Sustainable transition pathways with high penetration of variable renewable energy in the coal-based energy systems

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ABSTRACT

The sustainable transition of an entirely coal-powered energy system is a challenge that can be solved by integrating variable renewable energy sources and considering the synergic effect between energy supply and different sectors of energy consumption. This research shows how the scaling-up in variable renewable energy sources uptake and sector coupling while maintaining high flexibility in thermal power plants can be achieved in a coal-based energy system. The Kosovo energy system is modelled in the EnergyPLAN model as a case study. Appropriate energy transition pathways have been defined to meet the national energy policies by 2030. Five different scenarios that took into account the increase of renewable production capacities, flexible operation of coal-based thermal power plants and sector coupling options for a suitable primary energy mix by 2030 have been discussed. Significant differences in annualized technology and emission costs can be observed between scenarios. In addition, scenario three seems to be the least cost in comparison to other scenarios. The total CO_2 emissions for projected scenarios 1, 2, 3, 4 and 5 in 2030 accounted for 4.78, 5.28, 4.48, 3.97 and 4.95 $MtCO_2$/year, respectively. In addition, the total annual costs for projected scenarios 1, 2, 3, 4 and 5 in 2030 accounted for 2168, 1611, 1993, 2479 and 2817 MEUR, respectively.

KEYWORDS

Sustainable Transition, Renewable Energy Sources, Sector Coupling, Coal Thermal Power Plants, EnergyPLAN, etc.

HIGHLIGHTS:

- Modelling the energy transition pathways in coal-based energy systems
- Sustainable primary energy mixes based on national energy policies and resources
- Scenario approach analysis using bottom-up EnergyPLAN model
- CO_2 emission reduction and economic viability of the proposed energy system by 2030
- Sector coupling increases the economic viability among energy transition pathways

INTRODUCTION

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. Countries worldwide are implementing energy policies set in the Paris Agreement regarding the targets to decrease CO_2 emissions to the levels that would keep the Earth surface's temperature increase under 1.5-degree limit [1]. European Union (EU) countries have set the target to decrease the CO_2 emission by 40% in 2030 compared to 1990 and 80% by 2050 [2]. The decreasing cost in variable renewable energy sources (RES), especially wind and photovoltaics (PV), is one of the main drivers for developing energy policies to decrease CO_2 emissions. Based on the European power report [3], 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).

The electricity production from coal in the EU dropped by 32% and in particular, lignite coal-fired PP's output dropped by 16%, respectively [3]. This evolution of coal phasing out is attributed to the CO_2 emission price increase as well as the significant decrease in cost for variable renewable technologies. Thus, the power generation from coal is expected to decrease as many countries in the EU have announced their commitment to phase out coal. However, some EU member states like Bulgaria, Croatia, Poland, Romania, Slovenia and other energy community contracting parties from Western Balkan (Kosovo, Montenegro, Bosnia and Hercegovina, and Serbia) need to develop strategies for phasing out coal [3]. Countries of Western Balkan have not approved the carbon price mechanism yet, besides North Macedonia. However, the energy community secretariat announced that the same is under discussion and likely to be introduced to other contracting parties.

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, countries in the Western Balkan are in the process of developing it. Lignite coal is the primary fuel that powers the Kosovo energy system, especially in the electricity sector accounting for 97% of its electricity production [4]. Kosovo has two thermal PP's with total operational capacities between 750 - 1050 MW, which are quite old and operating with very low efficiencies. Nowadays, Kosovo plans to build the new thermal PP Kosova e Re with 450 MW based on coal [5]. However, the idea is not supported by Word Bank because they found out that there are more environmentally friendly and cost-effective solutions for electricity production in Kosovo [6]. Kittner *et al.* [7] develops an analytical platform for analyzing the economic viability of electricity production from fossil fuel and clean energy production technologies for the period 2015-2025 in Kosovo. The results show that alternatives to produce 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. Kabashi *et al* [8] develops a dynamic model to investigate greenhouse gas and air pollution reduction from the electricity and transport sector for the period 2000-2025 in Kosovo. The results indicate that energy policies and the introduction of new renewable technologies in electricity production can ensure sustainable development.

Energy efficiency and renewable energy are considered the main pillars for the transition of existing energy systems toward low carbon and smart energy systems. Lund *et al.* [9] addressed the smart energy system concept and concluded that the Smart Energy System concept represents a scientific shift in paradigms away from single-sector thinking to a coherent energy systems understanding of 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 [10]. Compared to body of research with similar goals, their modelling was based on sustainable use of biomass without exciding 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. Furthermore, they concluded that the production of synthetic fuels is needed in the transport sector for keeping biomass consumption within sustainable limits. A transition from a 50% RES based scenario towards a 100% RES scenario for Europe in 2050 is presented in [11]. Scenario analysis considered technical and political measures like decommission of the nuclear PP, utilization of large scale heat pump [12], heat saving, electric cars [13], providing rural areas with heat pumps, urban areas with district heating (DH) [14], converting heavy fuel vehicles with renewable electro fuels and replacing natural gas with methane. It was concluded 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 coupling the electricity, heating, cooling, and transport sectors, which enables variable renewable penetration of over 80% in the electricity sector. Seefried *et al.* [15] analyses the flexibility in energy systems, flexibility options that are categorized along with existing literature and a method is explained to approach the estimation of flexibility potential by means of two example regions. Results demonstrate a transferable method to quantify and compare the technical potentials of the flexibility options on a regional level. Pavičević *et al*. [16] applied the Dispa-SET model that couples the energy systems of six countries 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 2020 and 2030, can be achieved without compromising the system's stability.

Models considering 100% renewable energy system by 2050 were developed for different countries across Europe such as Germany [17], Portugal [18], [19] Ireland [20], Latvia [21], Croatia [22], Macedonia [23] and Denmark [24].

As current research focuses on sustainable decarbonization of coal-based energy systems, the following research papers provide a review of methods used for similar studies. For instance, sustainable transition pathways by 2050 for decarbonizing a 100% energy system based on fossil fuel were investigated in [25]. Pathways considered 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. Pupo-Roncallo *et al*. [26] show different RES integration pathways into the Columbian energy system. The aim was to build a hydro dominated power system and analyze the impacts of variable RES integration. The results show that Wind, PV and bioenergy scale-up could achieve a 20% reduction in CO_2 emissions and total fuel consumption for the country by 2030. A model was developed for analyzing the CO_2 emissions from fossil fuel combustion and estimating the national carbon intensity target by 2050, using Poland as a case study [27]. 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. Also, coal could remain in the energy mix only when 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, which will be costly and technologically challenging. In addition, the study suggests the deployment of carbon-negative bioenergy as well as CO_2 recycling as promising energy decarbonization options. Chwieduk *et al*. [28] studied the effectiveness of the operation of central DH systems and heat distribution systems. Based on the results, authors predict the improvement in the effectiveness of the energy production, distribution, and use. The results show that the application of micro-scale PV systems would help residential buildings be more energy-efficient and reduce energy consumption significantly. Even if the grid cannot be used as a virtual electricity store, the direct self-consumption of buildings can reduce their energy consumption by 30% on average. The influence of wind energy on thermal power plants in the Polish energy system was analyzed in [29]. 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. Laha *et al*. [30] presented 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 study concluded that it is possible to design a renewable-based scenario by significantly increasing power production capacities (Wind, PV and Hydro, biomass and nuclear power), improving PV and Wind capacity factors to 21% and 27%, respectively. The results also show that the optimal utilization of biomass and nuclear power could avoid the country import dependencies. There are other energy systems partly based on coal. For instance, in Portugal, 30% of electricity production is based on coal, hence research was developed for achieving CO_2 emissions reduction, using the Portuguese Government plans for the upcoming decades, and a high share of renewable energy supply [31]. The study concludes that a minimum thermal PP capacity is required in the power system for maintaining the security of power supply under sustainable levels and hence highlights the importance of hydro pumped energy storage for integration of variable renewable energy. Brauers *et al*. [32] investigated the reasons for the different developments and aims to identify the main drivers of coal phase-out by using Triple Embeddedness Framework. The coal phase-out in the UK was agreed to happen in 2024, while the coal phase-out in Germany was scheduled by law for 2038 at the latest. Moreover, the results demostrate that the policy outcomes regarding coal consumption are deeply influenced by several actor groups, namely, coal companies, unions, environmental NGOs, and the government. Hurlbert *et al*. [33] employs a method to study the structural, institutional and historical context of power production and energy systems transitions in Saskatchewan. Research analyses the actors, their problemitizations, and narrative processes complement the discussion of transitions away from coal and advancing renewables. The outputs provide policy implications for future coal phase-out including the rise of renewable cooperatives and prosumers.

As shown above, many studies focus on the transition roadmaps towards 100% RES energy system; however, very few studies focus on the sustainable transition of coal-based energy systems. Current research shows how EU energy policies and carbon taxing mechanisms can be implemented in third countries without defined long-term energy policies [34], showing technological, economic, and environmental consequences. In terms of the local context, there is a lack of research on long-term energy planning considering hourly modelling of energy supply and demand. In a global context, each energy system is different in terms of climate, energy production and conversion technologies, energy resource potential and use. Hence, current research highlights the fundamental key indicators that should be considered when assessing energy transition pathways in coal-based energy systems.

1.1 The problem formulation and research questions

The role of sector coupling in accelerating the sustainable transition compared to single sector decarbonisation is studied in this research. The study shows the technical challenges and environmental implications for integrating new technologies while considering total energy system costs. In addition, the research applies scenario approach analysis rather than optimization analysis for estimating the cost-effectiveness between different energy policies. These policies are created by considering projects under development, projects under construction, and new proposed projects in power generation and coupling between sectors for shedding light on sustainable transition pathways of a highly based fossil fuel energy system. Furthermore, this research aims to show the 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 resources. The EnergyPLAN model was used for modelling the transition pathways using scenario approach analysis as the same satisfies the need for hourly modelling of low carbon energy systems. Scenarios are developed for the reference years 2015 and 2030. To this end, current research develops scenarios that incorporate different energy production and conversion technologies, variable renewable energy, old and new coal-based power plants, district heating, power to heat, heat storage and transmission grid, among others. The model incorporates all aspects that are crucial for analyzing the transition of coal-based energy systems under consideration of flexibility while keeping complexity manageable. By using the EnergyPLAN model, the following research questions are addresed:

- (i) What technologies constitute a sustainable primary energy supply mix, and how do these technologies relate to each other during the transition?
- (ii) How does the RES scaling up in the power sector with high utilization of transmission grid capacities affect the cost-effectivity of sustainable transition compared to the RES scaling up and synergic effect between the electricity and heating sector?
- (iii) Under what energy policies coal transition process would be technically possible, economically viable and ecologically acceptable?
- (iv) What would be the role of the carbon price in cost-effective energy policies during the coal transition?

The model allows deriving some fundamental insight into the critical factors for a sustainable transition of coal-based energy systems in cold climate zones. It is however, subject to several limitations, which are discussed in section 2.1.

The remainder of the paper is structured as follows: Section 2.1 addresses the model set up, section 2.2 shows the data sources used in the model, section 2.3 specifies the modelling of different transition pathways using scenario approach analysis. Section 3 describes the case study and model validation. The results are described in Section 4; section 4.1 specifies business as usual (BAU) energy system in 2030; section 4.2 specifies all energy production and conversion technologies; section 4.3 shows the technical, economic and environmental implications. The results are discussed compared to other coal-based energy systems in Section 5 and the major conclusions in Section 6, respectively.

METHODS

2.1 EnergyPLAN

A model was developed in EnergyPLAN tool, for the reference years 2015 and base scenario in 2030 for assessing sustainable transition pathways in a coal-based energy system. Low carbon energy systems include a significant share of renewables, as shown from other research reviewed in the introduction section, their hourly modelling and simulation are needed for capturing the variability of RES power production and system balancing. The current model considers hourly energy supply and demand modelling and simulation for an energy system targeting its future clean energy package by 2030. EnergyPLAN is a bottom-up specialized modelling tool used to assess the large-scale integration of RES and the impacts of heating, cooling, electricity, and transport 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. It is already a well-established tool for modelling large scale integration of RES in future energy systems based on conventional plants [35], an increase of CHP for DH [36], optimal combinations of PV, wind and wave power [37], increase on solar PV [38], the optimal combination of RES in islands [39], and impact of wind and PV in power system load [40]. Furthermore, this tool has been very useful for modelling low carbon energy systems, particularly the concept of the smart energy system. Østergaard [41] reviewed the application of the EnergyPLAN model on the geographic level and the types of simulations or scenario analyses performed on the model. Also, a review of the types of performance indicators applied in said energy systems simulations was given and finally details existing advanced energy system performance indicators were provided, as well as a proposition of additional indicators. The schematic diagram of the EnergyPLAN model is shown in the figure. 1.

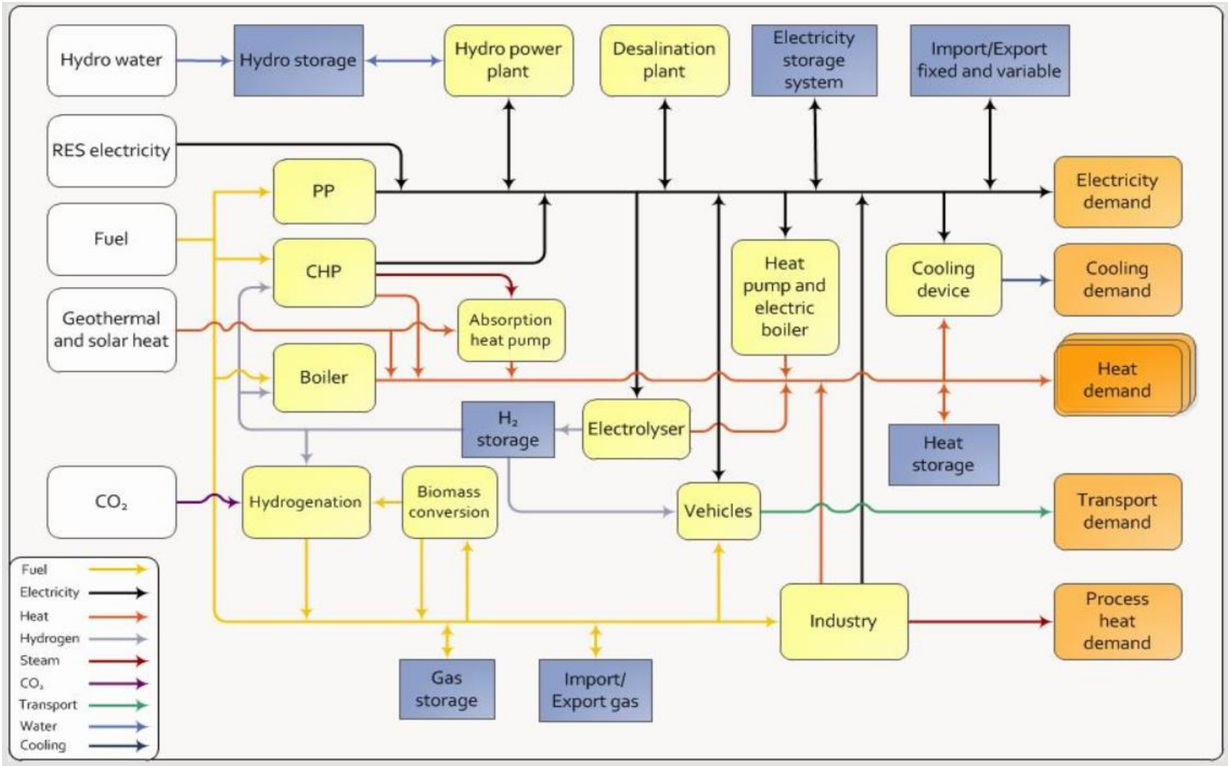

Figure 1. EnergyPLAN model [42]

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 [42]. The model outputs show the consequences of the technical and market simulation strategies that lead to sustainable designing and planning of energy systems.

Overview of several 100% renewable energy systems modelled was given in [43], [44]. As it is a well-established tool for similar applications, EnergyPLAN was chosen to be a modelling tool for testing different energy policies proposed for the year 2030. Technical simulation strategy with the sub-strategy balancing both heat and electricity demand was selected. A minimum CHP and PP capacity was set for electric stabilization requirements and was assumed the same in all analyzed scenarios (scen. 1- 5). In addition to this assumption, authors in [31] concluded that a minimum PP capacity is required in the power system to maintain the power supply's security under sustainable levels. However, the ramping up and down thermal PP flexibility and their minimum capacity depend on the age and development of new technologies. Different balancing modes can be utilized in energy systems to enhance flexibility because the low carbon energy systems require significant penetration of variable RES. Energy systems can use pumped hydro energy storage, power to heat, power to cold, and other power-to-x like electrification of transport, hydrogen production, synthetic fuel production etc., for enhancing the flexibility of their energy systems. For the case study chosen, the dammed hydro potential is very limited and the residential sector is the largest consumer, hence the balancing mode power to heat in both DH and individual heating was prioritized among other power to x options. Furthermore, the reviewed body of research shows that power to heat is cheaper in comparison to other flexibility options. In terms of balancing the system, the thermal energy storage in DH was considered as well. Critical excess electricity production balancing mode was left to zero to define the excess power production and ability of an energy system to accommodate such capacities of variable RES. It's important to emphasize that some excess production will be curtailed but within the economically acceptable amounts [12]. The energy system, besides scenario 5, was simulated in an island mode even though there is a well-established power transmission capacity accounting for 1250 MW.

Regarding the economic analysis, the model takes into account the technology installation cost, as well as the fixed O&M costs, without considering the cost of fuels for the nominal operation of technologies. A CO_2 price was assumed to consider in the model. Different energy system configurations were simulated in conjunction with the technology and carbon emission costs to define which technology and scenario is the most cost-effective solution for achieving sustainability when considering the lifespan of proposed technologies.

2.2 Data collection

Using the historical energy consumptions and the calculated energy consumption per capita and per sector, the total final energy demand for the base year 2030 was estimated. The hourly supply and demand distribution data has remained the same as in the reference scenario 2015. Hourly distribution of individual and DH demand was calculated using the total aggregated heat demand and heating degree day method. Using the same approach, the cooling load profile was estimated. Import electricity cost around 60 EUR/MWh was considered [45]. The investment and O&M costs for other technologies in the energy system and their lifespans are taken from various sources [46], [47], [48]. An initial CO_2 tax assumed around 30 EUR/tCO_2 was considered for avoiding carbon electricity exports.

2.3 Modelling sustainable transition pathways

The preliminary research questions are designed, to show which energy system's configuration can perform in a cost-effective and environmentally friendly manner targeting:

- Modelling and analysis of a sustainable transition in coal energy systems seeming to utilize locally available energy resources
- Achieving a 32% share of RES in final energy consumption
- Reducing CO_2 emissions by half compared to the BAU scenario in 2030
- The annual total energy system cost, considering the initial and O&M costs of technologies as well as CO_2 emissions

A scenario approach is employed to show how coal-dependent energy systems can gradually change their configuration to become environmentally acceptable. In total, 5 different scenarios have been developed for the year 2030, besides the BAU scenario, to assess the EU energy policy impact on the overall energy system performance and hence the energy system costs. A detailed description of scenarios is provided bellow.

- The BAU 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. These changes in technologies include 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% share, 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% share, respectively. In addition, the scenario also considers the replacement of oil-based DH with biomass.

- Scenario 3 it's 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 BAU 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. There are no additional 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 for meeting the demand of inefficient lignite coal thermal PP's phasing out by 2030 and filling 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 BAU scenario in 2030.

CASE STUDY

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 2015 reference model for the Kosovo energy system are discussed in [12]. The parameters used for model validation in comparison to historical data in EnergyPLAN are summarized in table 1.

Table 1. Model validation with respect to historical data in 2015 [12], [49]

	Model	**Actual**	**Difference**
PP electricity, TWh	2.77	2.74	3 %
CHP operating Mode	-	-	
PP, 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 %

The efficiency of PP is 26%, while the efficiency of CHP is 32%, respectively. Current research shows additional approaches that are used for defining the BAU 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. Distribution for a river hydropower plant was generated using the monthly energy production recorded data in 2015 [45]. The hourly electricity demand profile was taken from Kostt [50]. PV and Wind power supply distributions were generated using wind speed and solar irradiation data from Meteonorm [51] for high potential areas in Kosovo. The capacity factor for wind and PV power plants was estimated at 25% and 18%, respectively. The BAU 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 are additional changes in the energy system needed to meet the 2030 EU target 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?

RESULTS

4.1 Kosovo Energy System by 2030

Figure 2 presents the total final energy consumption by sectors and CO_2 emissions from 2000-2015. It can be noted 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 was significantly increased from 5.11 Mt in 2000 to 8.62 Mt in 2015.

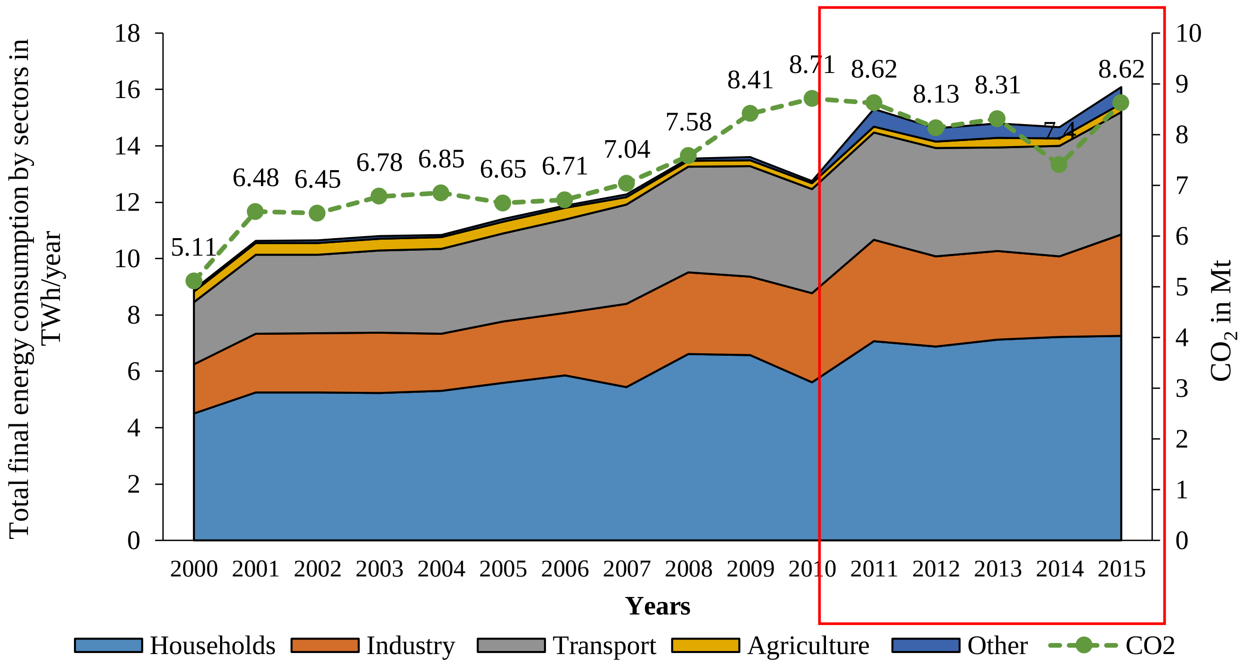

Figure 2. Total final energy consumption by sectors and CO_2 emissions over the period 2000-2015 [4]

An average specific energy consumption per capita per sector was calculated using the recorded data from 2010 - 2018 (see table 2) for estimating the energy demand projections. The total final energy consumed in a sector during a specific 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 2. 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 sector in the Kosovo energy system, the annual average 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 [52]. Population projections scenarios, low, medium and high case, over the period 2010-2060 were carried out by the Kosovo Agency of Statistics, as shown in table 3.

Table 2. Averaged annual specific energy consumption per capita (2010-2018) [4], [45], [53]

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

Table 3. Population projection scenarios [53]

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 number of the population for the year 2030 and the results of the calculation are shown in figure 3.

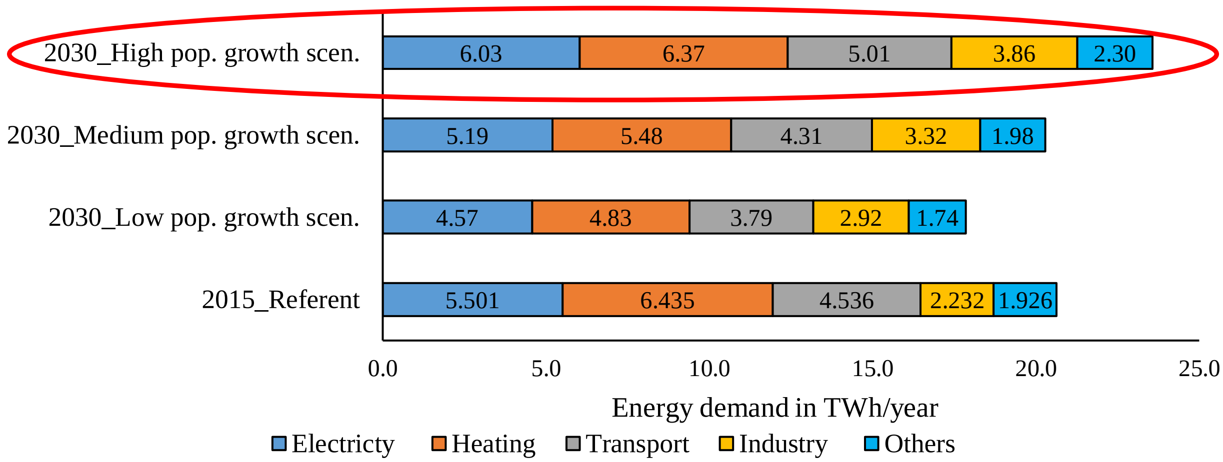

Figure 3. Energy demand projections by sectors

Between three demand projected scenarios, the highest demanded one was considered for further analysis. 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 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 [12] and the results of modelling are shown in table 4a and 4b. The same share of final energy demand in each sector is assumed for BAU in 2030 compared to 2015. The same approach was used for all sectors, except the electricity sector, where the newly installed small hydropower plants and wind turbines that are 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 4a. Electricity production by source

	Electricity production in TWh/year		
BAU scenario 2030	**Fuel**	**2015**	**2030**
	Coal	5.359	5.551
	Oil	0.000	0.000
	NG	0.000	0.000
	Biomass	0.000	0.000
	Nuclear	0.000	0.000
	Wind	0.000	0.032
	Solar PV	0.000	0.000
	Hydro	0.142	0.227
	Excess Heat	0.000	0.000
	Geothermal	0.000	0.000

	Import/export	0.715	0.220

Table 4b. Final energy consumption by sectors for the base year 2015 [12] and projected for BAU 2030

	Heating TWh			**Industry TWh**			**Transportation TWh**			**Other TWh**		
BAU scenario 2030	**Fuel**	**2015**	**2030**	**Fuel**	**2015**	**2030**	**Fuel**	**2015**	**2030**	**Fuel**	**2015**	**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 (Figure 3) with the specific share of the final energy demand mix, the projected final energy demand in transport was estimated to account for diesel 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.

4.2 Energy system scenarios for 2030

Five different scenarios were developed for 2030 to meet the final energy demand already explained in table 4b. 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. Compared to BAU, these scenarios apply different energy supply solutions and synergic effects between the electricity and heating sector, as shown in table 5. 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 the main objective in all scenarios. 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. In [12] it was shown 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 5). Besides, Kosovo has an excellent power transmission capacity of 1250 MW, which can allow surplus electricity production export flow.

The BAU scenario shows the case of not considering any policy to invest in technology for meeting the country 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 the reference year 2015. Demand is increased in all sectors as shown in table 4b, 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 a hydro power plant of 94 MW, which are already installed in the power system since 2018. No investment in energy production and conversion is considered in this scenario, reflecting the case of undertaking no policies to meet RES final energy consumption and emission reduction goals.

Scenario 1 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 increase of the DH system to around 50% of total heat demand was considered. Such expansion was proposed by Word bank; however, papers [54], [55] 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 scenario 2, 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 hydropower 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 105 MW, Konznice 34.5 MW, 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. Capacities regarding RES integration can be easily 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 BAU 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 5.

Scenario 5 highlight the impact of power sector decarbonization 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. 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 terms of Kosovo, to meet the 32% RES share in final energy consumption, wind and PV power capacities should be increase 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 5. 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
Electricity	Installing large scale heat pump in Cogeneration based DH with a 30MWel capacity 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 Wind power from 33 MW to 237.7MW Increase in PV power from 0.6 MW to 30 MW Increase in hydro power from 75 to 236 MW	Coal and oil boilers are not used for individual heating 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%	Construction of new PP with total capacity 450MW based on coal & CCS capacity 42MW Increase in wind power from 32 MW to 620 MW Increase in hydro power from 75 to 150 MW	No changes were proposed No changes were proposed
	Increase in hydro power from 75 to 150 MW Increase in wind power from 32 MW to 180 MW Increase in PV power from 0.6 MW to 30 MW	No changes were proposed	Installing large scale heat pump in new CHP based DH with a 50 MWel capacity (group 2) Installing large scale diurnal thermal energy storage in DH with 10 GWh Replacement of Gjakova oil-based DH with biomass	Increase in PV power from 0.6 MW to 300 MW No changes were proposed	
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		

4.3. Technical, economic and environmental aspects of proposed energy system scenarios in 2030

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 4. 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 BAU 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 BAU 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 [56], [57]. It can be seen that the primary energy supply can be reduced significantly compared to the BAU scenario if proper decision-making energy policies are considered. The total primary energy supply in the BAU scenario was 31.5 TWh/year, but the same was significantly lower in other sectors, accounting for 23.5 TWh/year, respectively.

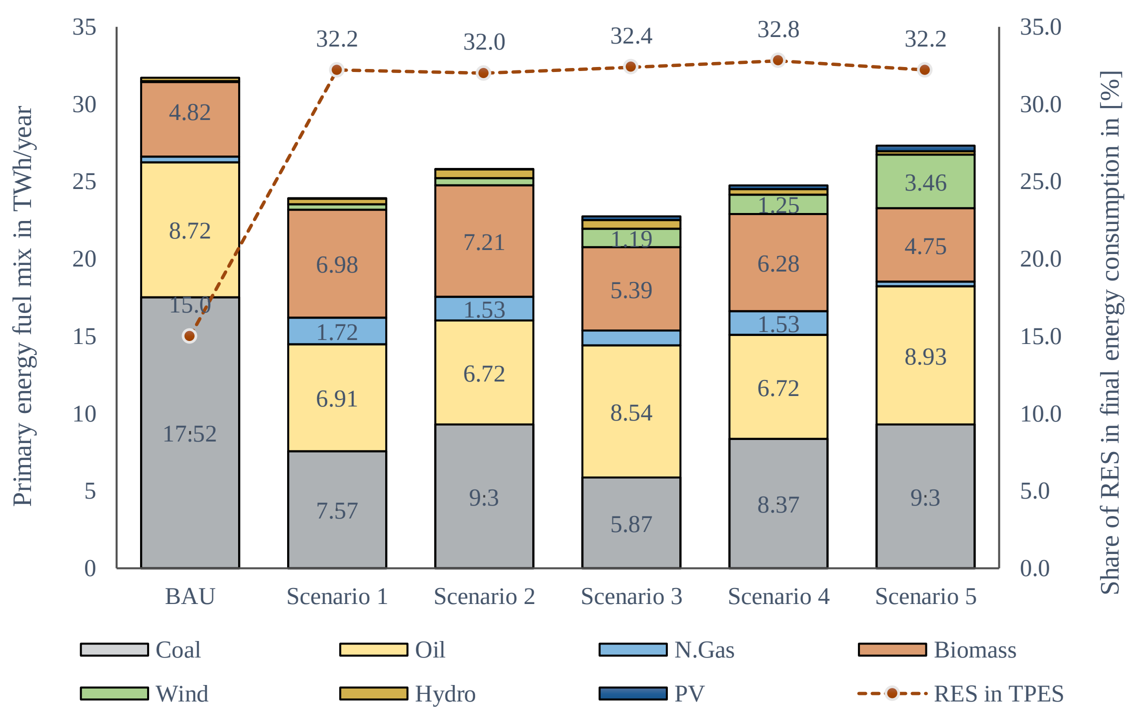

Figure 4. Total primary energy supply mix and share of RES in total final energy consumption by 2030.

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 a strong interconnection grid network is already established with neighbouring systems. There are four 400 kilovolt lines with Albania, North Macedonia, Serbia and Montenegro. Their combined capacity is around 2300 MW. 400 kV 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 BAU 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 that increase the flexibility of the power system. Table 5 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's ability to accommodate variable RES. Figure 5 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 simulations have shown that the share of renewable energy sources in electricity production in the BAU 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.

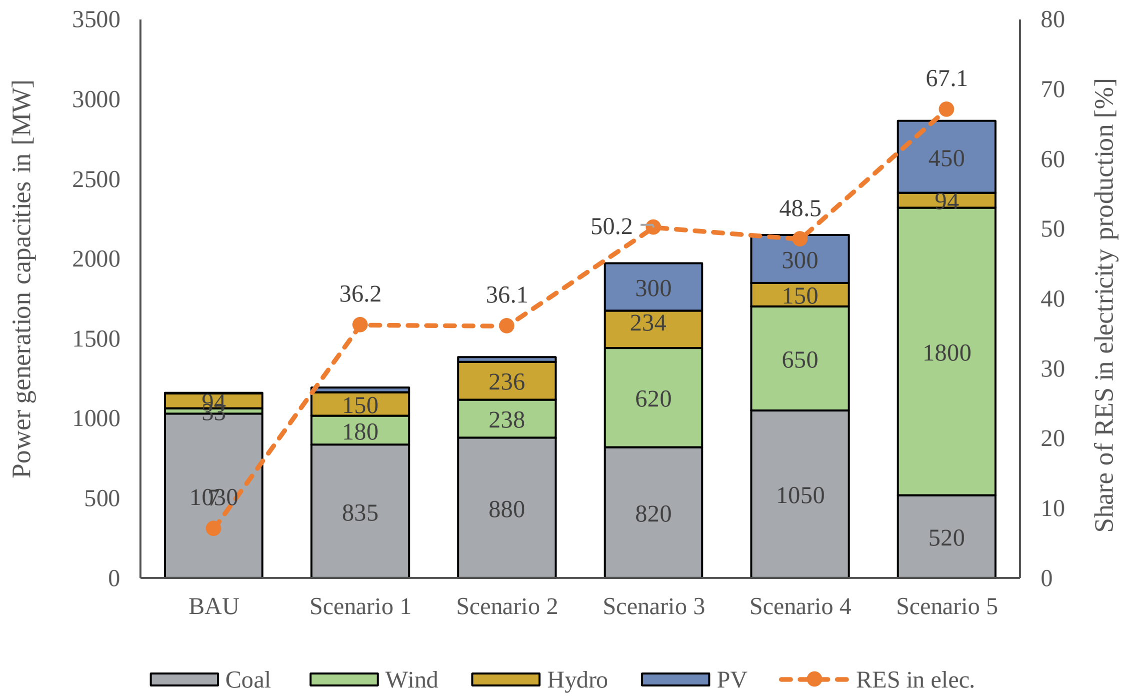

Figure 5. Power generation capacities and share of RES electricity production by 2030.

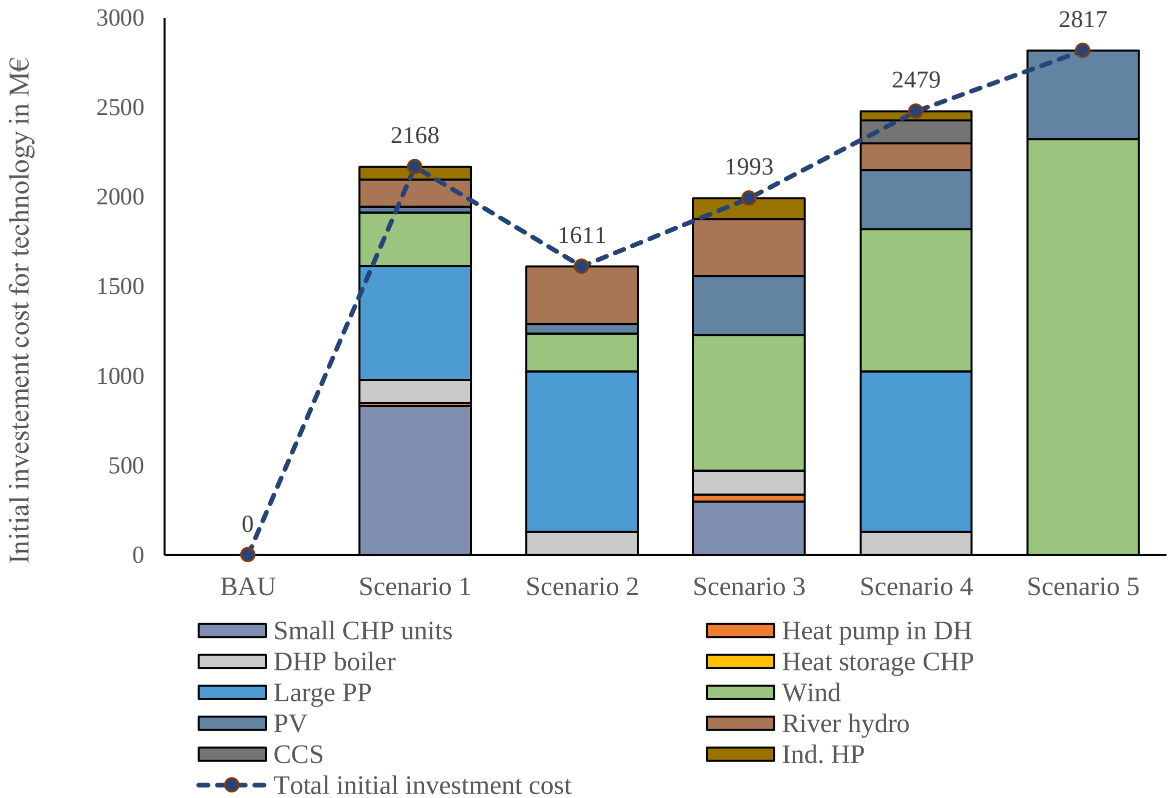

Figure 6. Initial investment cost by technology in MEUR.

The initial investment cost per technology and their total investment cost per scenario are shown in figure 6. The costs presented here reflect only the costs for additional energy production and conversion, excluding the costs for power generation capacities already installed. 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 major 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 7 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 7.

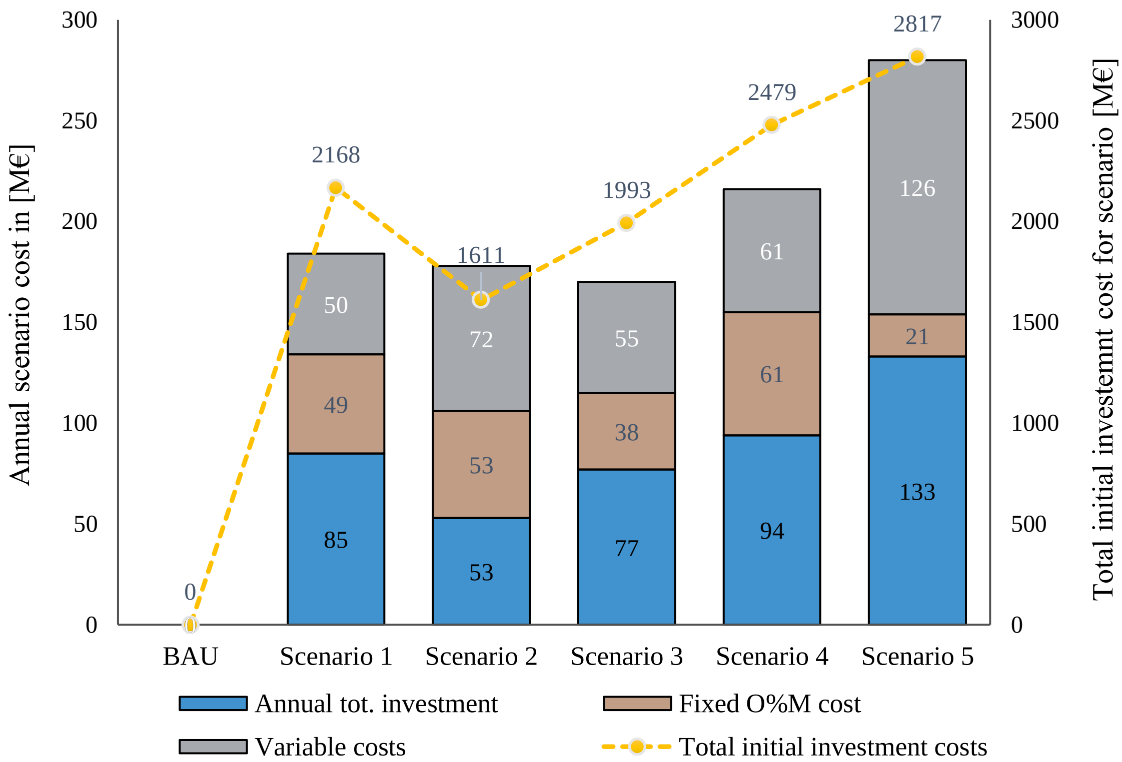

Figure 7. Annual and initial investment costs per scenario in MEUR

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 [58]. The annual costs per scenario shown in figure 8 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 BAU. A similar trend of CO_2 emission reduction was achieved in the second, third, fourth and fifth scenario compared to BAU 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 CO_2 emission costs among scenarios, the total annual energy system costs account for 280.2 MEUR for BAU scenario, and 327, 336, 304, 335, 399 MEUR for scenarios 1, 2, 3, 4 and 5, respectively. It can be noted that for the BAU scenario, 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 technology-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 8. Even though the annual scenario cost was higher in scenario 1 (184 MEUR) than scenario 2 (178 MEUR), when considering CO_2 emission costs, the total annual scenario cost changes its cost-effectiveness to 327 and 336 MEUR 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).

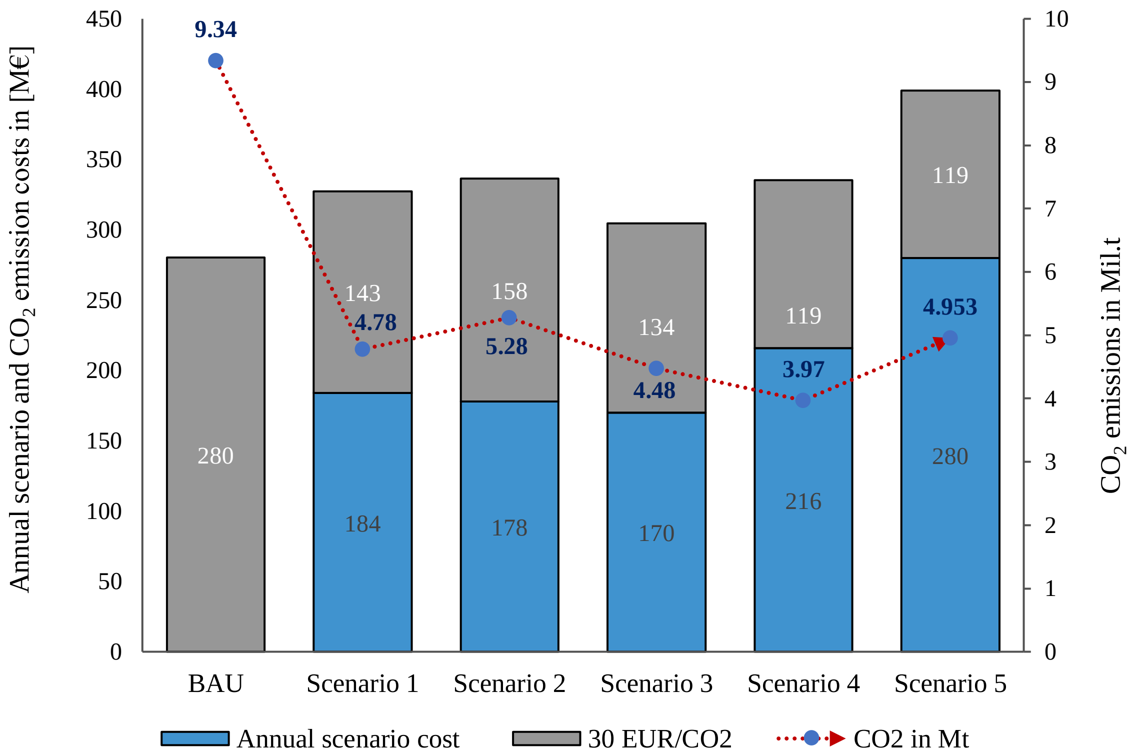

Figure 8. Annual scenario and CO_2 emission costs.

DISCUSSION

Solar and Wind power technologies are being considered as the main technologies for energy transition until 2030 especially in the EU, where the electricity production from these technologies in 2019 surpassed the electricity production from coal. In terms of designing the transition of coal-based energy systems towards low carbon energy systems, for the case of Poland, it was shown 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. In Kosovo, the potential for utilization of variable renewable capacities for meeting 2030 is very realistic and possible. For designing 100% RES for Kosovo, further research would be needed to identify renewable energy, biomass, and biogas potential. In terms of the Indian energy system, it was shown that a transition from coal to renewables is possible with an increase in wind, PV, Hydro, biomass and nuclear power. In terms of Kosovo, the utilization of hydro is very limited and biomass is already being consumed near its sustainable limits. There is potential for increasing Wind and PV power plants in Kosovo, however a synergic effect when using high efficient energy conversion technologies between electricity and heating can lead to a more cost-effective transition, rather than increasing RES solely in the power sector. Nuclear power in Kosovo does not seem to have any future.

On the other hand, research for Poland also shows that with the application of CCS technologies in coal-fired PP and other industrial processes, the coal can be utilized, but it will be costly and technologically challenging. In Kosovo, the application of CCS in PP's would reduce electricity production since a quite large amount of electricity is consumed for running the technology and the infrastructure for installing such technology is limited and very challenging. Even if this technology will be developed by 2030, current installed PP capacities would not be enough for covering the electricity demand. An increase in PP capacity of 450 MW with a 42 MW electric capacity to run the CCS would be needed for meeting the electricity demand and 32% RES share in final energy consumption in the Kosovo energy system. Another critical factor for the coal-based energy system is the operational flexibility of PP and CHP plants. Research agrees that a minimum CHP should remain in the energy system to maintain the power supply's security under sustainable levels. This is critical for the Kosovo energy system. Even in 2030, with a 32% share RES in final energy consumption, coal will be the primary energy supply fuel utilized for electricity production.

CONCLUSIONS

A realistic model was developed and a method proposed for the analysis of 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 analyzing 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 CAPEX 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 the transition of a coal-based energy system towards one focused on renewable energy can happen 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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