Increasing the penetration of renewable energy sources by using power to heat technologies in power systems based on coal

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FACULTY OF MECHANICAL ENGINEERING AND NAVAL ARCHITECTURE

DRILON MEHA

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DOCTORAL THESIS

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Abstract

The transition of the coal-based energy system is a challenge that can be solved by considering the integration of variable renewable energy sources and synergic effects between electricity, heating, cooling, transport and industrial sectors. This thesis focuses mostly on the integration of variable renewables using power-to-heat technologies in district heating systems. As 70-80% of total energy consumption in buildings takes the form of heat consumed for space heating purposes, spatial identification is crucial for planning and designing sustainable district heating systems. Hence, this thesis studies the quantification and validation of heat demand distribution within a small municipality using a newly developed Bottom-up and Top-down heat mapping method. The Bottom-up mapping method is based on building features such as surface floor area, building

height, building use, and the heated area share. In contrast, the top-down mapping method relies on energy balances and population distribution densities. The results are shown spatially in grids with high spatial resolution. The finding shows that current models overestimate the heat demand, while with the proposed method, the error between existing and proposed models is negligible. The bottom-up heat demand maps are further improved by considering domestic hot water besides space heating demand. Domestic hot water should be taken into account when assessing district heating potential, as up to 30% of total final energy consumption in buildings in developed countries takes the form of heat used to prepare domestic hot water. Hence, this thesis develops a spatial-temporal method for annual hot water demand in conjunction with space heating demand while technically and economically assessing the expansion potential of the district heating systems. The main findings show that the actual district heating can be increased four times when excluding domestic hot water and five times when considering both space heating and domestic hot water demand. The thesis also considers the heat saving potential in buildings by developing a robust information socket of the urban building stock. Such information is used for assessing the impact of energy efficiency measures on space heating demand savings and CO_2 emission reduction potential in the existing buildings based on a Geographical Information System tool. The findings show that space heat demand saving potential for scenarios 1 and 2 compared to the reference scenario was 50 % and 68.5%, respectively. As the transport and heating sectors account for the largest energy consumers in energy systems, their electrification plays a major role in decarbonising the said sectors. Many solutions support the decarbonization of energy systems by increasing the integration of variable renewable energy and utilizing the synergic effect between electricity, transport and heating sectors. In that regard, this thesis emphasizes the importance of utilizing heat pumps for individual heating solutions and electric vehicles in the transport sector as the main sources for enhancing the energy system flexibility and emphasizing their consequences in thermal power plant operational capacities and efficiencies. The findings show that electrification of heating and transport sectors significantly impacts variable renewable integration and CO_2 emission reduction; hence, the same poses major challenges for the nominal operation of thermal power plants. Besides using power-to-heat technologies for individual heating, the thesis also concentrates on increasing the share of variable renewable using power-to-heat technologies in district heating systems. The main goal is to identify the influence of using district heating systems coupled with the power-to-heat technologies based on the flexible operation of coal-based

thermal power plants and limited electricity system interconnections on the maximum integration of variable renewables. Results show that wind and PV power plant capacities installed in the existing Kosovo energy system, when operating in an isolated mode, are 450 MW and 300 MW, respectively. Additional capacities around 800 MW for wind and 385 MW for PV can be further integrated into this isolated energy system with the contribution of power-to-heat technologies coupled with thermal energy storage in district heating with a fixed capacity. Finally, the previous findings were used to asses sustainable energy transition pathways for coal-based energy systems. The method shows how the scaling-up in variable renewable energy sources and sector coupling (electricity and heating) while maintaining high flexibility in thermal power plants can shed light on achieving sustainability in a coal-based energy system. Five different scenarios have been created. Significant differences in annualized technology and emission costs can be observed between scenarios. In addition, scenario three seems to have the least cost in comparison to other scenarios. The total CO_2 emissions for projected scenarios 1, 2, 3, 4, 5 in 2030 accounted for 4.78, 5.28, 4.48, 3.97 and 4.95 $MtCO_2$/year. In addition, the total annual costs for projected scenarios 1, 2, 3, 4, 5 in 2030 accounted for 2168, 1611, 1993, 2479 and 2817 Mil. EUR respectively.

Keywords

Heat demand, district heating, power-to-heat, flexibility, coal thermal power plants, variable renewables

Nomenclature

E_{tot}^{res} , kWh – total thermal energy (heat) demand by residential buildings

E_{coal}^{res} , kWh – coal energy consumption by residential buildings

E_{oil}^{res} , kWh – oil energy consumption by residential buildings

$E_{biomass}^{res}$, kWh – biomass energy consumption by residential buildings

$E_{elec.}^{res}$, kWh – electricity energy consumption by residential buildings

E_{DH}^{res} , kWh – district heat consumption by residential buildings

η_{coal} – the efficiency of conversion of chemical energy of coal into heat

η_{oil} – the efficiency of conversion of chemical energy of oil into heat

$\eta_{biomass}$ – the efficiency of conversion of chemical energy of biomass into heat

$\eta_{ele.-thermal}$ – the efficiency of conversion of electrical energy into heat

a_1, % – is the percentage factor of total final thermal energy used by residential buildings for space heating purposes

E_{tot}^{com}, kWh – the thermal energy demand used for space heating by commercial buildings

E_{coal}^{com}, kWh – coal energy consumption by commercial buildings

E_{oil}^{com}, kWh – oil energy consumption by commercial buildings

$E_{biomass}^{com}$, kWh –biomass energy consumption by commercial buildings

$E_{elec.}^{com}$, kWh – electricity energy consumption by commercial buildings

E_{DH}^{com}, kWh – district heat consumption by commercial buildings

$E_{thermal}^{com}$, kWh – the final thermal energy demand by commercial buildings

Where: a_2 and a_3 – are the percentage factors of total final thermal energy demand by commercial end-users (public and private buildings) for space heating purposes

$E_{tot}^{thermal}$, kWh – the total heat demand for space heating accounting for both residential and commercial building

$e_{thermal}^{capita}$, kWh /capita – the specific heat demand for space heating per capita

$n_{capitals}$, – number of inhabitants in a respective year

A_f^b, m^2 – building floor area

n_f – number of building floor

c_r, % – calibration ratio between net and gross building heated area

$A_{n.h}^b$, m^2 – net building heated area

$A_{g.h}^b$, m^2 – gross building heated area

$A_{p.h}^b$, m^2 – partially heated area of a building

$Q_{s.h}^b$, kWh/year – space heating demand per building

e_{sh}^{b}, kWh/m²year – annual specific space heating demand per building category

$Q_{s.h}^{grid}, \mathrm{kWh/year}$ – total space heating demand in a cell with 250 m x 250 m

$Q_{s.h}^{city}, \mathrm{kWh/year}$ – overall city space heating demand

c_{pw}, Wh/kg˚C – specific heat capacity at constant pressure

m_{wi}, l/day – domestic hot water flow rate

t_{hw}, ˚C – hot water supply temperature

t_{cw}, ˚C – cold water temperature

$A_{n.a}^{b}$, m^2 – net area of a building

$A_{t.n.a}^{grid}$, m^2 – total net area of the buildings in a grid with 250 m x 250 m

P_{c}^{grid}, number of occupants – number of people in a grid with 250 m x 250 m

$a_{a.n.a}^{c}$, $m^2/\mathrm{occupant}$ – average net building area per occupant

$Q_{h.w}^{grid}$, $\mathrm{kWh/day}$ – domestic hot water demand per grid

$e_{h.w}^{c}$, $\mathrm{kWh/occupant} \cdot$ day – specific hot water demand per occupant

$Q_{t.h}^{grid}$, $\mathrm{MWh/year}$ – total aggregated heat demand in a grid with 250 m x 250 m

DH_{p}, EUR/year – district heating potential

C_{heat}, $\mathrm{EUR/year}$ – price of heat

LCOH, $\mathrm{EUR/year}$ – levelized cost of heat

$l_{g.e}$, m/m² – specific equivalent network length within a grid size with 250 m x 250 m

$C_{g.e}$, EUR/m – cost of distribution network installation length in a grid with 250 m x 250 m for inner cities

$l_{eg.DH}$, m – existing district network length

A_{nDH}, m^2 – net area of buildings connected to district heating (DH)

$A_{p.DH}$, m^2 – potential net building areas for connection to expanded DH, m²

A_{grid}, m^2 – area of the ground distributed network

T_{am}, ˚C – ambient dry air temperature

T_{in}, ˚C – building design air temperature

$A^b_{n.h}$, m^2 – the total net space heated area of a building

A^b_f, m^2 –the building footprint area

n_f – the number of floors

c_r – the calibration ratio between net and gross area of a particular building

$Q_{building}$, kWh/year – the space heating demand for the building

e_a, kWh/m^2year – specific space heating demand

$Q_{grid,}$ kWh/year – the actual space heating demand in a grid with 200 m × 200 m

Q^{EEs}_{grid}, kWh/year – the space heating demand with standard energy efficiency measures in a grid with 200 m × 200 m

Q^{EEa}_{grid}, kWh/year – the space heating demand with advanced energy efficiency measures in a grid with 200 m × 200 m

$Q_{SH,city}$, kWh/year – the total annual space heating demand of the city

e_i, % – the share of primary energy supply source to cover final energy demand in buildings

Q_{PES}, kWh/year – the useful space heating demand produced from different primary energy supply (PES) sources

Q_{coal}, kWh/year – the useful heat produced from coal

Q_{oil}, kWh/year – the useful heat produced from oil

$Q_{biomass}$, kWh/year – the useful heat produced from biomass

Q_{elec}, kWh/year – the useful heat produced from electricity

Q_{solar}, kWh/year – the useful heat produced from solar thermal collectors

Q_{DH}, kWh/year – the useful heat produced from district heating

η_{coal} – the efficiency of conversion of coal into heat

η_{oil} – the efficiency of conversion of oil into heat

$\eta_{biomass}$ – the efficiency of conversion of biomass into heat

η_{solar} – the efficiency of solar thermal collectors

$\eta_{ele.production}$ – the efficiency of conversion of PES mix into electricity

$\eta_{DH,production}$– the efficiency of district heat production

$gCO_{2(fuel,mix)}$ – kg/kWh carbon dioxide emission factor

λ, W/m°C – layer thermal conductivity

U, W/m^2°C – overall heat transfer coefficient

ABBREVIATIONS

CO_2 Carbon Dioxide

DH District Heating

IEA International Energy Agency

GHG Greenhouse Gas Emissions

EU European Countries

4GDH Fourth Generation of District Heating

GIS Geographical Information System

DHW Domestic Hot Water

vRES Variable Renewable Energy Sources

HDD Heating Degree Day

EV Electric Vehicles

V_2G Vehicle to Grid

P_tH Power to Heat

TPP Thermal Power Plants

HS Heat Storage

HP Heat Pump

DHC District Heating and Cooling

PV Photovoltaics

PP Power Plants

RES Renewable Energy Sources

TPES Total Primary Energy Supply

CCS Carbon Capture and Storage

QGIS Quantum Geographical Information System

LCOH Levelized Cost of Heat

EEs Standard Energy Efficiency

EEa Advanced Energy Efficiency

CEEP Critical Excess Electricity Production

RLC Relative Loading Capacity

CHP Combined Heat and Power Plants

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INTRODUCTION

Europe has set the targets to decrease the CO_2 emission by 40% in 2030 and 80% for 2050 compared to 1990 levels [1]. The heating sector accounts for the largest energy sector, hence the decarbonisation of said system is a challenge. Energy systems are the primary pollutants that are contributing to climate change. Many countries across Europe and beyond are developing energy transition roadmaps that show how to design sustainable, reliable and environmentally friendly energy systems. This thesis mainly concentrates on developing methods to assess the decarbonisation of coal-based energy systems by considering the integration of electricity and heating sectors. Apart from that, this thesis also focuses on road transport electrification as a supporting source of flexibility to increase the share of variable renewables in coal-based energy systems. The heating sector in Kosovo accounts for 38% of total final energy consumption, hence the proper planning and design of heating systems can be led to sustainable decarbonization of coal-based energy systems. This thesis is composed of six sections. Section 1 addresses the heat demand mapping in developing countries; section 2 addresses the impact of energy efficiency measures in heat savings in buildings; section 3 addresses the potential assessment to expand district heating (DH) systems in cities. Section 4 shows the impact of individual heat and road transport electrification to increase the penetration of variable renewables in coal-based energy systems. Section 5 shows the role of power-to-heat technologies in DH. Finally, section 6 shows how the electricity and heating sector coupling can help pay the way for a sustainable transition of coal-based energy systems.

1.1 Literature review

The following sections show the literature review of recent scientific articles. It shows the articles that assessed heat demand mapping using bottom-up and top-down approaches, then a study on DH assessment is provided along with heat demand saving papers. The literature review continues focusing on papers that show the contribution of power to heat technologies for both individual and DH as well as transport electrification to increase the share of variable renewables. Finally, a review on sustainable transition in coal-based energy systems is provided.

1.1.1 Heat demand mapping

There are many tools available that are used for modelling and analysis of energy systems. Space heating in buildings, in cold climates, plays a significant role as 31% of the primary energy supply worldwide is converted into thermal energy, respectively heat [1] according to International Energy Agency (IEA). The final energy end-use for residential energy consumption in Kosovo is 31%, and 10% for services (commercial and public consumers). In addition, the share of energy consumed for space heating in total final country energy end-use for the reference year 2015 was 33% [2].

The decarbonization of heating systems is a curtail step for designing low carbon energy systems. Spatial mapping of space heating demand in buildings can contribute to better planning and design strategies that accelerate the decarbonization of the heating sector. Figure 1 shows the existing and proposed heat demand mapping models. The top-down model (reference scenario) is used to asses mapping at the regional level, while bottom-up mapping assesses mapping at a local level (scenarios 1 & 2). The input data for the top-down mapping are energy balance, population density maps and land use, while input data for bottom-up mapping are building features and building thermal performance. The outputs from the top-down mapping are heat demand maps with limited spatial resolution, while the results from bottom-up mapping are heat maps with adjustable spatial resolution. Top-down mapping can be used for assessing regional heat mapping for all countries, while bottom-up is high data-intensive; hence, it is applied only locally. The time and resources used to evaluate the bottom-up model are more intensive in comparison to top-down mapping.

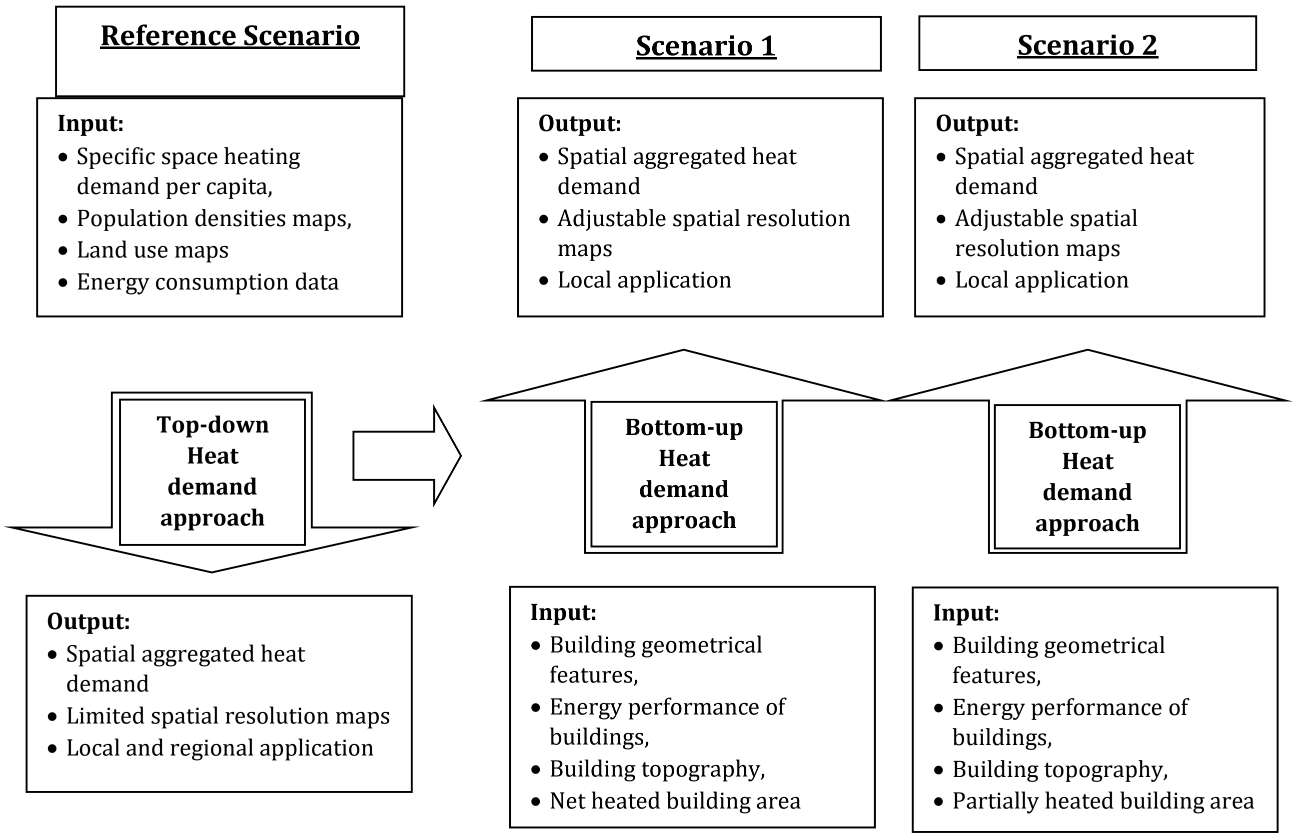


Figure 1 Top-down and Bottom-up approaches that are used for modelling spatially space heating demand

Furthermore, the time consumed for data collection and proceeding takes a quite long time; for that purpose, the bottom-up approach is mostly used locally. Bottom-up is a more utilized approach in studies researching the expansion of DH systems [3], [4], thermal energy planning and modelling [5], [6] analyzing different configurations of DH and its distribution heat losses [7], utilization of waste heat resources [8], [9], [10] integration of renewable technologies in DH [11], [12]. In contrast, the top-down approach is generally used for heat mapping in large area locations. The resolutions of maps obtained from top-down approaches are dependent on other spatial provided datasets, which is not the case with bottom-up mapping, that allows adjusting maps with desired resolution.

Different mapping approaches and bottom-up modelling methods for different building stocks are reviewed to identify the energy consumption in the residential sector [13]. A novel top-down methodology for determining heat demand for space heating as a function of usage and time using aggregated load data on heat demand, focusing on residential space heating, is provided in [14].

Results obtained identified the aggregated heat demand curve suitable for usage in energy system modelling. The energy demand for space heating and hot water is spatially considered in the residential and commercial sectors using a top-down approach based on the USA's high-resolution population distribution and land use data [15]. Similarly, a top-down method for quantifying country-specific heat demand DH potentials for different heat demand levels across Europe was developed in [16].

A bottom-up approach for estimating the heat demand of residential buildings spatially is provided in [17]. The findings demonstrate the geo-referencing of residential heat demand and the development of a replicable methodology at different scales. The authors concluded that the presented method overestimates the heating demand; hence new data can improve the quality of the results. Research [18] develops a model that characterizes the energy performance of the built environment at a territorial scale. The model took into account: data available in the Energy Certificate of Buildings database, data about the age of the buildings and the energy reference surfaces available in the official statistics database. A bottom-up approach for calculating useful heat demand for space heating and hot water was developed for the city of Krakow [19]. The heat demand was aggregated in a grid with 100 m × 100 m spatial resolution to deliver a map for 21 buildings. Results demonstrate that the residential buildings, respectively one and multifamily houses, have the highest share of overall space heating demand compared with other building categories. A similar study based on a bottom-up approach is provided in ref. [20]. The outcomes provided a raster aggregated layer grid with 200 m × 200 m of the annual heat demand for space heating and hot water. The following section shows the heat demand saving potential when considering typical building refurbishment measures in buildings.

1.1.2 Space heating demand savings

Space heating demand in buildings accounts for the largest share in final energy consumption [1]. When considering different countries with different climates, it is found that buildings cause 19% of total greenhouse gas emissions (GHG) worldwide [21]. At the same time, half of the final energy demand is consumed for heating and cooling in the European Union (EU) [22]. About 25-30% of the final energy demand of EU countries is consumed for covering space heating demand in buildings [22]. In terms of Kosovo, this number is even higher, accounting for 33% share. Figure

2 illustrates the final energy demand mix in Kosovo. Compared to other sectors, space heating in buildings accounts for the largest share.

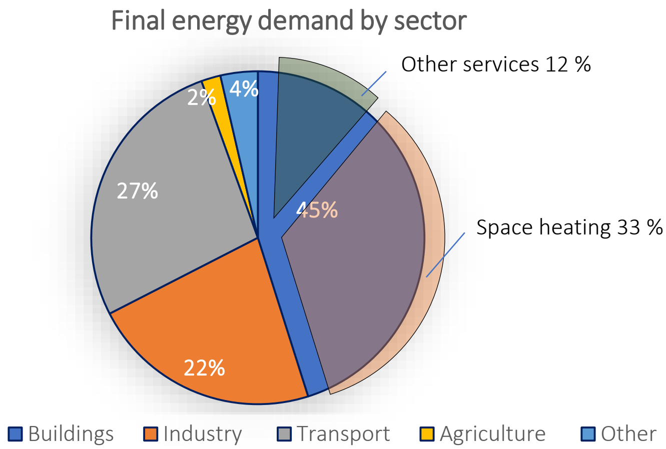


Figure 2 Final energy demand by sector [1]

The European heating and cooling strategy [23] shows that heating and cooling in Europe accounts for more than 50% of total final energy demand [24]. Research [25] shows that modern district heating systems are the leading technologies for decarbonising the heating sectors. 4thGeneration of District Heating (4GDH) will supply existing, renovated and new buildings with low-temperature district heat for space heating and domestic hot water demand, distribute heat in networks with very low heat losses, recycle heat from low-temperature sources, integrate renewable heat, aid in the integration of variable renewables, ensure suitable planning cost and effective structures for a transformation toward sustainable energy systems [25].

Energy efficiency and renewable heating supply solutions are considered the main options for decarbonising heating systems and reducing building space heating demand. The main focus is on the thermal performance improvement of buildings through deep renovations and replacing buildings with net-zero energy buildings [26]. However, models that consider the spatial analysis of space heat-saving potential are lacking. Besides Denmark with a detailed geospatial building dataset, other EU countries are not able to asses heat mapping using a bottom-up approach at the national level. In addition, other countries may have detailed data for a particular city but not for the entire country. A thermal atlas was developed in [27] to improve the geospatial knowledge for heating and cooling across Europe. The main objectives were to create a comprehensive model that quantifies heat demand, groups coherent areas into supply zones and produces supply curves for respective zones. Both top-down and bottom-up models were used. The research concludes that it is far-fetched yet to expect databases for other European countries, which would allow for bottom-up modelling of the heating sector. In addition, [28] develops a method for assessing heat demand mapping and district heating potential in data scare areas. The model considers publically available data to asses the aggregated heat demand, bottom-up mapping for validation purposes and top-down mapping for the entire observed area.

Geometrical building features and energy balance are considered for assessing space heating demand in buildings. In general, bottom-up and top-down models evaluate the heat demand spatially in buildings using a Geographical Information System (GIS) tool at the local and regional levels. The heat demand of buildings was estimated spatially using available building data and energy audits for building samples [29]. The research concludes that integrating building topography and energy data in a GIS platform allows for a more comprehensive framework of heating performance in buildings. A model for assessing the heat demand of building stock in the Newcastle Upon Tyne was developed in [30]. The research concludes that the future energy planning infrastructure would not be adequate unless spatial heat mapping is available at an appropriate level. The space heating demand of heritage buildings was estimated spatially by considering geometrical building features and ages [31]. The results show the space heating demand spatially and hence suggest a zone energy indicator. A simplified model for spatially characterising the built environment's heat demand was provided in [18]. The model takes into account the energy reference data, energy certificate of building and building age. A high spatial resolution model is designed to estimate the thermal energy performance gap of Portuguese residential building stock [32]. Both theoretical and actual heating demands of buildings were estimated.

In most EU countries, buildings are built between 1950 and 1975, and they need renovation [33]. Many research studies consider the renovation and retrofitting process in buildings. For instance, research [34] estimates the societal and economic challenges of renovating and retrofitting strategies for multi-family dwellings in Gothenburg. A heat atlas is generated for 2.5 million buildings in Denmark to determine heat demand, possible heat saving and associated costs [35]. The model was used as a container for storing data about the physical properties of the Danish building stock.

A bottom-up statistical methodology based on GIS to estimate the heat demand and the saving potential of residential building stock across the entire city of Rotterdam was developed in [36]. The heat demand was apportioned to different end-uses and corrected for the weather. Then the heat savings potential was estimated by accounting for the implementation of typical refurbishment measures. A bottom-up model is developed to model the heating demand of residential buildings for Kragujevac [37]. Different thicknesses of polystyrene thermal insulation in external walls and installation of new windows were considered for identifying the reductions of the total annual space heating demand. The research concludes that potential heat saving in buildings varies based on the year of construction. Two bottom-up models were used to estimate the spatial heating demand of the Swiss building stock [38]. The main finding shows that for applying the heat demand model, a realistic saving potential is calculated for the existing building stock, and this potential could be achieved through a deep retrofit program.

Besides the significant role of energy efficiency measures to reduce GHG emissions, they can also integrate renewable energy sources. An optimization platform was developed to analyse a Swiss village's renewable energy integration and building renovation [39]. The research concludes that retrofitting all buildings according to the Minergie standard [40] reduces the space heating demand by 70-85% and reduces the fluctuations in energy demand, thereby allowing more renewable energy integration.

The subsequent section shows the DH system's potential assessment that considers both space heating and domestic hot water demand of buildings.

1.1.3 District heating potential analysis

Around 40% of the total final energy demand in buildings is consumed for space heating and domestic hot water (DHW) [1]. Domestic hot water in buildings accounts for the second-largest energy consumption after space heating in most countries worldwide. In Europe, DHW accounts for 14% of total final energy demand, while in the US, the same is even higher, accounting for up to 18% share [41]. In the future, DHW demand is expected to increase as opposed to space heating in buildings which is likely to decrease because of the building refurbishment measures [42]. Renewable heating solutions can improve the performance of DHW production according to [43], [44], [45].

Research [46] shows that 13.1 EJ in 2010 was the heat demand of residential and commercial buildings in Europe. Fossils fuels cover 66% of total heat demand in the EU, while district heating covers 12% [46]. The building sector accounts for 44% of total energy demand in Kosovo [2]. 80% of the total final energy demand in buildings covers space heating and DHW demand [47]. Additionally, 1/3 of the total final energy demand in a building takes the form of heat consumed for DHW and space heating purposes. In Kosovo, the DH share is lower than in EU countries accounting for 8.5% [2], and the same is used only for covering the space heating demand of buildings excluding DHW.

In general, DH systems supply the space heating demand of buildings without considering domestic hot water; however, future district heating systems as the 4GDH will supply buildings with DHW besides space heating. The same technology is critical for a sustainable transition of heating systems [48], [49] aiming towards smart energy systems. In addition, the 4GDH will meet the challenge of supplying with space heating and DHW increasing energy-efficient buildings [25]. As future DH systems will play a critical role in sustainable energy transition, they should be expanded up to the economically feasible level. The majority of district heating assessments do not consider DHW when assessing DH potential. As DH is going towards low supply temperature around 55°C or even ultra low-temperature supply (35 - 45°C), there are increasing studies on how to produce DHW for such cases [50], [51]. Both top-down and bottom-up heat demand mapping methods assess the DH potential both locally and regionally. DH potential assessment considers heat supply costs, network distribution costs and district heating prices, among others. Research [24] suggests that DH potential assessments should consider their critical role in the decarbonising energy system besides the consideration mentioned above.

The assessment for expanding the DH system in the EU between 1990 and 2050 is conducted in [24]. The results showed that with DH, the EU energy system would achieve the same reductions in primary energy supply and CO_2 emissions as the existing alternatives proposed, but with reduced cost by approximately 15%.

Spatial analysis with Geographical Information System (GIS) tools are critical for modelling, planning and designing renewable DH systems. A heat atlas that contains detailed information for more than 2.5 million buildings in Denmark is developed in [52]. The research concludes that heat atlases will be critical tools for planning the expansion of DH networks and introducing heat-saving measures. The DH potential assessment for Denmark is elaborated in [53]. The research concludes that DH can cover up to 57% of total Danish heat demand. Another investigation for Denmark [59] concludes that the Danish district heating system can be increased up to 70% while the rest of the heat is to be covered by individual heat pumps. A method for analysing the role of district heating to increase the share of variable renewables is provided in [54], [55]. The finding shows that the role of DH to increase the share of variable Renewable Energy Sources (vRES) is significant.

Heat pumps in DH can significantly increase the integration of vRES. Besides spatial analysis, temporal analysis of DHW and space heating in DH is critical for comprehensive analysis of DH coupled with energy systems. Different factors that influence DHW demand in different buildings were analyzed in [56]. In addition, [57] presents the monthly and hourly DHW demand for residential buildings in Finland, while [58] and [59] investigate the DHW demand for residential buildings in Canada and Switzerland, respectively. An innovative method for displaying hourly real-time space heating demand profiles was developed in [60]. The method shows the calculation procedure for displaying the real-time hourly heat demand for each building in a district based on the basic cartography, cadaster, and heating degree-day (HDD) values.

The following section shows the individual heat and road transport electrification to increase the share of variable renewables in coal-based energy systems.

1.1.4 Heat and transport electrification

Heating and transport account for the largest energy sectors in energy systems, hence, decarbonization is a curtail step for achieving sustainability. The technical and affordable decarbonization of said sectors can be achieved by considering an integrated, holistic inclusion of electricity, heating, and transport sector that can transform coal-based energy systems into sustainable energy systems [48], [49]. According to IEA, the heat and transport sectors are responsible for over 55-60% of total CO_2 emissions from energy systems worldwide [1]. Oil products are the main energy sources used in the transport sector, while biomass, natural gas, oil products, and electricity are in the heating sector. In terms of Kosovo, these numbers are even higher. The transport sector composes 27% of total final energy consumption, while the heating sector accounts for 38.2% [2]. Additionally, the transport sector is entirely based on imported oil products, mainly diesel, petrol, LPG and kerosene, accounting for 69%, 24%, 6% and 1%, respectively. The main energy sources used for the heating sector are biomass, electricity, coal and oil products accounting for 48%, 33%, 11% and 9%, respectively, in final heat consumption [2], [61].

Electrification of these sectors has a significant role in decarbonising fossil fuel-dependent energy systems. Sustainable electrification of the transport and heating sector requires a massive penetration of renewable electricity production in energy systems. Wind and solar PV are the cheapest available power production technologies in the market. The impact of electrification of private transport and space heating for the Italian energy system in terms of critical environmental and techno-economic indicators, was developed for evaluating to what extent increasing the electricity demand supports the development of variable renewables [62]. The main findings confirm that transport and heating electrification can significantly reduce CO_2 emissions, around 25% - 30%, if pursued independently.

Different approaches, technologies, and strategies are reviewed to manage large-scale schemes of variable renewable electricity such as solar and wind power in energy systems [63], [64]. Research [65] compares different technologies to facilitate the integration of vRES in energy systems. The study highlights that large-scale heat pumps prove to be the most promising technology for effectively reducing excess renewable electricity production. Furthermore, the study shows that flexible electricity demand and electric boilers are low-cost solutions, but their fuel efficiency improvement is somewhat limited. Battery electric vehicles (EV's) constitute the most promising transport integration technology compared with hydrogen fuel cell vehicles.

The effects of the availability of electric boilers in the German control power market on overall system-wide costs and CO_2 emissions of the power supply using a model-based analysis for 2012 and 2025 were investigated in [66]. Power-to-heat plants can dissolve the conflict of must-run generation of baseload power plants for control power provision. Therefore, they can enhance the integration of fluctuating renewable energy sources, reducing the overall CO_2 emissions of the power supply.

The role of heat pump systems in terms of economic alternatives for recovering heat from different sources and using it in various industrial, commercial and residential applications is reviewed in [67], while the application and control approaches of heat pump systems in smart grids in [68] respectively. Individual heat pumps also have a significant impact on vRES integration and especially wind integration. A model that shows how heat pumps can influence the integration of wind power by optimizing both investments and operation and covering various heat storage options [69]. Results indicate that the heat pumps can substantially facilitate larger wind power integration and reduce system costs, fuel consumption, and CO_2 emissions. The Danish energy system in 2020 with 50% wind power is modelled to show that individual heat pumps and heat storage can contribute to the integration of wind power [70]. Heat accumulation tanks and passive heat storage were investigated as alternative storage options to increase wind power utilization and provide cost-effective fuel savings. Results show that passive heat storage can enable equivalent to larger reductions in excess electricity production and fuel consumption than heat storage tanks.

Research [71] analyzed the integration of solar photovoltaics, demand – response technologies (power-to-heat and vehicle-to-grid concepts) needed to balance the Croatian energy system in 2030. The findings show that with the introduction of EV's, and heat storage in combined thermal power plants while maintaining the flexible operation of power plants, up to 2000 MW solar photovoltaic capacity can be integrated into the Croatian power system. The interconnections of a group of islands to integrate the production from locally available renewable energy sources is investigated in [72]. Scenarios with different integration dynamics of vRES and electric vehicles were modelled with the EnergyPLAN model, while the interconnection analysis was carried out with the MultiNode tool expansion. The results indicated that the interconnections increased the share of energy from renewable energy sources in the final energy consumption and declined the total critical excess electricity production, while vehicle-to-grid (V2G) technology-enabled exploitation of synergies between sectors. A study that shows to what extent the electricity storage can contribute to a significant renewable penetration by absorbing otherwise curtailed renewable surplus and quantitatively defines the associated costs is developed in [73]. A variety of future scenarios are defined for the Italian case based on a progressively increasing renewable and storage capacity feeding an ever-larger electrified demand mostly made up of EV's and, to some extent, heat pumps and power-to-gas/liquid technologies. The findings show the remarkable role of electricity storage in increasing system flexibility and reducing, in the range of 24 – 44%, the renewable capacity required to meet a given sustainability target. The decarbonization of the Nicaragua transport sector and hence the adoption of EV's, and a shift to electrofuels is investigated in [74]. The findings show that the adoption of EVs and electrofuels create synergies between the two sectors, making them suitable options to integrate higher shares of variable renewable energy in the generation mix. Furthermore, the same increases the overall efficiency of the system and reduce operating costs and CO_2 emissions. Research [75] analyzes the impacts of future scenarios of EV's on the German power system, drawing on different assumptions on the charging mode. The results show that only in additional model runs, in which we link the introduction of EVs to a respective deployment of additional variable renewables, EV's become largely CO_2-neutral. Similar research was developed in [76] to analyse the impact of different EV charging strategies on the German power system in 2030 by explicitly including neighbouring countries. The findings show that the curtailment of renewable energy sources is reduced independently of the charging strategy. Hence, concerning system cost and emissions, the charging strategy V_2G proves to be the most beneficial.

There are numerous technologies available in the market for cost-effective decarbonization of these sectors. In the transport sector, three main options to integrate clean energy sources exist; electrification of the transport sector, liquid biofuels and biogas or biomethane. The share of biofuels and biogas in transport fuel consumption at a global level is relatively low, accounting for 3% and 3.6%, respectively [77]. In addition, transport can be electrified directly with batteries or with the use of electrolysis. Trains, trams are examples of direct electrification, which require a cable all the time. In Kosovo, this form of electrification would not significantly impact the transport sector with trains and trams. EV's use batteries to store electricity while eliminating the road restriction, as they do not require cables as direct electrification. Nowadays, there are EV's commercially available that can replace passenger and light-duty internal combustion engine vehicles. In Kosovo, 87% is the share of individual passenger vehicles in the transport sector, 10% is the share of light-duty vehicles, and 3% is for heavy vehicles like trucks, busses, tractors etc. This means that 97% of the Kosovo transport sector can be electrified using commercially available EV's. The electrification of transport can contribute to the integration of vRES hence increasing the flexibility of energy systems that will maintain a balance between electricity supply and demand. The V_2G is also a promising technology that can use EVs as distributed power generation sources at times of high peak energy demand. The electrification of the transport sector will face increasing costs for EV's, charging infrastructure, and reliable and clean power supply, especially in developing countries.

The use of heat pumps for providing buildings with space heating and domestic hot water can also increase the flexibility of energy systems and decrease the excess power production, allowing more integration of variable renewable while reducing the total CO_2 emissions. Space heating and domestic hot water demand account for 30% of total final energy consumption in Europe, while in Kosovo, this number is even higher at 38.2% [2]. The share of DH in Europe is 12% of total heat demand, while in Kosovo, this share is lower, accounting for 8.5% [78].

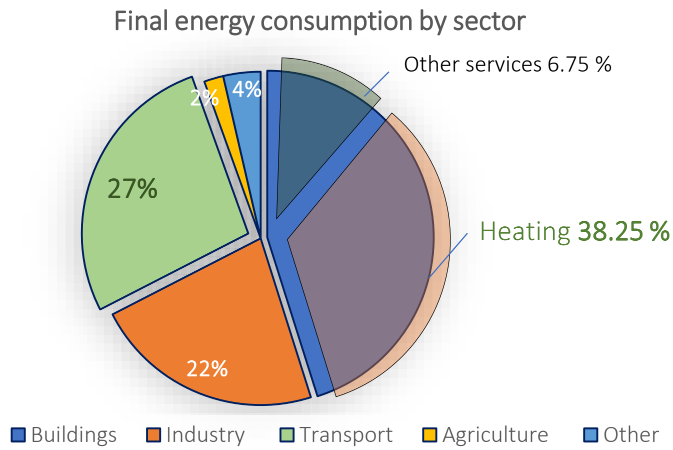


Figure 3 Final energy consumption by sector [2]

The main options for decarbonization of the heating sector are the expansion of smart district heating systems in urban areas referred to in the literature as 4th Generation District Heating (4GDH) [25] and integration of centralized and decentralized heat pumps in both DH and individual heating solutions [79]. The following section shows the literature review of P_tH technologies in DH systems to increase the share of variable renewables.

1.1.5 Power to heat technologies in district heating

Research shows that renewable energy sources are becoming a more cost-effective solution for electricity production than conventional technologies. Especially wind and PV are gaining increasing attention worldwide as clean energy production technologies. However, because of their variability, they need additional energy storage technologies to maintain the security of supply and balance energy demand and supply requirements. There is research that shows how to increase the flexibility of energy systems. Flexibility refers to the ability of an energy system to integrate a significant share of vRES.

The flexibility of energy systems can be increased in different ways. For instance, hydro-based energy systems can use dammed hydro reservoirs, or other systems can use flexible thermal power plants (TPP), combined heat and power plants, different energy storage options, grid-connected electric vehicles, hydrogenation, etc. Countries with cold climates can use power-to-heat (P_tH) and thermal energy storage to capture the excess electricity production and prove enough flexibility through the synergetic effect between the electricity and heating sectors [80]. As the thesis focuses on P_tH to increase the share of variable renewables, the following shows close related research articles. Traditionally, the conversion of electricity into heat was not a good option (as the energy was produced through the Rankine cycle), but the flexible use of renewable energy sources (RES) electricity for heating purposes combined with heat storage (HS) has recently gained increasing attention as an additional source for providing higher flexibility of energy systems that will be capable of integrating more variable renewables [81]. A comparative analysis between energy conversion technologies like heat pumps (HPs), electric boilers, battery electric vehicles, hydrogen fuel cell vehicles with the main aim to integrate the fluctuating renewable energy sources into energy systems is given in [65]. It was proved that large scale HPs are very promising technologies for effectively reducing excess electricity production. In addition to that, the scope of the P_tH technologies will be turning electricity into heat with the aim of compression HPs, or electric heaters coupled with thermal energy storage.

In some industrialized countries, decarbonization of the heating sector is a precondition for achieving climate policy targets. In 2007, 48% of the final energy consumption in EU 27 took the form of heat. That means that the heat was the most significant final energy consumed, which attracted the intention of scientists to put their research efforts into DH. Different primary energy resources integration into district heating and cooling (DHC) showed that these heating and cooling systems will be part of future energy systems called the fourth generation of DH [82]. Integration of large HPs into DH is a frequently mentioned solution as a flexible demand for electricity and an energy-efficient heat producer [83]. The main idea was to make an HP use a low-temperature waste or ambient heat source. The latest literature review in renewable energy integration into energy systems showed that P_tH technologies can cost-effectively contribute to fossil fuel substitution, renewables integration and decarbonization [84]. The literature review shows that the central role stands for HPs, to be decentralized or connected to DH grids. Electric boilers are identified as a relevant option too. Moreover, case studies focused on combined analyses of P_tH and other options referred to as power-to-x, for instance, electrolytic hydrogen generation, may shed light on the comparative attractiveness of P_tH.

The modelling and optimization tools are reviewed to show the role of DH and thermal storage for integrating a high share of variable renewables in energy systems [85]. In addition, the potential use of P_tH technologies in German DH grids for the year 2015-2030 was analyzed in [86]. It was found that the maximum theoretical potential use of P_tH technologies in Germany is 32 GWel. The future potential of decentralized P_tH (integration of electric boilers in conventional oil and gas boiler systems) as an additional demand-side flexibility option for the German electricity sector was investigated in [87]. A model that represents the system performance of the HP connected in DH distribution and transmission networks is given in [88]. Results have shown better performance was for HP that are connected in DH distribution.

The potential synergies of variable wind power and flexible electrified heating systems (heat pumps and electric thermal storage) for Beijing over the period 2009-2020 is elaborated in [89]. It was found that significant wind penetration and CO_2 emission reduction can be obtained when using HPs and electric thermal storage compared with the BAU scenario. Research [90] makes a comparative analysis between electric boilers and HPs used for capturing the intermittency of an energy system powered mostly by wind plants and cogeneration. It was found that well-designed HP concepts are more cost-effective than electric boilers. According to [91] significant electricity grid and storage savings can be achieved if choosing DH rather thant electric heating or individual heat pumps. A similar study was conducted by [92] to quantify the enhanced flexibility by the thermal storage of building stock equipped with HPs, to power systems with significant wind power penetration. A similar study for assessing the contribution of large scale wind power integration with HPs for New York City was elaborated in [93]. I has shown significant increases in wind-generated electricity utilization with the increased use of HPs, allowing for a higher installed capacity of wind power.

The following section shows how the coupling of heating and electricity sectors can shed light on achieving sustainable energy targets in coal-based energy systems.

1.1.6 Energy transition pathways in coal-based energy systems

Mitigation of climate change is gaining increasing attention. CO_2 emissions from energy systems are one of the main threats that are contributing to climate change. Thus, many countries are developing energy transition roadmaps towards more sustainable, reliable and environmentally friendly energy systems. Governments worldwide are implementing energy policies set in Paris Agreement regarding the targets to decrease CO_2 emissions to the levels that would keep the surface earth temperature under a 1.5-degree limit [94]. The decreasing cost in vRES, especially wind and photovoltaics (PV), is one of the main drivers for developing energy policies to decrease CO_2 emissions. The European power report in [95] shows that renewables reached a 35% share of EU electricity demand in 2019. In addition, renewable electricity production from wind and PV surpassed for the first time the electricity production from coal-fired thermal power plants (PP).

Moreover, the electricity production from coal in the EU dropped by 32%, and in particular, lignite coal-fired PP’s dropped by 16% respectively [95]. This evolution of coal phasing out is attributed to the CO_2 emission price increase and the significant decrease in variable renewable technologies costs. Thus, the power generation from coal is expected to decrease since many countries in the EU have announced their commitment to phase out Coal in 2019. However, some EU member states like Bulgaria, Croatia, Poland, Romania, Slovenia and other energy community contracting parties from Western Balkan (Kosovo, Montenegro, Bosnia Hercegovina, and Serbia) have to develop strategies for phasing out coal [95]. Countries of Western Balkan, have not approved the carbon price mechanism yet, except North Macedonia. However, the energy community secretariat announced that the same is under discussion and likely to be introduced in other contracting parties.

In this framework, current research focuses on developing a method to show technical, economic and environmental implications of lignite-fired thermal PP, renewable energy integration, sector coupling and introduction of the carbon price mechanism for a coal-based energy system. Kosovo, a country located in the South-Eastern part of Europe, has not adopted the clean energy package for 2030 nor 2050 like EU countries yet; however, it is in the development phase. Lignite coal is the main fuel that powers the Kosovo energy system, especially in the electricity sector accounting for 97% share of its electricity production [1]. Kosovo has two thermal PP’s with total operational capacities between 750 - 1050 MW, which are quite old and operating with very low efficiencies. Recently, Kosovo is looking into building the new thermal PP Kosova e Re with 450 MW based on coal [96]. However, Word Bank does not support the same because they found out more environmentally friendly and cost-effective solutions for electricity production in Kosovo [97]. Research [98] develops an analytical platform for analyzing the economic viability of electricity production from fossil fuel and clean energy production technologies for 2015-2025 in Kosovo. The results show alternatives to producing electricity with lower costs rather than constructing a new thermal PP (the most expensive pathway to meet future electricity demand) exist. These alternatives include a mix of solar PV, wind, hydropower, biomass, and natural gas for electricity production in the primary energy supply mix. A dynamic model using scenario approach analysis was developed to investigate greenhouse gas and air pollution reduction from the electricity and transport sector for the period 2000-2025 in Kosovo [99]. The results indicate that energy policies and introducing new renewable technologies in electricity production can ensure sustainable development in Kosovo.

Energy efficiency and renewable energy are considered the main pillars for transitioning existing energy systems toward low carbon and smart energy systems [48]. Smart Energy System concept represents a scientific shift in paradigms away from single-sector thinking to a coherent energy system understanding on how to benefit from integrating all sectors and infrastructures. This concept is the foundation for developing low carbon energy systems. The energy transition towards zero carbon emission by 2050 for Southeast European countries is researched in [100]. Compared to other research with similar goals, their modelling was based on sustainable use of biomass without exceeding its assessed potential and scale-up in RES technologies. They concluded that a mix of power generation technologies (Wind, PV, Hydro, Concentrated Solar Power, biomass Combined Heat and Power Plant (CHP) and Geothermal) need to be utilized with no more than 30% share for a single technology and the production of synthetic fuels is needed in the transport sector for keeping the biomass consumption in sustainable limits. A transition from a 50% RES-based scenario to a 100% RES scenario for Europe in 2050 is presented in [101]. These scenarios considered technical and political certainty like decommission of the nuclear PP, utilization of large scale heat pump [54], heat saving, electric cars [102], providing rural areas with heat pumps, urban areas with DH [103], converting heavy fuel vehicles with renewable electro fuels and replacing natural gas with methane. They stated that using a smart energy approach makes a 100% RES energy system for Europe technically possible without consuming an unsustainable amount of bioenergy. This was due to the additional flexibility that was created by connecting the electricity, heating, cooling, and transport sectors, which enables variable renewable penetration of over 80% in the electricity sector. Research [104] analyses the flexibility in energy systems, flexibility options that are categorised along with existing literature and a method is explained to approach the estimation of flexibility potential using two example regions.

The results demonstrate a practicable, transferable method to quantify and compare the technical potentials of the flexibility options at a high regional level. Research [105] applies the Dispa-SET model that couples six countries' energy systems in the Western Balkans region. The results indicate that the integration of additional wind and solar capacities, compared to the short and long-term national strategies for the years 2020 and 2030, can be achieved without compromising the system's stability.

As current research focuses on sustainable decarbonisation of coal-based energy systems, the following research papers review methods used for similar studies. For instance, research [106] demonstrates sustainable transition pathways by 2050 for decarbonizing a 100%
energy system based on fossil fuel. It considers the large-scale integration of RES for Jiangsu province. The results show the primary technology mix for power generation, RES share in final energy consumption, socioeconomic costs and CO_2 emissions as valuable inputs for designing Jiangsu's future energy policies. A model for analysing the CO_2 emissions from fossil fuel combustion and estimating the national carbon intensity target by 2050, using Poland as a case study, was developed [107]. It was concluded that for meeting 80% emission reduction by 2050, the Polish energy system would require significant structural changes because the energy sector is based on coal and the potential for harvesting renewables is very limited. It was asserted that coal could remain only if Carbon Capture and Storage (CCS) is applied to all coal-fired thermal PP's and coal-based industrial processes. Furthermore, the study shows that besides biomass, other renewables and optionally nuclear energy must be significantly increased, and the same will be both costly and technologically challenging. In addition, the study suggests the deployment of carbon-negative bioenergy and CO_2 recycling as promising energy decarbonisation options. The influence of the wind energy sector on thermal power plants in the Polish energy system was analyzed in [108]. A conclusion is that the current share of wind energy at the level of 10% is enough to have an adverse effect on the coal power plants, but depending on the structure of the power system, it may increase its overall efficiency. Research [109] presents a comprehensive hourly-resolution scenario for the Indian electricity system with the main aim to investigate the transition from fossil to renewable energy-based power generation. 76% of power generation in India is based on coal. The research concludes that it is possible to design a renewable-based scenario by increasing the power production capacities (Wind, PV and Hydro, biomass and nuclear

power), and improving PV and Wind power capacities to 21% and 27%, respectively. The results also show that biomass and nuclear power utilisation could avoid the country import dependencies.

1.1 Objectives

The main objectives of this thesis are the following:

1. To develop a method for assessing district heating potential when considering both space heating and domestic hot water demand in developing nations
2. To identify the space heat demand saving potential spatially considering a novel bottom-up approach
3. To identify the maximal integration of variable RES using the modelling of power systems that are based on the flexible operation of coal-based power plants
4. To determine the maximal penetration of variable renewables when different power-to-heat capacities that are implemented into DH systems coupled with coal-based power systems with and without interconnections of electricity transmissions lines
5. To demonstrate the impact of transport and heating sector electrification to integrate vRES in coal-based energy systems while highlighting decreasing efficiencies and additional increasing emission due to thermal power plant cycling
6. To define a technically feasible, environmentally friendly and economically realistic roadmap for a sustainable transition of coal-based energy systems in line with EU climate and energy targets while using locally available sources

The hypothesis of this research is that the coupling of the power system with modern DH with power-to-heat technologies can significantly increase the integration of variable renewables into a coal-based energy system in an economically and ecologically acceptable way.

2. METHODS

Different methods were developed to show the contribution of P_tH technologies in coal-based energy systems to increase the share of vRES. The methods are based on spatial mapping of heat demand and statistical analysis of P_tH in coal-based energy systems. Two approaches were used for local and regional mapping of space heating and domestic hot water demand: top-down and bottom-up. Besides, the thesis also concentrates on spatial mapping of domestic hot water and space heat savings based on locally available data. Furthermore, the thesis highlights the contribution of P_tH technologies for both individual and district heating to increase the share of renewables in coal-dependent energy systems. Finally, the thesis presents how the targets to decrease CO_2 emission by 2030 can be achieved from a technical, economic, and environmental perspective by implementing different proposed methods.

2.1 Heat demand mapping method

Cities respectively urban areas are places with high population densities. About 70% of the European population is based on cities making them suitable areas for implementing energy efficiency measures aiming to decrease energy consumption. As already mentioned, about 25 to 30% of total final energy demand takes the form of heat in European countries, hence proper planning of heat demand and supply can significantly reduce CO_2 emissions from the heating sector. Spatial mapping of space heat demand in urban areas aims the sustainable planning of DH systems, temporal modelling of space heating demand curves that can be used for energy system analysis. The spatial mapping results are essential for identifying heat sources and sinks, waste heat resources, and sustainable planning of renewable energy supply, among others.

Based on available data, there are two commonly used methods for spatial mapping of heat demand: top-down and bottom-up. The top-down approach requires less data compared to the bottom-up approach, which is highly dependent on data. For the same reason, top-down is used regionally while bottom-up is used locally. Both methods require data that takes into account the energy consumption, climate, and building features. A description of said method and the validation procedure is described in the following section. The process of mapping assessed in this thesis consists of two parts, first the quantification of heat demand with a top-down approach and then the validation of bottom-up mapping approaches with the aim of two estimated scenarios. A detailed description of the discussed methods and the data used for established scenarios are given in the subsequent section.

2.1.1 Top-down heat demand mapping

The top-down mapping is used for quantifying the space heating demand of residential and commercial end-users. The method considers both statistical and spatial population distribution datasets. The model considers only space heating of buildings by excluding domestic hot water, industrial and process heating demand. Annual final energy demand was taken from the International Energy Agency for the reference year 2015 [1]. The primary energy supply mix used to produce space heating is available for some countries, while spatial population density maps are available for any country [110]. For the same reason, the top-down approach can be applied to any country if the country energy balance is known.

The total heat demand by residential buildings is calculated with:

$$E_{tot}^{res} = E_{coal}^{res} \cdot \eta_{coal} + E_{oil}^{res} \cdot \eta_{oil} + E_{biomass}^{res} \cdot \eta_{biomass} + E_{elec.}^{res} \cdot \eta_{ele.-thermal} + E_{DH}^{res} \quad (1)$$

E_{coal}^{res}, kWh – Coal energy consumption by residential buildings, E_{oil}^{res}, kWh – Oil energy consumption by residential buildings, $E_{biomass}^{res}$, kWh – Biomass energy consumption by residential buildings, $E_{elec.}^{res}$, kWh – Electric energy consumption by residential buildings, E_{DH}^{res}, kWh – District heat consumption by residential buildings, η_{coal} - The efficiency of conversion of chemical energy of coal into heat, η_{oil} - The efficiency of conversion of chemical energy of oil into heat, $\eta_{biomass}$ - The efficiency of conversion of chemical energy of biomass into heat, $\eta_{ele.-thermal}$ - The efficiency of conversion of electrical energy into heat

The final heat demand used for space heating by residential buildings is obtained by multiplying a factor of the percentage of final energy consumed for space heating with the overall energy consumption from the residential end-users [1]:

$$E_{thermal}^{res} = E_{tot}^{res} \cdot a_1 \quad (2)$$

Where: a_1 - is the percentage factor of total final thermal energy used by residential buildings for space heating purposes [47].

Similarly, the heat demand used for space heating by commercial buildings is given by:

$$E_{tot}^{com} = E_{coal}^{com} \cdot \eta_{coal} + E_{oil}^{com} \cdot \eta_{oil} + E_{biomass}^{com} \cdot \eta_{biomass} + E_{elec.}^{com} \cdot \eta_{ele.-thermal} + E_{DH}^{com} \tag{3}$$

E_{coal}^{com}, kWh – Coal energy consumption by commercial buildings, E_{oil}^{com}, kWh – Oil energy consumption by commercial buildings, $E_{biomass}^{com}$, kWh – Biomass energy consumption by commercial buildings, $E_{elec.}^{com}$, kWh – Electricity energy consumption by commercial buildings; E_{DH}^{com}, kWh – District heat consumption by commercial buildings

The conversion efficiencies presented in equation (3) are the same as those described for residential buildings.

The final heat demand by commercial buildings is written as:

$$E_{thermal}^{com} = E_{tot}^{com} \cdot \left(\frac{a_2 + a_3}{2} \right) \tag{4}$$

Where: a_2 and a_3 - are the percentage factors of total final thermal energy demand by commercial end-users (public and private buildings) for space heating purposes [47].

Then, the total heat demand for space heating accounting for both residential and commercial buildings is calculated with:

$$E_{tot}^{thermal} = E_{thermal}^{res} + E_{thermal}^{com} \tag{5}$$

In addition, the specific heat demand for space heating per capita was obtained by dividing the overall country space heating demand consumed by residential and commercial buildings with its inhabitants in a respective year:

$$e_{thermal}^{capita} = \frac{E_{total}^{thermal}}{n_{capitals}} \tag{6}$$

To acquire a heat density map, the per capita specific space heating demand values obtained from equation (6) have to be multiplied with a grid with 250 m × 250 m representing the distribution population density of residential and commercial end-users. The process is carried out in a freely available Quantum Geographical Information System QGIS tool [111]. Data on the distributed population densities in the resolution of 250 m × 250 m were taken from the reference [110] and multiplied with the specific space heating demand per capita estimated by following the above-described procedure (1-6). In addition, the heat demand map for any country can be developed using this top-down approach.

2.1.2 Bottom-up heat demand mapping

Bottom-up mapping is quite data-intensive therefore this method is used mostly for mapping of urban areas locations respectively cities. The method considers the building feature, building form of use, and climate of a respective location. The needed data for bottom-up mapping is specific space heating demand per different building categories and the topography of buildings. This method creates a heat matrix with a high 100m × 100m resolution to quantify heat demand. The same is used for assessing the heat demand mapping process using QGIS and EXCEL calculation tools.

The bottom-up heat demand mapping consisted of the main three steps:

Mapping of building area location

Mapping of building floors

Mapping of building categories

Depending on these information layers, a gross area matrix is created. Such a matrix is used to create the heat demand map when multiplying the net building areas with the specific heat demand of buildings. In that way, the heat demand by buildings spatially has been estimated. Afterwards, the heat demand consumed by residential, commercial, public buildings was aggregated spatially in 100 m × 100 m grids. The model considered different building categories like houses, houses without thermal insulation in external walls, apartments, offices, public and industrial buildings.

Because buildings in developing area locations are not heated up to their net areas, two bottom-up scenarios have been created and compared with the top-down approach.

In the first scenario, all building categories are heated up to their net area, while in the second scenario, houses with and without thermal insulation in external walls are heated partially (Figure

4). In addition to that, this scenario assumes that expect houses all other building categories, including apartment buildings, offices, public and industrial buildings, are heated up to their net area.

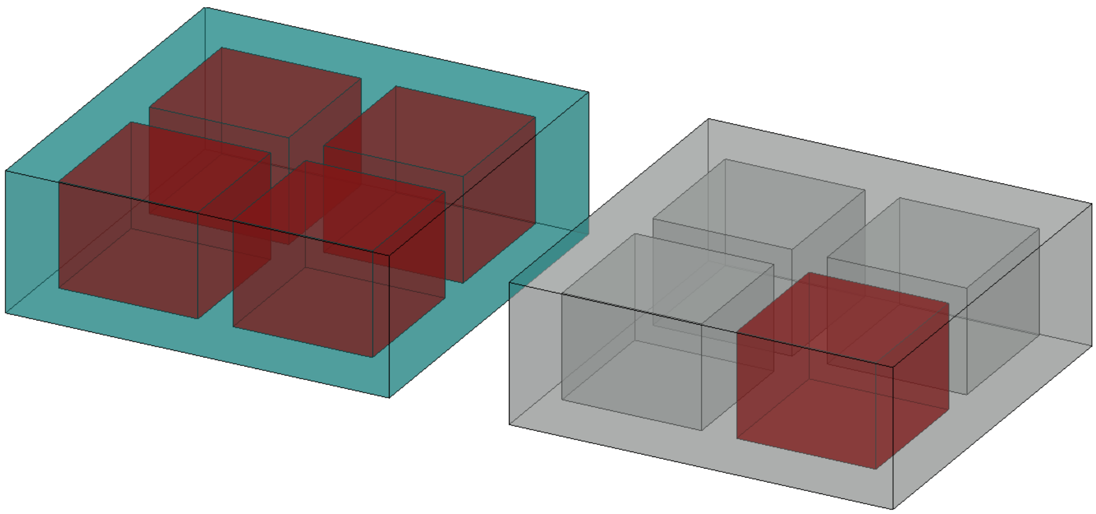


Figure 4 Houses being heated to their net area left side (Scenario 1) and houses partially heated right side (Scenario 2)

2.2 Spatial and temporal mapping of space heating and domestic hot water demand

Spatial quantification of space heating demand is a highly researched field. The majority of models consider only space heating when assessing the potential of the DH system. As already ellaborated in the Introduction section, the DH systems has the potential to play a significant role in decarbonising existing energy systems. The DH systems have a vital role in the transition towards smart energy systems. The existing models exclude domestic hot water when assessing future DH potential. Hence, this thesis concentrates on developing a spatial method that considers domestic hot water in addition to space heating. Moreover, it also develops a method for investigating temporal space heating and domestic hot water demand over a year. It considers hourly, daily, weekly and seasonal patterns of domestic hot water and space heating demand.

Spatial quantification of heat demand is essential for analyzing the expansion potential of DH systems within the city, while temporal analysis aims to estimate the comprehensive analysis of energy systems. The combined spatial and temporal mapping results are important for assessing the transition of seasonal to the annual operation of the DH system. This thesis provides the assessment of future DH systems considering both space heating and domestic hot water demand. The spatial-temporal method developed in this thesis consists of the main steps:

- Space heating demand of the city using a bottom-up approach
- Annual modelling of DHW demand in DH systems in hourly intervals
- Spatial quantification of DHW demand using a top-down approach
- Spatial quantification of total aggregated space heating and DHW demand in 250m x250m grid
- An assessment for quantifying economically feasible expansion potential of the DH system
- Annual modelling of space heating demand in hourly intervals using HDD method

2.2.1 Bottom-up and top-down hot water and space heating demand mapping

The bottom-up approach is used for assessing the space heating demand of buildings in urban area locations spatially. The same depends on building features and weather dependencies. For a comprehensive re-presentation of buildings in the model, seven different building categories are considered and divided according to their purpose of use and construction materials. For instance, house (single-family house = insulated), nhouse (single-family house = non thermal insulated), apartment, commercial, public, office and industrial buildings. The building category is considered in the model, as different buildings have different energy needs.

Moreover, as some buildings in the city are partially heated, two bottom-up scenarios have been developed in the model to consider that buildings are heated up to their net heated area (fully heated) and partially heated. The mathematical description used for spatial quantification of space heating demand is provided in the upcoming section. The comparison and model calibration between bottom-up and top-down space heating demand methods is described before this chapter and carried out in more detail in [112].

Space heating demand

For replicating the method in both developed and developing locations, two scenarios that consider the net space areas of buildings partially and fully heated were investigated. The space heating demand of buildings depends on climatic conditions and rural and urban settings. Based on developed or developing regions, partial heating of buildings can also be considered in the model.

Fully heated buildings

The total net space heated area of a building is calculated with:

$$A_{n.h}^{b} = A_{f}^{b} \times n_f \times c_r \quad (7)$$

where: A_f^b - is the building floor area, n_f - is the number of building floor [-], c_r - is the calibration ratio between net and gross building heated area and is calculated with:

$$c_r = A_{n.h}^{b} / A_{g,h}^{b} \quad (8)$$

$A_{n.h}^{b}$ – is the net building heated area, $A_{g.h}^{b}$ - is the gross building heated area.

Data regarding the building floor areas (building topography) is available in some countries through various agencies like Eurostat [113] and, if needed, can also be created manually using an open layer plugin in QGIS, which is considered in this research. The data for the number of floors can be given by cadastre or identified by visual inspection of buildings using tools like Google Earth Pro [114]. Data regarding building categories is also country-specific and for example, in EU, it is provided by Eurostat, and for the missing data, it can also be visually collected using Google Earth Pro. This data is essential for the spatial space heat demand mapping process in a QGIS tool [115] as already explained in [112].

Partially heated buildings

In general, not all buildings in developing countries are fully heated. Buildings heated partially are especially encountered in individual houses and nhouse[1] categories, among others. The only difference between houses and nhouses is the application of thermal insulation in external walls, influencing their thermal performance. The share of heated rooms in individual houses and the average surface heated area per room is represented in equation (9) through correction factor f_h [-]. In addition, the total heated area of a building partially heated is calculated with:

$$A_{p.h}^{b} = A_{n.h}^{b} \times f_h \quad (9)$$

where: $A_{p.h}^{b}$ is the partially heated area of a building, n_f is the number of building floors [-]

The total space heating demand per building is calculated with:

[1] **nhouse-** houses without any layer in external walls. These houses are made of blocks with 25cm width and plastered with gypsum on inner wall side.

$$Q_{s.h}^{b} = A_{n.h}^{b} \times e_{h}^{b} \text{ and } Q_{s.h}^{b} = A_{p.h}^{b} \times e_{h}^{b} \tag{10}$$

where: $Q_{s.h}^{b}$ is the space heating demand per building, e_{sh}^{b} is annual specific space heating demand per building category.

Specific space heating demand for different building categories can be taken from local energy auditing reports and other building energy certificates. The quality of the space heat mapping results can be further increased with additional data regarding the age of the building and the actual thermal energy performance of each particular building. In the proposed methodology, the age of the building is neglected as it is difficult to obtain such detailed data. To account for the majority of city building categories in the model, data regarding the thermal energy performance of sample buildings are considered and summarized in Table 1.

Table 1 Building categories and their specific space heating demand [116]

CATEGORY	Specific heating demand, kWh/m^{2}year
Apartment	161
Commercial	160
House	153
Industry	94
Nhouse	272
Office	135
Public	272

Once the space heating demand of each particular building in the city is estimated, a grid with adjustable resolution can be added to quantify the spatial distribution of the space heating demand. Total aggregated space heating demand in a cell with 250 m x 250 m (grid) $Q_{s.h}^{grid}$ was the sum of zth buildings intersecting the boundary cell:

$$Q_{s.h}^{grid} = \sum_{x=1}^{z} Q_{s.h_x}^{b} \tag{11}$$

By summing up the total space heating demand of all buildings in the city, the overall city space heating demand $Q_{s.h}^{city}$ is calculated:

$$Q_{s.h}^{city} = \sum_{i=1}^{n} Q_{s.h\ \ x}^{grid} = \sum_{i=1}^{n} \left(\sum_{x=1}^{z} Q_{s.h_x}^{b}\right)_i \tag{12}$$

2.2.2 Temporal modelling of domestic hot water

Hot water demand per occupant depends on standards defined by the country and the type of use in the building. Research conducted in [56] investigated DHW profiles in residential buildings for EU member states, Canada and the USA and their results are shown in Figure 5. It can be seen that there is a significant difference between daily DHW demands in different countries. For instance, in Canada average daily DHW demand is 94 l/day/occupant, while in other countries like Spain this value is significantly lower 30 l/day/occupant. Besides DHW demand per occupant, the increase in the water temperature difference is another critical parameter when quantifying spatially and modelling the DHW temporally. For instance, hot water supply temperature in EU is 55°C, in Canada is 57.3°C, Japan is less than 65°C and the USA is 57.3 °C [56].

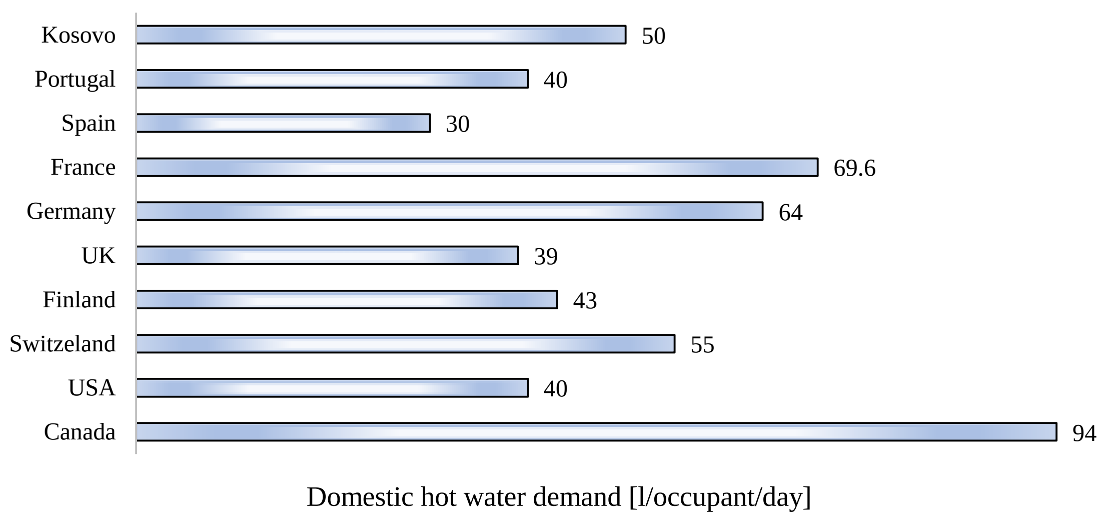


Figure 5 Daily hot water demand per residential occupant by country [56], [117]

Hourly modelling of DHW demand profiles in a DH can contribute in developing control strategies, where demand follows supply, hence in-depth knowledge of the features of demand profiles on an hourly basis will allow the energy modellers and planners to design sustainable heating solutions. The hourly DHW demand profile changes in different building categories. DHW demand profile is complicated and strongly fluctuates over time. Among others, lifestyle, weather conditions, occupant behaviour toward DHW usages, occupant number, social and economic condition were found the most significant variables in DHW consumption. A comparison between daily DHW profiles for different building categories is shown in Figure 6. It can be seen that restaurant buildings have the highest peak load demand during the mid-day, which is not the case with residential buildings where the peak loads appear in the morning and evening. The same can be used for spatial quantification and hourly modelling of DHW demand in DH systems using this thesis' spatial and temporal heat demand mapping approach.

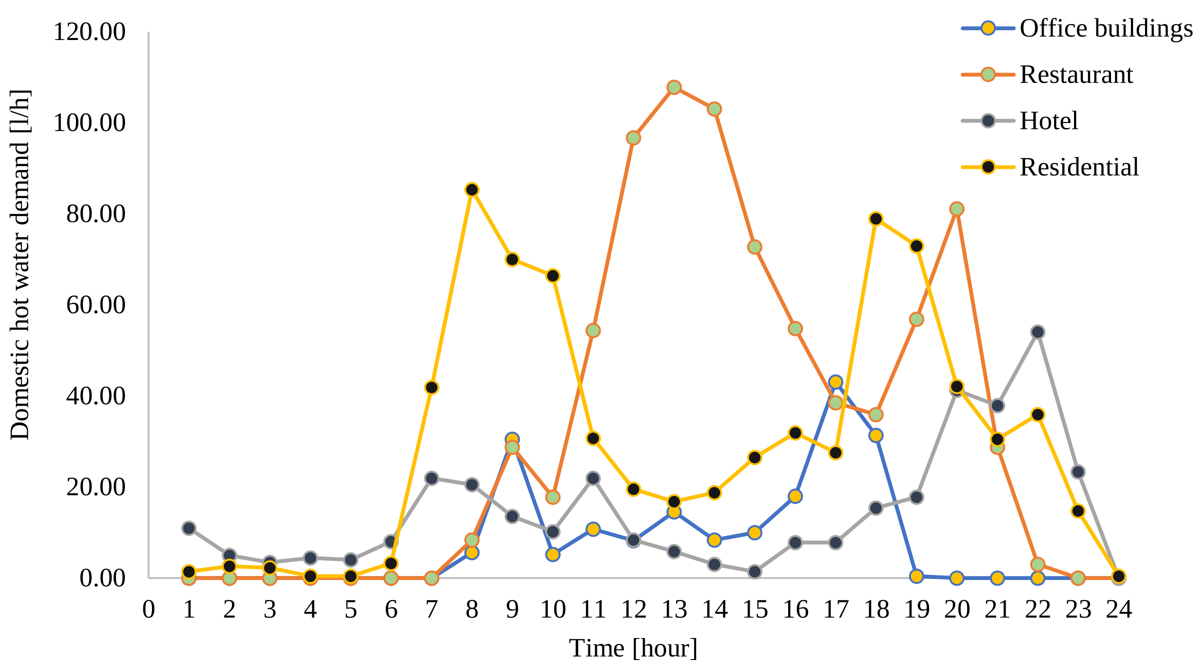


Figure 6 Comparison of average daily DHW profiles for different building types [56] [118] [119] [120] [121]

As over 95% of the assessed city[2] is occupied with residential buildings, only residential DHW profile is considered for further analysis. Figure 7 shows the relative distribution of the DHW demand profile for a residential consumer. Relative values of this profile were considered for modelling the hourly DHW demand profile for residential consumers. The reason for such an assumption is that the DHW demand profile is approximately similar for residential consumers, and it is sparsely dependent on geographical locations [56].

[2] The city assessed for the proposed method is Prishtina in Kosovo.

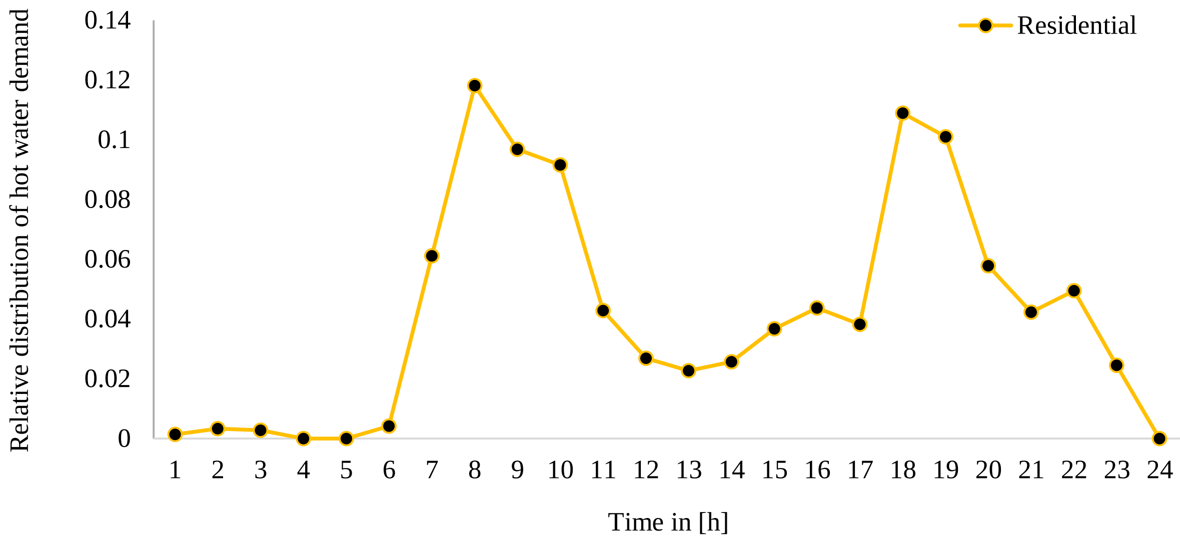


Figure 7 Relative distribution of DHW demand profile for residential end-user in the winter season [56], [121]

Different seasons also affect the DHW profile, shown in Figure 8, as the DHW needs of the residential consumer change based on activities during a particular season. Based on this, the hourly demand profiles between four seasons are considered in the proposed approach. It is observed that DHW demand during the spring season is the smallest and the most significant demand is observed for the winter season.

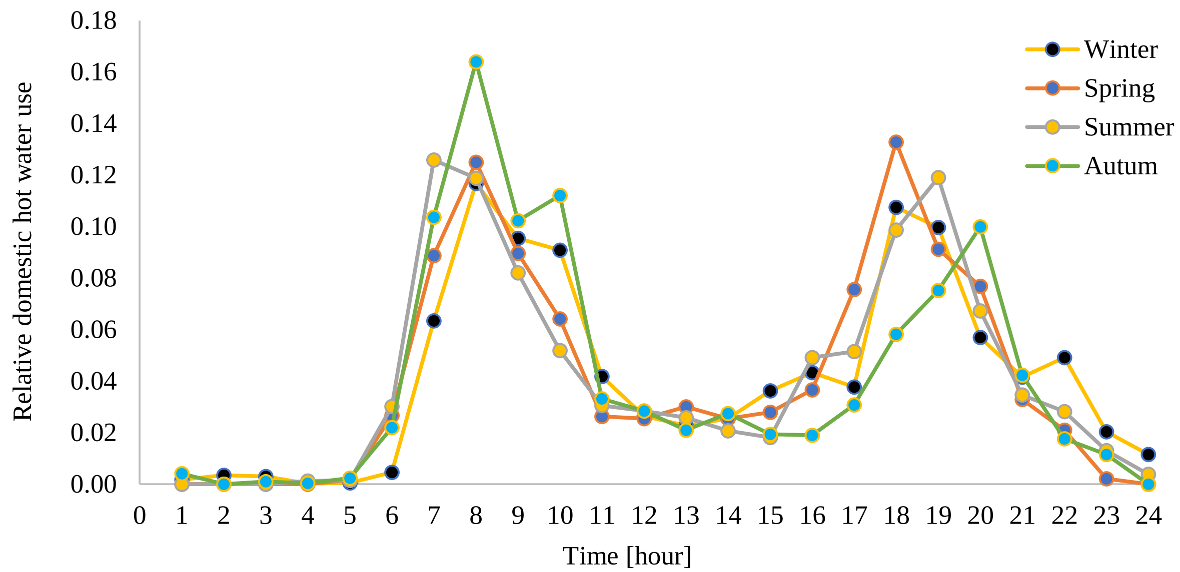


Figure 8 Relative seasonal influence on the daily DHW profile for residential buildings [121]

Research has also shown weekly DHW demand profiles variations besides hourly, daily and seasonal variations. Figure 9 shows DHW for the residential consumers estimated by different researchers. The weekly DHW relative profile by Krippelova et al. was considered in this research.

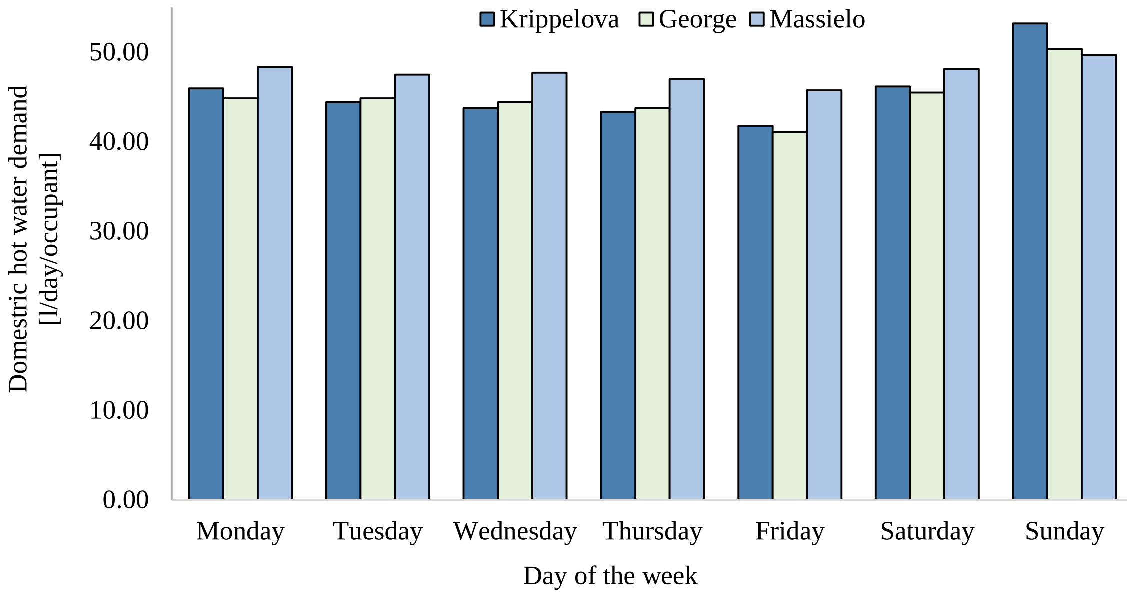


Figure 9 Daily average DHW demand per occupant according to different studies on residential buildings for a week [122], [123], [124]

Using the results of DHW modelling per day and the hourly DHW profiles in the four seasons, the hourly hot water flow rate ($\boldsymbol{m_{wi}}$) in [l/h] during one year is calculated. Then, the increase of DHW water temperature difference (the difference between hot and cold water temperature) is needed. The hot water supply temperature ($\boldsymbol{t_{hw}}$) is considered the same as in EU countries which is 55˚C. The cold water temperature ($\boldsymbol{t_{cw}}$) during the heating season (between 15 October – 15 April) is considered as 5˚C, while for the remaining time of the year it is considered to be 15˚C. Specific water heat capacity at constant pressure ($\boldsymbol{c_{pw}}$) is 1.1667 Wh/kg ˚C. Then using the equation number (13), the hourly DHW heating demand is estimated:

$$Q_{wi} = m_{wi} \cdot c_{pw} \cdot (t_{hw} - t_{cw}) \qquad (13)$$

2.2.3 Spatial mapping of domestic hot water

For the spatial distribution of DHW, a relation between net areas of buildings and occupants was found. As residential consumers are considered in the model, it is found that the daily heating demand is 2.10 kWh/year/occupant according to standard EN 16147:2011. This approach can be used for calculating hourly heat demand curves.

The total net area $A_{t.n.a}^{grid}$ in a grid size with 250 m x 250 m is calculated as the sum of z[th] building net areas intersecting the boundary of the grid:

$$A_{t.n.a}^{grid} = \sum_{x=1}^{z} (A_{n.a}^{b})_x \tag{14}$$

The number of people in a grid P_c^{grid}, is determined using the approach for an average net building area per occupant $a_{a.n.a}^{c}$:

$$P_c^{grid} = A_{t.n.a}^{grid} / a_{a.n.a}^{c} \tag{15}$$

In this way, the DHW heating demand per grid $Q_{h.w}^{grid}$ is calculated by multiplying the number of occupants of the corresponding cell with specific hot water demand per occupant $e_{h.w}^{c}$, which is calculated according to standard EN 16147:2011.

$$Q_{h.w}^{grid} = P_c^{grid} \times e_{h.w}^{c} \tag{16}$$

2.2.4 Total aggregated heat demand

Space heating and DHW heating demands are summed up for defining the total aggregated heat demand of a corresponding cell $\boldsymbol{Q_{t.h}^{grid}}$ with 250 m x 250 m using equation (17).

$$Q_{t.h}^{grid} = Q_{h.w}^{grid} + Q_{s.h}^{grid} \tag{17}$$

where: $Q_{h.w}^{grid}$ is annual DHW heating demand and $Q_{s.h}^{grid}$ is the annual space heating demand.

The total aggregated heat demand results in a grid with 250 m x 250 m are further used for analysing economically viable DH expansion potential.

2.2.5 District heating expansion potential

Feasibility analysis for expansion of DH up to the economically viable level was carried out in 250 m x 250 m aggregated total annual heat demand grid with equation (18). The same takes into account the actual specific price of heat for final end-users. The price of district heat is paid both in [EUR/MWh] and [EUR/m^2] and it includes the price of the connection fee. Apart from that, equation (18) includes the cost of installation and operation of heating technologies reflected by

Levelized Cost of Heat (LCOH) as well as the cost of expansion of the DH network. Grid areas with $DH_p \geq 0$ were considered as economically feasible area locations for expansion of the DH system [125]:

$$DH_p \geq Q_{t.h}^{grid} \times c_{heat} - Q_{t.h}^{grid} \times LCOH - 65200 \times l_{g.e} \times c_{g.e} \quad (18)$$

where: $Q_{t.h}^{grid}$ is the total aggregated heat demand in a single grid with 250 m x 250 m, C_{heat} is the price of heat, LCOH is the levelized cost of heat, $l_{g.e}$ is the specific equivalent network length within a grid size with 250 m x 250 m, $C_{g.e}$ is the cost of distribution network installation length in a grid with 250 m x 250 m for inner cities [126].

The levelized cost of heat was calculated using data from [127] for a DH based on a large scale heat pump. Data regarding the capital expenditure, discount rate, tax rate and present value of deprecation are considered from [127], while other remaining data regarding the capital, fixed and variable cost of technologies and lifetime of investment for large scale heat pumps in DH are taken from Danish technology report [128].

The specific equivalent length of the DH network within a grid with 250 m x 250 m is calculated by:

$$l_{g.e} = (l_{eg.DH}/A_{n.DH})/(l_{p.DH}/A_{grid}) \quad (19)$$

where: $l_{eg.DH,}$ is the existing district network length, A_{nDH} is the net area of buildings connected to DH, $A_{p.DH}$ is the potential net building areas for connection to expanded DH, A_{grid} is the area of the ground distributed network.

2.2.6 Heating Degree-Day Method

Heating degree days are used to quantify the space heating demand of buildings in DH temporally. HDD is depended on outdoor air temperatures and can be expressed in daily and hourly intervals by showing the amount of heat needed to heat the buildings up to the comfort level. The more detailed the recorded outdoor air temperature data, the more accurate is the HDD calculation. Weather data was taken from the Meteonorm software for the city [129]. HDD varies significantly in the geographical location of buildings, but since the application of the current method is applied at a city level, the outdoor air temperature is assumed to be the same for all the buildings. The definition of HDD's is based on the German norm DIN 4701 [117].

$$T_{am} \leq 12℃ \text{ and } T_{in} = 20℃ \tag{20}$$

Daily dry air temperature over the year is considered for the model, while the internal design air temperature in buildings is considered to be 20˚C and the HDD threshold to be 12˚C. HDD's are calculated between 15 October and 15 April. Degree days counted out of this interval equal zero. The result of the sample HDD calculation is described in Table 2.

Table 2 Heating degree-day evaluation

Day of the month	Daily mean outside air temperature [130]	HDD threshold 12˚C	HDD
15 November	5	12	15
15 January	-3	12	23
15 March	7	12	13

According to equation (21) the space heating demand is linear to ambient dry air temperature T_{am} as well as indoor air temperature T_{in}. The total (grid) hourly space heating demand Q_{sh}^{grid} is then a sum of space heating demand annually Q_{sh}^{grid} over all the buildings contained in a boundary grid divided by all $\sum_{i=1}^{8760} HDD\ s$ during the year times hourly heating degrees HDD:

$$Q_{s.h.d}^{grid} = Q_{s.h}^{grid} \times HDD / \sum_{i=1}^{8760} HDD \tag{21}$$

DHW demand is not dependent on outside air temperature variations as in HDD's, even though during the summer months there is a slightly low or little demand for DHW [56], which was considered while modelling DHW temporally in subsection 2.2.2

2.3 Energy efficiency and space heating demand reduction

This section assesses the contribution of energy efficiency measures to decrease the CO_2 emission from the residential and commercial sectors. The method is based on four main steps:

data collection and cleaning, bottom-up mapping of heating demand, mapping of heat-saving potential and CO_2 emissions. The proposed method is relevant for developing area locations that lack topography data from freely available sources. The results are important for local authorities that develop policies that are related to CO_2 emission reduction from the residential sector. A detailed description of each undertaken step is explained in the following subsections from 2.3.1 to 2.3.7.

2.3.1 Data

Data needed to develop a method for bottom-up mapping of the buildings' actual and reduced space heating demand was collected from spatial and statistical energy datasets. The data available from online data sources was not enough for the proposed methodology, therefore additional data was created manually. A systematic description of data collection and post-processing is provided in the following section.

2.3.2 Spatial data

Data sources like Eurostat [131] and Open Street Map [132] provide information regarding the topography of buildings. Such type of available data is limited to developing nations but available mainly for the developed countries. Research [27] concluded that even for developed countries in the EU such data provided by Open Street Map deliver an incomplete and occasionally erroneous cartographical representation of building footprints. They concluded that apart from statistical sources on national levels, no data exist, which contain concise, local information on physical building properties such as floor area, number of floors, height, age etc. However, it is far-fetched yet to expect databases for other European countries, which would allow for bottom-up modelling of the heating sector.

In contrast, for the considered case study shown in Figure 10, such data (building polygon areas) was available partially, therefore the missing data was created manually with the use of an open layer plugin (Google hybrid) [111]. In other cases, this data can be obtained from the municipality cadaster office, if available. Another needed spatial information for bottom-up mapping was the identification of different building categories. Figure 11 shows an urban built-up environment in a three-dimensional view. Since, the Eurostat and Open Street Map, provided only limited information regarding the building classification, Google Earth Pro [114] was used to visualise different building categories, like public, apartment, house, office, school etc. Apart from that, Google Earth Pro was also used for the identification of building floors.

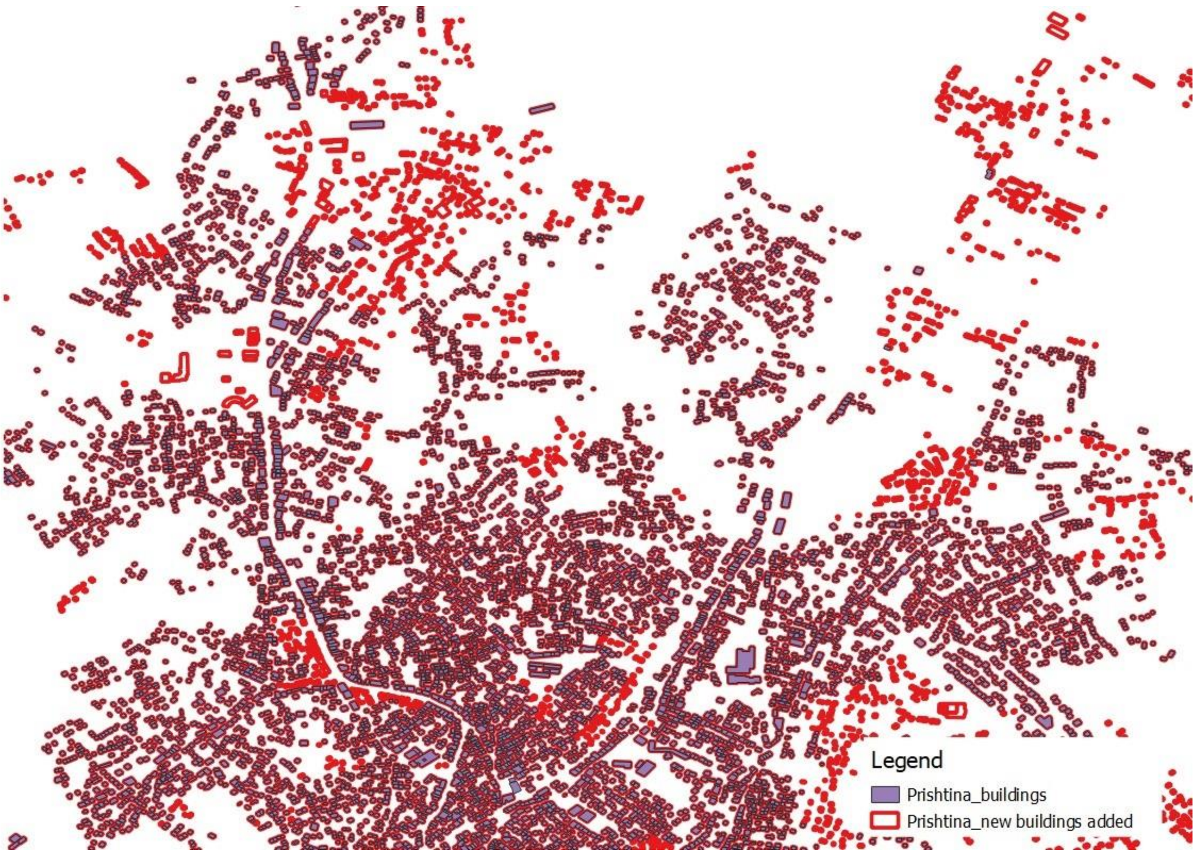
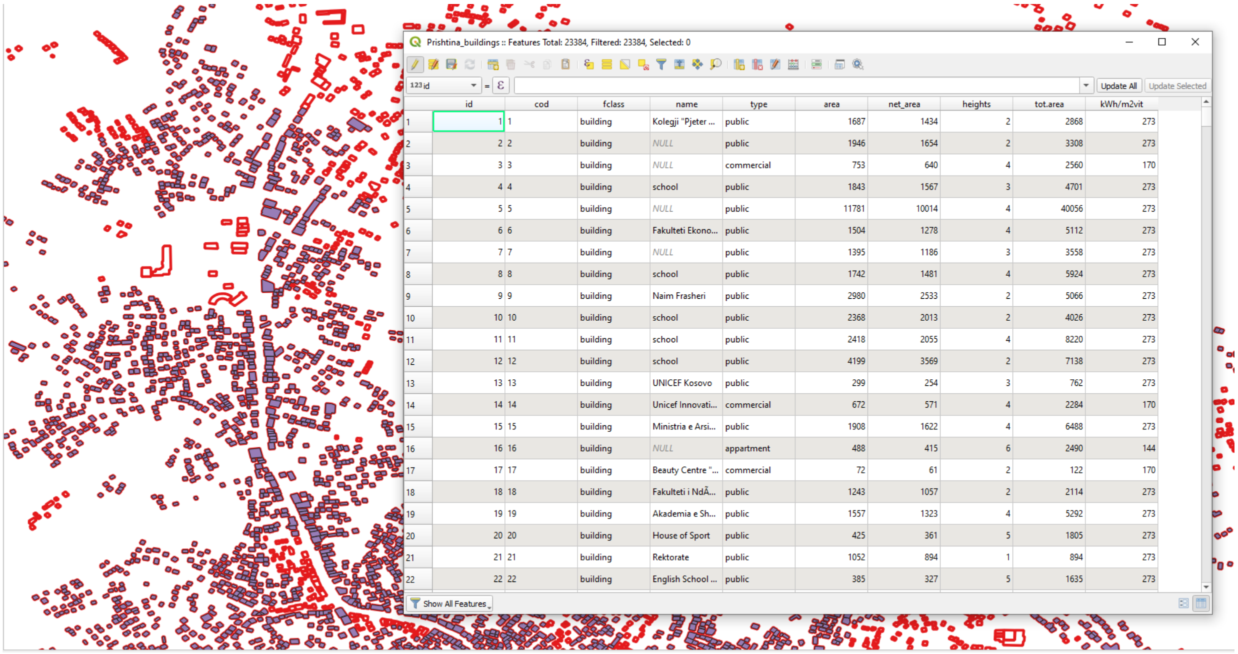


Figure 10 Existing and new added building's footprint

Figure 11 Three-dimensional (3D) building view (Google Earth Pro)

Figure 12 shows the building attribute table with input data regarding the building footprints, building type, number of heights, specific space heating demand for building category using attribute table for building features. The quality of input data can continually be improved with additional data in the future as building age and energy certificate for each building. The process of data classification, identification and post-processing in a GIS tool was performed to collect the required data for the model. These spatial data was used for mapping the net area of buildings.



	id	cod	fclass	name	type	area	net_area	heights	tot.area	kWh/m2vit
1	1	1	building	Kolegji "Pjeter ...	public	1687	1434	2	2868	273
2	2	2	building	NULL	public	1946	1654	2	3308	273
3	3	3	building	NULL	commercial	753	640	4	2560	170
4	4	4	building	school	public	1843	1567	3	4701	273
5	5	5	building	NULL	public	11781	10014	4	40056	273
6	6	6	building	Fakulteti Ekono...	public	1504	1278	4	5112	273
7	7	7	building	NULL	public	1395	1186	3	3558	273
8	8	8	building	school	public	1742	1481	4	5924	273
9	9	9	building	Naim Frasheri	public	2980	2533	2	5066	273
10	10	10	building	school	public	2368	2013	2	4026	273
11	11	11	building	school	public	2418	2055	4	8220	273
12	12	12	building	school	public	4199	3569	2	7138	273
13	13	13	building	UNICEF Kosovo	public	299	254	3	762	273
14	14	14	building	Unicef Innovati...	commercial	672	571	4	2284	170
15	15	15	building	Ministria e Arsi...	public	1908	1622	4	6488	273
16	16	16	building	NULL	appartment	488	415	6	2490	144
17	17	17	building	Beauty Centre "...	commercial	72	61	2	122	170
18	18	18	building	Fakulteti i NdÃ...	public	1243	1057	2	2114	273
19	19	19	building	Akademia e Sh...	public	1557	1323	4	5292	273
20	20	20	building	House of Sport	public	425	361	5	1805	273
21	21	21	building	Rektorate	public	1052	894	1	894	273
22	22	22	building	English School ...	public	385	327	5	1635	273

Figure 12 Attribute table including input data for building type, building footprint, number of floors, and building form of use.

2.3.3 Statistical energy-based data

Another critical information required for the bottom-up mapping is the specific heat demand per square meter for different building categories. This data was available only for residential buildings, however, for other building categories like public, office and industrial buildings, the data was collected from the energy auditors and other internal discussions with energy auditors of Kosovo and other reports (see Table 5 and 6). The heat demand in residential buildings is based on the seasonal method of the EN 13790 for the calculation of energy demand [116]. The method considers the internal and solar heat gains, ventilation losses and thermal inertia of buildings. The method used implies the typology and evaluation of energy efficiency measures in residential buildings in the EU, as explained in section 2.3.5. Data on specific heat demand for public, office and industrial buildings was collected from different building energy auditing reports. The method used to calculate heat demand in these energy auditing reports considers building envelope and ventilation heat losses [133], internal heat gains of buildings, excluding solar heat gains. The calculations are carried out in Excel sheet tables. The reviewing results of specific heat demand for different buildings are summarized in Table 6. The description of how this data was utilized in the model is discussed in the energy efficiency subsection (section 2.3.5).

2.3.4 Bottom-up heat demand mapping

The bottom-up method is used for assessing the heat demand densities in small urban areas. The process of heating demand mapping is elaborated in [14], [17], [19], [112], [134], [135], [136], [137]. The mapping process consists of the following steps: mapping building area locations, mapping building floors, and mapping of building categories. The total gross area per building can be estimated with the multiplication of building floor areas and the number of floors. In addition, the total net space heated area of a building was calculated with the equation below:

$$A_{n.h}^{b} = A_{f}^{b} \times n_{f} \times c_{r} \tag{22}$$

where: $A_{n.h}^{b}$, m^2 – is the total net space heated area of a building, A_{f}^{b}, m^2 – is the building footprint area, n_f – is the number of floors, c_r – is the calibration ratio between net and gross area of a particular building. The calibration ratio of 0.75 is considered for single-family houses, while for other building categories, the calibration ratio of 0.8 is considered.

Space heating demand for each building was calculated using the specific space heating demand (from the Table 5) and net heated area of a particular building

$$Q_{building} = A_{n.h}^{b} \times e_{a} \tag{23}$$

where: $Q_{building}$, kWh/year – is the space heating demand for the building, e_a, kWh/m^2year – is specific space heating demand.

The actual space heating demand of buildings was aggregated and distributed spatially in a grid with 200 m × 200 m.

$$Q_{grid} = \sum_{i=1}^{n} Q_{building.i} \tag{24}$$

where: $Q_{grid,}$ kWh/year – is the actual space heating demand in a grid with 200 m × 200 m.

The bottom-up heat demand mapping is used to assess the city's actual heating demand, which is named a reference scenario for further analysis. The next step includes the integration of typical energy efficiency measures in the model.

2.3.5 Energy Efficiency measures

The method proposed for evaluating the impact of energy efficiency measures in buildings was in accordance with the TABULA EU project [116], which takes into account the classification of typology and evaluation of energy efficiency measures of the residential and commercial buildings. The same is also applied for EU countries; thus, the proposed method can be utilized in these countries. The method of TABULA is based on the standard EN 13790 for the calculation of heat demand in residential and commercial buildings. This methodology proposes two scenarios for improving energy performance in the existing building stock.

- Standard energy efficiency measures (Scenario 1)
- Advanced energy efficiency measures (Scenario 2)

Both scenarios consider the refurbishment of the building envelopes, the replacement of windows and doors, and the utilization of thermal insulation in external walls and roofs. The only difference between the standard (EEs) and advanced energy efficiency (EEa) scenario is the application of higher thermal performance components.

Similar refurbishment measures are proposed for other building categories rather than residential and commercial buildings. A review of energy auditing reports for office, public (schools, hospitals) and industrial building categories was carried out for identifying typical renovation measures in those buildings. These measures were also divided into two scenarios for residential and commercial buildings. The proposed typical building envelope measures for these building categories are summarized in Table 6. Energy efficiency measures are taken into account in the spatial analysis with the reduced specific space heating demand e_a per floor area of the buildings.

2.3.6 Mapping of heating demand saving potential

The bottom-up head demand mapping approach mainly is used for identifying the spatial allocation of heat demand. For the proposed research, the results of calculated heat demand in the reference scenario were additionally used to identify the spatial distribution of space heating demand within a city to locate the hotspots. Based on considered energy efficiency scenarios that were considered from both residential topography and the auditing processes, the spatial distribution of heat demand savings potential was calculated. Such a process is calculated by multiplying the net heated areas of buildings with reduced space heating demand in refurbishment buildings.

The results of the space heat demand saving potential spatially with EEs measures in existing building stock are shown as a percentage of reduced and actual space heating demand of building contained in a 200m× 200m grid as follow:

$$\%EEs = \frac{Q_{grid}^{EEs}}{Q_{grid}} \times 100 \quad (25)$$

Similarly, the reduction potential of space heat demand with EEa measures for grid and district is calculated as below:

$$\%EEa = \frac{Q_{grid}^{EEa}}{Q_{grid}} \times 100 \quad (26)$$

2.3.7 Energy and environment impact assessment

Based on the bottom-up heat modelling, the annual space heating of buildings for the entire city was estimated. Useful space heating demand and primary energy supply mix in buildings were used for assessing the effects of energy efficiency measures in CO_2 emission reduction potential within the city.

The useful space heating in buildings is obtained by summing up the total heat demand of buildings in the city as shown in equation (27):

$$Q_{SH,city} = \sum_{i=1}^{n} Q_{buildings,i} \quad (27)$$

where: $Q_{SH,city}$, kWh/year – is the total annual space heating demand of the city.

The primary energy supply mix for covering space heating demand is assumed the same as the primary energy supply mix to cover the total final energy demand in buildings. We undertake this process when the primary energy carriers that supply space heating in buildings are unknown; however, the energy carriers that supply total final energy demand in respective buildings are known. Based on the aggregated value of total space heating demand in buildings and the share factors (e_i), the useful space heat demand for different shares of primary energy carriers can be estimated using the following equation:

$$Q_{PES,i} = Q_{SH,city} \cdot e_i \tag{28}$$

where: $e_{i,}$ % – is the share of primary energy supply source to cover final energy demand in buildings, $Q_{PES,i}$, kWh/year – is the useful space heating demand produced from different i^{th} primary energy supply sources.

The primary energy supply carrier used to cover space heating demand in different buildings consists of coal, oil, and biomass. The share of primary energy supply sources covering final energy demand for residential and public buildings can be found in local energy balances.

Considering the same share of primary energy supply mix as for final energy demand in buildings, the useful space heating demand is calculated with the following equation:

$$Q_{SH,city} = Q_{coal} + Q_{oil} + Q_{biomass} + Q_{elec} + Q_{solar} + Q_{DH} \tag{29}$$

where: Q_{coal}, kWh/year – is the useful heat produced from coal, Q_{oil}, kWh/year – is the useful heat produced from oil, $Q_{biomass}$, kWh/year – is the useful heat produced from biomass, Q_{elec}, kWh/year – is the useful heat produced from electricity, Q_{solar}, kWh/year - is the useful heat produced from solar thermal collectors, Q_{DH}, kWh/year – is the useful heat produced from district heating.

The conversion efficiencies were used for the estimation of primary energy supply sources utilized for covering useful space heating demand in buildings. The primary energy supply (PES) can be estimated using the conversion efficiencies for different heat production technologies as follow:

$$\begin{aligned} E_{PES} = Q_{coal}/\eta_{coal} + Q_{oil}/\eta_{oil} + Q_{biomass}/\eta_{biomass} + Q_{elec}/\eta_{ele.production} \\ +Q_{solar}/\eta_{solar} + Q_{DH}/\eta_{DH,production} = \textstyle\sum_i^n (Q_{PES}/\eta)_i \end{aligned} \tag{30}$$

where: η_{coal} - is the efficiency of conversion of coal into heat, η_{oil} - is the efficiency of conversion of oil into heat, $\eta_{biomass}$ - is the efficiency of conversion of biomass into heat, η_{solar}- is the efficiency of solar thermal collectors, $\eta_{ele.production}$ - is the efficiency of conversion of PES mix into electricity, $\eta_{DH,production}$- is the efficiency of district heat production.

The actual carbon dioxide emissions were estimated using the primary energy supply mix and different CO_2 emission factors for fuel types as shown in equation (31)

$$CO_2 emissions = gCO_{2(fuel,mix)} \cdot E_{PES} = gCO_{2(fuel)i} \cdot \sum_i^n (Q_{PES}/\eta)_i \quad (31)$$

The country's primary electricity production mix was considered for the estimation of CO_2 emission factor $gCO_{2(fuel,mix)}$. DH system is based on the cogeneration plant, which uses lignite coal for electricity and heat production. In addition, the CO_2 emission factor was considered the same as for individual coal boilers.

The same procedure, as described above, was undertaken for calculating the total CO_2 emissions from the refurbished buildings in scenarios 1 and 2, respectively.

2.4 EnergyPLAN

EnergyPLAN is a bottom-up specialized modelling tool used to assess large-scale integration of RES, impacts of heating, cooling, electricity, and transport sector in energy systems. The coupling among heating, cooling, electricity, and transport sectors can also contribute to designing energy systems with better performances and lower costs. EnergyPLAN uses hourly distributions of resources and demand for one year to produce hourly outputs. General inputs in the model are energy demands, RES, power plant capacities, costs, import/exports of electricity production, etc. The outputs are energy balances, energy production, fuel consumption, imports, exports, and total costs [138]. The model outputs show the consequences of the technical and market simulation strategies that lead to sustainable designing and planning of energy systems.

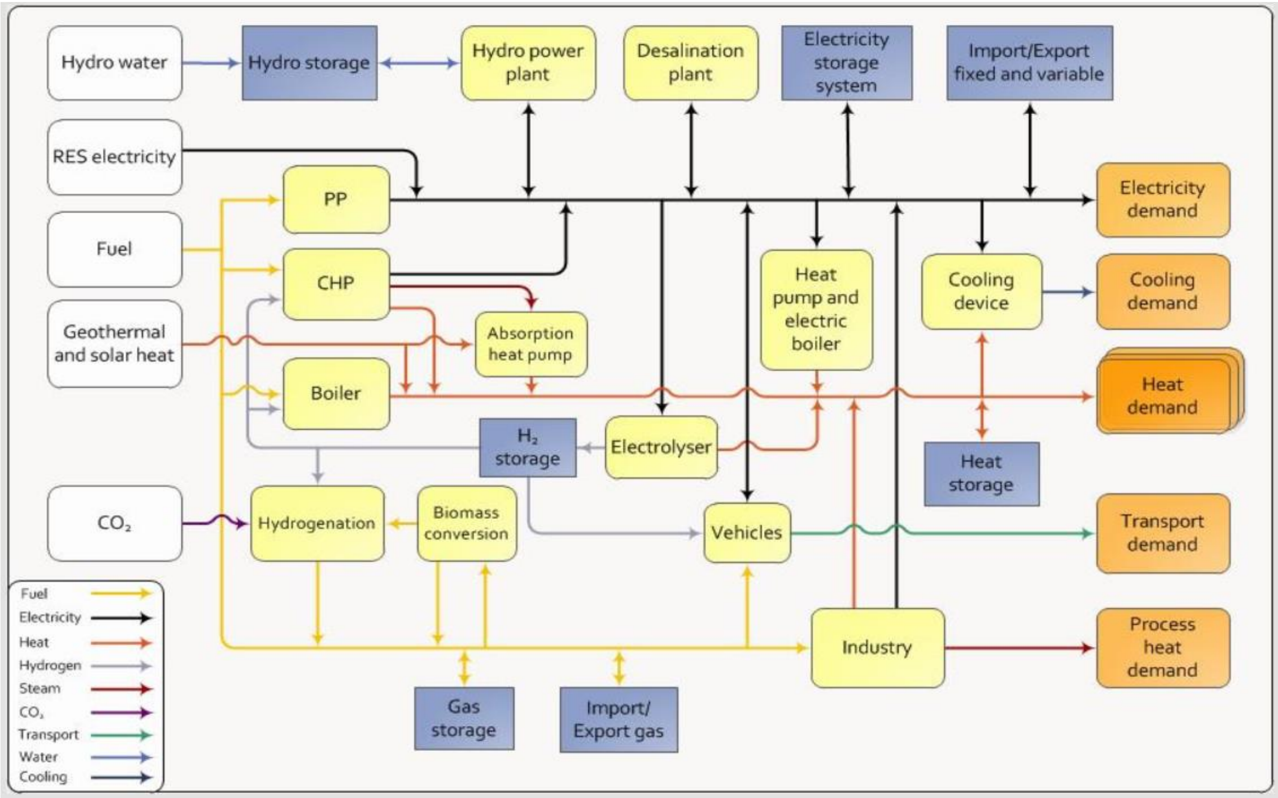


Figure 13 EnergyPLAN model [138]

EnergyPLAN is already a well-established tool for modelling large scale integration of RES in future energy systems based on conventional plants [139], an increase of CHP for DH [140], optimal combinations of PV, wind and wave power [141], increase on solar PV [71], the optimal combination of RES in islands [142], and impact of wind and PV in power system load [143]. Furthermore, this tool is very useful for modelling low carbon energy systems and the concept of the smart energy system. Research [144] reviews the application of the EnergyPLAN model on the geographic level and the types of simulations or scenario analyses performed on the model. Secondly, it reviews the types of performance indicators applied in said energy systems simulations and thirdly it reviews and details existing advanced energy system performance indicators and proposed additional indicators. The schematic diagram of the EnergyPLAN model is shown in the Figure 13.

As it is a well-established tool for similar applications, EnergyPLAN was chosen to be a modelling tool for testing different energy policies using scenario analysis. Technical simulation strategy with the sub-strategy balancing both heat and electricity demand in EnergyPLAN was selected. A minimum CHP and PP capacity was set for electric stabilization requirements and was assumed the same in all analysed scenarios. In addition to this assumption, research [145] concluded that a minimum PP capacity is required in the power system to maintain the power supply's security under sustainable levels.

The EnergyPLAN model in this thesis is used for:

- Assessing individual heating and road transport electrification
- Assessing the district heating electrification
- Assessing different energy transition pathways

Critical excess electricity production is defined as produced electricity that exceeds both the power system's electricity demand and export transmission line capacities. It should be avoided in a power system; otherwise, such electricity production will be curtailed. Research [141] shows that a small value of CEEP can be tolerated since it is not always economically viable to build electricity storage in a power system for a concise period during the year when CEEP appears. In addition, the value of CEEP around 5% of total electricity produced by RES is used as a criterion for defining RES integration limit [54], [71], [141]. In the current research, CEEP was used for defining the integration of vRES in a coal-based energy system when considering three major sources of flexibility. Sources of flexibility include the electrification of the transport sector with individual and light-duty vehicles, district heating with large-scale heat pumps, and individual heating with heat pumps.

2.4.1 Individual heat and road transport

Several scenarios have been created to increase the share of vRES in power supply and replace individual fuel boilers with individual heat pumps, internal combustion engines with electric cars and light-duty vehicles on the demand side.

The electrification of transport increases the energy system flexibility allowing more vRES integration in respective power systems. The average electricity consumption and battery capacity was taken from [62], while the driving habits have remained the same as in the reference case. The model further considers the potential adaptation of EV’s in energy systems with significant penetration of vRES using the V2G concept. It is assumed in all scenarios that passenger cars and light-duty vehicles (minibuses and pickups) participate in smart charging and 50% of these vehicles choose to participate in V2G.

Heat electrification also plays a major role in vRES integration and hence power system flexibility increase. Future heat electrification scenarios consider an increasing penetration of individual heat pumps with heat storage to reduce other means of consumption. The same, consider that coal and oil boilers should be replaced first and then individual electric heaters while keeping the biomass consumption under sustainable limits.

In energy systems with a high share of vRES, TPP’s must operate with high operational flexibility. Flexibility refers to the short-term TPP perspective and describes the ability of power generation technologies to produce electricity. It includes the capability to adjust the status and the generation of TPP’s. Parameters that characterize TPP’s flexibility are start-up time, ramping load, minimum load, and minimum up and down. The report [146] shows that for lignite TPP’s with an optimized plant design, reducing the minimum load to 35% or even 17.5% (using a two boiler concept) is expected. The minimum load capacity of TPP’s was considered at 20% of total operational lignite coal TPP’s capacities. This means that variable renewable electricity production will be prioritized for utilization in power systems when available by merit order compared to electricity produced from TPP’s. Moreover, in a few scenarios, the model considers that the flexibility of TPP’s will increase to 100% to account for the potential for increasing the vRES at these TPP operating conditions. In addition, TPP’s will play a significant role in balancing the system and maintaining the power supply's high reliability.

Significant integration of vRES in power systems will make TPP’s operate below their rated capacity and hence reduce the efficiency of the entire process, which is expressed by part-load efficiency. The decrease in TPP efficiency increases fuel consumption, CO_2 emissions and thus overall power generation costs. The amount of energy needed to keep the TPP running and thus synchronized decreases at high load operating capacities. In order to cope with the variability and uncertainty introduced by vRES in power systems, the flexible planning and operation of generating units is crucial. Research [147], [148] develops a unit commitment model to study this interaction between the market clearing frequency and the start-up capabilities of combined-cycle gas turbines. Results indicate that higher market clearing frequencies lead to lower operating costs, driven by decreasing volumes of operating reserves and facilitated by the fast start-up capabilities of combined-cycle gas turbines.

Different research summarized in [146] shows that part-load TPP efficiency decreases from 5 to 10% in comparison to efficiency estimated at rated power production. Low-efficiency TPP is subject to higher losses because of TPP cycling. Figure 14 shows how the efficiency of coal-based TPP's changes at different loading conditions.

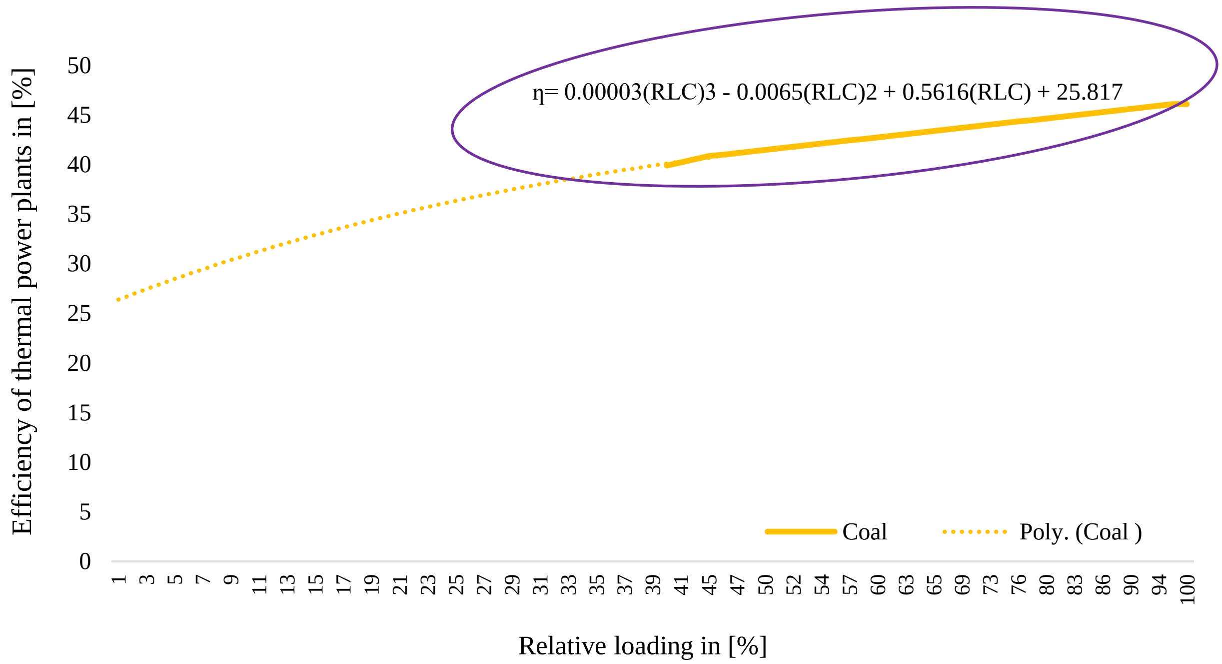


Figure 14 Efficiency of the coal-based TPP in part-load operation [146]

The equation provided in Figure 14, describes best the part-load efficiency of coal-based TPP's for different loading capacities. (RLC) is the relative loading capacity of TPP's in %. The relative profile of part-load efficiencies for coal-based TPP's was taken from the source of graph 14 and recalculated for existing TPP's. The equations that describe the part-load efficiency of the existing and revitalized TPP are provided in the case study section.

2.4.2 Power to Heat in district heating

The Kosovo energy system is selected to assess the impact of power to heat technology in district heating to increase the share of variable RES integration in coal-based energy systems.

Scenario analysis are used to describe the method, while the description of the same is provided below:

RES integration, interconnections and no P_tH scenario: since the economic viable DH share is around 50-57% of total country heating demand, this scenario considers the share of DH around 50%. It also supposes that the fuel that was consumed in certain technologies (biomass, oil and gas boilers) for providing individual heating solutions has remained the same even after increasing the DH share to 50%. Therefore, no additional P_tH technology (compression heat pump or electric heater) was added, which means that the flexibility of the power system has remained the same as in the reference scenario. In addition, the existing Kosovo power system was simulated to identify the flexibility this power system offers and how much RES power capacities can be added to the current energy system when operating with different interconnection capacities.

RES integration, interconnections and P_tH scenario: In this scenario, compared to the previous one, the role of P_tH technologies for increasing additional Wind, PV and RES power capacities was identified. The simulation results show the contribution of P_tH for adding additional Wind, PV and RES power capacities in the current power system operating with different interconnection capacities. Sensitivity analysis for different transmission line capacities was carried out to determine the influence of P_tH technologies for Wind, PV and RES integration in isolated, limited and very well-connected power systems.

Electricity demand, interconnections and P_tH scenario: The contribution of P_tH technologies to add additional RES power capacities and the percentage of total country electricity demand in TWh/year that would have been covered because of the utilization potential of P_tH technologies in the current power system is estimated. This scenario is modelled by considering different interconnection capacities. First, the yearly electricity production by increased Wind, PV and RES capacities due to the flexibility offered by interconnections and PtH technologies is calculated and then divided by the total country electricity consumption.

RES integration, no interconnections and different P_tH capacities: In previous scenarios, a fixed (P_tH = HP + HS) capacity was used for estimating Wind, PV and RES integration potential. In contrast, this scenario considers different HP and heat storage capacities in DH and identifies different P_tH sizes needed for maximum integration of Wind, PV and RES power plants. All these analyses are carried out for an isolated energy system, where the contribution of P_tH to integrate variable RES is significant.

Total Primary Energy Supply and CO_2 emission savings: Maximum utilization capacity estimated for different sizes of P_tH technologies in DH that contributed to RES integration was used for estimation of total primary energy supply (TPES) savings and CO_2 emission reductions compared to the reference scenario. TPES (TWh/year) and CO_2 emissions (Mt) savings compared to the reference scenario are shown when variable RES technologies are integrated into the power system in a separate and combined manner.

2.4.3 Coal-based energy system transition pathways

Scenarios show how coal-dependent energy systems can gradually change their configuration to become environmentally acceptable. Five different scenarios have been developed for the year 2030, besides the base scenario, to assess the EU energy policy impact on the overall energy system performance and the energy system costs. A detailed description of scenarios is provided below.

The base scenario shows the case of not undertaking any policy to meet the targets by 2030. It assumes that the same share of fuel in all sectors will be consumed in 2030 as compared to the reference year 2015.

Scenario 1 considers the same energy policies in the selected coal-dependent energy system as for EU member states. Apart from established targets for 2020, this scenario further considers additional technology penetration in the heating sector to meet 2030 targets like the integration of large-scale heat pumps in DH, 20% individual electric heaters to be replaced with individual heat pumps in areas without access to DH, 50% of actual DH demand, to be replaced by new biomass boilers and an increase of the DH system to 50% of actual DH demand. Furthermore, it also considers the scaling up in variable RES and construction of large-scale CHP based on coal and biomass co-firing with 70 and 30%, respectively.

Scenario 2 considers a significant increase in PV, wind and hydropower production and the construction of new PP based on coal and biomass co-firing with 80 and 20%, respectively. In addition, the scenario also considers the replacement of oil-based DH with biomass.

Scenario 3 is an ambitious scenario that considers a high penetration of RES in the electricity and heating sector. It does not consider the construction or reconstruction of a large PP, however, it considers the construction of small CHP's at the municipality level for covering both electricity and future DH demands. It examines the integration of RES in the electricity sector without causing excess electricity production and power curtailment. Furthermore, it also reflects the significant integration of individual and large-scale heat pumps both for individual and DH purposes, thermal energy storage in DH and a small penetration of electric vehicles in the transport sector. In addition, it also assumes that individual coal and oil boilers will entirely switch to other individual heat pump and DH supply options.

Scenario 4 analyses the implications of CCS technologies in new constructed PP. The electricity consumed for powering CCS technology in a PP was left the same as the one proposed in the EnergyPLAN model accounting for 0.37 MWh_{el}/tCO_2. The capacity of CCS was not applied to all PP capacities, only for that portion for which it would be enough to decrease the emissions by half compared to the reference scenario. Furthermore, this scenario also considers significant integration of variable renewables especially Wind and PV with less attention to hydro to cover the electricity demand, but with no additional significant proposed changes in the heating sector except a 15% replacement of individual electric heaters with individual heat pumps.

Scenario 5 considers significant scaling-up of variable RES (wind and PV) in the power sector to meet the demand of inefficient lignite coal thermal PP's phasing out by 2030 and fill the targets regarding 32% share in final energy consumption. Wind and PV ratios in the power sector are selected by considering the assessed technical potential of these energy production sources. This scenario does not take into account further measures for increasing the flexibility of the energy system among sector coupling options, besides it considers that the interconnection lines are fully utilized for export excess electricity production in times the production from variable RES surpasses the electricity demand. Other assumptions remain the same as for the base scenario in 2030.

3. RESULTS AND DISCUSSIONS

The following sections show the results of case studies both at the local and regional levels. The results of heat demand mapping are shown for a small city named Gllogoc, while DH and heat saving potential assessments are carried out for Prishtina city. Comprehensive analysis of electrification of transport and heating sectors, the role of P_tH technologies in DH, and sustainable transition pathways are carried out using the Kosovo energy system as a case study. The detailed description and elaboration are provided in the following sections.

3.1 Heat demand mapping method for small municipalities

Three districts of Gllogoc municipality in Kosovo are used as a case study to demonstrate the top-down and bottom-up heat demand mapping method. Data regarding floor areas of buildings is created manually using the plugin of Google Satellite in QGIS 2.18.19. Because of the lack of freely available data, visual inspections of buildings were performed for identifying the number of floors, building form of use and their building categories. In other locations outside Kosovo, the identification of buildings in a three-dimensional view can be made with Google Earth Pro, or any other Geo portal tool.

For this research, 1940 buildings were analyzed and grouped into six categories. The survey accounted for 1172 houses, 604 houses without thermal insulation in external walls, 106 apartment buildings, 5 offices, 43 public buildings including (schools, hospitals, and buildings of the municipality) and 10 buildings used for industrial purposes (including Feronkeli industry). Houses are considered buildings that are built after the year 2000, so they are quite new. The external walls for most houses are composed of clay blocks with a thickness of 25 cm, insulated with an insulation layer 5-10 cm and plastered on both sides with gypsum layers. The roof of the reinforced concrete slabs combined with hollowed clay elements is covered with titles. The floor is made of concrete construction with the final wooden flooring and ceiling with lime plaster. Energy auditors estimated that the energy performance in houses accounts for an annual specific space heating demand of around 150 kWh/m^{2}year [116].

Other houses, also new constructed (so-called houses without thermal insulation in external walls), are made of clay blocks with a thickness of 25 cm, plastered with gypsum from the inner side. They do not have thermal insulation in external walls. The roof and the floor are the same as for insulated houses. For this kind of construction, according to the energy performance of actual building stock, the annual specific heat demand for space heating is evaluated to be 262.5 kWh/m^{2}year [116]. Specific heat demand for other building categories is taken from the paper [55], which is similar to those presented for buildings in Kosovo (Table 3).

Table 3 Building categories used in this survey [116].

Category	**Specific heat demand in [kWh/m^2 year]**	**Number of buildings [-]**
Houses	150	1172
Houses without thermal insulation	262.5	604
Apartment building	161.25	106
Offices	135	5
Public buildings	270	43
Industry	110	10

A similar mapping method can be used to assess the heat demand mapping for other small municipalities, but this way of assessing mapping is very time consuming and the quality of results strongly depends on datasets and assumptions adopted in the model. For validation of the model, two bottom-up heat demand scenarios have been created. In the second scenario with partially heated rooms, for Gllogoc district, it was assumed the same share of heated rooms like Ferizaj district, because of the same building infrastructure. Similar results for the share of heated rooms in houses was obtained for other municipalities in the study [149]. Figure 15 presents the share, in percentage, of partially heated houses for Gllogoc. It can be noted that 43% of houses have installed heat providers only in one room, 22% in two rooms, 13% in three rooms, 4% in four rooms and 18% in more rooms, respectively.

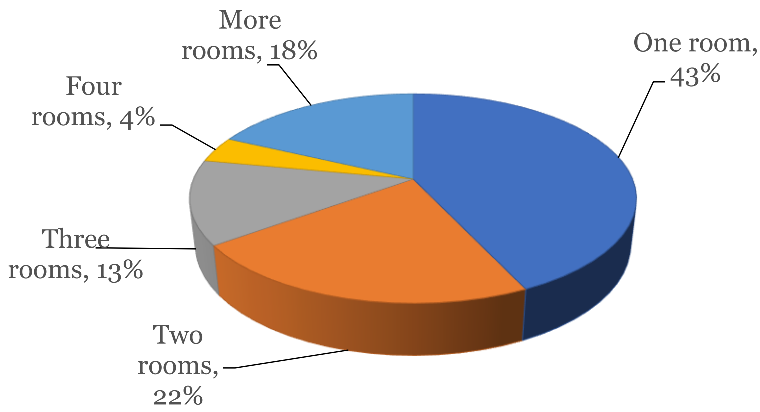


Figure 15 The share of partially heated house rooms in three districts of Gllogoc city.

From the pie graph of Figure 16, it can be noted that when considering that all the buildings are heated to their net area (Scenario 1), houses with and without thermal insulation will be the main heat consumers. In contrast, when considering the share of partially heated rooms in houses (Scenario 2), apartments and public buildings have the largest heat demand compared to other building categories Figure 17.

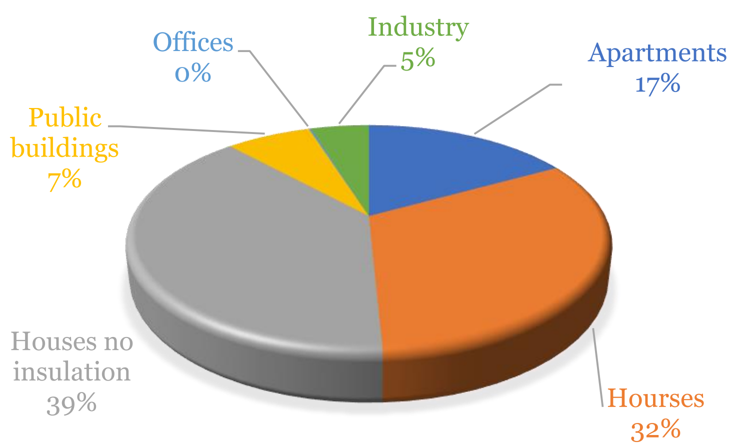


Figure 16 The share of classified buildings in overall estimated bottom-up heat demand mapping scenario (Scenario 1)

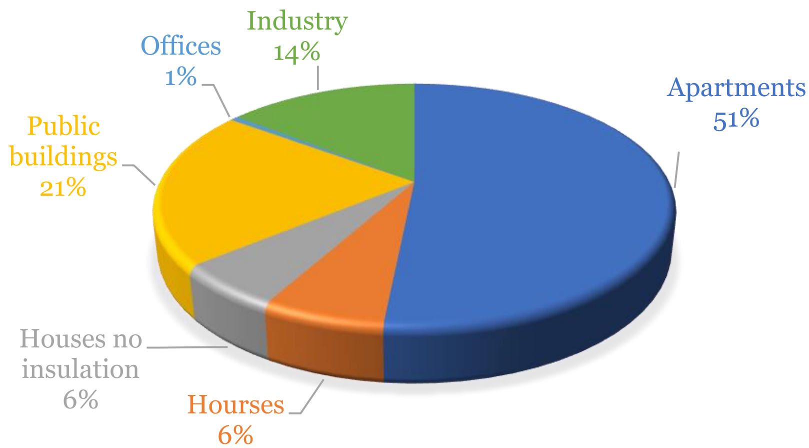


Figure 17 The share of classified buildings in overall estimated bottom-up heat demand mapping scenario (Scenario 2)

Figure 18 shows the gross area matrix composed of three information layers, mapping the floor areas, mapping the number of floors, and mapping the building categories. The left map in Figure 18, shows the heated and not heated buildings, while the middle and right-side maps show the buildings that were not being heated and hence were excluded from the analysis. Such buildings included garages and cow farms, among others. Two metrics showing the heat demand spatially for buildings that are being heated up to their net area (Scenario 1) and partially heated (Scenario 2) have been created, and the results of both are presented in Figure 23 and 24, respectively.

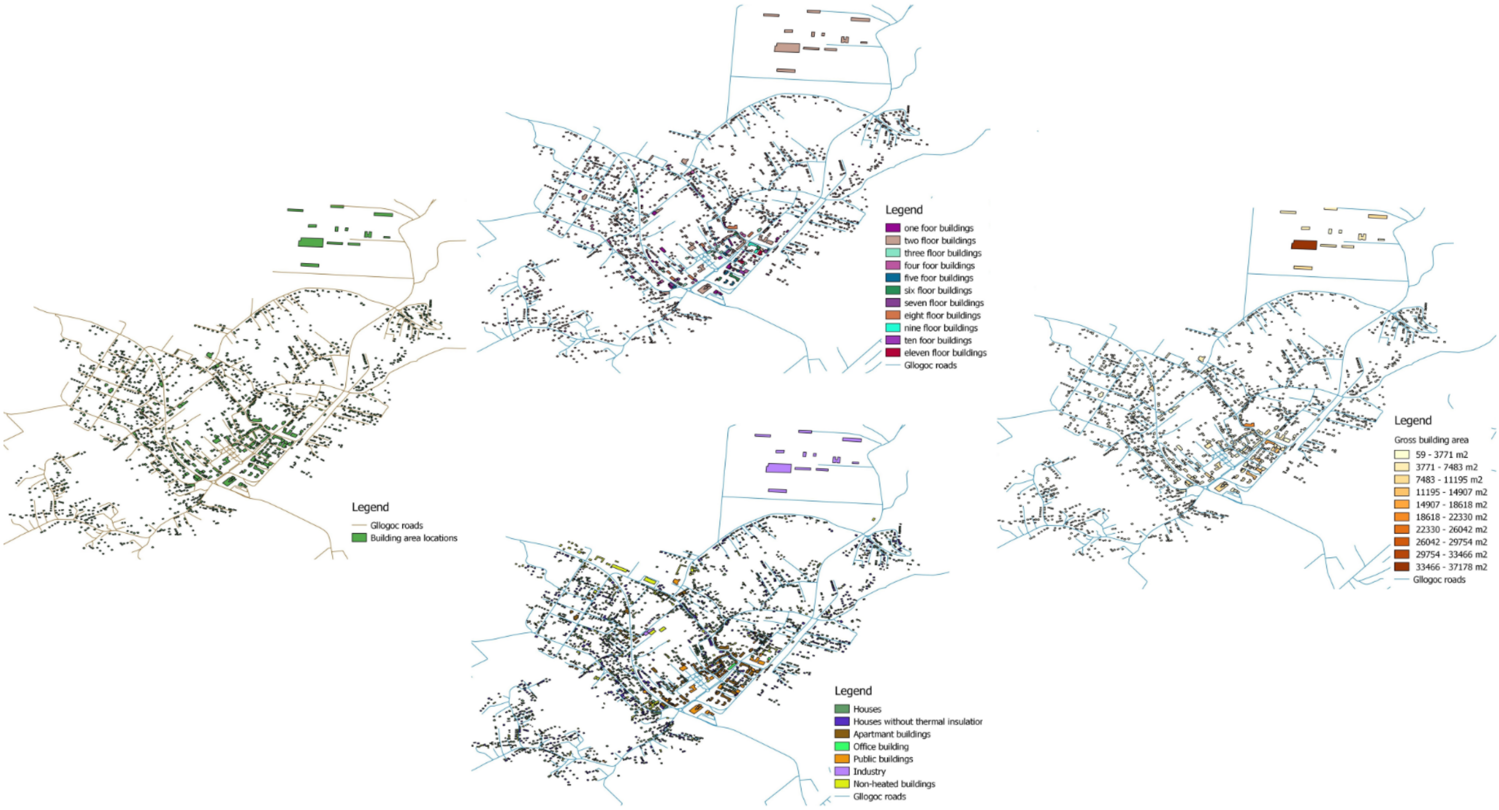


Figure 18 Gross area matrix. Step 1 – mapping of building area locations, Step 2 – mapping the number of floors, Step 3 – mapping the classified buildings, and Step 4 – mapping of building gross areas

A spatially-gridded useful heat demand distribution (heat demand map) for Gllogoc city using a top-down heat demand mapping approach, for the reference year 2015, is presented in Figure 19. The grids are composed of 250 m × 250 m spatial resolution. Each cell contains information, which can be observed as the thermal energy (heat) demand consumed for space heating annually in MWh. When summing up all heat demand aggregated into those grids, it was found that the overall heat demand in the three districts of Gllogoc city accounts **53.14** GWh/year.

The results of the top-down heat mapping approach displayed within Gllogoc city units (Figure 19) might be useful information for the local stakeholders to identify the utilization of DH potential for the assessed area location. In addition, that was not the objective of this work; therefore, the top-down heat demand mapping results have been used to calibrate the heat demand consumed by buildings with the aim of two bottom-up heat mapping scenarios.

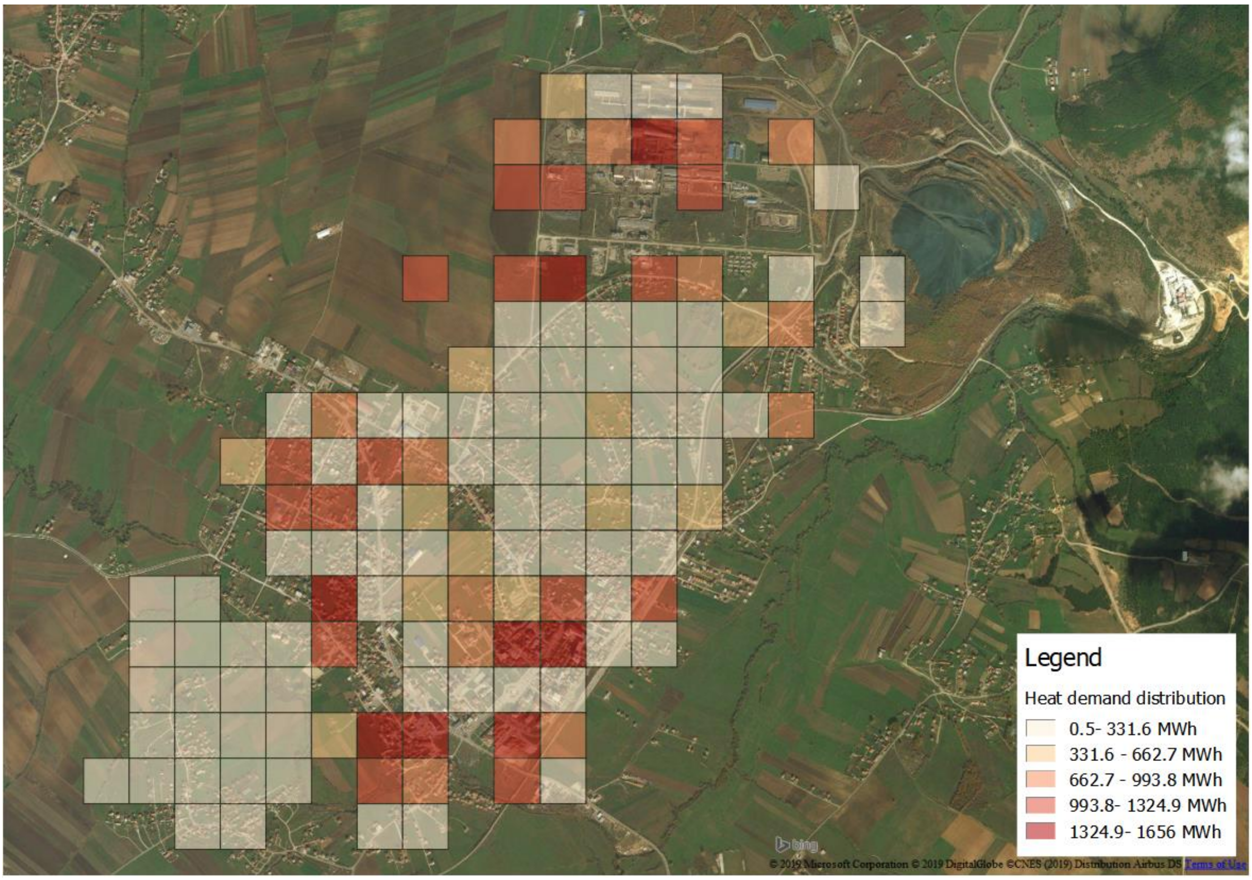


Figure 19 Heat demand distribution in Gllogoc city using top-down mapping.

It can be seen that the top-down approach used for assessing heat demand allocation in small cities would not be suitable enough, because the method itself does not take into account building features and climate impacts. Furthermore, some grids have indicated relatively high thermal energy demand by residential and commercial end-users (dark red grids), even though there was no built-up area in those grids. This strengthens the conclusion that this way of assessing heat demand mapping is not appropriate for small cities, but it may work for counties and large urban area locations. In contrast, a bottom-up mapping approach is used for better allocation of heat demand distribution in small cities.

A heat demand map for Kosovo for the reference year 2015 is presented in Figure 20. The grid has 250 m × 250 m spatial resolution, and each cell contains the information, which can be viewed as the heat demand used for space heating in MWh per year. The results displayed within-country administrative units are helpful information for the local stakeholders to identify the hot spots of heat demand for a particular location. With this information, the costs of heat, as well as emission data, can be estimated. Furthermore, the maps can be used to assess DH systems' economic viability to find out which areas can be connected to DH grids.

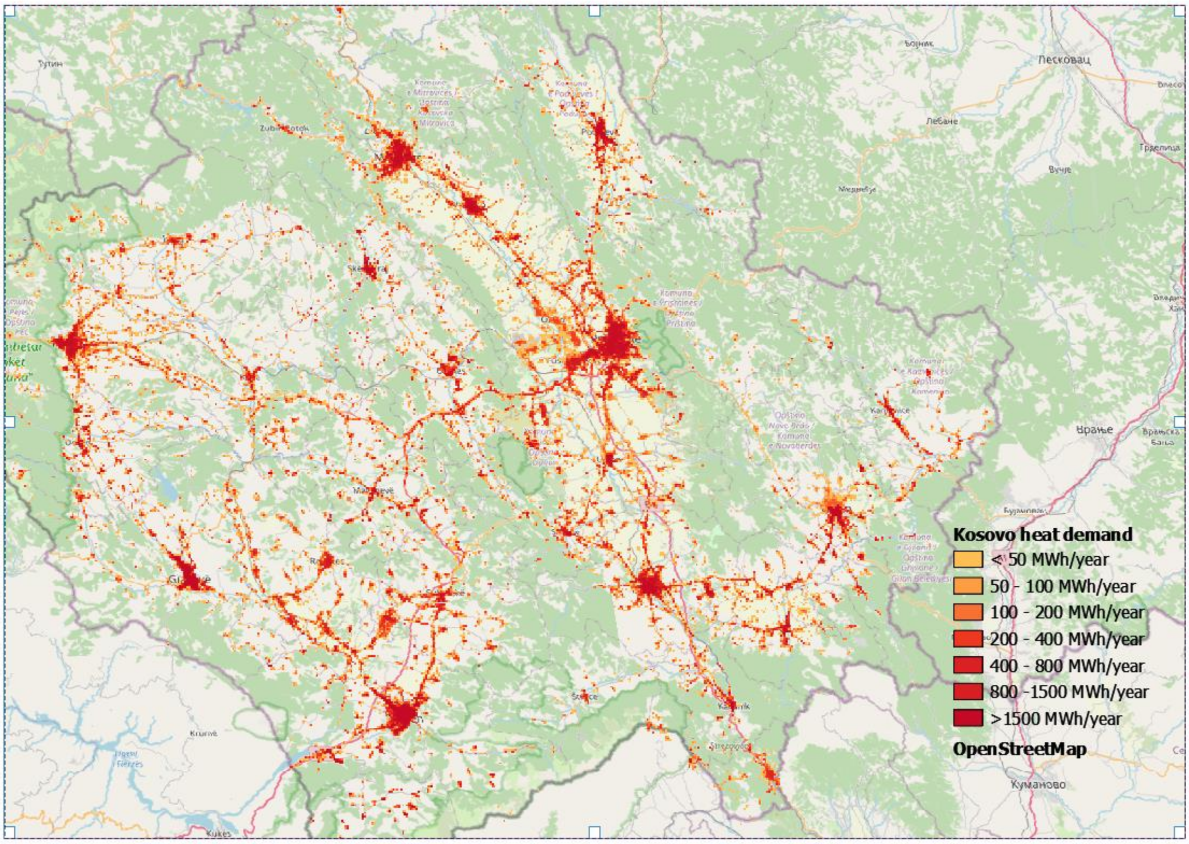


Figure 20 Heat demand distribution map for space heating. Case of study, Kosovo

The following maps in Figure 21 and 22 show the actual heat demand for space heating for two different municipalities in Kosovo. These maps are created using municipality administrative borders and the extracted heat demand from the Kosovo map.

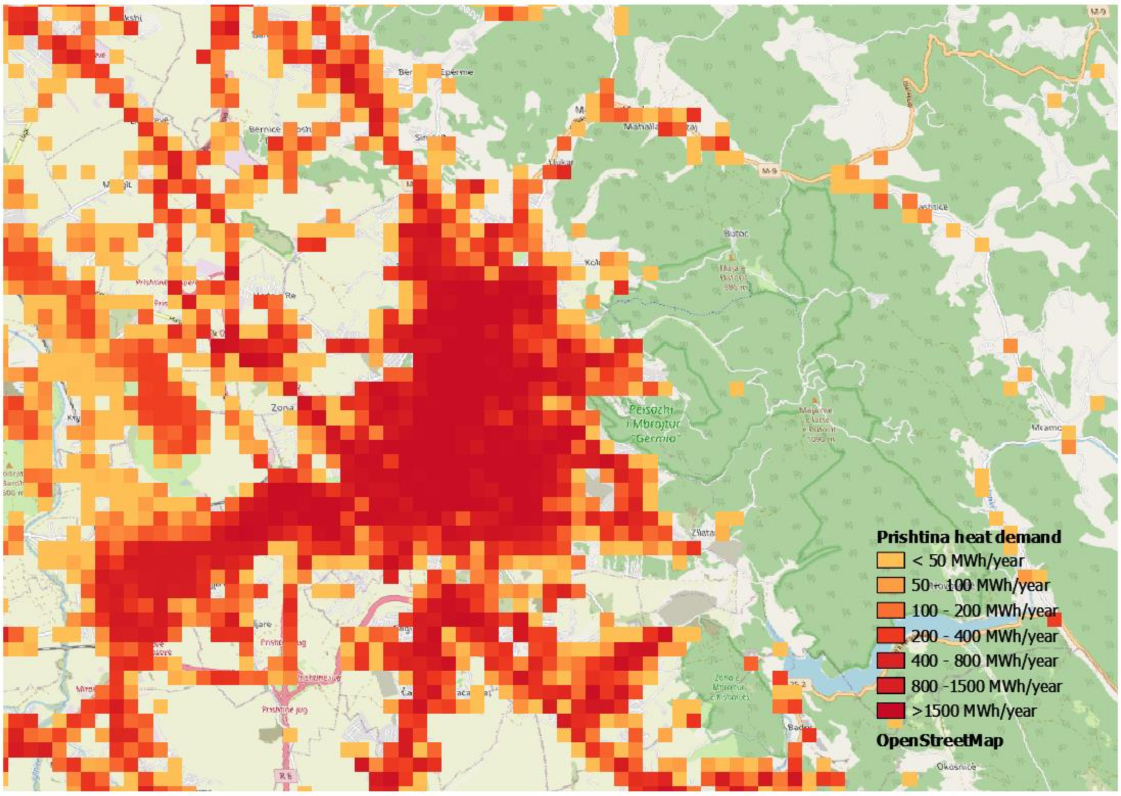


Figure 21 Heat demand distributed by 250m×250m and used for space heating in Prishtina municipality

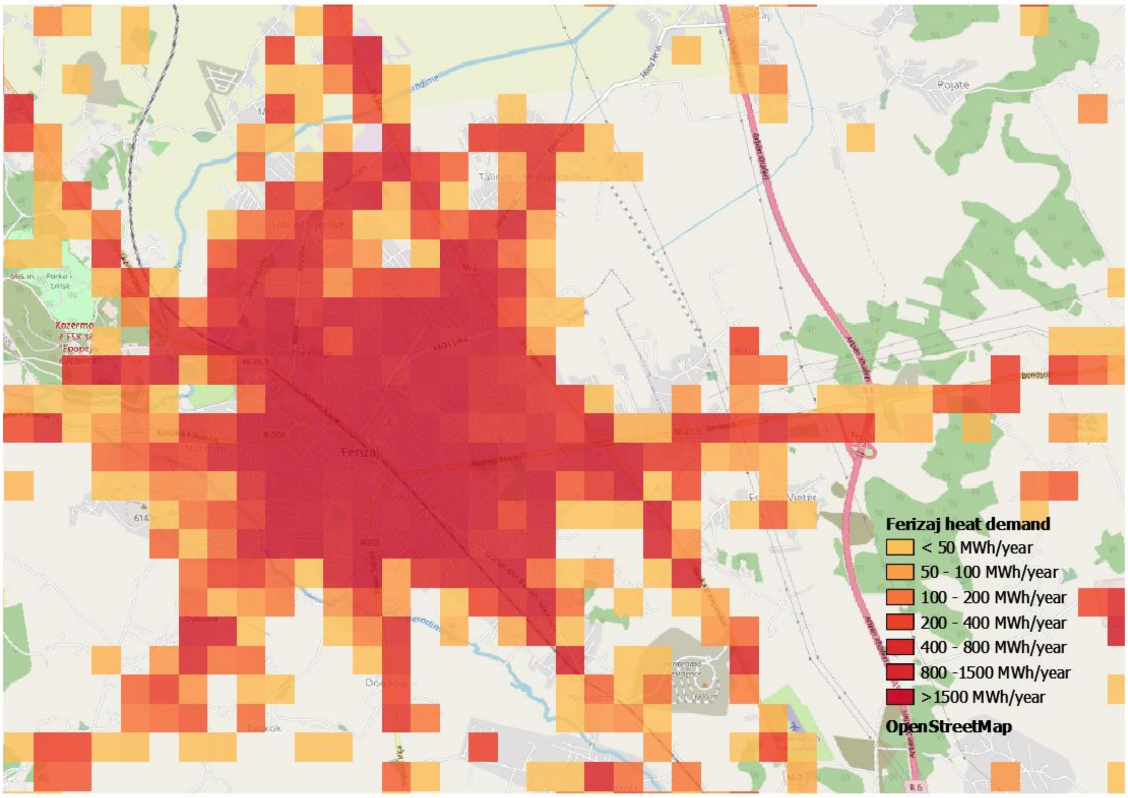


Figure 22 Heat demand distributed by 250m×250m and used for space heating in the municipality of Ferizaj

In the first bottom-up heat mapping scenario assessed, all the buildings were heated up to their net areas. In Figure 23, the obtained results of heat demand consumed by buildings and the heat demand aggregated on 100 m × 100 m grids for scenario 1 are displayed. In such a way, an overall heat demand **152.9** GWh/year by three districts of Gllogoc city was estimated. The results of the first bottom-up scenario revealed to be three times higher than the heat demand assessed with the top-down approach.

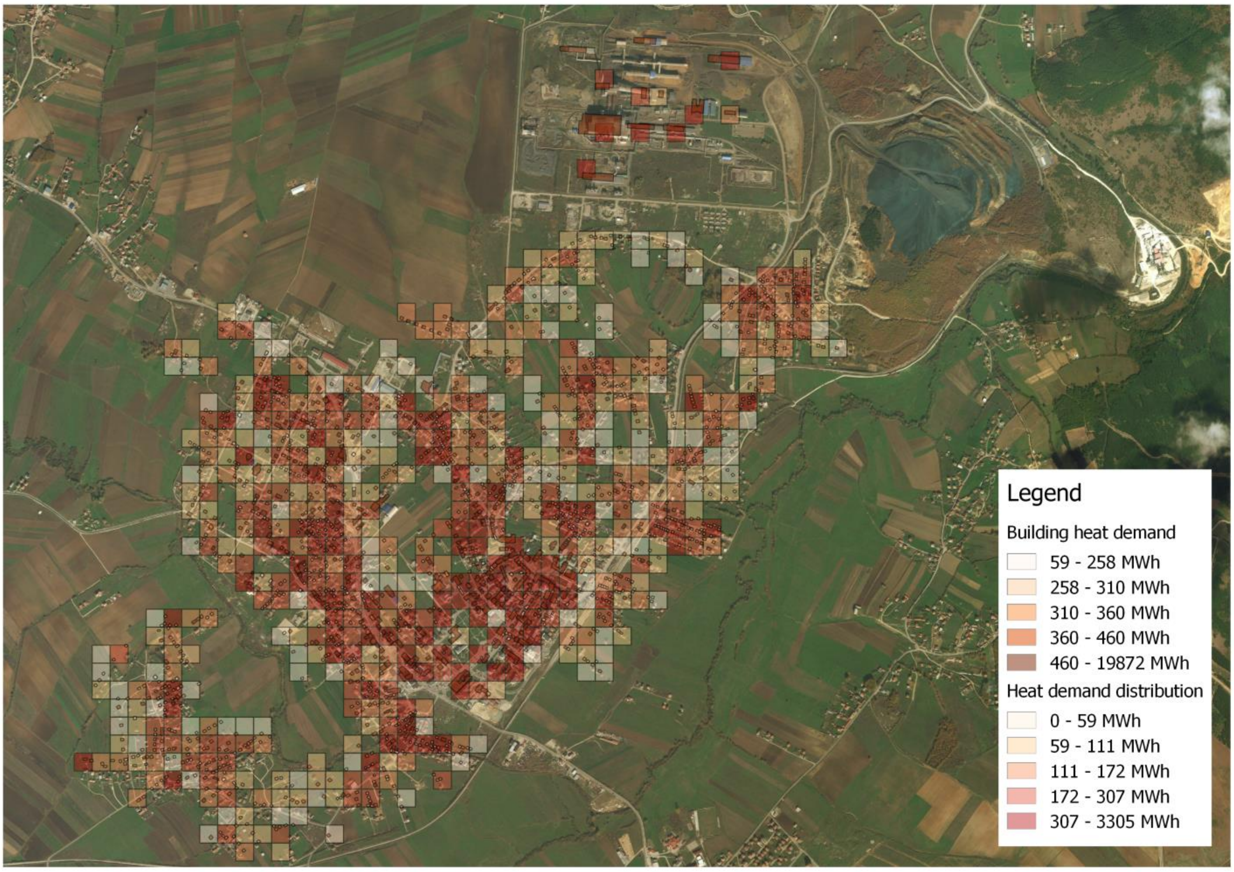


Figure 23 Heat demand distribution in Gllogoc city using bottom-up mapping (scenario 1).

Other bottom-up approaches presented in the literature review section have been using the first scenario methodology for their validation, which was not the case with the current study. In Scenario 1, higher heat demand (dark red colour coding) is obtained for apartments when compared with other building categories, which reveals similar conclusions pointed out in other research studies [55], [19]. Furthermore, in the first scenario, houses without thermal insulation in external walls were found to be the main heat consumers accounting 59.5 GWh/year, followed by houses with 49.4 GWh/year, apartments 25.8 GWh/year, public 10.5 GWh/year, industrial 7.18 GWh/year and 0.29 GWh/year office buildings, respectively.

In the second bottom-up Scenario 2, the share of heated rooms in houses with and without thermal insulation in external walls was considered. Consequently, the overall heat demand consumed by entirely assessed buildings was estimated to be **50.6** GWh/year, which was quite near the results obtained from top-down mapping. In contrast, when considering the share of heated rooms in the second bottom-up scenario, the heat consumed by houses has changed drastically compared with previous scenario 1. It was found that the apartments are the main heat consumers in the small city assessed accounting 25.8 GWh/year, followed by public buildings with 10.5 GWh/year, industrial 7.18 GWh/year, houses 3.5 GWh/year, houses without thermal insulation 3.2 GWh/year, and office buildings 0.3 GWh/year, respectively. This leads to the conclusion that when assessing heat demand mapping with a bottom-up approach in underdeveloped area locations, a particular focus should be given to apartment and public buildings, while less attention should be paid to houses that are partially heated. In Figure 24, map grids showing higher dark red colours, are indicated by the area location of the apartment and public buildings, respectively. Therefore, the heat demand is also located mostly in area locations with a high share of apartments.

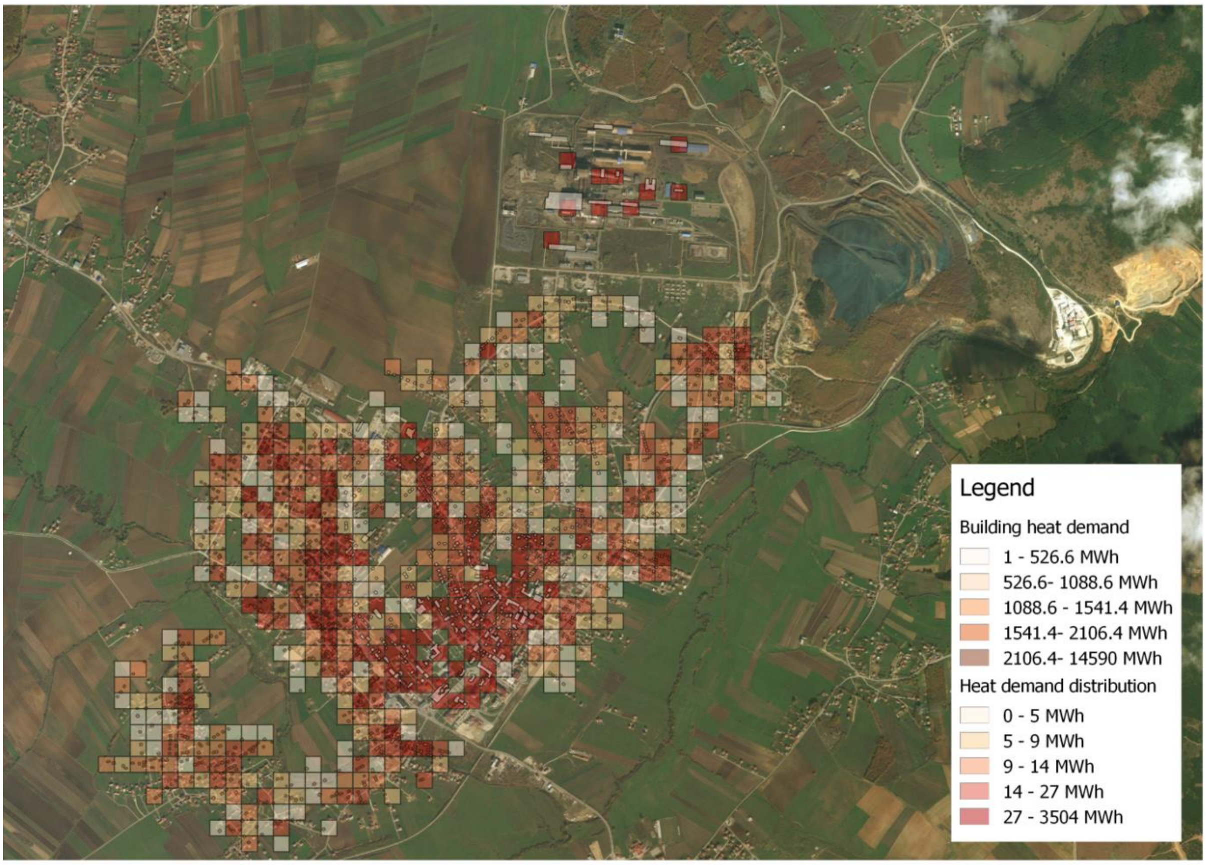


Figure 24 Heat demand distribution in Gllogoc city using bottom-up mapping (Scenario 2).

In addition to that, the building height does not impact final heat demand mapping results for such houses. For that reason, when assessing another bottom-up mapping for buildings that experience similar physical and behavioural conditions, house heights can be neglected. The assumption that can be adopted is that all the houses are heated partially up to an average surface. For houses with insulation, such average surface resulted in 53 m^2, while for the houses without thermal insulation, 45 m^2.

Another assumption made in the second scenario is the neglect of identified houses, which are heated partially to one, two, three or even more rooms due to the lack of available provided data. On the other hand, since houses' overall heat demand consumed annually is small compared with the apartment and public buildings, such an assumption does not significantly impact final bottom-up heat demand distribution maps.

Similar bottom-up mapping methodology can be used to assess other heat demand maps in other cities with similar physical and behavioural experiences of buildings, respectively. Since the other municipalities in Kosovo have shown almost an equal share of heating rooms, the methodology and assumption presented in this research can be used for assessing the other heat demand maps respectively for analyzing the utilization potential of future DH in this and other cities.

3.2 Assessment of future district heating systems

This section introduces a DH assessment that considers space heating and domestic hot water demand of buildings. It shows spatially and temporally the heat demand of buildings in existing and expanded DH systems.

3.2.1 District heating system of Prishtina

As a case study for testing the method, existing DH system of Prishtina was selected. The city has already established a DH system since 2014, which is based on cogeneration coal-based thermal power plant Kosova B [150]. However, only a small part of the city, around 19% of total heat demand, is already connected to DH. Figure 25 shows the actual DH network, respectively, buildings that are being supplied with district heat. The model contains detailed information for 23384 buildings regarding their thermal energy performance and building topography. For validation of the bottom-up space heat demand mapping approach with recorded annual DH data from the local heat distribution company, two factors have been considered: the net area of buildings already connected to DH and the space heating demand of these buildings. The calibration ratio c_r, around 0.7 - 0.8 for different building categories, was considered to estimate the net area of buildings in the GIS model. Apart from this, the local DH distribution company provided data regarding the net building areas of consumers already connected to existing DH. Similar numbers of net heated areas for identified buildings connected to DH were obtained when running calculations in the GIS model and the results of modelling are summarized in Table 4. In addition to using the data for net heated areas of buildings and specific heat demand for building category, the space heating demand of buildings already connected to DH was also calculated. The comparative results between building space heat demand recorded and modelled with GIS show a good agreement. The difference between modelled and recorded data is less than 5%, which indicates the model's accuracy. The GIS model used for validation considers only the space heat demand of buildings, excluding DHW, because existing DH is used only for covering the space heating demand of buildings. The space heat demand of buildings reported from the DH distribution company and calculated in GIS were 230 and 235 GWh/year, respectively. In contrast, the validation results can be further improved using different calibration ratios (ratio between net and a gross area of the building), the share of heated areas in buildings, the space heating demand of buildings, and hot water demand.

Table 4 Validation of the GIS model with recorded data from existing DH [150]

	GIS model	**Actual DH**	**The difference in [%]**
Surface net heated area of buildings connected to existing DH, m^2	641005	620798	3.2
Space heat demand of buildings connected to existing DH, GWh/year	235	230	2.2

Polygon areas with red colour, shown in Figure 25, are buildings that are being supplied by the existing DH system. The analysis shows that not all buildings that are close to the DH grid are connected. When classifying the building categories that are connected to the DH system, it was found that the main heat consumers are apartment, public and commercial buildings, with only a few houses. In total, 411 thermal substations in existing DH are used for exchanging heat. Plate heat exchangers are the most widely used in these thermal substations [150].

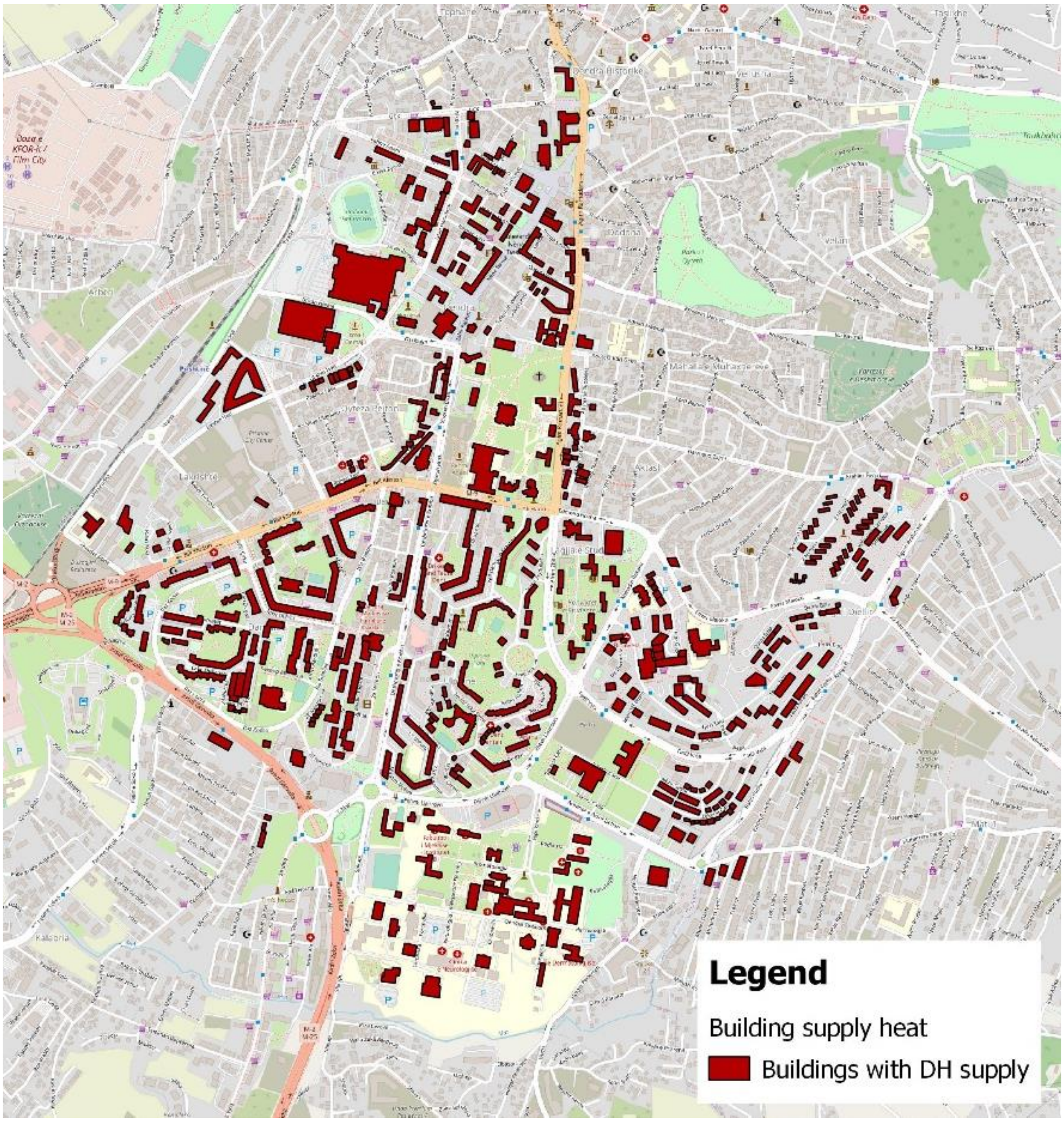


Figure 25 Buildings being supplied by the actual district heating network in Prishtina

The actual installed thermal capacity of the cogeneration system in Prishtina is 140 MW_{th}. Annual thermal energy production recorded in 2018 was 250 GWh_{th}/year. The maximum utilized capacity was 70 MWth, which means that there is a significant potential to expand the existing DH system using actual thermal capacities. There are plans for increasing the cogeneration capacities from actual and new thermal power plants (if built) up to 280 MW_{th}. The main objectives of DH Company are the maximum utilization of available heat supply capacities, increasing the reliability of heating supply, plan the expansion of DH and integrate renewable heating solutions. For integrating renewable technologies and expansion analysis of DH system, spatial and temporal analysis of space heating and DHW demand are crucial. Figure

26 shows the ambient air temperature fluctuations and actual space heating demand of buildings Q_{SH} that are connected to existing DH distributed on hourly intervals during one year using the HDD method. The total annual aggregated heat demand of buildings in DH was 230 GWh/year. The heat supplied by existing DH is used only for covering the space heating of buildings. The heating season in Kosovo is between 15 October and 15 April, because in this interval, the air temperature is lower than the HDD threshold of 12°C. Annual HDD in Prishtina account for 2830 degree days/year.

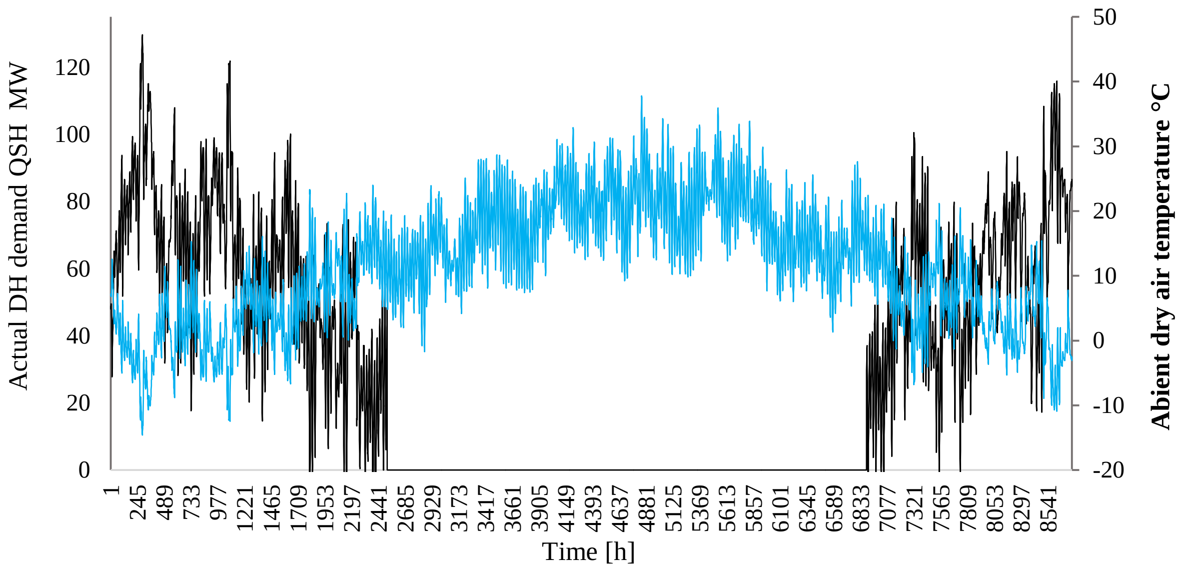


Figure 26 QSH Actual space heating demand curve of Prishtina DH for one-hour resolution (in black), local Prishtina ambient dry air temperature (in blue)

3.2.2 Space heating and domestic hot water heating demand in existing district heating system

Using a bottom-up heat demand mapping approach described in method section 2.2.1, the space heating demand spatially distributed over a grid with 250 m x 250 m in existing DH is quantified. The results of space heating demand spatially are shown in Figure 27.

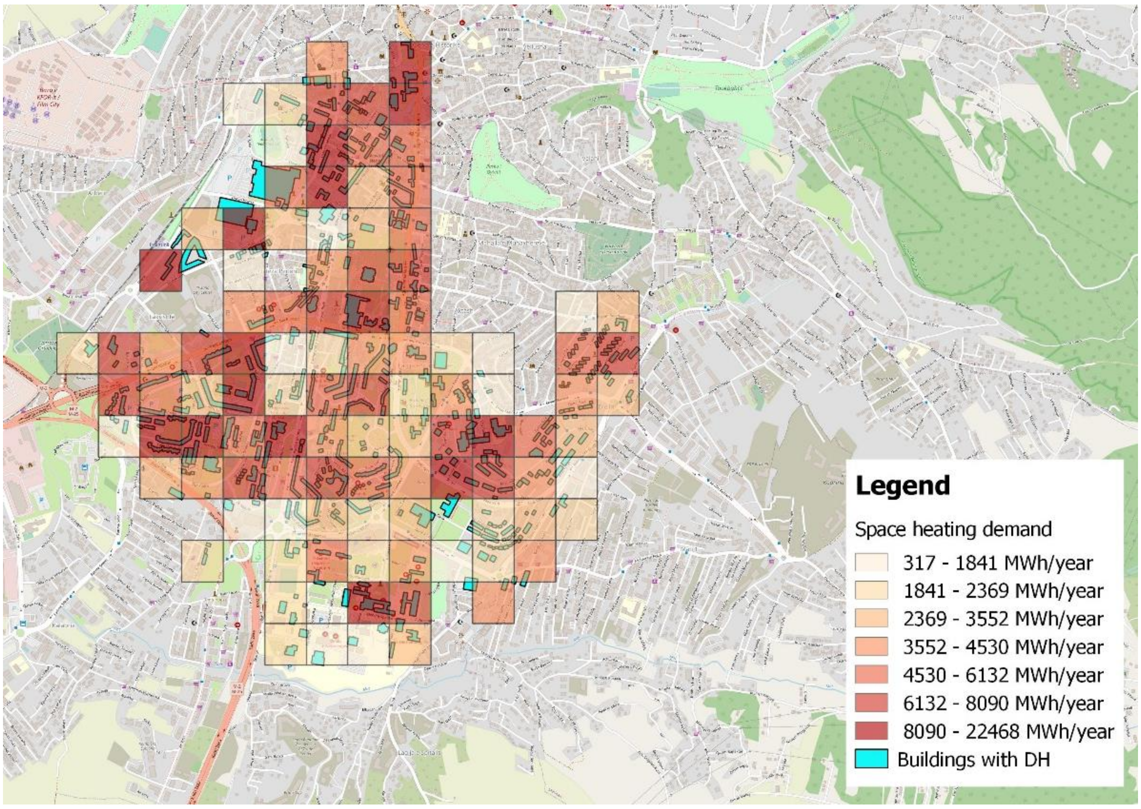


Figure 27 Actual space heating demand for the buildings connected to DH

As the existing DH supplies only the space heating demand of buildings, the spatial analysis proposed in this research for quantifying DHW focuses first on buildings already connected to DH. The description of the method is given in subsection 2.2.3. The average net area of building per occupant in Prishtina varies from 20-80 m^2/ occupant, so a net area of 60 m^2 per occupant was assumed and used for the analysis of DHW demand mapping spatially. Using the attributes for buildings distributed in a grid (250 m x 250 m) respectively by dividing the net build-up areas in a grid with assumed net surface building area per occupant, a density population grid was estimated, then validated using the actual number of consumers connected to DH. A hot water temperature increase of 40˚C and a hot water demand of 50 l/d/occupant during the heating season were considered to estimate DHW heating demand per occupant. DHW heating demand during the winter is the largest in comparison to other seasons, hence it is considered in spatial mapping.

In contrast, daily DHW demand during the summer months is slightly smaller than other months, and different countries apply different hot water temperatures [56]. Also, the profile of hot water demand is different for different building categories. However, as more than 95% of the consumers are residential for the considered case study, their distribution profile was considered.

The calculated DHW demand per occupant was multiplied by the number of people in a respective cell. In this way, the DHW heating demand spatially was estimated and the results of modelling are shown in Figure 28. It was estimated that the total DHW heating demand for existing buildings that are already connected to the DH of Prishtina would be 57.67 MWh_{th}/year. In this regard, the space heating and DHW demand would account for 97.7 and 2.3% of total heat demand in the existing DH.

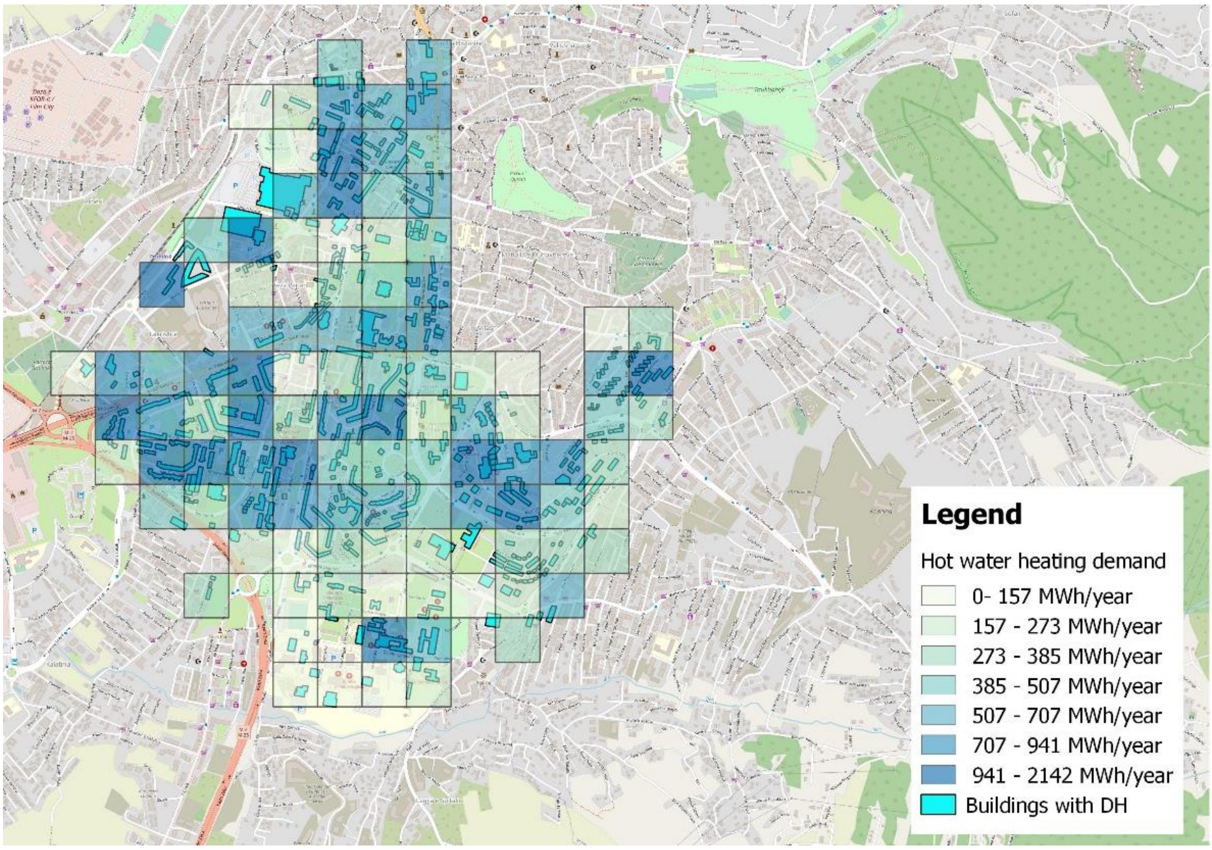


Figure 28 Spatial distribution of DHW heating demand for building already connected to DH

Besides estimating DHW heating demand spatially, its hourly demand profile is another critical parameter that should be taken into account when planning and modelling modern DH systems. Figure 29 shows the modelling of space heating and DHW demand for the existing DH of Prishtina over the year in hourly intervals. Hot water modelling was based on the actual number of residential buildings connected to DH.

Figure 30 shows the results of DHW modelling for one week during four seasons. A week in January, April, July and September was considered for comparative analysis of DHW demand profiles in DH. Significant differences in DHW demand profiles can be observed, especially between the spring and winter seasons. The largest heating demand for DHW account for winter, then autumn, summer and spring, respectively. It reveals that the hourly DHW demand profile for actual residential end-users that are connected to DH would change in hourly, daily, and seasonal intervals. For instance, the maximum DHW demand during the winter and spring seasons would be 93 m^3/h and 50 m^3/h, respectively.

Moreover, significant differences in hot water heating demand during the days of the week in a particular season can be observed. The results show that weekends have a higher demand than weekdays, and the same trend was observed in four seasons. Moreover, the maximum DHW heating demand of around 5.2 MWh/h was observed during the winter season on Sundays. This means that the heat distribution company would need an additional 5.2 MW capacity in Prishtina to cover both space and DHW heating demand.

The existing DH system in Prishtina is not operating annually; hence the DHW demand of buildings is entirely being supplied by electric heaters which electricity production is based on lignite coal. This study would be beneficial for assessing the feasibility of DH to switch to annual operation. In addition, the operation of DH annually may lead to substantial benefits such as building's supply with space heating and DHW, recycle heat from waste sources, integrate renewable heat, ensure sustainable transformation towards clean energy systems, among other [25].

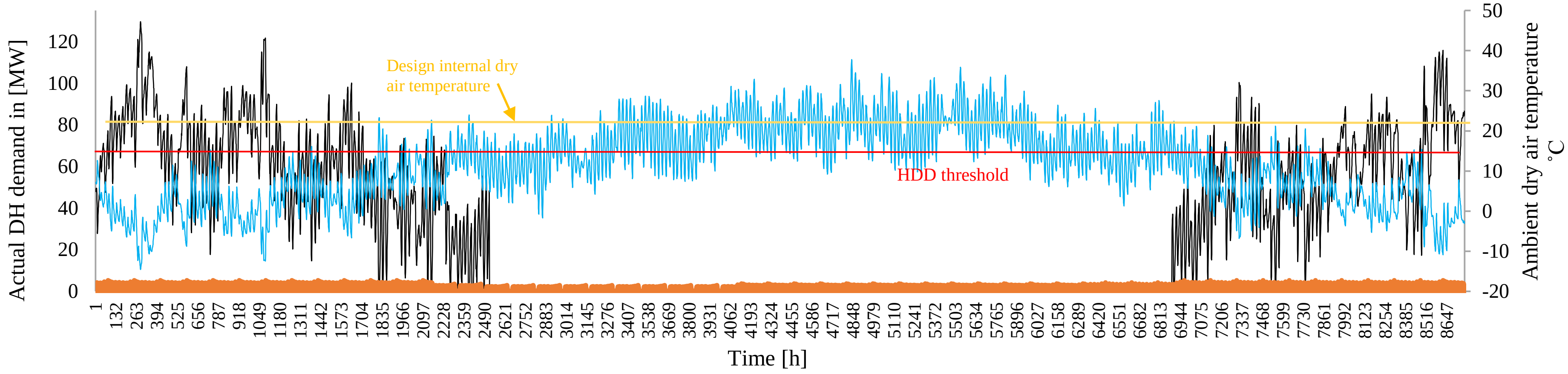


Figure 29 QSH Actual space heating demand curve of Prishtina DH for one- hour resolution (in black), local Prishtina ambient dry air temperature (in blue), Tin internal desired dry air temperature (in yellow) and the definition of HDD threshold with 12°C (in red)

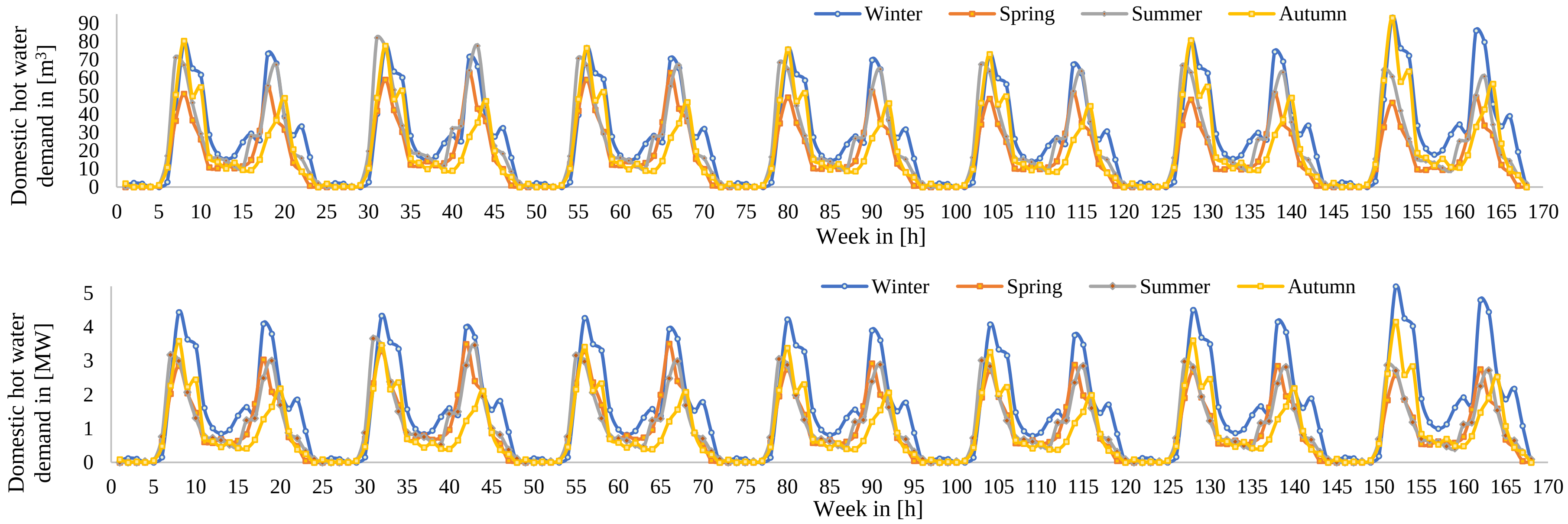


Figure 30 Hourly hot water demand in [m3] and residential hot water heating demand QHW in existing DH [MW]

3.2.3 Space heating and domestic hot water heating demand in expanded district heating system

The following section shows the spatial results of space heating demand, DHW heating demand, and the spatial analysis for the expansion of DH in Prishtina. Furthermore, is also shows the temporal modelling of space heating and DHW demand in potential DH systems. The results of the space heat demand of buildings distributed spatially in a grid with 250 m x 250 m are presented in Figure 31. In this scenario, it was considered that the houses are being heated to their net area, which is not reflecting the actual scenario for assessed area locations. Another scenario where houses are heated partially was considered in this research and the results are shown in Figure 35.

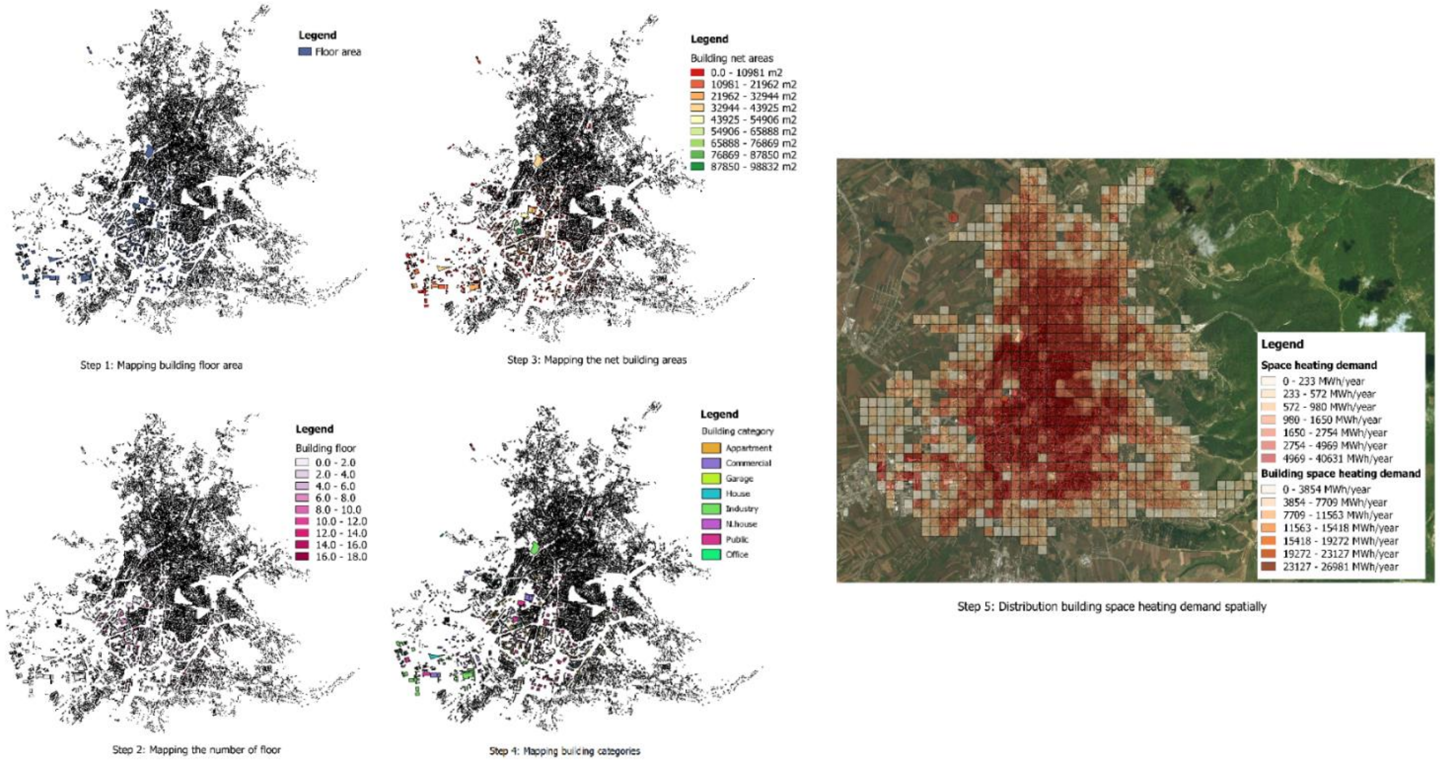


Figure 31 Bottom-up mapping approach for estimation of actual building space heating demand

Using the same approach presented schematically in Figure 28, the DHW demand for the entire city spatially was estimated (Figure 32). The first step (left top picture) shows the net building area, the second step (left bottom picture) shows the number of population in a corresponding cell and the third step (right picture) shows the aggregated DHW heating demand annually. It can be seen that grids with higher DHW heating demand match spatially with high space heating density grids in Figure 31.

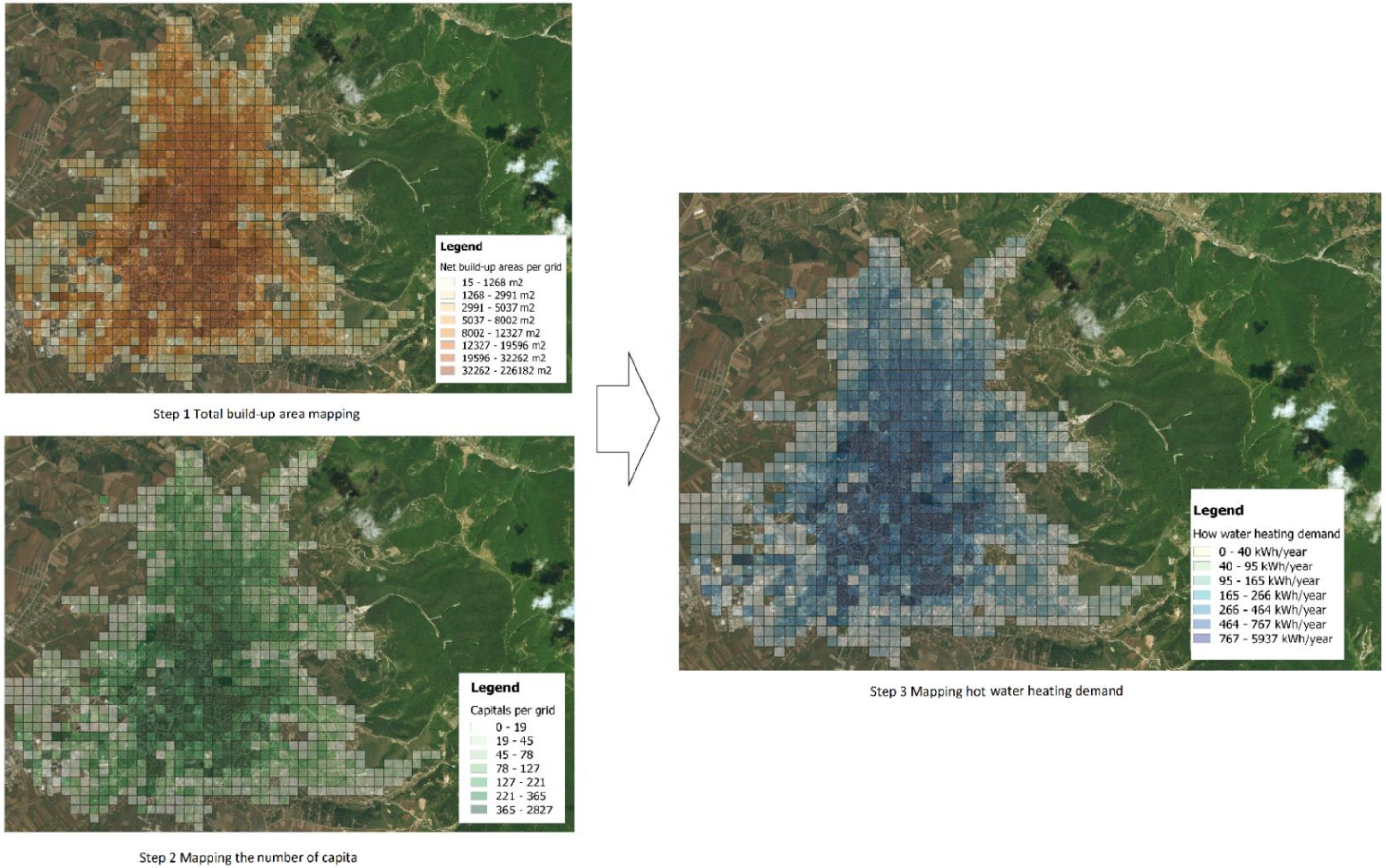


Figure 32 Top-down mapping approach for estimation of DHW heating demand spatially

The grids of DHW and space heating demand were aggregated to quantify the total heat demand of the city, which is used for further analysis of DH expansion potential. The results of total heat demand of the city with a spatial resolution grid of 250 m x 250 m are presented in Figure 33. Heat demand for space heating and DHW accounted for 1.95 and 0.217 TWh/year respectively. In this way, the total aggregated city heat demand was estimated to be 2.167 TWh/year. These results are obtained while considering that all building categories are heated to their net areas (fully heated), which may not be reflecting a real case. In contrast, when considering buildings that are heated partially in the model (the share of heated rooms in houses that are being heated partially in Prishtina) it was estimated that the total city space heating demand is 1.61 TWh/year and the hot water demand has remained the same (0.217 TWh/year) as in the previous scenario.

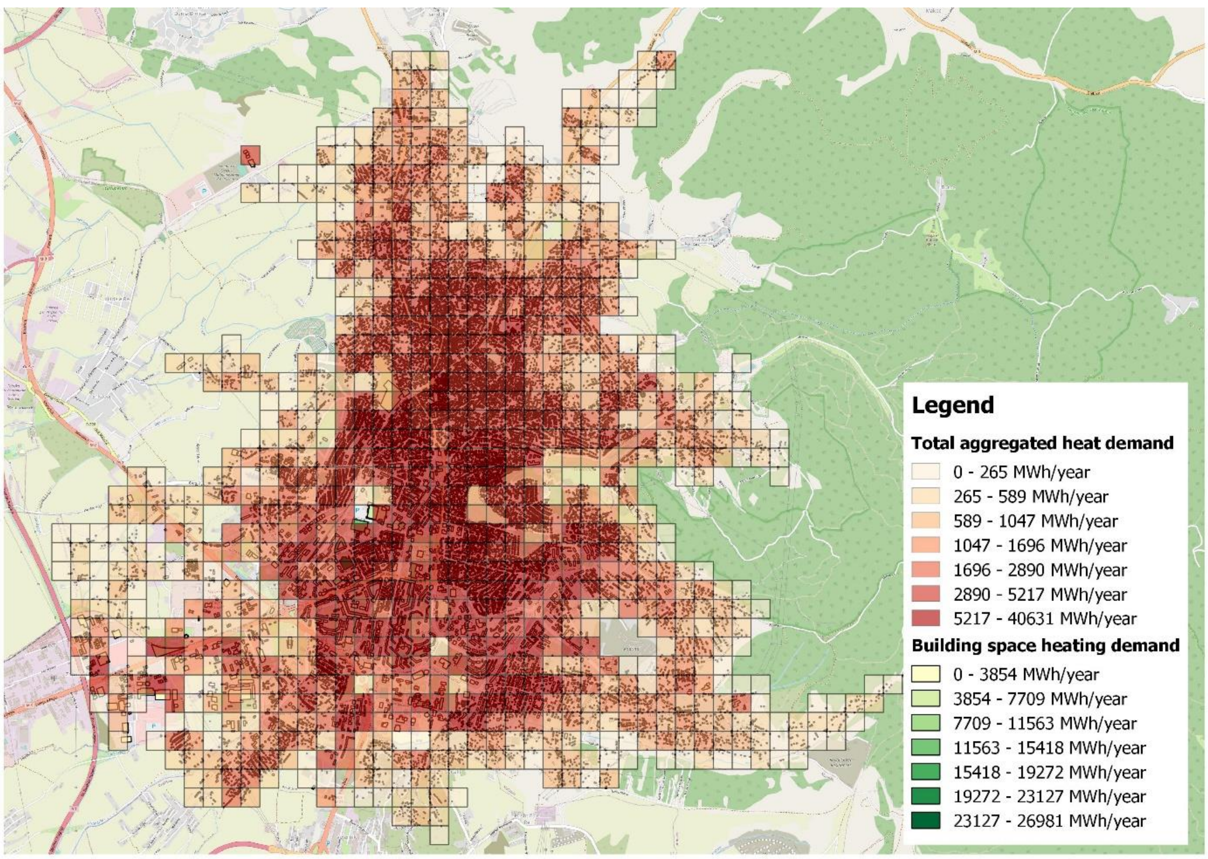


Figure 33 Total heat demand aggregated in a map with a 250 m x 250 m grid including heat demand for space heating and hot water preparation

Figure 34 shows spatially the red grids with 250 m x 250 m, where it is economically feasible to expand the DH system. The analysis was performed considering actual heat prices, levelized cost of heat, as well as the cost of DH expansion network. In Prishtina, the specific cost of district heat that consumers pay to heat distribution company is 58.8 EUR/MWh_{th}, the levelized cost of heat was calculated as 40.3 EUR/MWh_{th} using the prices of heat supply technologies [128] and the specific cost of DH expansion in inner cities was considered as 289 EUR/m. These input data was integrated into a GIS model using the equation (15). In this way, grids with a value greater than zero are considered economically feasible areas for DH network supply. The total aggregated heat demand that is feasible to be connected to DH is 1.80 TWh_{th}/year in the scenario where buildings are fully heated. While considering the partially heated rooms in houses, the total aggregated heat demand in DH was reduced to 1.316 TWh_{th}/year.

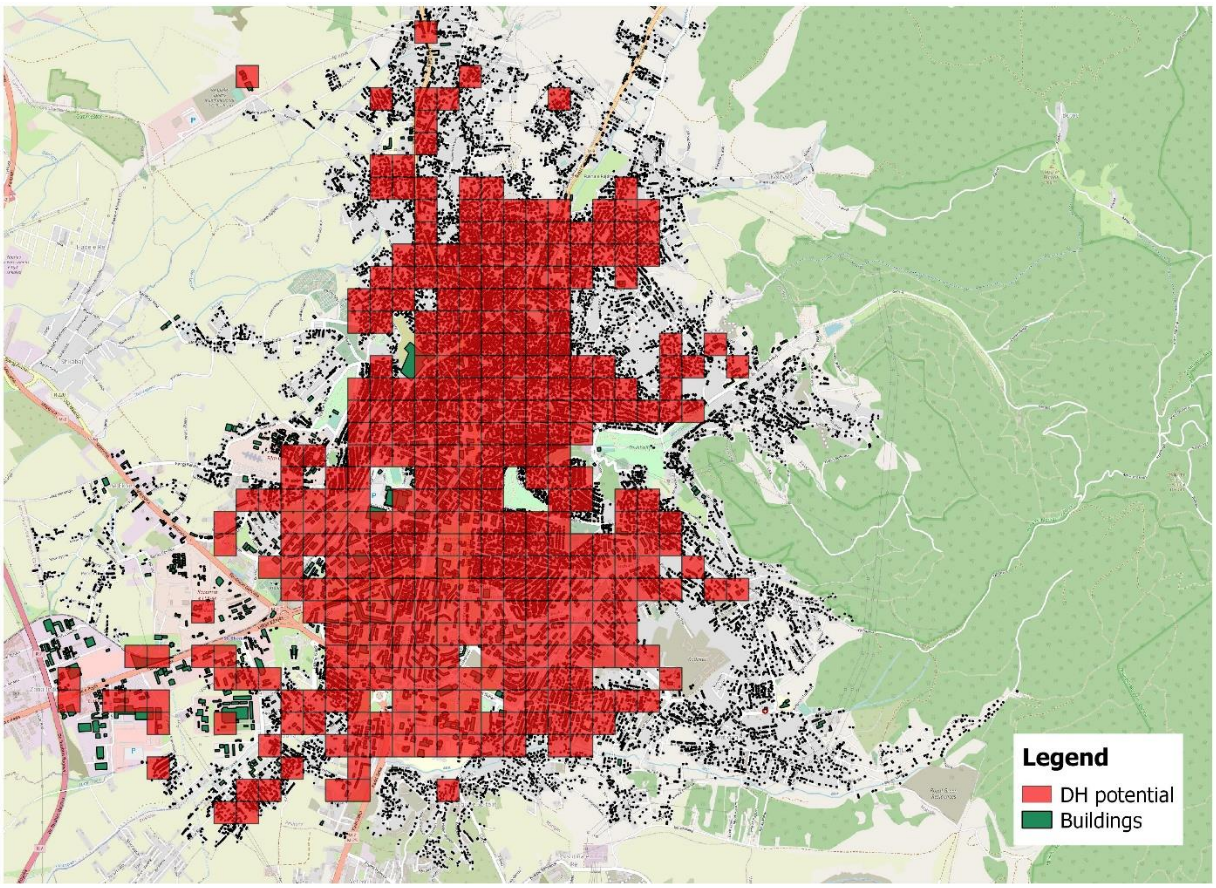


Figure 34 District heating potential

Figure 35 shows the results of hourly modelling of DHW and space heating demand in economically viable expanded DH network, when buildings are heated-up partially to their net areas. The results show that the existing DH system can be expanded four times, when excluding DHW from the analysis. Moreover, it was estimated that the space heating demand of buildings in the expanded DH system accounts for 1.143 TWh/year. The maximum utilized capacity to power such demand would be 600 MW.

In contrast, when considering DHW demand, besides the space heating demand of buildings, it was found that DH could be expanded five times in comparison to the existing DH share. The modelling of hot water heating demand in potential DH is shown in Figure 36. Again, higher demand for hot water is observed during the winter in comparison to other seasons. The estimated maximum DHW capacity would be 70 MW during Sundays of the winter season. It means that DHW demand capacity would account for 10% of the total potential installed DH capacity.

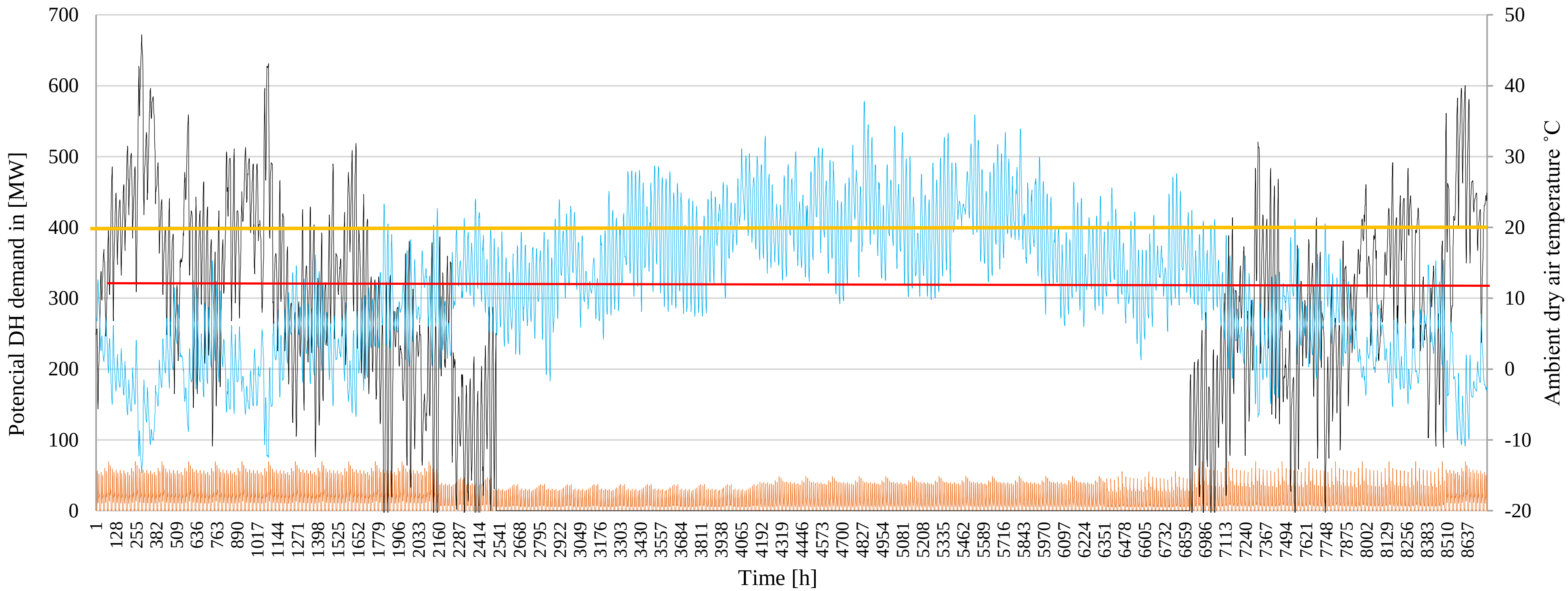


Figure 35 QSH potential space heating demand profile of Prishtina DH for one- hour resolution (in black) when houses are partially heated, local Prishtina ambient dry air temperature (in blue), Tin internal desired dry air temperature (in yellow) and the HDD threshold

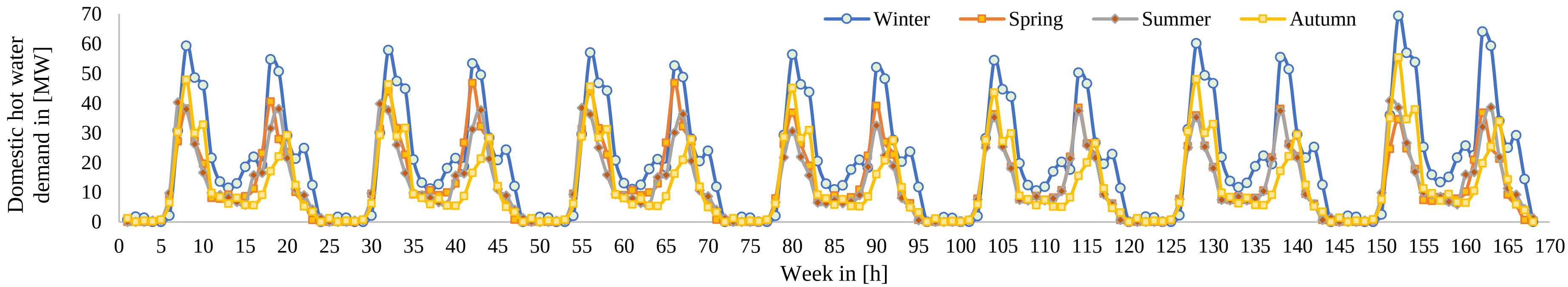


Figure 36 Hourly residential hot water heating demand QHW in [MW]

3.3 Space heat demand saving potential in urban areas

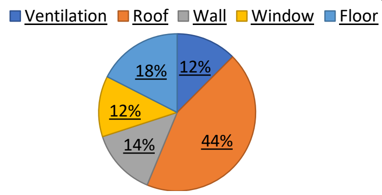
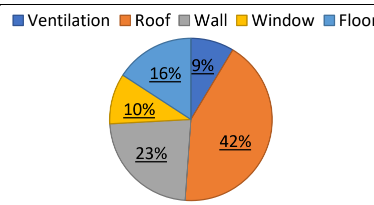
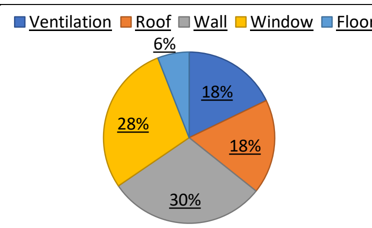
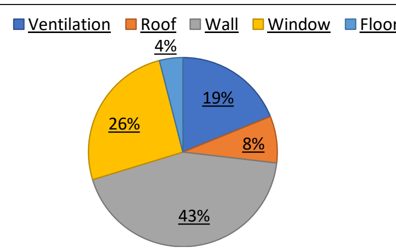
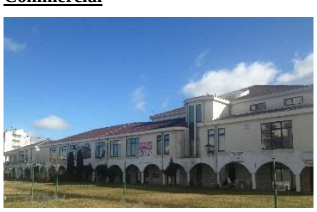
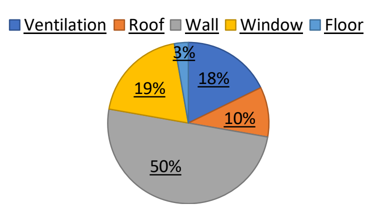
A case study of Prishtina, Kosovo is conducted to assess the potential of space heating demand savings and CO_2 emission reduction based on the proposed method. The building stock of Prishtina city consisted of about 23384 buildings. Buildings were categorized into 7 different categories according to their purpose of use and construction materials like a house (single-family house), nhouse (single-family house), apartment, commercial, public, office and industrial buildings. These categories were considered in the model to better represent existing building stock as they describe the majority of the existing buildings. The input data in the GIS model can continually be improved in terms of data regarding the energy certificate for every single building. There is no data regarding the building age spatially; however, buildings were divided to consider for the majority of buildings built in a certain period. For instance, half of the individual houses in Kosovo, are built after the 2000 year [151]. To consider the building age in the model, the individual houses have been divided into two categories. Sample buildings considered in this research are summarized in Table 5.

House represents a single-family individual house with one, two or three floors, which is thermally insulated and plastered from both inside and outside. Nhouse are single-family individual houses that do not have thermal insulation in external walls and are not plastered from outside. Apartments are considered as residential buildings occupied with many residential consumers. Commercial buildings include buildings that are used for commercial purposes like shopping mall centres, convenience stores and other buildings with multiuse purposes. Public buildings included school, hospital, universities, and libraries. Thermal performances for different building categories, that are shown in Table 5, are reviewed from local sources and energy auditing reports. Residential buildings (house, nhouse, apartment) are the most important as they cover over 90% of buildings in the city.

Table 6 shows the typical building envelope refurbishment measures according to European standard EN 13790 for residential buildings. Table 6 also shows the refurbishment measures for other building categories rather than residential ones provided by local energy auditors. The reviewed refurbishment measures include thermal properties for both buildings thermal insulation materials and new window installation. The building refurbishment measures are considered within the model with standard and advanced specific heating demand; however, they are not calculated by authors, but they are considered from different sources labelled in the Table 6.

Based on the described method and input data, a simulation was performed to calculate space heating saving potential for Prishtina.

Table 5 Building block description and actual space heating demand per different building category

Actual building stock description[3]	Percentage of actual heat loss	Actual specific heat demand in kWh/m^{2}year
House 		**153** [152], [153]
N.house 		**272** [152]., [153]
Apartment 		**144** [152]., [153]
Office 		**151** [153]
Commercial 		**169** [152]., [153]

[3] Building sample's images are made by authors

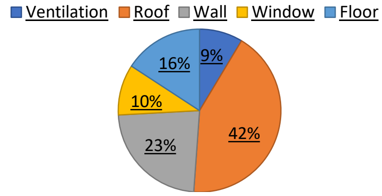
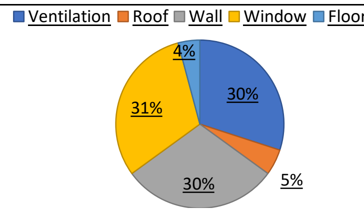
Public 		**272** [153], [154], [155]
Industrial 		**94** [156]

Table 6 Proposed energy efficiency measures in the actual building stock [152], [153], [154], [155], [157], [156].

Building type	Proposed EEs measures	Proposed EEa measures	EEs. specific heating demand in kWh/m^2year	EEa. specific heating demand in kWh/m^2year
House	• Insulation of external walls with 10 cm and λ= 0.04 W/m°C. • Insulation on the roof slab with 10 cm thermal insulation layer (λ=0.04 W/m°C). • Replacement of windows with new low E-double glazing window with U=1.6 W/m^2°C	• Insulation of walls with 20cm thermal insulation layer (λ= 0.04W/m°C). • Insulation on the roof slab with 20cm thermal insulation layer (λ = 0.04 W/ m°C) and insulation on the floor slab with 10 cm thermal insulation layer (λ= 0.04 W/m°C). • Replacement of windows, with new low-E triple glazing windows with U=1.0 W/m^2°C	**93**	**55**
N.house	• Insulation of walls with 10 cm thermal insulation layer (λ= 0.04 W/m°C). • Insulation on the roof slab with 10 cm thermal insulation layer (λ= 0.04 W/m°C). • Replacement of windows with new low E-double glazing window with U=1.4W/m2°C	• Insulation of walls with 20 cm thermal insulation layer (λ= 0.04 W/m°C). • Insulation on the roof slab with 20 cm thermal insulation layer (λ= 0.04W / m°C) and insulation on the floor slab with 10 cm thermal insulation layer (λ = 0.04 W/m°C . • Replacement of windows with new low E triple glazing windows with U=1.0 W/m2°C	**125**	**55**
Apartment	• Insulation of walls with 10cm thermal insulation layer (λ= 0.04 W/m°C). • Insulation on the slab above unheated space and Insulation on the roof slab with 10 cm thermal insulation layer (λ= 0.04 W/m°C). • Replacement of windows, with new windows with two layers of low-E glass with U=1.6 W/m2°C	• Insulation of walls with 20cm thermal insulation layer (λ= 0.04 W/m°C). • Insulation on the slab above unheated space and insulation on the roof slab with 20 cm thermal insulation layer (λ= 0.04 W/m°C). • Replacement of windows, with new windows two layers of low-e glass with U=1.0 W/m2°C	**50**	**40**
Office	• Insulation of walls with 10cm thermal insulation layer (λ= 0.04W/m°C) and the attic walls with 5 cm thermal insulation layer (λ= 0.04W/m°C). • Insulation of the roof with 10 cm of thermal insulation (λ=0.04W/m°C). • Floor slab above the unheated space without any changes. • Replacement of windows, with new double glazed windows with low-E with U=1.60W/m2°C	• Insulation of walls with 20 cm thermal insulation layer (λ= 0.04W/m°C) and the attic walls with 15cm thermal insulation layer (λ= 0.04W/m°C). • Insulation of roof with 20cm of thermal insulation (λ=0.04W/m°C). Insulation on the floor slab above the unheated space with 10cm thermal insulation layer (λ= 0.04W/m°C). • Replacement of windows with new triple glazed windows with low-E with U=1.0W/m2°C	**84**	**64**
Commercial	• Insulation of walls with 10cm thermal insulation layer (λ= 0.04W/m°C). • No interventions on the roof and floor. • Replacement of windows, with new double-glazed windows with low E to achieve U=1.60W/m2°C	• Insulation of walls with 20 cm thermal insulation layer (λ= 0.04W/m°C). • Insulation of construction towards unheated attic with 15 cm of thermal insulation (λ =0.04W/m°C). • Insulation on the ground slab with 15 cm thermal insulation layer (λ= 0.04W/m°C). • Replacement of windows, with new triple glazed windows with low-E to achieve U=1.0W/m2°C	**96**	**65**
Public	• Insulation of walls with 10cm thermal insulation layer (λ= 0.04 W/m°C). • Insulation on the roof slab with 10cm thermal insulation layer (λ= 0.04 W/m°C). • Replacement of windows with new low e double glazing windows with U=1.4W/m2°C	• Insulation of walls with 20cm thermal insulation layer (λ= 0.04 W/m°C). • Insulation on the roof slab with 20cm thermal insulation layer (λ= 0.04 W/ m°C) and insulation on the floor slab with 10cm thermal insulation layer (λ= 0.04W/m°C). • Replacement of windows with new low-E triple glazing window with U=1.0W/m2°C	**125**	**55**
Industrial	• Equipment heat gains, un-comfort conditions, and small space heating demand reviled with no EE measured proposed for buildings of this category.	• Equipment heat gains, un-comfort conditions, and small space heating demand reviled with no EE measured proposed for buildings of this category.	**94**	**94**

The 3D modelling result for actual building stock of Prishtina is calculated based on the discussed method as shown in Figure 37. A colour code was used for the visualization of building heights. Red geometry codes in Figure 37, expresses the tallest buildings in the city up to 18 floors, while blue ones are buildings with one to two floors.

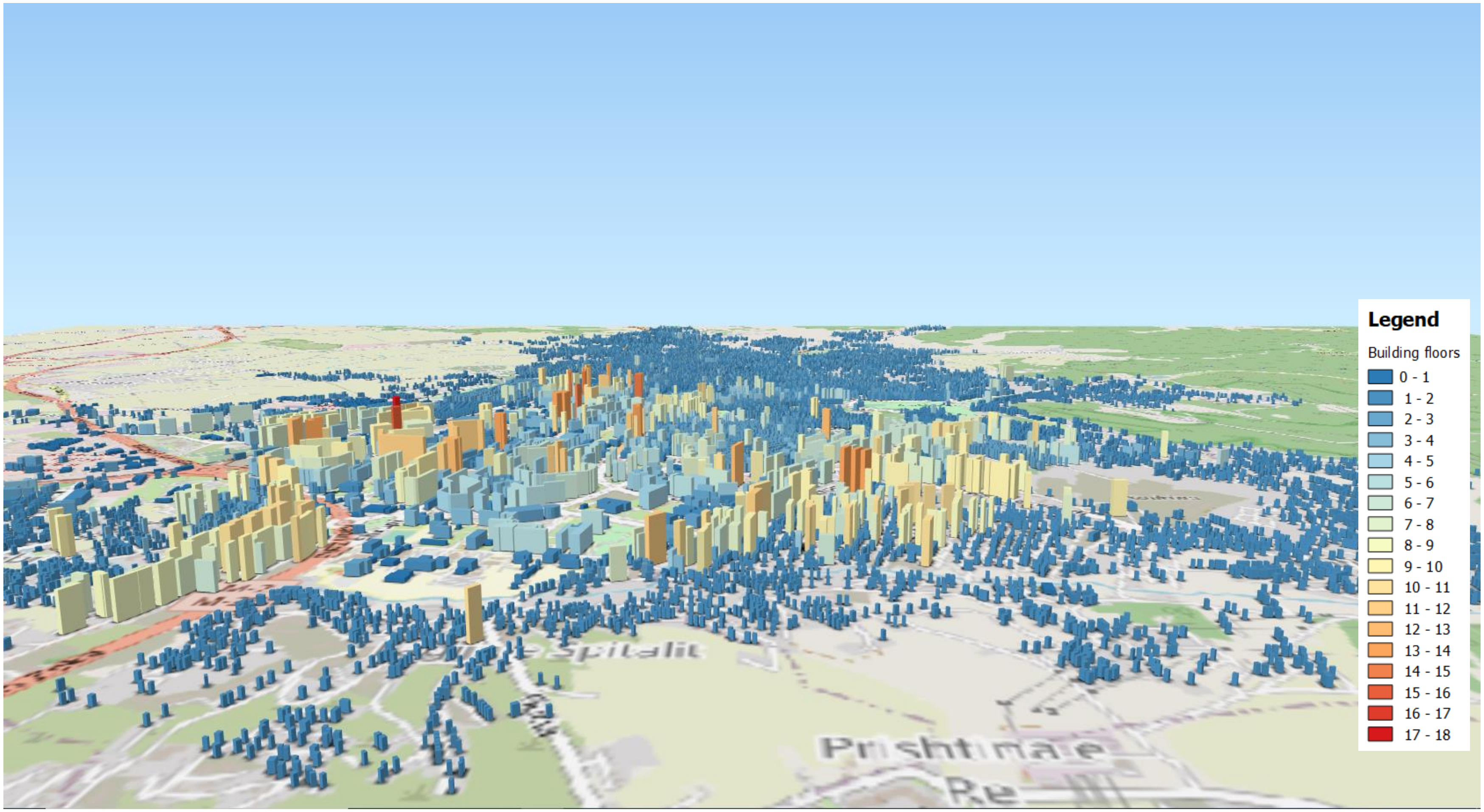


Figure 37 Prishtina building stock presented in 3D view

The actual space heating demand for buildings is given in the Table 7 while its aggregated values, distributed spatially in a 200 m × 200 m grid, are presented in Figure 38. It is found out that the total actual heat demand of buildings in Prishtina city is 968.8 GWh/year for houses, 752.2 GWh/year for apartments, 38.54 GWh/year for nhouse, 106.7 GWh/year for commercial buildings, 2.23 GWh/year for offices, 377.5 GWh/year for public buildings and 30.02 GWh for industrial buildings. It can be shown that the heat demand is spatially concentrated in the apartment building areas, which is shown with a dark red colour code (Figure 38). Other building features like building footprint area, net areas and their actual and reduced heat demand for each category are given in the Table 7.

Table 7 Building's net area and their heat demand saving results

CATEGORY	Number of buildings	Building footprint area m^2	Total net building heated area m^2	Actual heat demand GWh/year	Heat demand after applying EEs GWh/year	Heat demand after applying EEa GWh/year
Apartment	1024	862,542.0	5,223,644.0	752.2	261.2	208.9
Commercial	225	301,284.0	627,632.0	106.6	60.2	40.7
House	20450	3,406,174.0	6,331,997.0	968.8	588.7	348.2
Industry	272	330,838.0	319,245.0	30.0	30.0	30.0
Nhouse	477	75,974.0	141,700.0	38.5	17.7	7.8
Office	13	10,398.0	14,641.0	2.2	1.2	0.9
Public	301	459,833.0	1,236,230.0	337.4	154.5	68.0
Not heated area[4]	622	76,454.0	73,134.0	0.00	0.00	0.0
TOTAL	**23384**	**5,523,497.0**	**13,968,223.0**	**2,235.9**	**1,118.3**	**704.7**

[4] Not heated area= include areas like parking slots, garage, depot.. etc, which are not being heated and hence are excluded in the model.

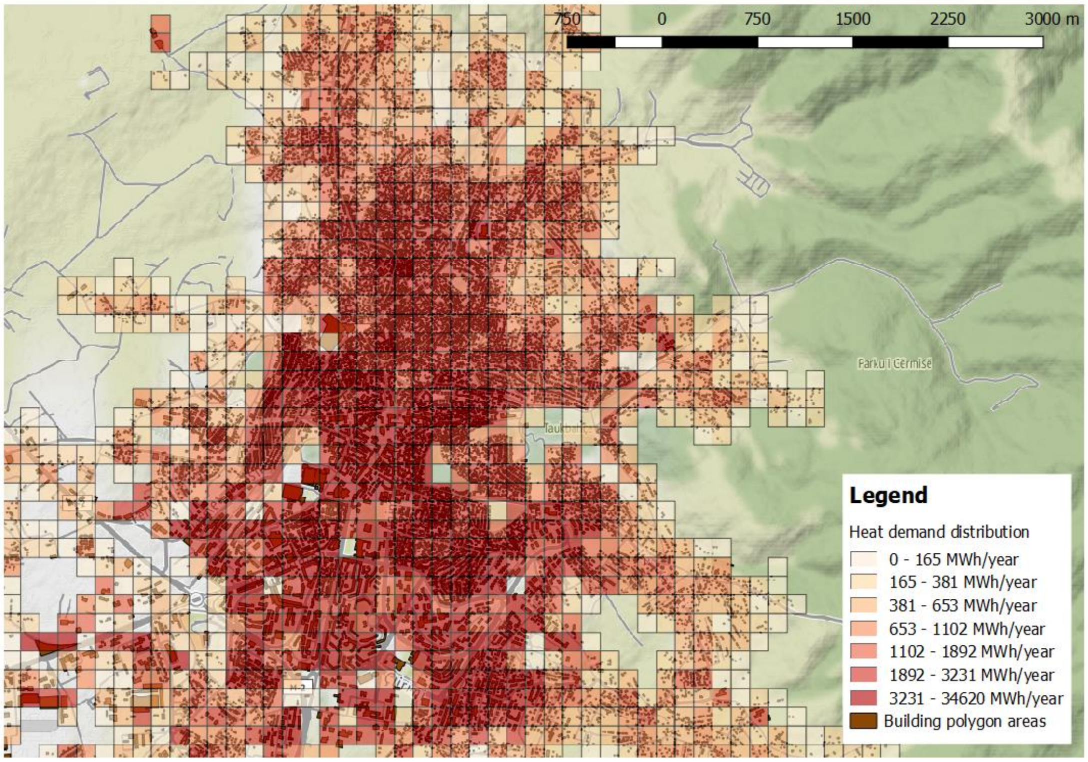


Figure 38 The actual space heating demand for buildings aggregated in a 200m × 200m grid.

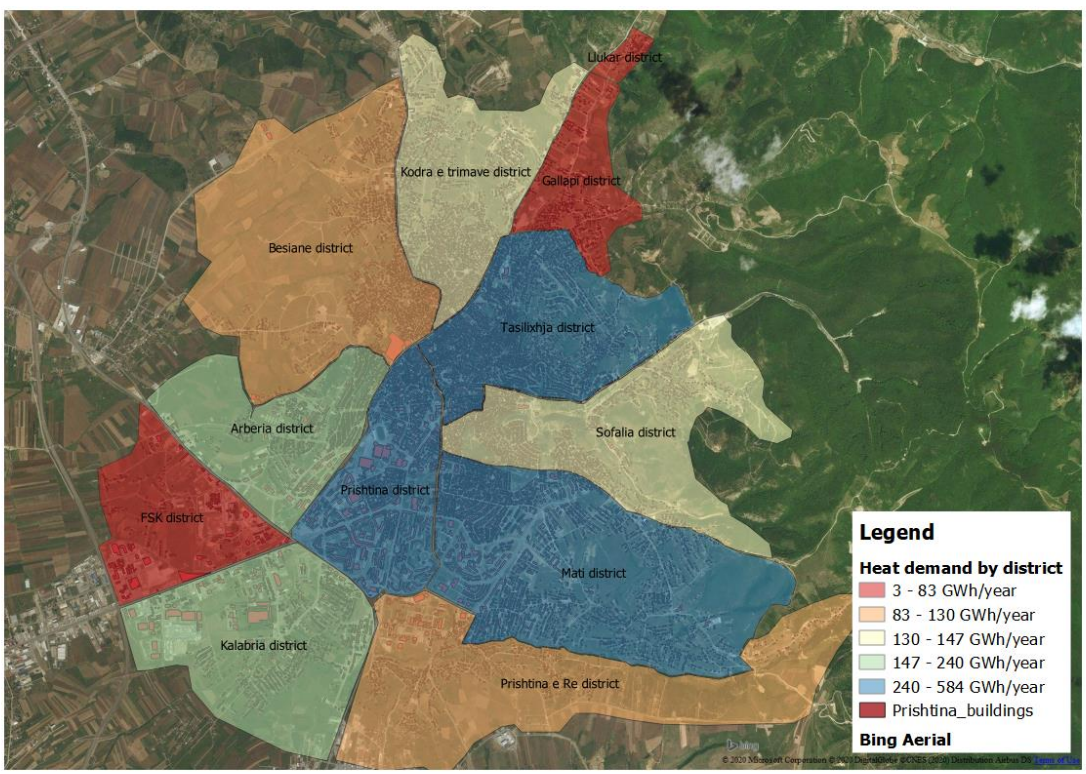


Figure 39 Actual space heating demand for buildings aggregated in Prishtina city districts.

The actual space heat demand of buildings was aggregated in Prishtina districts (Figure 39) in order to identify which districts have larger heat demands and which ones have a higher potential for space heating demand reduction when applying standard and advanced EE measures. It can be shown that Prishtina, Mati and Talixhje have higher heat demand than the other districts in the city. This is because most of the high-rise buildings are located in these districts, especially in the Prishtina district, where more than 80% of the district area is occupied with apartments and other high-rise buildings. Higher demand districts are shown with green polygon code, while the ones with lesser heat demand (Kodra e Trimave, Besiane, Gallap, Prishtina e Re, Kalabria and Arberia district) are shown with red colours, and light brown color in Figure 39.

In Figure 40, the city's space heat demand reduction potential with EEs measures is presented. Significant reduction of actual space heating demand potential of around 55-65% was identified in the locations occupied with high rise buildings, specifically apartments (green grids). Similarly, a high reduction potential was identified in high-density built-up areas with mixed buildings (apartments and individual houses), accounting for around 45-53% reduction potential. In contrast, smaller reduction potential was identified in red grid areas accounting for 37-41%, almost entirely occupied by single-family buildings or individual houses compared to their actual heating demand.

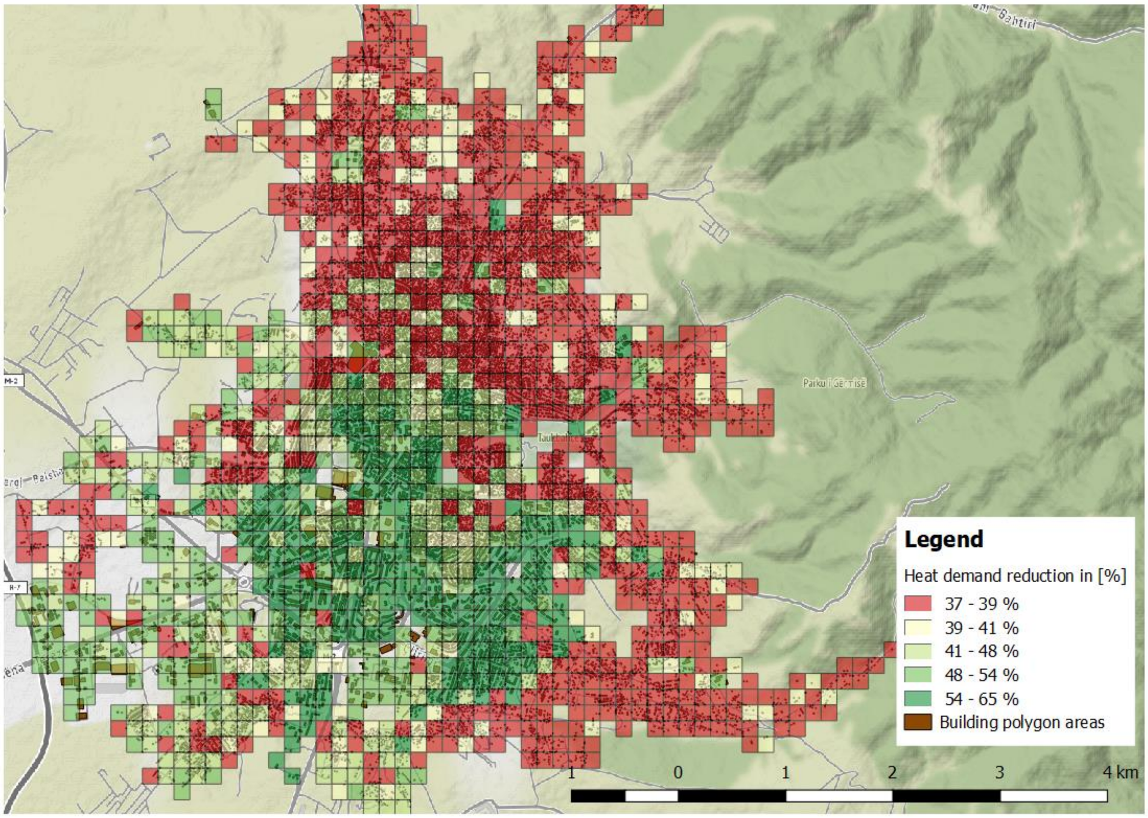


Figure 40 Space heating demand saving potential in a 200 m × 200 m grid for Scenario 1 (EEs measures in buildings)

The space heating demand reduction by districts when applying EEs measures in actual building stock is shown in Figure 41. Similarly, in districts of Prishtina and Mati significant heat demand reduction potential was identified accounting for a reduction 329 and 284 GWh/year respectively. Furthermore, by following the same procedure for the estimation of space heating demand reduction potential with EEa measures (as discussed for scenario 1), the space heating demand saving potential can be estimated spatially for different levels of details and the results for a district-level are shown in Figure 42 and 43 respectively. In Figure 42, a significant heat-saving potential is obtained for locations occupied with high rise building, dark green colored grids accounting for 80% of the reduction, while the least potential with red colored grids is around 58%.

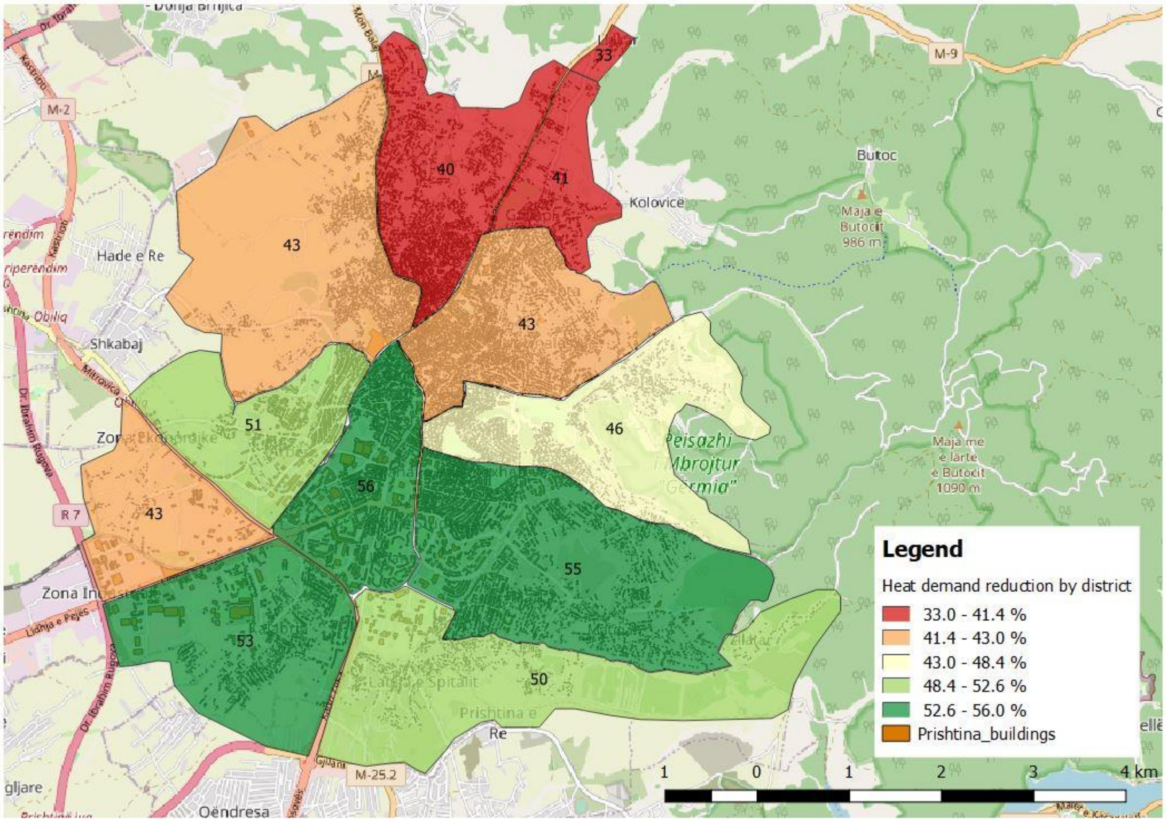


Figure 41 Space heat demand saving potential by districts for Scenario 1, (EEs measures in buildings)

While observing each space heat demand building category, it was found that the space heat demand reduction when applying EEa measures for houses, nhouses, apartments, commercial, public, office, and industrial buildings accounted for 348.2 GWh/year, 7.81 GWh/year, 208.9 GWh/year, 40.8 GWh/year, 68 GWh/year, 0.94 GWh/year and 11.17 GWh/year respectively (see Table 6). The space heating demand reduction potential for districts while applying EEa measures is shown in Figure 42. In addition, in districts with a high density of high-rise buildings, significant space heat demand reduction potential was identified, especially for the district of Prishtina, Mati and Taslixhja, leading to a reduction of 421, 360 and 169 GWh/year, respectively (Figure 43).

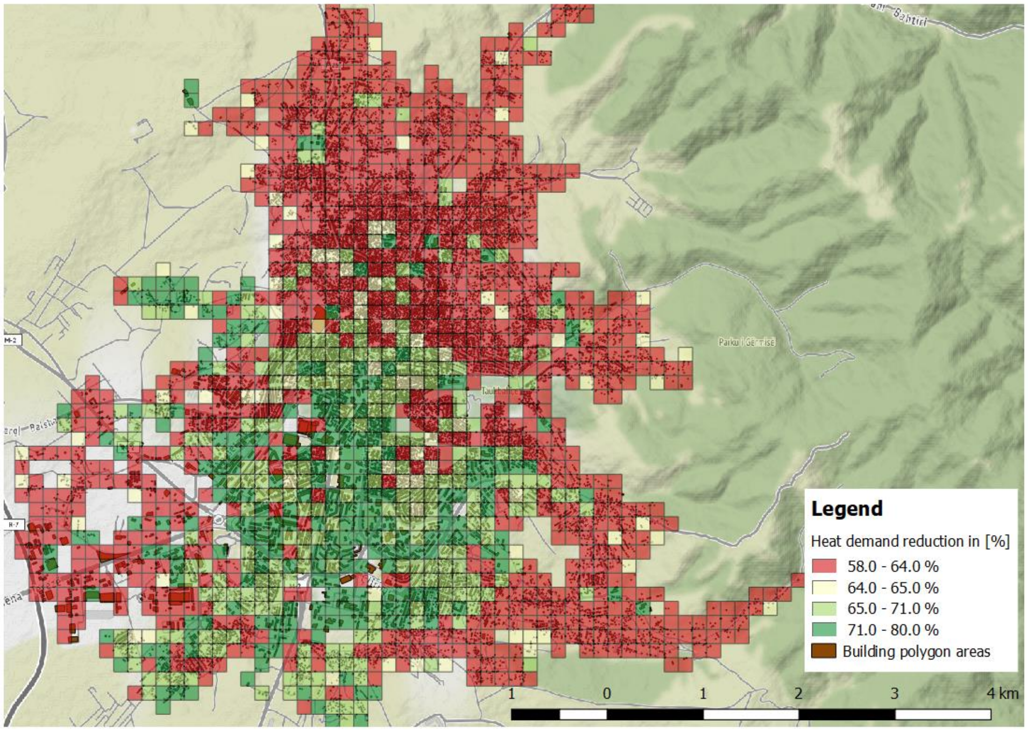


Figure 42 Space heating demand saving potential in a 200 m × 200 m grid, Scenario 2 (EEa measures in buildings)

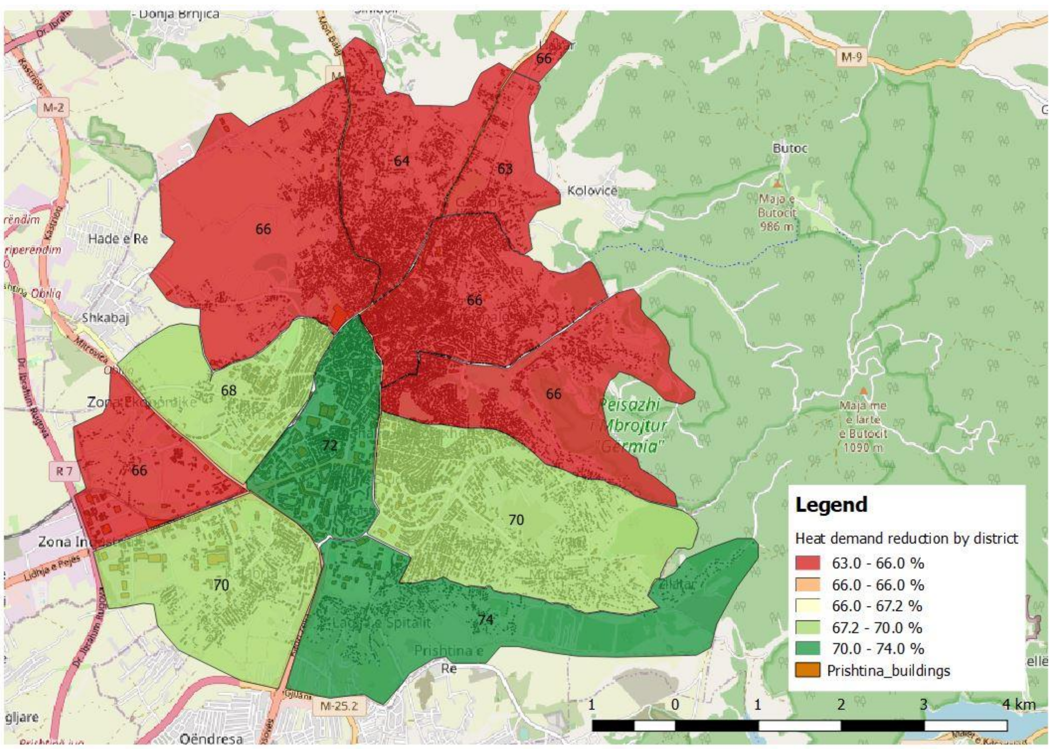


Figure 43 Space heat demand saving potential by districts, Scenario 2 (EEa measures in buildings)

Figure 44 shows the heat demand duration curve over the heating season in Prishtina for three different cases (reference case with actual heat demand, scenario 1 for heat demand with EEs and Scenario 2 for heat demand with EEa). The load curves are generated using the hourly heating degree day method [78]. Load heat curves are created using hourly air temperature data, for ten years, downloaded from the Meteonorm [129] for the climate conditions in Prishtina. For the actual space heating demand estimated, the maximal needed thermal capacity from heat providers is around 1115 MW_{th}. Such capacity is needed only for a short period when the external dry air temperatures reach maximal minus values around -15°C. In Prishtina the heating season lasts for six months, accounting for 4230 h/year demand to be heated. In contrast, such heat demand capacity can be significantly reduced to around 50% and 68% of the actual maximum capacity when applying standard and advanced EE measures in the actual building envelope components.

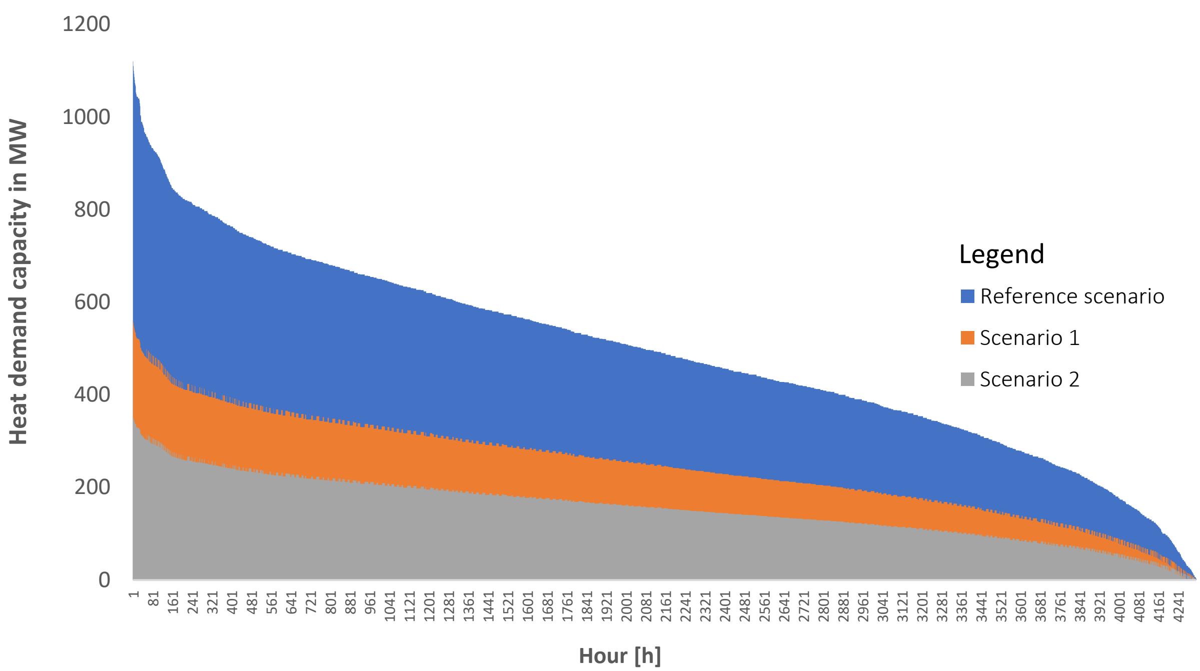


Figure 44 Actual and reduced space heating demand capacity in [MW]

Figure 45 shows the actual and reduced space heating demand for building categories in a district. It can be seen that the different building heat demand varies, considering the share and overall heat demand for different building categories in a district. The largest heat demand is identified in Prishtina, Mati, and Tasligjia districts. In other districts, the overall share of the heat demand is less significant because the main heat consumers in such districts are houses. This is not the case, for Prishtina e re[5] and Kalabria districts, where public and apartment buildings still are the main heat consumers, but the overall heat demand is not that significant compared to previously discussed districts. In Prishtina district, apartments are the main heat consumers accounting for an actual heat demand of 275 GWh/year (blue column), public buildings 160 GWh/year and commercial and public buildings almost the same share accounting for 68 GWh/year. The share of other building categories (industrial, office) in this district is very small compared to the other heat consumers. The second bar (red in the bar chart in Figure 45) shows the reduced space heating demand after applying EEs measures accounting for 95 GWh/year, public buildings 75GWh/year, commercial and house categories 40 GWh/year. Similarly, the third bar (green) shows the reduced space heating demand after applying EEa measures. It can be seen that there is not a significant difference between standard and advanced EE measures in the overall heat demand reduction especially in the apartment, commercial and industrial buildings. Similar conclusions can be observed for the other districts shown in Figure 45.

[5] Prishtina e re, Kalabria, Tasligjia, Mati, Kodra e trimave are original Albanian names of Prishtina city districts

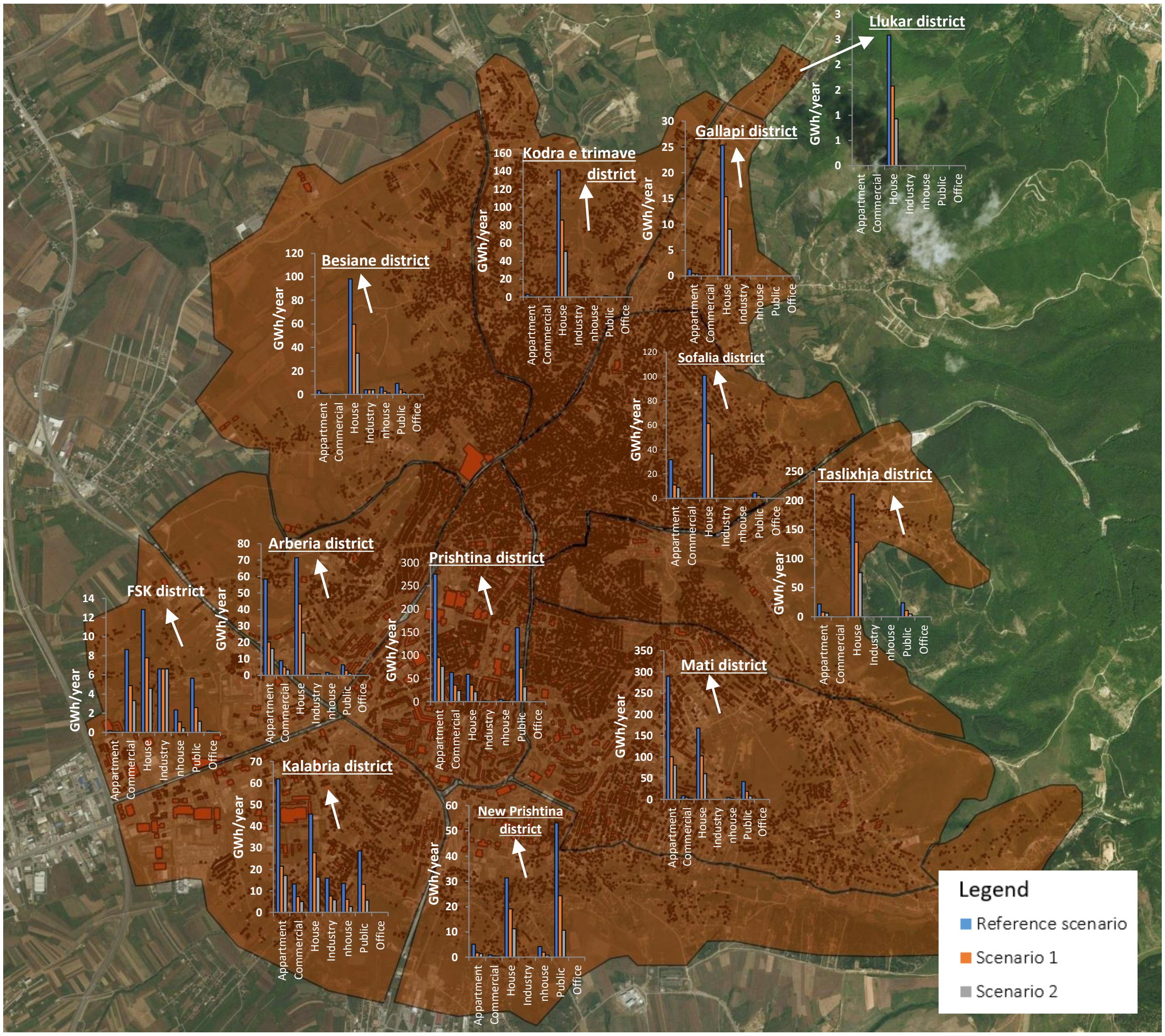


Figure 45 Actual and reduced space heating demand for different building categories distributed spatially in districts. Blue bar shows the actual heat demand of buildings, red bar shows the reduced space heating demand for buildings after applying EEs measures, and grey bar shows the reduced space heating demand for buildings after applying EEa measures.

Figure 46 shows the actual and reduced CO_2 emissions from space heating of buildings. The emissions were calculated for different cases, considering public and residential buildings' actual and reduced space heating demand with energy efficiency measures. The results have shown that actual CO_2 emission is from public and residential buildings account for 90.1 million kgCO_2/year and 412.1 million kgCO_2/year, respectively. With standard energy efficiency measures, the overall CO_2 emission was reduced significantly compared to the reference scenario (actual heat demand), accounting for a decrease of 50%. Even higher CO_2 emission reduction potential was observed with the utilization of advanced energy efficiency measures in buildings. Current research is of high importance for developing future policies that are related to emission reduction potential in residential buildings. So far, most of the energy efficiency projects are focused on public buildings, but future targets of the ministry are to support energy efficiency measures in residential buildings as well. In addition, the potential for reducing CO_2 emissions in residential buildings is significant.

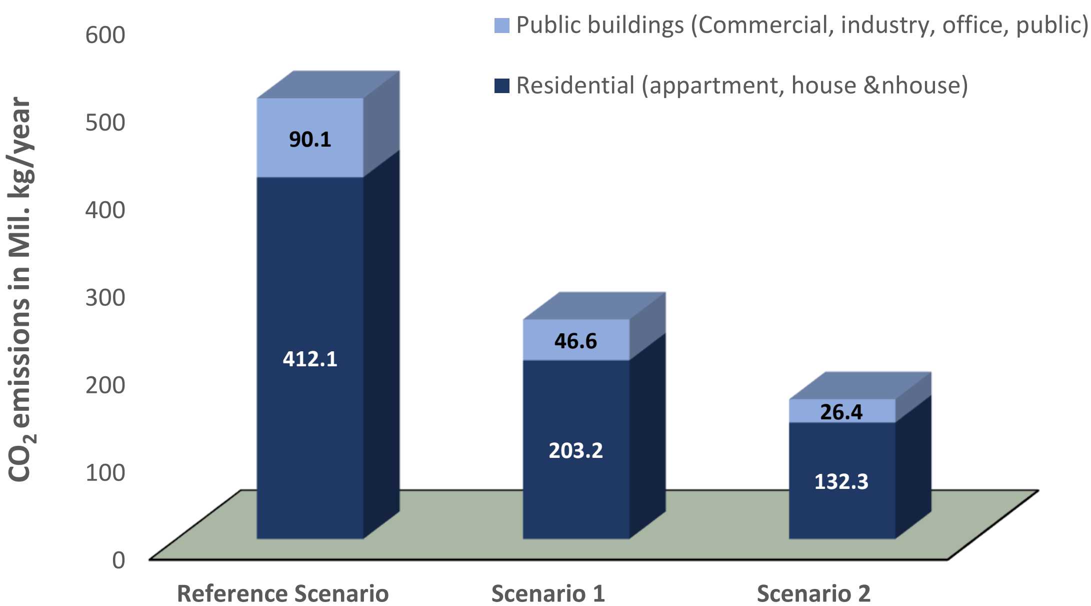


Figure 46 Total actual and reduced CO2 emissions due to energy efficiency measures in buildings

3.4 Individual heating and road transport electrification

A model based on historical data, for the reference year 2015, was modelled in EnergyPLAN for which enough data was found in the existing literature. The details of modelling of the reference model for the Kosovo energy system, are discussed in [54], [158]. The parameters used for model validation in comparison to historical data are summarized in Table 8.

Table 8 Model validation with respect to historical data in 2015 [159], [160]

	Model	Actual	Difference
TPP electricity, TWh	2.77	2.74	3 %
CHP operating Mode	-	-	
TPP, TWh	1.32	1.35	-3 %
CHP, TWh	1.29	1.32	-3 %
RES electricity, TWh	0.14	0.14	0 %
CO_2 emissions, Mton	8.39	8.6	2.5 %

According to IRENA, [161], [162] the technical and economically viable renewable electricity production potential for Kosovo is estimated. It was found that the technical potential of variable wind is around 2400 MW, while the PV potential 581 MW respectively. Considering this potential, a sum of vRES accounting for 5 MW wind and 1 MW PV is considered in the model.

Electrification of the transport sector

In 2015 Kosovo had registered 322652 motor vehicles [2], [163]. Figure 47., shows the share of vehicle use and their categories. Passenger and light-duty vehicles compose 97% of the transport sector in Kosovo. As these conventional vehicles can easily be electrified (replaced with EV's), an average electricity consumption of 173.6 Wh/km and battery capacity of 26.9 kWh was considered in the model [62], [164]. The annual average distances for respective vehicles was taken from [165]. Moreover, the model further considers the potential adaptation of EV's in energy systems with significant penetration of vRES using the V2G concept. It is assumed that 97% of transport vehicles which is composed of passenger cars and light-duty vehicles (minibuses and pickups) participate in smart charging and 50% of these vehicles choose to participate in V2G.

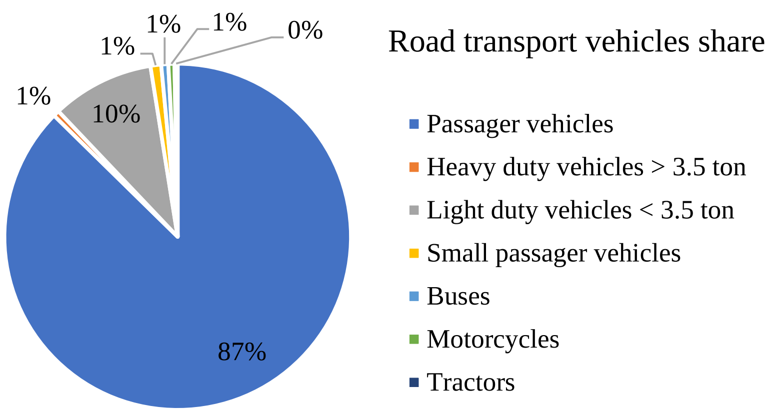


Figure 47 Share of Kosovo road transport vehicles

Table 9 shows the exiting state and future scenarios in the transport sector by considering a linear replacement of existing passenger and light-duty vehicles with electric ones up to full electrification of these vehicles. The number of vehicles and driving habits (km/year) has remained the same as in the reference scenario 2015.

Table 9 Passenger and light duty vehicle fuel demand. Current and future scenarios

Electric vehicle share	**0%**	**10%**	**20%**	**30%**	**40%**	**50%**	**60%**	**70%**	**80%**	**90%**	**100%**
Others (TWh/year)	**2015**	-	-	-	-	-	-	-	-	-	-
Diesel	3.107	2.713	2.411	2.110	1.808	1.507	1.206	0.904	0.603	0.301	0.000
Petrol	1.094	0.955	0.849	0.743	0.636	0.530	0.424	0.318	0.212	0.106	0.000
Cerosine	0.063	0.055	0.049	0.043	0.037	0.031	0.025	0.018	0.012	0.006	0.000
LPG	0.272	0.238	0.211	0.185	0.158	0.132	0.106	0.079	0.053	0.026	0.000

Electrification of individual heating

Individual heating in Kosovo is composed of electric heaters, biomass, oil and coal boilers. There is a regulation in place for abandoning the utilization of coal for individual heating solutions. On the other side, biomass is being consumed near suitable limits and in many cases, even industrial wood is used for heating purposes in individual boilers having many negative consequences in the local ecosystem. Table 10 shows the existing state and future scenarios for the decarbonization of individual heating in Kosovo. Different strategies for electrification of individual heating were assumed. All scenarios consider an increasing penetration of individual heat pumps in terms of the reduction of other means of consumption. The scenarios consider that coal and oil boilers should be replaced first and then individual heaters while keeping the biomass consumption under sustainable limits. The model also considers that the heat pump will be coupled with hot water storage tanks. Heat storage capacity was calculated by considering an average stored heat over the year 2.10 kWh/year/person and the number of people in the respective year. The results are summarized in Table 10.

Table 10 Individual heating demand. Current and future scenarios

Individual heat pump share		**10%**	**20%**	**30%**	**40%**	**50%**	**60%**	**70%**
Other sources (TWh/year)	**2015**							
Coal boiler	0.646							
Oil boiler	0.517	0.517						
Ngas boiler		0.000						
Biomass boiler	2.801	2.801	2.801	2.284	2.211	1.606	1.606	1.606
Heat pump		0.646	1.163	2.196	2.358	2.947	3.537	4.126
Electric heating	1.930	1.930	1.930	1.414	1.341	1.341	0.751	0.162
Heat storage (GWh/year)		0.372	0.744	1.116	1.488	1.860	2.232	2.604
Total	**5.894**	**5.894**	**5.894**	**5.894**	**5.894**	**5.894**	**5.894**	**5.894**

3.4.1 The flexibility of coal-based thermal power plants

Existing thermal power plants

Kosovo has two TPP's with total operational capacities between 750 - 1050 MW, which are quite old and operating with very low efficiencies. For the model validation state with respect to recorded data, the annual average efficiency of TPP Kosova A was 26%, while the efficiency of TPP Kosova B was 32%, respectively. By considering these numbers and the relative profiles of part-load efficiency shown in Method section 2.4.2, part-load efficiency equations for exiting TPP's in Kosovo were calculated.

The hourly part-load efficiency of TPP Kosova A is calculated with the following equation:

$$\eta_A = 8.7418 + 3.7555 \cdot \ln(\% \, RLC_A) \tag{32}$$

where: RLC_A, % - relative loading capacity of existing TPP Kosova A

Similarly, the hourly part-load efficiency of TPP Kosova B is calculated with:

$$\eta_B = 10.759 + 4.6221 \cdot \ln(\% RLC_B) \tag{33}$$

where: RLC_B, % - relative loading capacity of existing TPP Kosova B

In practice, it would be more economically viable first to revitalize TPP to increase their efficiency and continue integrating a significant amount of vRES in the power system as at high TPP efficiency, their cycling will have much less impact on fuel consumed respectively in CO_2 emission increase.

Revitalized thermal power plants

The model considers that old TPP will be revitalized and hence their efficiency will increase significantly. For TPP Kosovo A it was considered that maximal efficiency at related power would be 35%, while the efficiency of TPP Kosova B can go even higher to 40% as the technology is newer and fully automated. Similarly, when considering that TPP will operate under their related power because of the renewables, their hourly part-load efficiency will change according to these new equations for respective TPP's. The hourly part-load efficiency of TPP Kosova A will be calculated with:

$$\eta_A = 11.768 + 5.0555 \cdot \ln(\% RLC_A) \tag{34}$$

RLC_A, % - relative loading capacity of revitalized TPP Kosova A

Similarly, the hourly part-load efficiency of TPP Kosova B:

$$\eta_B = 13.449 + 5.7777 \cdot \ln(\% RLC_B) \tag{35}$$

RLC_B, % - relative loading capacity of revitalized TPP Kosovo B

By averaging hourly TPP efficiencies, the annual averaged part-load efficiency was calculated, which are lower in comparison to averaged efficiencies estimated for rated TPP capacities. The results of annual averaged part-load efficiencies are provided in the result and discussion section.

3.4.2 Critical excess electricity production

The following part shows the role of road transport and individual heat electrification in coal-based energy systems to support the vRES integration. Figure 48 shows the critical excess electricity production in the Kosovo power system when increasing the share of vRES integration and EV's while maintaining high flexibility in Kosovo TPP's. The 5% CEEP limit shows the capacities of vRES that can be integrated into the existing power system. For instance, when the energy system is operating with state S_1, 528 MW wind and 132 MW PV can be utilized in the power system. These capacities can be further increased using the synergic coupling between the electricity and transport sectors. At the energy system operating state S_3, all passenger and light-duty vehicles are replaced with electric ones. The outcome is that 701 MW wind and 136 MW PV can be utilized in the power system without exceeding power flows that the system can handle. The contribution of 97% transport electrification to integrate vRES, while maintaining 80% flexible existing TPP's, is significant accounting for 173 MW wind and 4 MW PV capacity. This contribution can be further enhanced if TPP's become fully flexible (S_4). At this state, 825 MW wind and 206 MW PV can be utilized in power grids while maintaining high reliability of the power supply. Said differently, the maximal contribution of 97% transport electrification with passenger and light-duty EV's to integrate vRES in the existing Kosovo power system accounts for 297 MW wind and 74 MW PV capacity, respectively.

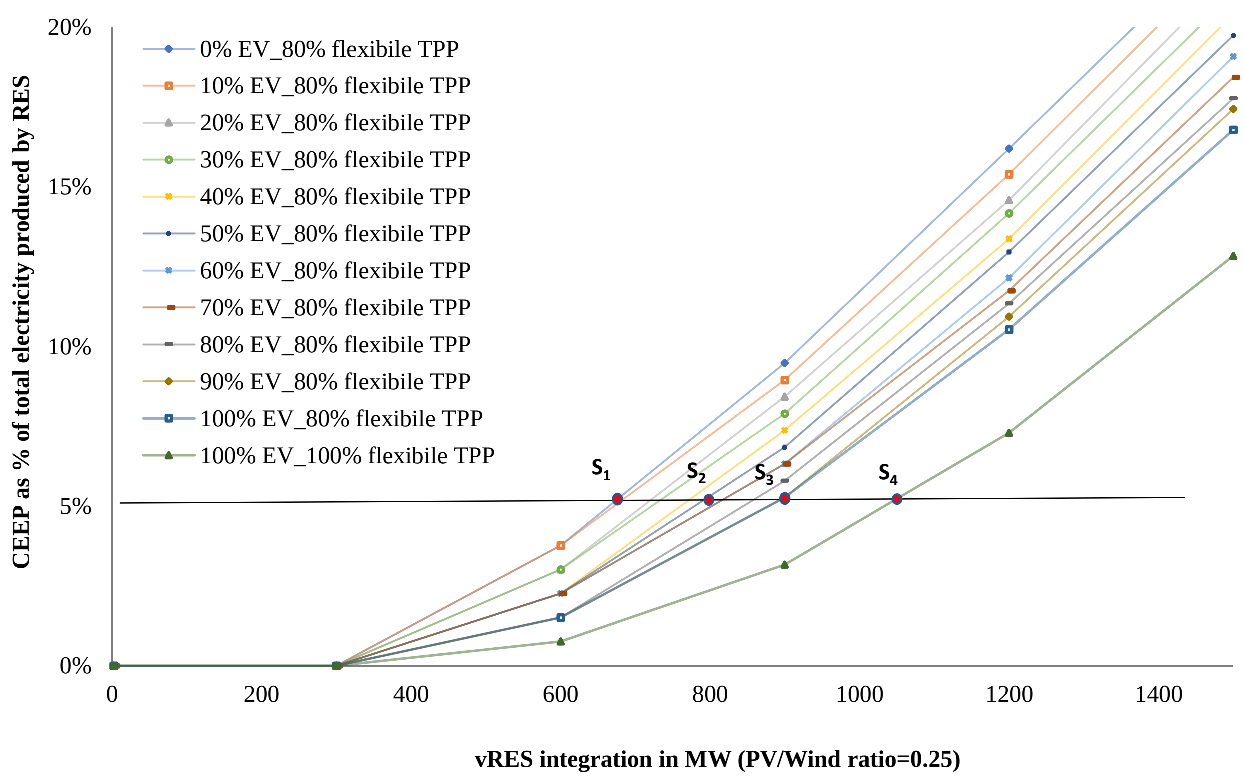


Figure 48 Percentage share of CEEP (TWh/year) in total electricity production by variable RES (TWh/year) for different share of EV's and flexibilities of Kosovo TPP's

Similarly, the CEEP method was used to show the contribution of heat pumps for individual heating and hence increase the share of vRES. As shown from Table 10, the individual electric heaters in Kosovo supply 33% of the total individual heating demand. The utilization of heat pumps for individual heating would not significantly impact vRES integration, as opposed to their significant impact on reducing CO_2 emissions. Figure 49 shows the impact of heat pumps in a coal-based energy system with high flexibility of TPP, hence increasing the vRES integration. A comparison between energy system operating states S_5 and S_6 shows that additional 50 MW wind and 13 MW PV capacity can be integrated into the Kosovo power system when increasing the share of individual heat pumps to 70% of total heat demand, while maintaining 80% flexible existing TPP's. The contribution of heat pumps to integrate vRES can be further increased if TPP's become fully flexible. A comparison between Kosovo energy system operating states S_5 and S_7 with 70% share of heat pumps for individual heating in a coal-based energy system with 100% flexible TPP's shows that power system can additionally integrate 175 MW wind and 43 MW PV respectively.

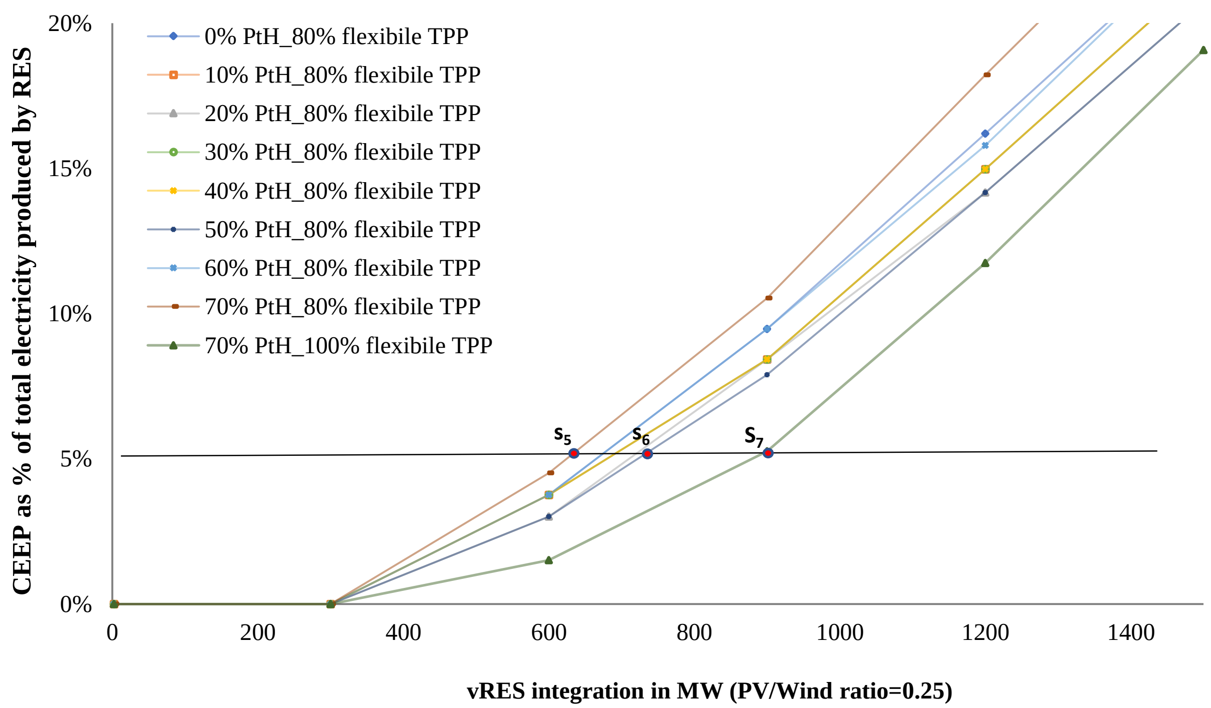


Figure 49 Percentage share of CEEP (TWh/year) in total electricity production by variable RES (TWh/year) for different shares of individual heat pumps and flexibilities of Kosovo TPP's

The increasing capacities of vRES (1MW vRES = 0.75 MW Wind and 0.25 MW PV) in power systems will challenge existing power production technologies' operational capacities, especially TPP's. When Wind and PV is available, the TPP's will reduce their operational capacities to utilise these sources in the power system. The same will decrease the operational efficiencies of existing TPP's, hence negatively impacting the total emissions. Figure 50 shows hourly electricity production in a coal-based energy system with significant integration of vRES according to scenario S_4. In this state, the Kosovo power system operates with a significant amount of variable renewable electricity production. At this operating state, the TPP's becomes fully flexible, allowing maximum utilization of vRES in the power system when available. The other capacities of TPP's hydropower plants have remained the same as in the base year 2015. Figure 51 shows the part-load efficiencies of existing Kosovo TPP's. The relative loading capacities of TPP's with a significant amount of vRES were calculated in hourly intervals using hourly data from the EnergyPLAN model. The relative loading capacity is the ratio between the hourly part-load operation capacity of the TPP's and installed operational capacity. The relative values were used for calculating hourly efficiencies of Kosova A and Kosova B TPP's. Figure 51 shows that the part-load efficiency of TPP's will change significantly when huge amounts of variable wind and PV are integrated into the power system. From the energy system validation mode, the annual averaged efficiency of TPP's Kosova A and B is 26% and 32%, respectively.

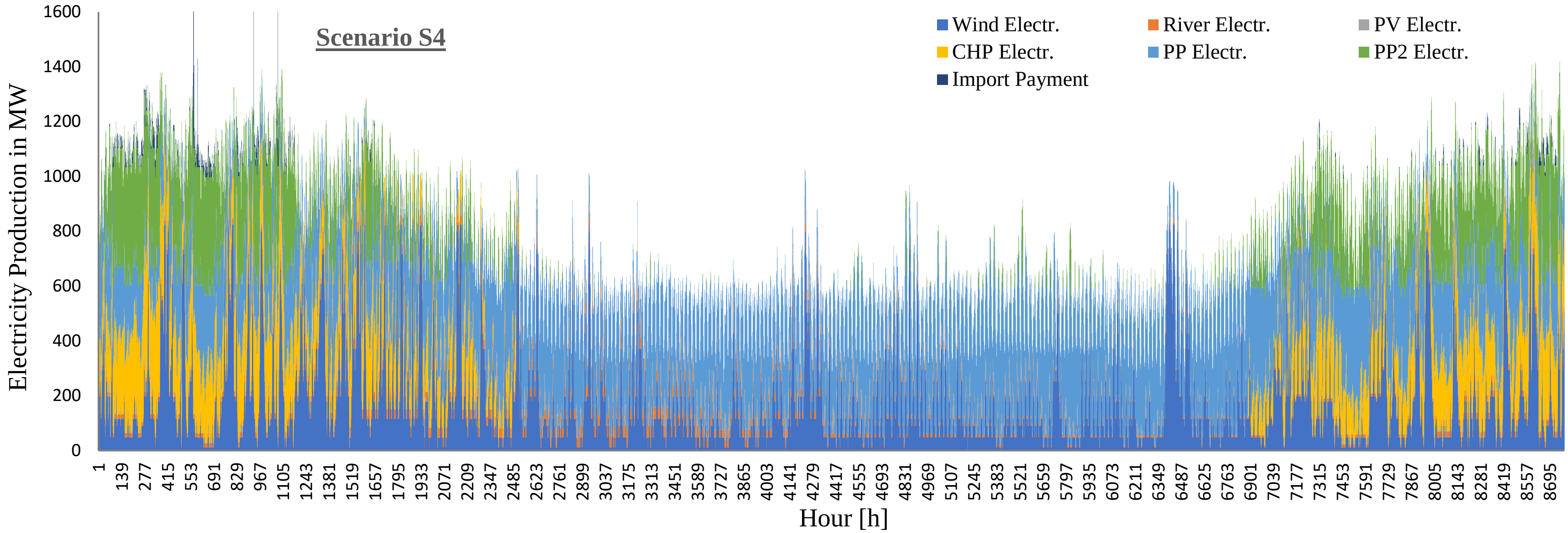


Figure 50 Hourly electricity production mix over a year according to scenario S4

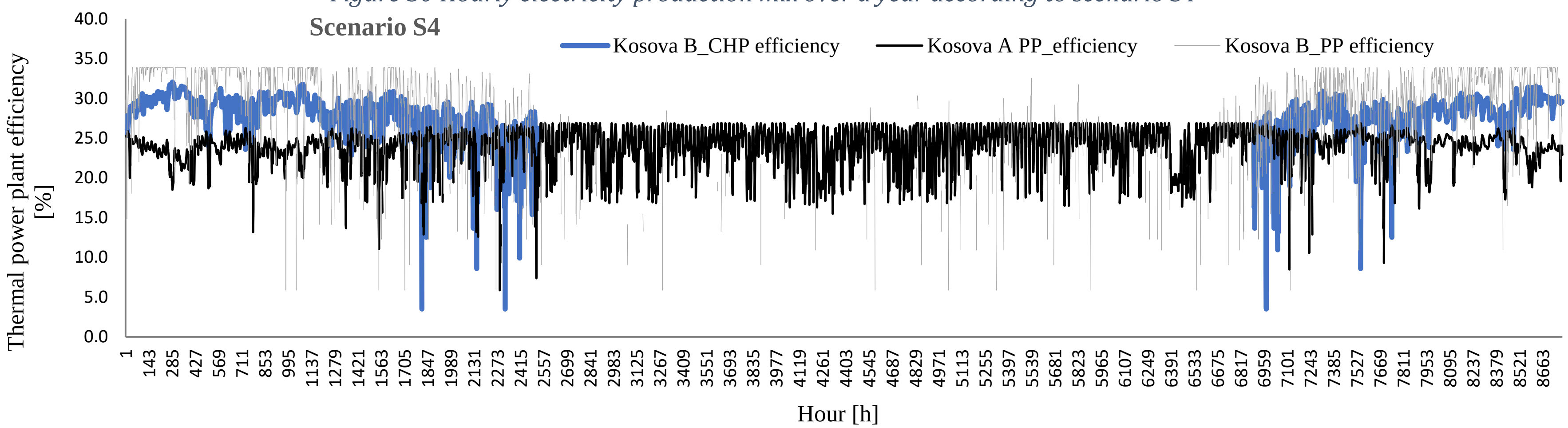


Figure 51 Hourly efficiencies of exiting TPP over a year according to scenario S4

Because of the TPP cycling, the annual average efficiency of TPP's will decrease. The annual averaged part-load efficiency calculated values for different scenarios are summarized in Table 11. For instance, for scenario S_1, the annual averaged efficiency of exiting Kosova A and B TPP would decrease from 26% and 32% to 23.5% and 29.9%, respectively. This decrease in TPP efficiency significantly impacts CO_2 emission increase by around 4% of total CO_2 emissions.

Table 11 The annual average efficiencies of existing Kosovo TPP's

Existing TPP conditions	Kosova B (TPP) efficiency	Kosova A (TPP) efficiency	Annual averaged part load Kosova B (TPP) efficiency	Annual averaged part load Kosova A (TPP) efficiency
Reference Case	32.0%	26.0%	32.0%	26.0%
S1	32.0%	26.0%	29.9%	23.5%
S2	32.0%	26.0%	30.7%	23.7%
S3	32.0%	26.0%	30.0%	23.9%
S4	32.0%	26.0%	29.7%	24.0%
S5	32.0%	26.0%	29.9%	23.5%
S6	32.0%	26.0%	30.8%	23.5%
S7	32.0%	26.0%	28.6%	23.3%

Figure 52 shows the Kosovo energy system CO_2 emissions under different energy regulation strategies. The actual annual CO_2 emissions from the Kosovo energy system are 8.36 Mton/year. The blue bar in Figure 52 shows the annual CO_2 emissions under the assumption that efficiencies of TPP's will remain the same as in the reference case, even after integrating a significant amount of vRES. For instance, scenario S1 with no change in annual TPP efficiency will decrease the annual CO2 emissions to 6.92 Mton/year. However, this would not be reflecting the real case as at this operating state; additional 0.28 Mton CO_2 emissions will be generated from TPP's because of their part-load operation (cycling). Similar trends can be observed for other energy system operating boundary conditions. The maximum CO_2 emission reduction potential from transport electrification can be observed when comparing the reference case with scenario S_4. As previously described scenario S_4 consider that the transport sector will be fully electrified and hence existing TPP's will operate with full flexibility. The maximum CO_2 emission reduction potential for respective case is 8.36 – (5.95 + 0.31) = 2.09 Mton/year. Similarly, if we compare the reference case with 70% individual heat electrification with heat pumps and full flexible TPP's (Scenario S_7), a significant emission reduction potential of 8.36 – (5.7 + 0.33) = 2.33 Mton/year can be achieved. This means that 70% of heat electrification has a greater impact than 97% of transport electrification in CO_2 emission reduction.

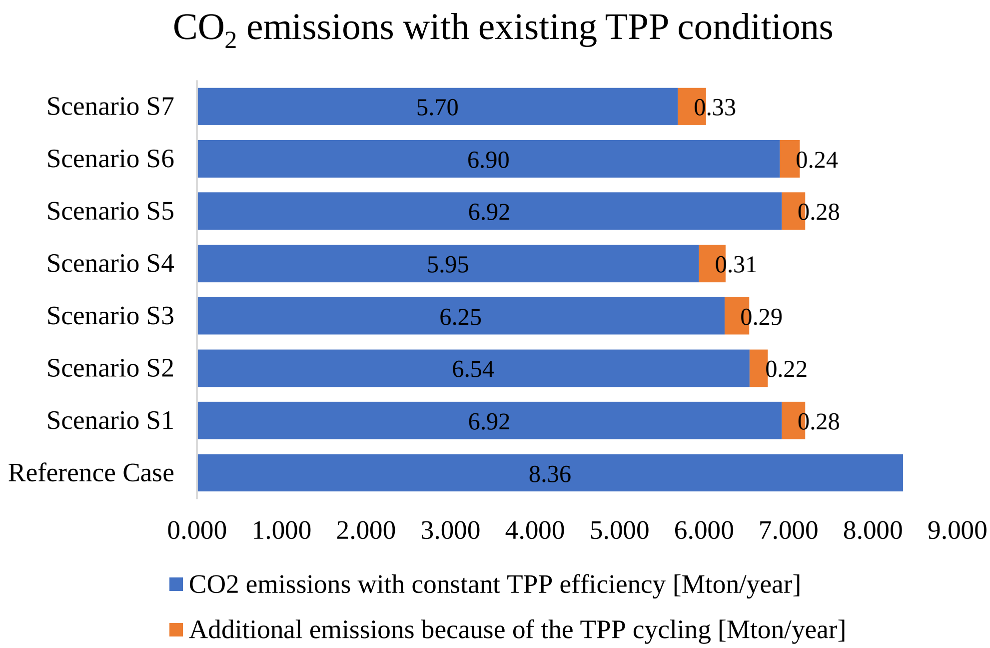


Figure 52 Carbon dioxide emissions from Kosovo energy system with existing operating TPP efficiencies

Table 12 consider that TPP's will be revitalized; hence their efficiency will increase significantly. For instance, it was assumed that exiting efficiencies of TPP Kosova A and B can be increased from 26% and 32% to 35% and 40%, respectively. The outcome is that CO_2 emissions will decrease from 8.36 Mton/year to 7.32 Mton/year, even for the reference case. In comparison to existing TPP efficiencies, a significant CO_2 emission reduction can be observed.

Table 12 The annual average efficiencies of revitalized Kosovo TPP's

Improved TPP conditions	Kosova B (TPP) efficiency	Kosova A (TPP) efficiency	Annual averaged partial load Kosova B (TPP) efficiency	Annual averaged partial load Kosova A (TPP) efficiency
Reference Case	32.0%	26.0%	32.0%	26.0%
S1	40.0%	35.0%	37.4%	31.7%
S2	40.0%	35.0%	38.4%	31.9%
S3	40.0%	35.0%	37.5%	32.1%
S4	40.0%	35.0%	37.2%	32.3%
S5	40.0%	35.0%	37.4%	31.7%
S6	40.0%	35.0%	38.5%	31.7%
S7	40.0%	35.0%	38.5%	31.4%

Let's take scenario S_4 (Figure 53) with 97% electrification of the transport sector, increased efficiencies of TPP up to 35% for Kosova A and 40% for Kosova B, 100% flexible TPP's and compare with a reference scenario in 2015. It can be observed that significant emissions can be achieved around 8.36 - (5.09+0.24) = 3.03 Mton/year. Similarly, for scenario S_7 with 70% heat electrification, increased efficiencies of TPP to 35% for Kosova A and 40% for Kosova B, 100% flexible TPP's compared to the reference case, 8.36 - (5.09 + 0.13) = 3.14 Mton/year CO_2 emission can be achieved.

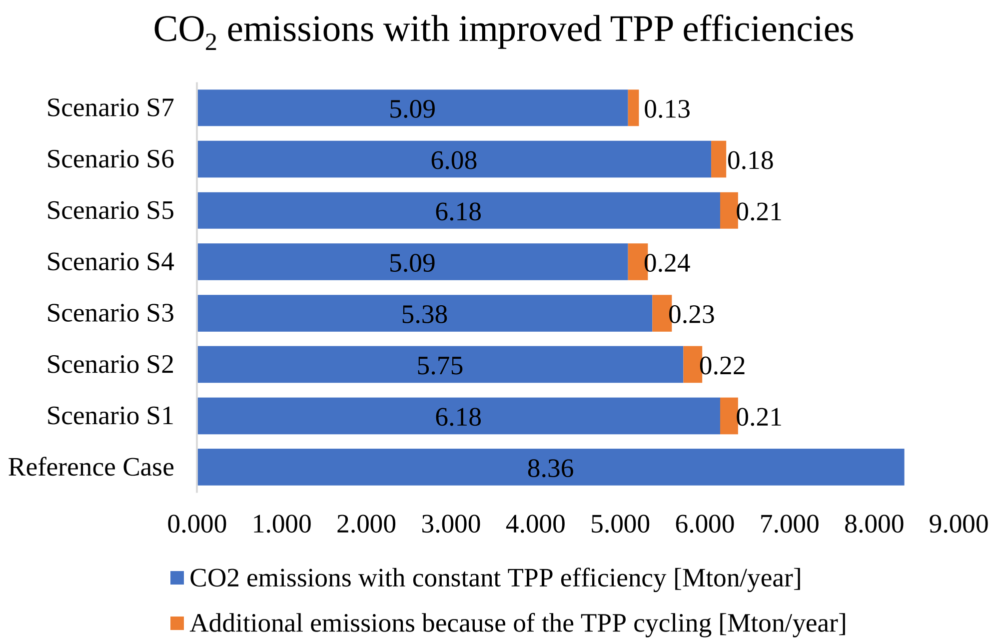


Figure 53 Carbon dioxide emissions from Kosovo energy system with improved operating TPP efficiencies

When comparing CO_2 emissions for a coal-based energy system with low operating TPP efficiencies and revitalized ones, it reveals that the improvement on TPP efficiencies can contribute significantly to CO_2 emission decrease. Furthermore, the findings show that for high operating TPP efficiencies, the losses due to TPP cycling are smaller, resulting in a smaller CO_2 emission increase. If we compare Scenario S_7 for the case when the energy system is operating with low efficiency (Figure 53), with scenario S_7 when the efficiency is improved because of the TPP revitalization, the resulting CO_2 emissions decrease because of TPP cycling accounts for 0.33-0.13= 0.20 Mton/year.

3.5 Variable renewables in coal-based energy system using power to heat technologies

Two scenarios have been developed and compared to demonstrate the role of DH and different PtH technologies in variable RES integration, TPES savings, and CO_2 emission reduction. The reference scenario was modelled using recorded energy supply and demand data for the year 2015. The second scenario considers that DH is increased to 50% of total heat demand, and different P_tH technologies are applied. The results of modelling for both scenarios are shown in the following sections.

3.5.1 Modelling of the Reference Scenario

A model for the base year was defined for the Kosovo energy system at 2015, with the main aim to show the contribution that P_tH technologies can have as an additional source of the flexibility of coal-based power systems for increasing the share of variable renewables. Table 13 shows the recorded data that were used to describe the country energy demands for the reference year. It reviles that the electricity sector consumes more energy than other sectors followed by heating and transport respectively.

Table 13 Energy consumption by sectors with respect to Kosovo energy system [160] ,[166], [167]

Energy consumption by sector	**(TWh/year)**
Electricity	5.670
Heating	5.210
Cooling	0.055
Industry	2.233
Other consumption	1.827
Transportation	4.536

Table 14 shows the fuels consumed by each sector. When paying particular attention to electricity production, it can be noted that over 97% of total electricity production in Kosovo is based on lignite coal.

Table 14 Kosovo energy system supply by source [160], [166], [167]

Electricity production (TWh)		Individual Heating (TWh)		District Heating (TWh)	Cooling (TWh)	Industry (TWh)	Transportation (TWh)	Other consumption (TWh)
Fuel	**2015**	**Fuel**	**2015**	**2015**	**2015**	**2015**	**2015**	**2015**
Coal	5.359	**Coal**	0.646	0.265	-	0.302	-	0.214
River Hydro	0.142	**Oil**	0.517	0.277	-	1.744	-	0.343
Wind	0.000	**Biomass**	2.800	-	-	0.186	-	1.269
PV	0.000	**Electricity**	1.930	-	0.055	-	-	-
		NG	-	-	-	-	-	-
		Diesel	-	-	-	-	3.107	-
		Petrol	-	-	-	-	1.157	-
		LPG	-	-	-	-	0.272	-

Tables 15 and 16, show the power plant capacities for conventional and renewable supply technologies. Kosovo has two power plant units named Kosovo A and Kosovo B and their net, minimum operation capacities, and electrical and thermal efficiencies are shown in the following tables.

Table 15 Net, minimum Power Plant capacities and their efficiencies [160]

Group	Capacity (MW)	Min Capacity (MW)	η_{el}	η_{th}
PP	432	70	0.3	-
CHP	538	70	0.4	0.104

Table 16 RES plant capacities [160]

Group	Capacity (MW)
River Hydro	75.5
Wind	1.36
Photovoltaic	0.6

Except input data provided so far, the software model also requires the energy demand and supply distributions for each technology. The distribution of electricity demand was taken from [160], while distributions for the heating and cooling demands were created using the hourly heating and cooling degree day's method. Despite distribution data for energy demands, distribution data is also created for supply-side technologies like Wind, PV, River Hydro and DH. Such data was saved and imported to the model as txt.files. The data in the model were compared with the recorded data for validating the model. The results of the validation are presented in Table 17.

Table 17 Model validation with respect to actual data [160]

	Model	**Actual**	**Difference**
PP electricity	2.77	2.74	3%
CHP operating Mode	-	-	
PP	1.32	1.35	-3%
CHP	1.29	1.32	-3%
RES electricity	0.14	0.14	0%

3.5.2 Modelling of Power-to-Heat technologies

In the second scenario, the DH demand was increased five times to 50% of total country heat demand in 2015. This utilization potential of total heat demand to be covered by DH was estimated in several research papers [53], [55].

Table 18 Heat supply options in DH with a 50% share of total country heat demand

Individual Heating (TWh)		**District Heating (TWh)**	
Fuel		**Fuel**	
Coal	0.2761	**Coal+HP+HS**	2.7062
Oil	0.2201	Oil	0.2775
Biomass	1.2007		
Electricity	1.9300		

It was shown that the potential use of P_tH technologies in DH from 30 to 50% of the total DH demand by [86]. In this regard, the compression HPs with 150 MW_{el} capacity coupled with 10 GWh/annually heat storage was integrated into this fictive DH. For installing such HP capacity, a linear decrease of fuel consumed for individual heating solutions compared with the reference scenario is assumed (see Table 18).

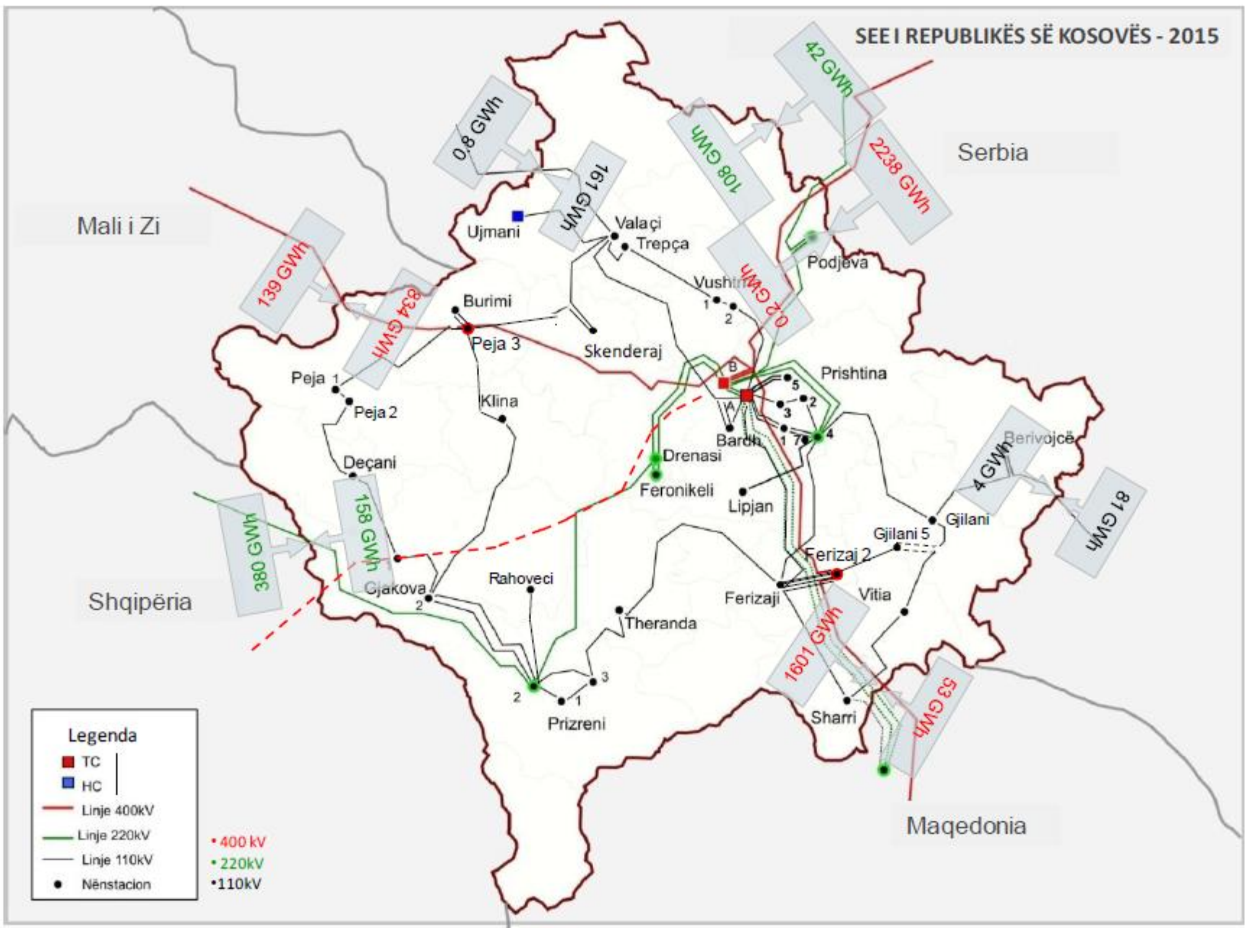


Figure 54 Kosovo power system interconnections [160]

Moreover, existing TPP were assumed to be very flexible accounting for a minimum capacity of around 20% of their net operation capacity. The electricity imports and exports through the interconnection line capacities with neighbouring countries are shown in Figure 54 for the reference year 2015.

Figure 55 presents the critical excess electricity production by wind power plants. CEEP appears in power systems, when the electricity production exceeds the electricity demand as well as the interconnection line capacities. In addition to that, the graph shows that P_tH technologies can significantly decrease the CEEP, created by wind power plants, even though in a very well-connected power system.

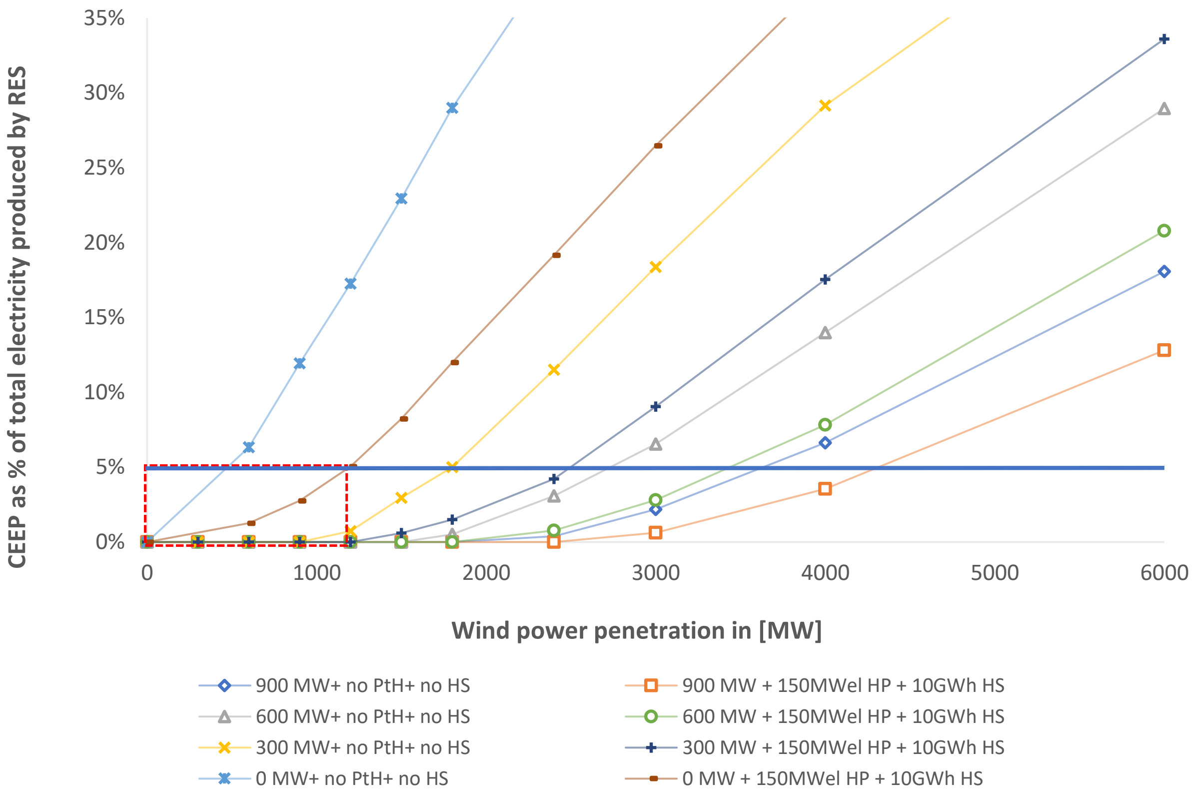


Figure 55 CEEP production by the wind power plants penetration for different interconnection capacities coupled and uncoupled with PtH technologies in DH with 50% share of heat demand

The contribution of P_tH technologies increases with the increasing penetration of wind generators. Higher CEEP reduction because of the P_tH technologies is acquired for an isolated energy system (0 MW interconnection), while less contribution is obtained in a very well interconnected power system (for instance CEEP reduction for interconnection line capacity 900MW).

Similarly, another graph for showing the contribution of P_tH technologies for capturing the excess electricity of solar PV plants is shown in Figure 56. As displayed in this graph the CEEP reduction because of the P_tH technologies coupled with PV is significantly smaller compared to wind power plants. Because of the seasonal operation of DH systems, with the P_tH technologies operating during the heating season and by this time the contribution of solar irradiation reaching the PV panels on Earth's surface is smaller compared with Wind power plants. If all the PV panels are placed in an optimum angle, the PV power production curve reaches its maximum during the summer months.

If the country has high cooling needs, the use of PtH (cool) technologies would significantly reduce CEEP. Similarly, a higher contribution of P_tH technologies for integrating PV is obtained in an isolated power system, while it is negligible for a very well connected one.

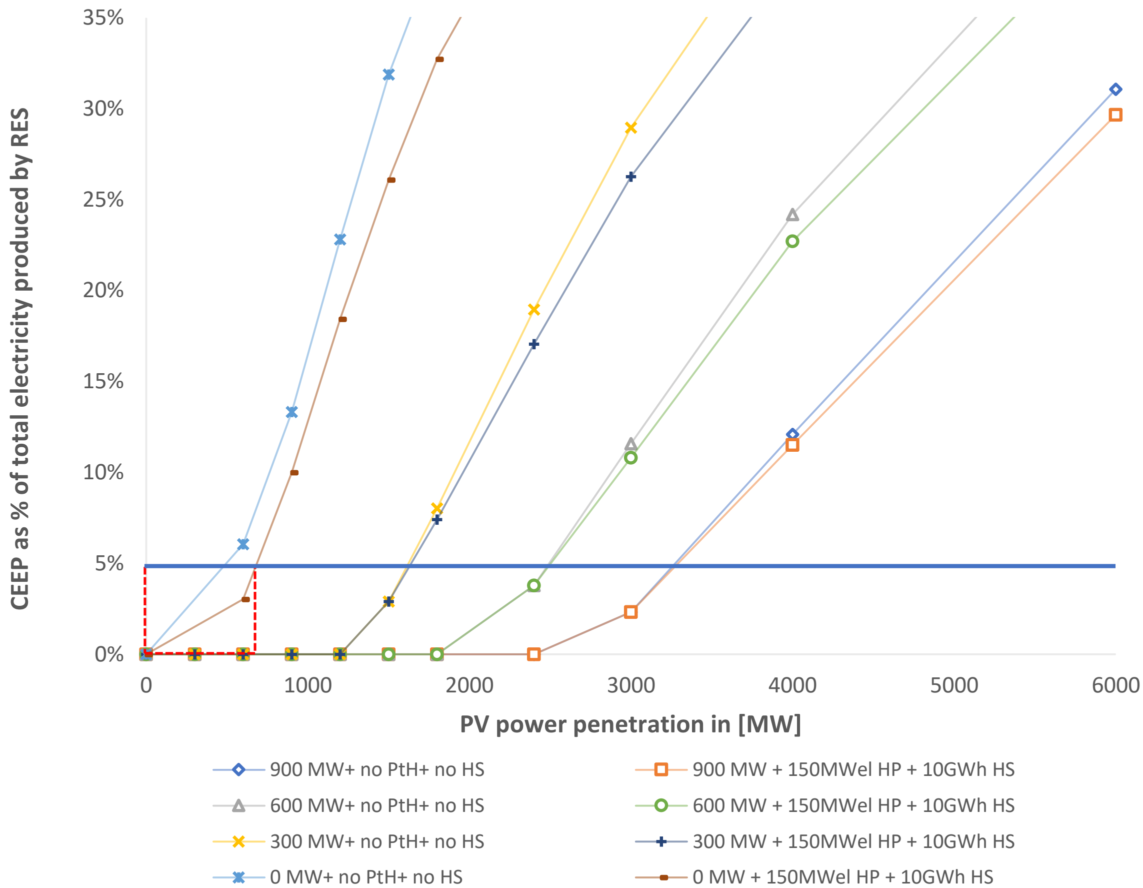


Figure 56 CEEP production by the PV power plants penetration for different interconnection capacities coupled and uncoupled with PtH technologies in DH with 50% share of heat demand

On the other hand, PtH technologies' contribution to decreasing the CEEP in an optimum power generation mix composed of wind and PV power plants is shown in Figure 57. It demonstrates that a higher share of variable renewable power plant capacities can be integrated into coal-based power systems compared with wind and solar power plants for the same interconnection line capacity compared with separate integration of wind and PV power plants.

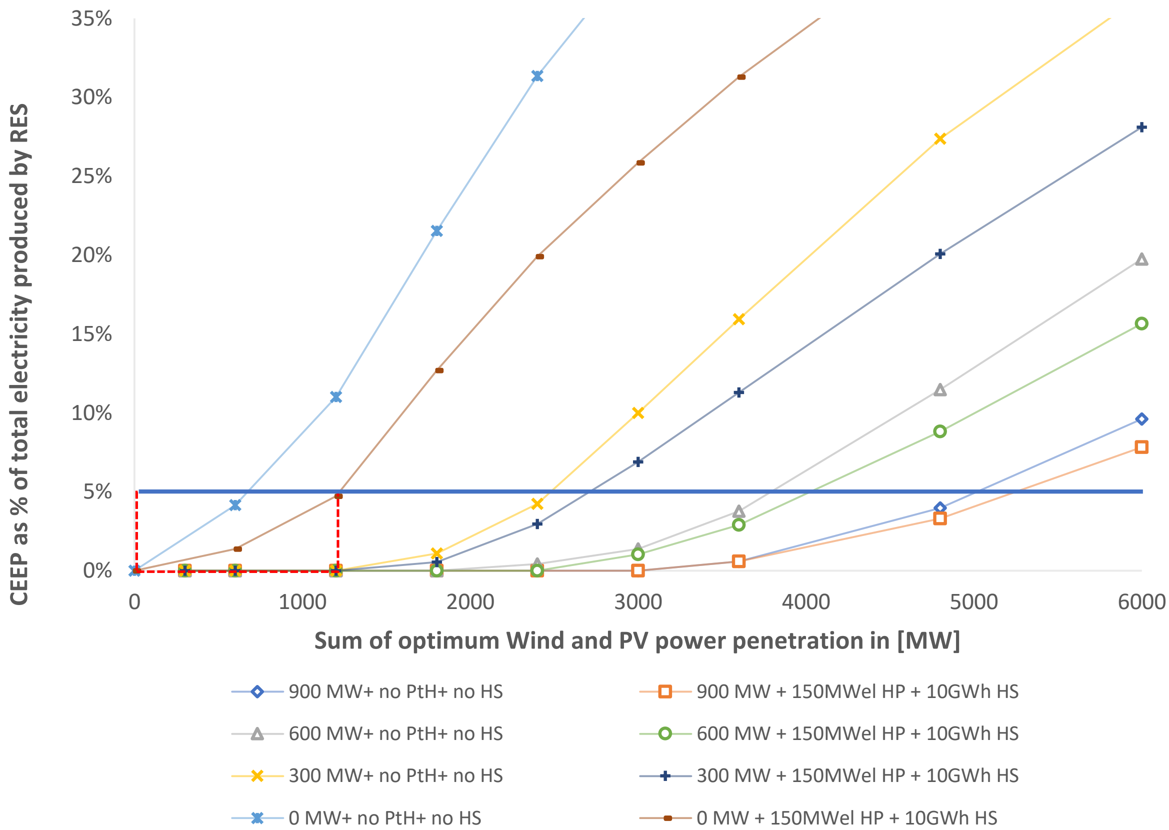


Figure 57 Wind and PV power penetration enabled by PtH and transmission, with the criterion <5% CEEP

Usually, during the modelling of energy systems, an amount of 5% for CEEP is used as criteria that underline how much variable renewable power plants can be integrated into the energy system. When looking at how much renewable wind power can be integrated into an isolated coal-based energy system (0 MW interconnection) without P_tH technologies (Figure 58), it was found that the wind power that can be installed is 450 MW. An additional capacity of 800 MW of wind power plants might have been integrated into this energy system with the contribution of P_tH technologies coupled with thermal energy storage in DH. In case the interconnection capacities increase, the contribution of P_tH slightly decreases, but even though in a well-interconnected power system (900 MW) the contribution of P_tH is significant for wind power penetration allowing an additional capacity of 622 MW (Figure 58).

Following the same procedure, the PV and RES power penetration was investigated. From the PV penetration perspective Figure 59, shows the contribution of P_tH in isolated power system (0

MW interconnection) is significant 385 MW, while for very well-connected power system (900 MW interconnection) such contribution is not visible, since the export of any excess electricity from solar PV has the priority.

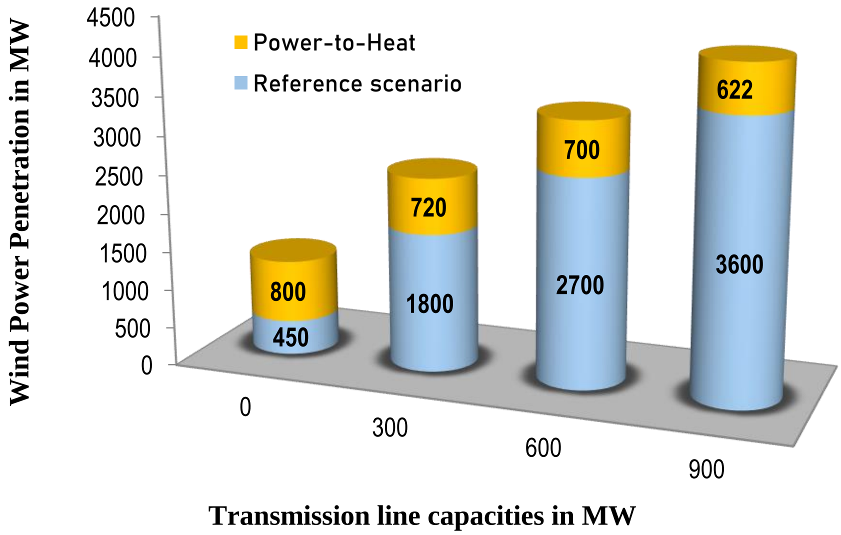


Figure 58 Wind power penetration using PtH technologies in DH with a 50% share of total heat demand

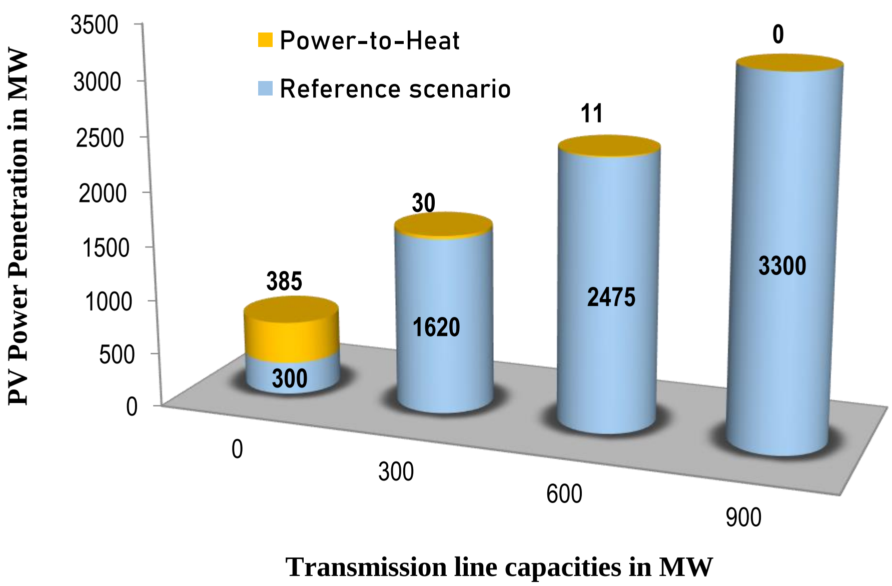


Figure 59 Solar PV power penetration using PtH technologies in DH with a 50% share of total heat demand

This is the reason why power to gas, electric vehicles with battery or power-to-x technology would make sense for creating better flexibility of Kosovo power system, especially during the summer time. From the other hand, the contribution of interconnection capacities in the current power system is significant (see the blue part of Figure 58, 59 and 60).

Figure 60, also underlines the variable power penetration for optimum Wind and PV plants in a power system that is based entirely on coal. It can be shown that when the power system is entirely isolated, the contribution of P_tH increases the variable RES power penetration for 515 MW (257.5 MW Wind and 257.5 MW PV respectively).

An interesting result reveals for the increasing interconnection capacity 300, 600, and 900 MW, the mix of variable renewable power penetration increases to 200, 229 and 280 MW respectively, as a contribution of P_tH technologies, which was not the case when these renewable plants were integrated separately into the power system.

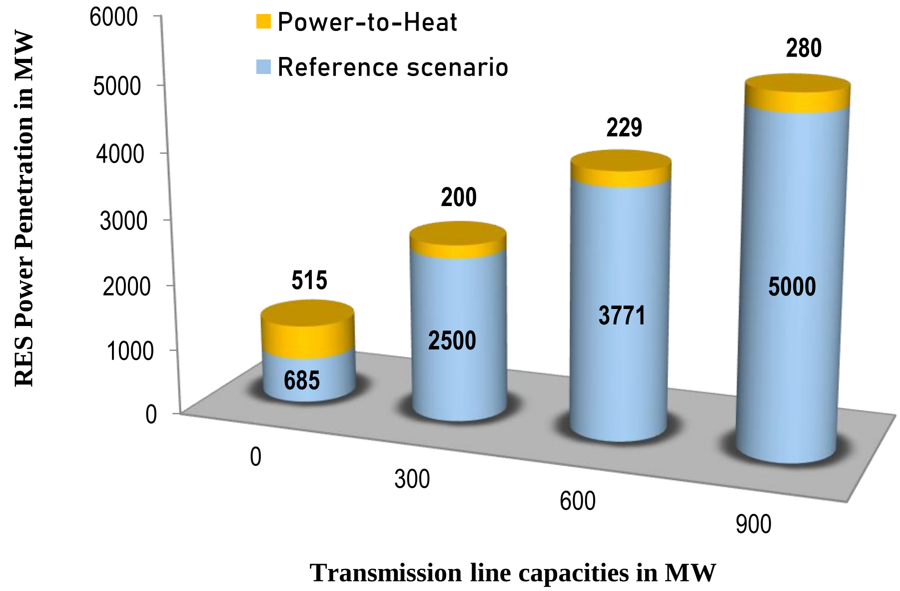


Figure 60 Variable RES power penetration using PtH technologies in DH with a 50% share of total heat demand

Because of the different power plant technologies have different capacity factors, the annual energy produced by such technologies is a better option for showing the contribution of P_tH technologies. In Figure 61, the annual electricity (TWh/year) produced by PV plants, orange colour, as a contribution of P_tH technologies divided by total country electricity production is given.

An interesting result reveals for the increasing interconnection capacity 300, 600, and 900 MW, the mix of variable renewable power penetration increases to 200, 229 and 280 MW respectively, as a contribution of P_tH technologies, which was not the case when these renewable plants were integrated separately into the power system.

It can be shown in Figure 61 that the contribution of P_tH for integrating RES electricity in coal based power system is significant to account for 14%, 13%, 13%, 11% of total country electricity demands for interconnection capacities 0 MW, 300MW, 600 MW, 900 MW respectively. In the same way, were created the graphs of Figure 62 and 63. It is worth observing that PV penetration because of the P_tH only become favourable if the interconnection capacity is 0 MW, otherwise, no contribution was found (Figure 62). Obviously, better results can be obtained for optimum RES power mix (Figure 63), with the use of P_tH that can allow larger use of potential surplus RES.

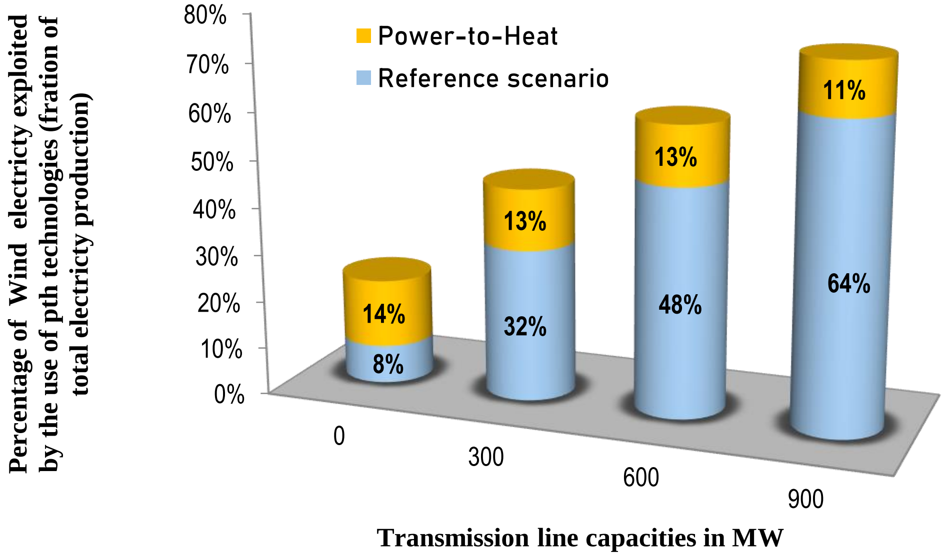


Figure 61 Percentage of wind electricity exploited using P_tH technologies and increased transmission line capacities

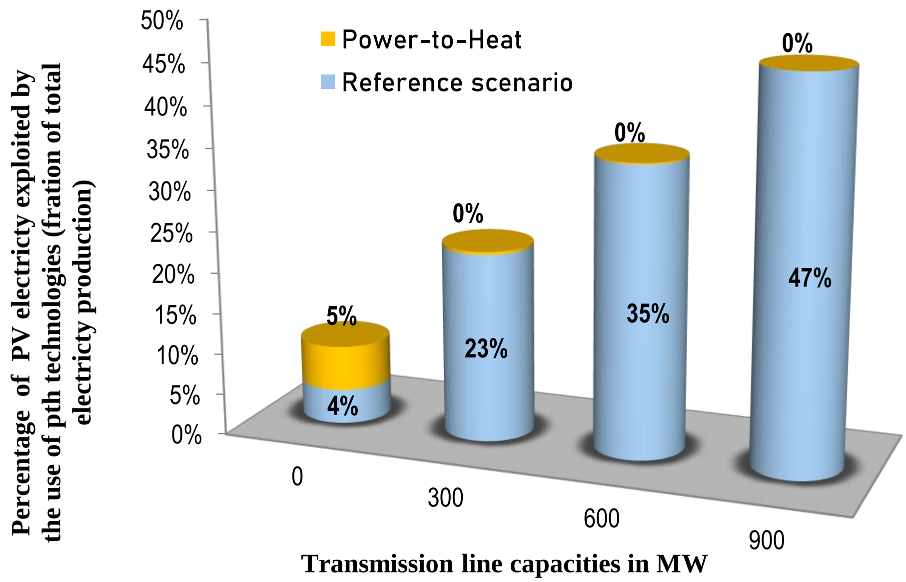


Figure 62 Percentage of PV electricity exploited using P_tH technologies and increased transmission line capacities.

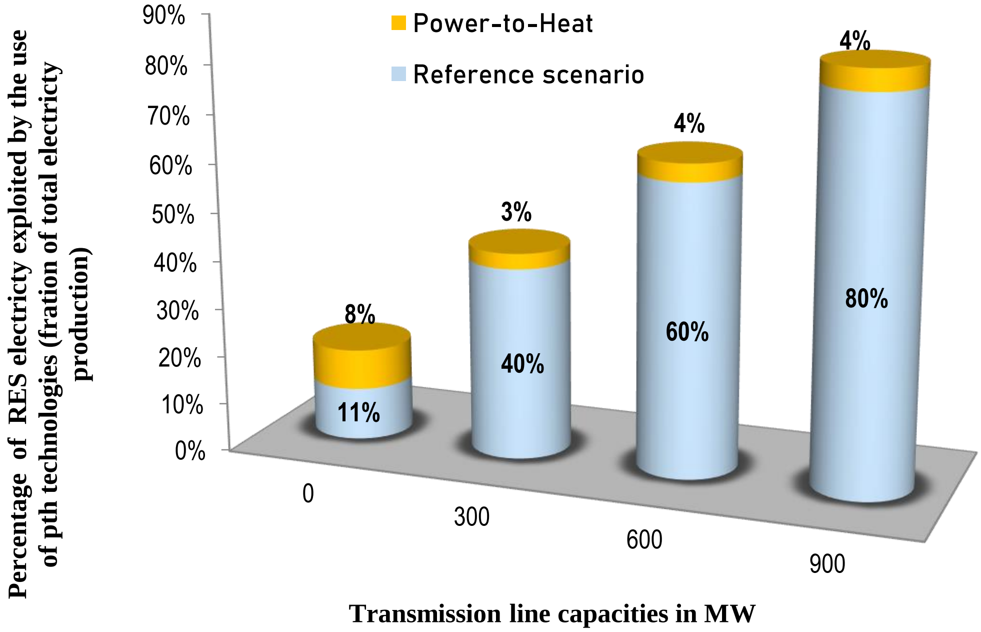


Figure 63 Percentage of variable RES electricity exploited using P_tH technologies and increased transmission line capacities

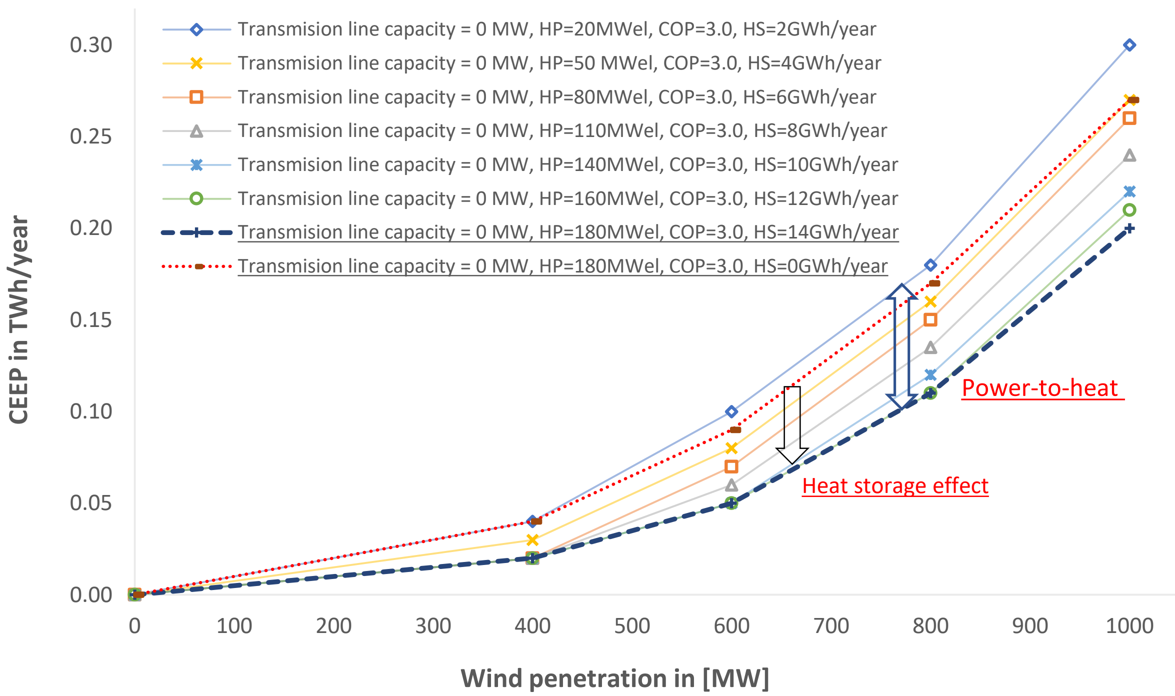


Figure 64 CEEP wind production in TWh/year for different HP and HS capacities in DH with 50% share of total heat demand

Apart from RES integration in Kosovo energy system for different interconnection capacities, with a fixed size of P_tH, additional analyses were carried out to emphasize the contribution of different P_tH = HP+HS capacities in CEEP reduction in Figure 64 and wind power integration in Figure 65. Different capacities of compression heat pumps and thermal energy storages in DH for an isolated energy system were investigated for demonstrating their impact in CEEP reduction from variable RES technologies. Figure 65 shows that the critical wind penetration zone is between 0 - 1000 MW for an energy system operating in an isolated mode, which is why this zone is considered for further analysis. Zone area between the top and bottom curves (Figure 65), shows additional flexibility that is created in the energy system because of the utilization of different HP+HS capacities. Curves that are built with smaller HP+HS capacities show higher excess wind power production leading to the smaller ability of power system to integrate wind power plants. The upper limit about 180 MW_{el} capacity for compression HP's was selected to cover around 40% of total heat demand if operating with such capacity and the priority was given to HP against other DH fuel-supplying options. Two dot curves (red and dark blue ones) with same HP capacity 180 MW_{el}, but with and without thermal energy storage options (in Figure 65) were investigated to show the contribution of HS in CEEP reduction. It can be seen that HS application with the power-to-heat has a significant contribution to CEEP reduction potential especially in energy systems with high penetration of wind power plants. Diurnal thermal energy storage in DH was considered in all analysed scenarios. However, in market different heat storage technologies are used for storing heat diurnally and seasonally in the form of sensible, latent and chemical storages. Figure 65 shows the CEEP in the percentage of total electricity production by RES. CEEP percentage 5% is considered as criteria for estimating wind power integration in the energy system with different HP+HS capacities. It can be seen that wind power integration can be increased significantly from 400 MW (curve HP=20MWel, COP=3 & HS=2HWh/year) to 680 MW (curve HP=180 MW_{el}, COP=3 & HS=14GWh/year). Larger HP+HS capacities for actual energy system do not have any effect on wind power integration since they do not interfere with CEEP percentage 5%. This is the case when comparing bottom curves (curve HP=160 MW_{el}, COP=3 & HS=12 GWh/year and curve HP=180 MW_{el}, COP=3 & HS=14 GWh/year), which show that they have exceeding the limits regarding the contribution of P_tH in wind power integration.

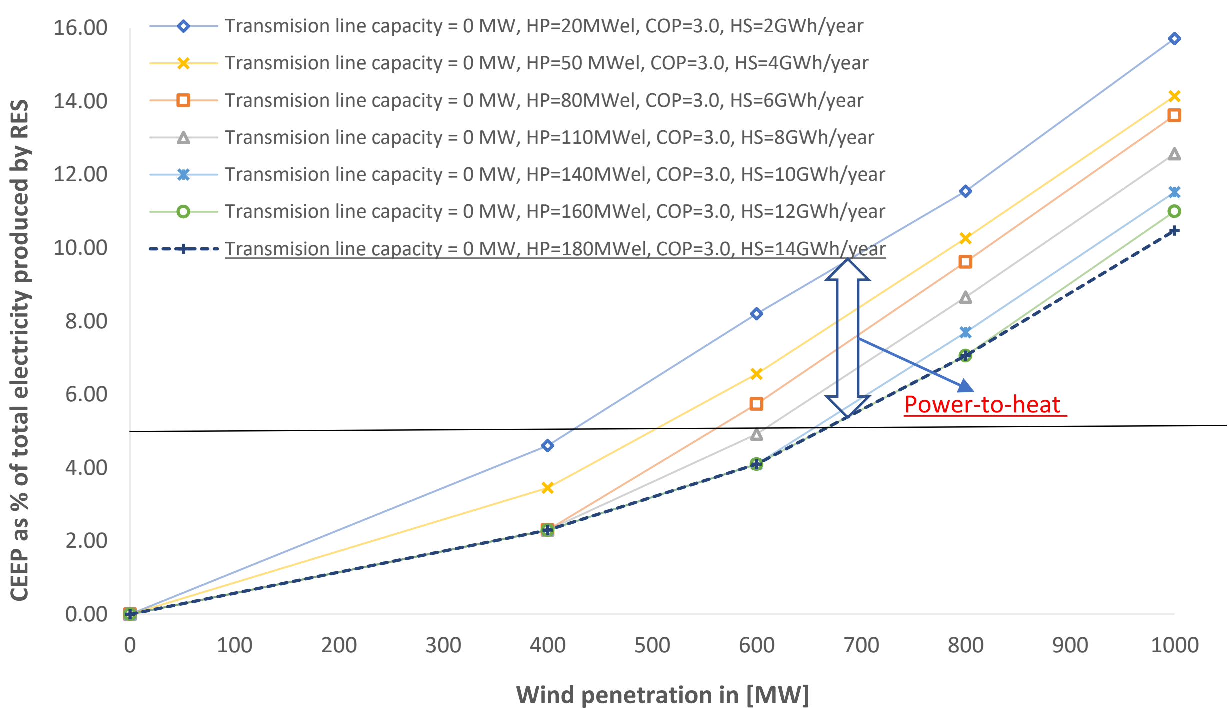


Figure 65 Wind percentages of CEEP for different P_tH and HS capacities in DH with 50% share of total heat demand

Using a similar procedure, CEEP curves (expressed in TWh/year and CEEP % of total electricity production by RES) for solar PV power integration were constructed in Figures 66 and 67 respectively. Smaller contribution of HP+HS capacities were identified for solar PV integration compared with Wind. The reason for that is that DH has been operating between 15 October to 15 April to cover both space heating and hot water demand, in times, where the availability of solar irradiation is low. The remaining time, DH has been used to cover just hot water demand and that demand was low compared with space heating demand. It means that there are not needed significant HP+HS capacities because the heat demand by DH is low. This fact is illustrated in Figure 66 and 67, where is shown CEEP for different HP+HS capacities for increasing flexibility of the energy system as well as for PV integration. The only curve with HP=20MW$_{el}$, COP=3, HS=2GWh/year has shown not enough HP+HS capacities available to integration maximum share of PV power plants. All other capacities have shown the same ability to reduce CEEP and utilize maximum integration of PV. It was shown in Figure 67, that because of the application of different HP+HS capacities in DH, the maximum integration of solar PV increase is around 80 MW.

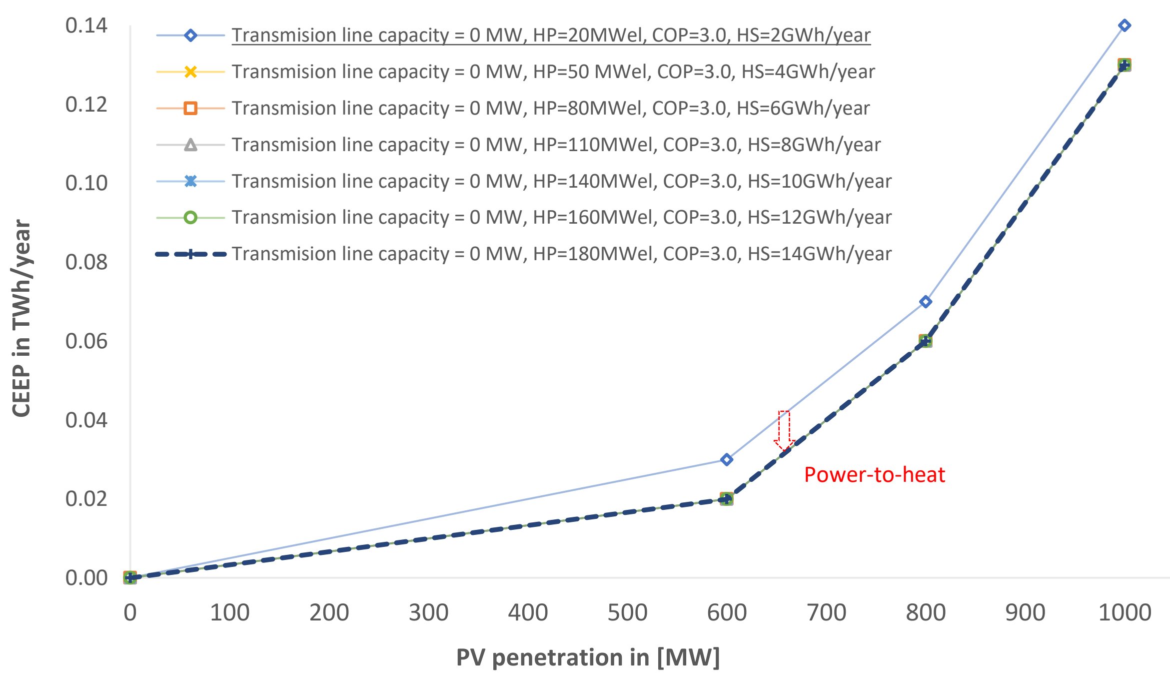


Figure 66 CEEP solar PV production in TWh/year for different HP+HS capacities in DH with 50% share of total heat demand

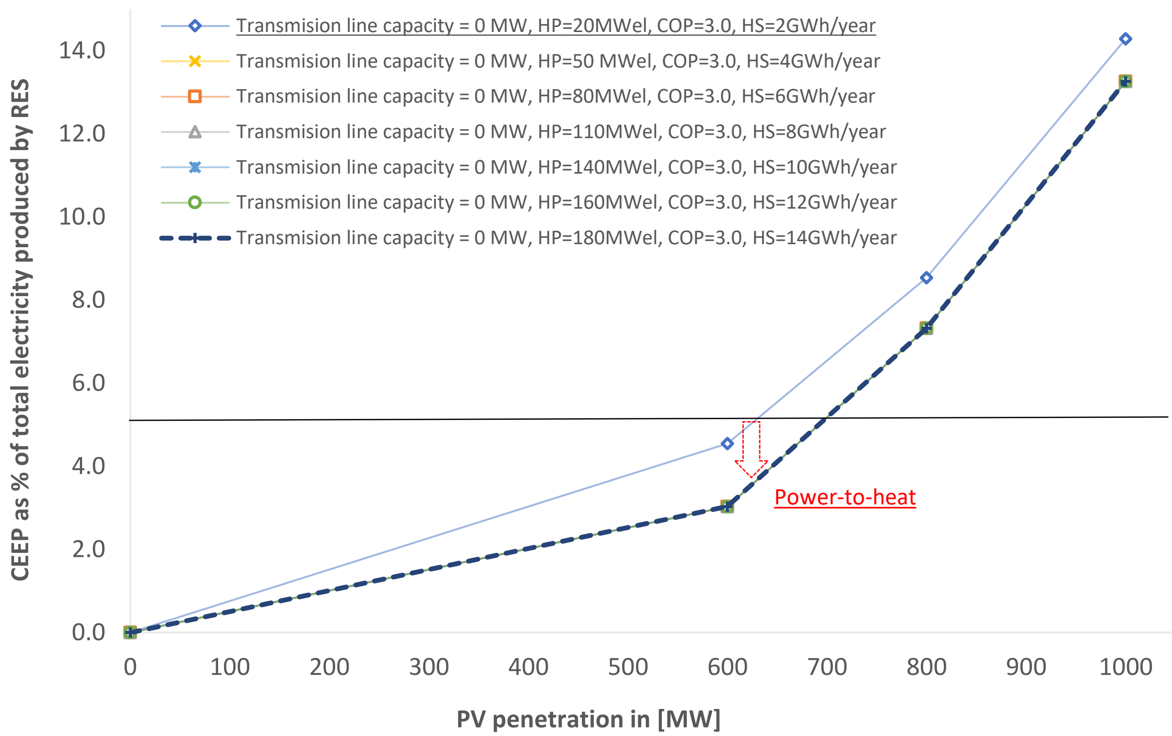


Figure 67 Solar PV percentages of CEEP for different HP+HS capacities in DH with 50% share of total heat demand

Apart seperate integration of Wind and PV power plants, additional analysis considering both integrations of Wind and PV in energy system happening at the same time were considered. The sum of integration of PV and Wind is called RES integration, counting a power integration 1MW per wind and 1MW per PV respectively. When comparing the contribution of different HP+HS capacities for seperate and combined variable RES integration, the larger effect was identified to separate wind integration compared with PV and combined RES integration. Figure 68 and 69 presents the CEEP reduction as a function of RES power penetration (sum of wind and PV). It can be seen that CEEP can be reduced significantly for different HP+HS capacities. For illustration, let's take the maximum RES power penetration 2000MW, where the contribution of P_tH and HS to reduce CEEP is 0.73 - 0.61 = 0.12 TWh/year.

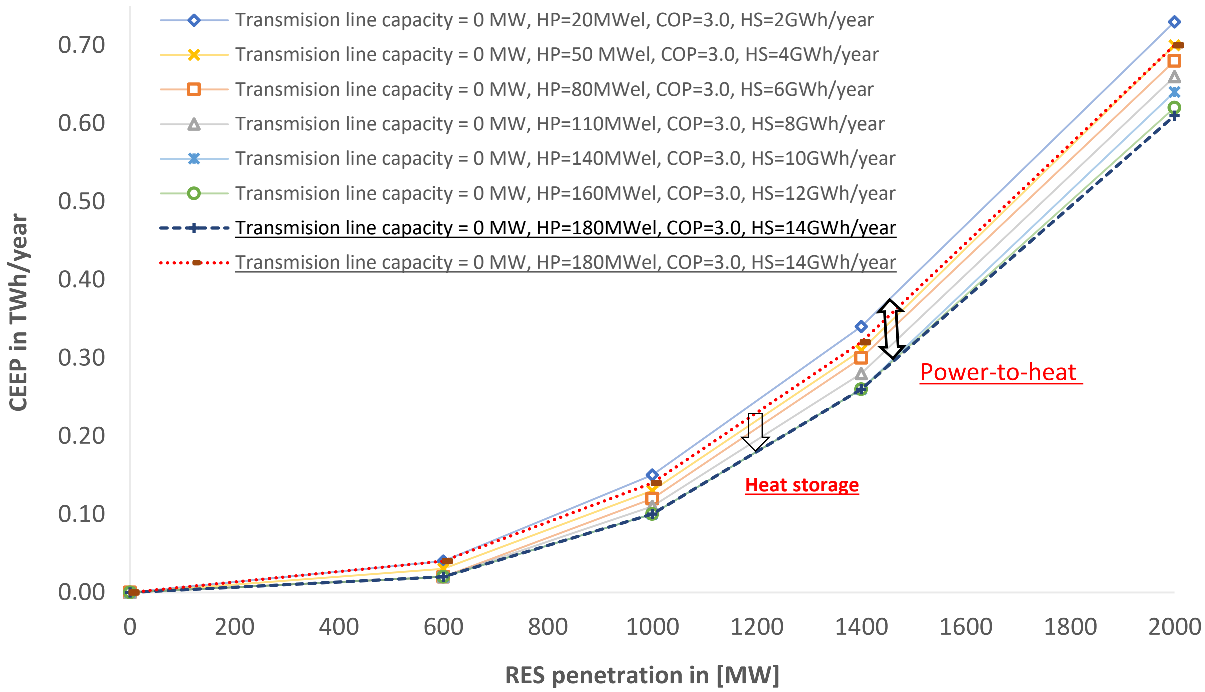


Figure 68 CEEP variable RES production in [TWh/year] for different HP and HS capacities in DH with 50% share of total heat demand

An increase of RES power (sum of =1 MW_{Wind} +1 MW_{PV}) integration around 800 - 600=200 MW was identified because of the application of different HP+HS capacities in DH. Compared to separate wind integration, smaller capacities of P_tH and HS capacities are needed for maximum utilization of variable RES. Figure 69, shows that curve with HP=110 MW_{el}, COP=3 and HS=8 GWh/year is the maximum needed capacity of P_tH contributing in RES integration. Larger capacities mean oversizing of P_tH technologies for variable RES integration.

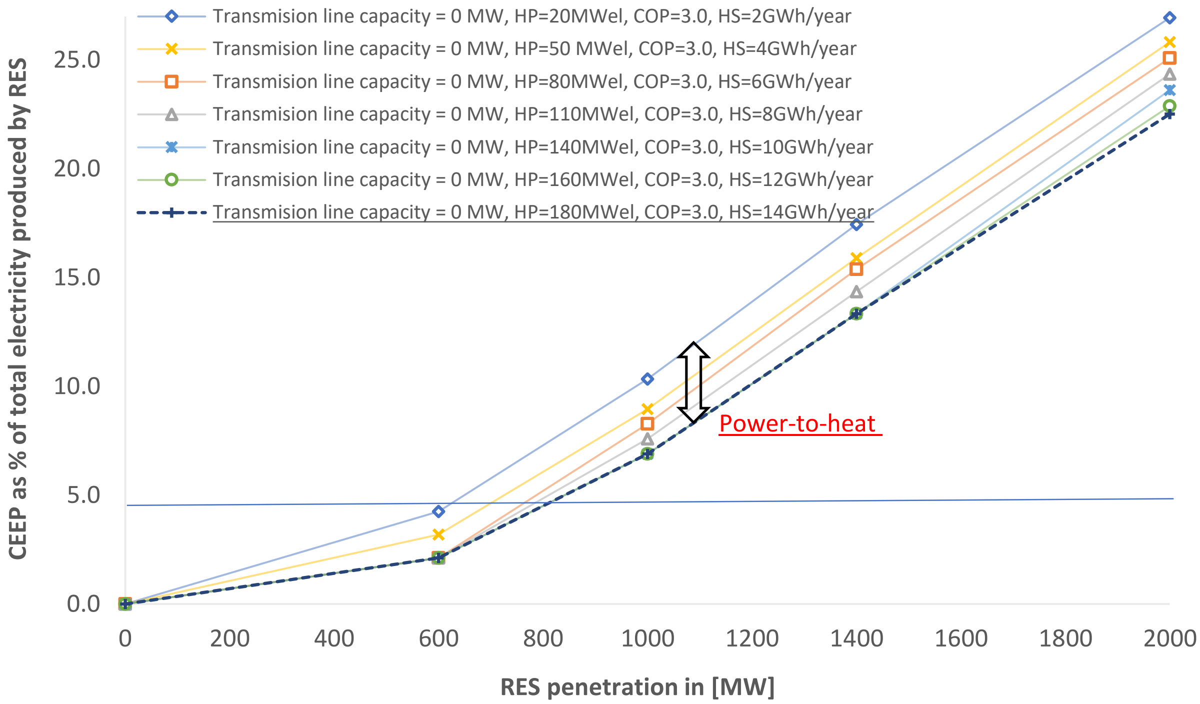


Figure 69 Sum of RES power penetration enabled by different HP and HS capacities in a DH, with the criterion <5% CEEP

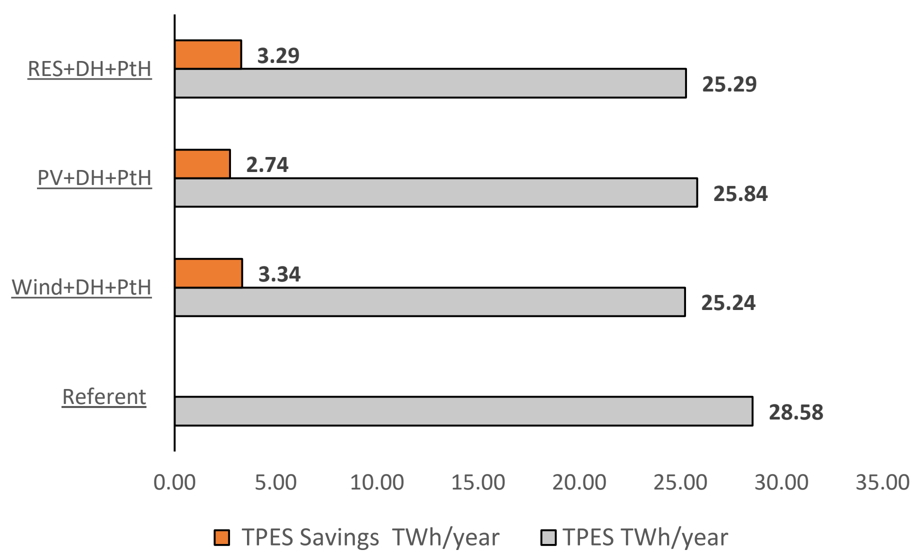


Figure 70 Total primary energy supply and its savings

Besides the contribution of DH and P_tH to increase the share of variable RES power plants in power systems, they can additionally contribute to increasing TPES savings and CO_2 emission reductions. Results shown in Figure 70 and 71 are acquired, for an energy system operating in an isolated mode. In the reference scenario, TPES were estimated at 28.58 TWh/year. Considering an extension of DH up to 50% of total heat demand, and maximum estimated capacity of P_tH (HP=180MWel, COP=3, HS=16GWh/year) that can contribute to RES integration, TPES savings for separate and combined integration of RES were estimated as well. In addition to that when considering just wind penetration in an isolated power system (around 661 MW see Figure 65 with a significant share of DH+HP+HS), it was found that 3.34 TWh/year of TPES could be saved. This means that wind penetration can contribute to decease TPES for 12% compared with its penetration in the reference scenario. Similarly, the contribution of PV power plants to decrease TPES was estimated accounting for a decrease of around 10% compared to reference scenario. A higher contribution of DH and P_tH in TPES saving was estimated for the combined integration of variables RES (3.29 TWh/year) compared with separate integration of PV power plants (2.74 TWh/year). However, this was not the case, when comparing combined RES and Wind integration, for which the last one showed the highest TPES saving potential.

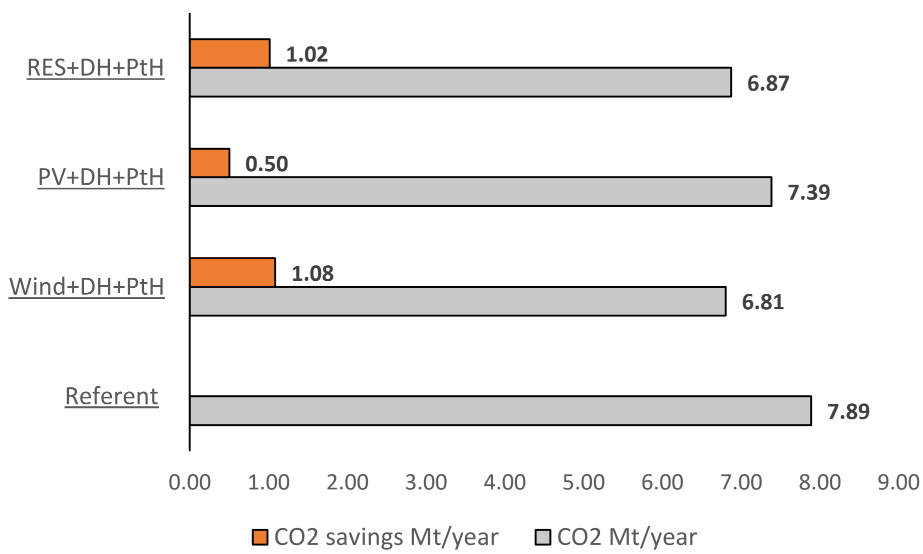


Figure 71 Total annual CO2 emissions

Figure 71 presents total annual CO_2 emissions and it's savings because of the separate and combined variable RES integration and the increase DH+P_tH capacities compared to reference scenario. DH supplying 50% of total heat demand with the capacity of P_tH (HP=180 MW_{el}, COP=3, HS=16 GWh/year) was considered for estimation of CO_2 emission and its savings. It was estimated that separate wind integration has a greater impact in CO_2 emission reduction accounting for 1.08 Mt/year, compared to PV with 0.5 Mt/year and combined RES integration 1.02 Mt/year respectively. From the other hand, total annual CO_2 emissions released by energy system estimated in the reference model accounted for 7.89 Mt/year. It means that wind, PV and combined RES penetration can contribute to annual emission savings compared with emissions estimated in reference scenario for 14%, 6% and 13%, respectively.

3.6 Energy Transition pathways with high penetration of Renewables

The following shows additional approaches that are used for defining the base scenario for 2030. Besides general data that can be applied to all coal-based energy systems, the following ones are related to the Kosovo energy system. The efficiency of PP is 26%, while the efficiency of CHP is 32%, respectively. Distribution for a river hydropower plant was generated using the monthly energy production recorded data in 2015 [61]. The hourly electricity demand profile was taken from Kostt [168]. PV and Wind power supply distributions were generated using wind speed and solar irradiation data from Meteonorm [129] for high potential areas in Kosovo. The capacity factor for wind and PV power plants was estimated at 25% and 18%, respectively. The base scenario for 2030 does not consider the scaling up in power generation capacities besides already installed RES capacities operating since 2018. Scenarios were developed to answer the following research questions

- What additional changes in the energy system are needed to meet the 2030 EU target when compared with already established country energy policies in 2020?
- Can a coal-based energy system meet the target 2030, only by utilizing current and developing RES country projects?
- What if the new PP is not built, what changes are needed to design a reliable, sustainable and environmentally friendly energy system?

3.6.1 Kosovo Energy System in 2030

Figure 72 presents the total final energy consumption by sectors and CO_2 emissions from 2000 to 2015. It can be seen that the demand by sectors has significantly increased over time, especially in the household and transport sector. Apart from energy demand increase, the carbon intensity is significantly increased from 5.11 Mt in 2000 to 8.62 Mt in 2015.

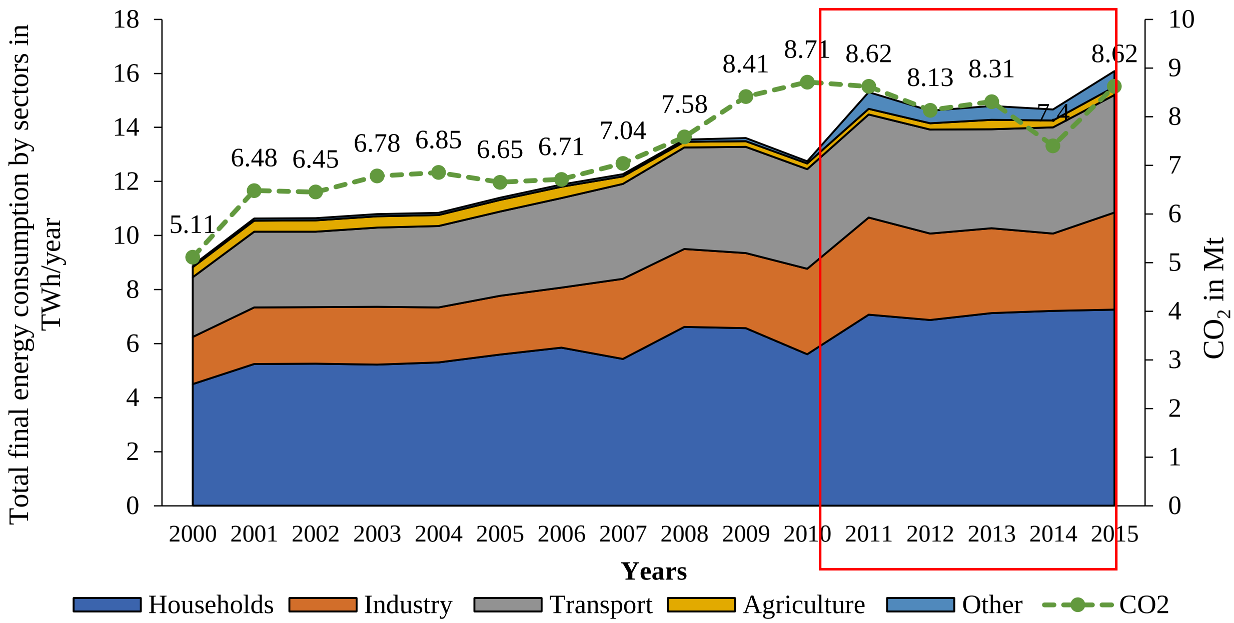


Figure 72 Total final energy consumption by sectors and CO_2 emissions over the period 2000-2015

An average specific energy consumption per capita per sector was estimated using the recorded data from 2010 - 2018 (see Table 19) for energy demand projections. The total final energy consumed in a sector during a certain year was divided by the population density of that respective year. In this way, the per capita specific energy consumed by sector in a respective year was estimated. Then an averaged value for the period 2010-2018, was estimated and the results of the calculation are presented in Table 19. This period was considered because of the fewer power outages leading to the satisfying of power demand-supply requirements. Because the household sector accounts for the largest energy consumption in the Kosovo energy system, the average annual per capita specific heat demand was the largest 3.009 MWh/capita, among other sectors. This is because 75 - 85% of the final energy in the household sector is consumed for space heating and hot water preparation [149]. Population projections scenarios, low, medium and high case, over the period 2010-2060 were carried out by Kosovo Statistic Agency, as shown in Table 20.

Table 19 Averaged annual specific energy consumption per capita (2010-2018) [1], [61], [2]

Specific energy consumption	Electricity	Heating	Transport	Industry	Others
MWh/capita*year	2.850	3.009	2.365	1.823	1.087

Table 20 Population projection scenarios [2]

Population projection	2030
Low case	1603544
Medium Case	1821470
High Case	**2116862**

The energy demand by sector for 2030 was estimated when multiplying the per capita specific energy demand by sector with the projected population for the year 2030. The results of the calculation are shown in Figure 73.

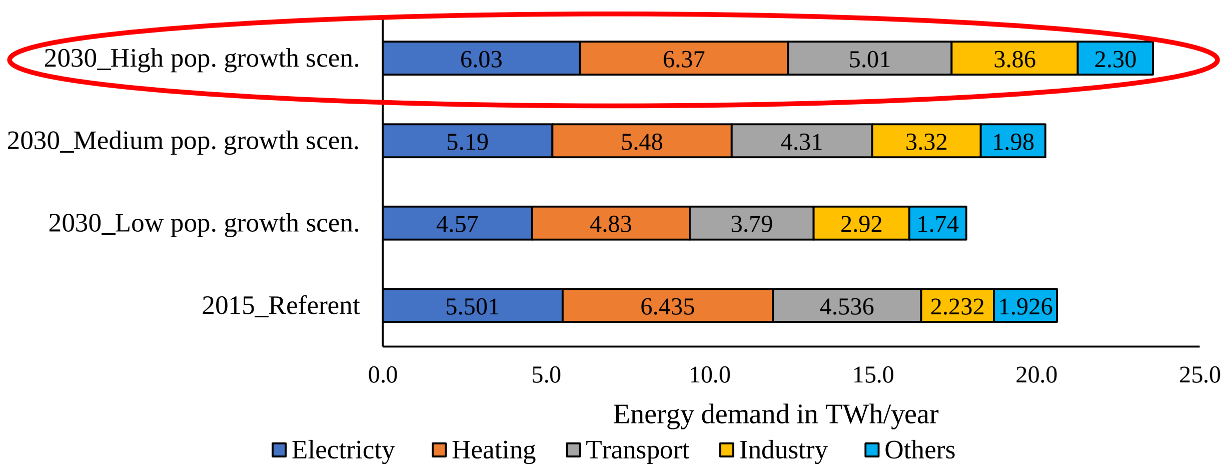


Figure 73 Energy demand projections by sectors

Over three demand projected scenarios, the highest demanded one was selected for designing and modelling sustainable transition pathways for the Kosovo energy system in 2030. It can be noted that energy demand for heating has remained the same as in reference scenario 2015, while energy demand in other sectors is significantly increased. Specific heat demand per capita can be further decreased with the application of energy efficiency measures, but that is not the purpose of current research. The reference scenario for the year 2015 is already modelled in previous research [54] and the results of modelling are shown in Table 21. The same share of final energy carrier in each sector by 2015 is assumed for the year 2030. The same approach was used for all sectors, except the electricity sector, where the newly installed small hydropower plants and wind turbines operating since 2018, compared to the reference year 2015, are considered. Hence, they cover a small electricity demand. For illustration, the total final energy consumed in the transport sector in 2015 was 4.537 TWh/year, and the specific share of diesel consumed in total final transport demand was 68%, petrol 26% and LPG 6%.

Table 21 Electricity production by source

<table>
<tr><th rowspan="14">Base scenario 2030</th><th colspan="3">Electricity production in TWh/year</th></tr>
<tr><th>Fuel</th><th>2015</th><th>2030</th></tr>
<tr><td>Coal</td><td>5.359</td><td>5.551</td></tr>
<tr><td>Oil</td><td>0.000</td><td>0.000</td></tr>
<tr><td>NG</td><td>0.000</td><td>0.000</td></tr>
<tr><td>Biomass</td><td>0.000</td><td>0.000</td></tr>
<tr><td>Nuclear</td><td>0.000</td><td>0.000</td></tr>
<tr><td>Wind</td><td>0.000</td><td>0.032</td></tr>
<tr><td>Solar PV</td><td>0.000</td><td>0.000</td></tr>
<tr><td>Hydro</td><td>0.142</td><td>0.227</td></tr>
<tr><td>Excess Heat</td><td>0.000</td><td>0.000</td></tr>
<tr><td>Geothermal</td><td>0.000</td><td>0.000</td></tr>
<tr><td>Import/export</td><td>0.715</td><td>0.220</td></tr>
</table>

Table 22 Final energy consumption by sectors for the reference year 2015 [169] and projected for the base year 2030

	Heating TWh			**Industry TWh**			**Transportation TWh**			**Other TWh**		
	Fuel	**2015**	**2030**	**Fuel**	**2015**	**2030**	**Fuel**	**2015**	**2030**	**Fuel**	**2015**	**2030**
Base scenario 2030	Coal	0.911	0.892	Coal	0.302	0.540	JP	0.000	0.000	Coal	0.214	0.253
	Oil	0.794	0.764	Oil	1.744	3.011	Diesel	3.107	3.407	Oil	0.343	0.414
	NG	0.000	0.000	NG	0.000	0.000	Petrol	1.157	1.303	NG	0.000	0.000
	Biomass	2.800	2.803	Biomass	0.186	0.309	NG	0.000	0.000	Biomass	1.369	1.633
	Electricity	1.930	1.911			**3.860**	LPG	0.272	0.301			**2.300**
	Solar	0.000	0.000				Electric	0.000	0.000			
			6.370						**5.010**			

By combining the increased energy demand by sectors with the specific share of the final energy demand mix, the projected final energy demand in transport was estimated to account for diesel 0.68*5.010=3.407 TWh/year, petrol 1.303 and LPG 0.301 TWh/year. This means that the technology expansion in transport and other sectors will continue with the same trend because no action or policies are considered to change it. This scenario reflects the fact of not implying any energy policy neither investing in new technologies. This is not defined according to any national documents; however, this reflects the worst-case scenario.

3.6.2 Energy system scenarios for 2030

Five different scenarios were developed for 2030 to meet the final energy demand already explained in Table 22. These scenarios were created to identify the future energy system costs, investigate the uncertainties in decision-making processes regarding the construction of new thermal PP Kosova e Re and demonstrate if there are other sustainable energy transition pathways and how to assess them, especially in the power generation sector. Compared to base one, these scenarios apply different energy supply solutions and synergic effects between the electricity and heating sector, as already shown in Table 23. Scenarios were developed in line with Kosovo goal regarding the RES share in final energy demand and CO_2 emission reduction targets. Kosovo cannot apply the target of reducing CO_2 emissions by 40% compared to 1990 levels because from 2000-2010 the power supply has not met the demands due to frequent outages. Because of that, RES share, 32% in total final energy consumption, seemed a more reasonable target and was considered in all scenarios as the main objective. Furthermore, scenarios were developed to utilize the local assessed potential of renewable energy resources while less being dependent on imports. Because the country has not yet developed any strategy for 2030, actual research may be very relevant for preparing future strategies for energy transition and RES penetration. It was shown in research [54] how much variable Wind, PV and combined RES can be integrated into the existing Kosovo power system and how the increasing penetration of RES can be achieved by coupling the heating and electricity sector. Capacities shown in scenarios are modelled based on the current ability of the Kosovo power system to accommodate such variable RES (Table 23). Besides, Kosovo has an excellent power transmission capacity of 1250 MW, which can allow surplus electricity production export flow.

The base scenario shows the case of not considering any policy to invest in technology for meeting the global commitment regarding climate change mitigation. In this scenario, current PP technologies will continue to supply the main electricity demand, and the efficiencies of TPP remains the same as in 2015. Demand is increased in all sectors as shown in Table 22, however no penetration of new technologies is considered. PP Kosova A will operate with an installed operational capacity of 450 MW with a total efficiency of 26%. Kosova B will operate with an operational capacity of 520 MWel and a total efficiency of 32%. Other energy production capacities have remained the same as in 2015, except a wind power capacity of 33.36 MW and hydro power plant of 94 MW, which are already installed in the power system since 2018. No investment in energy production and conversation is considered in this scenario, reflecting the case of undertaking no policies to meet RES final energy consumption and emission reduction goals.

The first scenario shows the current policies regarding RES penetration in the electricity sector by 2020. We applied the same RES capacities set by Kosovo authorities in the power sector for wind power plants 180 MW, PV 30 MW, hydro 150 MW, and biomass 11 MW, but new policy solutions regarding the heating sector were proposed in this scenario to meet the country commitment. An expansion increase of the DH system to around 50% of total heat demand was considered. Such expansion was proposed by Word bank, however, papers [78], [112] show that there is a significant potential for expansion of DH, even in Prishtina municipality, which is around 5 km away from thermal PP's and applies a cogeneration system. Replacement of oil-based Gjakova DH with Biomass DH was reflected as well, since this project is already under the development phase. Furthermore, 20% of individual electric heaters are proposed to be replaced with individual heat pumps in areas with no connection to the DH system. Apart from that, a new construction CHP called Kosova e Re with an installed capacity of 450 MW, (320MW_{el} and 130MW_{th}) was considered.

In the second scenario, compared to the first one, some of the developing projects regarding RES integration in electric power supply (Wind and Hydro) that have applied for licenses in the Kosovo energy regulatory office are shown. This scenario considers significant changes in the electricity sector and no changes in other sectors. Kosovo energy strategy 2017-2026 foresees the utilization of 236 MW hydro-power plants. Wind power projects which are in the status of preliminary and final authorization received by the Kosovo Energy Regulatory Office are considered. The total capacity of wind power developing projects account for 237.7 MW: Selac I, II, III with 105MW, Konznice 34.5MW, Wind park Zadric I, II 64.8 MW. Golesh 1.345 MW and Kitka 32.48 MW are already operating. The PV power plant capacity has remained the same as in scenario 1. A reconstruction of a thermal PP Kosova A (A_1 and A_2 proposed by Word Bank) with an installed capacity of 450 MW based on coal and biomass co-firing shares 80 for coal and 20% biomass is considered. Replacement of oil-based Gjakova DH with biomass DH is considered as well.

A renewable-based energy system was considered in scenario 3. This scenario applies available technologies but with significant changes in the heating and electricity sector. RES integration capabilities can be efficiently utilized even in a closed Kosovo power system if proposed changes in the heating sector are considered. It does not consider the construction of large PP New Kosova or Kosova A reconstruction, however, it considers small CHP construction, which will be based on coal and operating in different Kosovo municipalities covering both electricity and future DH demands. Furthermore, it also reflects the significant integration of individual and large-scale heat pumps both for individual and DH purposes and thermal energy storage in DH.

Scenario 4, considers the application of developing technologies like carbon capture and storage (CCS) in a newly constructed PP with 450 MW. The electricity consumed for CCS technology was set 0.37 MWh/tCO_2 and hence a calculated CCS capacity of 42 MW was needed for cutting emission by half. Because of significant electric consumption by CCS technology, significant scaling-up in variable Wind and PV share was considered for meeting the electricity demand. Hydropower plant capacity and Gjakova DH fuel replacement have remained the same as in the base scenario. Additionally, 15% of individual electric heaters are proposed to be replaced with individual heat pumps. A detailed description of the energy supply proposed scenarios is presented in Table 23.

Scenario 5 highlight the impact of power sector decarbonisation by considering the phasing out of PP Kosova A and an aggressive penetration of variable RES in the power sector. According to IRENA, the Kosovo Wind power potential is around 2400 MW, while the PV power potential is 560 MW respectively. Research shows that more variable RES can be integrated into power systems when the ratio of 1 MW Wind and 1 MW PV is considered. In Kosovo, to meet the 32% RES share in final energy consumption, wind and PV power capacities should be increased to 1800 MW and 450 MW respectively. This is only possible when the existing interconnection cable capacities 1250 MW are fully utilized to avoid power curtailment. This scenario does not consider the synergic effect between the electricity and heating sectors.

Table 23 Proposed Kosovo energy supply scenarios for 2030

	Scenario 1	**Scenario 2**	**Scenario 3**	**Scenario 4**	**Scenario 5**
Heating	20% replacement of individual electric heaters with individual HP Utilization of DH up to 18% share of total heat demand (DH demand = 1.0 TWh/year)	Replacement of Gjakova oil-based DH with biomass Construction of PP with an installed power 450 MW based on coal and biomass co-firing with 80 and 20% respectively.	100% replacement of individual electric heaters with individual HP Utilization of DH up to 25% share of total heat demand (DH = 1.27 TWh/year)	15% of electricity consumed individual electric heaters is replaced by individual HP Replacement of Gjakova oil-based DH with biomass	Increase in wind power from 32 MW to 1800 MW Increase in PV power from 0.6 MW to 450 MW Utilize fully 1250 MW transmission cable capacities
	Installing large scale heat pump in Cogeneration based DH with a 30MWel capacity	Increase in Wind power from 33 MW to 237.7MW	Coal and oil boilers are not used for individual heating	Construction of new PP with total capacity 450MW based on coal & CCS capacity 42MW	No changes were proposed No changes were proposed
Electricity	Replacement of Gjakova oil-based DH boiler with biomass Construction of new CHP with total capacity 450MW, (320MWel and 130MWh) based on coal and biomass co-firing with 70 and 30% respectively.	Increase in PV power from 0.6 MW to 30 MW Increase in hydro power from 75 to 236 MW	Installing large scale heat pump in Cogeneration based DH with a 20 MWel capacity (group 3) Biomass used for individual heating is reduced by 50%	Increase in wind power from 32 MW to 620 MW Increase in hydro power from 75 to 150 MW	
	Increase in hydro power from 75 to 150 MW	No changes were proposed	Installing large scale heat pump in new CHP based DH with a 50 MWel capacity (group 2)	Increase in PV power from 0.6 MW to 300 MW	
	Increase in wind power from 32 MW to 180 MW		Installing large scale diurnal thermal energy storage in DH with 10 GWh	No changes were proposed	
	Increase in PV power from 0.6 MW to 30 MW		Replacement of Gjakova oil-based DH with biomass		
Transport, industry and other sectors	No changes were proposed		Construction of new CHP with total capacity 300MW, (150MWel and 150MWh) based on coal. Increase in wind power from 32 MW to 620 MW Increase in hydro power from 75 to 234 MW Increase in PV power from 0.6 MW to 300 MW 7% of diesel-based vehicles are replaced with electric cars		

3.6.3 Technical, economic and environmental analysis

The adaption of the EU's clean energy package for 2030 in a highly dependent coal-based energy system is considered in this research. The introduction of a carbon pricing system per tonne of CO_2 around 30 EUR/tCO_2 was also considered. The results of the modelling are presented in Figure 74. The primary energy supply mix differs significantly between scenarios because of the renewable scale-up and benefit synergies between sectors. The share of RES in final energy consumption for the base scenario, with no investment in technology, was 15%. In all other sectors, the target was met, accounting for 32% RES share in final energy consumption. Significant coal supply in primary energy mix around 17.52 TWh/year, in the base scenario, is due to the use of old and inefficient coal thermal PP's for electricity production. Oil products that are consumed predominantly in the transport sector are entirely imported. Biomass utilization in all scenarios was considered by considering its maximum utilization potential already researched in paper [170], [171]. It can be seen that the primary energy supply can be reduced significantly compared to the base scenario if proper decision-making energy policies are considered. The total primary energy supply in the base scenario was 31.5 TWh/year, but in other sectors, the same was significantly lower, accounting for 23.5 TWh/year, respectively.

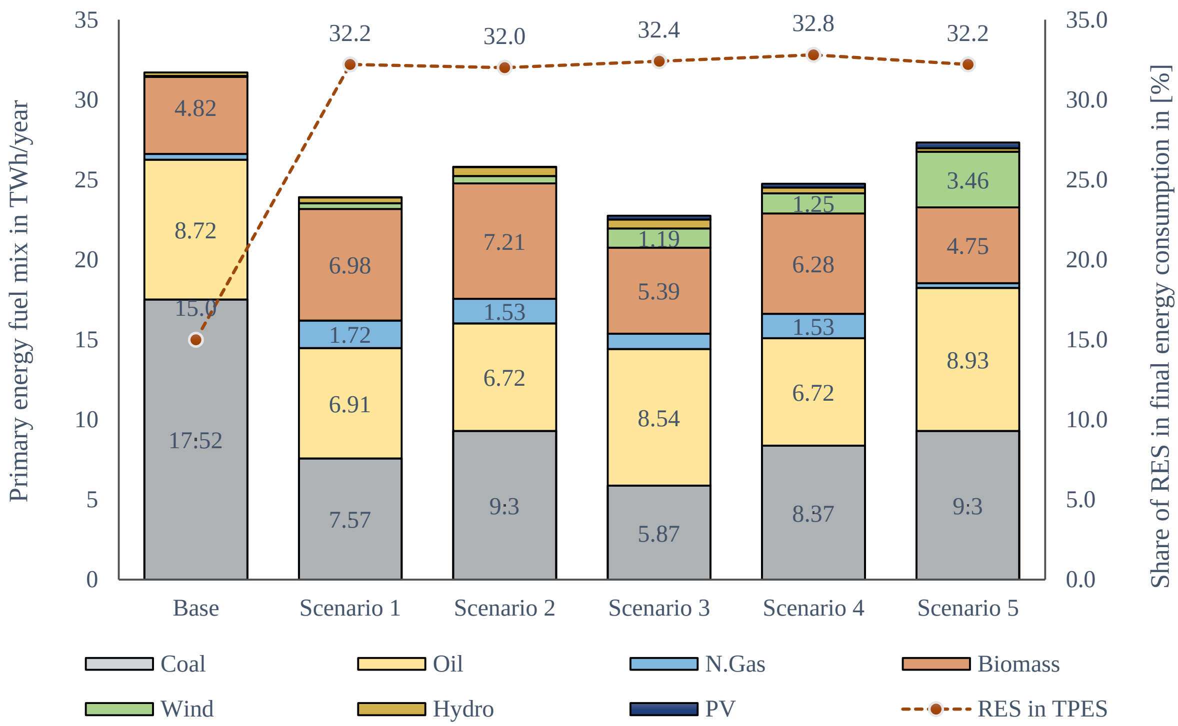


Figure 74 Total primary energy supply mix and share of RES in total final energy consumption by 2030.

In 2030, the total electricity demand was 6.03 TWh/year, which is slightly higher than the actual demand of 5.5 TWh/year recorded in 2015. Kosovo power system was simulated as an insulated system, however, there is already established a strong interconnection grid network. There are four 400 kilovolt lines with Albania, North Macedonia, Serbia and Montenegro. Their combined capacity is around 2300 MW. 400kV line is not energized for import/export utilization due to political issues, however scenario 5 considers that 1250 MW transmission cable capacity is fully utilized for power flow. Recorded historical data over the years have shown that electricity import from other countries was from 12% to 18% of total annual domestic electricity consumption and the import electricity price differed from 40 to 80 EUR/MWh. Electricity import in base scenario was 3.6% of total domestic electricity demand, and in other scenarios 1, 2, 3, 4 and 5 this share accounted for 0.3%, 5.1%, 2.65%, 0.5% and 8.2% respectively. RES capacities can be easily integrated into the Kosovo power system because of the significant interconnection capacity as well as available synergies between sectors. Research showed the actual RES capacities that can be integrated into the Kosovo power system without exceeding the critical excess electric production limits. Current scenarios were simulated based on the Kosovo power system able to accommodate variable RES. Figure 75 presents the power generation capacities as well as the share of RES in electricity production in all scenarios. The total actual installed capacities for electricity production in Kosovo is about 1560 MW. However, only 750-1030 MW of thermal PP capacity is operational because of mechanical and electrical issues that result in forced outages. Results of hourly model simulations have shown that the share of renewable energy sources in electricity production in the base scenario was 7%, while in scenarios 1, 2, 3, 4 and 5, this share was significantly increased to 36.2%, 36.1%, 50.2%, 48.5% and 67.1% respectively.

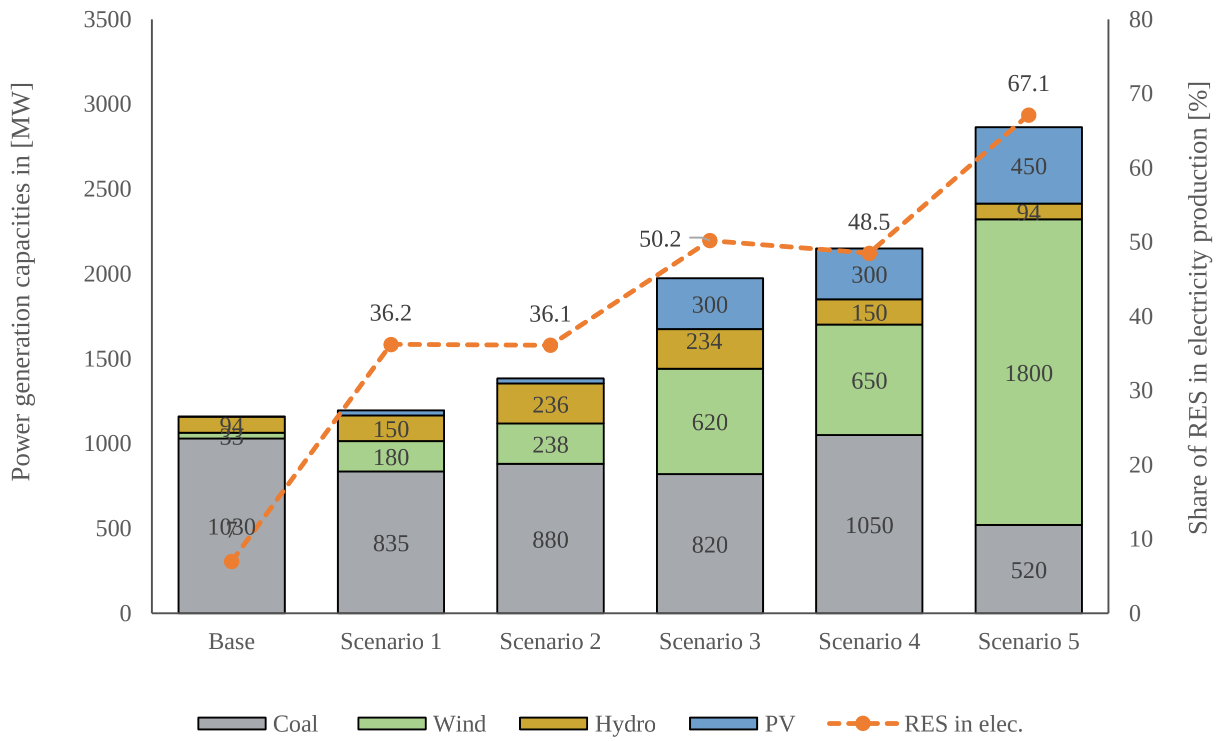


Figure 75 Power generation capacities and share of RES electricity production by 2030.

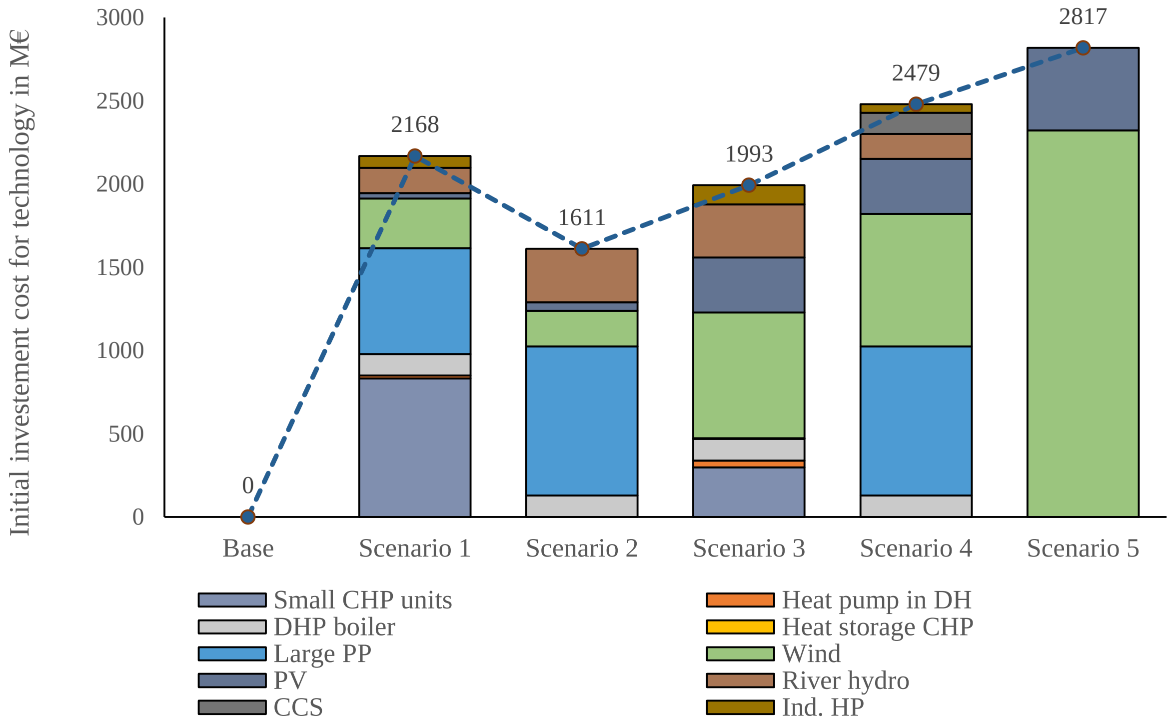


Figure 76 Initial investment cost by technology in Million EUR.

The initial investment cost per technology and their total investment cost per scenario are shown in Figure 76. The costs presented here reflect only the costs for additional energy production and conversion excluding the costs for power generation capacities that are already installed and being operated. It can be shown that scenario 5 is the most expensive; however, scenario 4 is the most environmentally friendly compared to other scenarios. It is a risky scenario because the CCS technology is not a mature technology used for large-scale applications. In terms of initial investment costs, the most cost-effective scenario is scenario number 2, which is particularly based on scaling up RES sources in the power sector and constructing a new PP while paying less attention to other sectors. Scenario 3 is a renewable-based scenario, where the main investments are made in Wind, PV, hydro and small CHP construction. In scenario 1, 48% of total investment cost (2168 m€) is investing in CHP, 29% large PP, 14% wind, 7% hydropower, 6% DH fuel replacement, 3% for individual HP and 2% for PV solar power plants. In scenario 2, 56% of the total initial investment contribution is in PP, 20% hydropower, 13% wind, 8% DH fuel replacement to biomass, and 3% PV. In scenario 3, the largest initial investment contribution is wind 38%, PV 17%, hydro 16%, small CHP 15% and smaller shares around 6% per individual HP and DH fuel replacement, 2% for HP in DH. In scenario, 4 besides investments in RES, additional investment costs for CCS technologies are applied. Planned thermal PP capacities were considered, but additional RES capacities were needed for meeting the final RES energy consumption target. Scenario 5 considers aggressive variable RES investments in the power sector, especially wind and PV, accounting for 82% and 18% of total initial investments, respectively.

Figure 77 shows the same investment cost in annual basic. This cost is calculated by dividing the total investment cost by the lifespan of a certain technology. Furthermore, the fixed O&M costs are calculated annually and the results are shown in a stacked diagram. Besides investment and fixed costs, the variable cost which is related to the 0&M of proposed new technology, is considered. All these costs are shown in Figure 77.

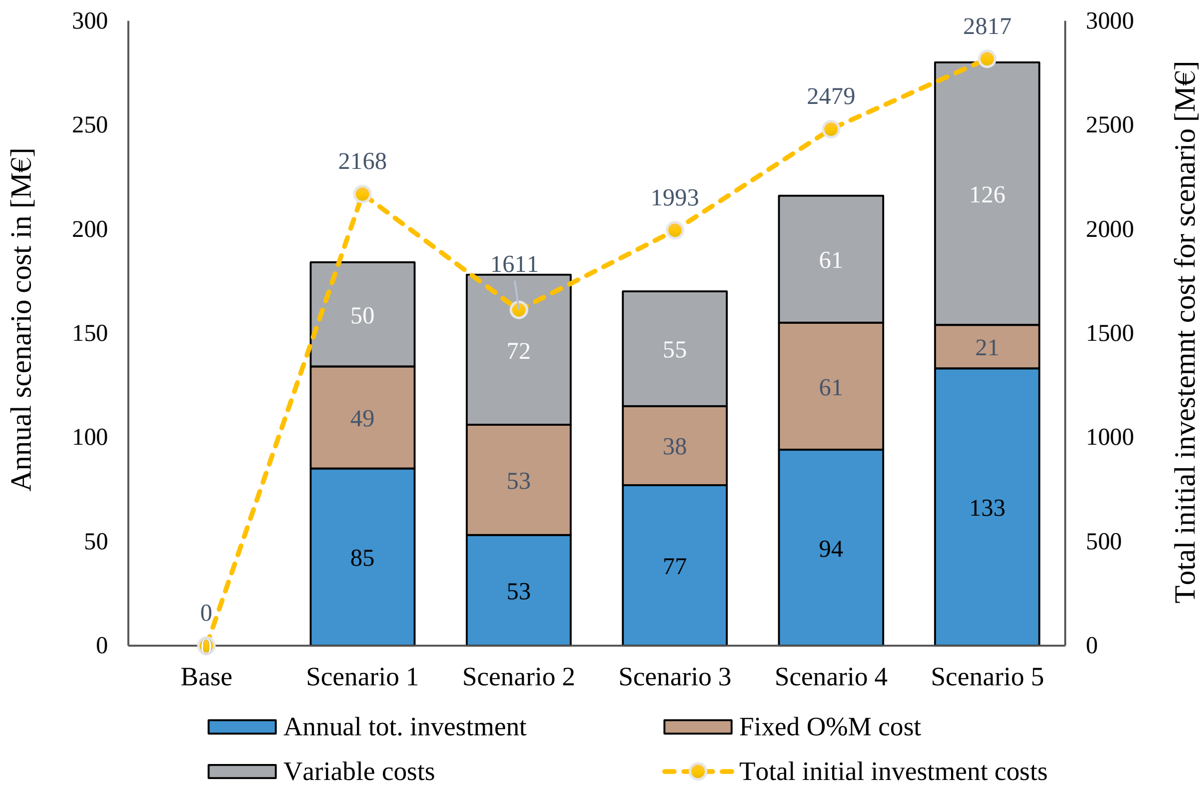


Figure 77 Annual and initial investment costs per scenario in Million EUR.

A carbon pricing tax of around 30 EUR/tCO_2 was considered to comply with EU goals. The energy community secretariat proposed policies for introducing a minimum carbon pricing system for the countries of Western Balkan to avoid the carbon border adjustment mechanism for electricity export [172]. The annual costs per scenario shown in Figure 78 are the sum of investment, fixed O&M and variable costs. The results of modelling and simulation showed which scenario is the most environmentally friendly and economically viable. CO_2 emission has been increased significantly from 8.6 Mt in 2015 up to 9.34 Mt by 2030 if no policy is undertaken. Significant CO_2 emission reduction was achieved around 4.5 Mt when comparing the first scenario with the base one. A similar trend of CO_2 emission reduction was achieved in the second, third, fourth and fifth scenario compared to base one accounting for 4.06 Mt, 4.86 Mt, 5.37 Mt, and 4.38 Mt, respectively. The higher emission reduction potential is observed when applying CCS technologies as well as in renewable-based scenario 3. Considering technology penetration and CO2 emission costs among scenarios, the total annual energy system costs account for 280.2 mil. EUR for base scenario, and 327, 336, 304, 335, 399 mil. EUR per scenario 1, 2, 3, 4 and 5 respectively. It can be seen that for the base scenario, with no policy undertaken, the annual price of CO_2 increases up to the annual price of scenario 3, which considers significant penetration of variable RES. This further emphasizes the importance of RES integration and their future energy system viability. Scenarios 2 and 4 and 5 are the least cost-effective scenarios regarding the total investment cost compared to other mature based energy scenarios. Scenario 5 highlights the impact of investing in a power sector, without considering sector coupling, leading to an inefficient, high cost and less environmentally friendly transition pathway. The issue with scenario 4, is the application of CCS which is still in the development phase. Renewable based scenario 3, with sector coupling, was the cheapest even when considering a very high carbon tax fee among other scenarios. Scenarios 1 and 2, applies different energy production and conversion technologies, hence they have different annual emission costs as shown in Figure 78. Even though the annual scenario cost was higher in scenario 1 (184 mil. EUR) than scenario 2 (178 mil. EUR), when considering CO2 emission costs, the total annual scenario cost changes its cost-effectiveness to 327 and 336 mil. EUR for respective scenarios. In addition, scenario 1 is a more environmentally friendly solution due to a lower impact on the environment. In conclusion, considering the technology development, total annual energy system costs, and environmental impact among scenarios, the renewable-based scenario is considered the best available solution (scenario 3).

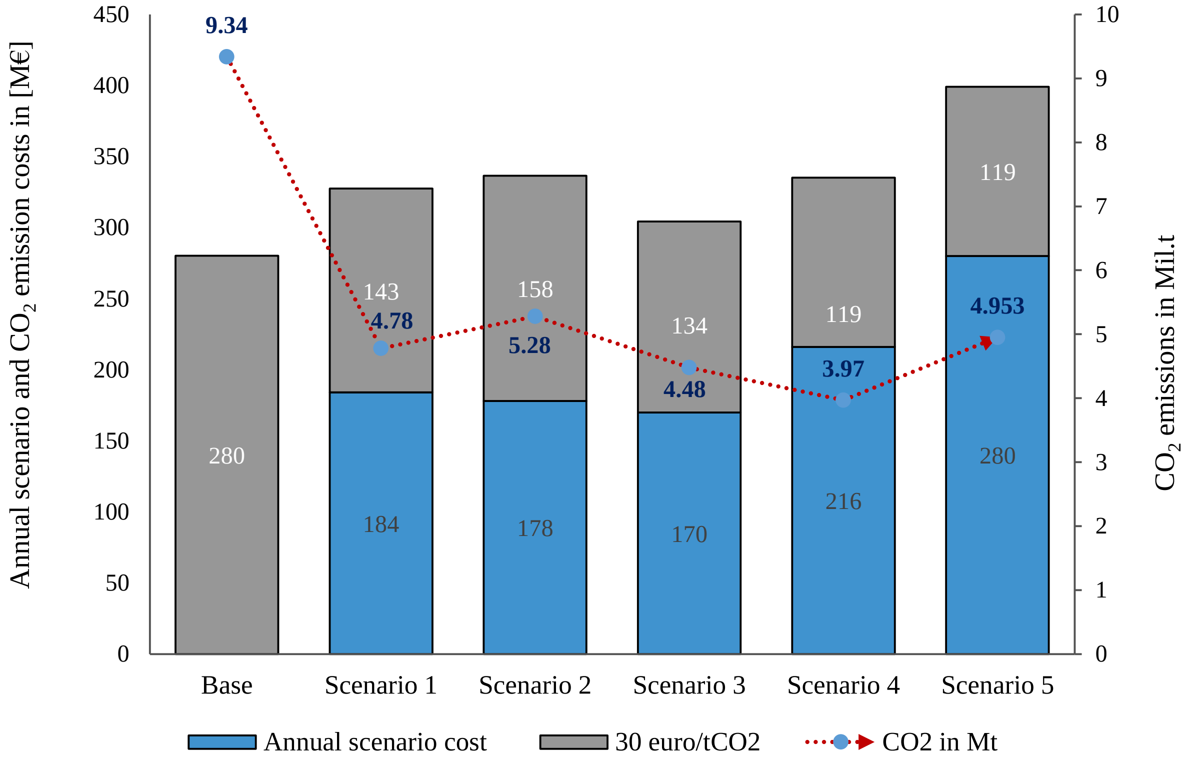


Figure 78 Annual scenario and CO2 emission costs

4. CONCLUSIONS AND RECOMMENDATIONS

The methodology used to assess the impact of power to heat technologies to integrate variable renewable energy sources in coal-based energy systems is described in detail in the previous sections. Firstly, the heat demand of buildings is estimated using two different approaches, bottom-up and top-down. Then the assessment potential of future district heating systems is performed considering domestic hot water demand of buildings besides space heating. Additionally, the space heat demand saving potential was estimated using available data from energy auditors. The role of individual heating and transport electrification in coal-based energy systems was carried out besides the use of power to heat technologies in district heating systems. Particular findings were used to asses sustainable transition pathways in coal-based energy systems.

The results of the bottom-up mapping method are compared with the top-down mapping results, and then validated. The model considers both residential and commercial end-users. Two bottom-up scenarios were developed. Scenario 1 considers buildings that are heated up to their net heated areas, while the second scenario considers buildings partially heated. For the same reason, the proposed approach can be used for assessing mapping in both developed and developing nations. The findings show that heat demand in the first scenario is tripled (153/51 GWh/year) in comparison to top-down heat demand mapping, while for the second scenario, the same difference is almost negligible 53-51=2 GWh/year. The bottom-up mapping requires more detailed data, resources, and time than top-down mapping, which is less data-intensive.

An assumption, which neglects the height of houses in the second scenario, is applied. The same can be used by other models when assessing bottom-up mapping in developing area locations. In addition, the second scenario considers that all the houses are heated partially up to an average surface. Such surface can be taken from building cadaster datasets. For houses with insulation, such average surface was 53 m2, while for the houses without thermal insulation was 45 m^2 respectively. The model does not differentiate between partially heated rooms in houses due to the lack of available provided data. However, since the overall heat demand consumed annually by houses is small compared with the apartment and public buildings, such an assumption does not significantly impact final bottom-up heat demand maps.

The method is replicable as it can be used for assessing heat demand maps in other cities with similar physical and boundary operating conditions of buildings, respectively houses. Since the other municipalities in Kosovo have shown almost the same share of heating rooms, the methodology and assumptions presented in this research can be used for assessing other heat demand maps.

A spatial-temporal method for obtaining the bottom-up aggregated space heating and DHW demand maps and curves for actual and potential DH demand has been developed. The method has been applied to the urban building stock of Prishtina. Compared to other bottom-up approaches that are applied to estimate DH potential, this research has further considered the analysis of DHW demand. Apart from that, this research takes into account the impact of fully and partially heated buildings, which reinforces the application of this approach in both developed and developing countries. It was estimated that the total potential heat demand for space heating and DHW that is feasible to be supplied by the DH system is 1.80 TWh/year when considering that buildings are heated to their net heated area. However, this is not the actual case for Kosovo, since houses are not being heated to their net heated areas. When considering this in the model, the total estimated heat demand that is feasible for being supplied by DH is reduced to 1.32 TWh/year. The actual heat supply by DH for buildings in Prishtina is 250 GWh/year and is used only for space heating purposes, so the potential for expansion of DH in this city is significant. This means that actual DH in Prishtina is supplying only 19% of feasible potential DH demand.

This research also developed a method for modelling the hourly distribution of DHW demand in DH considering hourly, daily, weekly and seasonal variations in hot water demand profile. The temporal distribution of space heating and DHW demand is important for energy systems' planning and modelling analysis. In terms of needed capacities to meet the demand in the expanded potential of DH, research has shown that for space heating, the maximal capacity would be around 600 MW. Additional 70 MW thermal capacity would be needed for covering DHW demand in DH during the winter season.

A similar approach can be used in other urban areas if the specific data on the building floor, height, and energy performance certificate per building category is known. However, for all other urban areas in Kosovo, such data is not available. There exists only spatial data regarding the 2D urban area views recorded from space satellites, which can be applied for the production of building floor areas, but the evaluation of building heights and their categories can only be done through the visual investigation of buildings or by using surveys. Such a process of data collection and processing requires a considerable amount of time and resources, hence this method for data collection could prove to be a non-feasible approach. Temporal heat demand profile (both space heating and DHW) can be of high importance when studying renewable heat integration in the DH system (for instance: solar thermal collectors, waste heat resources, the power to heat technologies, among others). It is important that actual DH systems that operate seasonally should switch to annual operation because of the increasing utilization of RES. Local authorities, utilities and policymakers can harness the results regarding the expansion priorities of DH to utilize their maximum heat production potential and plan, developing new capacities, increasing the reliability of heating supply as well as meeting the targets and obligations regarding the energy efficiency implementation measures.

The following presents a method for spatial evaluation of space heating demand and CO_2 emission saving potential based on energy efficiency measures in buildings. The method has been applied to a municipality in Kosovo. Two energy efficiency scenarios have been proposed and the results show that there is a significant potential for both space heating demand and CO_2 emission reduction within the city. For the first and second scenarios, the space heat demand savings accounted for 1.12 TWh/year and 1.53 TWh/year, respectively, when compared with the actual space heating demand of the existing buildings stock (reference scenario). The simulation results were shown in a layer grid map with 200 m × 200 m and a district-based map of the city. Higher space heating demand saving potential was identified in districts with high rise buildings and apartments while less saving potential in areas populated by individual houses as the main building category.

When observing at the building level, the results of scenario 1 have shown that applying EEs, apartments can save up to 65.2% of their actual space heat demand, commercial 43.5%, houses 39.2%, public 54.2%, nhouse 53% and office buildings 44.8% respectively. In the second scenario, compared to actual space heat demand, apartments can save 72.2%, commercial 61.7%, houses 64.1%, public 79.8%, nhouse 79.5% and office buildings 57.8%. Apart from the analysis of space heating demand distribution spatially, it was further shown that the required capacity of heat can be reduced significantly with proposed EEs and EEa measures accounting for 50% and 68% as compared with the actual needed capacity. Furthermore, it was shown that with the application of energy efficiency measures in buildings, the CO_2 emissions can be reduced significantly, accounting for a decrease of 49.7% in scenario 1 and 68.3% for scenario 2, when compared with the reference scenario.

The approach elaborated in this thesis can be applied in data-scarce areas for bottom-up modelling of the heating sector. The proposed method contributes to applying GIS-based research for space heat savings' studies and is replicable as it can be used for rural and urban areas equally. The results from this approach can be continually improved and updated with new information regarding the building energy certificates, energy efficiency measures proposed by energy audits for buildings, among others. The application of this approach at the national level still lacks, as there is no complete spatial data regarding the building geometries (footprints areas and number of floors), building energy certificate, energy audits, building age and building form of use. Moreover, the data sources used in this approach to identify building's form of use and building categories in other urban areas are lacking.

This thesis developed a method for assessing the role of transport and heating sectors electrification as a supporting mechanism to integrate variable RES and highlighting the consequences on thermal power plant operation capacities and efficiencies for a highly dependent coal-based energy system. A reference year was modelled and hence validated with recorded data for the base year 2015, for which enough data was found in the existing literature. Different scenarios were developed in this study to define variable wind and PV capacities that can be integrated into a coal-based power system with the increasing share of EV's (passenger and light-duty vehicles) and individual heat pumps while maintaining high flexibility TPP's. Moreover, the results also show what would be the consequences of the increasing share of variable RES capacities in a coal-based energy system in terms of TPP efficiency decrease and hence CO_2 emission increase.

It was shown in scenario S_1 that exiting the Kosovo power system, when operating in an island mode, can integrate 528 MW wind and 132 MW PV in the power system. If all passenger and light-duty vehicles are electrified (Scenario S_3), while maintaining 80% flexible TPP, 701 MW wind and 136 MW PV can be utilized in the Kosovo power grid without curtailing the power flow and maintaining high reliability of power supply. In case thermal power plants become fully flexible (Scenario S_4), even more vRES can be integrated into the power grid accounting for 825 MW wind and 206 MW PV, respectively. It was concluded that the maximum contribution of transport electrification with passenger and light-duty EV's to integrate variable renewables in the Kosovo power grid is significant, accounting for 297 MW wind and 74 MW PV capacity, respectively. When increasing the vRES in power grids, TPP will operate with part-load capacities to allow renewable utilization in power grids. This will make TPP's operate bellow their related power, hence decreasing the efficiency of the entire process, known as part-load efficiency of TPP or power plant cycling. The decrease in efficiency will result in a CO_2 emission increase. For instance, for Scenario S_1, the annual averaged efficiency of exiting Kosova A and B TPP would decrease from 26% and 32% to 23.5% and 29.9%, respectively. In addition, the total CO_2 emissions of the energy system will increase due to TPP cycling from 6.92 to 7.2 Mton/year. In the case of full transport electrification according to scenario S_4, the CO_2 emission because of TPP cycling will increase from 5.95 plus 0.31 to 6.26 Mton/year respectively.

Moreover, the study highlighted the contribution of individual heat electrification as a supporting measure to integrate vRES in a coal-based energy system. It was demonstrated that maximum utilization of vRES capacities of around 701 MW for wind and 175.3 MW PV can be integrated into the existing Kosovo power grid with 70% heat electrification with heat pumps, while maintaining 100% flexible thermal power plants (Scenario S_7). When considering cycling in existing TPP, the total CO_2 emissions for the same energy system operating state (S_7) accounts for 5.7+0.33 = 6.03Mton/year.

When comparing 97% of transport electrification with 70% heat electrification, while maintaining 100% flexible thermal power plants, the resulting CO_2 emissions account for 6.26 and 6.03 Mton/year, respectively. This means that heat electrification according to scenario S_7, has a greater impact in terms of CO_2 emission decrease when compared with transport electrification scenario S_4. In scenarios considering the revitalization of TPP's, the resulting CO_2 emissions decrease significantly. For instance, when comparing Scenario S_4 with existing and revitalized TPP efficiencies, the total CO_2 emissions will decrease from 6.24 to 5.33 Mton/year. Similarly, for scenario S_7 with existing and revitalized TPP efficiencies, the total CO_2 emissions will decrease from 6.03 to 5.22 Mton/year. The study also reveals that at high TPP efficiencies, the CO_2 emissions because of cycling decrease significantly.

The following conclusions demonstrate a significant positive contribution to the implementation of P_tH technologies on the increased potential for renewable penetration into coal-based power systems with limited transmission line capacities. It has been shown that PtH technologies can provide a significant increase of coal-based power system flexibility. A higher share of variable renewables will, of course, positively affect the reduction of CO_2 emissions and fuel consumption. The integration of HPs into DH could increase the potential for increasing the RES significantly, especially in isolated energy systems.

It was found that the wind and PV power plant capacities that can be installed in the actual Kosovo energy system, when operating in an isolated mode, are 450 MW and 300 MW, respectively. Additional power plant capacities around 800 MW for wind and 385 MW for PV can be further integrated into this isolated energy system with the contribution of P_tH technologies coupled with thermal energy storage in DH. It was shown that such additional wind and PV capacities will cover 14% and 5% of the total annual electricity demand. Apart from this, 515 MW was estimated variable RES (sum of Wind+PV) integration because of the application of P_tH in DH, covering for 8 % of total annual electricity demand. Expect such analysis, different P_tH

capacities were assessed to estimate their impact on CEEP reduction and variable RES integration in an isolated energy system. It was found that maximum integration capacities for wind, PV and RES happens at different HP+HS capacities. For instance, for maximum integration of wind power plant, the following capacities are needed HP=180 MW_{el}, COP=3 & HS=14 GWh/year. In contrast, very small capacities of HP+HS (HP=40 MW_{el}, COP=3 & HS=4 GWh/year) is needed for maximum utilization of PV power plants. Compared to separate wind integration, smaller capacities of HP+HS are needed for maximum utilization of variable RES. With other words, HP+HS capacity needed account for HP=110 MW_{el}, COP=3 and HS=8 GWh/year.

Besides the contribution of DH and P_tH to increase the share of variable RES power plants in power systems, they can additionally contribute to increasing TPES and CO_2 emission savings. DH supplying 50% of total heat demand with the capacity of P_tH (HP=180 MW_{el}, COP=3, HS=16 GWh/year) was considered for estimation of TPES saving and CO_2 emission reduction. It was found that separate integration of wind can contribute to decreasing TPES and CO_2 emissions for 12% and 14% compared to the reference scenario. TPES and CO_2 emission savings for separate integration PV power plant compared with the reference scenario were estimated 10% and 6%, respectively. Finally, the combined integration of RES can contribute to 12% TPES and 13% CO_2 emissions savings.

It has been demonstrated that PtH will provide enough system flexibility to integrate a high share of wind penetration even in a very well-connected power system. The contribution of P_tH technologies for PV penetration in the current power system based on coal is not that significant because the power production from PV happens during the summer months when the heating season ends. Because of the limited countries energy system flexibility potential, this research opens the way for further examinations on P_tH coupled with power-to-x (gas, liquid, electric vehicle batteries, or electrification of transport sector) technologies that will be able to provide enough power system flexibility to capture the excess production from RES, especially during the summer months.

Finally, a realistic model was developed for analysing future energy transition pathways of coal-based energy systems aiming towards transition into systems based on variable renewable energy supply. Historical datasets were used to model the energy demand projections by 2030, where 2015 was considered the reference year for the model verification. Energy demand projection for 2030 per sector was modelled for analysing the Kosovo energy system from technical, economic and environmental aspects.

Five different scenarios were modelled using an energy system simulation tool called EnergyPLAN. Scenarios consider the installed projects, developing projects, projects under construction, future proposed projects by different authorities, penetration of new technologies, carbon tax, as well as targeted country energy policies by 2030. EU clean energy package adaptation regarding the 32% share of RES in final energy consumption in Kosovo energy system by 2030 was the main objective of this research. Five proposed transition pathways 1 - 5 have been modelled to fulfil this target, however significant differences in annual investment and CO_2 emission costs were observed. Besides adding a CO_2 emission cost in scenarios, this difference becomes even higher and changes the cost-effectiveness between scenarios. All scenarios consider a significant scale-up in RES deployment and sector coupling options, but renewable-based scenario 3 was found to be the best out of the proposed solutions. It is the least-cost scenario compared to other ones when considering the total instalment and CO_2 emission costs. The share of RES in electricity production accounted for 50.2%. CO_2 emissions account for 4.48 Mt, a bit higher than scenario 4 with 3.97 Mt, however, it is modelled based on proved technologies. This is not the case for scenario 4, which considers the application of developing technologies like CCS technologies. Furthermore, the results show how cost-effectively a coal-based energy system can transition towards one focused on renewable energy by considering the aggressive integration of variable renewables in the power system and synergies between sectors. It can be concluded that Kosovo needs to be concentrated on variable renewable scaling-up and utilization of high efficient electricity conversion technologies into heat for achieving a secure, cost-effective and sustainable energy system to comply with EU goals.

Future work of this research would be the realistic model analysis of energy transition pathways for 2050, which requires further research on the exploration of real energy source potential for decreasing the dependence on energy imports, especially in the transport sector, which is entirely based on import. Furthermore, bottom-up models should be developed for modelling country energy demand projections by 2030 and 2050, considering the adaptation of the EU proposed energy efficiency target needed for enhancing energy transition.

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