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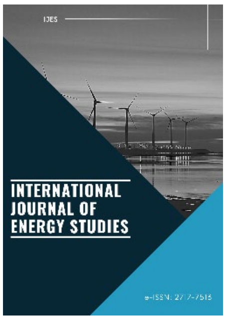

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A roadmap for the utilization of renewable energy sources for the sustainable development of Turkey's electricity energy system

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Highlights

- Electricity Planning According to Turkey's National Energy Plan.
- Renewable Energy Systems Simulation with EnergyPLAN.
- Nuclear Energy Simulation.

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ABSTRACT

Turkey's achievement of sustainable energy goals can be realized through the enhancement of renewable energy capacity and the strategic integration of nuclear energy. This study aims to promote the use of renewable energy sources and evaluate the impacts of integrating nuclear energy into the energy system to support Turkey's sustainable energy objectives. Within the framework of the Turkish National Energy Plan, two scenario groups covering the 2025-2050 period were developed using the EnergyPLAN simulation program (version 16.22). The first scenario group focuses solely on the gradual increase of renewable energy capacity, while the second scenario group examines the effects of nuclear energy on energy security and carbon emissions. The results indicate that, in scenarios without nuclear energy, CO_2 emissions decrease by 28%, whereas, with the integration of nuclear energy, this reduction reaches 39%. This comprehensive assessment provides important recommendations that contribute to Turkey's energy security and sustainable development strategies.

Keywords: Turkey's national energy plan, Renewable energy simulation, EnergyPLAN

1. INTRODUCTION

With the rapidly increasing population and industrialization in Turkey, energy consumption has also begun to rise. Technological advancements, digitalization, and the growing use of electronic devices in all aspects of life have led to an increasing demand for electrical energy every day [1]. It is crucial to ensure that this rising energy demand is met continuously, reliably, cost-effectively, and from clean sources while also being used efficiently. However, some energy production methods cause significant harm to both the environment and human health. This raises the question of how to mitigate these negative effects and how to meet energy needs in a more sustainable and humane manner. In this context, it is inevitable for countries to focus more on producing energy from domestic and renewable sources to provide a cleaner world for their citizens [2]. These inevitable circumstances have also led to changes in Turkey's energy landscape. As of the end of August 2024, the country's installed capacity has reached 113,932 MW.

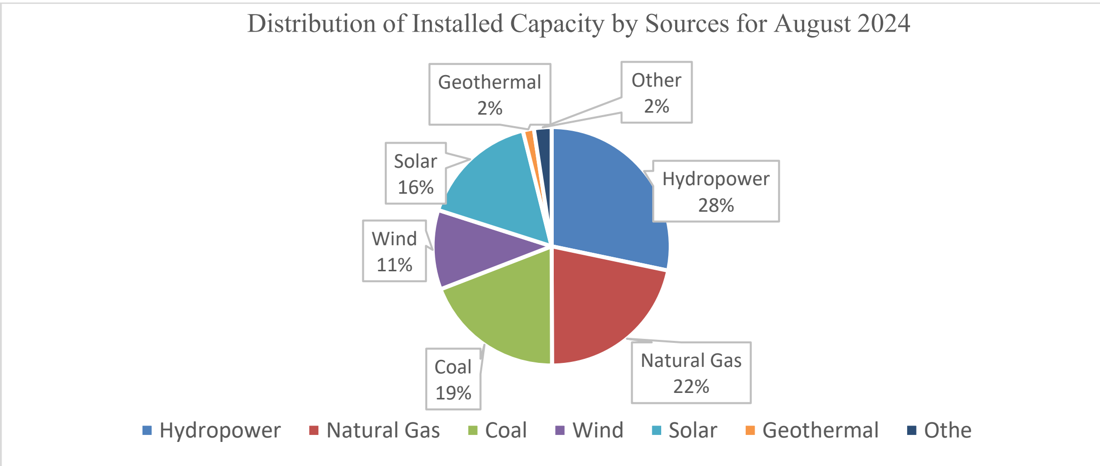

Figure 1. Distribution of Installed Capacity by Sources in 2024

As shown in Figure 1, as of the end of August 2024, the distribution of Turkey's installed capacity by energy source is as follows: 28.3% hydropower, 21.7% natural gas, 19.2% coal, 10.8% wind, 16.2% solar, 1.5% geothermal, and 2.4% from other sources [3].

As seen above, Turkey's electricity demand is currently met primarily through fossil fuels. However, due to the non-renewable nature of fossil fuels and their environmental impact, transitioning to renewable energy is one of the primary objectives outlined in the Turkey National Energy Plan. In this regard, various scenarios have been developed using EnergyPLAN, with reference to the Turkey National Energy Plan, to establish a roadmap for the transition to renewable energy.

A review of studies using EnergyPLAN in the literature reveals that while some focus solely on the electricity system, others include sectors such as industry, heating, cooling, transportation, and electric vehicles, aiming to model the entire energy system. In this study, in line with its objectives, only studies related to the electricity sector will be considered.

In recent years, many countries have been working towards reducing their dependence on fossil fuels and developing sustainable energy systems based on renewable sources. In this context, Bačeković et al. [4] compared two different models to establish a 100% renewable energy system for Zagreb, Croatia, analyzing an independent sector-based model and an integrated smart energy system model using EnergyPLAN. Similarly, Akpahou et al. [5] evaluated three strategic scenarios for increasing renewable energy production in Benin's energy supply by 2050. Additionally, Galimova et al. [6] examined Greenland’s transition from a fossil fuel-based system to a fully renewable energy system between 2019 and 2050, investigating the country’s potential as a future e-fuel and e-chemical production hub for Europe, Japan, and South Korea.

Other studies have focused on modeling renewable energy transitions in various regions. For example, Menapace et al. [7] developed 100% renewable energy models optimizing biomass use and integration with national energy systems in Bozen-Bolzano. Cabrera et al. [8] proposed smart renewable energy strategies by modeling Gran Canaria’s entire energy system through a cross-sectoral approach. Bamisile et al. [9] developed three different decarbonization models for Sichuan, China, in line with net-zero emission targets, analyzing reductions in carbon emissions. Similarly, Arévalo et al. [10] conducted a technical and economic analysis of hybrid renewable energy systems in the Galápagos Islands, proposing strategies for sustainable energy supply until 2050. Luo et al. [11] examined Sichuan’s deep decarbonization process by 2050, simulating three different transition pathways—imported electricity, biomass, and natural gas—using the EnergyPLAN model.

One of the studies specific to Turkey, conducted by Kılıçkaplan et al. [12], demonstrated that the country could meet its electricity, water treatment, and industrial gas demand with 100% renewable energy by 2050, highlighting the critical role of solar and wind energy in this transition.

Meanwhile, nuclear energy remains a significant energy option debated both globally and in Turkey. While environmentalists generally oppose nuclear power plants, some scientists and government officials emphasize their environmental and economic benefits. Supportive studies include Aktepe and Gökkaya [13], who argue that nuclear energy diversifies energy supply, does not produce greenhouse gas emissions compared to fossil fuels, and significantly contributes to electricity generation with low fuel costs. Zaimoğlu and Erkurt [14] state that nuclear energy is an indispensable resource for economic growth and plays a crucial role in enhancing energy independence. İşeri [15] and Özalp [16] assert that Turkey should adopt nuclear energy to ensure long-term energy security and stress the importance of raising public awareness on the matter.

On the other hand, there are also studies opposing nuclear energy. Hobley [17] compared nuclear and renewable energy-based scenarios in the context of the United Kingdom's emission reduction targets and concluded that the renewable energy scenario was more suitable. Zakeri et al. [18] suggested that Finland could achieve its renewable energy goals primarily through wind and biomass-based solutions, but also noted that nuclear power plants could weaken the integration of wind energy. Additionally, energy debates extend to various dimensions, including media, public acceptance, and education. Bulut and Karlıdağ [19] analyzed the nuclear energy discourse in Turkey from a media perspective, examining news discourse on the Akkuyu Nuclear Power Plant between 2010 and 2017 and revealing how media influences public perception of energy policies. Eş, Mercan, and Ayas [20] evaluated nuclear energy within a socio-scientific debate framework, addressing its public acceptance, environmental impacts, and educational dimensions, emphasizing that increasing knowledge on the subject contributes to more informed decision-making processes. Similarly, Özdemir [21] explored how discussions on socio-scientific issues shape individuals' attitudes toward nuclear power plants, demonstrating that such discussions enhance awareness and lead to more balanced and informed perspectives. Literature reviews on energy policies indicate that renewable energy and nuclear energy will play different roles in future energy strategies. Studies on renewable energy systems highlight their strong potential for enhancing environmental sustainability and achieving energy independence, while also acknowledging the technological, economic, and infrastructural challenges associated with this transition. Key challenges in integrating renewable energy systems include energy storage solutions and sectoral integration, whereas nuclear energy advocates emphasize its advantages in ensuring low-carbon emissions and energy security. However, nuclear energy remains a complex issue due to social and environmental concerns such as waste management and safety. Examining energy transition processes in other countries reveals that European nations primarily focus on renewable energy to reduce their reliance on external energy sources, while nuclear energy is adopted as a solution in some Asian countries. Turkey follows a strategy that incorporates both approaches, increasing investments in renewable energy while also pursuing nuclear power. However, the economic and technical challenges encountered during the energy transition process play a critical role in shaping Turkey's long-term strategies. In this regard, experiences from successful case studies serve as valuable guidance for Turkey's energy policies. Most of the studies reviewed above aim to increase the share of various energy sources in production to facilitate the transition to renewable energy, while some focus on interpreting energy mix strategies. While some studies pursue complete decarbonization, others conduct technical and economic analyses of renewable energy sources. Unlike these studies, the present research is based on government policies, specifically the Turkey National Energy Plan, and develops various scenarios to assess the feasibility of achieving the targeted levels of renewable energy utilization over the years. A distinctive aspect of this study is the creation of 10 different scenarios based on whether nuclear energy is included in the system, allowing for a separate evaluation of its contribution. Another significant contribution of this study is the development of a roadmap aimed at reducing carbon emissions, one of the critical challenges of our time.

2. MATERIAL AND METHOD

To model Turkey's energy system and analyze its environmental and economic impacts, the EnergyPLAN software (Version 16.22) was utilized. EnergyPLAN is a bottom-up approach-based simulation tool designed to optimize energy supply. It is also a simulation model that incorporates various technical and economic external variables [22]. EnergyPLAN is a Delphi-based input/output simulation model that encompasses electricity, heating, cooling, industry, and transportation sectors. It simulates the operation of the energy system on an hourly basis. Since EnergyPLAN is developed based on a decarbonized energy production model, it prioritizes renewable energy sources in its modeling approach. The main input and output parameters defined within the EnergyPLAN model are schematically illustrated in the figure.

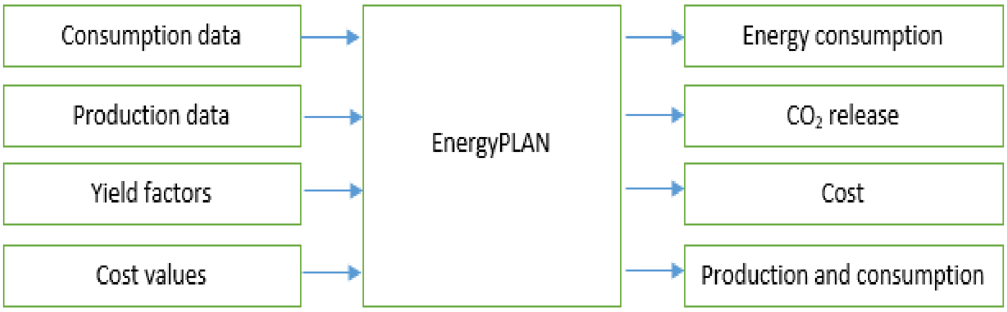

Figure 2. EnergyPLAN inputs and outputs

According to Figure 2, the parameters used in the EnergyPLAN software to create the reference scenario are as follows:

Installed capacities: Determined based on TEİAŞ (Turkish Electricity Transmission Corporation) data. Demand data: Based on forecast data from the Turkey National Energy Plan. Electricity generation data: Based on EPİAŞ (Energy Markets Operation Corporation) data. The input data for EnergyPLAN consists of hourly electricity generation and demand data for the year 2021. These data were obtained from EPİAŞ's hourly generation records and uploaded to EnergyPLAN as an 8,784-hour data file. Efficiency/performance values: The efficiency factors of the energy sources used in the model are provided in the Table 1 below [23].

Table 1. Efficiency Factors of Energy Sources

Energy Source	Efficiency Factor (%)
Solar	20-25
Wind	25-45
Geothermal	80-90
Hydropower	35-40
Natural Gas	85-90
Coal	50-85
Others	50-90

The reference energy model represents the energy system existing in 2021. All verified energy system data for 2021 were obtained and entered into the EnergyPLAN software. Additionally, Turkey's total electricity demand for 2021 was recorded as 331.6 TWh/year in the program [24].

The installed capacity by energy sources and the annual generation amounts by sources for Turkey in 2021 are provided below.

Table 2. Turkey's installed power and production capacity according to resources[3,25]

Energy Plants	Installed Capacity (MW)	Annual Electricity Production (TWh/year)
Natural Gas	25,574	111.20
Dammed	23,280	40.75
Wind	10,607	31.45
Lignite	10,120	43.00
Imported Coal	8,994	54.95
River	8,212	15.20
Solar	7,816	13.94
Geothermal	1,676	10.79
Biomass	1,645	5.90
Coal	841	3.88
Asphaltite	405	2.37

The installed capacity values shown in Table 2 were obtained from TEİAŞ [3], and the hourly electricity generation data by source for 2021 were taken from the EPİAŞ [25] website. The hourly electricity generation data for each source were uploaded to the EnergyPLAN software as separate text files. The text files were created vertically with 8,784 rows, representing the number of hours in a year. After the data were uploaded and the program was run, the obtained results were compared with the actual data.

Following the creation of the reference energy system using 2021 data in line with the Turkey National Energy Plan, changes were made to the installed capacity values according to the determined scenarios, or sources not included in the reference scenario were added to create alternative scenarios. In this study, alternative scenarios will be examined in two groups: "with nuclear" and "without nuclear." In the first group, six scenarios were created for the years 2025, 2030, 2035, 2040, 2045, and 2050, in which renewable sources were increased by varying amounts. In the second group, four additional scenarios were created for 2035, 2040, 2045, and

2050 by including nuclear energy in the first group of scenarios. The generated scenarios were analyzed in terms of CO_2 emissions.

2.1. Development of the First Group of Scenarios

Various data were entered into the EnergyPLAN software to create the scenarios. These include 8,784-hour consumption data as well as 8,784-hour production data by source. Additionally, the installed power capacity (MW) and annual electricity consumption amounts (TWh) were entered. According to the Turkey National Energy Plan, electricity consumption is expected to reach 380.2 TWh in 2025, 455.3 TWh in 2030, 510.5 TWh in 2035, 583 TWh in 2040, 670 TWh in 2045, and 770 TWh in 2050 [3,24].

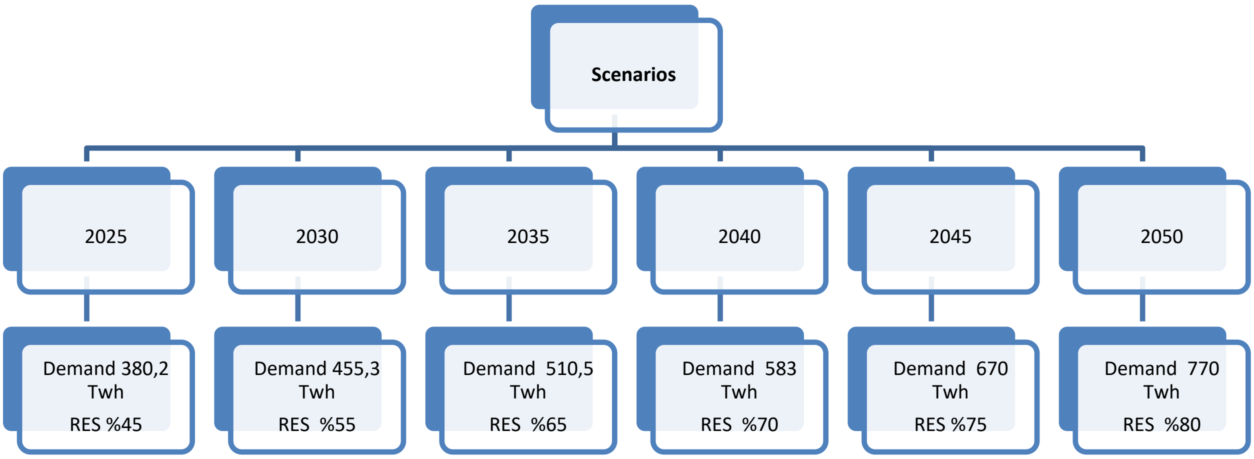

Figure 3. First group of scenarios

Figure 3 presents the demand forecasts planned to be used in scenarios created in five-year periods, along with the share of renewable energy sources (RES) planned to meet this demand in total production.

Scientific Basis: The process of determining wind and solar energy capacity growth rates has considered historical development trends, regional meteorological data, and technological advancements. In this context, growth rates and potential analyses have been elaborated in detail.

Technical and Economic Criteria: In scenario development, not only technical data but also economic parameters were taken into account. Economic analyses included cost-effectiveness of renewable energy investments, incentive mechanisms, market conditions, and information obtained from international data sources (e.g., Denmark Energy Agency, EnergyPLAN Cost

Database, SHURA Energy Transition Center studies, IEA World Energy Outlook). Based on this data, investment costs and capacity expansion limits were defined, enhancing the technical and economic feasibility of the scenarios. Additionally, future energy demand projections were evaluated using data from the National Energy Plan. Demand growth projections for each five-year period were analyzed, aiming to plan energy supply in alignment with these forecasts. Thus, the process of increasing production capacity seeks to maintain the balance between supply and demand while developing a sustainable energy system. This revised section clarifies the scientific and technical parameters underlying the scenarios, demonstrating that our study is built on a solid foundation.

The assumptions determined are as follows:

- A gradual increase method will be applied.
- Scenarios will be defined for the years 2025, 2030, 2035, 2040, 2045, and 2050, following the 2021 reference scenario.
- The scenario for 2025 assumes that 45% of the total energy will be sourced from renewable energy.
- The scenario for 2030 assumes that 55% of the total energy will be sourced from renewable energy.
- The scenario for 2035 assumes that 60% of the total energy will be sourced from renewable energy.
- The scenario for 2040 assumes that 70% of the total energy will be sourced from renewable energy.
- The scenario for 2045 assumes that 75% of the total energy will be sourced from renewable energy.
- For 2050, the target is for 80% of the total energy to be sourced from renewable energy.

Assumptions for the Scenario of 2025 (45% Renewable Energy Share):

- The total demand is set at 380.2 TWh.
- Installed wind and solar capacity is increased by 50% compared to 2021.
- Installed geothermal, hydropower, and biomass capacity is increased by 25% compared to 2021.

Assumptions for the Scenario of 2030 (55% Renewable Energy Share):

- The total demand is set at 455.3 TWh.
- Installed wind and solar capacity is increased by 50% compared to 2025.
- Installed geothermal, hydropower, and biomass capacity is increased by 50% compared to 2025.

Assumptions for the Scenario of 2035 (65% Renewable Energy Share):

- The total demand is set at 510.5 TWh.
- Installed wind and solar capacity is increased by 40% compared to 2030.
- Installed geothermal, hydropower, and biomass capacity is increased by 35% compared to 2030.

Assumptions for the Scenario of 2040 (70% Renewable Energy Share):

- The total demand is set at 583 TWh.
- Installed wind and solar capacity is increased by 25% compared to 2035.
- Installed geothermal, hydropower, and biomass capacity is increased by 25% compared to 2035.

Assumptions for the Scenario of 2045 (75% Renewable Energy Share):

- The total demand is set at 670 TWh.
- Installed wind and solar capacity is increased by 30% compared to 2040.
- Installed geothermal, hydropower, and biomass capacity is increased by 20% compared to 2040.

Assumptions for the Scenario of 2050 (80% Renewable Energy Share):

- The total demand is set at 770 TWh.
- Installed wind and solar capacity is increased by 30% compared to 2045.
- Installed geothermal, hydropower, and biomass capacity is increased by 20% compared to 2045.

Additionally, in this study, balancing energy production and consumption in every hour of the day is determined as a fundamental goal. Energy storage technologies are not extensively covered within the model. Instead, it is assumed that the excess energy generated from renewable sources will be prioritized for export. The EnergyPLAN simulation program was run based on these assumptions, and the results obtained from the scenarios are presented in the discussion section.

2.2. Development of the Second Group of Scenarios

The purpose of developing the second group of scenarios is to reflect the differing opinions on the use of nuclear energy. Like in many other countries, nuclear energy is a controversial topic in Turkey, with supporters and opponents. While environmentalists generally oppose nuclear power plants, some scientists and government officials emphasize their potential environmental and economic benefits. Proponents of nuclear energy highlight its contribution to energy supply security due to diversification, the absence of greenhouse gas emissions compared to fossil fuels, its capacity to generate large amounts of electricity, and relatively low fuel costs [13]. To compare these aspects, the second group of scenarios was created by incorporating nuclear energy into the existing first group of scenarios. While the total annual consumption remained unchanged, nuclear energy was added in varying proportions to the energy mix over the years. According to the Turkey National Energy Plan, the installed capacity of nuclear energy is expected to reach 7,200 MW by 2035 [26]. By 2050, this capacity is projected to increase to 20,000 MW [27]. The share of nuclear energy in total consumption, according to the "Turkey Renewable Energy Outlook," is presented in the table below [28].

Table 3. Nuclear energy outlook

Year	Installed Capacity (MW)	Rate in Total Energy Consumption (%)
2035	7200	%8
2040	11450	%11
2045	15700	%12
2050	20000	%15

According to Table 3, the electricity production from nuclear energy is expected to account for 8% of the total production in 2035, with this share projected to reach 15% by 2050. Based on these figures, nuclear energy was incorporated into the system, and four additional scenarios were developed.

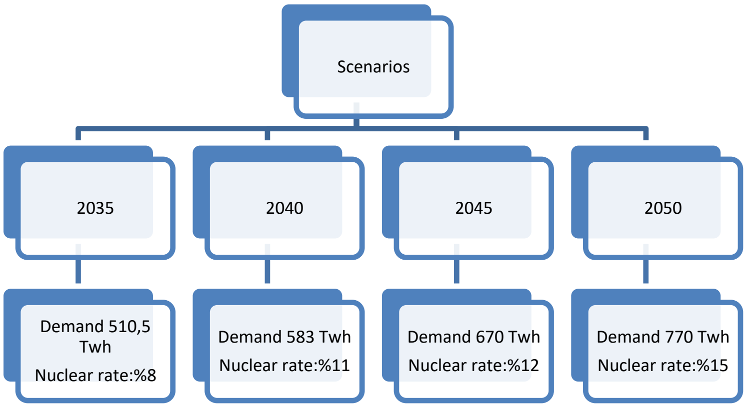

Figure 4. Scenarios with the inclusion of nuclear energy in the system

Figure 4 presents demand projections and the expected share of nuclear energy over the years, as outlined in the Turkish National Energy Plan [26]. Using these demand estimates and nuclear energy proportions, scenarios were developed to analyze their outcomes. The results, including energy production values and CO_2 emissions generated from energy consumption, will be discussed in detail in the discussion section.

3. RESULTS AND DISCUSSIONS

To create the scenarios, Turkey's installed capacity and hourly electricity generation data for each energy source in the reference year 2021 were prepared as separate text files and uploaded into the EnergyPLAN software. After loading the data and running the program, the results obtained were compared with the actual data to validate the model.

Table 4. The model validation between TEİAŞ data and the EnergyPLAN model output

Demand and Supply (TWh)	TEİAŞ	EnergyPLAN	Difference (%)
Demand	331.06	331.06	0.00
Dammed	40.75	40.75	0.00
River	15.20	15.20	0.00
Solar	13.94	13.94	0.00
Geothermal	10.79	10.79	0.00
Wind	31.45	31.45	0.00
Natural Gas	111.20	111.21	0.00
Coal	101.83	100.57	0.01
Biomass	5,90	7,15	0,21

According to Table 4, when the supply/demand data obtained from TEİAŞ and EPİAŞ [3, 25] are compared with the supply/demand data generated using EnergyPLAN, it is observed that the differences are either zero or close to zero. This indicates that the outputs of EnergyPLAN accurately represent the data with high precision. Through these verification steps, it has been demonstrated that the reference scenario developed accurately reflects the current system and that future scenarios can be built on this reference scenario.

In addition to validating the program based on annual production quantities, monthly average supply data and resource-based monthly evaluations were also conducted and compared with the program's outputs. The results confirmed once again that the data were correctly entered into the software.

Table 5. Comparison of monthly average energy supply data

MONTHS	**Monthly Average Energy Supply Data (MW)**		
	TEİAŞ	EnergyPLAN	Difference (%)
January	36149	36405	0,007
February	36003	36296	0,008
March	37104	37396	0,008
April	35580	35627	0,001
May	33305	33661	0,011
June	36718	37257	0,015
July	40649	40830	0,004
August	43182	43580	0,009
September	37955	38000	0,001
October	35093	35329	0,007
November	36855	37200	0,009
December	38874	39087	0,005

Table 6. Monthly average hydroelectric dam supply data

MONTHS	Monthly Average Hydroelectric Dammed Supply Data (MW)		
	TEİAŞ	EnergyPLAN	Difference (%)
January	4573	4586	0,003
February	4373	4428	0,013
March	5993	6087	0,016
April	6995	6906	0,013
May	5040	5050	0,002
June	4720	4899	0,038
July	5471	5325	0,027
August	5206	5192	0,003
September	2811	2786	0,009
October	3217	3284	0,021
November	3326	3268	0,017
December	3780	3824	0,012

When examining the average supply data presented in Table 5 and the hydropower reservoir-based supply data given as an example in Table 6, it is observed that the TEİAŞ data and the EnergyPLAN data are very close in value. This confirms that EnergyPLAN accurately reflects the system.

After defining the reference system and completing the program validation, alternative scenarios were created based on the defined assumptions. The results of the first group of electricity scenarios, which do not include nuclear energy for 2025, 2030, 2035, 2040, 2045, and 2050, are presented below.

Table 7. Percentage values of production by sources in the first group of scenarios

Year	Coal (%)	Natural Gas (%)	Biomass (%)	Geothermal (%)	River (%)	Wind (%)	Solar (%)	Dammed (%)	Total (%)
2021	%30	%34	%2	%3	%5	%10	%4	%12	%100
2025	%24	%31	%2	%4	%5	%16	%7	%11	%100
2030	%20	%25	%3	%5	%6	%21	%8	%12	%100
2035	%15	%20	%3	%5	%8	%26	%11	%12	%100
2040	%13	%17	%3	%6	%8	%28	%12	%13	%100
2045	%11	%14	%3	%6	%9	%32	%13	%12	%100
2050	%9	%11	%3	%4	%9	%36	%15	%13	%100

Table 7 presents the percentage changes in energy sources over the years as a result of the scenarios. According to Table 7, while the use of renewable energy sources increases over the years, the use of fossil fuels shows a decreasing trend. The graph below is designed to visualize these values for easier and clearer understanding.

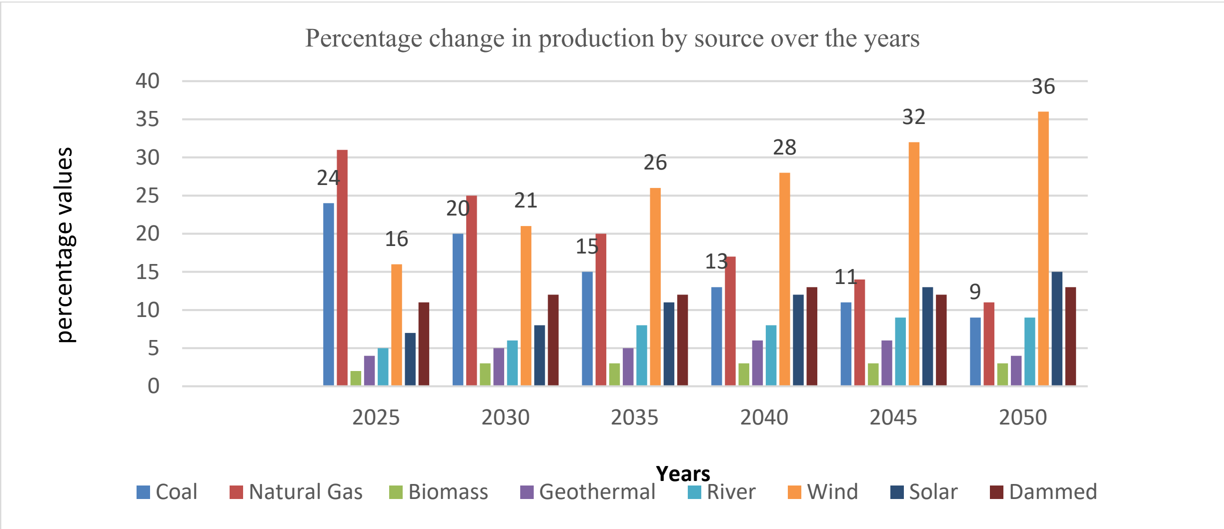

Figure 5. Results of the first group of scenarios

As an example, if coal and wind energy are highlighted: according to Figure 5, the share of coal, one of the fossil fuel sources, was 30% in the reference year 2021, while it was found to be 24% in 2025, 20% in 2030, 15% in 2035, 13% in 2040, 11% in 2045, and 9% in 2050. On the other hand, the share of wind energy, one of the renewable energy sources, was 10% in the reference year 2021, increasing to 16% in 2025, 21% in 2030, 26% in 2035, 28% in 2040, 32% in 2045, and 36% in 2050.

Additionally, the scenario results have also been evaluated in terms of the total CO_2 emissions resulting from the use of energy sources.

Table 8. The results of the first group of scenarios in terms of CO_2 emissions amount

Year	CO_2 Emissions (Mt)
2021	57,09
2025	54,87
2030	54,65
2035	47,9
2040	46,52
2045	44,46
2050	40,94

When looking at the overall scenario results given in Table 8, a decrease in the use of fossil fuels is observed, while the use of renewable sources increases. This reduction in fossil fuel usage also achieves the goal of reducing the CO_2 emissions resulting from energy consumption. The CO_2 amounts calculated by the EnergyPLAN program based on the first group of scenarios are presented below.

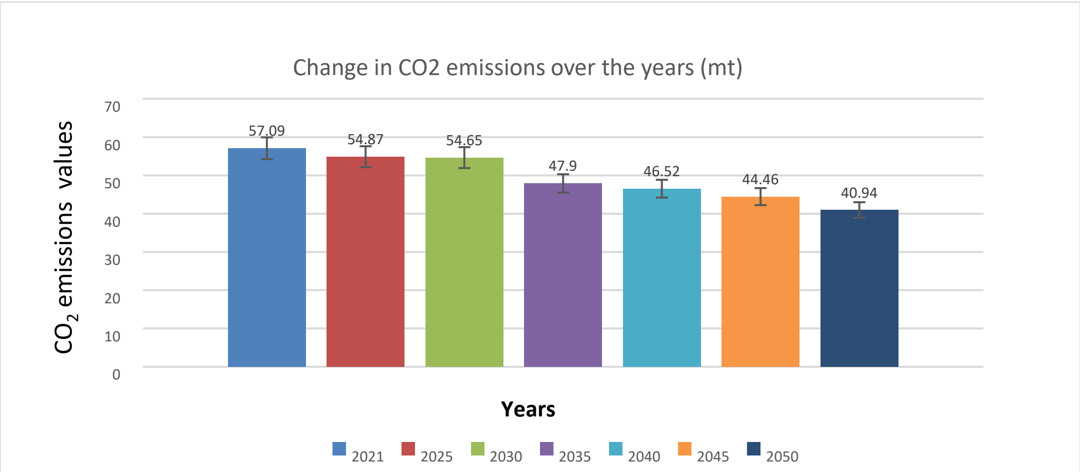

Figure 6. Annual CO_2 variation by the first group of scenarios

Looking at Figure 6, it is evident that the reduction in fossil fuel usage and the increase in renewable energy consumption, as per the first group of electricity scenarios, have successfully reduced carbon dioxide emissions, marking significant steps toward a cleaner environment. The CO_2 emission amount, which was 57.09 million tons (mt) in 2021, decreased to 40.94 mt in 2050, showing a 28% reduction. When energy scenarios including nuclear sources were created, the assumptions of the first group were used, with the only addition being the nuclear energy source data. After entering all the data, the EnergyPLAN program was run, and the following results were obtained.

Table 9. Percentage values of production by sources in the second group of scenarios

Year	**Coal (%)**	**Natural Gas (%)**	**Biomass (%)**	**Geothermal (%)**	**Nuclear (%)**	**River (%)**	**Wind (%)**	**Solar (%)**	**Dammed (%)**	**Total (%)**
2021	%30	%34	%2	%3	%0	%5	%10	%4	%12	%100
2035	%14	%18	%3	%5	%7	%7	%24	%10	%12	%100
2040	%11	%15	%3	%6	%10	%7	%26	%11	%11	%100
2045	%9	%12	%3	%5	%11	%8	%29	%12	%11	%100
2050	%7	%9	%2	%4	%14	%8	%32	%13	%11	%100

Table 10. The results of the second group of scenarios in terms of CO_2 emissions amount

Year	**CO_2 Emissions (Mt)**
2035	47,05
2040	44,29
2045	41,18
2050	34,84

According to Table 9, with the addition of nuclear energy to the current system, the use of nuclear sources increases over the years, while the consumption rates of coal and natural gas decrease. Consequently, the reduction in fossil fuel usage also results in a decrease in CO_2 emissions (Table 10). To enhance clarity, the results of the second group of scenarios are visually presented in Figure 7.

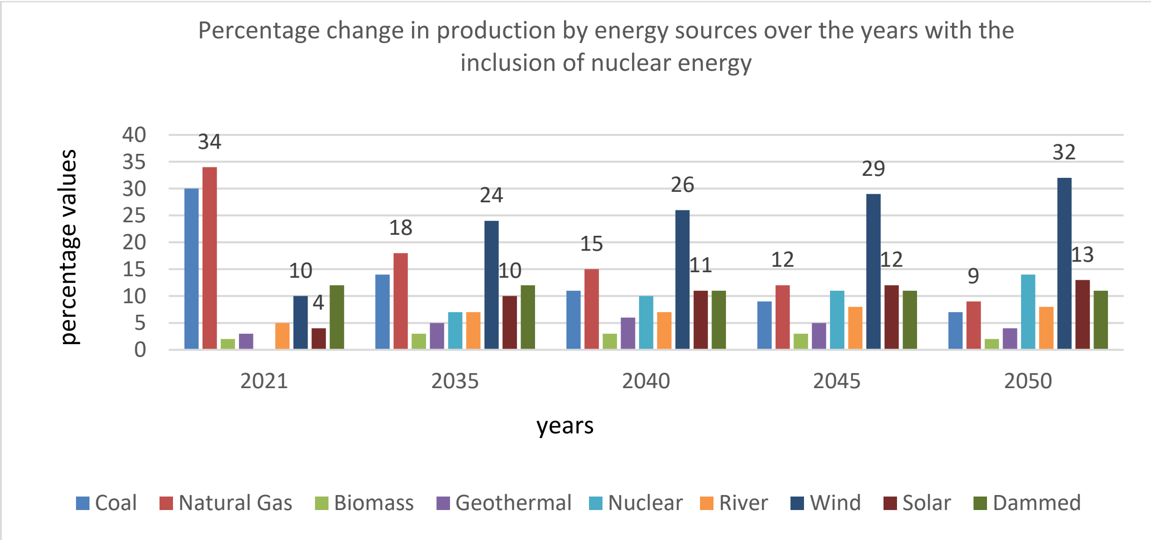

Figure 7. Scenarios with the inclusion of nuclear energy

According to Figure 7, with the inclusion of nuclear energy into the system, renewable energy sources continued to increase, albeit partially, while fossil fuel consumption decreased. For example, when considering natural gas (a fossil fuel) and solar energy (a renewable resource):

- In the reference year 2021, the share of natural gas was 34%, which decreased to 18% in 2035, 15% in 2040, 12% in 2045, and 9% in 2050.
- The share of solar energy in the reference year 2021 was 4%, which increased to 10% in 2035, 11% in 2040, 12% in 2045, and 13% in 2050.

These results indicate that the study's goals of increasing the use of renewable energy sources and reducing carbon dioxide emissions have been achieved.

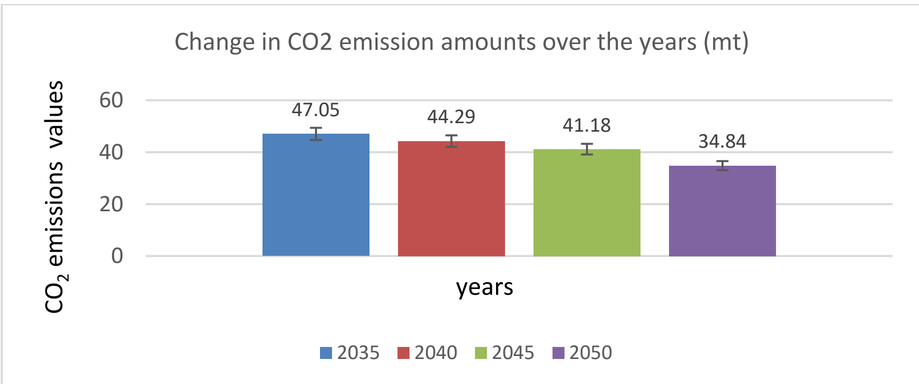

Figure 8. CO_2 variation according to the second group of scenarios

Figure 8 shows the CO_2 emissions resulting from the second group of scenarios. According to the data, CO_2 emissions, which were 47.05 million tons in 2035, decreased by 26% to 34.84 million tons by 2050. When all scenario results are considered, both groups show a decrease in CO_2 emissions. In the reference year 2021, the CO_2 amount was 57.09 million tons. In the first group of scenarios, where nuclear energy was not included, CO_2 emissions decreased to 40.94 million tons by 2050. In the second group of scenarios, where nuclear energy was included, a larger reduction in emissions was observed, with CO_2 emissions decreasing to 34.84 million tons by 2050. This decrease is attributed to the increased use of nuclear energy, which emits significantly less CO_2 compared to fossil fuels, serving as an alternative to meet energy demands. Another scenario evaluation criterion, namely the costs, is presented in Table 11. In order to determine the energy system costs, various inputs were taken into account, including investment expenses, fixed operation and maintenance costs, as well as unit fuel costs. The data sources utilized include the Danish Energy Agency (DEA) [29], the EnergyPLAN cost database [30], and the SHURA report titled "Turkey's Optimum Electricity Production Capacity Towards 2030" [31]. For carbon pricing, the 2040 estimate provided by the International Energy Agency's "World Energy Outlook 2020" report [32] was used. It was assumed that the cost data from the SHURA report would remain applicable through 2040. All costs are presented in Danish Krone (DKK).

Table 11. Cost Values by Scenarios

SCENARIOS(RES %)	**COSTS(Million DKK)**			
	Total variable cost	**Fixed operating costs**	**Annual investment costs**	**Total annual costs**
2025 (%45)	100031	7070	29293	136395
2030 (%55)	104473	9895	38940	153308
2035 (%60)	96265	13049	49413	158727
2040 (%70)	97892	15956	59267	173115
2045 (%75)	98594	19516	70326	188436
2050 (%80)	97624	24465	86191	208279

In general, when the scenarios are evaluated in terms of cost, it is observed that as the share of renewable energy in electricity consumption increases, the total variable cost decreases, while the operating cost, investment cost, and total annual cost increase.

To enhance the reliability of the obtained scenario results and assess the system's response to different variables, a sensitivity analysis was conducted.

Independent Variables (X): Renewable Energy Share (%): The ratio of renewable energy used in the system to total energy production. Balance/Imp (MW): The amount of electricity imported or exported to maintain grid balance.

Dependent Variables (Y): Total System Cost (DKK): The total annual cost of the energy system. CO_2 Emissions (Mt): The carbon emissions resulting from energy production.

Using these variables, correlation analysis, regression analysis, and Monte Carlo simulation were performed to statistically evaluate the impact of different scenarios on the energy system. A dataset was prepared based on the created scenarios, as shown below:

Table 12. Sensitivity Analysis Data

Scenarios	Renewable Share (%)	Balance/Imp (MW)	Total System Cost (DKK)	CO_2 Emissions (Mt)
S1	45	26588	136395	54,87
S2	55	28314	153308	54,85
S3	65	26884	158727	47,90
S4	70	27912	173115	46,52
S5	75	28849	188436	44,56
S6	80	29609	208279	40,94

Using the data provided in Table 12, correlation analysis, regression analysis, and Monte Carlo simulation were performed in Python, yielding the following results:

Correlation Analysis: Renewable Energy Share vs. Total System Cost (0.95): A strong positive correlation exists, indicating that as the share of renewable energy increases, system costs also rise. Renewable Energy Share vs. CO_2 Emissions (-0.96): A very strong negative correlation is observed, meaning that as the share of renewable energy increases, CO_2 emissions decrease. Balance/Imp vs. CO_2 Emissions (-0.66): A moderate negative correlation exists, suggesting that as import and balancing capacity increase, CO_2 emissions decrease.

Regression Analysis: R^2: 0.971 → The model explains 97% of the variability in system costs, demonstrating a very good fit. Renewable Energy Share Coefficient: 9,998 M DKK → A 1% increase in renewable energy share leads to an average increase of 9,998 M DKK in system costs. Balance/Imp Coefficient: 61.7 M DKK → A 1 MW increase in balancing capacity results in an approximately 61.7 M DKK increase in system costs. P-values: The effect of renewable energy share is statistically significant ($p = 0.021$). However, for Balance/Imp, $p = 0.093$, suggesting that further data may be required for stronger statistical validation.

Monte Carlo Simulation:

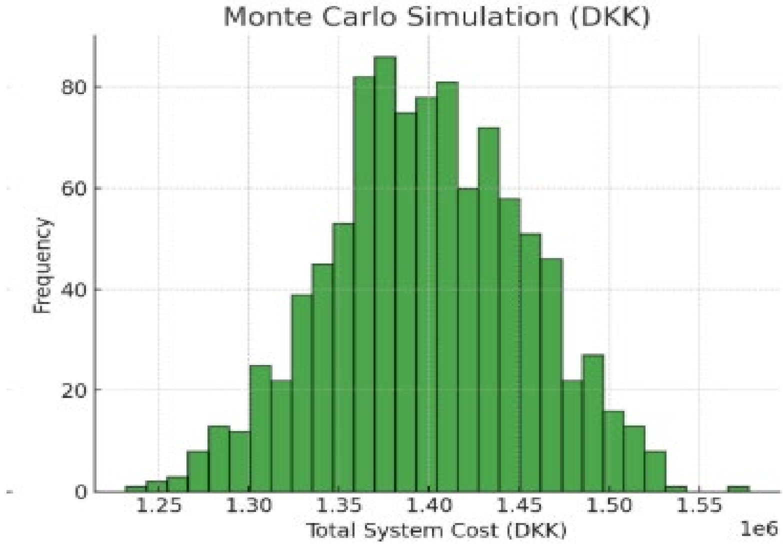

Figure 9. Cost Estimation Histogram

According to the system cost estimation histogram presented in Figure 9, the results approximate a normal distribution, with values mostly concentrated between 1.35 - 1.45 million DKK. This suggests that, in most cases, system costs are expected to fall within this range.

Conclusions and Recommendations

- Although increasing the share of renewable energy leads to higher costs, it significantly reduces CO_2 emissions.
- When increasing the share of renewables in the energy system, balancing mechanisms and import options should be carefully considered.
- To ensure grid stability at lower costs, investments in energy storage technologies (e.g., batteries, pumped hydro) should be explored.

- More comprehensive analyses could be conducted by testing different sensitivity scenarios, including price fluctuations, demand growth, and policy impacts.

4. CONCLUSIONS

The transition from fossil fuels to renewable energy sources is a critical priority for Turkey's energy transformation. According to the simulations conducted in this study, in scenarios where nuclear energy is not included, CO_2 emissions are reduced by 28% by 2050, whereas the integration of nuclear energy increases this reduction to 39%. The study develops energy scenarios in line with the Turkey National Energy Plan, outlining strategies to reduce fossil fuel consumption and increase renewable energy capacity. Additionally, it provides a comprehensive contribution to the literature by analyzing the role of nuclear energy in sustainable energy systems specifically for Turkey. However, the long-term sustainability of nuclear energy also brings certain challenges that require careful consideration. In particular, the limited availability of fuel resources such as uranium, the need for reactor technology renewal, and the safe management of radioactive waste necessitate long-term strategic planning. In this context, investing in advanced reactor technologies, developing waste recycling systems, and implementing energy source diversification strategies are of critical importance. The simulation results indicate that while an increase in the share of renewable energy significantly reduces CO_2 emissions, it also raises system costs. Specifically, it has been determined that each 1% increase in the share of renewable energy increases system costs by an average of 9,998 M DKK. In this regard, policy recommendations to enhance energy security include: increasing the capacity of wind, solar, and geothermal energy, expanding nuclear energy capacity to 20,000 MW by 2050, and strengthening energy storage and smart grid infrastructure. These strategies, supported by carbon tax policies, renewable energy incentives, and R&D investments, will accelerate the transition to a low-carbon future and enhance energy security.

As a suggestion for future research, new analyses can be conducted by incorporating heat, transportation, and electric vehicles into various scenario models in addition to the data used in this study.

NOMENCLATURE

CO_2 : Carbon Dioxide

DEA :Danish Energy Agency

DKK: Danish Krone

EPİAŞ :Energy Markets Operation Corporation

MW : Megawatt

Mt :Million tons

RES :Renewable Energy Sources

TEİAŞ :Turkish Electricity Transmission Corporation

DECLARATION OF ETHICAL STANDARDS

The authors of the paper submitted declare that nothing which is necessary for achieving the paper requires ethical committee and/or legal-special permissions.

CONTRIBUTION OF THE AUTHORS

Emine Ertane Baş: Writing, Methodology, Experiment, Visualization, Review & Editing.

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Vecihi Yiğit: Writing, Methodology, Experiment, Visualization, Review & Editing.

CONFLICT OF INTEREST

There is no conflict of interest in this study.

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