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Spatial evaluation of the nuclear power plant installation based on energy demand for sustainable energy policy

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Abstract

Knowing the energy demand guides the future investments of countries. Nuclear power plant (NPP) is an important resource to guide sustainable energy policies in sectoral investments. The first step for the reliable, accurate and energy-demand-based use of this resource is the NPP installation on a suitable site. Therefore, spatial evaluation is required for NPP in terms of planning and management. The purpose of this study was to identify the potential province for NPP installation depending on the energy demand and to select the most suitable sites in this province by using geographic information system integrated with fuzzy analytic hierarchy process from multi-criteria decision making. First of all, the energy demand map for Turkey was produced by considering the demographic and economic criteria. From this map, it was concluded that "Bursa" has a very high energy potential province. Then, the suitability map was created by handling the environmental, social and safety criteria for site selection in Bursa. Results showed that Bursa has a very high suitability site for NPP, which spans 1092 km^2 (10%) after deducting the restricted sites, relatively and least suitable sites. Finally, nine candidate sites were selected from among the most suitable sites, and these sites were evaluated in terms of tourism, agricultural activities, sufficient cooling water and area sizes. As a result of the evaluations, two priority sites (CS-7 and CS-9) for NPP were found in Bursa. The examination of NPP site suitability would assist in the country's development and spatial plans.

Keywords Nuclear power plant · Energy demand · Spatial evaluation · Geographic information system · Fuzzy analytic hierarchy process

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1 Introduction

Energy is an indispensable part of today's civilization, and energy use plays a very important role in human well-being (Gralla et al., 2017). The world population, which has been more than two quarters since 1950, is expected to increase by 40% only by 2050 (Idris & Abd Latif, 2012; Uyan, 2017). In recent years, energy consumption in the world has intensified with the increasing population and rapid economic growth. People and businesses demand cheap and reliable energy (Lang, 2017). In 2018, Germany is the country that consumes the most energy, with a share of 16.29% (333.9 million TOE: Tonne of Oil Equivalent) in primary energy consumption among 21 countries across Europe. France comes next with a share of 11.58% (273.5 million TOE). On the other hand, Turkey ranks sixth among these countries with a rate of 7.45% (Petroleum, 2019). Although the population is considered to be the main factor in increasing the energy consumption of countries, there are also economic effects that are not dependent on the population. The Turkish economy has experienced an almost uninterrupted growth process since the first quarter of 2002, when the effects of the global financial crisis were felt. As a result of this growth period, Turkey has become the world's seventeenth largest economy. Turkey aims to be among the top ten economies of the world with a gross domestic product (GDP) of 2 trillion USD or a GDP per capita of 25 thousand USD (Arslan & Serttaş, 2017).

Accordingly, the country's growing economy leads to increases in energy demand. Researches conducted in the last ten years show that Turkey ranks first in Europe in terms of electricity and natural gas demand growth rates. Since energy resources are limited in Turkey, it imports a large amount (72% part) to meet the ever-increasing energy demand. However, the country should meet the majority of energy demands directly on its own, and importing energy should not be among the priority plans of the country (Sonmez et al., 2017). Examples of energy import problems encountered in daily life can be given as follows: As a result of the West's involvement in the ongoing tension between Russia and Ukraine in the recent period, in addition to a possible military conflict, the energy restriction that may affect the entire European continent remains on the agenda. There has been a tension due to Russia's use of natural gas sales as a geopolitical weapon and the possibility of cutting off gas flow to Europe. Considering all negative scenarios, foreign dependency in energy supply is a handicap for countries. Therefore, the main energy policy of the country should focus on minimizing foreign dependency, diversifying energy resources, the most effective and efficient use of energy, and meeting the demands in a safe and continuous manner. If energy, which is a condition of sustainable development, is considered together with economic and environmental factors, it can make a great contribution to industrialization and the general development of societies (Kok & Benli, 2017).

Nowadays, nuclear power plant (NPP) is included in the energy portfolio to increase the diversity of energy sources. International Atomic Energy Agency (IAEA) sees nuclear energy as a source of electricity generation in the advanced countries of the world since the 1950s. The development of a convenient infrastructure for the sustainability, benefits and safety of nuclear energy is a critical issue, especially for these countries (IAEA-NES, 2015). In preparing the nuclear infrastructure, several activities need to be completed. These activities consist of three phases as the development of a national infrastructure. The process begins with a country carefully considering the nuclear power option in the context of its overall energy policy and the decision is made. Once a decision is taken, the supporting frameworks, institutions and infrastructure need to be developed, leading to initiating a successful bidding process (IAEA, 2015). With innovative technology, the plant itself is built and made ready for operation. Since other countries are importers, they cannot create these stages according to themselves and determine NPP's infrastructure according to the supplier countries from which it imports.

Only six advanced countries—Korea, France, Japan, China, Russia, and the USA — are regarded as having the capability to export energy from NPPs (Lévêque, 2014; Roh et al., 2019). On a country basis, France meets more than 70% of its electricity demand, the European Union 26%, South Korea 30% and the USA 20% from nuclear energy (Çelik, 2015; WNA, 2020). There are 54 reactors under construction led by China with 11 reactors, India with 7, Russia with 6, South Korea with 5 and the UAE with 4 units. Argentina, Brazil, Finland, France and Turkey all have 1 reactor under construction (Ho et al., 2019; PRIS, 2021). These constructions are carried out by the above-mentioned six countries that can export NPPs. Six countries are suppliers in over 90% of all international nuclear agreements (Jewell et al., 2019). There are two NPP projects in Turkey, one at the construction stage and the other at the project stage. The first nuclear power plant to be put into effect will be Mersin (Akkuyu) NPP with a capacity of 4800 MW. After that, it is aimed to install Sinop NPP with a capacity of 4400 MW. It is predicted that Akkuyu NPP will be able to meet 9.2% of the country's total electrical energy needs, with full capacity generation planned in 2022 (URL1). Although Turkey's 2023 energy program has various targets, nuclear energy is considered the contentious topic in this agenda and there are ongoing attempts in the country the installation of a third power plant (Melikoglu, 2016). Among Turkey's neighboring countries, Armenia has 1, Bulgaria has 2, Iran has 1, Russia has 35, Ukraine has 15, and Romania has 2 nuclear reactors. Although most of these facilities have expired, they continue their activities. It is very important to meet the energy demand from NPPs, especially for these countries whose population is continuously increasing. In the economy, which is the yield of nuclear energy, governments must invest seriously in such infrastructures to be close to the supplier countries (Jensen-Eriksen, 2022).

Launching a nuclear power project is a major undertaking that requires careful planning and preparation. NPP cannot be installed anywhere as requested and cannot be concluded in the short term. As a result of long-term planning, it should be placed in the most suitable areas and the place where it will be installed should be decided with a special safety approach (Agyekum et al., 2021). Therefore, site selection studies should be carried out taking into account different criteria and validating a certain set of constraints (Devanand et al., 2019). Multi-criteria decision-making (MCDM) methods have been increasingly used to support decision makers in many different fields (Sisman & Aydinoglu, 2020). The MCDM method supports decision making between various options by evaluating different criteria (Godskesen et al., 2018). Geographic information system (GIS) is a computer system designed to assist users in spatial decision-making processes for solving complex problems in the world (Jahangiri et al., 2016). Especially, GIS tools have been combined with MCDM methods to be used frequently in different site selection planning processes. The literature on land use/land cover in the installation of plants, intentional and geographical–spatial location (Sadeghfam & Abadi, 2021), suitable sites and policies of sustainable energy have been growing most recently. Some of the literature has examined the correct operation of NPPs, calculating risk degrees and increasing plant safety (Gracia et al., 2020; Ramana, 2009; Wheatley et al., 2016). The remaining focus on site selection for the plant installation using various methods such as GIS, weighted linear combination (WLC), spatial-weighted analysis and artificial intelligence (Susiati et al., 2022).

As an example of the GIS and MCDM method, Shahi et al. (2018) investigated the cause-and-effect model of fuzzy DEMATEL. The model was altered to construct a NPP to display both the cause-and-effect relationship among effective criteria in the decision-making process and the final weight for each criterion. Damoom et al. (2019) combined GIS and MCDM for the assessment of NPP site suitability in their selected study area in Saudi Arabia. A similar study was followed by Erdoğan and Kaya (2016) which integrated type-2 fuzzy analytic hierarchy process (FAHP) and the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) to find the best NPP location alternative for Turkey. However, they did not research the spatial factor for this deciding the best location of NPPs. Bilgilioğlu (2022) realized site selection for the storage of radioactive materials occurred in the Akkuyu NPP in Turkey using the GIS-based AHP technique. This study is crucial to properly dispose of waste so that nuclear waste does not negatively affect society. Krütli et al. (2010) presented a literature that units the decision-making process with specific types and extents of public participation and illustrate their arguments using a proposed site selection process for nuclear waste. Ekmekçioglu et al. (2011) achieved a study on site selection for building an NPP in Turkey using MCDM techniques and Strengths, Weaknesses, Opportunities and Threats (SWOT) analysis based on the fuzzy logic method. It is understood from the literature that MCDM methods are quite effective in modeling the complexity and uncertainty of preference information. However, it is more important which criteria will be used rather than applying these methods (Akar et al., 2022). Because, the use of different criteria for the same purpose directly changes the results in practice. The methods, considerations and criteria usually used in the literature are summarized in Table 1.

In NPP studies, it is understood that most of the criteria considered for the suitable location research are spatial data, while others are location-related attribute information such as population, temperature and wind speed. The vast majority of these criteria are included in the IAEA (2015) safety guide. As mentioned above, the criteria discussed in the studies due to country/region differences have varied. It is difficult to obtain some data in country conditions. These countries may have restricted data due to security or privacy policies. Most of the studies either analyzed site suitability for NPP installation with location-based factors or identified optimal sites at the local scale/specific study area (Basu, 2019; Nugroho et al., 2021). While analyzing NPP site suitability, one of the MCDM techniques used alone or combined different techniques such as GIS and fuzzy TOPSIS (Kurt, 2014; Wang et al., 2018). However, there are very few studies that meet these energy needs with nuclear plants, by detecting the regions with energy demand country-wide (Dazhong & Yingyun, 2002; Kim et al., 2011). This paper emphasizes not only the suitability of the NPP site, but also the necessity of starting the installation of an NPP as a means of meeting up with the nation's growing energy demand.

Our study presents a systematic approach that minimizes risks in terms of demographic, economic, environmental, social and safety aspects in choosing suitable sites for NPP installation. In addition, for identifying NPP site suitability, a scientific-based process was designed for each step of the decision makers, from the beginning to the end. The most suitable site selection process was carried out in two stages, global (macro-level) and local (micro-level). In the first stage, the energy demand map was produced and the potential province for NPP installation was identified in Turkey depending on the energy demand. In the second stage, candidate site(s) were selected based on regional/spatial criteria in the identified province. Both stages were analyzed with the GIS-based FAHP method. The study is thought to have an impact on encouraging the most effective and efficient plant installation through spatial relationships, by supporting the suitable site selection and by displaying the security, social, environmental and economic contributions. The paper describes the methodology in Sect. 2. The material/method including the criteria determination, FAHP method from MCDM, and GIS application are mentioned in Sect. 3. The

Table 1 Literature review on methodologies for NPP potential sites

References	Method	Study area	Considerations	Criteria
Chen et al. (2008)	Network analysis in GIS	Taiwan	Route selection of nuclear waste transport	Travel time, transportation risk and exposed population
Omitaomu et al. (2012)	OR-SAGE	USA	Adapting a GIS-based MCDA for evaluating new power generating sites	Population, slope, seismicity, wetlands, landslide, floodplain, stream flow, protected lands, airports, military bases, petroleum, aquifer, railroad, salt formations and solar radiation
Kurt (2014)	Fuzzy TOPSIS and generalized Choquet fuzzy integral	Turkey	Preparing the most proper plan for site selection of an NPP	Geological criteria, meteorological criteria, socioeconomic criteria, and geographical criteria
Abudeif et al. (2015)	AHP, WLC and Boolean logic	Egypt	Deciding the most suitable sites to characterize a NPP installation	Environmental and social criteria, health and safety criteria, economic and engineering criteria
Li et al. (2016)	Web-GIS	China	Developing the health surveillance and risk assessment system based on Web-GIS for the residents near an NPP	Management, health hazards and risk assessment factors
Almalki et al. (2019)	AHP and Geospatial analysis	Canada	Establishing the process for geographical considerations in site selection for small modular reactors	Population, land use, wetlands, agricultural areas, protected land, airports, earthquake and surface-faulting hazards, slope, electricity infrastructure, surface water, existing power plants, flooding, transportation and groundwater
Al Osaimi and Qoradi (2020)	MCDM	Saudi Arabia	Creating the geographical database to support the decision making and examination of suitable sites for nuclear reactor facilities	Faults, ground deformation, Holocene volcano, landslide, karst, liquefaction, urban area, population, pipeline, oil fields, industrial city, airport, highway, railway, wadi, cultural heritage sites, night-light, agricultural and refinery
Eluyemi et al. (2020)	GIS Analysis	Nigeria	Proposing the embark on site suitability assessment for NPP sitting and related industrial constructions	Hydrology, geology, environment, volcanology, river flooding, coastal flooding, population, human induced events and seismology

Table 1 (continued)

References	Method	Study area	Considerations	Criteria
Salsabila et al. (2021)	MCDM	Indonesia	Analyzing the exclusion and discretionary criteria for potential NPP	Population, geology, terrain shape, rock type, existence and sufficiency of cooling water and road network
Iban and Sahin (2022)	Random forest class. on the GEE, and LULC change analysis	Turkey	Monitoring land-use and land-cover (LULC) change near the Akkuyu NPP site	Landsat-8 OLI images

results of the study are presented, examined and discussed in Sect. 4. Finally, the conclusions are stated in Sect. 5.

2 Methodology

Developing countries tend to seek new energy sources due to their high demand for electrical energy. Nowadays, nuclear energy stands out as a result of the increasing need for power plants to meet the energy demand. New generation nuclear technologies provide significant advantages in terms of reducing carbon emissions, especially in environmental conditions such as global warming and climate change (Baskurt & Aydin, 2018). In addition, low operating and fuel costs, meeting the needs in the long term and a balanced distribution of fuel resources around the world are other advantages. NPPs are needed to generate nuclear energy. NPP should be planned and placed in the most reasonable places throughout the installation process. According to the SSG-35 (Specific Safety Guide), the process of selecting a suitable site, called "Sitting", is a versatile process that includes safety considerations. This sitting process consists of four main stages and is listed as follows (IAEA, 2015): (1) The sitting process starts with the determination of the "region of interest/site research". When the first step, called site research, is completed, the potential site(s) are uncovered. (2) At potential sites, spatial analyses are performed using exclusionary and optional criteria, and candidate site(s) are selected. (3) Whether the sites selected as candidates are suitable for power plant installation are examined in detail during the site characterization phase. (4) Finally, field studies are carried out at candidate sites to verify acceptability from a safety point of view.

Following the most suitable site selection process for NPP installation plays a critical role in assessing environmental adequacy and minimizing the negative impact on the environment. With the correct management of the process, the radiological effects on people and the environment can be minimized and the risks can be kept as low as possible in possible accidents. As a result of behaviors such as ignoring environmental factors and pollution caused by radioactive compounds, installed power plants may cause negative effects on the environment-ecology (Barzehkar et al., 2016). As a result, in order to choose the most suitable site, critical evaluation should be made at the micro- and macro-levels according to the appropriate criteria and method determined specifically for the subject. Moreover, the site selection process should be superintended from the start by clearly defined sets of methods and criteria, with the necessary elements (Agyekum et al., 2021).

Currently, this paper focuses on the stage of potential site research and the selection of candidate sites. The purpose is to identify the potential province depending on the energy demand for NPP installation in Turkey and select candidate sites as a result of spatial analysis using regional criteria in this province. The spatial evaluation process prepared within the scope of the study is shown in Fig. 1.

3 Materials and methods

3.1 Criteria determination

The criteria used in the study are divided into two parts according to the identification of the province according to the energy demand and the selection of the candidate sites. In the

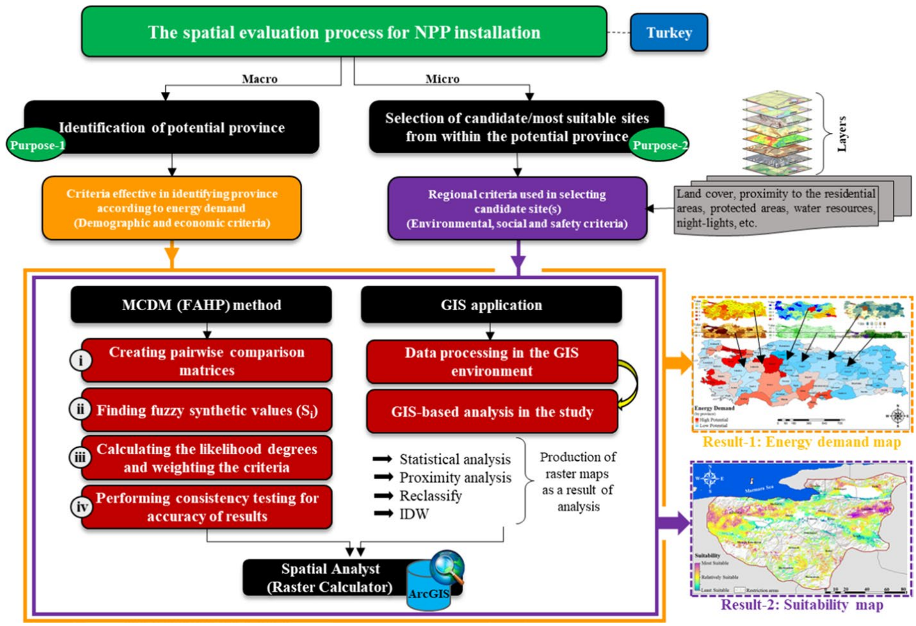


Fig. 1 The spatial evaluation process used in this study

first step, the region where the NPP will be established is researched to meet the energy demand most effectively and efficiently. It is of great importance to identify the region in terms of minimizing energy losses during energy transfer to regions that need energy the most. In the second step, candidate site(s) are selected from this region by using regional criteria.

3.1.1 Criteria used in identifying the potential province

The purpose of planning for electrical energy is to meet the demand in an economical, high quality and reliable way (Yavuzdemir, 2014). To meet the energy demand sustainably, it is crucial to consider activities such as making reliable demand forecasts, preparing accurate spatial and strategic plans, and establishing country energy policies (Yavuzaslan, 2018). When the share of preferred sources for daily energy use is examined, the shares of fossil fuels continue to be in the first place, although the shares of fossil fuels have relatively decreased. However, the search for new resources should continue in addition to the energy resources used in the current situation. As a result of the increasing electrical energy demand in Turkey, decision makers will likely turn to nuclear energy as a suitable energy alternative.

It is seen that Turkey, which has been on the agenda in terms of energy policies in the recent period, has tended to follow an energy policy in a way that will provide electrical energy production with nuclear energy. In this respect, it is an important development that Turkey has chosen the nuclear energy alternative, which it has put in the first place as an energy policy tool. On the other hand, the correct use of the energy produced is also a critical issue (Çadırcı & Güner, 2020). Since electrical energy is a type of energy that cannot be stored/preserved, can be lost during its transmission and must be consumed instantly, the issues of its supply, demand, transmission and distribution should be considered (Lior, 2010; Wang et al., 2021). If the energy demand is below the supply, it will cause restrictions in the system. If the demand is more than the supply, the electricity consumption will be overcharged. For this reason, it is a prerequisite to correctly estimate the consumption demand and to carry out the planning accordingly to meet the supply (Bolturk, 2013). Especially, during the transmission distribution of the energy produced depending on the energy demand, it is necessary to choose the place where the production will be made in order not to experience energy losses and to keep the cost low. Many different methods are preferred in energy consumption and demand prediction studies (Amarawickrama & Hunt, 2008; Gürbüz et al., 2013; Liu et al., 2020). These methods calculate energy demand predictions for the future by using relevant criteria. Criteria affecting electrical energy demand differ according to literature (Table 2).

Literature and expert experiences have been utilized to determine the criteria used in the NPP site selection. Experts include groups of economic, energy systems, electrical, environmental, mining, nuclear energy, geological, industrial and survey engineers according to their professional activities. These people also played an active role in determining the criteria weights. As a result, nine criteria that have a significant impact on energy demand have been preferred to identify the potential province in Turkey. The criteria are divided into two main categories, demographic and economic. Population, annual population growth rate, average household size and education criteria are used for the demographic category, while export, import, industry, per capita GDP and average electrical energy consumption criteria are used for the economic category (Table 3).

The criteria that are directly related to the energy demand and determined to be effective for the site selection of NPP are explained below. The criteria were obtained from the Turkish Statistical Institute, and the dataset for each criterion was prepared in Microsoft Excel and made ready for GIS application.

Table 2 Criteria affecting the electrical energy demand

References	Subject	Criteria
Mohamed and Bodger (2005)	Energy consumption	EP, GDP, POP, IS
Pao (2006)	Energy consumption	NI, GDP, CPI, POP
Geem and Roper (2009)	Energy demand	GDP, POP, I, E
Ekonomou (2010)	Energy consumption	GDP, IPC, NEC, T
Behrang et al. (2011)	Energy demand	GDP, POP, I, E
Kialashaki and Reisel (2013)	Energy demand	GDP, POP, AHS, EP, TNGB, EL
Uzlu et al. (2014)	Energy demand	GDP, POP, I, E
Kaytez et al. (2015)	Energy consumption	IPC, GEG, TS, POP, NEC
Kavaklioglu (2019)	Energy consumption	POP, GDP, I, E
Peña-Guzmán and Rey (2020)	Electric power consumption	T, GDP, TEB, NEC, TNGB

NI national income, *GDP* gross domestic product, *CPI* consumer price index, *POP* population, *IPC* installed power capacity, *NEC* net electricity consumption, *T* temperature, *I* import, *E* export, *EP* electricity price, *IS* industrial sector, *TS* total subscribership, *GEG* gross electricity generation, *TEB* total energy billing, *TNGB* total natural gas billing, *AHS* average household size, *EL* education level

Table 3 Criteria used to identify potential province

Category		Criteria (C)	Type of analysis
Demographic	C_1	Total population	Statistical analysis (GIS), multi-criteria decision making (MCDM)
	C_2	Annual population growth rate	
	C_3	Average household size	
	C_4	Educational level	
Economic	C_5	Export	Statistical analysis (GIS), multi-criteria decision making (MCDM)
	C_6	Import	
	C_7	Industrial sector	
	C_8	Gross domestic product per capita	
	C_9	Average electrical energy consumption	

3.1.2 Demographic category

C_1 (Total population): It shows the annual total number of individuals on a provincial basis. The high population increases the energy demand (Pao, 2006). Therefore, since the living conditions and consumed energy are higher in provinces with a high population than in provinces with a low population, demands increase accordingly (Yılmaz, 2012). For this study, the distribution of the total population in 2021 by provinces was used.

C_2 (Annual population growth rate): It is the indicator of the difference between the birth and death rates of the annual population in the province. The higher the annual population growth, which is also caused by internal and external migration throughout the province, the higher the energy demand. The average annual population growth rate of Turkey is 13.65 per thousand. Annual population growth rate, total population and energy demands show a linear relationship with each other (Yu & Zhu, 2012). In this study, population growth was used the data determined by provinces in 2021.

C_3 (Average household size): It is the average number of people who make up the household on a provincial basis. According to the data of the National Address-Based Population Registration System in Turkey, the average household size is 3.40. This value, which varies according to each province, expresses the number of individuals living in the household, and the increase in the value also increases the energy demand (Du et al., 2021). In this context, the average household size in 2021 was used as demographic data.

C_4 (Educational level): It refers to the number of academically educated individuals. Variability in energy demand can be observed according to the education level of the population. For example, the energy to be spent will differ depending on the number of individuals working in offices, industrial zones and business centers. Therefore, the number of individuals working in the society will have affected the energy demand depending on the level of education (Kialashaki & Reisel, 2013). The average rate of educated individuals in Turkey is 40%.

3.1.3 Economic category

C_5 (Export): It is the total of products sold to foreign countries. The exports in Turkey increased by 35% in the first six months of 2021. Energy is needed for the production and transportation of exported goods. For this reason, high exports are seen as a factor that increases energy demand (Shahzad et al., 2021).

C_6 (Import): It refers to the total value of products purchased from foreign countries. The imports in Turkey showed an increase of 25.5% for the first six months of 2021. Food products are also imported apart from construction, industry and many industrial products. Energy is needed both for the import of products and for the processing of incoming products. Therefore, as in exports, high imports are seen as a factor that increases energy demand.

C_7 (Industrial sector): It expresses the annual production of the industrial sector (tons). Today, the industrial sector in Turkey accounts for 27% of GDP and about 93% of exports. Therefore, it is one of the factors that have a linear effect on energy demand (Medić et al., 2014; Mohamed & Bodger, 2005).

C_8 (Gross domestic product-per capita): It is the annual total income per capita on a provincial basis (Turkish Liras). It does not reflect the differences in the cost of living and inflation rates of the countries. If GDP per capita is high, energy demand is high (Ersoy, 2012). GDP data can be determined according to provinces.

C_9 (Average electrical energy consumption): It represents the annual total consumed electrical energy (MWh). Considering the ease of use and prevalence of electricity in all areas, it can be expected that increases in consumption will increase social welfare. The use of many tools and devices that make daily life easier depends on electricity (Nişancı, 2005). Therefore, electricity consumption is among the most important factors affecting energy demand. Within the scope of the study, the average electrical energy consumption in 2021 was used as economic data.

3.1.4 Criteria used in selecting the candidate sites

Fifteen criteria were handled to choose candidate sites. Some of these criteria also have sub-criteria. The criteria are land cover, proximity to residential areas, proximity to protected areas, proximity to water resources, proximity to power transmission lines, night-lights, proximity to the coast, proximity to fault lines, seismicity, transportation network, geological structure, slope, aspect, average temperature and wind speed, respectively. These criteria were evaluated in a single category as environmental, social and safety. Regional criteria are compatible with the criteria defined by the IAEA (2015), and the type of analysis applied to each criterion varies (Table 4). These were defined as the criteria that have the greatest impact on the process of candidate site selection, and each is briefly described below.

3.1.5 Environment, social and safety category

C_{10} (Land Cover): Land cover is one of the most critical factors affecting the decision to install an NPP. For energy investments to be made in the right places, the land vegetation should be examined beforehand. For human health, ecosystem and social safety, there should be no NPPs as much as possible in certain areas such as crop-growing fields, rocky areas, pasture areas, vineyards/gardens, and agricultural lands (Idris & Abd Latif, 2012). It would be more appropriate to install these facilities in areas far from the public and in sparsely vegetated areas that are unsuitable for agriculture. In terms of facility safety, the power plants should be built on solid ground instead of ground where there is a danger of breaking or collapsing. In this study, sparsely vegetated areas

Table 4 Criteria, buffer area, scores and analysis type for selecting the candidate sites

Category	Criteria (C)	Buffer area	Score	Type of analysis
Environmental, social and safety				
C_{10}	*Land cover*	Suitability of land cover for plant installation		Reclassify
	Sparsely vegetated areas		100	
	Arable land (non-irrigate/irrigated)		80	
	Pastures		60	
	Rocks areas		40	
	Permanent crops (fruit, garden, etc.)		20	
	Swamps		Restriction (0)	
C_{11}	*Proximity to residential areas*	< 1000 m	restriction (0)	Proximity analysis (multiple ring buffer)
	Airport	1000–2000 m	25	
	Construction sites	2000–3000 m	50	
	Industrial/commercial units	3000–4000 m	75	
	Sport and leisure facilities	4000 m <	100	
	Urban fabric			
C_{12}	*Proximity to protected areas*			Proximity analysis (multiple ring buffer) and reclassify
	Forests, park, natural site and parks	–	Restriction (0)	
	Military regions	< 2000 m	Restriction (0)	
		2000–5000 m	50	
		5000 m <	100	
C_{13}	*Proximity to water resources*	< 1000 m	Restriction (0)	Proximity analysis (multiple ring buffer)
	Waterbodies (lakes, dam, pond, aquarium)	1000–2000 m	25	
		2000–3000 m	50	
		3000–5000 m	75	
		5000 m <	100	

Table 4 (continued)

Category	Criteria (C)	Buffer area	Score	Type of analysis
C_{14}	*Proximity to power transmission lines*	< 2 km	100	Proximity analysis (multiple ring buffer)
	Power transmission lines (main arteries)	2–4 km	80	
		4–6 km	60	
		6–8 km	40	
		8–10 km	20	
		10 km <	Restriction (0)	
C_{15}	Night-lights (proximity to living spaces)	From dark to light	100–75–50–25	Proximity analysis (multiple ring buffer)
		Light (bright)	Restriction (0)	
C_{16}	*Proximity to the coast*	< 2 km	100	Proximity analysis (multiple ring buffer)
	Proximity to the Marmara Sea	2–4 km	90	
		4–6 km	80	
		6–8 km	70	
		8–10 km	60	
		10 km <	50	
C_{17}	Proximity to fault lines	< 1500 m	Restriction (0)	Proximity analysis (multiple ring buffer)
		1500–3000 m	25	
		3000–4500 m	50	
		4500–6000 m	75	
		6000 m <	100	
C_{18}	Seismicity	< 1000 m	Restriction (0)	Proximity analysis (multiple ring buffer)
		1000–2000 m	20	
		2000–3000 m	40	
		3000–4000 m	60	
		4000–5000 m	80	
		5000 m <	100	
C_{19}	*Transportation network*	< 250 m	100	Proximity analysis (Multiple ring buffer)
	Roads, avenues, track, rail networks	250–500 m	80	
		500–1000 m	60	
		1000–2000 m	40	
		2000–4000 m	20	
		4000 m <	5	

Table 4 (continued)

Category	Criteria (C)	Buffer area	Score	Type of analysis
C_{20}	Geological structure	Porous structure	0	Reclassify
		Non-porous structure	100	
C_{21}	Slope	0–5 (%)	100	Reclassify
		5–10 (%)	70	
		10–20 (%)	30	
		20–80 (%)	Restriction (0)	
C_{22}	Aspect	North	45	Reclassify
		Northwest, Northeast	50	
		West, East	55	
		Southwest, Southeast	60	
		South	65	
		Flat	70	
C_{23}	Average temperature and wind speed	Low	73–70	Inverse distance weighting (IDW) and reclassify
C_{24}		Medium	72–60	
		High	71–50	

received high (100) points for NPP site selection, while swamps with irrigated structures received low (0) points. That the swamp areas get a score of 0 means that they are considered as restriction criteria.

C_{11} (Proximity to residential areas): Locating NPPs close to residential areas causes negative environmental effects. In any risky situation that may occur in the facilities, human life is adversely affected and may cause problems with massive effects (Facella et al., 2012). In particular, it is essential to install NPPs far from urban areas in order not to get the reaction of the population and not to endanger human health in the residential areas. In this context, the airport, sports and leisure facilities, industrial and commercial units, construction areas and urban fabric areas and their vicinity of 1000 m were chosen as the restriction (0) area. The farther the NPP is from the residential areas (4000 m <), the more suitable.

C_{12} (Proximity to protected areas): Protected areas refer to particular areas such as natural reserves, natural flora/fauna, historical sites and military zone where nuclear power plants are not allowed (Barzehkar et al., 2016). For the construction of NPP, forests, parks, natural areas, national parks and military zones are considered protected areas. Hence, the facility locations needed to be far enough from the natural landscapes. In practice, forests, parks, natural areas and national parks are considered restriction areas (MCT, 1983). In terms of safety, the military zone and its vicinity of 2000 m are considered restriction areas, while the criteria score (from 50 to 100) increases as they have moved away (MND, 1981).

C_{13} (Proximity to water resources): Cooling water is used to cope with the high temperature created by the energy generated in NPP. Water resources are needed to supply cooling water. However, more proper water resources (such as the sea) should be preferred instead of water bodies qualified as closed areas. Due to the increase in water temperature caused by heat transfer, aquatic organisms will be adversely affected and areas with water will be exposed to physical changes. Moreover, NPPs pollute the water they use with radioactive materials such as uranium and cesium (Keeney, 1987). In this study, bodies of water (closed areas) such as lakes, ponds, dams and aquariums were selected as important ecological areas. Closed areas and their vicinity of 1000 m were marked as restriction areas. Locations far from bodies of water (5000 m <) were decided as more suitable areas.

C_{14} (Proximity to power transmission lines): The availability of electrical networks around the site is an advantage in terms of cost and time. Therefore, NPPs should be close to existing energy transmission lines (Baskurt & Aydin, 2018).

C_{15} (Night-lights): It is an indicator of civilization/life signs and plays a major role in detecting areas with high populations. Night-lights are directly related to residential areas and city centers and can provide information about the expansion direction of the city (Levin et al, 2020). Human activities are active in areas where night-lights are intense, less human activities occur in the rest of the places. In this study, places with high light intensity were not preferred, because it is not desired that the new facilities to be installed will negatively affect human activities.

C_{16} (Proximity to the coast): The presence of water is necessary not only to cool the high temperature caused by energy but also to remove heat in the event of an accident. However, for certain reasons, it was stated that the facilities were far from bodies of water. Although NPPs are desired to be far from bodies of water, cooling water is needed to reduce the high-temperature effect. For this reason, proximity to the coast was considered a criterion to carry sufficient cooling water to the facility (Ekmekçioglu et al., 2011). The regions closest to the Marmara Sea were considered suitable areas to supply the water needed by the region.

C_{17} (Proximity to fault lines): Presence of active faults is important for site selection. Since earthquakes will cause emergencies, surface movements directly affect NPP safety (Baskurt & Aydin, 2018). Hence, appropriately selected areas should be away from fault lines.

C_{18} (Seismicity): Seismic activity is an important factor affecting the safety of NPP. Low geological structure and seismic risk are interrelated. The areas affected by earthquake intensities higher than a certain value in the past should be restricted, and areas with minimum deformation in the ground should be preferred (Shahi et al., 2018). In the study, earthquake points of magnitude 4.5 and higher were identified in the last three years. Scoring was carried out according to the distance from these points. The areas closer than 1000 m to earthquake points were restricted.

C_{19} (Transportation network): Distance to roads is considered a crucial economic factor. The transportation network for transporting heavy equipment is a cost-saving advantage for potential sites. Alternative sites must be accessible before a new road is built. In addition, construction and maintenance costs will be significantly lower due to the easy access of vehicles to the site. Railways and highways may be suitable for transportation due to their technical features, curves, bridges and tunnels (IAEA, 2015).

C_{20} (Geological structure): Ground layers that may react undesirably should be avoided in seismic movements. Grounds with the potential for liquefaction or subsidence, thick soft ground layers, abnormal ground conditions, a high groundwater level, areas containing underground voids, and porous ground structures should be avoided (IAEA, 2015). While the areas with porous (soft) ground were not found suitable in this study, it was decided that the areas with non-porous (solid) ground were the most suitable.

C_{21} (Slope): The slope is important in identifying the suitable area for the nuclear plant. High-sloping land requires digging or filling or even building barriers against landslides. This directly affects not only the construction cost of the facility, but also its safety (Barzehkar et al., 2016). Therefore, high-sloping lands are not suitable for plant installation.

C_{22} (Aspect): Aspect effect is determined according to the direction of the mountains with different elevations in a region to receive the sun's rays or the angle of their exposure to the sun (Zolekar & Bhagat, 2015). Especially people change the structure of settlements by choosing north and south for their living activities. Based on the preference situation, while the density of settlements is high in certain directions, less density is encountered in opposite directions. For this reason, settlement density and aspect effect were evaluated together as effective criteria for the selection of facility sites.

C_{23} (Average temperature): The cooling water tower of the power plants is dependent on heat exchange with the outside. For every 1 °C increase in atmospheric temperature, the thermal efficiency of the nuclear power unit drops by about 0.006%. Therefore, candidate sites with a lower average temperature are more suitable for the study (Erol et al., 2014).

C_{24} (Average wind speed): Wind speed affects not only the design load of nuclear plants, but also the distribution of radioactive emissions under normal and accidental conditions. The lower the wind speed is, the more suitable the candidate sites are (Erol et al., 2014).

3.2 MCDM: FAHP method for site selection

MCDM is used to best solve the challenges faced by decision makers by using a large amount of information. In cases where the number of options is high, it helps the decision maker to make quick and easy decisions by keeping the decision-making mechanism under control (Malczewski, 1997). Many methods can be encountered in the literature for site selection applications. These are method applications such as ELECTRE (Kumar et al., 2016), FAHP (Mallick, 2021), entropy (Li et al., 2022), VIKOR (Bera et al., 2022) and hybrid method (Petrov, 2022; Ustaoglu et al., 2021). Choosing the method according to the type of problem is the most reasonable approach.

In this study (for both 1st and 2nd stages), criteria weights were calculated according to FAHP. FAHP provides an understandable approach that helps users make effective decisions (Erdoğan & Kaya, 2016; Fard et al., 2022). In addition, numerical variables in a fuzzy environment can be handled in a way that allows the use of linguistic terms and includes human emotion, thought and logic. The first applications of FAHP were made by Van Laarhoven and Pedrycz (1983), who compared fuzzy ratios using fuzzy numbers. Buckley (1985) developed the geometric mean method. Then, Chang (1996) put forward the extent analysis method by combining triangular fuzzy numbers and order analysis method. Within the framework of the application, Chang's approach was preferred for the calculation of criterion weights with FAHP. The processing steps of this approach can be given as follows:

1. Creating pairwise comparison matrices
2. Finding fuzzy synthetic values (S_i)
3. Calculating the likelihood degrees and weighting the criteria
4. Performing consistency testing for accuracy of results

Triangular fuzzy numbers (TFNs) are used to compare criteria in FAHP. The relative strength of each pair is expressed in TFN, which can be represented as $\mu(x) = (l, m, u)$ (Fig. 2). The numbers l, m and u represent the smallest possible value, the largest value and the possible large value for a fuzzy event, respectively (Çanlı & Kandakoğlu, 2007).

The representations of each TFN are defined with the help of triangular membership functions as in Eq. (1).

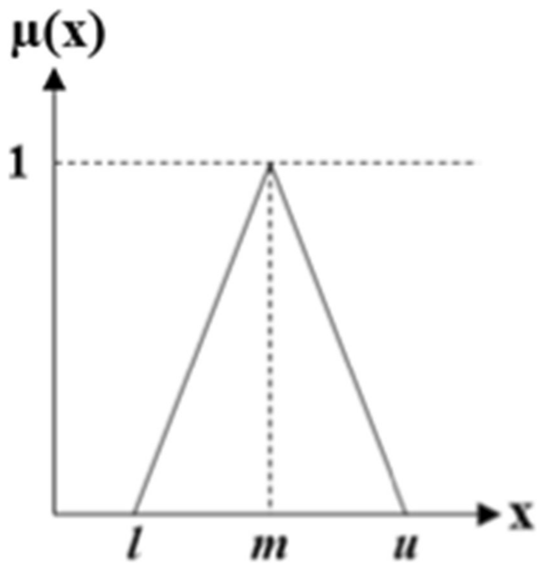


Fig. 2 Triangular fuzzy numbers (l, m and u)

$$\mu(x;l,m,u) = \begin{Bmatrix} \frac{x-l}{m-l}; & l \le x \le m \\ \frac{u-x}{u-m}; & m \le x \le u \\ 0; & \text{otherwise} \end{Bmatrix} \tag{1}$$

The fuzzy value scale used during the pairwise comparison of the criteria can be presented as shown in Table 5.

Many different operations can be performed on TFNs. Consider $M_1=(l_1, m_1, u_1)$ and $M_2=(l_2, m_2, u_2)$ as two TFNs. The mathematical operations of M_1 and M_2 are as follows.

- $M_1 \oplus M_2=(l_1, m_1, u_1)+(l_2, m_2, u_2)=(l_1+l_2, m_1+m_2, u_1+u_2)$,
- $M_1 \odot M_2=(l_1, m_1, u_1).(l_2, m_2, u_2)=(l_1.l_2, m_1.m_2, u_1.u_2)$,
- $(M_1)^{-1}=(l_1, m_1, u_1)^{-1} \sim (1/u_1, 1/m_1, 1/l_1)$.

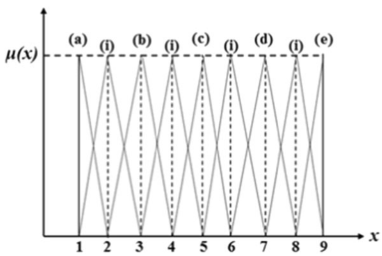
The pairwise comparison matrix is formed separately with the help of a fuzzy value scale according to the opinions of each decision maker. The relation $a_{ij}=1/a_{ji}$ applied in the AHP method is also valid for the fuzzy matrix. Using TFNs, the comparison matrix $A=(\tilde{a}_{ij})$, $i, j=1, 2, \ldots$, n is formed as in Eq. (2).

$$A = \left(\tilde{a}_{ij}\right) = \begin{pmatrix} (1,1,1) & \tilde{a}_{12}, & \ldots, \tilde{a}_{1n} \\ \tilde{a}_{21}, & (1,1,1) & \ldots, \tilde{a}_{1n} \\ \ldots & \ldots, & (1,1,1) \ \ldots \\ \tilde{a}_{n1}, & \tilde{a}_{n2}, & \ldots, (1,1,1) \end{pmatrix}; \quad a_{ij} = \left(a_i, b_i, c_i\right) \text{if} \frac{1}{a_{ji}} = \left(\frac{1}{c_i}, \frac{1}{b_i}, \frac{1}{a_i}\right) \tag{2}$$

Provided that $X=\{x_1, x_2, \ldots, x_n\}$ set of criteria and $U=\{u_1, u_2, \ldots, u_n\}$ set of goal, for each goal, a synthetic analysis (g_i) is made by considering each factor. The m synthetic analysis value for the targets is $i=1, 2\ldots n$ and $j=1, 2\ldots m$. $M^1_{gi}, M^2_{gi}, \ldots, M^n_{gi}$,

Table 5 Linguistic variables of FAHP and fuzzy value scale

Linguistic variables	Fuzzy value scale
Equal importance (a)	(1, 1, 1)
Low importance (b)	(2, 3, 4)
Medium importance (*c*)	(4, 5, 6)
High importance (*d*)	(6, 7, 8)
Absolutely more importance (*e*)	(9, 9, 9)
Intermediate values (*i*)	(1, 2, 3)
	(3, 4, 5)
	(5, 6, 7)
	(7, 8, 9)



expressed in the form of TFNs (Ataei et al., 2012; Chang, 1996). $M^j{}_{gi}$ ($j = 1, 2, \ldots, m$) values were TFNs showing the lowest, most probable, and highest values of the parameters. Meanwhile, fuzzy synthetic values (S_i) should be found. The fuzzy synthetic values for the criteria are calculated by Eq. (3), where S_i represents synthesis values and $M^j{}_{gi}$ represents expanded values for each target.

$$S_i = \sum_{j=1}^{m} M_{g_i}^j \odot \left[\sum_{i=1}^{n} \sum_{j=1}^{m} M_{g_i}^j \right]^{-1} \quad (3)$$

After the synthetic values are obtained, the degrees of these values are compared: As $M_1 = (l_1, m_1, u_1)$ and $M_2 = (l_2, m_2, u_2)$ are two TFNs, the likelihood of the event $M_2 \geq M_1$ is calculated as in Eq. (4).

$$V\left(M_2 \geq M_1\right) = \sup\left[\min\left(\mu_{M_1}(x), \mu_{M_2}(y)\right)\right] \quad (4)$$

Equation (4) is applied to calculate both the $V(M_2 \geq M_1)$ value and the $V(M_1 \geq M_2)$ value. Of two fuzzy numbers M_1 and M_2, the probability that M_2 is greater than M_1 is equal to the value of the membership function at the intersection of these two fuzzy numbers (Eq. 5).

$$V\left(M_2 \geq M_1\right) = hgt\left(M_1 \cap M_2\right) = \mu_{M_2}(d) = \left\{ \begin{array}{cc} 1, & \left(m_2 \geq m_1\right) \\ 0, & \left(l_1 \geq u_2\right) \\ \frac{l_1 - u_2}{(m_2 - u_2) - (m_1 - l_1)}, & \text{otherwise} \end{array} \right\} \quad (5)$$

The degree of probability of a convex fuzzy number greater than "k" fuzzy numbers, $M_i = (i = 1, 2, \ldots, k)$ is defined as in Eqs. (6) and (7).

$$\begin{aligned} V\left(M \geq M_1, M_2, \ldots, M_k\right) &= V\left[\left(M \geq M_1\right) \text{and} \left(M \geq M_2\right) \ldots \left(M \geq M_k\right)\right] \\ &= \min V\left(M \geq M_i\right), \quad i = 1, 2, \ldots, k \end{aligned} \quad (6)$$

$$k = 1, 2, \ldots, n; k \neq j \text{ as } d'\left(A_i\right) = \min\ V\left(S_i \geq S_k\right) \quad (7)$$

Once the probability degrees are found, the weight vector is determined as in Eq. (8).

$$W' = \left(d'(A_1), d'\left(A_2\right), \ldots, d'\left(A_n\right)\right)^T \quad (8)$$

Finally, normalized weight vectors (W) are obtained by normalization (Eq. 9), where W is a non-fuzzy vector.

$$W = \left(d(A_1), d\left(A_2\right), \ldots, d\left(A_n\right)\right)^T \quad (9)$$

The accuracy of FAHP results is decided by performing the consistency test. Consistency index (CI) is found using $\text{CI} = (\lambda_{\max} - n)/(n - 1)$ formula, where $\lambda_{\max}$ is the eigenvalue and n is the matrix size. Consistency ratio (CR) is found using CR = CI/RI formula, where RI is the random index in Table 6. If $\text{CR} \leq 0.10$, the matrix is acceptable and the weight coefficients obtained from the comparison matrix are significant. Otherwise, these matrices need to be reevaluated.

Table 6 Random index (RI)

n	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.48	1.56	1.57	1.59

3.3 GIS application

Analyses were made in the GIS software for the site suitability of NPP. For the macro-level purpose of this paper, the data of the criteria (statistical, location information, quantitative and qualitative features, etc.) were arranged. Demographic and economic (C_1–C_9) criteria were integrated into ArcGIS 10.5.1, and then, statistical analyses were made for all provinces in Turkey within the provincial administrative borders. Since analysis results and criteria weights would be combined, analysis maps were converted to raster format. The raster data of each criterion were reclassified from 1 (low value) to 5 (high value) with the reclassification tool. All rasters and their weights were combined with the raster calculator to produce the energy demand map. In the micro-level site selection, criteria with different scales were brought together, standardized and analyzed. Proximity analysis and reclassification (0–100 points) were applied to the environmental, social and safety (C_{10}-C_{24}) criteria. As stated before, all criteria and their weights were combined with the raster calculator to produce the suitability map.

4 Results and discussion

4.1 FAHP weighting results of the criteria

A total of 24 main criteria, including (a) demographic, (b) economic, (c) environmental, social and safety categories, and their sub-criteria were discussed in the methodology for choosing the most suitable site for NPP. It was thought that the NPP to be installed in the region will be able to meet the energy needs as a result of electricity generation, and it was planned to be installed on a suitable site in terms of location. In this context, demographic (C_1–C_4) and economic (C_5–C_9) criteria that reveal the energy demands were used while identifying the potential province at the macro-level (Table 3). Pairwise comparisons for each criterion were created, and criteria weights were calculated using the GNU Octave (open-source) scientific programming language.

Table 7 presents pairwise comparison matrices and criteria weights. These matrices were prepared in line with expert opinions (economic, energy systems, electrical and industrial engineers). After the criteria weights were found, a consistency test was applied to verify the results. Test results are $\lambda_{max} = 9.9934$, CI = 0.1242 and CR = 0.0856, respectively. Since the CR value remained below 0.10, it was concluded that the results were consistent and the weight coefficients obtained from the comparison matrix were significant.

As seen in Table 7, the C_9 (0.2518) criteria has the highest weight. Today, as a result of factors such as industrialization, widespread use of machinery/equipment, technological developments, population growth, the consumption of electrical energy and accordingly the energy demand is continuously increasing. For this reason, the consumption of electrical energy made energy one of the most important elements of the economy and it was seen

Table 7 The pairwise comparison and criteria (C_1–C_9) weights

Criteria	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9
C_1	(1,1,1)	(1/4,1/3,1/2)	(4,5,6)	(4,5,6)	(1/5,1/4,1/3)	(1,1,1)	(1,1,1)	(4,5,6)	(1/4,1/3,1/2)
C_2	(2,3,4)	(1,1,1)	(5,6,7)	(6,7,8)	(1,1,1)	(4,5,6)	(1,2,3)	(5,6,7)	(1,1,1)
C_3	(1/6,1/5,1/4)	(1/7,1/6,1/5)	(1,1,1)	(1,1,1)	(1/8,1/7,1/6)	(1/4,1/3,1/2)	(1/4,1/3,1/2)	(1,1,1)	(1/8,1/7,1/6)
C_4	(1/6,1/5,1/4)	(1/8,1/7,1/6)	(1,1,1)	(1,1,1)	(1/8,1/7,1/6)	(1/5,1/4,1/3)	(1/5,1/4,1/3)	(1,1,1)	(1/7,1/6,1/5)
C_5	(3,4,5)	(1,1,1)	(6,7,8)	(6,7,8)	(1,1,1)	(4,5,6)	(4,5,6)	(5,6,7)	(1/3,1/2,1/1)
C_6	(1,1,1)	(1/6,1/5,1/4)	(2,3,4)	(3,4,5)	(1/6,1/5,1/4)	(1,1,1)	(1,1,1)	(2,3,4)	(1/6,1/5,1/4)
C_7	(1,1,1)	(1/3,1/2,1/1)	(2,3,4)	(3,4,5)	(1/6,1/5,1/4)	(1,1,1)	(1,1,1)	(2,3,4)	(1/6,1/5,1/4)
C_8	(1/6,1/5,1/4)	(1/7,1/6,1/5)	(1,1,1)	(1,1,1)	(1/7,1/6,1/5)	(1/4,1/3,1/2)	(1/4,1/3,1/2)	(1,1,1)	(1/8,1/7,1/6)
C_9	(2,3,4)	(1,1,1)	(6,7,8)	(5,6,7)	(1,2,3)	(4,5,6)	(4,5,6)	(6,7,8)	(1,1,1)
Weight (W_i)	↓	↓	↓	↓	↓	↓	↓	↓	↓
	0.0900	0.2063	0.0274	0.0254	0.2277	0.0674	0.0761	0.0279	0.2518

$\lambda_{max} = 9.9934$, CI = 0.1242, consistency ratio (CR) = 0.0856, CR ≤ 0.10, Acceptable ✓

that it has a high impact on energy demand. After the C_9 criteria, the C_5 (0.2277) and C_2 (0.2063) criteria also have higher weights. Two criteria that increase electricity consumption, especially in developing countries are population growth and exports. In this respect, population growth and exports directly trigger energy demand. The criteria with the lowest weight were found as C_4 (0.0254). Although the weight of this criteria is less compared to other criteria, it should be said that it affects a certain amount of energy demand. If a general evaluation is made within the scope of the study, while the C_2, C_5 and C_9 criteria have high importance in identifying the potential province, the C_1, C_6 and C_7 criteria have medium importance and C_3, C_4 and C_8 criteria are of low importance.

So far, energy demand criteria were taken into account and the weights of these criteria were found. Hierarchical structure was generally arranged according to the ability to meet energy needs and to be located in a convenient location. After this stage, it was planned to select the candidate sites from the potential province by using the regional criteria related to the subject. Regional (C_{10} to C_{24}) criteria were used while choosing candidate sites at the micro-level (Table 4). Comparison matrices were created with the help of IAEA special safety guide and expert opinions (energy systems, environmental, mining, nuclear energy, geological and geomatics engineers). The criteria weights were calculated with the GNU Octave software as previously stated (Table 8). Finally, a consistency test was applied to verify the results ($\lambda_{max} = 16.5879$, CI = 0.1134, CR = 0.0713). According to the CR value, the results were consistent and the weight coefficients were significant.

As a result, C_{17} (0.1733), C_{14} (0.1431), C_{12} (0.1246) and C_{13} (0.1228) criteria were found to be more effective in selecting candidate sites for NPP site suitability. The least effective criteria were listed as C_{22} (0.0102), C_{23} (0.0106) and C_{24} (0.0109) (Table 8). The reason why the criteria weights are like this is as follows: The safety of NPP should be at a high level and the negative impact of these power plants on the environment and social life should be minimized. Therefore, while more attention should be paid to insurmountable problems such as natural disasters, loss of fertile lands, deterioration of the ecological system and natural balance, it would be beneficial to pay less attention to the problems that have solutions. In this study, as in the SSG-35, the negative effects on the environment and social aspects were tried to be minimized by keeping safety in the foreground. The study includes restriction/exclusionary criteria. These criteria were assigned a score of "0" during the spatial analysis (justifications are available in the criteria explanations). For this reason, the criteria with 0 points would be 0 points when multiplied by any weight, and these criteria were evaluated as restriction criteria.

4.2 Turkey's energy demand map and province identification

The first stage of this study was based on energy demand. Here, data layers were prepared by organizing C_1–C_9 criteria in the GIS environment. The weights (Table 7) calculated by FAHP method for these criteria were integrated into data layers, and an energy demand map was produced for Turkey. When the Mersin (Akkuyu NPP) and Sinop (Sinop NPP) projects are evaluated, it can be said that Mersin is more effective than Sinop in installing the NPP. The produced map can be used as a guide in identifying potential provinces for plant/facility installation with other energy sources other than NPP. On the other hand, the provinces with the highest energy demand are Istanbul, Izmir, Ankara and Bursa (Fig. 3). C_2, C_5 and C_9 criteria, which have the highest weights, had a great impact on the identification of the provinces in need of energy the most. When the analysis results were compared with traditional studies, it was found

Table 8 The pairwise comparison and criteria (C_{10}–C_{24}) weights

Criteria	C_{10}	C_{11}	C_{12}	C_{13}	C_{14}	C_{15}	C_{16}	C_{17}	C_{18}	C_{19}	C_{20}	C_{21}	C_{22}	C_{23}	C_{24}
C_{10}	(1,1,1)	(2,3,4)	(1/4,1/3,1/2)	(1/4,1/3,1/2)	(1/5,1/4,1/3)	(1,1,1)	(1/4,1/3,1/2)	(1/5,1/4,1/3)	(1/3,1/2,1/1)	(1,1,1)	(1,1,1)	(3,4,5)	(4,5,6)	(4,5,6)	(4,5,6)
C_{11}	(1/4,1/3,1/2)	(1,1,1)	(1/6,1/5,1/4)	(1/6,1/5,1/4)	(1/3,1/2,1/1)	(1,1,1)	(1,1,1)	(1/5,1/4,1/3)	(1/3,1/2,1/1)	(1,1,1)	(1,2,3)	(4,5,6)	(5,6,7)	(5,6,7)	(5,6,7)
C_{12}	(2,3,4)	(4,5,6)	(1,1,1)	(1,1,1)	(1,1,1)	(2,3,4)	(3,4,5)	(1/4,1/3,1/2)	(1,1,1)	(2,3,4)	(4,5,6)	(7,8,9)	(7,8,9)	(6,7,8)	(6,7,8)
C_{13}	(2,3,4)	(4,5,6)	(1,1,1)	(1,1,1)	(1,1,1)	(2,3,4)	(3,4,5)	(1/4,1/3,1/2)	(1,1,1)	(3,4,5)	(2,3,4)	(7,8,9)	(7,8,9)	(6,7,8)	(6,7,8)
C_{14}	(3,4,5)	(1,2,3)	(1,1,1)	(1,1,1)	(1,1,1)	(3,4,5)	(4,5,6)	(1,1,1)	(2,3,4)	(4,5,6)	(2,3,4)	(6,7,8)	(9,9,9)	(7,8,9)	(6,7,8)
C_{15}	(1,1,1)	(1,1,1)	(1/4,1/3,1/2)	(1/4,1/3,1/2)	(1/5,1/4,1/3)	(1,1,1)	(2,3,4)	(1/5,1/4,1/3)	(1/3,1/2,1/1)	(2,3,4)	(1,2,3)	(3,4,5)	(6,7,8)	(4,5,6)	(4,5,6)
C_{16}	(2,3,4)	(1,1,1)	(1/5,1/4,1/3)	(1/5,1/4,1/3)	(1/6,1/5,1/4)	(1/4,1/3,1/2)	(1,1,1)	(1/6,1/5,1/4)	(1/5,1/4,1/3)	(1,1,1)	(1,1,1)	(1,2,3)	(6,7,8)	(6,7,8)	(4,5,6)
C_{17}	(3,4,5)	(3,4,5)	(2,3,4)	(2,3,4)	(1,1,1)	(3,4,5)	(4,5,6)	(1,1,1)	(4,5,6)	(3,4,5)	(3,4,5)	(4,5,6)	(6,7,8)	(6,7,8)	(6,7,8)
C_{18}	(1,2,3)	(1,2,3)	(1,1,1)	(1,1,1)	(1/4,1/3,1/2)	(1,2,3)	(3,4,5)	(1/6,1/5,1/4)	(1,1,1)	(1,2,3)	(1,2,3)	(2,3,4)	(6,7,8)	(6,7,8)	(6,7,8)
C_{19}	(1,1,1)	(1,1,1)	(1/4,1/3,1/2)	(1/5,1/4,1/3)	(1/6,1/5,1/4)	(1/4,1/3,1/2)	(1,1,1)	(1/5,1/4,1/3)	(1/3,1/2,1/1)	(1,1,1)	(1,1,1)	(1,1,1)	(6,7,8)	(5,6,7)	(6,7,8)
C_{20}	(1,1,1)	(1/3,1/2,1/1)	(1/6,1/5,1/4)	(1/4,1/3,1/2)	(1/4,1/3,1/2)	(1/3,1/2,1/1)	(1,1,1)	(1/5,1/4,1/3)	(1/3,1/2,1/1)	(1,1,1)	(1,1,1)	(3,4,5)	(6,7,8)	(6,7,8)	(5,6,7)
C_{21}	(1/5,1/4,1/3)	(1/6,1/5,1/4)	(1/9,1/8,1/7)	(1/9,1/8,1/7)	(1/8,1/7,1/6)	(1/5,1/4,1/3)	(1/3,1/2,1/1)	(1/6,1/5,1/4)	(1/4,1/3,1/2)	(1,1,1)	(1/5,1/4,1/3)	(1,1,1)	(3,4,5)	(4,5,6)	(4,5,6)
C_{22}	(1/6,1/5,1/4)	(1/7,1/6,1/5)	(1/9,1/8,1/7)	(1/9,1/8,1/7)	(1/9,1/9,1/9)	(1/8,1/7,1/6)	(1/8,1/7,1/6)	(1/8,1/7,1/6)	(1/8,1/7,1/6)	(1/8,1/7,1/6)	(1/8,1/7,1/6)	(1/5,1/4,1/3)	(1,1,1)	(1,1,1)	(1,1,1)
C_{23}	(1/6,1/5,1/4)	(1/7,1/6,1/5)	(1/8,1/7,1/6)	(1/8,1/7,1/6)	(1/9,1/8,1/7)	(1/6,1/5,1/4)	(1/8,1/7,1/6)	(1/8,1/7,1/6)	(1/8,1/7,1/6)	(1/7,1/6,1/5)	(1/8,1/7,1/6)	(1/6,1/5,1/4)	(1,1,1)	(1,1,1)	(1,1,1)
C_{24}	(1/6,1/5,1/4)	(1/7,1/6,1/5)	(1/8,1/7,1/6)	(1/8,1/7,1/6)	(1/8,1/7,1/6)	(1/6,1/5,1/4)	(1/8,1/7,1/6)	(1/8,1/7,1/6)	(1/8,1/7,1/6)	(1/8,1/7,1/6)	(1/7,1/6,1/5)	(1/6,1/5,1/4)	(1,1,1)	(1,1,1)	(1,1,1)
Weight (W_i)	↓ 0.0497	↓ 0.0498	↓ 0.1246	↓ 0.1228	↓ 0.1431	↓ 0.0614	↓ 0.0444	↓ 0.1733	↓ 0.0855	↓ 0.0421	↓ 0.0481	↓ 0.0235	↓ 0.0102	↓ 0.0106	↓ 0.0109

$\lambda_{max} = 16.5879$, CI = 0.1134, consistency ratio (CR) = 0.0713, CR ≤ 0.10, Acceptable

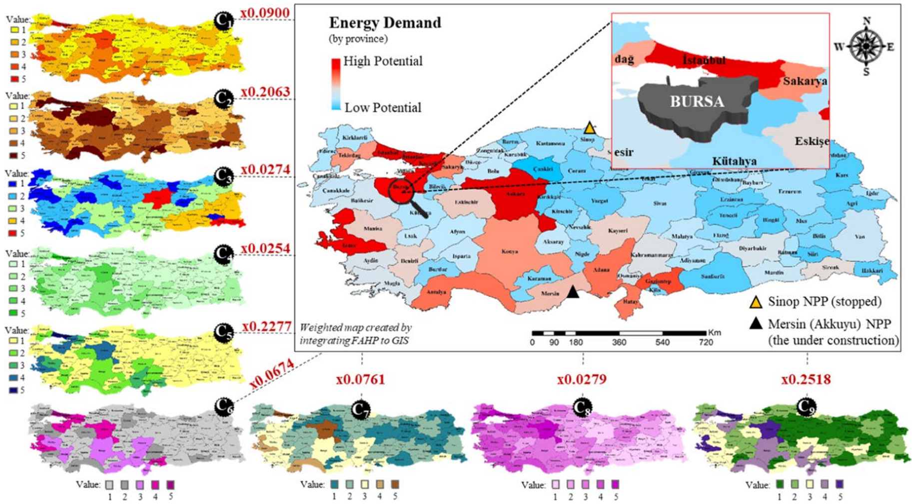


Fig. 3 Turkey's energy demand map and identified province (Bursa)

that they were consistent with each other. It was concluded that there is high energy consumption in the provinces of the Marmara Region of Turkey, such as Bursa, Çanakkale and Istanbul (Koçak & Boran, 2019; Ulku & Yalpir, 2021).

However, potentially identified provinces should not be considered unidirectional. Kaijser and Meyer (2018) stated that apart from energy needs, it is necessary to pay attention to the fact that the plants are far from the country's borders in terms of safety (enemy or terrorist attacks, etc.). In addition, the radioactive material to be used for and waste from NPP energy production will be transported. The application of the right methods, the conscious and complete application of nuclear safety methods in the process of removing the spent fuel from the reactor and storing it first, and then transporting it to the plant where it will be disposed of, will minimize the possible impact of radioactive wastes (RWM, 2017). Although there will be no waste from the NPP to be installed in our country soon, this issue needs to be taken seriously during the operation of the plants from the very beginning (Bulut, 2018). In order to increase the safety in the transportation of radioactive material and waste, it will be inevitable for the provinces with waste transportation ports to stand out when maritime transportation is also considered (Jeong et al., 2011). Considering the proximity to the sea, national safety and waste transportation port to supply cooling water, Istanbul, Izmir and Bursa come to the fore as potential provinces. Ankara does not fully meet these conditions. According to 2021 data, the populations of Istanbul, Izmir and Bursa provinces are 16 million, 4.5 million and 3.1 million, respectively. Although the population factor has the effect of increasing the energy demand, an unexpected nuclear leak from NPP will have consequences that lead to the death of large masses (Brown & White, 1987). Therefore, the new plant(s) should not inhibit people's activities/quality of life and should not create a public reaction. As a result of all the evaluations, "Bursa" was identified as the potential province in the study (Fig. 3).

Identification as a potential province consists of four reasons and is listed as follows. (a) being a region with high-energy demand, (b) being at a central point to meet the energy demand in different provinces, (c) not having an excessive population density, and (d) being less risky than other provinces when the possible risk factors are considered. Implementation to selecting the candidate sites (in Bursa) will continue in the next section.

4.3 NPP suitability map and candidate sites selection

The selection of a suitable site for the NPP installation is a process that must be thoroughly planned or designed. This process may vary depending on the cost of plant installation, public response, safety, health, and planned energy policies. However, the only thing that does not change is the right planning and implementation. Otherwise, full efficiency cannot be obtained from the desired targets and the process becomes complicated. In the site selection process, many criteria should be considered, such as the nuclear safety system, information system, land use, availability of cooling water, human activities and environmental impacts. As well, the NPP must meet spatial conditions so that the energy produced can be used beneficially and healthily.

Now, the selection of candidate sites that provide the best conditions for NPP installation in Bursa was discussed. Fifteen regional criteria (C_{10}–C_{24}) contained in the environmental, social and safety categories (criteria compatible with IAEA) were employed for the assessment. Proximity analyses or reclassifications were performed in the GIS environment for each criterion. Inverse distance weighting (IDW) was used to analyze only the average temperature and wind speed. Hereby, regional criteria were scored and criteria maps were created for each (Fig. 4). Score of criteria and type of analysis are shown in detail in Table 4.

C_{17} came to the fore in terms of the safety of the nuclear plant. After the C_{17} criteria, C_{12}, C_{13} and C_{14} were listed as three important criteria. The lowest criteria scores were C_{22}, C_{23} and C_{24}. Especially, it was seen that the risky, environmental and economic criteria were more effective than the other criteria. Concerns about risk must be seriously considered when designing a nuclear reactor, as seen in the recent disaster at Fukushima (Japan). It must have access to a reliable water source that can provide water for an extended period to cool the reactor in an emergency. Also, the proximity of the NPP to transmission lines will both reduce the cost of establishing a new line and prevent transmission losses.

The weights (Table 8) obtained from the FAHP method were combined with the criteria maps and the NPP suitability map was produced for Bursa (Fig. 5). This suitability map was represented under four groups as the restriction, least suitable, relatively suitable and most suitable sites. According to the results, it was concluded that 53% (5873 km^2) of the area in Bursa province is the restriction area for NPP. It was seen that the most suitable sites have a total area of 1092 km^2 (10%). It was evaluated that an area of 564 km^2 would not be preferred for NPP installation and there might be undesirable situations. Relatively suitable sites (32% ~ 3514 km^2) are predictable places for plant installation in case of necessity, but it is better not to choose them.

In this study, the most suitable sites were given priority while evaluating site suitability for NPP installation, and then, 9 candidate sites (CS) with the highest raster value were selected from these sites (Figs. 5 and 6). Due to the large number of CS and their proximity to each other, these sites were specifically ranked in terms of tourism, sufficient cooling water, agricultural activities and area sizes (Table 9). Bursa province is an important location for tourism. According to statistics, it is seen that Cappadocia ranks first with 15.6% in tourism destinations for domestic tourists in Turkey, followed by Bursa with 13.2%. In terms of tourism destinations for foreign tourists, Bursa ranks fourth after Istanbul, Cappadocia and Antalya with 19.6% (URL2, 2022). Bursa

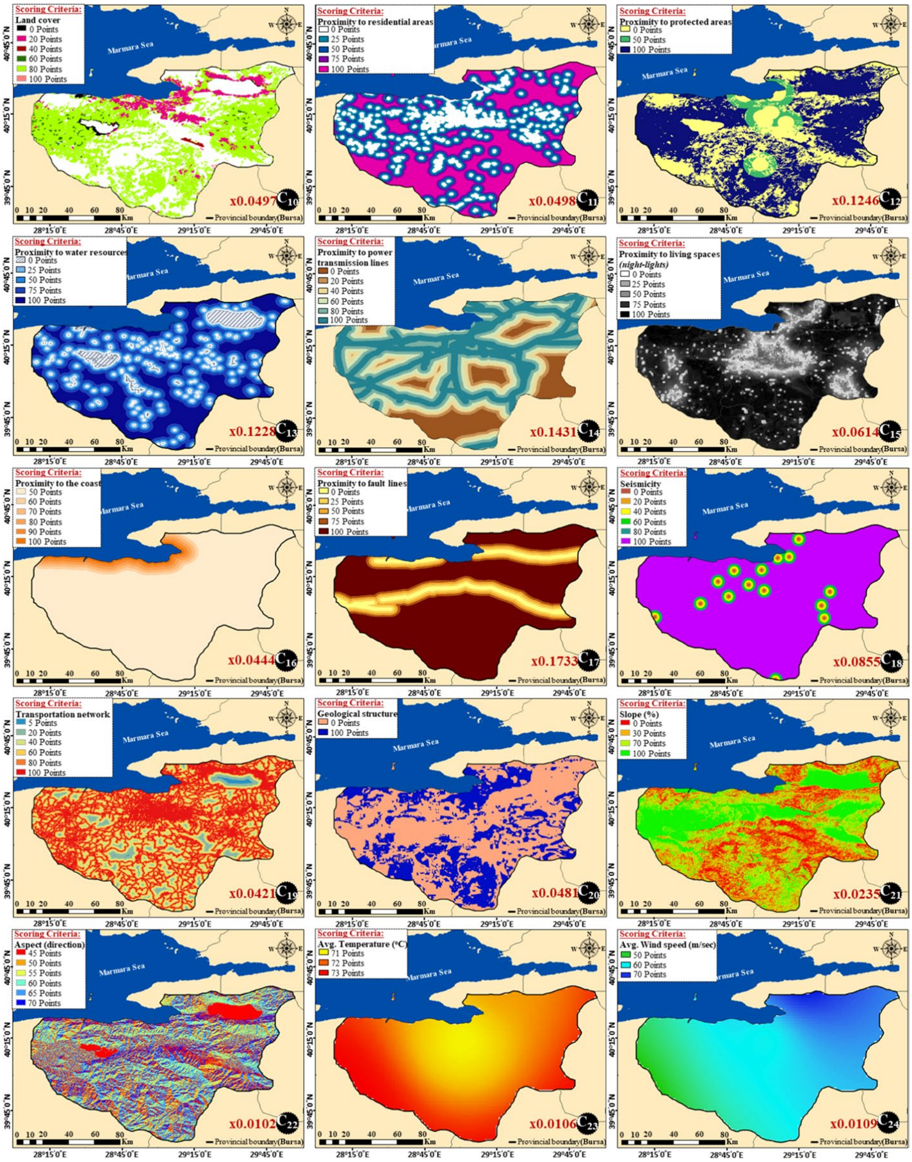


Fig. 4 Criteria maps scored in determining site suitability of NPP

Uludag and its 6 districts (Mudanya, Karacabey, Mustafa Kemalpaşa, Gemlik, Keles and Inegol) have outstanding with their ski tourism, historical, cultural and natural beauties. Therefore, CS-2, CS-3, CS-4, CS-5 and CS-6 were kept in the background for NPP installation (Fig. 6). CS-5 and CS-6 are also the regions where the highest quality olives are grown in Turkey and are under legal protection together with their surroundings. These CS were evaluated in the lowest ranks in terms of preferability, considering the public reaction and the agricultural activities. Since CS-1 is far from

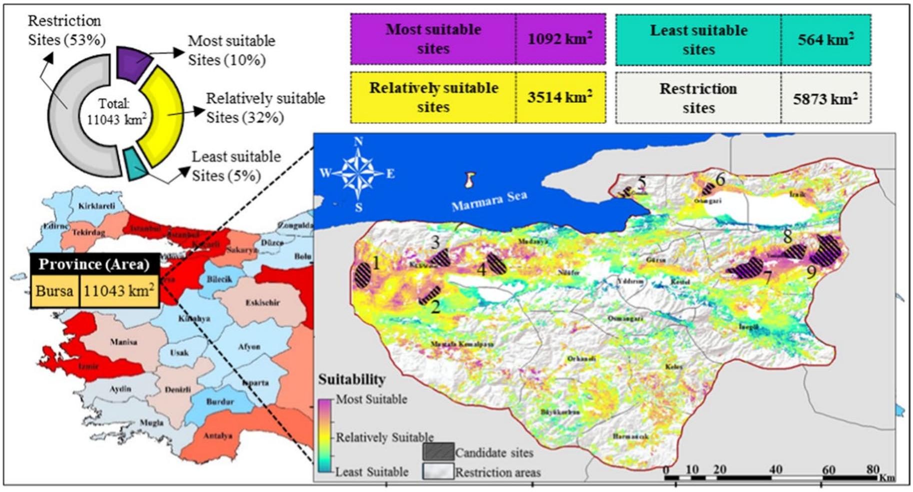


Fig. 5 Suitability map for NPP site selection (Bursa, Turkey)

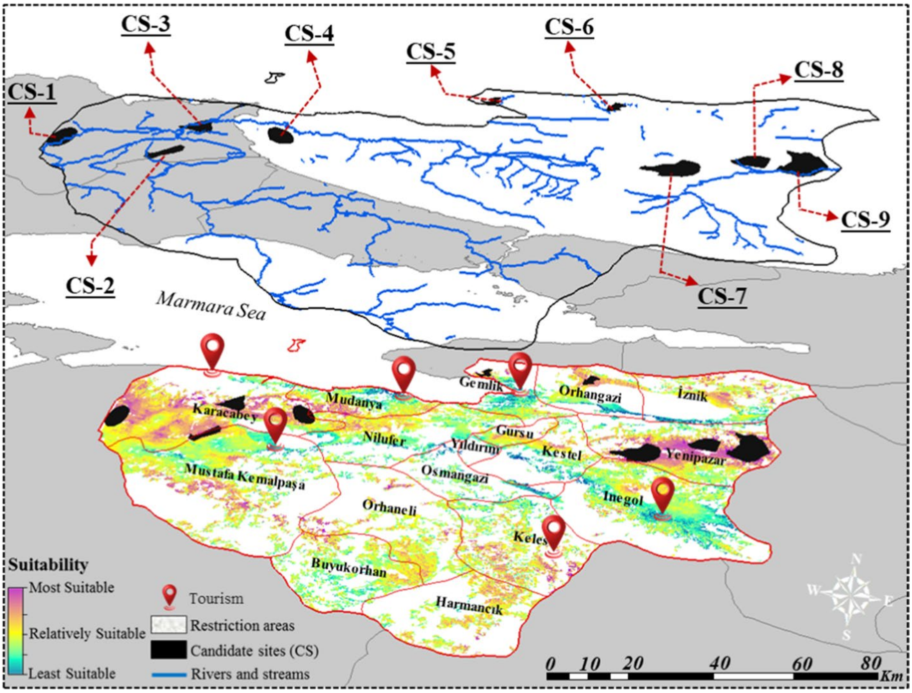


Fig. 6 Evaluation of candidate sites from various perspectives

Istanbul (the province with high energy needs) compared to other CS, it was not considered a priority. CS-7, CS-8 and CS-9 were concluded to be more suitable for NPP installation.

Table 9 Ranking of the candidate sites

	CS-1 ($116\ km^2$)	CS-2 ($87\ km^2$)	CS-3 ($90\ km^2$)	CS-4 ($95\ km^2$)	CS-5 ($40\ km^2$)	CS-6 ($44\ km^2$)	CS-7 ($205\ km^2$)	CS-8 ($100\ km^2$)	CS-9 ($315\ km^2$)
Tourism	*	*	*	*	*	*	**	**	**
Agricultural activities	**	**	**	**	*	*	**	**	**
Sufficient cooling water	*	*	**	**	**	*	**	**	**
Area sizes	*	*	*	*	*	*	**	*	**
Rank	4	4	3	3	4	5	1	2	1

While double-star (**) indicates that the CS may be preferred more for NPP installation, single-star (*) indicates that the CS may be less preferred

Sufficient cooling water was previously evaluated as proximity to the sea, but more detailed research was aimed here. Because if a power plant is to be installed in a place without a coast, the cooling water must be supplied from a different source. Moreover, there is a need for cooling water to reduce the high temperature, and easy transportation of water is essential to remove the heat that may occur in case of an accident. Waterways (rivers and streams) in Bursa were prepared in layers using ArcGIS 10.5.1 software. CS and waterways in the suitability map were evaluated together (Fig. 6). As a result, no risk factors were detected in CS-7, CS-8 and CS-9 and additionally, the presence of water was observed.

Finally, the examination of area sizes in NPP installation is important to increase the use potential of the site. Namely, the large area is an indicator of the availability of more alternative sites in the area to be evaluated in the NPP installation. It is indispensable for the investor that there are a lot of alternative sites that offer the chance to reduce the cost for the NPP, which can create trading competition. At the same time, it has the effect of increasing the probability of finding the site belonging to the treasury. All study results in ranking the CS are summarized in Table 9. CS-7 and CS-9 were at the top of the rankings, while CS-6 was at the bottom of the rankings. So, two priority sites for NPP were found in Bursa.

In the evaluation of suitability as a power plant site for Turkey, the effects of natural and man-made external events that may occur at the proposed site, location characteristics that may affect the transport of radioactive materials that may be released from the plant, and lastly, population/habitat that may prevent the applicability of emergency measures are accepted as environmental considerations (RNPPA, 2009). If it cannot be shown that the weaknesses identified during the site evaluation regarding these three considerations can be eliminated by protection measures or administrative procedures, it is decided that the site is not suitable.

Reports should also be handled in addition to these environmental considerations. Environmental Impact Assessment (EIA) is indispensable in taking measures against environmental risks or minimizing these risks. For all projects planned in Turkey, an Environmental Impact Assessment Report (EIAR) is prepared to determine the damage to the environment by public institutions, universities or project supervisors. This report must be submitted to the Ministry of Environment, Urbanization and Climate Change (TEIAR, 2022). For example, the EIAR prepared for the ongoing NPP construction in Mersin/Turkey was approved by the relevant ministry in 2014. Review and evaluation meetings were held for the prepared report. Non-governmental organizations such as Greenpeace and the Turkish Anti-Erosion Foundation also attended these meetings. The EIAR was revised and finalized in line with the opinions of all parties. This report, with all its annexes, is over 5500 pages in total and is a very detailed and comprehensive study. In our study, which was completed following the IAEA and Turkish Energy, Nuclear and Mineral Research Agency (TENMAK in Turkish) instructions, the EIA report and relevant regulations constitute the supplementary framework for taking environmental precautions.

5 Conclusion

The need to meet energy demand in cities has emerged by raising the population and energy consumption. Although increasing concerns about their environmental effects, the sustainability of different energy sources has gained importance as a result of the rapid growth of world energy demand. Among these sources, nuclear energy comes to the fore due to reasons such as being a non-carbon-generating electricity, heat generation method and providing resource security. However, some topics should need attention. Site selection studies are essential for the prevention of accidents and the mitigation of their consequences in NPP. For this reason, attention should be paid not only to construction, operation and organization studies but also to site selection activities.

This study addressed the two purposes of identifying the potential province for NPP installation depending on the energy demand and selecting candidate sites in the identified province. To determine the energy demand in Turkey, which is the first purpose, the energy demand map was produced by considering the demographic and economic criteria. The energy demand map that we produced using the GIS-FAHP was analyzed under two classes high and low potential. According to the analysis results, it was shown that “Bursa” has a very high potential province, and so, was decided as the study area. However, it should not be forgotten that it is not correct to focus only on energy demand for the installation of a power plant. Considerations such as energy demand, being a central point, low population density and low-risk area were also handled while identifying the potential province. Presenting a country-wide energy demand map is important for managing energy, meeting needs, using investment tools according to supply and demand, and exporting energy. This map can be used not only for NPP but also for renewable energy investments.

For the candidate site selection in Bursa province, which is the second purpose, the suitability map was generated by handling the environmental, social and safety criteria. This map was evaluated under four classes of suitability, namely restriction, least suitable, relatively suitable and most suitable sites. Around 10% of the study area was found to be the most suitable for the installation of the power plant, whereas 58% were unsuitable sites (least suitable and restricted). Results showed that Bursa has a very high suitability site for NPPs, which spans 1092 Km^2 (10%) after deducting the restricted sites, relatively and least suitable sites. Finally, nine candidate sites were selected from among the most suitable sites for NPP, and these sites were evaluated according to various perspectives such as tourism, agricultural activities, sufficient cooling water and area sizes. While CS-7 and CS-9 were decided for NPP installation, CS-6 was appointed as the least preferred NPP site.

The proposed methodology for managing nuclear energy with a sustainable policy is compatible with the instructions of organizations such as IAEA and TENMAK and is developed new alternative solutions to problems. In addition, this methodology will contribute greatly to the spatial prioritization of investment instruments by being included in the country’s development plans or spatial plans. The spatial evaluation process will be fully supportive in terms of scientific, administrative and legal aspects when public/people and field reconnaissance, which are the limitations of this study, are included in the methodology. Nuclear energy studies should be carefully supported and carried out with great care to prevent the depletion of energy resources, which is a global problem. The government should raise public awareness through various social media. Each country should establish its national and general strategies for the proper management of security risks.

Data availability The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declaration

Conflict of interest I hereby certify that this paper consists of an original, unpublished work that is not under consideration for publication elsewhere and all co-authors have seen and approved the final version of the paper. In addition, all the authors declare that they have no conflicts of interest.

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