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ORIGINAL PAPER

For reducing CO_2 emissions, what is the most effective: making power plants more efficient or developing renewable resources?

S. Ziyaei[1] · M. Panahi[1] · D. Manzour[2] · A. R. Karbasi[3] · H. Ghaffarzadeh[1]

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Abstract
The present study evaluated carbon reduction policies (decarbonization) by comparing energy efficiency improvement in thermal power plants and the incremental development of renewable and clean power plants in different scenarios in the power generation sector. For this purpose, the optimal portfolio for power generation expansion was considered until 2050. Likewise, regarding environmental considerations, the values of environmental emissions and their external costs in different power generation methods were modeled for the first time in an inclusive electricity system. Then, the Matrix Laboratory and Long-Range Energy Alternative Planning software were used to model electricity supply and demand toward long-time planning and estimate and solve technical, economic, and environmental functions. The modeling outcomes showed that, under the Steam Power Plant repowering scenario, the efficiency-improving actions in thermal power plants were prioritized over the development of clean and renewable power plants, including large hydroelectric and nuclear power plants, and could reduce the total power generation cost by 38% until 2050 and environmental and greenhouse gases emissions by 3,572 MMT and 2,624 MMTDCO2E compared to the BAU scenario. It was also found that although developing renewable energies could decrease the external environmental costs by 73,188 million U.S dollars in the 2017–2050 period relative to the other scenarios, its development would not be optimal technically and economically since it was a function of technical, economic, environmental, and political factors and was not the sole approach to reducing carbon emissions in all countries.

Keywords Power generation expansion planning · Decarbonization · Energy efficiency in thermal power plants · Development of renewable and clean energy · Environmental external cost · Long-range energy alternative planning · Matrix laboratory

Abbreviations

CO_2	Carbon dioxide
Kwh	Kilowatt-hour
Gwh	Gigawatt-hour
MW	Megawatt
Inv	Investment cost
FO&M	Fixed operation and maintenance cost
VO&M	Variable operation and maintenance cost
CF	Capacity factor
EFF	Efficiency
LOLE	Loss of load expectation
LEAP	Long-range energy alternative planning
GDP	Gross domestic product
MATLAB	Matrix laboratory
GLPK	GNU linear programming kit
GT	Gas turbine
NGCC	Natural gas combined cycle
WHR	Waste heat recovery
$MMTDCO_2E$	Million metric tons domestic CO_2 equivalent
GHGs	Green house gases
MMT	Million metric tone
NGE	Natural gas equivalent
BAU	Business as usual
PGEP	Power generation expansion planning
EPA	Environmental protection agency
IEA	International energy agency
DOE	Department of environment

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✉ M. Panahi
m.panahi@srbiau.ac.ir

[1] Faculty of Natural Resources and Environment, Science and Research Branch, Islamic Azad University, Tehran, Iran

[2] Faculty of Economics, Imam Sadiq University, Tehran, Iran

[3] Department of Environmental Engineering, Graduate Faculty of Environment, University of Tehran, Tehran, Iran

VED	Value of environmental damages
LDC	Load duration curve
SPR	Steam power plant repowering
RPD	Renewable power plants development
NPD	Nuclear power plants development
LPD	Large hydroelectric power plants development
ATPD	Advanced thermal power plants repowering
GT to NGCC	Gas turbine to natural gas combined cycle
CCS	Carbon capture and storage
DG	Distributed generation
N2O	Dinitrogen oxide
CH4	Methane
CCHP	Combined cooling, heat and power
USC	Ultra-supercritical coal
IGCC	Integrated gasification combined cycle
GAMS	General algebraic modeling system
EEP	Energy efficiency package
EPI	Electricity price increase
ATD	Advanced technology development
NDC	Nationally determined contribution
PGE	Power generation expansion

Introduction

The emission of air pollutants, especially CO_2, brings about significant and detrimental impacts, like climate change and global warming (Florides and Christodoulides 2009; Solomon et al. 2009; Shrivastava et al. 2020; Hertzberg and Schreuder 2016). Due to the growth in economic development, population, and use of technologies, the demand for different energy carriers (fossil fuels) has increased (Naseri and Ahadi 2016; Onozaki 2009; Promjiraprawat and Limmeechokchai 2012; Yan et al. 2019; Zhao et al. 2021). However, if the energy demand and consumption continue increasing in the next years, we will not only have limited access to existing energy sources but also witness an ascent of emissions more than ever. Among different energy-consuming sectors, the power generation sector is the most significant source that uses fossil fuels and emits carbon dioxide as the chief greenhouse gas (Hardisty et al. 2012; David Samuel et al. 2021; Pratap Raghuvanish et al. 2006; Mostafaeipour et al. 2022). EPA (2022) showed that the power generation sector contributed to almost 36% of CO_2 emissions in 2021, while this value was about 25% in 2017. Thus, over one-third of GHGs are emitted due to the consumption of fossil fuels in the electricity generation sector of power plants (IEA 2019).

Therefore, the world faces two challenges, i.e., the increasing demand for electricity, on the one hand, and reducing the emission of pollutants and GHGs (especially CO_2), on the other hand (Gencer et al. 2020; Ziyaei et al. 2023b; Williams et al. 2012). The genesis of such intricacies compels governments, companies, investors, and people to generate sustainable and efficient electricity in the world in order to decrease the environmental impacts of these emissions. Based on their circumstances and concerns, different countries make and implement various legal policies and actions (Chang and Carballo 2011). Among these programs, we can refer to reducing carbon in this industry, increasing electricity generation by renewable and clean energies (CCC 2010; Eurelectric 2018; Hanisch et al. 2018), raising the efficiency of thermal power plants (Ozer et al. 2013), enhancing energy efficiency (Nebernegg et al. 2019; Sepulveda et al. 2018), using systems and technologies that reduce carbon and pollutants (Kusumadewi et al. 2017a, b; UNEP 2016), setting taxes (Ambec and Crampes 2019), etc.

Due to its hydrocarbon resources (being the second and fourth owner of gas and oil reservoirs) and location in the earth's desert belt, Iran is a significant country influencing and influenced by climate change (Naseri and Ahadi 2016; Barzaman et al. (2022); Ardestani et al. 2017; IEA 2015). Iran was ranked seventh in the world in 2021 in emitting carbon pollutants ("Greenhouse gas emission by country 2022"). Notably, the electricity generation sector in this country maximally contributes to carbon production in this sector (Ministry of Energy 2018). Owing to the high volume of GHGs emissions and electricity consumption in this country, the respective decarbonization programs in the strategic climate change document target 4–12% of the total emissions and obliges the country to fulfill its commitments to emission reduction in climate change conventions, Kyoto protocol's, Paris Agreement, etc. Some of these programs incorporate enhancing energy efficiency, increasing the contribution of renewable and clean energies to electricity generation, employing low-carbon technologies in power plant units, modifying price, incentive, and punitive policies toward raising energy efficiency, developing renewable energies, tools, and economic and financial motives, and creating market-centered mechanisms for developing renewable and clean power plants until the 2030 and 2050 horizons (DOE 2016).

With the help of technical and economic models, such as the Power Generation Expansion Planning (PGEP) and Matrix Laboratory (MATLAB), the present study evaluated and compared the effects of the significant policies proposed by the Iranian government for decarbonization and attainment of Kyoto Protocol's objectives in the electricity supply domain until 2050. In this regard, besides chief technical assumptions in the conventional PGEP model, the authors considered the goals set for reducing CO_2 emissions in Iran and minimizing the external effects and environmental costs of various power generation methods as the constraints of the functions. Also, the negative external costs of the types of electricity generation methods considered in the model have been calculated with appropriate economic methods (Benefit Transfer). These computations were made for the first time in the country, and their cost, environmental, and technical effectiveness were evaluated in power generation expansion plans with regard to the decarbonization policy in this industry.

The results of this research will offer a proper vision for developing sustainable power generation systems by raising the contribution of renewable energies and enhancing energy efficiency in Iranian power plants in different scenarios. Besides, they can commensurately link energy planning to policy-making in this domain and enlighten investors and the government in selecting technically, economically, and environmentally sustainable power generation methods with cost-effective approaches. Furthermore, the results of this research will present useful insight to developing and even developed countries that have similar power generation structures. The scenario-derived outcomes are applicable in other countries with gross fossil fuel resources and high capacities for renewable energy sources.

The structure of the present study is as follows: "The Literature Review" section, which reviews the existing literature. "The Research Methodology" section explains the data, research methods, and the employed models. "The Results" section presents the results of the study, and the "Discussions" section discusses the results in accordance with other relevant literature and states the study's limitations. Finally, the "Conclusion" section explains the results of the scenarios, policies of the study, and recommendations for future studies.

Literature review

A glance at the respective literature reveals that numerous studies have tackled PGEP using renewable energy resources and examined its role in decreasing environmental emissions, especially CO_2, such that many references have recognized replacing renewable energies with fossil fuels as an imperative in many references (Abolhosseini, Heshmati, and Altmann 2014; Alvarez-Herranz et al. 2017; David Samuel and Gulum 2019; Dogan and Seker 2016; Mustafa Kama, Ashraf, and Fernandez 2022; Panwar et al. 2011; Ponce and Rehman Khan 2021; Prince Nathaniel and Okechukwu Iheonu 2019; Wang et al. 2020). This is while the contribution of the approaches that enhance energy efficiency or productivity in power plants (the electricity supply sector) has been only limited to efficiency enhancement in thermal power plants in the respective literature, and CO_2 emission reduction and decarbonization have not been considered as the purposes of studies. For instance, Cho et al. (2009) showed that Combined Cooling, Heating, and Power (CCHP) systems could optimally increase efficiency in power plants by minimizing energy costs. Franco and Diaz. (2009), recognized new technologies and USC and IGCC as approaches that raised security and diversity in power supply. The results of another study revealed that thermal power plant repowering was a suitable solution for increasing the quantity and quality of the generated power (Nikbakht Naserabad et al. 2018). Carapelluci and Giordano. (2021) asserted that gas turbine-based technical approaches could be used to enhance the efficiency of power plants by 70% and obtain acceptable economic results. Furthermore, Kabiri et al. (2021) discovered that using solar collectors to improve the performance of thermal power plants was a low-cost and efficient approach since it reduced total costs by 40–50% and gave rise to other environmental effects, e.g., freshwater production.

Furthermore, in studies on power generation optimization through linear programming models, the development of renewable energies has played a bolder salient role in emission-reducing than energy efficiency goals in thermal power plants, and energy efficiency has sometimes been neglected or evaluated by other specific objectives. For instance, to obtain development paths in the electricity domain, Chinese researchers defined a current policy scenario, a new policy scenario, and a renewing the structure of the current electricity industry scenario to reduce CO_2 emission. The results displayed that the demand-side management of electricity and innovating and improving the current thermal power plants were more privileged in the short run, while developing hydroelectric and nuclear power plants was efficient in the long run (Cai et al. 2007). Beer. (2007) examined power generation development by enhancing the efficiency of various power plants. The results showed that a robust and practical tool for reducing CO_2 in fossil power plants was to enhance efficiency by using Carbon Capture and Storage (CCS) technologies. To develop an optimal power generation plan to reduce CO_2 emissions, Muis et al. (2010) employed a mixed-integer linear programming model and the GAMS software. According to the results of this research, gas, combined-cycle, nuclear, and biomass power plants should be optimally integrated for a 50% reduction of emissions, and the selection of power plant type is a function of investment costs and resource accessibility. Promjiraprawat and Limmeechokchai. (2012) applied PGEP and GAMS models to obtain an optimal energy generation plan aiming to reduce emissions in Thailand in 2030. In this respect, they pursued energy productivity in the energy consumption sector and renewable energy development in the power generation sector. The results showed that actions targeting energy conservation reduced costs and CO_2 emissions compared to renewable energy development. In 2015, an Iranian study utilized the MESSAGE software to identify and prioritize renewable and low-carbon electricity generation technologies. Reducing investment costs was the objective function of this study. The results showed that wind and solar photovoltaic power plants were the first and second priorities for power generation (Aryanpur and Shafiei 2015). Likewise, Handayani et al. (2019) displayed that by turning power generation technology to wind and solar photovoltaic systems, the total power generation cost and CO_2 emissions decreased by 4–10% and 25% compared to other renewable and nuclear energies. Bayomi and Fernandez. (2019) showed that power generation in developing countries should be improved and developed by energy productivity actions in the demand sector. Yan et al. (2019) discovered that promoting power generation structure and raising productivity in thermal power generation could give rise to optimal and coordinated development in China until 2030 and decrease CO_2 emissions. Furthermore, in an Iranian study in 2022, the researchers examined CO_2 reduction scenarios in the supply and demand sector using the LEAP model. The results showed that the three scenarios of EEP (Energy Efficiency Package), EPI (Electricity Price Increase), and ATD (Advanced Technology Development) would experience 25%, 22%, and 12% lower emissions than the BAU scenario, enabling this country to fulfill its conditioned Nationally Determined Contribution (NDC) until 2030 (Sabeti et al. 2022).

Hence, by reviewing the present literature, we can assert that the gaps in the studies, compared to the present research, are tied to energy efficiency in the power supply sector, on the one hand, and the constraints related to PGEP functions, on the other hand. Current studies on energy efficiency highly focus on consumer and demand management approaches and neglect efficiency enhancement on the demand side of electricity. Moreover, these studies have attempted to enhance the efficiency of thermal power plants using various technical approaches and disregarded carbon reduction (decarbonization) goals. Besides, they have sought to reduce GHG emissions with economic modeling by minimizing generation, operation, repair, and maintenance costs while not accentuating the environmental costs of different emitted pollutants. However, the technical, managerial, operative, and environmental approaches should be heeded along with conventional costs. Meanwhile, the reviewed studies have only concentrated on scenarios targeting clean and renewable energy development, energy efficiency enhancement in power plants, or energy productivity actions in the demand sector. To the best of the researchers' knowledge, no study has inclusively considered decarbonization scenarios in the supply sector of the power industry regarding technical, economic, environmental, and managerial considerations.

To bridge this gap, the present study evaluates an optimal power generation expansion plan consisting of significant decarbonization scenarios on the supply-side management of the power sector to attain the determined goals in the strategic climate change document of Iran and the objectives of international conventions. Every scenario and sub-scenario are compared technically, economically, and environmentally, and the best PGE alternative is introduced after the application of economic and environmental constraints. In addition, considering all significant PGEP parameters, it seems that the presented approaches in this research are highly applicable in the country and can be considered by respective investors, decision-makers, and managers. These approaches may also be useful for countries with similar power generation structures and open a new horizon for further research.

Materials and methods

Power expansion, management, and planning models concentrate on the demand and supply sides. The model applied in this study is a PGEP model for future years and focuses on the supply-side management of electricity. It is presented based on the conventional power generation expansion principles and developed and optimized by numerous economic, technical, and environmental parameters. Figure 1 displays the stepwise process of this research.

According to the methodology presented in Fig. 1, every PGEP phase is introduced concisely in the following.

Step 1: Identifying the components of the reference energy system

According to Fig. 2, the reference energy flow system comprises resource-supply and demand-side components. Electricity is generated by various power plants that use primary and secondary resources and reaches the transfer, distribution, and consumption phases after being imported and exported. The examined power plants encompass the existing steam, advanced steam, repowered steam, existing combined-cycle, advanced combined-cycle, existing gas, advanced gas, diesel, photovoltaic solar, wind, anaerobic digestion, gasification, landfill, geothermal, large hydropower (> 10 MW), small hydropower, heat recovery, and nuclear power plants.

Step 2: Identification of the electricity demand forecasting method

It is imperative to predict electricity consumption accurately to manage its sustainable and optimal supply (Lee and Tong 2011; Zhang et al. 2020). In this respect, predicting electricity demand is a prerequisite (Nawaz Khan

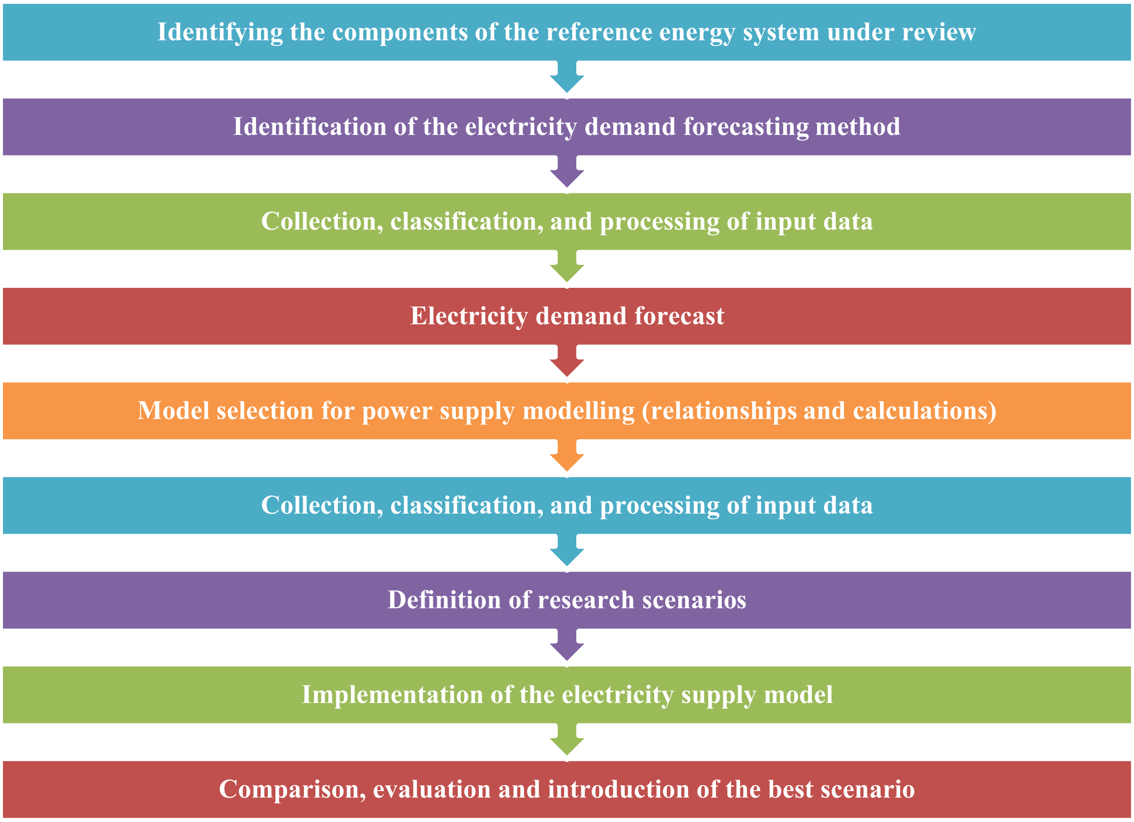


Fig. 1 Research methodology phases

et al. 2020). Accurate prediction of demand helps reduce generation costs, enhances system reliability, develop proper capacity, and direct repair and maintenance plans of power plants (Amina and Kodogiannis 2011). On the other hand, this prediction supports development and can convince foreign investors, private sectors, etc., in highly insecure environments, like developing countries (Ouedraogo 2017).

Figure 3 illustrates the examined demand side in Iran, shown in Fig. 2 as the electricity consumption domain. This domain falls into the household, industrial, agricultural, street lighting, and commercial categories.

In this study, demand was predicted by activity level analysis run in the LEAP software (Eq. 1). In this method, the energy demand results from multiplying activity volume by the energy consumption intensity.

$$EL_y = \sum_{d=1}^{D} \sum_{j=1}^{J} \sum_{m=1}^{M} \sum_{k=1}^{K} Ac_{i,j,m,k,y} \times ELI_{i,j,m,k,y} \quad (1)$$

In this equation, d represents energy-consuming sectors, j denotes electricity consumption, K is the main sub-sectors of electricity consumption, m indicates the ultimate energy consumption, y is the year, EL is electricity demand, ELI represents the electricity consumption intensity, and Ac is the activity volume of the sector.

Step 3: Collection, classification, and processing of input data

Demand estimation requires demographic, economic, social, and other data. Table 1 represents the most significant input data for demand estimation.

Moreover, it is necessary to predict some data needed till the planning horizon according to historical data and available studies, e.g., the population growth rate, GDP growth rate, and value-added elasticity. The research conducted by the Iranian Statistics Center estimated the population growth rate at 0.98% on average during the 2017–2050 period (Fathi 2020). The population growth was estimated at 1.25, 1.11, 0.98, 0.93, 0.91, 0.87, and 0.79 per 5-year interval. The annual GDP growth rate is considered 5% on average, according to the Iranian economic development plans (Ministery of Economics 2015). Moreover, using the Add Trendline tool in Excel with the Power or Cobb–Douglas

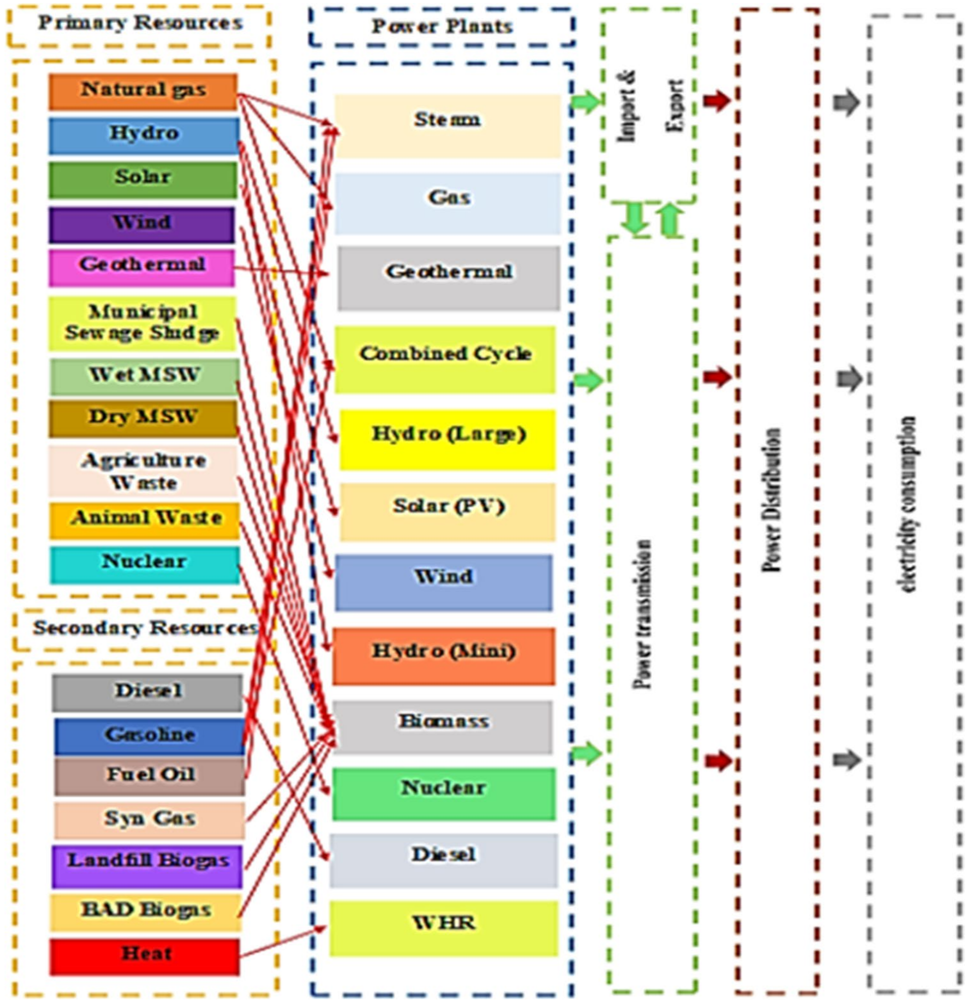


Fig. 2 Reference energy flow system in Iran

function, the authors estimated the value-added elasticity for agricultural, industrial, service, and transport sectors at 0.63, 0.83, 1.14, and 0.83 and considered them in computations.

Step 4: Model selection for power supply modelling

This research employed mathematical programming for optimization toward an optimal and sustainable supply of electricity. For this purpose, the MATLAB software and GLPK solver were utilized. MATLAB is a high-level optimization and modeling system used for solving complex and large mathematical models. It can solve linear, nonlinear, hybrid, etc. models by diverse user-selected methods and algorithms. This software starts from an objective function with a real value and formulates a specific optimization technique or theory (Teshager 2011).

The objective function in this study is minimizing electricity generation costs, and its constraints include a linear composition of mixed-integer decision variables described below:

$$Min_{u,p}Obj_{cost} = \sum_{y=1}^{Y} \left[I_y + \left(F_y + V_y \right) + E_y - S_y \right] \tag{2}$$

where I represents the total initial investment cost, F is the total fixed operation, repair, and maintenance cost, V indicates the total variable operation, repair, and maintenance cost, E represents the total environmental cost of different power generation methods, and S indicates the total disposal value in year Y, all estimated by the following equations:

$$I_y = \left(\frac{1}{1+D} \right)^{y-1} \left[\sum_{t=1}^{T} \left[I_t \times Cap_t \times U_{t,y} \right] \right] \tag{3}$$

$$F_y = \left(\frac{1}{1+D} \right)^{y-\frac{1}{2}} \sum_{t=1}^{T} \sum_{y=1}^{y} \left[F_t \times Cap_t \times U_{t,y} \right] + \left[\sum_{j=1}^{J} F_j ExistCap_j \right] \tag{4}$$

$$V_y = N \times \left(\frac{1}{1+D} \right)^{y-\frac{1}{2}} \sum_{l=1}^{L} L \left[\sum_{t=1}^{T} \left[V_t \times P_{t,y,l} \right] + \sum_{j=1}^{J} \left[V_j \times P_{j,y,l} \right] \right] \tag{5}$$

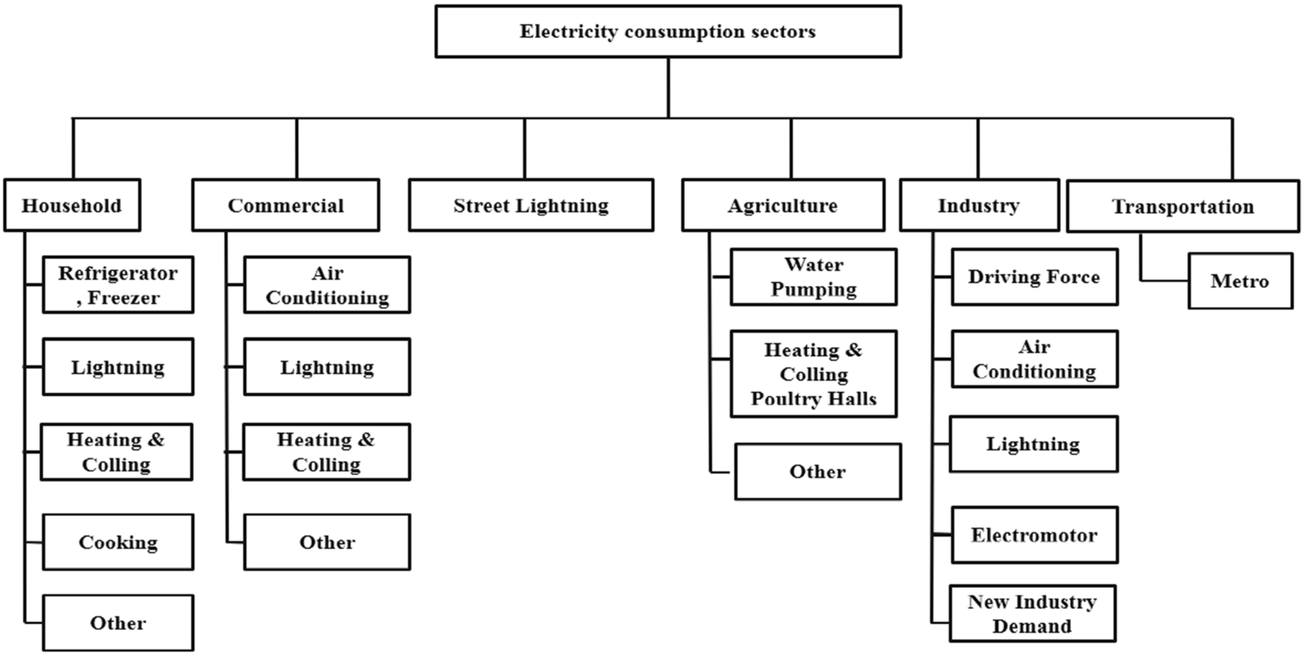


Fig. 3 The major power consumption sectors for predicting demand in the present study

Table 1 Some historical data during 2011–2016

Parameters / Year			2011	2012	2013	2014	2015	2016
Population × (1000)			7515	76,082	77,025	77,980	78,947	79,926
Household × (1000)			21,186	22,023	22,898	23,812	24,766	25,764
GDP (Billion Rials)			648,741	616,154	605,311	616,679	622,845	675,787
Value Added (Billion Rials)			639,408	608,622	600,901	613,162	619,294	668,838
Electricity (Gwh)	Commercial	Household	56,774	61,351	64,379	71,163	76,103	78,378
		Commercial	29,415	30,409	31,208	35,171	38,875	40,534
		Agriculture	30,020	31,647	33,103	35,188	30,687	36,222
		S Lighting	3752	3635	3765	3837	4017	4699
		Transport	353	366	325	385	570	436
		Industry	63,591	66,741	70,309	74,070	71,657	7716

Household size and population, *GDP* value-added, and electricity consumption were obtained based on reports presented by (Results of the 2016 National Population and Housing Census) (Fathi 2020), (Iran's Quarterly National Accounts (base year = 1376), the years 1385-1395) (Ministry of Economics 2015), (Table of seasonal added value at fixed price) (Central Bank of the Islamic Republican of Iran, 2020) and (Ministery of Energy 2018), respectively

$$E_y = N \times \left(\frac{1}{1+D}\right)^y \sum_{y=1}^{Y} \sum_{t=1}^{T} \left[VED_{t,y} \times P_{t,y}\right] + \sum_{j=1}^{J} \left[VED_j \times P_{j,y}\right] \tag{6}$$

$$S_y = \left(\frac{1}{1+D}\right)^Y \sum_{t=1}^{T} \left[\delta_t^{Y-y+1} \times I_t \times Cap_t \times U_{t,y}\right] \tag{7}$$

where D represents the discount rate, N is the number of operation hours of electric power plants, L denotes sub-periods, J stands for the available technologies, T indicates new technologies, and P is the rate of power generated from every technology. Besides, Cap is the power generation capacity of the technology, U is the number of technologies, δ is the disposal rate per technology, and VED is the pecuniary value of environmental damages.

Furthermore, the functions of the problem constraints that are indispensable for power generation development are described in Eqs. 8–21. Equation 8 defines the maximum number of constructed units of different power plant types. These established units should be smaller or equal to the number of candidate units of the considered power plant t in year y. Equation 9 displays the capacity constraint, where the capacity of every technology should be higher than the generation rate and load activity per region. This measure obtained by the capacity factor should be larger than the real generation rate. The maximum and minimum reserve values and the installed capacity in the grid should fall into the permissible Min–Max range. Equation 11 presents the net power generation per year. The entry of new power plants for electricity generation and the retirement of old power plants are considered, and it is assumed that power generation is constant during the year. The reliability index of Loss of Load Expectation (LOLE) and the constraint of applying power generation sources are presented in Eqs. 12 and 13–18, respectively. According to these equations, the generation of power from renewable and fossil energy sources cannot exceed the potential of these sources. Equations 19 and 20 present the annual plan for the increasing use of new thermal power plants and the supply of electricity demand. In both sub-periods, the total power generated from the present electric and selected new power plants should suffice the demand predicted in the demand estimation scenario, with the Load Duration Curve (LDC), and completely cover the electric demand. Equation 21 shows the retirement constraint of old power plants.

$$0 \le n_{t,y} \le n_{t,y}^{max} \tag{8}$$

$$TotalCap_{t,y} = NewCap_{t,y} + RessidualCap_{t,y} \tag{9}$$

$$\left(1 + R_{min}\right) \times Load_{y,1} \le D_{p,y} \le \left(1 + R_{max}\right) \times Load_{1,y} \tag{10}$$

$$D_{p,y} = \sum_{l=1}^{y} \left[\sum_{t=1}^{T} \left[Cap_t \times U_{t,y}\right] - \sum_{j=1}^{J} \left[Retire_{j,l}\right] \right] + \sum_{j=1}^{J} \left[ExistCap_j\right] \tag{11}$$

$$LOLE \le Cr_y \tag{12}$$

$$\sum_{y=1}^{Y} Cap_t \times U_{t,y} \le CRE_t \tag{13}$$

$$\sum_{y=1}^{Y} \left[\sum_{t=1}^{T} \left[Cap_t \times U_{t,y}\right] + \sum_{j=1}^{J} \left[ExistCap_j\right] \right] = PRE_{t,y} \tag{14}$$

$$Production_{y.f.l} \ge Demand_{y.f.l} + Consumption_{y.f.l} \tag{15}$$

$$Consumption_{y,f,l} = \tag{16}$$

$$Production_{y,f,l} = \sum_{t=1}^{T} \left[\left[\sum_{l=1}^{y} PC_{l,y,t} \right] \times PCR_{y,f,t} \right] \tag{17}$$

$$\sum_{y=1}^{Y} Cap_t \times U_{t,y} \le CRT_t \tag{18}$$

$$\sum_{y=1}^{Y} \left[\sum_{t=1}^{T} \left[Cap_t \times U_{t,y}\right] + \sum_{j=1}^{J} \left[ExistCap_j\right] \right] = PRT_{t,y} \tag{19}$$

$$\sum_{t=1}^{T} \left[\sum_{l=1}^{L} \left[P_{t,l,y}\right] \right] + \sum_{j=1}^{J} \left[\sum_{l=1}^{L} \left[P_{j,l,y}\right] \right] \le Load_{L,y} \tag{20}$$

$$TotalCap_{t,y} = Cap_t \times \left(y + Life_t\right) \tag{21}$$

In these equations, f represents fuel, FC denotes fossil fuel consumption, and PC is fossil fuel production. FCR and PCR stand for the fossil fuel consumption and production rates, CRT is the maximum expansion capacity of thermal power plants, PRT shows the expansion plans of thermal power plants, and CRE indicates the maximum expansion capacity of clean and renewable power plants. Besides, PRE-stands for the expansion plans of renewable power plants, Cry represents the critical limit of LOLE, and D is the maximum load of the grid. R_{min} and R_{max} are also defined as the minimum and maximum reserve values of the grid.

In addition, reducing CO_2 emissions (decarbonization) is another objective of this study and is defined and modelled as a constraint (Eq. 12).

$$N \times \sum_{y=1}^{Y} \left[\sum_{l}^{L} L \left[\sum_{t=1}^{T} \left(EF_t \times P_{t,l,y}\right) + \sum_{j=1}^{J} (EF_j \times P_{j,l,y}) \right] \right] \le E_{CO_2}^{max} \tag{22}$$

where EF is the CO2 emission factor per technology, P is the electricity production rate per technology, and $E_{CO_2}^{max}$ is the maximum permissible value of CO_2 emissions according to the international commitments in the Iranian power generation sector.

Step 5: Collection, classification, and processing of input data

Our PGEP required key data and significant assumptions. For modeling the 2017–2050 period considered. The discount rate was assumed 14%, and the disposal value of all technologies was determined at 10% of the initial investment costs. The price of the consumed fossil fuel in thermal power plants was considered at 13 cents per m^3 for natural gas and 62 and 60 cents per liter for gasoline and fuel oil (Ziyaei et al. 2021 ; Ziyaei et al 2023a, b). The potential of fossil and renewable energies for power generation was estimated at 10,000, 18,000, 1500, 4000, 29,000, 13,000, 102,000, 11,000, and 12 MW for solar, wind, geothermal, biomass, hydroelectric, nuclear, oil, gas, and coal power plants according to the studies conducted by Renewable Energy and Energy Efficiency Organization in Iran. Other significant assumptions and data are described in Table 2.

Step 6: Definition of research scenarios

Defining different scenarios in the research paves the way for recognizing different political electricity expansion paths technically, economically, and environmentally (Craig et al. 2002; Meadowcroft 2009). Seven scenarios defined in this study are presented in Table 3 in detail.

Results and discussion

Results

This section presents the PGEP results on both the electricity demand and supply sides.

Electricity demand

The electricity demand for Iran was predicted according to the research methodology and presented data (Fig. 4). As shown in the figure, electricity demand increases from 255,000 GWh in 2017 to 965,000 GWh in 2050, i.e., the average demand growth is about 4% in this interval. The industrial and household sectors allocated the maximum demand to themselves in 2017, while the maximum share will belong to the commercial and household sectors in 2050. The growth in the service and commercial sectors is 14%. Notably, these sectors will change to big power consumers of the country in 2050 due to the enhancement of equipment and technologies in these sectors.

The electricity distribution rate equals the demand rate. Nonetheless, considering its losses, as well as the exports, imports, and safety margin of the system (about 30%), 1,104,000 GWh of electricity should be delivered to the power transfer system, highlighting the need for capacity building.

Table 2 Important and basic assumptions for modelling

Technologies	Costs				Life (year)	CF	Eff (%)
	Inv ($/kw)	FO&M ($/kw)	VO&M (c$/kwh)	Env (c$/kwh)			
WHR	750	15.8	0.0005	0.052	20	0.50	100
Solar (PV)	1100	26.8	0.0000	0.014	20	0.22	100
Wind (onshore)	1300	12.0	0.0000	0.003	30	0.36	100
Hydro (mini)	1895	16.0	0.0000	0.000	20	0.38	100
Hydro (Large)	1500	13.5	0.0000	0.000	30	0.35	100
Geothermal	3830	132.0	0.0000	0.000	25	0.85	100
Gasifier	3000	0.0	0.0030	0.006	20	0.73	28.0
Landfill	2453	94.5	0.0440	0.006	20	0.73	27.0
Nuclear	5530	57.6	0.0080	0.006	30	0.80	33.0
Diesel	380	25.0	0.0005	0.135	20	0.75	35.1
Anaerobic digestion	2650	203.5	0.0030	0.006	20	0.73	28.0
Steam existing	1100	12.3	0.0005	0.116	20	0.80	35.1
Steam repowered	670	12.3	0.0005	N/A	20	0.80	64.6
Steam advanced	1080	15.8	0.0006	N/A	20	0.80	42.0
NGCC existing	700	9.8	0.4700	0.093	25	0.90	44.3
Convert to NGCC	410	9.8	0.4700	N/A	25	0.90	43.7
NGCC advanced	775	13.2	0.4700	N/A	25	0.90	58.0
GT existing	425	9.8	0.6400	0.052	20	0.70	31.4
GT advanced	450	12.8	0.5300	N/A	20	0.70	38.0

Electricity production

Electric power plants are the most significant components of the power supply system (Weisser 2007; Kotelnikov et al. 2017). The below figure displays the power generation rate of power plants per year and each power plant per scenario.

In the Business-As-Usual (BAU) scenario, the combined-cycle power plants will still be the largest power generators (Fig. 5). Furthermore, the contribution of these power plants will increase from 37 to 51% by 2050. Steam power plants are ranked second, and the power generated by these power plants will reach 35% by 2050. Besides, gas power plants will be less attractive concerning their generation and fuel costs and pollution, and their contribution will decrease from 26 to 4%. In addition, nuclear, large hydroelectric, and renewable power plants are also less attractive (11%), such that the share of nuclear and hydroelectric power plants will be lower than the base year, and renewable solar and wind power plants will have a slightly increased contribution. In the Renewable Power Plant Development (RPD) scenario, the maximum power generation contribution belongs to the existing combined-cycle power plants in the 2017–2030 interval and then to the advanced combined-cycle power plants until 2050. Renewable and clean power plants have a share of about 16%. Compared to the base scenario, it seems normal if the natural renewable power plant expansion goals are considered. In reference to the base scenario, steam power plants lose their attractiveness in this scenario, and the advanced combined-cycle power plants are highly privileged. The share of the existing combined-cycle power plants is also high in the Steam Power Plant Repowering (SPR) scenario, and the advanced combined-cycle power plants are prioritized in second place. Clean and renewable power plants have a 14% contribution. Steam power plants are not prioritized for power generation in this scenario if we even apply emission and cost constraints, and the advanced steam power plants allocate a trivial but larger generation percentage to themselves as compared with the other scenarios. In the Large Hydroelectric Power Plant Development (LPD) scenario, the existing combined-cycle power plants constitute power generation priorities in all planning years, and the contribution of the other power plants, along with the steam power plants, is almost negligible. Moreover, due to the precedence of hydroelectric sources for power generation, the contribution of these power plants will decrease to 6% in 2050 concerning the climatic conditions of the country and the constraints. However, this portion will be larger than those of other scenarios. Similar to the SPR scenario, the maximum contribution will first belong to the existing and then to the advanced combined-cycle power plants until 2050 in the Advanced Thermal Power Plant Development (ATPD) scenario and the share of clean and renewable power plants will equal 14% of the total generation rate. Considering the assumptions presented in this scenario, the contribution of the advanced steam and gas power plants will increase and reach 11% of the total rate in 2050 due to the decline in the generation of the existing gas power plants for the investment costs and CO_2 pollution of these power plants. In the gas-to-combined-cycle conversion scenario, the maximum contribution is related to the existing and advanced combined-cycle power plants. In this scenario, the generation rate of gas power plants decreases from 30% in the base year to 2% in 2050, and the combined-cycle power plants will supply a larger portion of electricity compared to the other scenarios. Along with the advantageousness of the advanced combined-cycle power plants in the Nuclear Power Plant Development (NPD) scenario, nuclear power plants will considerably grow compared to the other scenarios and have a 5% share. This is while this value equals 3% in the base scenario in its most optimal state. Considering the significance of power generation in this scenario, nuclear power plants will fail to generate power in Iran due to high investment costs and other technical and political circumstances. Likewise, clean and renewable power plants will contribute to 20% of power generation in this scenario owing to the increased share of nuclear power plants and raised production of gasification and biomass power plants for their roles in reducing emissions in this scenario.

Fuel consumption

The examined fuels included fossil fuels (Natural gas, fuel oil, diesel, and coal) and clean and renewable fuels (wind, hydro, solar, nuclear, syngas, dry and wet wastes, sewage, etc.). The modeling results show that the total fuel demand in the power plants is about 79.5 billion m^3 NGE. Compared to the other scenarios, this value will become the highest in BAU and reach 268.5 billion m^3 in 2050. This amount of fuel surpasses the technical and economic capacity of the country, and the inefficient utilization of this fuel will accompany undesirable consequences. Among the other scenarios, SPR minimally demands fuel consumption since the existing and advanced combined-cycle power plants will have larger contributions, and clean and renewable power plants, which do not need fossil fuels, will also have extra generation. As a result, we can reduce the consumption of fossil fuels due to the decrease in the demand for electricity production in the examined scenarios. We can also enhance efficiency by increasing exports to global markets with higher prices than domestic subsidy consumption and create a suitable contribution to the country. The below figure shows the degressive trend of fuel consumption in every scenario compared to BAU. The fuel consumption decreases by 143.5 billion m^3 NGE in SPR compared to the reference scenario.

Table 3 Details of designed scenarios

Scenario name	Quantitative description
Business as usual (BAU)	Reflecting the probable situation based on the changes of the existing trend
Renewable Power plants development (RPD)	-Installing 5,000-megawatt renewable power plants by 2021 -Installing 12,000-megawatt renewable power plants by 2050 -Share of each of the sources of renewable energies, such as solar, wind, hydroelectric under 10-megawatt, WHR, biomass and geothermal is 50, 40, 7, 2, 1, and – percent, respectively
Nuclear Power plants development (NPD)	-Installing 20,000-megawatt nuclear power plants by 2050
Large Hydroelectric Power plants development (LPD)	-Installing 25,000-megawatt large hydroelectric power plants by 2050
Advanced Thermal Power plants development (ATPD)	-Constructing new steam, gas, and combined cycle power plants with high efficiency, with the capacity of 5500, -15,500-megawatt, respectively
Steam power plant repowering (SPR)	-Repowering of steam power plants with a capacity of 2,300-megawatts
Alteration of gas turbines to natural gas combined cycle (GT to NGCC)	-Converting the turbine of gas power plants to a combined cycle with a capacity of 10,000-megawatt

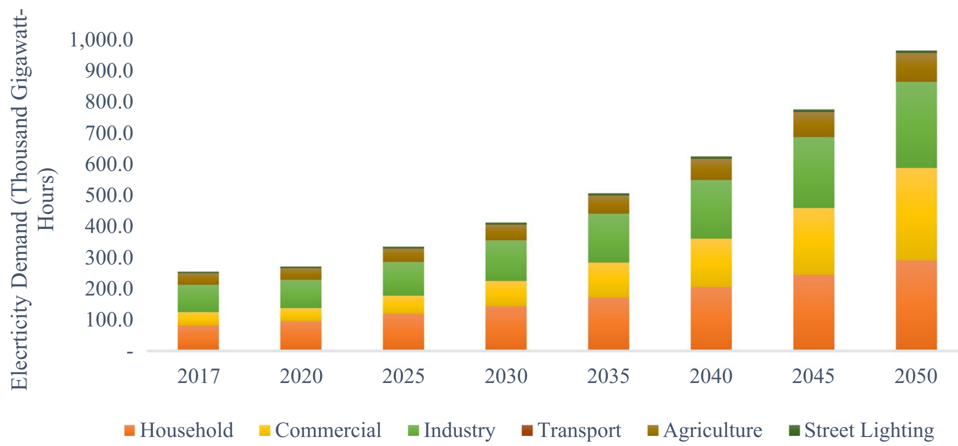


Fig.4 Estimation of electricity demand in different end use sectors of Iran in the BAU scenario by 2050

Share of renewable and clean power plants

An examination of the modeling results shows that the contribution of renewable power plants, which was 0.1% of the country's total electricity capacity in 2017, fluctuates and becomes the lowest in the reference scenario and the highest in the LPD scenario in 2050. The share of renewable power plants generally peaks in the country almost in 2035. Similar to renewable ones, clean nuclear and hydroelectric power plants with > 10 MW generations experience degressive trends after peaking around the year 2020 and reach the highest level in 2050 in the NPD and LPD scenarios, i.e., 2.7% and 2.8%, respectively. The reasons for the downtrend of these resources in generating electricity are the finiteness of clean and renewable energies (hydroelectric power plants rely on water reservoirs at drought times), on the one hand, and the increased demand for electricity and the need for exploiting thermal power plants due to generation costs, on the other hand. Also, the expansion plans of these resources, which are among the limitations of the model in computations, do not allow this share of resources to grow. The below figure depicts the realization of the scenarios regarding the contribution of clean and renewable power plants.

Environmental pollution emission

Combustion in electric thermal power plants is one of the main sources that emit greenhouse and contaminating gases, besides giving rise to other environmental consequences, such as water, soil, noise, and landscape pollution. The present study has identified other environmental impacts of electricity generation, along with the effects of GHGs emissions, in different power plants and determined and modeled the emission rate per kwh of power generation.

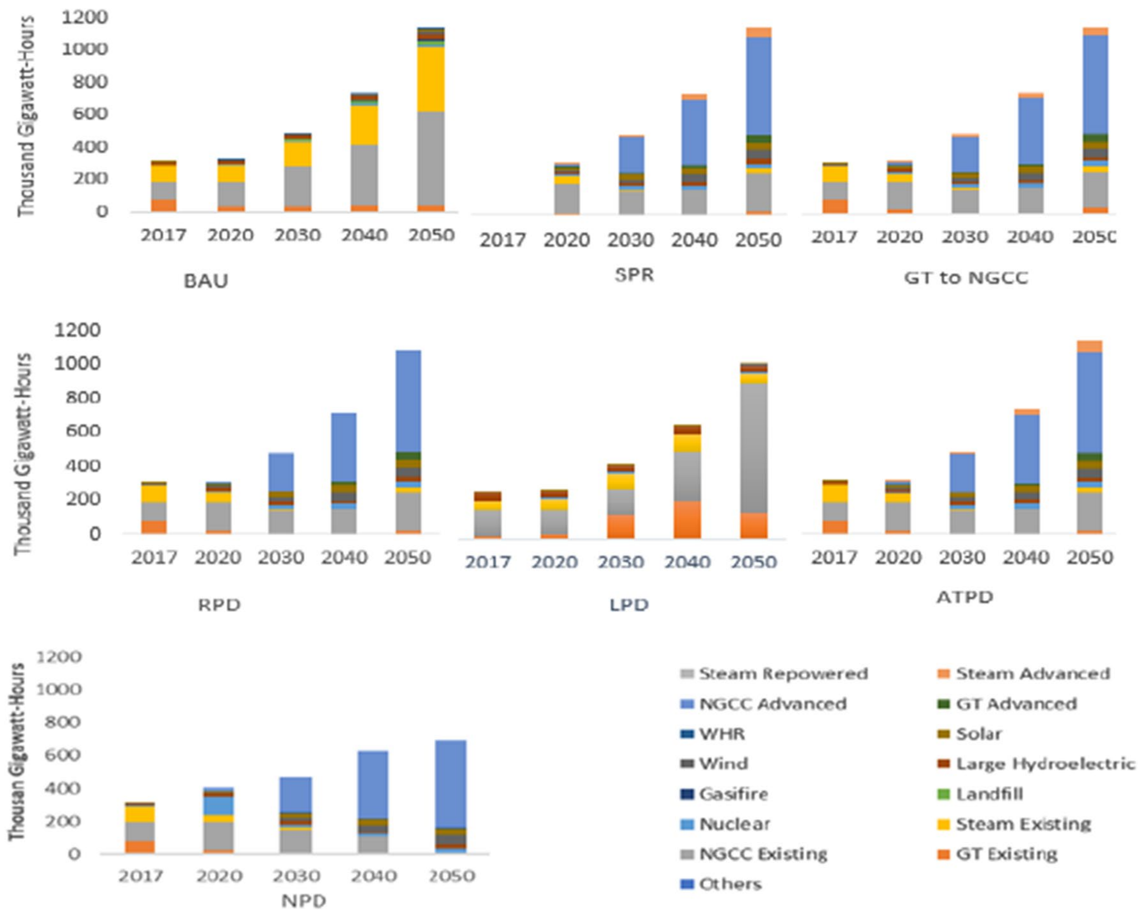


Fig. 5 Power generation in all scenarios

Decarbonization

The results of predicting the emission of greenhouse gases (CO_2, CH_4, and N_2O) resulting from fuel combustion in electric power plants reveal that the emission rate of these pollutants will increase from 163.4 $MMTCO_2E$ to 227.2 and 518.7 $MMTCO_2E$ in 2030 and 2050. The reason for this considerable growth is the increased in electricity generation of power plants to supply the demand and the moderate development of clean and renewable resources in this scenario. The maximum and minimum emission of these pollutants occurs in the BAU and SPR scenarios, respectively. All in all, the SPR scenario will experience the highest emission reduction in the 2017–2050 interval, i.e., 1347 $MMTCO_2E$ (Table 4), due to the declined demand for fossil fuels.

The main emitters of greenhouse gases in 2017 are steam power plants in all scenarios and the existing combined-cycle power plants until 2030. Then, the advanced combined-cycle power plants allocate the highest share to themselves until 2050 (Fig. 5). Considering the constraints of the research modeling, these power plants will generate more electricity due to their lower production costs and pollution compared to the other methods, and the enhanced contribution to emissions results from their higher electricity generation (Figs. 6, 7 and 8).

In addition, the results show that in the BAU scenario, Iran cannot realize the goal of reducing GHGs emissions (decarbonization) in the Kyoto Protocol in the power generation sector till 2030, i.e., 4% of the total emissions in unconditioned commitments. This is while the attainment of this goal by 2036 becomes feasible for the country in the case of changing the policies and applying the research scenarios. Of course, with regard to the rises in power generation and demand after this interim, it will be impossible to reduce emissions even by applying efficiency-improving plans in thermal power plants and developing renewable systems (Fig. 9).

Other environmental impacts reduction

Besides emitting greenhouse and polluting gases, electric power plants give rise to other environmental impacts, such as water contamination, biodiversity decline, visual effects, wastes, noise pollution, electromagnetic pollution, soil contamination, soil corrosion, air pollution, water resources deterioration, global warming, landscape pollution, ecosystem changes, etc., in the fabrication and operation stages of different power plants (Atilgan & Azapagic 2015; Chan et al. 2017; Cho & Strezov 2020; Klugmann Radziemska 2014; Kumar 2020; Saeeidi et al. 2005; Sundqvist & Soderholm 2002; Varun et al. 2009; Vezmar et al. 2014; Ziyaei et al. 2021). Since the other presented environmental impacts in power plants are not consistent, a dimensionless unit was considered per impact, for which a weight unit was assigned for their compatibility with the other pollutants.

Figures 10 and 11 illustrate the environmental impacts of different electric power plants in every scenario. The results display that the rate of emissions has increased over time, and thermal power plants have extra environmental impacts than clean and renewable systems due to the change in the electricity generation portfolio of the research scenarios and the raised contribution of these power plants to generation. Besides, the reason for the rise in the environmental impacts of all power plants is the surge in electricity generation from 2017 to 2050. Also, we will witness the lowest degree of emissions in all power plants during the 2017–2050 period in the SPR scenario. Considering the rate of generated power in all scenarios in 2017, 2030, and 2050, the maximum environmental emissions belong to the different types of biomass power plants in all scenarios. This rate is assigned to landfill power plants in the BAU scenario and MSW power plants in the other examined scenarios. Compared to the other systems, these power plants bring about numerous environmental impacts owing to producing large amounts of pollutants resulting from solid waste combustions.

Costs

The modeling results showed that the total electricity generation cost (including investment, fixed and variable operation, repair, maintenance, and environmental costs) in the BAU scenario will increase from \$21.4 billion in 2017 to \$41.3 billion in 2030 and \$104.6 billion in 2050. According to Fig. 12, the fuel cost is the most significant factor in the hike of these expenses in the base scenario in all years, and the share of other costs is below 10%. In the BAU scenario, clean and renewable power plants have lower contribution, while thermal power plants play significant roles. Hence, the high electricity generation cost in the country is due to the fuel cost in the existing combined-cycle thermal power plants. Environmental emissions and impacts increase in thermal power plants owing to the excess consumption of fossil fuels and, thus, electricity generation costs are also high.

In general, the SPR scenario has the greatest reduction in total electricity generation costs compared to the BAU scenario (Table 5).

As Fig. 13 displays, the initial investment costs and variable repair, maintenance, and operating expenses are higher in 2030 in all scenarios than in the base scenario. The reason lies in the shifts in electricity generation policies from thermal to clean and renewable generation with higher initial investment, repair, and maintenance costs. Furthermore, the maximum investment cost belongs to the GT to NGCC scenario, which is definitely not prioritized by investors in the power generation domain.

In 2050, all electricity generation costs will be higher than the research scenarios, reflecting the significance of considering these scenarios. Even the permanence of BAU for supplying power demand is economically unjustified and will bring about high costs for investors, operators, and the government. Thus, it is paramount to consider approaches to reducing costs in the electricity generation sector. As explained, SPR is the best scenario for reducing electricity generation costs from 2017 to 2050, even with higher initial investment costs.

The environmental costs of power generation in all decarbonization scenarios are lower than BAU in this research (Fig. 14). The maximum decline in 2030 and 2050 belongs to the SPR scenario. Environmental costs decrease by \$1.8 billion and \$4.0 billion in 2030 and 2050 in this scenario relative to BAU. This scenario brings higher initial investment but less fuel and environmental costs than the other research scenarios. The reason for a drop in environmental costs in this scenario is the reduced demand for fossil fuels, on the one hand, and the non-emergence of other environmental impacts due to the construction of new power plants, e.g., land occupancy and other fabrication and operation consequences, on the other hand.

Table 4 Role of research scenarios in decreasing carbon emissions compared to the BAU scenario (MMTDCO_2E)

Scenarios	GHGs emissions			
2030	2050	2050	2030	
–	–	518.7	227.2	BAU
−71.3	−120.7	398.0	155.9	RPD
−67.8	−117.8	400.9	159.4	NPD
−68.9	−124.0	394.7	158.3	LPD
−72.3	−149.5	369.2	154.9	SPR
−66.2	−116.8	401.9	161.0	ATPD
−67.4	−115.1	403.6	159.8	GT to NGCC

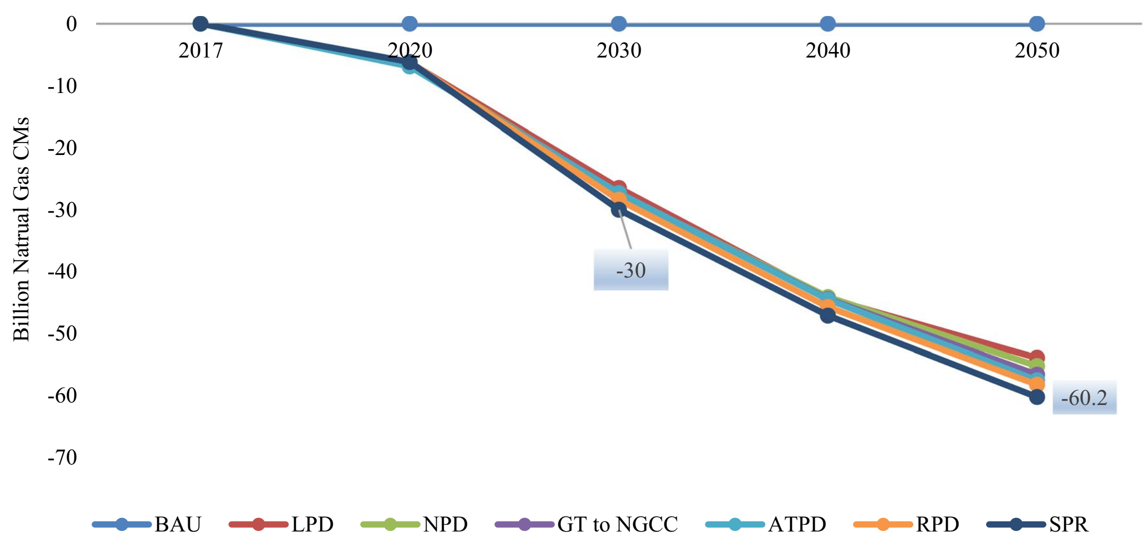


Fig. 6 Trend of fuel consumption by fuel type in the alternative scenario

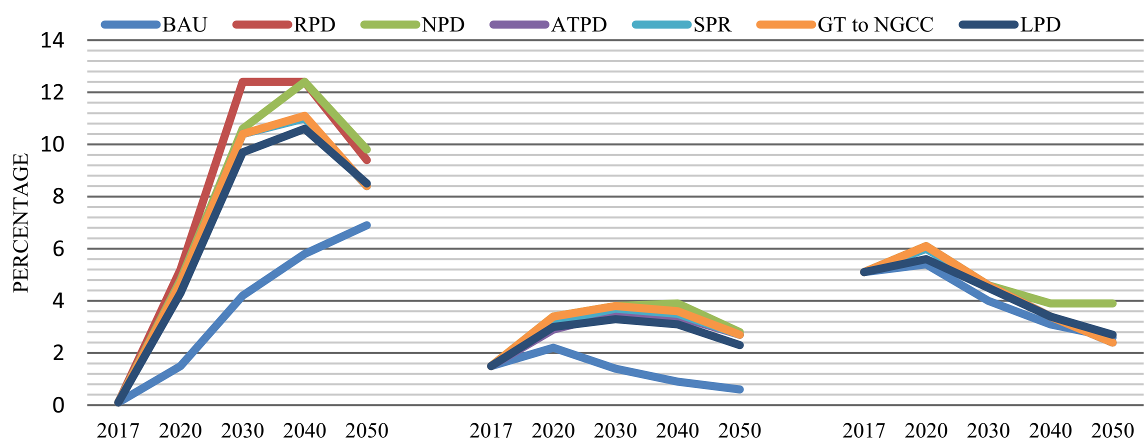


Fig. 7 The trend of changing the share of renewable and clean power plants in electricity production in each scenario

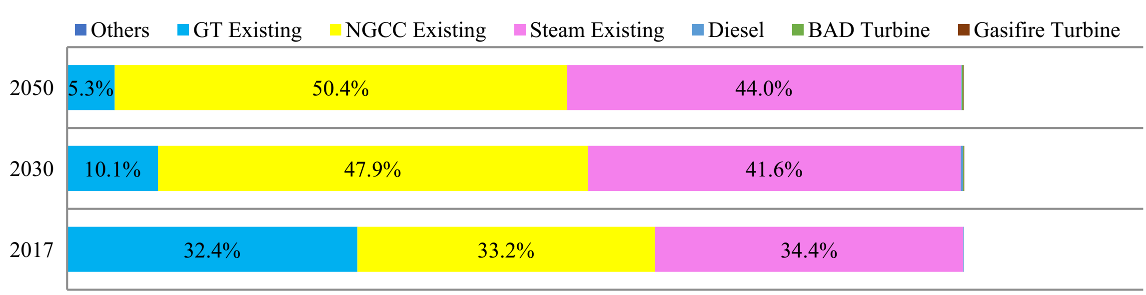


Fig. 8 Contribution of electricity-generating power plants to the emission of greenhouse gases

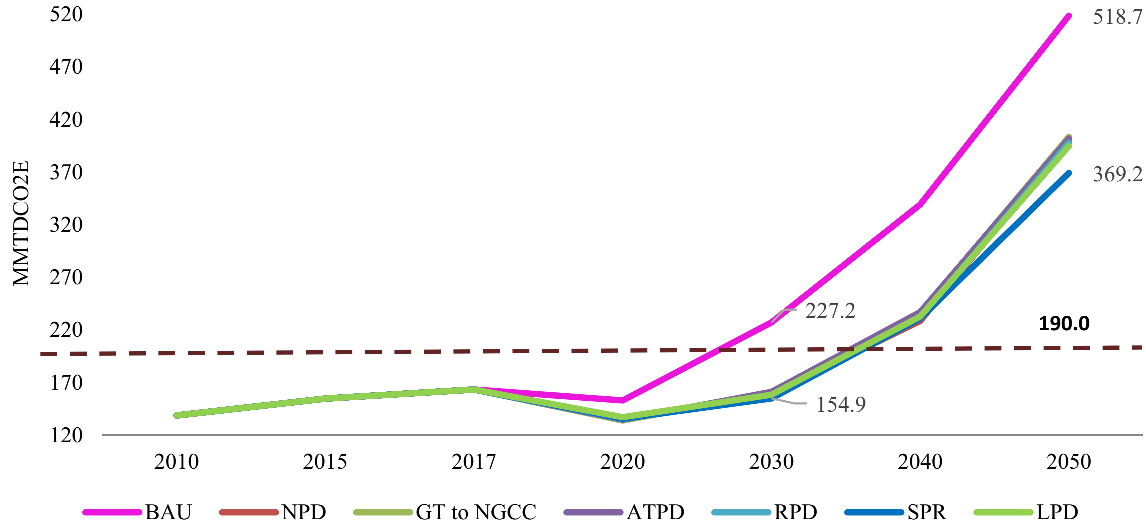


Fig. 9 Trend of GHGs emission in the BAU and research scenarios

Discussion

The present research defined decarbonization plans for reducing GHG emissions and pollutants in the strategic climate change document as decarbonization scenarios in the electricity generation sector and examined them technically, economically, and environmentally besides predicting the BAU scenario. For the first time in Iran, the authors estimated the environmental impacts of different power generation methods along with the emission of GHGs and pollutants and modeled them in equations. In the following, the results are discussed and compared with the findings of other studies.

Our results showed the impossibility of supplying the electricity demand of the country in the BAU scenario technically and economically until 2050, and electricity generation and fuel supply costs for power plants exceeded the technical and economic capacity of the country. Similar results are observed in studies carried out by (Aien and Mahdavi 2020; Dehghan et al. 2021; Kachoee et al. 2018; Kazemi et al. 2020; Rostami et al. 2018; Shafiei and Saboori Deilami 2011). Rostami et al. (2018) estimated the

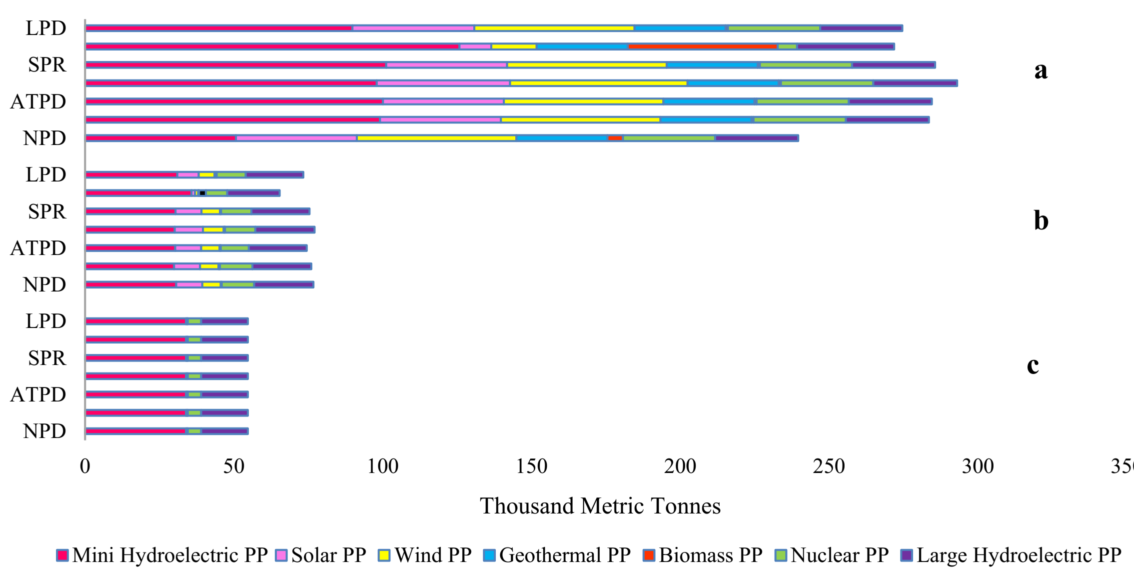


Fig. 10 Environmental effects in renewable powerplants in all research scenarios from 2017 to 2050, 2017 (**a**), 2030 (**b**), 2050 (**c**)

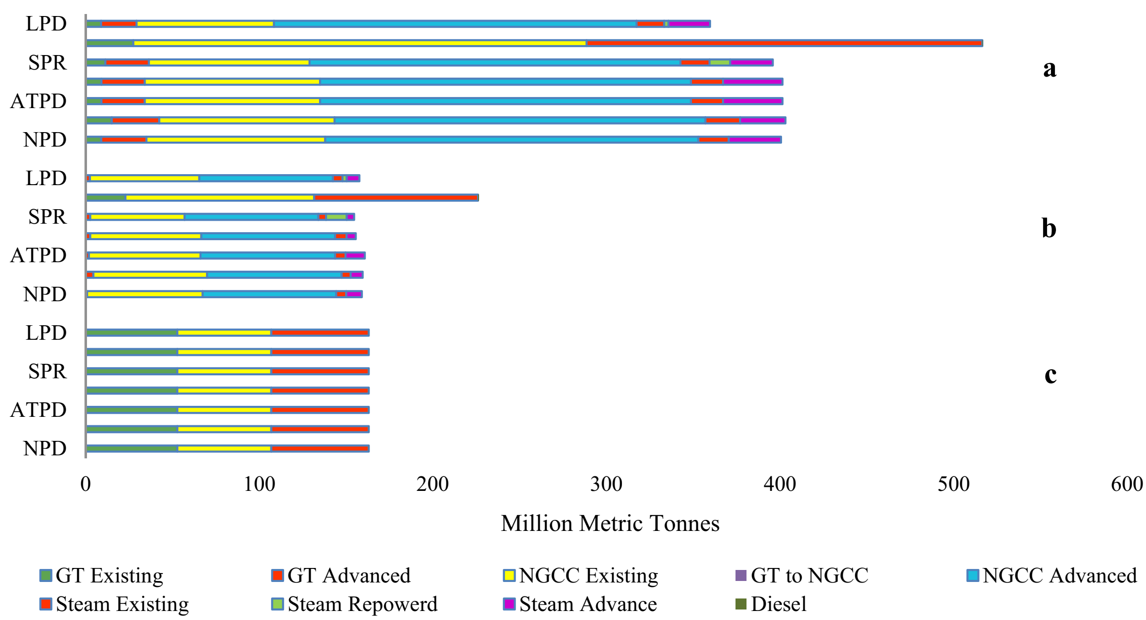
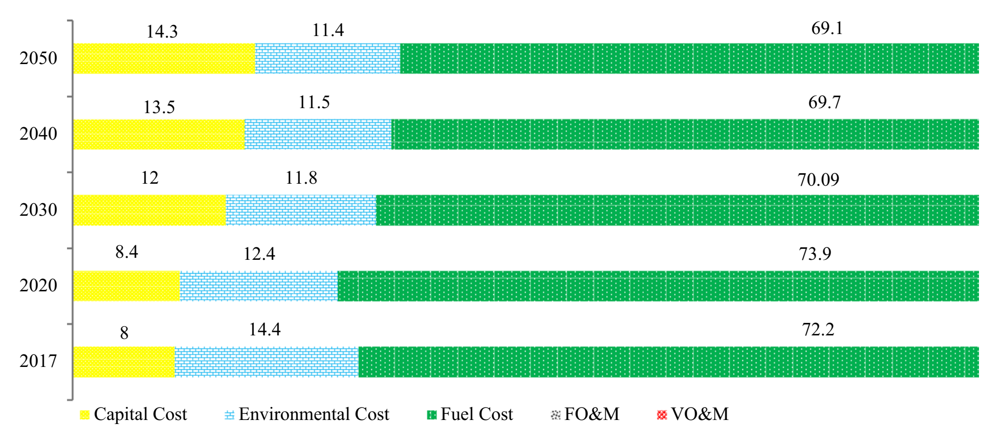


Fig. 11 Environmental effects in thermal powerplants in all research scenarios from 2017 to 2050, 2017 (**a**), 2030 (**b**), 2050 (**c**)

growth in electricity demand until 2050 at 43%. The maximum share belonged to the household sector, which has no positive impact on economic development and is only a consumer. Hence, it is suggested that proper approaches be adopted for the management of this issue. The results of this research are in line with the findings of the study by Pourshad et al. (2021). The approaches presented by this research and many other studies to managing electricity demand are divided into two supply-side and demand-side management categories. Golmohamadi. (2022); Ko et al. (2020); Masoomi et al. (2022); Milovanoff et al. (2018); Pourshad et al. (2021); and Warren. (2014) addressed approaches to the demand-side management of electricity for reducing consumption. Aryanpur et al. (2019), and Sadeghi and Larimian. (2018) referred to the supply-side management approaches and compared various thermal, clean, and renewable power generation methods. Several studies (Emodi et al. 2017; Rasaq 2019; Sabeti et al. 2022; Souhankar et al. 2022) introduced and modeled supply and demand-side management approaches simultaneously. Sabeti et al. (2022) showed that implementing supply and demand-side management policies could enhance the capacity of Iranian electric power plants, reduce respective costs by $5 billion, and decrease GHG emissions by 25%. The approaches to managing electricity demand and supply in this study were increasing the electricity price, repowering steam power plants, developing DG power plants, constructing new thermal and high-efficient power plants, developing CCS systems, converting gas power plants to combined-cycle systems, and energy efficiency

Fig. 12 Trend of powerplants costs in the BAU scenario (%)



portfolio in the electricity consumption sector. Besides, Souhankar et al. (2022) displayed that managing energy on the supply side, enhancing the efficiency of electricity transfer and distribution networks, and promoting equipment standards in all electricity generation, conversion, and transfer sectors simultaneously were the most crucial policies for reducing electricity demand. These results are in line with the findings of the present research but are not comparable since the demand-side approaches have not been modeled in this study. The outcomes also revealed the possibility of managing the supply side in Iranian power plants for the purpose of supplying electricity demand and helping consumption management. Being executable technically, economically, and environmentally, the decarbonization scenarios in this research can reduce power generation costs, the environmental impacts of different power generation methods, and fuel consumption and pave the way for achieving international commitments to decreasing GHG emissions and developing clean and renewable energies according to upstream documents.

In the present research, the SPR scenario, an efficiency-improving approach in steam thermal power plant, was introduced as the most suitable scenario. SPR maximally reduces GHG emissions compared to the other scenarios and is the most significant decarbonization method in the power industry of Iran. Moreover, the sum of environmental impacts and emissions in this scenario is also smaller. Similar results were also observed in many other studies. For a sustainable electricity supply, Ouedraogo (2017) used the LEAP software and modeled the demand and supply-side

Table 5 Electricity costs reduction in all scenarios compared to BAU scenario

Year/scenario	BAU	NPD	ATPD	RPD	SPR	GT to NGCC	LPD
2030	–	– 10.3	– 10.4	– 10.9	– 11.2	– 10.4	– 10.5
2050	–	– 32.6	– 32.5	– 32.5	– 32.9	– 32.4	– 32.3

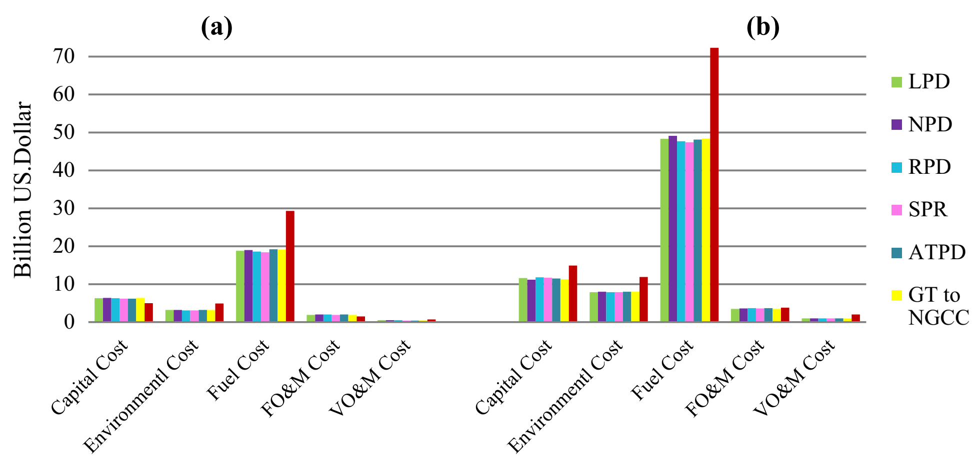


Fig. 13 Total electricity production cost in research scenarios in 2030 (**a**) and 2050 (**b**)

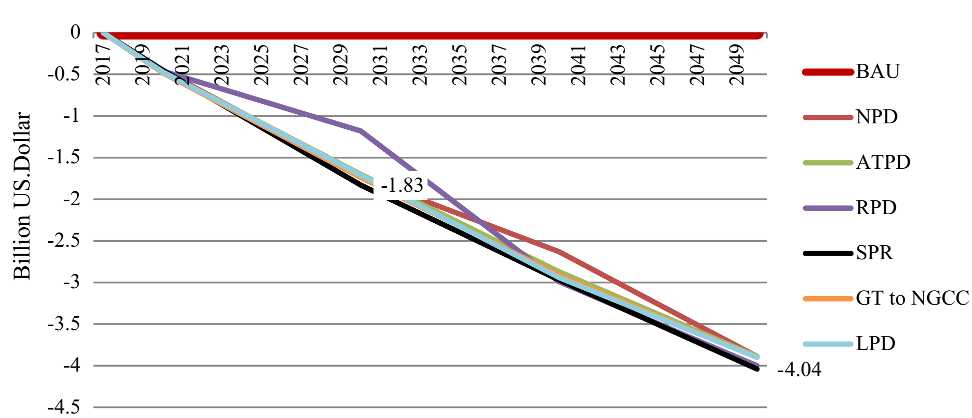


Fig. 14 Trend of environmental costs reduction in the research scenarios compared to BAU

management of electricity under three business-as-usual, renewable energy development, and electric energy efficiency scenarios in Africa. The results showed that the renewable energy development scenario was unsuitable for sustainable power supply, while the energy efficiency scenario was the most appropriate scenario since developing renewable energies faced many uncertainties. Bayomi and Fernandez. (2019) also found that sustainable power generation and development depended on actions tied to energy productivity and efficiency improvement. Applying the MESSAGE software, Ghadaksaz and Saboohi. (2020) discovered that a 46% improvement in the efficiency of thermal power plants by 2030 could reduce GHGs emissions by 12% and could be the most optimal alternative compared to the other demand–supply scenarios. With respect to the modeling results for the 2016–2030 horizon, the most promising choices are energy-efficiency improvement activities, such as repowering the existing gas turbine power plants, flaring gases and reducing leaks, and decreasing power transfer and distribution losses. Among other studies with similar results, we can refer to those conducted by Masoomi et al. (2020); IRENA. (2019); Ziyaei et al. (2023a); Cormos and Dinca. (2021), and Xu et al. (2014). However, our findings are not aligned with the research outcomes of Hardisty et al. (2012), arguing that the approach to efficiency improvement in electric power plants can have a significant contribution only in the short run. Another survey also displayed that efficiency improvement and energy productivity actions would be economic and optimal and present considerable results just by 2030 (Sabeti et al. 2022).

In this research, all scenarios and the privileged scenario revealed that thermal power plants contributed to 86% of power generation, and the role of the existing and advanced combined-cycle power plants was bolder. Hence, combined-cycle power plants are the most economical suppliers of electricity in all examined years. This result corresponds with the findings of Karbassi et al. (2007)'s study in Iran. The reason lies in the abundant resources of fossil energies, on the one hand, and the provision of subsidy fuels to the country's power plants, on the other hand. This study showed that improving energy efficiency in thermal power plants, e.g., generating power with combined-cycle systems, was the most economical power generation alternative. Another study, besides predicting electricity demand by 2040, examined likely alternatives for supplying power and developing a sustainable power generation system. The results displayed that hydroelectric and combined-cycle power plants would generate electricity in the next years, and combined-cycle thermal power plants would be the main supplier of power due to climate changes. This would reduce environmental emissions, fuel consumption, and generation costs besides conserving the environment (Rivera-Gonzalez et al., 2019). Developing new and high-efficient combined-cycle power plants was the most significant approach to obtaining sustainable power generation in Ghadaksaz and Saboohi. (2020)'s study. On the contrary, Kachoee et al. (2018) showed that developing clean and renewable power plants was the most important factor in generating sustainable electricity, reducing GHG emissions, and decarbonization in the power industry, although fossil fuels were the chief elements in power generation (90%). Also, Rajaeifar et al. (2017) introduced developing biomass power plants as the most significant method for carbon-free generation of sustainable electricity in this sector. This result conflicted with our findings. Of course, this research also revealed that the RPD scenario, after SPR, would accompany maximum reductions in GHG emissions, fossil fuel consumption, and total power generation costs. Therefore, if we can invest in improving the efficiency of thermal power plants, the assumptions of the RPD scenario will enable us to reach similar results but not as strong as the outcomes of the SPR scenario.

The findings also show that power generation sustainability depends on a set of economic, technical, and environmental parameters, and only modelling power generation development with the objective functions of minimizing costs or emissions was not effective. Hence, to decide on and implement power generation approaches, we need a set of factors that the present study attempted to consider. These results are in line with the findings of the study by Ramirez et al. (2020), who showed that targeting to reduce GHGs emissions and adopting respective approaches could potentially diminish the undesirable consequences of power generation but failed to create sustainability in power generation by itself. However, with contradictory results, Papadis and Tsatsaronis. (2020) found that sustainability resulted from reducing GHG emissions. Tri Vika Kusumadewi et al. (2017a, b) discovered that reducing power generation costs could not render sustainability and an optimal method for power generation development by itself, and technical and economic modeling was necessary. These results correspond with the findings of our research as well. Thus, decarbonization in the power sector is a complex topic and a function of technical, economic, environmental, and even political parameters that should be considered concurrently.

However, from an environmental economy perspective, our results showed that environmental costs resulting from damages to the environment impact the selection of scenarios. The modelling results displayed that the environmental costs of the Renewable Power Plant Development (RPD) scenario in 2030 and the Steam Power Plant Repowering (SPR) scenario in 2050 were the lowest compared to the other scenarios. This finding also aligns with the outcomes of the available international studies by Akella et al. (2009); Kåberger (2018); Khan et al. (2014); Maradin (2021), and Owen (2006), who introduced the estimation of these costs in thermal power plants as an approach to achieving clean and renewable power plants. More probably, the reasons for the scenario change lie in reducing environmental costs, developing renewable power plants until 2030 and then making them fewer by 2050, and expanding advanced combined-cycle power plants to supply electricity demand due to the technical, economic, and environmental limitations of renewable power plants. The findings also displayed that environmental costs were trivial but not negligible in renewable power plants since they amounted to a high value, i.e., $4982 million in the BAU scenario. Our estimations revealed that although thermal systems allocated the maximum GHGs emissions to themselves, different power generation methods could extensively impact the environmental costs of other power plants, such as noise and landscape pollution, soil corrosion, detriments to biodiversity, etc. This result was also obtained by Alizadeh and Avami. (2021); Caspary. (2009); Galetovic and Muñoz. (2013); Mahlangu and Thopil. (2018); Mousavi et al. (2012); Nabi Bid Hendi et al. (2021); Mustafa kama et al. (2022); Pojadas and Abundo. (2022) and Sebestyén. (2021). Hence, we conclude that Iran's condition is not suitable in terms of environmental and GHG emissions, and changes in power generation methods can reduce these costs by $96,035 million by 2050 in relation to the BAU scenario. This results was also obtained by Ziyaei et al (2023a). A review of the domestic literature illuminated that the present studies did not consider these costs or estimate all environmental impacts and thus faced modeling failure or result deviation. Ignoring these costs, on the one hand, and lacking respective computational knowledge due to its intricate approaches, on the other hand, were among the reasons.

Furthermore, the results showed that against these costs, the initial investment expenses for power generation development in 2030 in Iran were the highest in the GT to NGCC scenario and lowest in the BAU scenario. This is while the growth in electricity demand in 2050 will necessitate gross investments in the BAU scenario for power supply, and this scenario will impose the highest investment cost due to the high expenses of decarbonization approaches in the short run. On the whole, SPR, compared to BAU, had lower social costs that could also decrease by supportive methods, e.g., financial aids in the form of feed-in-tariffs, bids/tenders, etc.

Conclusion

The present study investigated electricity demand for sustainable power supply, generation, development, and planning. In this respect, decarbonization scenarios were designed, modelled, and compared in real terms according to technical, political, economic, and social capacities and upstream documents. With respect to the results of the BAU scenario, electricity demand will reach 965,000 GWh by 2050. This rate requires a $229 billion investment during the 2017–2050 period and gives rise to 9,692 MMTDCO2E GHGs emissions and 10,688MMT of other environmental emissions. Supplying this rate of demand, reducing emissions, and investing in this respect surpass the country's technical and economic capacities and imply severe dependence on power generation by low-cost and abundant fossil fuels. However, by applying optimal decarbonization policies to electricity generation and employing a mix of generation methods, we will achieve significant advantages besides supplying electricity demand, e.g., reducing environmental emissions and greenhouse and polluting gases, conserving the consumption of fossil fuels, decreasing initial investment costs and repair, operation, and maintenance expenses, not needing electricity imports, being able to export power, enhancing energy security, raising the contribution of clean and renewable energies to power generation, not depending on fossil fuels, improving the efficiency of thermal power plants, enhancing and renovating the existing systems, increasing the lifetime of the existing power plants, generating sustainable electricity, etc.

According to the results, although SPR, i.e., energy efficiency improvement in thermal power plants, was introduced as the most optimal scenario, embraced all the benefits above, and could reduce carbon emissions according to international commitments, it also considered the development of renewable, nuclear, hydroelectric, and high-efficient thermal power plants simultaneously. In this scenario, nuclear, large hydroelectric, and renewable power plants have developed by 2.7%, -1.7%, and 8.4% compared to the base year, and the contribution of the existing thermal power plants has decreased by 9.4%. Hence, achieving the decarbonization vision in the power generation of Iran according to international commitments depends on simultaneously implementing emission-reduction policies and considering all decarbonization strategies in this industry. This scenario decreases environmental costs, impacts the economy to a large extent, regards efficiency in thermal power plants, stabilizes renewable energies and their shares in the energy portfolio, and moves toward producing fossil energies and sustainable fuels by informing about the merits of renewable energies. However, renewable energies experience slight developments. Thus, until its selection as an optimal technology, we suggest moving toward renewable energies through the financial policies of the government, attracting the attention of governmental and private investors to their advantages, e.g., reducing environmental emissions and external environmental costs, and eliminating subsidies paid for fossil fuels delivered to thermal power plants to witness gross transformations in this industry.

Among the limitations of the study, we can refer to those derived from modelling since issues associated with policies that aim to reduce emissions and improve power generation methods call for a macro-level and multilateral analysis and investigation due to the extensive complexities and interrelationships of the technical components of the energy system with the entire political and economic parameters of the country. One of the factors neglected in the modeling is related to the demand-side management approaches of electricity, which can enormously impact the rating and selection of scenarios. Moreover, the outcomes should be considered cautiously since, as its innate weakness, the two-objective optimal model in this research chooses the outcomes of the most optimal generation technology based on production and carbon-reduction costs when all modeling constraints are met.

Besides, the modeling accompanied many uncertainties due to not including sudden and unexpected changes in the price or type of consumed fuel or variations in available resources and country policies. This may lead to differences between the real condition and model results. Yet, this study proved the necessity for improving energy productivity and efficiency in thermal power plants and developing clean and renewable systems. To this end, policymakers need to perceive concepts, identify barriers, embark on changing the current power generation policies, and plan for the future. However, the knowledge in this area is finite, and the costs of these changes are high. Thus, the proposed model can act as a planning tool for making decisions on improving the infrastructures of sustainable and new power generation systems.

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Author contributions The manuscript has five contributions including, Sadaf Ziyaei: Conceptualization, Data curation, Investigation, Methodology, Software, Formal analysis, Writing – original draft, Visualization. Mostafa Panahi: Supervision, Investigation, Formal analysis, Writing – review & editing, Validation. Davood Manzoor: Formal analysis, Writing – review & editing, Validation. Abdolreza Karbasi: Writing – review & editing. Hamidreza Ghaffarzadeh: Writing – review & editing.

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

Declarations

Conflict of interest All authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript. The authors declare they have no financial interests.

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