EUR which is significant for public buildings. However, the available support programs for investments in RES and energy efficiency measures could reduce the financial requirements and increase the viability of the solution. If careful planning of the long-term development of the energy system is carried out, then the proposed measures can be implemented gradually, reducing the investment burden.

The transition to a fossil fuel-free energy district would create added value for the University through a more resilient energy supply system even in adverse conditions. The diversification of energy sources and implemented storage solutions would allow increased flexibility and allow to choose the most beneficial power and heating sources depending on the external conditions. Furthermore, pioneering innovative technologies, such as hydrogen production and advanced building management systems, would not only benefit the Campus but also provide additional social benefits to the students. These technologies can enhance the learning experience by exposing students to cutting-edge solutions and preparing them for future careers in sustainable energy industries.

Future carbon-neutrality scenarios significantly interconnect with the national power grid due to external wind park solutions and the necessity to transmit the generated power. In optimization solutions, part of the generated electricity is transferred to the network at the respective hourly exchange price, so the total energy costs are negative, i.e., the electricity sold covers the costs of natural gas and purchased electricity. Therefore, ensuring the grid capacity and balancing of the overall power system outside the district should be considered at the national level.

There are several limitations associated with performed research. There is limited accuracy and completeness of the initial research data, particularly historical energy consumption data. Even though, detailed data have been gathered and validated for the studied district, the historical energy consumption patterns may differ from the existing consumption due to the remote study process during the pandemic and strict energy-saving measures with reduced indoor comfort in 2023. The obtained data have been normalized, however, the real energy consumption under normal building operation modes could differ.

The developed system dynamics model does not include transport demand, however, an electric car could function as an additional electricity storage solution. The average energy consumption of existing charging stations on Campus ranges from 90 to 170 MWh per year. In the optimization solutions, the excess electricity that is directed to the batteries is 1030–1300 MWh per year. Accordingly, if the electric car park is significantly increased, then the charging points can provide significant storage capacity if the car charging is managed according to the available renewable power.

The cost-optimal carbon neutrality solutions with RES technologies rely on assumptions regarding technical and economic parameters and limitations. The incorporated cost assumptions do not include additional costs which may occur during the installation of technologies, e.g., the necessity to strengthen the building constructions for the installation of solar PV panels and wind turbine. The accuracy of these assumptions could affect the validity of the optimization results. Additionally, there are several simplifications incorporated within the developed model associated with RES technologies, e.g. constant efficiency of heat pumps, and approximate and constant waste heat potential.

Within the framework of the study, no in-depth research has been carried out on the improvement of cooling systems in the Campus buildings. Some of the existing equipment is low efficiency, so it is desirable to change it to more efficient ones. Various alternative cooling solutions are not covered in this study, such as the use of river water for cooling through heat pumps or absorption coolers. Also, the impact of demand-side management on the use of energy produced by RES has not been evaluated. Further research would be needed to assess whether any additional measures can be taken using the thermal inertia of buildings to reduce the need for accumulation.

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