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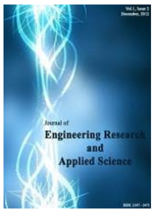

Nuclear power in Turkey for low carbon economy and energy security: a socioeconomic analysis

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Abstract
Nuclear energy is a proven solution with a long and well-established track record. Nuclear reactors are the low-carbon backbone of electricity systems, operating in the background, day in and day out, often out of sight and out of mind. Capable of generating immense amounts of clean power, they are the silent giants upon which we rely daily. In Turkey building up a nuclear power plant has always been a hot topic for discussion at least for 40 years. They raise three main advantages including cheap electricity, low carbon dioxide and reliability, and two disadvantages, including issues of nuclear waste and the risk of accident. This study aims to explore citizens' perceptions of the advantages and disadvantages of nuclear power plants (NPPs) through semi-structured interviews with people local to the Akkuyu region. In this paper we will examine the pros and cons of having nuclear power plants in Turkey mostly in terms of economic aspects considering economic and social costs as well as economic gains. In addition we will look at Turkey's nuclear energy policies. We will also mention about environmental effects debates of the NPPs in the country.

Keywords: Nuclear energy; energy security; benefits nuclear power in Turkey.

1. Introduction

The energy economy of Turkey is dominated by fossil fuels. The total primary energy supply in 2020 amounted to 140 Mtoe, with coal (26%), gas (30%) and oil (30%) having the largest shares. Electricity generation was 286 TWh, mostly produced from natural gas (22.14%), coal (33.5%), hydropower (26.56%) and other renewables (17.84%). Total primary energy supply per capita was 1.8 tons of oil equivalent (toe) and power generation per capita was 3.8 MWh. The main objectives of the current energy policy include increasing domestic resources, decreasing energy imports, diversifying supply sources, implementing oil and gas pipeline projects, increasing energy efficiency and renewable energy usage, decreasing fossil fuel consumption, improving competitiveness in electricity and natural gas markets, implementing natural gas storage projects and introducing nuclear energy [1-10].

The final energy demand in Turkey is increasing together with growing domestic production, leading to increasing CO_2 emissions from the energy sector. Nuclear energy is mentioned as a mitigation option together with focus areas such as renewable energy sources, energy efficiency and market mechanisms. Several factors motivate this study. Turkey is a potential nuclear newcomer country and nuclear energy is considered an important tool for economic development, while there are also increasing concerns about energy security and environmental protection. In addition, many recent studies have tended to focus on renewable and local energy resources, with limited analysis of the nuclear energy. The objective here is to provide a deeper scientific basis for considering the role of nuclear energy in climate change mitigation strategies in Turkey.

2. Current energy situation

Overarching Turkish energy policy focuses on assuring the supply of energy in a reliable, sufficient, timely manner. Energy and electricity production are to be obtained in economical and clean terms, and in such a way as to support and orient targeted growth and social development [1-3]. Prepared by the

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Ministry of Energy and Natural Resources (MENR), the National Energy and Mining Policy of Turkey has developed plans in line with three considerations: security of supply, indigenous production and potential projections of the foreseeable market [4]. Table 1 shows Turkey's energy production and consumption in 2020.

Table 1. Turkey's total energy production in 2020 (Mtoe)

Energy Sources	Production	Consumpt.
Hard coal & Lignite	14.8	40.1
Oil	3.4	34.2
Gas	0.4	40.1
Hydropower	6.7	6.7
Geothermal	10.6	10.6
Wood and Biomass	3.4	3.4
Solar/Wind/Other	4.2	4.2
TOTAL	**43.5**	**140.1**

Source. Refs. [1-5]

The main aims of security of supply are to achieve diversification of energy resources and markets, sustainability and reliability of resource transfer, and a reduction in the cost of imported energy products. Security of supply is also closely related to a strong economy and national security [1]. The issue of security of supply is discussed under five headings: diversification of energy resources and supplier countries, natural gas and oil storage facilities, capacity to provide natural gas to the system, energy delivery infrastructure and energy efficiency [2]. Indigenous energy production using national resources is important in achieving energy independence. In this regard, indigenization is critically important for Turkey to add a new dimension to its policies and strategies to reduce the country's dependence on imports. Many public and private sector institutions and organizations, in particular the MENR, are expending efforts to increase the use of national energy resources. In order to decrease Turkey's dependence on imported energy, there are plans to increase the use of renewable energy resources, domestic coal and nuclear energy, and to tap into domestic oil and natural gas reserves [1-5]. Table 2 shows Turkey's estimated available energy sources and Table 3 also shows Turkey's energy consumption from 2000 to 2020 [1-5].

Table 2. Turkey's estimated available energy sources

	Fossil Fuels			**Nuclear**		**Renewables**			
	Solid	Liquid	Gas	Uranium	Thorium	Hydro	Geothermal	Wind	Solar
Units	Million tons	Million tons	Bm^3	metric tons	metric tons	TWh/y	TWh/y	TWh/y	TWh/y
Total	12 615	45.2	6.7	16 738	380 000	160	12	153	380

All renewable values given as their maximum available potentials [2].

Table 3. Energy consumption

Energy consumption [PJ]	2000	2005	2010	2015	2020
Total	2 469	2 784	3 337	3 992	4 481
Coal, Lignite	506	502	684	593	571
Oil	1 092	1 091	1 187	1 466	1 692
Natural gas	204	416	542	885	1 192
Biomass & Waste	270	223	186	122	116
Electricity	345	462	610	770	970
Heat	53	90	127	156	190

Turkey intends to improve its electricity and natural gas market, restructure institutions in the energy sector and rehabilitate the infrastructure of the energy supply. The National Energy and Mining Policy reveals several strategies and objectives in order to create a more foreseeable, transparent and investor friendly energy market. In recent years, a series of major energy projects have been signed and these projects will contribute to Turkey's goal of having a greater role as an energy trading hub. Policy issues related to energy are within the responsibility of the MENR. Energy planning studies, taking into account short, medium and long-term policies and measures, are carried out by the MENR within the framework of the above listed objectives [1-6].

Although conventional resources exist in Turkey, these resources are not sufficient to meet the projected growth in energy demand, except for lignite and hydropower. To date, around 68.9% of energy demand is met through imports. Energy planning studies indicate that Turkey's energy demand will continue to increase in parallel with economic development, industrialization and urbanization. In this context, Turkey has intensified efforts at further diversification in primary energy sources, imports, technologies and infrastructures, while accelerating the production and utilization of remaining domestic resources potential and efficiency gains along the energy supply–demand chain [6-9].

3. The electricity generation system

3.1. Electricity system and decision-making process

In parallel with economic growth, electricity demand has shown a significant increase over the past decades, reaching 305 TWh by the end of 2020. Turkey has lignite, natural gas, renewables and hydropower resources for domestic electricity generation (Fig. 1). The share of domestic resources for electricity generation was 57% in 2020 [6]. Turkey attaches utmost importance to the utilization of the remaining potential, with due regard, to cope with the risks stemming from import dependency. Integration of nuclear power plants into the Turkish electricity grid is also being considered as an essential tool to enhance supply security, while strengthening greenhouse gas emission mitigation efforts. Table 4 shows Turkey's electricity production from 2000 to 2020 as GWh. As shown in Table 4, electric production of the country is increasing year by year due to economic and social developments. Table 5 also shows Turkey' energy related ratios [1-6].

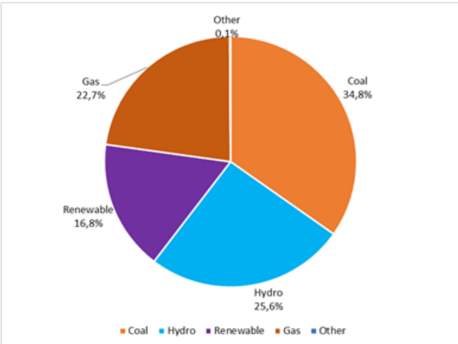


Figure 1. Electricity generation by energy sources (as of the end of 2020).

Table 4. Electricity production

Electricity production (GWh)	2000	2005	2010	2015	2020
Total	124 922	161 956	211 208	261 783	283 672
Coal & Lignite	38 187	43 192	55 047	76 166	96 950
Oil	9 311	5 483	2 180	2 224	306
Natural gas	46 216	73 445	98 144	99 218	62 288
Bioenergy & Waste	174	44	346	1 263	5 411
Hydro	30 879	39 561	51 796	67 146	78 823
Nuclear	0	0	0	0	0
Wind	33	59	2 916	11 652	22 376
Solar	0	0	0	194	10 250
Geothermal	76	94	668	3 425	9 084
Other	46	78	111	495	2 157

3.2. Structure of electric power sector

The MENR is the main body of the Turkish energy sector and is responsible for the preparation and implementation of energy policies, plans and programs, in coordination with its dependent and related institutions and other public and private entities. The Ministry is responsible for monitoring and taking measures regarding the security of the electricity supply. The Energy Market Regulatory Authority (EMRA) is the regulator of the electricity, natural gas, downstream petroleum and liquefied petroleum gas (LPG) products markets. EMRA is responsible for granting licenses for activities in the gas and electricity markets for generation, transmission, distribution, wholesale, retail, import and export. The Electricity Generation Company (EUAS) is the state-owned generation company responsible for the operation of existing power plants owned by the public [1-6].

The Turkish Electricity Transmission Company (TEIAS) is the transmission system operator and is responsible for planning, installing and operating the transmission grid, for providing system security. Within the context of the Decree Law No. 703 published in the Official Gazette No. 30473, Turkish Electricity Trading and Contracting Co. (TETAS) and EUAS unified under the structure of EUAS and duties, authorities and responsibilities of former TETAS are now being performed by EUAS. Electricity production, consumption and capacity are shown in Table 4, and energy related ratios are shown in Table 5 [6-9]. Figure 2 shows Turkey's source-based development of licensed electricity generation by years (GWh).

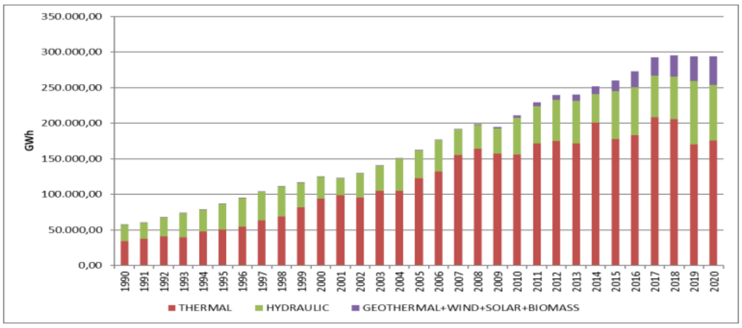


Figure 2. Source-based development of licensed electricity generation by years (GWh) [2]

Table 5. Energy related ratios

	1980	1990	2000	2010	2020
Energy consumption per capita (GJ/capita)	30.14	39.94	49.86	59.91	74.68
Electricity consumption per capita (kWh/capita) (gross)	554	1012	1903	2854	3668
Electricity production/Energy production (%)	11.5	19.7	40.60	57.55	58.71
Nuclear/Total electricity (%)	—	—	—	—	
Ratio of external dependency (%)	45.71	52.1	66.7	70.20	71.92

4. Nuclear power situation

4.1. Introduction

Since 1970, Turkey has had plans in place to establish nuclear power generation capabilities. In order to meet the increasing domestic demand for energy and reduce its dependence on energy imports, various initiatives were undertaken in the past to build Turkey's NPP. In 1993, the Supreme Council for Science and Technology identified nuclear electricity generation as the project of third highest priority for the country. In view of this decision, the Turkish Electricity Generation and Transmission Company (TEAS) included a nuclear power plant project in its 1993 investment program. In July 2000, after a series of delays, the government decided to postpone the project. Following this delay, the Law on Construction and Operation of Nuclear Power Plants and the Sale of Energy Generated (Law No. 5710) was ratified; it entered into force on 21 November 2007 [1-3, 9, 10].

The Regulation Regarding the Principles, Procedures, and Incentives for the Contracts and the Contest that will be made within the context of the Law on the Construction and Operation of Nuclear Power Plants and the Sale of the Energy Generated was published in the Official Gazette on 19 March 2008. The purpose of the regulation is to regulate the procedures and principles regarding the construction and operation of NPPs for electrical energy production, and to regulate energy sales. In accordance with this, the Turkish Atomic Energy Authority (TAEK) issued a set of criteria that establish general principles to ideally be met by investors [9-18].

4.2. Akkuyu Nuclear Power Plant

Direct negotiations with the Russian Federation to build an NPP on the Akkuyu site in Turkey started in February 2010 and concluded with an intergovernmental agreement (IGA) based on a build–own–operate (BOO) model. The agreement was signed on 12 May 2010. It aims to build nuclear capacity in Turkey through mutual cooperation, ranging from NPP construction and operation in Akkuyu–Mersin, to decommissioning. For the implementation phase of the project, the Akkuyu Nuclear Power Plant Electricity Generation Joint Stock Company (Akkuyu Project Company or APC) was established on 13 December 2010. On 7 February 2011, TAEK recognized APC as the owner, according to the Decree on Licensing of Nuclear Installations. Akkuyu NPP Electricity Generation JSC was renamed and registered as Akkuyu Nuclear JSC in September 2014 [9, 10].

On 3 March 2017, Akkuyu Nuclear JSC (APC) applied to TAEK for a construction licence for Akkuyu NPP Unit 1 and was awarded a limited work permit on 20 October 2017. Under this permit, APC began construction of that part of the building and infrastructure unrelated to nuclear safety, such as the port, road and personnel buildings. After reviewing the licence application documents, TAEK issued the construction licence on 2 April 2018. With this licence, APC started on construction of nuclear safety related buildings and infrastructures, such as a reactor or turbine buildings. On 3 April 2018, construction of the first unit of Akkuyu NPP formally launched with the pouring of concrete for the sub-base foundation of the nuclear island [9].

Akkuyu NPP's 2nd and 3rd units were awarded construction licenses by Nuclear Regulatory Authority (NDK) on 26 August 2019 and 13 November 2020 respectively [9]. Application for a construction license for the 4th unit was submitted to NDK on 12 May 2020. The construction of 2nd and 3rd units of Akkuyu NPP formally launched with the pouring of first concrete for the sub-base foundation of the nuclear island on 8 April 2020 and 10 March 2021, respectively. Within the framework of the agreement, the power generated by Akkuyu NPP will be transmitted from the Akkuyu NPP switchgear via 400 kV power lines to six transformer substations that are part of Turkey's unified energy system. The total length of the high voltage lines that will be built as part of the Akkuyu NPP power distribution scheme will exceed 1000 km. All the power lines to be connected to Akkuyu NPP will be built and maintained by the TEIAS [1-9].

4.3. Fuel cycle and waste management

A reactor materials unit, for the refining of uranium concentrate for conversion to UO_2 and for the manufacturing of sintered pellets, has been in operation at the ÇNAEM since 1986. Waste management is currently limited mainly to radioactive waste arising from the industrial and medical applications of nuclear technologies, and there is a facility for processing and storage of these wastes. Compaction, cementation and precipitation processes are carried out at this facility. According to the agreement with the Russian Federation, APC will be responsible for NPP fuel supply and waste management. Nuclear fuel will be sourced from suppliers based on long term agreements between APC and the suppliers [9]. In addition, APC will make the necessary payment to the national spent fuel and radioactive waste management fund stipulated by the applicable Turkish laws and regulations. Subject to a separate agreement that may be agreed to by the parties, spent nuclear fuel of Russian origin may be reprocessed in the Russian Federation [9].

4.4. Emergency preparedness

Ministry of Interior, Disaster and Emergency Management Authority (AFAD) is the coordinating authority assigned for all kinds of disasters and emergencies at all levels including large scale nuclear and radiological emergencies. AFAD has its own Disaster and Emergency Management Center (DEMC), similar to other stakeholders which have a role in emergency response according to the related regulation. All the responsible authorities take part in AFAD related to a particular emergency when effective response, coordination and collaboration at the national level are required for management of emergencies [9]. Also, provincial disaster and emergency directorates, affiliated with AFAD, were established within the body of governorships in different provinces. Disaster and Emergency Council which consists of representatives of all relevant institutions and organizations, is held under the authority of the Minister of the Interior [9].

The mission of the NDK is to undertake regulatory and inspection activities within the scope of emergency preparedness. NDK is recognized as the “national warning point” and “competent authority” by the IAEA according to the Convention on Early Notification of a Nuclear Accident and the Convention on Assistance in the Case of a Nuclear Accident or Radiological Emergency. NDK will provide technical consultancy in case of major radiation emergencies within the AFAD-DEMC regarding preparedness and response infrastructure which was established alongside the AFAD [9]. In this new framework, NDK is one of the support solution partners of the chemical, biological, radiological or nuclear (CBRN) service group which has been established within the framework of the National Disaster Response Plan (NDRP) [9].

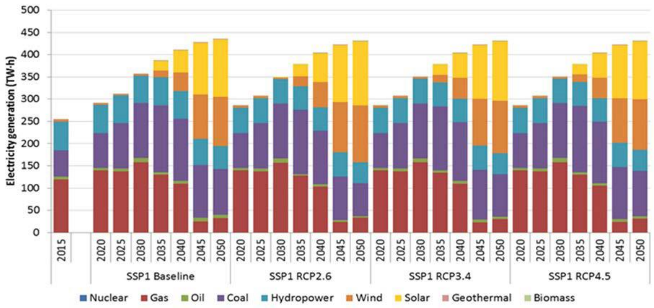
Akkuyu JSC is responsible for developing the on-site emergency plan determines the required actions for mitigation of the accident consequences, while respective governmental organizations will prepare the provincial radiation emergency plan that is associated with the NREP and NDRP. The off-site emergency plan regulates zones and distances of emergency planning and defines actions to be taken by authorized local and national authorities to protect the public, property and the environment in the event of a radiation emergency [9-18].

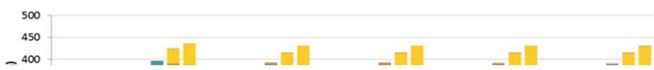
4.5. Methodology and assumptions

The backdrop for modelling energy and electricity demand and supply in Turkey are the shared socioeconomic pathways (SEPs) [13]. Three of the five SEPs are used in this study: SEP1 that involves low energy demand due to a major paradigm change and characterizes the low baseline; SEP2 represents the BAU case, i.e. development along historical patterns; and SEP3 with high energy demand represents the high baseline. The socioeconomic projections for Turkey are taken from MENR [14] and the techno-economic results of integrated assessment modelling studies evaluating the costs of carbon emissions reductions represented by the so-called representative concentration pathways (RCPs) describing GHG emission trajectories consistent with specific atmospheric GHG concentrations and levels of radiative forcing [15]. Final energy demand is calculated with the Kaya identity using population and GDP projections from the SSP database [16] and energy intensity of production for SSPs from Ref. [17, 18].

5. Results and discussions

Primary energy demand for fossil energy resources increases for both domestic and imported coal and imported natural gas and crude oil. Primary demand is projected to increases to 1361 TWh in the baseline scenario SEP1, to 1445 TWh in SEP2 and to 1733 TWh in SEP3 in 2050. Demand for primary renewables such as hydropower, biomass and geothermal also increases. Hydropower is also used to provide flexibility in the electricity transmission grid to supply peak load electricity. Biomass and geothermal sources are used for both electricity and heat generation. Primary renewable energy demand is estimated to reach 370 TWh in SEP1, 210 TWh in SEP2 and 188 TWh in SEP3 in 2050. Lastly, final electricity demand is projected to increase from 218 TWh in 2022 to 354 TWh in the SEP1, to 355 TWh in the SEP2 and to 396 TWh in the SEP3 scenario in 2050. Figure 3 shows the amount and composition of electricity generation in the three baseline and the related mitigation scenarios [13-18].





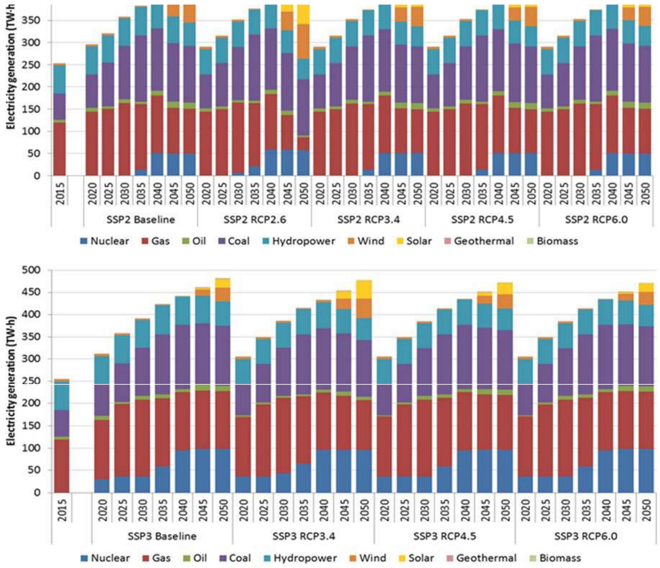


Figure 3. Turkey's electricity generation in various scenarios [15]. TWh = Terawatt-hour, SEP = Socio-economic pathway, RCP = Representative concentration pathway.

The results are highly sensitive to upper limits for imported coal as the model seeks to use this low-cost energy source in all scenarios [14]. As the low baseline case (SEP1) assumes a major paradigm shift towards sustainable development in which consumption is oriented toward low material, resource and energy intensity, it leads to stabilizing final energy demand and favors an intensive penetration of wind and solar energy, albeit with concerns over grid stability and flexibility. In this scenario, the role of nuclear power is highly sensitive to the potential decrease in capital costs after 2030 when more CO_2 emissions reductions are required and when CO_2 prices are higher [15-18].

Annual investment requirements in the electric power sector vary considerably across scenarios. Shares of technologies targeted by the investments also differ depending on the baseline pathway and the stringency of the climate change target. In SEP1, the total capital investment in renewable electricity is US $145 billion and in fossil power US $32 billion during the modelling period. Investment patterns are rather different in SEP2. Here the total installed capacity of nuclear power grows to 7000 MW_e and requires US $37 billion capital investment, complementing investment in RESs of US $89 billion and US $40 billion in fossil power during the modelling period. Nuclear power plays an even more important role in SSP3, with total installed capacity starting at 4000 MW(e) in 2020 and increasing to 14 000 MW_e in 2050, requiring US $74 billion capital investment. The total capital investment in renewable electricity is US $70.1 billion and in fossil power US $37 billion. Figure 4 shows CO_2 emissions from electricity generation over the entire time horizon in different scenarios.

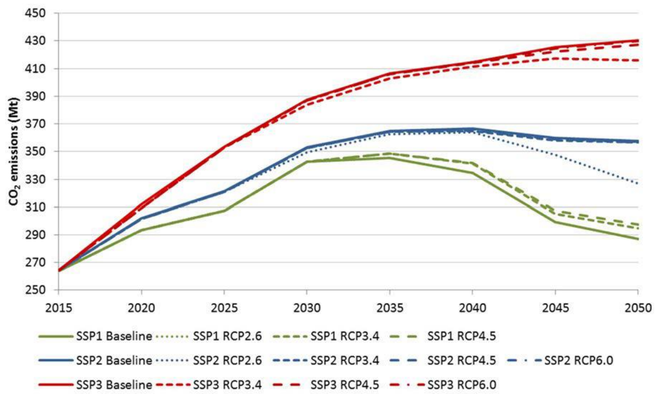


Figure 4. CO_2 emissions from electricity generation in various scenarios [15]. Note: Mt: Million ton, SSP: Shared Socioeconomic Pathway, RCP: Representative Concentration Pathway.

On the other hand, mitigation paths towards different climate change targets in the SSPs often overlap, hence some of them are not visible in Fig. 4. The more stringent the climate target, the larger the mitigation need and thus the lower the CO_2 emissions within the SSPs, except SSP1 in which the baseline emissions pathway itself achieves the required climate target. Note that RCP2.6 is not even an option in SSP3 in which baseline emissions make the required magnitude of emissions reductions practically impossible with the model assumptions. The model does not install more wind and solar energy and less coal and gas based capacities in this scenario because the large penetration of nuclear power competes with wind and solar energy for low carbon electricity generation. Therefore, this is also driven by intertemporal optimization of the energy system [9-18].

6. Conclusions

Climate change is one of the most important issues facing the world today. Nuclear power can make a significant contribution to reducing greenhouse gas emissions (GHGs) worldwide, while at the same time meeting the increasing demands for energy of a growing world population and supporting global sustainable development. Nuclear power has considerable potential to meet the challenge of climate change by providing electricity, district heating and high temperature heat for industrial processes while producing almost no GHGs. On the other hand, to address the challenges posed by climate change, and to achieve the goals established in the 2015 Paris Agreement Under the United Nations Framework Convention on Climate Change (UNFCCC), a significantly greater deployment of low carbon energy technologies is needed. Nuclear power has the potential to play a significant role in achieving these mitigation goals and, as a large scale, reliable, and concentrated source of energy, can also contribute to the broader economic and social dimensions of sustainable development. The potential role of nuclear power was also addressed in the 2018 Intergovernmental Panel on Climate Change (IPCC) Special Report on Global Warming of 1.5ºC.

Nuclear energy contributes to reducing the carbon intensity of the economy together with renewable energy in both the SEP2 and SEP3 scenarios. In the SEP3 scenarios, nuclear energy is deployed already in 2020 and provides a larger contribution to supply baseload electricity to satisfy the increasing energy demand driven by increasing population and production and slower improvement in energy intensity compared to the SEP2 scenarios. Realizing this potential of nuclear power across the scenarios naturally depends on the availability of front-end nuclear fuel services and measures to address back-end liabilities by the utilities and the government.

This study also demonstrates that the potential role of nuclear energy in climate change mitigation in the Turkish energy sector is sensitive to decreasing costs of renewable energy and increasing costs of NPPs. The intermittency of solar and wind power leads to their convergence to their upper limits in electricity generation by the end of the modelling period because the minimum requirement for grid flexibility puts constraints to generation from these sources in order to preserve capacity reserves for grid stability. Introducing nuclear energy in Turkey can be a policy option in climate change mitigation but possible negative economic and social consequences of building and operating NPPs go beyond emissions mitigation strategies. It is important to balance social, economic and environmental priorities in national mitigation strategies. Therefore, NDCs and energy supply security dimensions also need to be analyzed in future studies.

Acknowledgement

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