Research Article

Increasing Renewables and Building Retrofit in a Coal-Based Cogeneration District Heating System

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The 4th generation of district heating systems will play a major role in the sustainable decarbonization of energy systems by utilizing low-temperature technologies and resources. This paper aims to demonstrate the role of energy efficiency in buildings and the coupling of the power and heating sectors in a cogeneration coal-based district heating system, considering technical and environmental boundary conditions. Different scenarios that took into account the expanded district heating system, renewable integration via power-to-heat technologies, and energy efficiency measures in buildings have been created and discussed in this article. The EnergyPLAN model was used to assess the share of primary energy supply savings, electricity produced via renewables, and emission savings due to the implementation of planned research objectives. The findings show that district heating and energy efficiency measures in buildings significantly impact the savings of primary energy supply, variable renewable power integration, and CO2 emission decrease. Besides, the coupling of the power and heating sector increases the flexibility of the district heating systems, allowing for more penetration of variable renewable energy sources in energy systems.

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1. Introduction

District heating systems supply buildings with heat at a certain temperature. Depending on the water supply temperature, different generations of district heating systems exist. Lund et al. [1] define the generations of district heating systems by showing the differences and similarities between the generations of district heating (GDH) systems. It concludes that the label established from 1GDH to

4GDH implies a chronological succession, but the label 5GDH does not seem compatible with terms established in other generations of district heating. An economic driver is that low-temperature district heating enables an increase in energy generation efficiencies like solar thermal collectors, heat pumps, and combined heat and power plants. A low-temperature level enables heat sources to deliver the heat with lower investments [2]. The differences in heat supply costs for different temperature levels have been estimated for various heat supply options [3]. The results showed that high sensitivity to lower supply costs from lower temperatures was found for geothermal heat, industrial excess heat, and heat pumps, whereas low cost sensitivity was estimated for combined heat and power plants that use waste biomass. The research [4] concluded that district heating and cooling have an important role to play in future sustainable energy systems – including 100 percent renewable energy systems – but the present generation of district heating and cooling technologies will have to be developed further into a new generation in order to play such a role.

The transition from the second generation of district heating towards the fourth generation of district heating means that transformed district heating will be able to supply heat in a sustainable manner [5]. In other words, the 4th generation of district heating will supply existing buildings with low-temperature heat, utilize renewable heat like geothermal [6], biomass, solar thermal collectors [7], waste heat from buildings and industry [8], among others. The fourth generation will also be a perfect solution for integrating low-temperature heat sources and large-scale heat pumps coupled with thermal energy storage tanks. Besides, low-temperature district heating enables low energetic and exergetic heat losses, economically feasible integration of waste heat sources such as heat from data centers and supermarkets [9].

EnergyPLAN has been applied for analysing sector integration by using power-to-X in fully integrated energy systems for resource-efficient, renewable energy-based energy systems [10]. Research applying EnergyPLAN includes the analysis of district heating in energy systems, showing the role of district heating for the integration of variable renewable energy sources (VRES). Research [11] investigates the power-to-heat process carried out by heat pumps connected to a district heating network used to provide heating and to provide flexibility for the electricity sector. The results showed great benefits in terms of electrical flexibility with significant economic benefits thanks to highly efficient heat pumps. The role of power-to-heat technologies in district heating and cooling systems in mild and Mediterranean climates to increase flexibility for integrating variable renewables in the power sector is researched by [12]. The results indicate significant district heating and cooling potential for the utilization of wind and PV for electricity production. Integration of variable renewable energy sources in district heating is a frequently mentioned solution for decarbonizing the heating sector. Research [13] and [14] show the significant contribution of large-scale heat pumps in district heating to increase the share of VRES.

Technical, economic, and environmental benefits for different future district heating systems based on scenario modeling and system design optimization for centralized, ultra-low temperature, and bidirectional fifth-generation district heating and cooling (5thGDHC) are presented in [15]. Results suggest that for future building stock, the increased cooling demand makes the 5thGDHC system the most economically attractive choice. A dynamic modeling approach is developed in [16] to determine the links between different elements of the fourth generation of district heating systems. The results of modeling show that support in the form of subsidies has a greater impact on key targets than tax increases. Research [17] analyses near-optimal solutions that bridge the gap between simulation and optimization approaches by evaluating the relevance of these solutions in the context of energy planning. The proposed methodology serves as a tool for policymakers in evaluating energy system scenarios.

Pakare et al. [18] investigate different alternatives for heat loss reduction, including the renovation of existing heat pipes and lowering the heat carrier temperature for district heating in Latvia. The results show that national heat losses can be reduced from 12% to 6%. Additionally, the possibility of using low-cost plastic pipes increases the overall economic benefits of heating network renovation. Popovski et al. [19] discuss the compatibility of district heating networks with deep retrofits of buildings under various European climate conditions and city topologies. The results show that even in scenarios with a high refurbishment rate, between 23% and 68% of built-up areas, depending on city topography, are suitable for district heating supply in 2050.

Joelsson and Gustavsson [20] investigate the house envelope measures and conversion of heating systems for the reduction of primary energy use and CO_2 emissions in the existing Swedish building stock. The result showed that conversion to district heating based on biomass, together with house envelope measures, reduces primary energy use by 88% and CO_2 emissions by 96%, while reducing annual social costs by 7%. Ziemele et al. [21] develop a system dynamics model for determining whether energy efficiency policy can accelerate the shift from fossil fuels to renewables in the Latvian

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district heating system. The study concludes that it is possible to reach a 98% renewable energy share in district heating if the cost of gas boilers is reduced. Lidberg et al. [22] show the role of different building energy efficiency refurbishment measures in district heating systems. The results show a significant difference in primary energy savings for different refurbishment packages. The efficiency of district heating for Danish building typologies is presented in [23]. The results show that further energy efficiency improvement of the existing building stock is essential for the realization of the 4th generation of district heating technologies in Denmark. Hansen et al. [24] investigate the levelized cost of heating using district heating and individual heating solutions. The paper concludes that the annual cost of district heating is approximately 18% lower than an individual natural gas boiler and approximately 30% cheaper than an individual biomass boiler and an individual air-to-water heat pump. Åberg and Henning [25] analyze the potential reduction due to energy efficiency measures in the existing building stock. The energy system optimization model named MODEST was used to investigate the impact of heat demand reduction on heat and electricity production. The electricity to heat ratio for the system increased for heat demand reductions up to 30%. The space heating in buildings is expected to decrease [26], as opposed to domestic hot water, which is likely to increase due to an increase in the standard of living conditions [27].

Prishtina, the capital city of Kosovo, already has a district heating system based on a coal-based cogeneration plant [28]. The system belongs to the second generation of district heating systems, where the water supply temperature is 110°C, while the return temperature is 65°C [29][30]. Due to the high temperature, heat losses in the distribution system are around 8% of the total heat demand [31]. This district heating system should switch slowly towards the 4th generation of district heating systems, where the water supply temperature decreases significantly to 50-60°C, while the return temperature is around 25°C [32]. This transformation of the district heating system should happen from both the supply and demand sides. The 4th generation of district heating systems is expected to supply space heating and domestic hot water heating to existing and refurbished buildings [33].

There has been extensive research showing the impact of district heating on energy systems using the modelling tool EnergyPLAN. This paper, besides showing the contribution of district heating, also shows the impact of space heating demand reduction on the overall performance of the energy system. A frequently mentioned solution is that power-to-heat technologies in district heating are one of the most cost-effective solutions for the decarbonization of energy systems due to high energy conversion efficiency and the flexibility it offers in the power sector. This flexibility allows for more integration of variable renewable energy sources into the power grid. Overall, this paper shows, using a scenario approach analysis, how coal-based district heating systems can improve our understanding regarding the potential savings in district heating due to the application of locally proposed energy efficiency measures in buildings and the application of large-scale heat pumps in district heating systems to pave the way for more variable renewables in the power grid. So the main aim of this paper is to show how coal-dependent district heating systems can change their configuration to become more flexible in terms of allowing more renewable energy integration, more sustainable in terms of primary energy savings, and more environmentally friendly in terms of CO2 emission decrease while designing an energy system with better performance. An EnergyPLAN model is developed using a scenario approach analysis for a local case study with a target to be replicated for similar energy systems powered by coal cogeneration units. The results and discussion are elaborated, followed by the conclusion section.

The paper is structured as follows: Section 2 shows the method, Section 3 presents the case study, Section 4 discusses the results and discussions, and Section 5 presents the main conclusions, followed by the references in Section 6.

2. Method

A model was developed in the EnergyPLAN model for the reference year 2018 to assess the role of large-scale heat pumps in district heating to increase the share of variable renewable energy, hence decreasing the CO2 emissions from the coal-based district heating system. The model considers different local building energy efficiency retrofitting norms. The boundary conditions of increasing both district heating share and building retrofitting have been considered in EnergyPLAN, and the impact of the same on the overall performance of the energy system for a municipality has been considered. The EnergyPLAN model is a well-established tool for investigating the role of district heating and renewable energy integration in the energy system [10]. EnergyPLAN is a bottom-up modeling tool used to assess the large-scale integration of RES and the impacts of heating, cooling, electricity, and transport in energy systems [34]. The coupling among heating, cooling, electricity, and transport sectors contributes to designing energy systems with better performance and lower costs. The schematic diagram of EnergyPLAN is presented in Figure 1. EnergyPLAN uses hourly distributions of resources and demand for one year to produce hourly outputs. General inputs in the model are

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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.

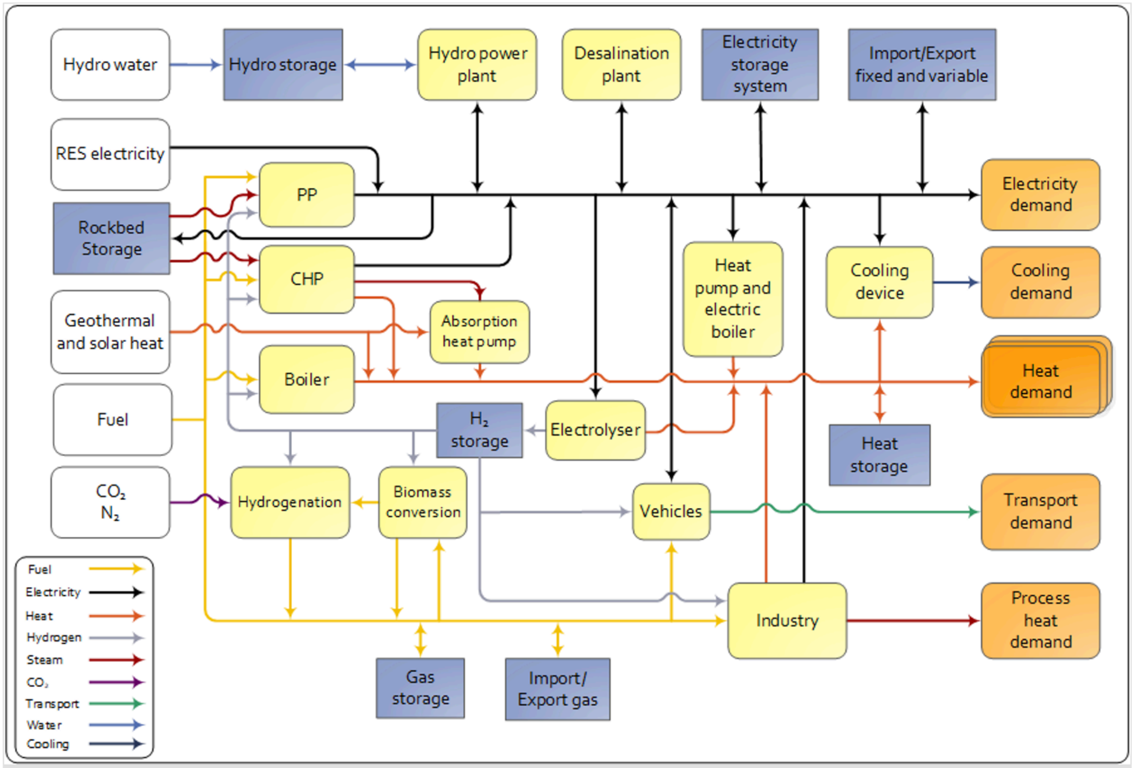

Figure 1. EnergyPLAN model

The boundary layer critical excess electricity production (CEEP) is used for sizing the capacities of variable wind integration in the power sector. A small value of CEEP around 5% [35][36] is acceptable as it is not economically viable to build energy storage technologies for a short period when excess electricity appears in power systems. Critical excess electricity production shows the surplus power that is generated in the power sector when the same overcomes the capacities of transmission lines and consumer demand. This surplus power can be usefully utilized through power sector integration via power-to-x technologies. In this paper, the same was used for highlighting the impact of power and heat sector integration via the application of heat pumps in district heating systems. The minimum capacity of central power plants was set to zero to consider power synchronization with demand in the power grid. The capacity factor for wind was set at 25%. The municipality model has been fully simulated as an integrated and interconnected system with other central power systems. The climate data needed to generate hourly distributions were taken from Meteonorm [37] for both wind and photovoltaic power plants. Other distribution data like electricity demand was taken from the Kosovar transmission system operator company (KOSTT) [38], and heating demand was calculated considering the heating degree day method.

The scenario approach analysis shows how a coal-based district heating system can change its configuration to become more technically and environmentally acceptable. Besides the reference scenario, four different scenarios were developed to assess the impact of district heating and heat savings on the overall energy system performance. The descriptions of the scenarios are provided in the table below.

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Scenario 1	Scenario 2	Scenario 3	Scenario 4
Scenario 1 considers the increase of the district heating system to 30% of total heat demand, while energy efficiency measures will reduce the heating demand up to 20% of total district heating demand. It considers that individual coal and oil boilers will be replaced entirely with electric heaters. The scenario is modelled as an island power system to show large-scale heat pumps' contribution to increasing the share of variable renewables. The scenario considers that heat in district heating will be supplied by coal cogeneration based district heating systems and compression heat pumps coupled with thermal energy storage.	Scenario 2 considers even further increase of district heating and heat saving in buildings accounting for 40% and 30% of total heat demand. This scenario considers that individual coal and oil boilers will be replaced 50% with individual heat pumps and 50% with electric heaters. The power system is modelled as an island power system. Similarly, the district heating will be supplied by coal-based cogeneration system and large scale heat pumps coupled with thermal energy storage in district heating.	Scenario 3 consider that district heating will be increased to 50% of total heat demand while the energy efficiency measures in buildings will reduce the heat demand to 40%. Similar to scenario two, this scenario considers that individual coal and oil boilers will be replaced 50% with individual heat pumps and 50% with electric heaters. A double increase of heat pump capacity compared with the first and second scenarios can be observed. The scenario considers the interconnection capacity for variable power transmission.	Scenario 4 considers that district heating will be increased up to 60% of total heat demand while the energy efficiency measures in buildings will decrease the heating demand by 50% compared to the reference case. In comparison to scenario 3, this scenario considers higher power transmission capacities and the application of solar thermal collectors in district heating in group 3, besides large-scale heat pumps, to produce heat in the district heating system

Table 1. Description of proposed scenarios

3. Case study

A model based on historical data for the reference year 2018 is modeled in EnergyPLAN. The capital city of Kosovo, Prishtina, is used as a case study to analyze the heating sector's decarbonization. Kosovo's hourly electricity demand profile was taken from KOSTT, while the distribution profile is assumed to be the same for Prishtina. PV and wind power supply distribution profiles were generated using the wind speed and solar irradiation data from Meteonorm. The capacity factors for wind and PV were estimated at 25% and 18%, respectively. The existing district heating system is supplied by a cogeneration-based system based on coal with a 140MW capacity. Data regarding the feasible district heating and heat saving potentials were taken from [28] and [26]. The actual district heating consumption is 0.2547 TWh/year. The total demand for individual heating is 1.09 TWh/year. Table 2 presents the energy consumption for different energy sectors.

Energy consumption by sector	(TWh/year)
Electricity	0.6369
Heating	1.3200
Cooling	0.0000
Industry	0.2585
Other consumption	0.2116
Transportation	0.5252

Table 2. Energy consumption by sectors with respect to Prishtina energy system [26][29][31]

Table 3 shows the primary energy sources for different energy sectors. The same are used as input data in EnergyPLAN when investigating the performance of the energy system with high penetration of renewable and energy retrofitting measures in buildings.

Electricity production (TWh)		Individual Heating (TWh)		District Heating (TWh)	Cooling (TWh)	Industry (TWh)	Transportation (TWh)	Other consumption (TWh)
Fuel	**2018**	**Fuel**	**2018**	**2018**	**2018**	**2018**	**2018**	**2018**
Coal	0.636	**Coal**	0.168	0.255	-	0.035	-	0.024
River Hydro	0.016	**Oil**	0.134	-	-	0.201	-	0.039
Wind	0.000	**Biomass**	0.729	-	-	0.021	-	0.147
PV	0.000	**Electricity**	0.352	-	-	-	-	-
		NG	-	-	-	-	-	-
		Diesel	-	-	-	-	0.359	-
		Petrol	-	-	-	-	0.133	-
		LPG	-	-	-	-	0.031	-

Table 3. Prishtina energy system supply by source [26][29][31]

4. Results and Discussion

Firstly, the approach for considering the utilization potential of renewable energy sources in the power sector is considered. Then, the results of scenarios are demonstrated in tables and are further discussed and compared while considering constraints from the excess power production. Finally, the results of scenarios in a comparative way are presented and discussed.

4.1. Critical Excess Electricity Production

The graph of Figure 2 is built by considering the assumptions in Scenario 1. These assumptions include a significant increase in district heating and building retrofitting share. Besides these boundary changes, the scenario also includes the replacement of conventional boilers with electric heaters and heat pumps with thermal energy storage. Here we highlight the increased flexibility benefits when applying power-to-heat technologies for renewable integration in the power sector when considering sector integration (heating and electricity). Critical Excess Electricity Production (CEEP) is used for demonstrating the surplus power that is generated in the power grid and cannot be accepted by both demand and transmission line capacities. The same must be avoided by the power grid; otherwise, the system may collapse. A small value of CEEP can be tolerated in the power grid. A 5% share of CEEP is considered in the model for demonstrating the wind power capacities that can be integrated into the Prishtina power grid. Sector integration with power-to-x technologies can contribute to decreasing CEEP in the power grid, allowing for more penetration of VRES. Here we demonstrate the power-to-heat impact to decrease the CEEP in the power grid. In addition, the graph of Figure 2 shows the role of large-scale heat pumps in district heating to decrease the critical excess power production, respectively, to increase the share of wind in the power system. The results show that around 100 MW of wind power can be integrated into the current Prishtina power grid. However, with the applications of heat pumps in district heating with a 20 MW_el capacity and 10 GWh thermal energy storage, this share can be increased up to 150 MW. By considering the same procedure for the share of variable RES in the power system for other scenarios, summarized in Table 1, the share of wind capacities in the power system was estimated.

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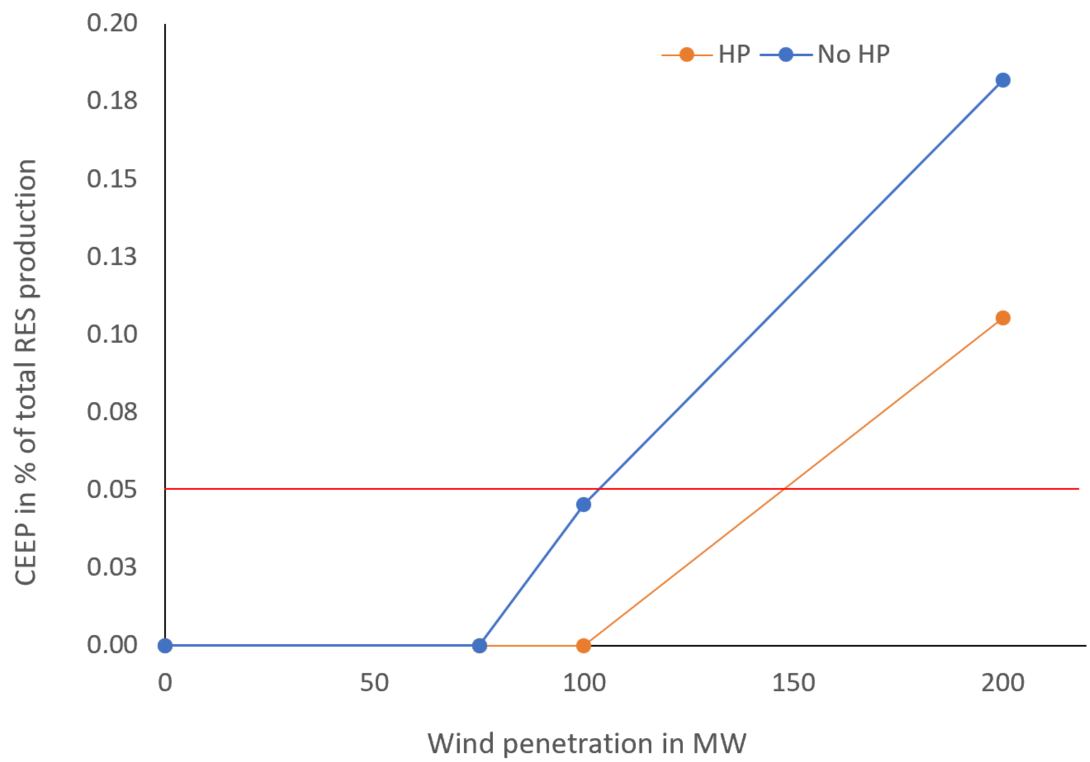

Figure 2. Critical excess electricity production vs wind power penetration in the Pristina power sector (Scenario 1)

4.2. Analysis of energy efficiency in buildings and renewable-based scenarios

Table 1 shows the results of modeled proposed scenarios for the decarbonization of the heating sector. These scenarios consider a significant increase in district heating systems, a reduction of space heating demand because of the energy efficiency measures in buildings, and a substantial increase of wind in the power grid due to the application of power-to-heat technologies in district heating systems. The results of the modeling are summarized in Table 4.

Reference scenario	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Actual heat demand 1.32TWh/year	Applying energy efficiency measures to reduce 20% the total heat demand of buildings	Applying energy efficiency measures to reduce 30% the total heat demand of buildings	Applying energy efficiency measures to reduce 40% the total heat demand of buildings	Applying energy efficiency measures to reduce 50% the total heat demand of buildings
	Increase the share of wind penetration in power system up to 150MW	Increase the share of wind penetration in power up to 125MW	Increase the share of wind penetration in power system up to 200MW	Increase the share of wind penetration in power system up to 250MW
District heating share 20%	Increase in district heating up to 30 of total heat demand	Increase in district heating up to 40% of total heat demand of the city	Increase in district heating up to 50% of total heat demand of the city	Increase in district heating up to 60% of total heat demand of the city
CHP based district heating system with an installed capacity 140MW	CHP 140MW, installing large scale heat pump in district heating with 20MW electric capacity	CHP 140MW, installing large scale heat pump in district heating with 25MW electric capacity	CHP 140MW, installing large scale heat pump in district heating with 50MW electric capacity	CHP 140MW, installing large scale heat pump in district heating with 50MW electric capacity

Table 4. Reference and proposed scenarios for the Pristina-based heating system.

In scenario one, the share of district heating is increased to 30% of the total heat demand of the buildings. The individual coal and oil boilers are fully replaced with electric heaters. The CEEP method demonstrated that 150 MW of wind could be easily integrated into an isolated power system when considering the contribution of heat pumps with 20 MWel and thermal energy storage with 10 GWh in district heating. In scenario two, the share of district heating is further increased to 40% of the total heat demand of the buildings. In the second scenario, coal and oil boilers are replaced with 50% individual heat pumps and 50% electric heaters. This scenario also considers the contribution of power to heat in district heating to increase the share of wind power up to 125 MW. Scenarios 1 and 2 are modeled as isolated power systems, while scenarios 3 and 4 consider the interconnection capacities of 50 MW and 100 MW, respectively. These transmission capacities significantly increase wind power in energy systems, hence decarbonizing the heating and electricity sectors.Besides the role of heat pumps in increasing the share of renewables, they will also contribute to the decarbonization of the electricity and heating sectors. Figure 3 shows the percentage of RES in electricity production. The highest share of RES in electricity production, around 62.3%, can be observed in scenario four, where the penetration of wind power in the power system is 250 MW. In scenario one, the share of RES for electricity production is 31%, and continues to increase in scenarios 3 and 4 as the wind power in the electricity sector increases. The CEEP method shows that heat pumps in district heating can increase the share of wind capacities in power systems up to 50 MW or 30% of power system flexibility offered without heat pumps. 10% is the share of electricity produced by RES as the contribution of the heat pump in district heating. This highlights the significant impact of large-scale heat pumps in district heating on increasing the share of RES in electricity production.

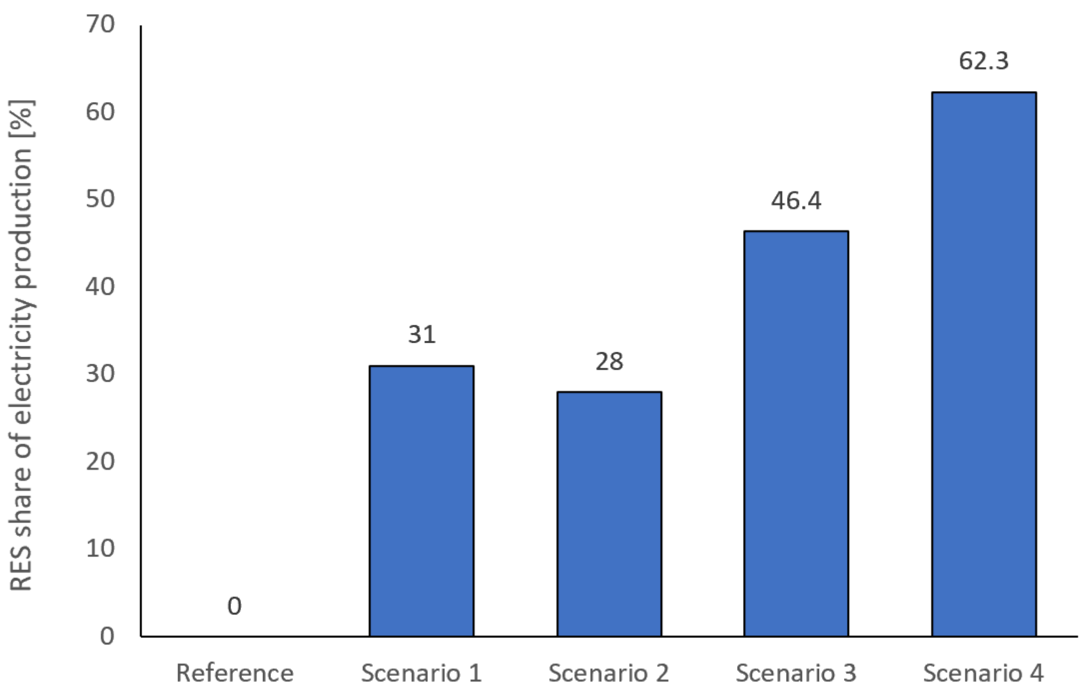

Figure 3. The share of RES for electricity production in percentage.

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Figure 4 shows the share of RES in the primary energy supply. It can be seen that even in the reference scenario, the share of RES is 18.5%, and this is due to the use of biomass for heating in wood stoves. The highest share of RES in the primary energy supply among scenarios can be observed in scenario 4, accounting for 30.2%. There are slight differences in the RES share between scenarios 1, 2, 3, and 4, and this is due to the decrease in space heating demand in buildings and the increase in wind power.

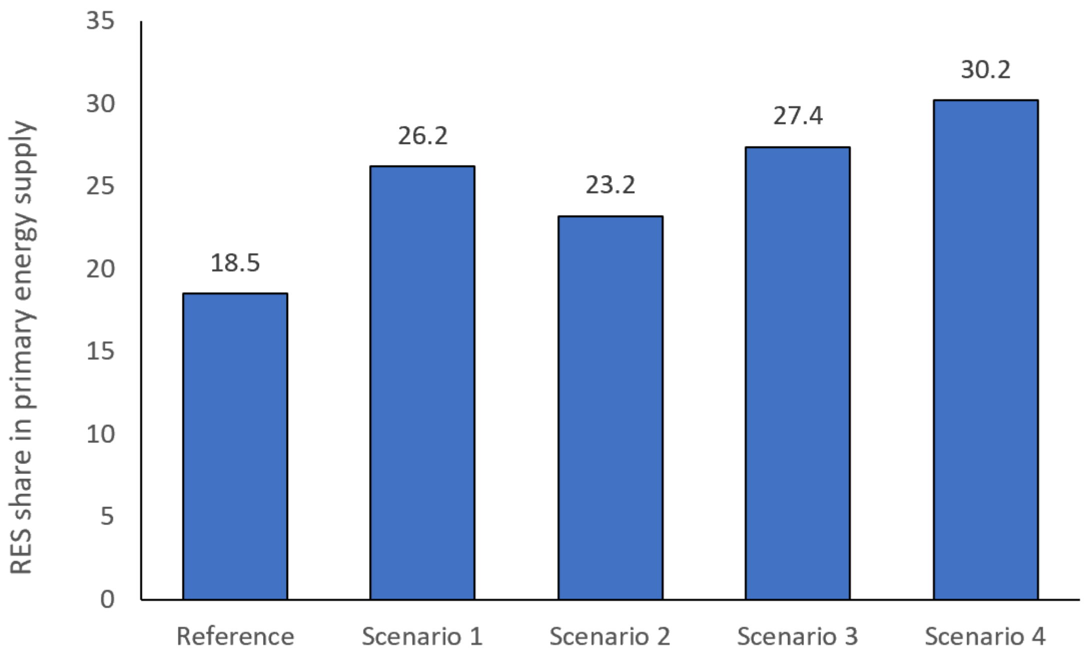

Figure 4. The share of RES in primary energy supply in percentage.

Figure 5 shows the decarbonization potential of electricity and the heating sector. It can be noted that the emission reduction potential between scenarios is significant. The emission decreases are due to the increase in the district heating system, an increase in wind in the power system, and a significant decrease in space heating demand because of energy efficiency measures. In the reference scenario, the CO_2 emissions accounted for 1.293 MtonCO_2/year, while in the first and second scenarios, the CO_2 emissions were decreased to 0.89 and 0.87 MtonCO_2/year, respectively. Even further emission decrease potential was observed for scenarios 3 and 4, accounting for 0.683 and 0.519 MtonCO_2/year, respectively. When comparing the reference scenario with other scenarios, the CO_2 emission decrease potential for scenarios 1, 2, 3, and 4 is 31%, 32.5%, 47.2%, and 59.8%, respectively.

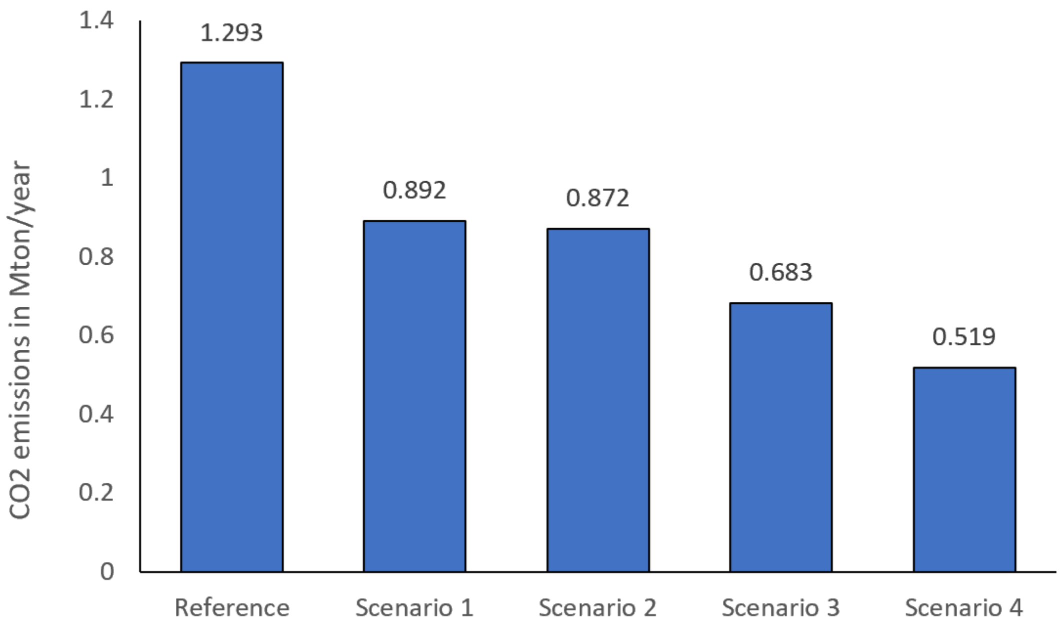

Figure 5. Total CO_2 emissions in Mton/year

5. Conclusions

This paper presents scenarios for the decarbonization of the second generation of district heating systems by considering a significant increase in the fourth generation of district heating systems and a reduction of space heating demand in buildings, considering locally proposed building retrofitting measures. The EnergyPLAN model was used to model the performance of the energy system. The results show that the actual wind power plant capacities that can be integrated into the Prishtina power system for scenarios 1, 2, 3, and 4 are 150 MW, 125 MW, 200 MW, and 250 MW, respectively. The share of electricity production for scenarios 1, 2, 3, and 4 was 31%, 28%, 46.4%, and 62.3%, respectively. The total CO_2 emissions for scenarios 1, 2, 3, and 4 were 0.892, 0.872, 0.683, and 0.519 MtonCO_2/year. In comparison with the reference case, the total CO_2 emission reduction potential for scenarios 1, 2, 3, and 4 was 31%, 32.5%, 47.2%, and 59.8%, respectively. The results demonstrate that large-scale heat pumps in district heating and heat-saving measures in buildings can contribute significantly to RES integration in the electricity sector, up to 62.3% of the total electricity demand, and achieve a 59.8% CO_2 emission reduction compared to the reference case. Future work on this paper might include a holistic approach that takes into account, besides technical analysis, the social

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and regulatory analysis to identify the barriers and opportunities for the development of the fourth generation of district heating systems in Prishtina.

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All authors contributed equally to the development of this model for assessing the future role of sustainable district heating systems, especially in coal-based power systems.

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