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Sustainable power generation through decarbonization in the power generation industry

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Abstract Due to using fossil energy resources, power generation is the most important factor of pollution and greenhouse gas emissions. Considering the importance of the issue, seven scenarios for decreasing greenhouse gas emissions in the power industry, including the development of renewable energies, energy efficiency in thermal power plants, and decreasing the emission of carbon according to international agreements, and the creation of sustainable power generation systems, were defined and evaluated technically, economically, and environmentally. In the current study, an optimization model for long-term power generation planning was used for two concepts of supply and demand. The results of comparing the scenarios showed that the development of renewable power plants was not solely a suitable and optimal way for decreasing greenhouse gas and carbon emissions. The strategies for improving efficiency in thermal power plants, including the development of combined cycle power plants and the repowering of steam power plants, are more suitable options for implementation, considering the constraints of the problem. Therefore, eliminating the existing circumstances and employing the combined scenario while considering the objectives of the study should be the only strategy for decarbonization in this industry, with the minimum cost and minimum rate of emission. By decreasing the share of thermal power plants, decreasing fuel demand, and increasing the share of renewable power plants to 20%, the combined scenario would decrease pollution and greenhouse gas emissions by up to 77.6 million tons of carbon dioxide, as well as the environmental costs up to 1894.5 million dollars, compared to the basic scenario up to 2030. Moreover, paying attention to the management strategies of a demand concept seems necessary from an economic viewpoint, in addition to other presented strategies.

Keywords Polluting and greenhouse gases · Sustainable power generation · Long-term power generation planning · Optimization

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Introduction

Due to such reasons as rapid population growth, the increase in the reliance on fossil fuels, and the excessive use of natural resources, different kinds of environmental pollution are emitted globally, which have extreme detrimental effects (Ediger et al., 2007; Fakher et al., 2021a, b; Rosen, 2009a, b). Meanwhile, the use of fossil fuels in the world is today deemed as one of the more important factors of global pollution and associated detrimental environmental effects (Barbir et al., 1990; Daragi & Bahrami Gholami, 2012; Masoomi et al., 2020; Rezafar & Aref, 2014). The most important environmental effect resulting from burning of fossil fuels is climate change (Anderson et al., 2016; EIA, 2020; Hansen et al., 2000; Ripple et al., 2020; Levin, 2013; McNutt & Ramakrishnan, 2020; Naeeni & Barari, 2020; Pandey et al., 2011; Teimouri et al., 2014; *Cause of global warming,* 2018). Climate change is a major threat to humankind and the earth's ecosystems (Goklany, 2012; Martins et al., 2019; UnitedNation, 2021). Climate change might cause global instability, starvation, poverty, war, food shortage, the spread of contagious diseases, tensions in the use of natural resources, and an increase in natural disasters (Mahmoudi et al., 2020; Shiravand & Hashemi, 2016). Considering low compatibility and flexibility, the effects of climate change are constantly imposing significant costs on the global economy, particularly in less developed countries (Claussen & Peace, 2007; Stern & Stern, 2007), all of which are a disturbing load on the economy and communities worldwide (Shiravand & Hashemi, 2016).

Around two-thirds of the greenhouse gas (GHG) emissions, which result in climate change in the world, are related to the energy supply sector (Climate change, 2020; Flavio et al., 2020). In addition to the GHG emissions, power generation and energy supply pose other environmental effects, such as water, soil, air, and noise pollution (Ambec & Crampes, 2019; Kumar et al., 2013). These effects occur due to the dispersion of salts, particulate matter, heavy metals, fat, grease, fuels, organic and pathogenic materials, nitrogen oxides, sulfur, carbon, sludge containing heavy metals, calcareous materials, iron, and aluminum, metal oxides (Gerlitzky et al., 1986; Munawer, 2018; Saeeidi et al., 2005). All of such cases might cause serious damage to the environment, economy, humans, and so on because of burning fossil fuels in power generation plants to supply energy and electricity (Aboumahboub et al., 2020; EIA, 2020; *Sources of greenhouse gas emissions*, 2020; IEA, 2019; Kargari & Mastouri, 2010; Kargari & Mastouri, 2011).

Power generation accounts for around one-fourth (25%) and 36% of the total CO_2 emissions in the world in 2017 and 2021 respectively (EPA, 2022). In 2017, the amount of CO_2 emissions resulting from burning fossil fuels was around 32.8 billion tons. The highest amount of CO_2 emissions in the world belonged to China, the USA, India, Russia, Japan, Korea, and Iran in 2017 and to China, the USA, India, Russia, Japan, Germany, and Iran in 2021 (Greenhouse gas emission by country, 2022).

By emitting around 576.1 million tons of CO_2 in 2017, Iran secured the eighth rank in the world. From 1990 to 2016, CO_2 emissions have grown by 5%, and Iran reached the seventh rank in the world in 2021. The reason is the burning of fossil fuels, natural gas, and oil in Iran because it is one of the countries with great fossil energy resources in the world (second and fourth ranks in terms of gas and oil resources, respectively) (Ardestani et al., 2017; EIA, 2015). Accordingly, around 92% of power generation in Iran occurs in thermal power plants using fossil fuels. The shares of hydroelectric and nuclear/renewable power plants are only 5% and 2.7%, respectively (Tavanir, 2017). Moreover, thermal power plants in Iran are the greatest source of CO_2 emissions compared to other existing sources and contribute to around 31% of the total emission of such a pollutant in Iran (Ministery of energy, 2017).

Therefore, the power generation sector, not only in Iran but also in the whole world, is currently facing two challenges, i.e., supplying the increasing demand for electrical energy and decreasing the emission of pollutants and greenhouse gases (especially CO_2) (Gencer et al., 2020; Williams et al., 2012). The problems arising from such issues have made governments, companies, investors, and people think about the necessity of sustainable power generation in the world to decrease the environmental effects of such emissions. For this purpose, many policies and plans have been formulated and executed in different governments due to the power demand in the following years. Various countries have formulated and executed different legal policies and measures, according to their conditions and concerns (Chang & Carballo, 2011). Some of such plans are the plan of decreasing carbon in this industry, increasing power generation using renewable energies, increasing the efficiency of thermal power plants, increasing the energy efficiency, using systems and technologies of decreasing carbon and pollutants, setting tax levies, setting standards on emissions, etc. (Ambec & Crampes, 2019; Aryanpur et al., 2019; Bank, 2018; CCC, 2010; Eurelectric, 2018; Haller et al., 2012; Hainsch et al., 2021; IPCC, 2019; Kusumadewi et al., 2017; Marion et al., 2001; Nebernegg et al., 2019; OECD, 2003; Ozer et al., 2013; Sepulveda et al., 2018;

UNEP, 2016; Van de Graaf & Colgan, 2016; Wang et al., 2020). According to the mentioned references, the best ways to reach an economy with low polluting emissions, particularly carbon, are the immediate use of renewable energies and doubling energy efficiency. The results have shown that using renewable energies along with the improvement of energy efficiency bears the minimum cost to decrease emissions by up to 90% in the energy sector (Flavio et al., 2020; IPCC, 2019; IRENA, 2018). As a result, using renewable energies and energy efficiency are among the popular methods employed by countries to reach their energy-related and environmental objectives and to decarburize and decrease the environmental effects of power generation and energy consumption in the future (Simsek et al., 2019). Therefore, one of the ways to reach sustainable development is to promote the energy sector in countries (Climate change, 2020).

In the current study, the scenarios of decarbonization are defined and evaluated technically and economically according to the global literature (as follows) on the 2030-time horizon. The meaning of decarbonization is to reduce CO_2 emission in the atmosphere according to global literature (Sun, 2005; Widerberg & Stripple, 2016; Nakićenović, 1996; Cheema-Fox et al., 2021; Steinberg, 1999; Papadis & Tsatsaronis, 2020; Loftus et al., 2015; Meckling et al., 2017). The scenarios of decarbonization in global literature include the business as usual (Haller et al., 2012; Sani et al., 2021), the development of renewable power plants (Haller et al., 2012; Tigas et al., 2015; Jägemann, 2014; Sani et al., 2021), changing types of electricity generation technologies (Jägemann, 2014; Zyśk et al., 2020), developing nuclear power plants (Abdulla et al., 2019; Loftus et al., 2015), increasing efficiency and energy efficiency (Förster et al., 2013), replacing fossil fuels with biofuels (Plazas-Niño et al., 2022; Ramirez et al., 2020), and increasing the efficiency turbines in thermal power plants (Ramirez et al., 2020). These scenarios are considered in this study.

Therefore, the present study seeks to find answers to the following questions: (i) What are the plans for decreasing pollution and GHGs emissions in the sustainable power generation sector, based on the existing rules, regulations, and literature? (ii) What is the benefit of executing each of such plans for decreasing the emissions and the environmental costs resulting from their effects at national and global levels? (iii) Which one of the plans of sustainable power generation, considering minimum costs (investment, repair, maintenance, and operating and environmental costs), will help us achieve the goal of decreasing global emissions?

It is important to discuss this issue because a suitable vision for developing a sustainable power generation system while increasing the share of renewable energies and the energy efficiency in thermal power plants in Iran should be presented within different scenarios. Moreover, an appropriate relationship should be established between energy planning and policymaking. The investors in this sector and the government can also employ the long-term model for energy options in the current study to gain a better understanding of the selection of the sustainable power generation method, in technical, economic, and environmental terms by employing the cost-effectiveness approach.

The structure of the present study is as follows: "Literature review" section which reviews the existing literature. "Methodology" section explains the data, research methods, and the employed models. "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 limitations. Finally, the "Conclusion" section explains the results of the scenarios, policies of the study, and recommendations for future studies.

Literature review

Many studies have investigated the reduction of GHG emissions in power generation systems, within different scenarios and methods; however, few studies have focused on sustainable power generation through decarbonization in this industry with cost limitations, etc. The results of some relevant studies are presented in the following.

Seo-Hoon et al. (2020) conducted a study using the LEAP model and three scenarios, namely, developing renewable energies, energy saving in buildings, and optimal policies in construction, to analyze and predict the amount of GHG emissions from 2015 to 2030. The results showed that the scenarios of developing renewable energies and energy saving in buildings caused 24.5 and 12.8% reductions in GHG emissions, respectively, compared to the basic scenario. In a study by Ramirez et al. (2020), the environmental function of the existing methods of power generation and supply in Ecuador was investigated by the lifecycle method. The results indicated that the environmental effects of power generation led to climate change and the development of hydroelectricity power plants would significantly decrease environmental emissions compared to other methods. However, power generation by hydroelectric power plants is extremely under the direct influence of climate change and is facing threats. Therefore, decarbonization, as a goal in power generation, does not play an absolute role in achieving sustainability, and other factors should also be taken into consideration. Moreover, the results of a study by Gerbaulet et al. (2019) indicated that in the absence of decarbonization limitations in power generation, fossil power plants with natural gas fuel would be the priority for power generation by 2030. The best approach to decrease them is to use renewable energies and carbon capture and storage in power plants. In a study by Shen et al. (2018), it was suggested to convert a thermal power generation system to a renewable one while considering the costs of carbon emissions. In a survey conducted by the European Union, the policies of sustainable power generation included three elements, decreasing emissions, developing renewable energies, and energy efficiency. The results showed that the three elements were intertwined and each of them should be considered a priority in the policies of sustainable power generation (Gao et al., 2018). A study was conducted in 2017 using the TIMES integrated optimal planning model to investigate the gradual decrease of carbon emissions in Canada by 2050. The study aimed at a 60% decrease in emissions with minimum costs. Therefore, the accessible scenarios were defined, and the results showed that decarbonization in power generation in thermal power plants, improvement of their efficiency, and saving the final energy should occur simultaneously. Besides, the key factor in decreasing carbon is energy efficiency and using renewable energies (Vaillancourt et al., 2017). Kusmadewi et al. (2017) used the LEAP model to investigate the reduction of CO_2 emissions by developing the renewable energies and advanced technologies for carbon capture and storage in the power generation system, and developing renewables was presented as the main strategy. Cheng and Wang (2014) investigated the scenarios of decreasing CO_2 emissions, and the results showed that energy efficiency and modifying the structure of power generation would result in 34.5 and 21.7% decreases in the total amount of emissions, respectively.

A study by Ambec and Crampes (2019) showed that decarbonization in power generation was not merely possible by developing renewable power plants, and to efficiently execute such a process, there should be carbon tax and feed-in tariffs to reduce power generation costs to be able to pay attention to the development of renewables as a policy. Hirth and Steckel (2016) investigated low-carbon power generation in three ways of renewable energies, nuclear energy, and carbon capture and storage compared to the conventical fossil-related methods. It was found that each of the three methods had high investment costs; the cost of the emission of each ton of global carbon had to decrease at least by 50% to develop such methods. Moreover, a study by Mileva et al. (2016) suggested that power supply is not merely possible through the development of renewable energies and it is necessary to use different technologies in combination to achieve appropriate decarbonization in power generation.

According to the mentioned references and such references as Flavio et al. (2020), Florini and Sovacool (2009; 2011), Gielen et al. (2019), and Luomi (2020) and Saderink (2020), the best ways to achieve an economy with low emissions of pollutants, particularly carbon, are the immediate use of renewable energies in power generation and increasing energy efficiency in all sectors of power generation, distribution, and consumption. The use of renewable energies along with the improvement of energy efficiency should result bring in minimum costs to achieve decreasing the energy sector emissions by 90% (Flavio et al., 2020; IPCC, 2019; IRENA, 2018; Papadis & Tsatsaronis, 2020).

As a result, using renewable energies and energy efficiency are among the popular methods employed by countries to reach their energy-related and environmental objectives and to decarburize and decrease the environmental effects of power generation and consumption in the future (Mileva et al., 2016; Simsek et al., 2019). To achieve sustainable development, the energy sector should be promoted by the same methods in different countries (Climate change, 2020). However, in some other studies, such as Mileva et al. (2016) and Hirth and Steckel (2016), the results of studies show that the policies for developing renewable power plants and energy efficiency do not have the required efficacy and decarbonization limitation alone does not contribute to the development of such policies. Therefore, it seems necessary to consider other limitations, such as cost limitations (generation and investment, repair, maintenance and operating, and environmental costs) and generation limitations (the potential of using new sources), as well as network reliability and other existing policies, such as accurate pricing of carbon, setting carbon taxes, and supportive policies through feed-in tariffs.

A review of the existing literature reveals that there is no comprehensive study taking into account all limitations and policies. The current study, therefore, presents and introduces the most suitable methods of power generation development by defining suitable and important scenarios of decarbonization in the power sector, by using a perfect combination of power generation methods by considering a complete set of technical, economic, and environmental limitations.

Methodology

The research model

The aim of planning for sustainable power generation is to identify the best policies that achieve all energy-related objectives. These objectives include the optimal development of power generation, decreasing greenhouse gas emissions, the development of available sources, and increasing efficiency through decreasing the consumption of fossil fuels with the minimum costs in the power generation system by analyzing different scenarios (Di Sbroiavacca et al., 2016).

In this study, appropriate scenarios of sustainable power generation are defined and analyzed considering minimum costs (investment, environmental, operating, repair, and maintenance costs) to examine the potential of reducing greenhouse gas emissions with the highest level of function.

The model of the study is the optimal model of OSeMOSYS/LEAP, which is a tool widely used for the analysis of energy policies and studies on reducing greenhouse gas emissions; it supports a wide range of methods (Awopone & Zobaa, 2017). This is a simulation and optimization model of the energy economy, which creates energy scenarios using a combination of data (SEI, 2011). This model might be used for energy modeling based on the analysis of energy supply and demand and environmental effects. It is used for the cost–benefit analysis based on the scenario (Heaps, 2016; Huang et al., 2016; Seo-Hoon et al., 2020). It might also be used for the analysis of energy consumption scenarios and CO_2 emissions as well as for the comparative simulation of the effects of different policies and technologies under different scenarios (Seo-Hoon et al., 2020; Wu & Peng, 2016). The scenario and function of optimization in this model are developed by a combination with the OSeMOSYS method, which is the method is a transparent and direct tool for modeling energy allowing simplification of complicated results and analyses (Howells et al., 2011).

The research methodology is presented in Fig. 1.

To manage a sustainable and optimal power supply, it is necessary to predict power consumption precisely (Lee & Tong, 2011; Zhang et al., 2020), the prerequisite of which is to predict power demands (Nawaz Khan et al., 2020).

To predict the demands, the current study employed the activity level analysis method, as indicated in Relationship 1, using LEAP software. In this method, energy demand is calculated when the activity volume is multiplied by energy consumption intensity. In this relationship, d is power consuming sectors, j is power consumption, K is power consuming subsectors, m is final power consumption, y is the year, EL is power demand, ELI is power consumption intensity, and Ac is the activity volume.

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

To present the long-term optimal plan of sustainable power generation by considering the scenarios, power demand, and limitations, the objective function is considered in the current study using the OseMOSYS model in combination with LEAP software, as shown in Relationship 2:

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

In this relationship, I is the investment cost, F is the fixed cost, V is the variable cost of repair, maintenance, and operating, E is the environmental cost, and S is the scrap value in the y year, which are determined depending on the type of technology, working hours, power generation capacity, the amount of pollutant emissions, and so on. Relationships 3–7 show their calculation methods in a discounted form:

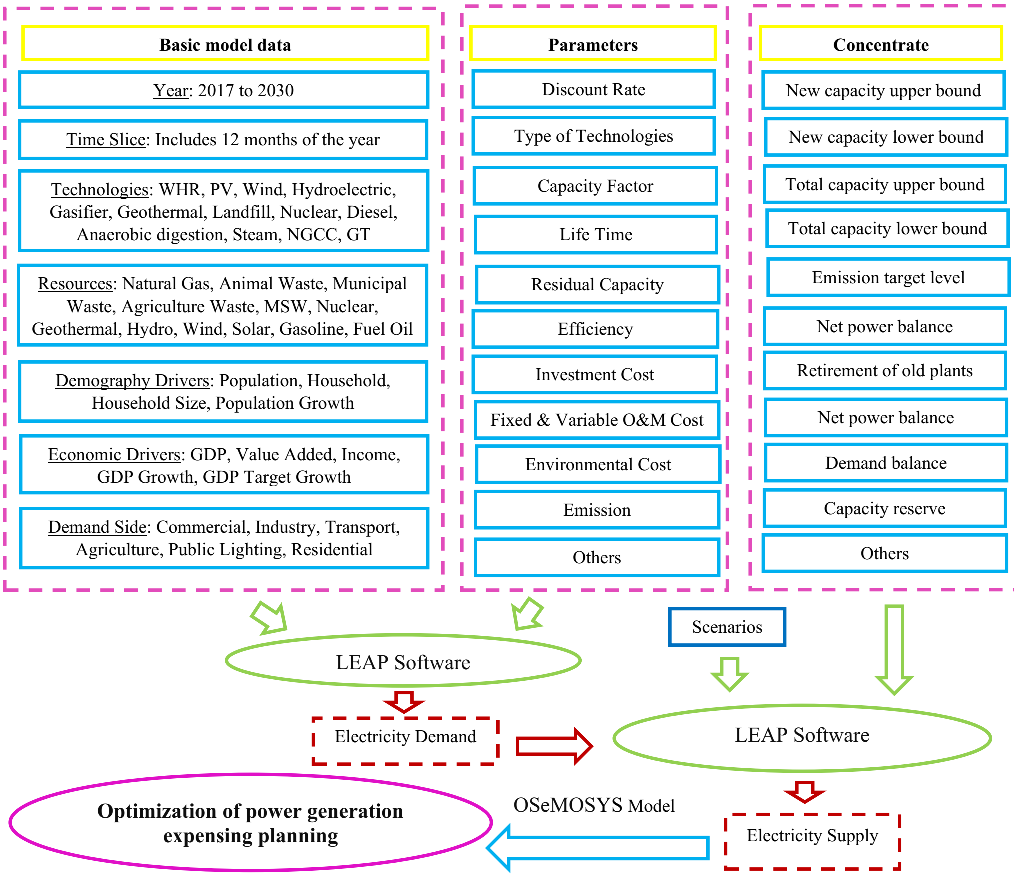


Fig. 1 The research methodology

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

$$S_y = \left(\frac{1}{1+D}\right)^{Y}\sum_{t=1}^{T}\left[\delta_t^{Y-y+1} \times I_t \times Cap_t \times U_{t,y}\right] \tag{4}$$

In Relationships 3 and 4, D is the discount rate (%), t is the technology, $Cap_{t,y}$ is the power generation capacity for t technology in the y year, and $U_{t,y}$ is the number of t technology in the y year.

$$F_y = \left(\frac{1}{1+D}\right)^{y-\frac{1}{2}}\sum_{t=1}^{T}\sum_{y=1}^{y}\left[F_t \times Cap_t \times U_{t,y}\right] + \left[\sum_{j=1}^{J} F_j \times ExistCap_j\right] \tag{5}$$

The fixed costs of repairing and maintaining each technology are calculated considering the capacity of technology t and j for each year.

$$V_y = N \times \left(\frac{1}{1+D}\right)^{y-\frac{1}{2}}\sum_{l=1}^{L} L\left[\sum_{t=1}^{T}\left[V_t \times P_{t,y,l}\right] + \sum_{j=1}^{J}\left[V_j \times P_{j,y,l}\right]\right] \tag{6}$$

Moreover, the variable costs of repair and maintenance are a function of the activity level of each technology (N in hour) in time slice (l in year) and are relevant to the amount of power generation by each technology. In this relationship, $P_{t,y,l}$ and $P_{j,y,l}$ are the amount of power generation for the technology t and j, respectively, in each time slice (month) in each year.

$$E_y = N \times \left(\frac{1}{1+D}\right)^{y}\sum_{y=1}^{Y}\sum_{t=1}^{T}\left[VED_{t,y} \times P_{t,y}\right] + \sum_{j=1}^{J}\left[VED_j \times P_{j,y}\right] \tag{7}$$

Environmental costs are a function of the activity level of each technology, at any given time, and are relevant to the amount of annual power generation by each technology. In this relationship, VED_j and VED_t are the value of the environmental damages resulting from *t* and *j* technology each year, which is determined depending on the volume of environmental pollutant emissions.

The volume of environmental pollutants emissions in each year is calculated by Relationship 8:

$$R_{e,f,y} = E_{f,y} \times EF_{f,y} \tag{8}$$

In this relationship, *R* represents the amount of *e* environmental pollutant emission, resulting from the consumed fuel *f* in the *y* year (in power plants with fossil fuels) or other pollutants (in renewable and clean power plants). Furthermore, *EF* is the coefficient of pollutant emissions resulting from combustion or other things in the *y* year.

Data

As described in the "Introduction" section, the country under study is Iran. In this section, the relevant data are presented for the purpose of modeling.

- Year: The basic year for modeling is 2017, and the forecast horizon is 2030.
- Sub-period: It includes 12 months in each year.
- Technology: It includes any type of fossil power plant (steam, gas, combined cycle, and diesel) and renewable power plants (solar, wind, geothermal, hydroelectric, nuclear, bio-mass including waste incineration, gasification, and anaerobic digestion).
- Sources: It includes various types of natural gas fuels, fuel oil, and gas oil in the area of fossil energy, and animal excreta, municipal wastewater, agricultural waste, industrial wastewater, as well as solar, wind, nuclear, geothermal, and hydropower energies in the area of renewable energies.
- Demand: The amount of power consumption in different parts of Iran shows that the amount of consumption reached around 184,182–237,436 GW per hour from 2010 to 2016, while it reached 260,264 GW per hour in 2017 (Ministry of energy, 2017). Therefore, the average growth of annual power demand is at least around 4%. To present a suitable structure, it is necessary to predict the power demand sector, which requires basic data (Lee & Tong, 2011), the most important of which are presented in the following.
- Demographic data: The population is an important factor in the increase in power demand (IEA, 2018). Based on the latest census conducted in 2017, the population of Iran is around 80,925,000 persons. The number of families in the same year was 26,551, and the family size was 3.05. The average growth of the population was around 1.43% from 2006 to 2017 (SCI, 2016). Considering that the growth rate of the population in Iran is decreasing, the growth rates of the population, as predicted by the Statistical Center of Iran, considered to be 1.25, 1.11, and 0.98% in the modeling hypotheses by considering a family size of 2.6 people for the years 2017, 2021–2026 and 2026–2031, respectively (SCI, 2017).
- Economic data: The amount of gross domestic product in 2016 was around 418 million USD. The rate of economic growth from 1991 to 2017 has been reported to be 4.3%, and the gross domestic product rate has been considered to be 5%, based on the plans for economic growth and development in Iran (Ministry of Economic, 2015).

  The major power consumption sectors are shown in Fig. 2 for the analysis and prediction of demands.
- Some of the important and influencing parameters and assumptions in calculations include power generation costs, the type of technologies, life cycle, and capacity coefficient, which are presented in Table 1. In addition, a discount rate of 14% was considered for calculations (Ziyaei et al., 2021).

The scenarios of the model

Considering the high volume of GHG emissions and the growth of electrical energy consumption in Iran, the decarbonization scenarios of the current study are described in Table 2. For this purpose, the climate change strategic document of Iran was used to execute the agreements regarding the reduction of emissions in climate change

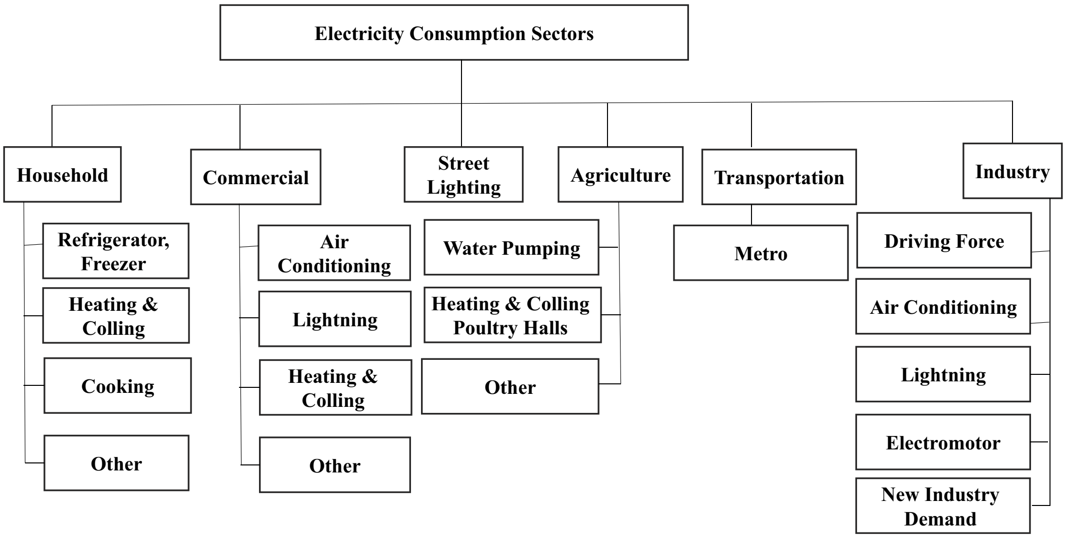


Fig. 2 The major power consumption sectors for predicting the demands in the present study

conventions, the Kyoto Protocol, the Paris Agreement, and other global agreements (DOE, 2016).

Results

In this section, the final results of the long-term optimal power generation modeling are presented using the scenarios and assumptions presented in the previous section. In fact, the scenario of each study presented in Table 2 explains an outline of the future situation, the framework of which forms a coordinated set of the external variables of the model, and the actions resulting from changes in such variables contribute to the development of sustainable power generation with the minimum cost. The conducted analyses made it possible to identify the potentials relevant to the policies.

Power demand

The important prerequisite to executing the plans of decarbonization for power generation is supplying power

Table 1 Important and basic assumptions for modeling

Technologies	Costs (c$/kwh)				Residual capacity (Kw)	Life (year)	CF	Eff (%)
	Inv ($/kw)	FO&M ($/kw)	VO&M ($/kwh)	Env (c$/kwh)				
WHR	750	57.6	0.001	0.052	0	20	0.50	100
Solar (PV)	933	26.1	0.005	0.014	42,800	20	0.22	100
Wind (onshore)	1100	11.9	0.005	0.003	191,000	20	0.36	100
Hydro (mini)	1895	16.0	0.000	0.000	83,300	20	0.38	100
Hydro (large)	1500	13.5	0.000	0.000	12,328,000	20	0.35	100
Geothermal	3830	13.2	0.000	0.000	0	20	0.85	100
Gasifier	3000	0.0	0.030	0.006	2000	20	0.73	28
Landfill	2407	94.5	0.040	0.006	1600	20	0.73	27
Nuclear	5530	57.6	0.010	0.006	915,000	30	0.80	33
Diesel	380	25.0	0.0005	0.135	283,800	30	0.75	35
Anaerobic digestion	2650	23.1	0.040	0.006	3000	30	0.73	28
Steam	1100	12.3	0.0005	0.116	14,876,000	30	0.80	42
NGCC	700	9.8	0.0004	0.093	18,945,000	30	0.70	65
GT	450	13.2	0.0006	0.052	21,102,000	30	0.70	37

Table 2 Details of research scenarios

Title of scenarios	Characteristics	Assumptions
Basic scenario	Reflecting the probable situation based on the changes in the existing trend	-
Development of renewable energies	Increasing the share of renewable energies in the basket of fuels	- Installing 5000-megawatt renewable power plants by 2021 - Installing 12,000-megawatt renewable power plants by 2030 - Share of each of the sources of renewable energies, such as solar, wind, hydroelectric under 10-megawatt, heat recovery, bio-mass, and geothermal is 50, 40, 7, 2, 1, and – percent, respectively
Increasing the efficiency of the thermal power plants	Increasing the efficiency of thermal power plants by using the methods of transforming gas power plants to combined cycle power plants, repowering steam power plants, and constructing new power plants with high efficiency	- Increasing the efficiency of thermal power plants, from 37 to 42 percent by 2021, and to 48 percent by 2030 - Transforming gas power plants to combined cycle power plants, repowering of steam power plants, constructing new steam, and gas and combined cycle power plants with high efficiency, and capacities of 10,000, 2300, 5500, -, and 15,500 megawatts, respectively
Decrease in greenhouse gas emissions	Creating an optimal structure for power generation by decreasing the environmental emissions	- The amount of greenhouse gas emissions in the power industry should not exceed 190 million tons of CO_2 (based on the figure agreed in the unconditional part of COP21 Agreements)
Combined or optimal policy	Combining the scenarios	-

demands, the amount of which in all consuming sectors will reach from 255 in 2017 to 412,000 GWh in 2030. On average, the total power demand has increased by around 4% (Fig. 3). The mentioned growth rate conforms to the power demand growth rate of the previous years in Iran.

Obviously, the household sector will have the largest share of the demand increase, and the industry sector is placed in the second rank. In the household sector, most of the demands are related to the space cooling subsector, and in the industry sector, it is related to industrial electromotors. The reason for the increasing demands for cooling the space is, on the one hand, related to the population and family growth and, on the other hand, the increase of air temperature and climate change in Iran, as an arid and warm country.

Power supply

To supply the demands estimated in the previous part, it is necessary to increase the capacity of power plants in Iran to generate at least 412,000 GWh of power, with 4.1% capacity building in sustainable and optimal form, reaching an amount of at least 120,000 megawatts by 2030. The need for capacity building in the power plants of Iran and the amount of generated power until the 2030-time horizon are presented in Figs. 4 and 5.

The minimum amount of capacity building for sustainable and optimal power generation by 2030 (Tables 3 and 4) shows that if the scenario of the status quo is relied on for the power generation, the minimum amount of capacity building is required in Iran compared to other scenarios. Moreover, maximum capacity building is related to the scenario of developing renewable energies. Since the objectives of this scenario emphasize the development of renewable energies, and such power plants have less power generation capacity (capacity coefficient) than thermal power plants, more capacities should be considered for such cases.

According to Fig. 5, the amount of power generation in all scenarios should reach at least 412,000

Sector / Year	2017	2020	2025	2030
Residential	82.5	95.6	119.3	144.3
Commercial	42.6	42.4	58.5	80.8
Industry	87.6	91.4	108.8	130.3
Transport	0.4	0.4	0.5	0.7
Agriculture	37.1	36.4	42.4	49.4
Public Lighting	4.8	5.3	5.9	6.4
Total	255.0	271.4	335.5	411.8

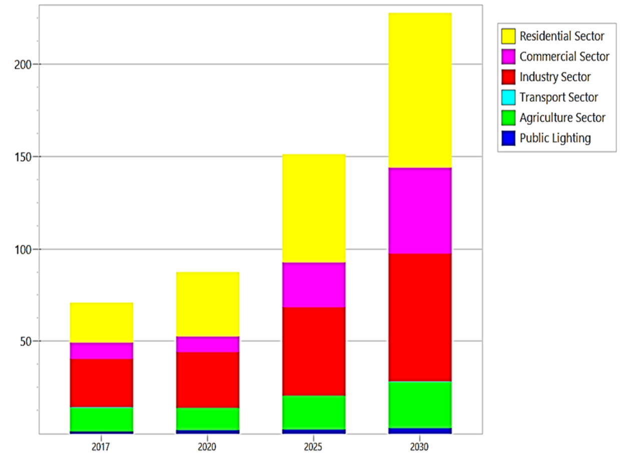


Fig. 3 Forecasting the rate of demands in different power consuming sectors (Thousand Gigawatt-Hours)

GWh by the end of 2030 to meet the power demands. Moreover, the transmission and distribution network losses are taken into consideration; the amount of power supply will reach around 488,000 GWh. In Fig. 6, the share of each power plant in different scenarios is presented by the 2030-time horizon.

The results showed the following:

- In the basic scenario, the average share of thermal power plants in power generation in Iran is around 90% from 2017 to 2030. The largest share in power generation in 2030 belongs to the existing combined cycle power plants. The share of nuclear and hydroelectric power plants with more than 10-megawatt capacity and renewables will be 1.4, 4, and 4.2%, respectively. The share of other power plants is 0.6%.
- In the scenario of renewable power plant development, thermal power plants have a share of 74% in 2030. The largest share (around 50%) is related to the existing advanced combined cycle power

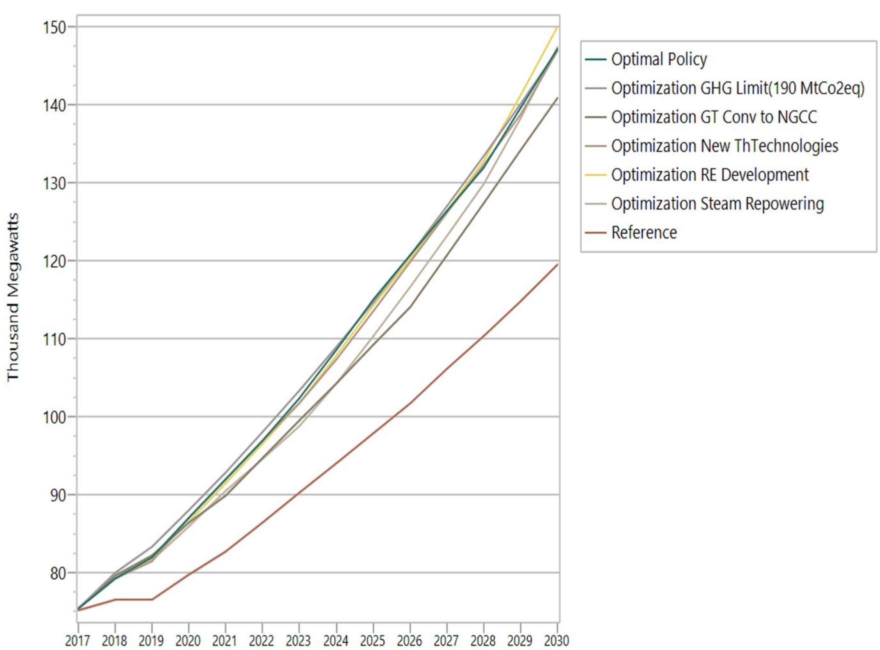


Fig. 4 The trend of the need for practical capacity building in power generation plants in each of the research scenarios by 2030

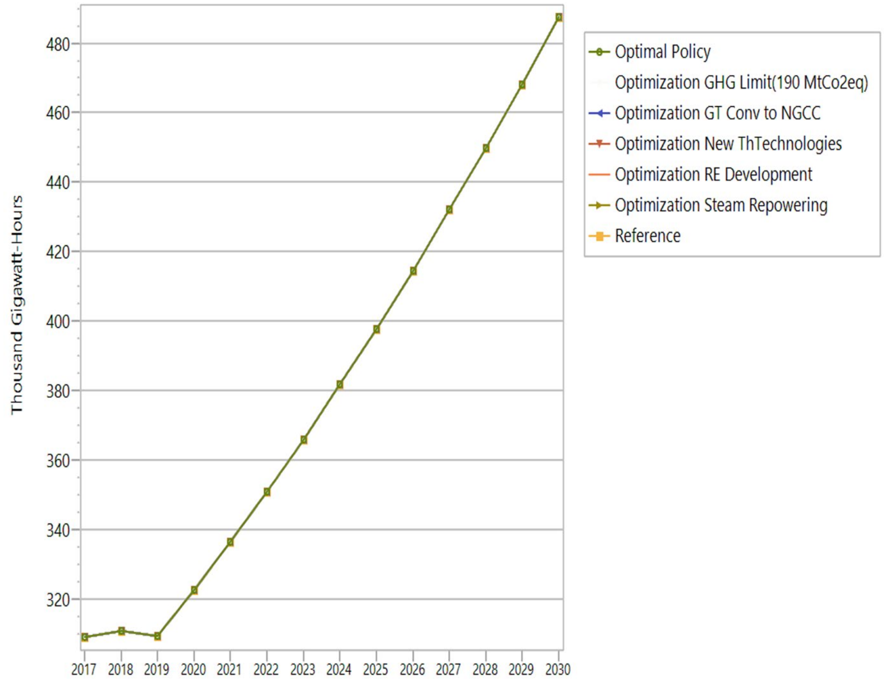


Fig. 5 The amount of power generation in each of the research scenarios by 2030

plants. The share of renewable power plants has increased by 19%, and solar power plants, which are of photovoltaic type, have the largest share (7%) among such power plants.

– In the scenario of decreasing GHG emissions, the share of thermal power plants is around 74.5% in 2030, and the largest share is related to the existing advanced combined cycle power plants. The share of steam, diesel, and gas power plants is less than 3% because the emissions of such power plants are more than combined cycle power plants.
– In the scenario of increasing the efficiency of thermal power plants, the share of thermal power plants in each subsector is around 70%, in 2030. The shares of renewable, big hydroelectric, and nuclear power plants are 24, 1.7, and 3.7%, respectively. This scenario suggests the utmost use of renewable energies.
– In the combined scenario, the shares of thermal and renewable power plants in power generation are 67 and 20%, respectively, and the shares of renewable, nuclear, and hydroelectric power plants have

Table 3 The trend of the need for practical capacity building in power generation plants in each of the research scenarios

Scenarios/year		2017	2020	2025	2030
References		75.5	79.8	97.9	119.6
RE development		75.5	86.6	114.4	150.0
Efficiency	Convert GT to NGCC	75.5	86.4	109.2	140.9
	New technologies	75.5	87.1	113.7	146.9
	Steam repowering	75.5	85.9	110.4	147.4
GHG limit		75.5	88.0	114.8	147.0
Optimal policy		75.5	87.0	115.1	147.2

Table 4 The amount of demand for fuels consumed by Iranian power plants in different scenarios (billion cubic meters of natural gas)

Scenarios/year		2017	2020	2025	2030
References		79.5	76.4	94.4	115.7
RE development		79.5	70.3	77.4	87.3
Efficiency	Convert GT to NGCC	79.5	69.7	76.8	88.5
	New technologies	79.5	69.5	76.9	88.4
	Steam repowering	79.5	70.2	77.3	85.7
GHG limit		79.5	69.9	78.1	88.3
Optimal policy		79.5	69.2	73.7	84.2

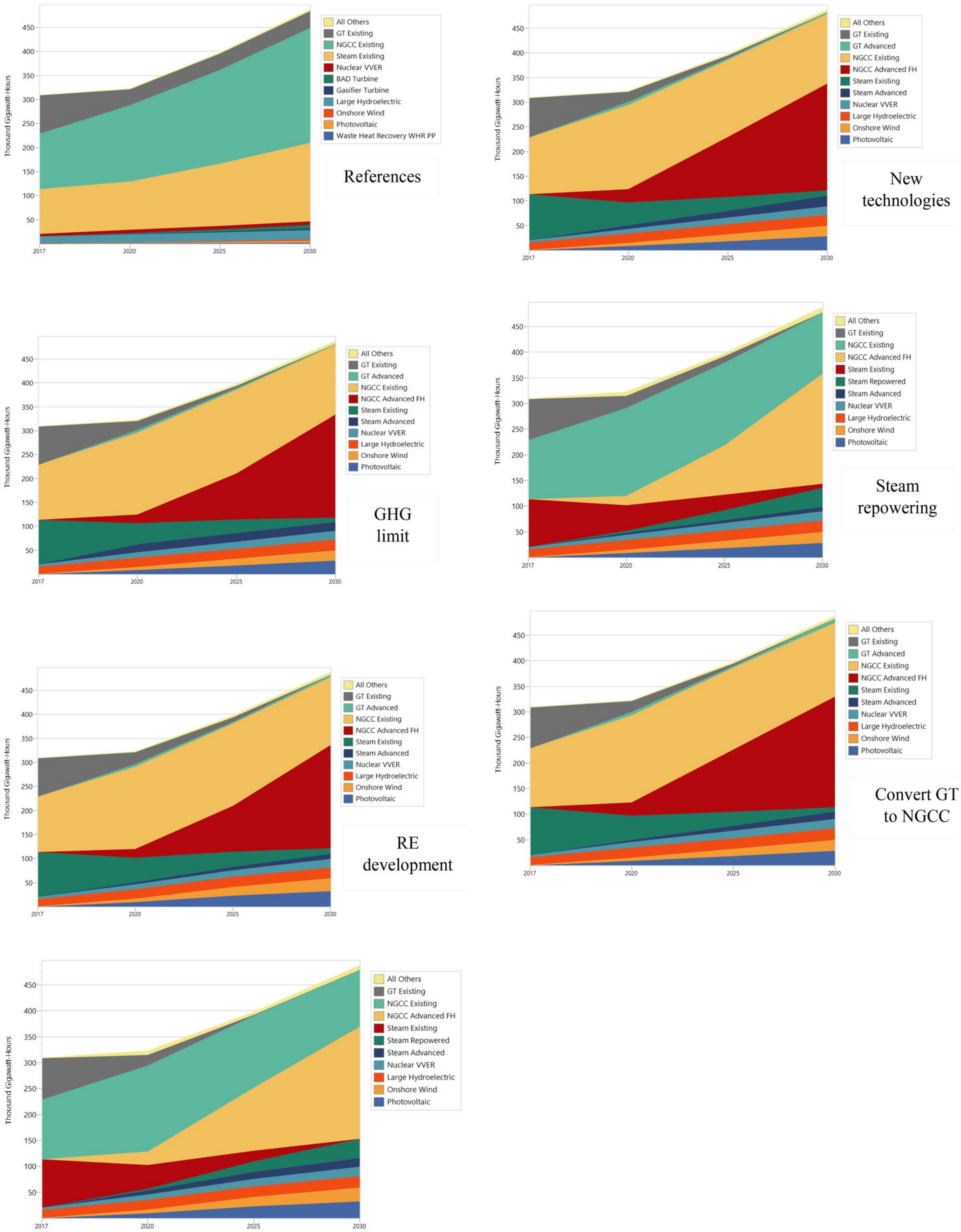


Fig. 6 The amount of power generation in different types of power plants in different scenarios

increased to some extent. In this scenario, minimal use is observed for polluting thermal power plants.

Fuel demand

Thermal power plants require consuming different types of fossil fuels for power generation (Sims et al., 2003). In this part, the fuel demand of power plants for power generation is presented for each of the scenarios (Table 4).

The reviews of the research scenarios on the demand for fuel consumed by Iranian power plants show that demands for fossil fuels are significantly different from each other in different scenarios. The largest and the minimum demands for fuels belong to the basic scenario of minimum demand and the scenario of combined and optimal policymaking, respectively. Repowering of steam power plants in the scenario of increasing the efficiency of thermal power plants is placed in the next rank. According to the results of the limitations applied and the objectives of the research, including the decrease of private and external costs of power generation and the decrease of carbon emissions, the consumption of fossil fuels was decreasing constantly from 2017 to 2020. However, to supply the power demand in the 2030-time horizon, there will be an increase again in demand for fossil fuels, and strategies for demand management should be employed to manage such an issue.

Greenhouse gas emissions

The results show that the GHG emissions will reach from 163 million tons of CO_2 in the basic scenario to 227 million tons, with an increase of 64 million tons compared to the basic year. In Fig. 7, the shares of various power plants in the emissions are demonstrated in different scenarios.

As indicated by the results, the largest amount of greenhouse and polluting gas emissions in the basic scenario in 2030 is related to the steam and combined cycle power plants. In other scenarios, it belongs to the existing combined cycle power plants and advanced combined cycle power plants. The share of steam power plants in other scenarios is less than the other thermal power plants due to creating much pollution, reaching at most around 4%. In 2017, on the other hand, the largest amount of emissions belonged to the existing steam power plants and existing combined cycle power plants. The share of existing gas power plants in all research scenarios was almost the same in all research scenarios.

Moreover, the results of the modeling show that the strategies of decreasing carbon (decarbonization) to achieve sustainable power generation in Iran have

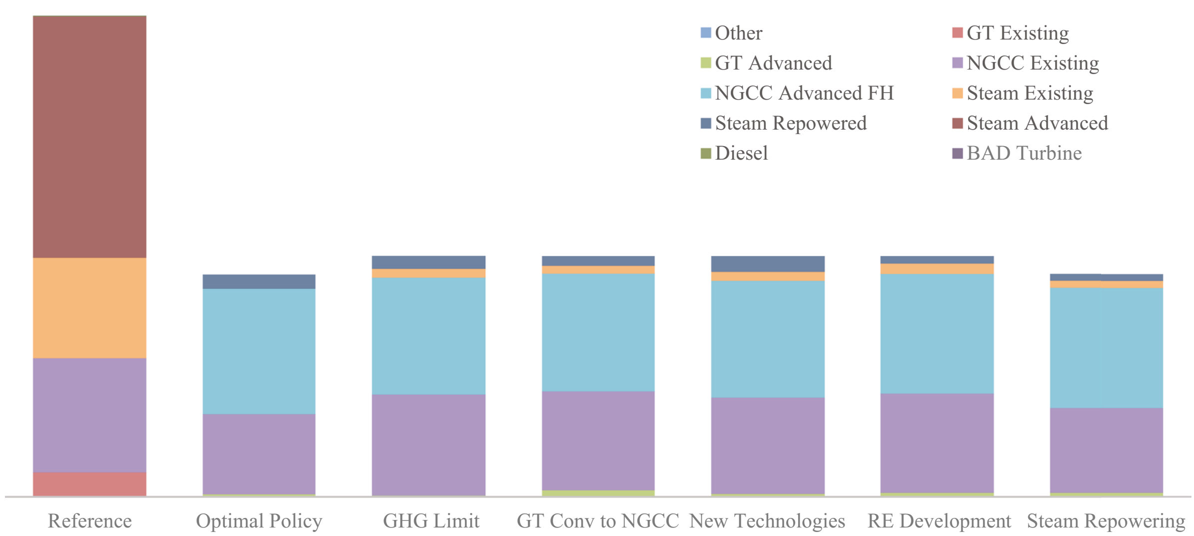


Fig. 7 The amount of greenhouse gas emissions resulting from power generation in different scenarios in different types of power plants in 2030

Scenarios / Year		2017	2020	2025	2030
Refrences		-	-	-	-
RE development		-	-18.4	-42.0	-67.8
Ffficiency	Convert GT to NGCC	-	-19.0	-44.7	-67.4
	New technologies	-	-18.2	-43.3	-66.2
	Steam repowering	-	-17.6	-44.9	-71.4
GHG limit		-	-17.3	-42.9	-72.4
Optimal Policy		-	-19.9	-52.6	-77.6

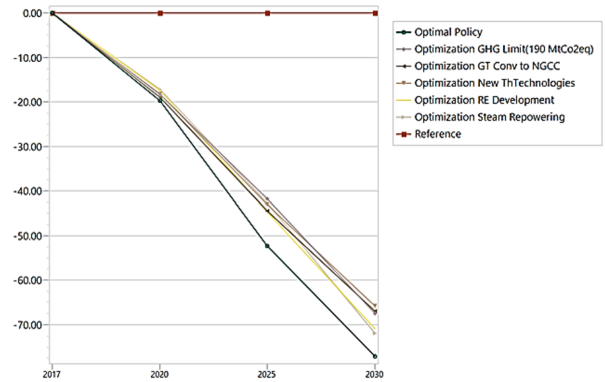


Fig. 8 The downward trend of polluting and greenhouse gas emissions in each downward scenario compared to the basic scenario (MMTCO2 eq)

decreased greenhouse and polluting gas emissions from 66 to 77 million tons of CO_2 compared to the basic scenario (Fig. 8).

The results show that the maximum reduction of GHG emissions is related to the scenario of optimal (combined) policy and repowering steam power plants. The maximum reductions are 77.6 and 72.4 million tons CO_2 equivalent, respectively, in 2030, considering the assumptions of modeling, with the minimum production, investment, and operation and environmental costs. It indicates that executing the optimal policy and more cost-effective scenarios including the repowering of steam power plants makes it possible to achieve much more remarkable results than the scenario of decreasing greenhouse gases, according to the commitments of Iran in internal conventions. It is worthy of note that more costs are required to achieve the research objectives in all scenarios of the research. However, thermal power plants have a large share in power generation; thus, strategies for increasing efficiency, especially the repowering of thermal power plants, seem to be more reasonable than the other scenarios. The proposed optimal portfolio in the two top scenarios is presented in Fig. 9.

According to the results, the most sustainable power generation method is to use the existing combined cycle power plants, the development of advanced combined cycle power plants, the repowering of steam power plants, developing solar power plants (photovoltaic), and moving toward this path. The shares of each of the mentioned strategies are respectively 44, 22, 8, and 7% in 2030.

Costs of power generation

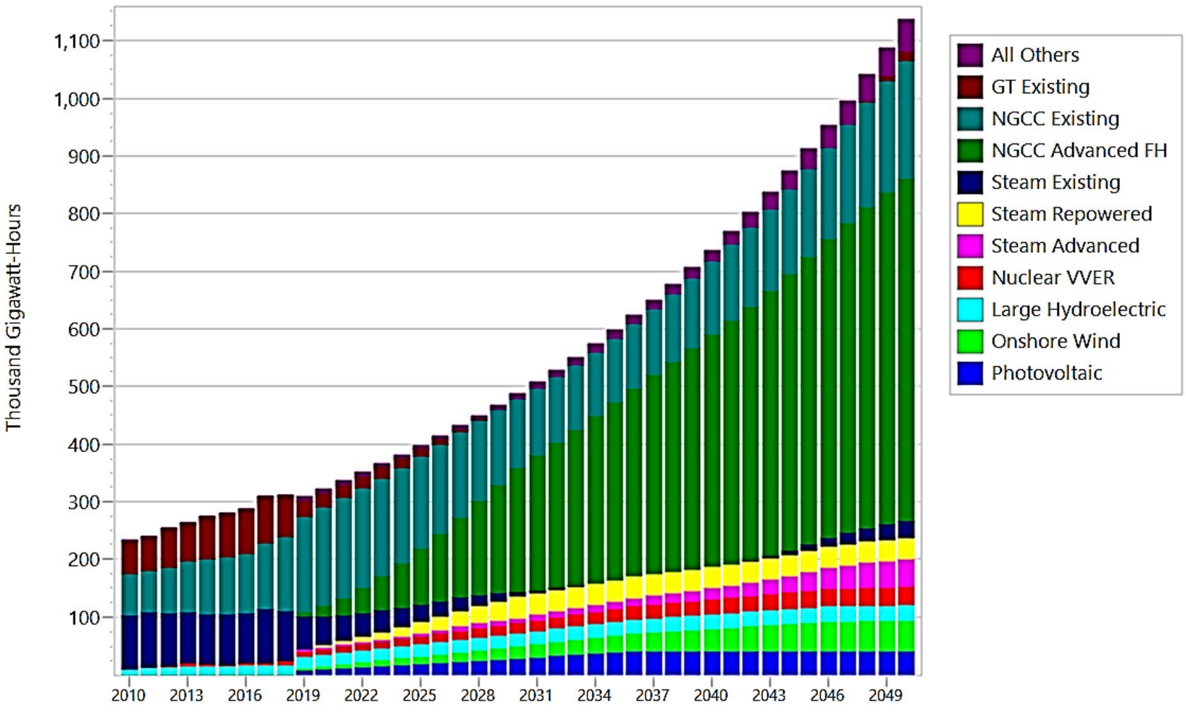
Another advantage of the carbon reduction scenario in the power generation sector is to decrease the external and internal costs of power generation. The reduction rates of different costs in this scenario compared to the basic scenario are described in Table 5.

The results show the following:

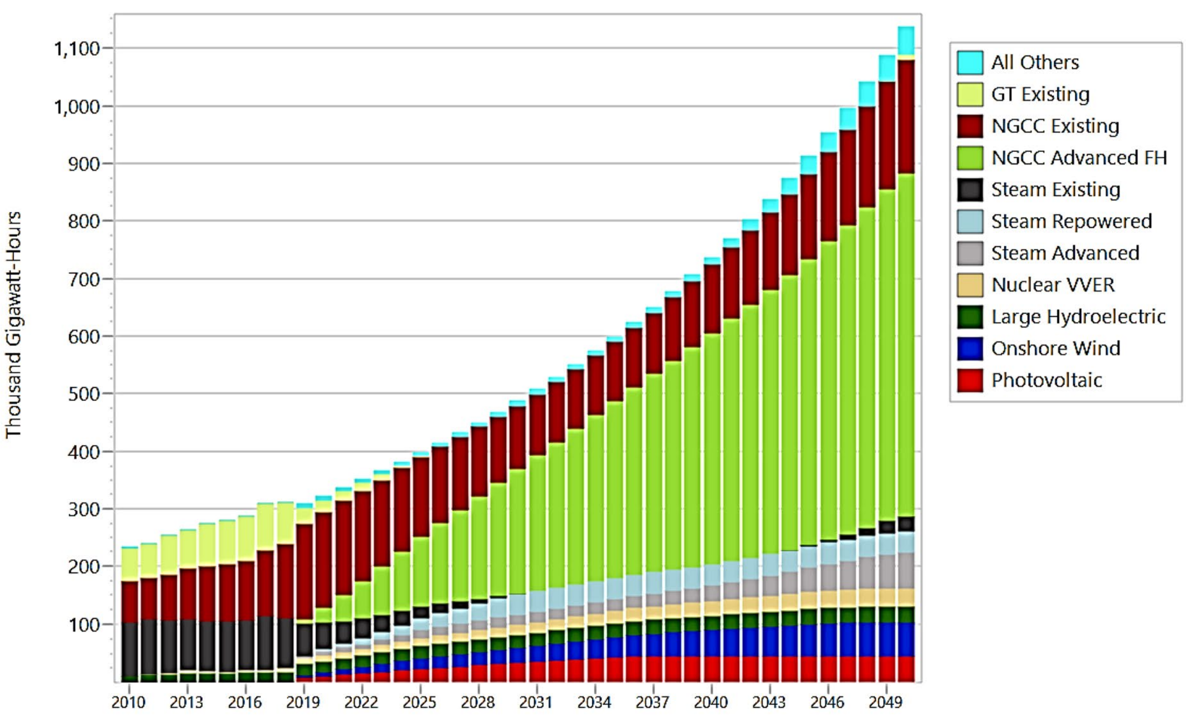
To generate sustainable power, many initial investments are required in all scenarios compared to the basic scenario. The cost of investment is a restricting factor in the development of the selected scenario. Therefore, countries move towards a strategy that demands less investment costs for decarbonization since investments are required for capacity building in new power plants. In the current study, the cost of the initial investment in the scenario of the repowering of thermal power plants is less than the other scenarios and is more than the other scenarios as for the combined scenario.

The fixed and variable costs of investment in the scenario of the repowering of thermal power plants are more than the optimal or combined scenario. The minimum amount of variable costs, the main part of which is related to the fuel price, is relevant to the combined and renewable scenarios due to the increase of renewable power plants in the power supply portfolio of Iran. Furthermore, the maximum variable cost belongs to the basic scenario.

The environmental costs in the optimal or combined policy scenario had a greater reduction than the basic scenario, followed by the scenarios of developing renewable



Steam repowering



Optimal Policy

Fig. 9 The less-polluting optimal and sustainable portfolio of power generation in each type of power plant power plants and the repowering of thermal power plants because they have reduced the use of customary methods for power generation (thermal power plants) and have developed other methods. Therefore, an advantage of changing the power supply portfolio in Iran is the reduction of environmental costs by 2030, at least and at most for 1739 and 1895 million dollars, respectively.

Discussion

Comparing the results

In this section, the results of the current study are compared to those of several domestic studies (see Table 6).

Considering our investigations, the following issues are worthy of note:

- The strategies of decarbonization in the power generation sector include the development of renewable energies and increasing energy efficiency. In addition to the abovementioned studies, the issue is also discussed by some other foreign and domestic sources (Aryanpur et al., 2019; Flavio et al., 2020; Gielen et al., 2019; Karbassi et al., 2007; Khanna et al., 2019; Omer, 2007; Strielkowski et al., 2021; Tigas et al., 2015; Vaillancourt et al., 2017; Wang et al., 2019; Yang et al., 2010). In the current study, it is recognized as the decarbonization scenario, along with the other scenarios. The scenarios substituting the existing situation actually propose the probable ways of developing renewables, optimizing the thermal power generation sector (increasing the efficacy), and decreasing the emissions of pollutants according to the national and global agreements, by paying attention to sustainable power generation.
- Power demands are increasing annually, and to supply the power demands in the 2030-time horizon, we will witness the increase of demands for fossil fuels (due to the need to increase the power generation capacity) and the increase of emissions. Because fuel consumption in thermal power plants has a direct relationship with pollutant and GHG emissions, the increase of this factor will increase emissions, and vice versa. The results of the present study are in line with those reported by Yophy et al. (2011), Masoomi et al. (2020), and Rivera-Gonzalez et al. (2019). Therefore, beyond the studied scenarios, the management of demands in the sector of supplying and converting the power generation portfolio to clean and renewable power plants, might have a greater contribution to decarbonization in this sector. These findings are supported by Shimoda et al. (2021), Barrett et al. (2022), Sakamoto et al. (2021), and Pinner (2018). Additionally, focusing on this sector also requires investment in informing and training, which should be taken into consideration in cost calculations.
- Power generation using renewable energy sources should increase due to not consuming fossil fuels. The same findings were concluded by Solaymani (2021), Kaberger (2018), and Armando (2007). Under some conditions, however, using such sources increases power demands due to being clean or having fewer emissions than customary power plants. The result matches that of Sepulveda et al. (2018) and contrasts with that of Liang et al. (2019) and Zhao et al. (2014). Some problems of developing such power plants are the lack of 24-h accountability to power consumers (fluctuations in the power supply), higher investment costs, lack of the potential to use different types of such sources in each geographical area, and so on, which might make them not to be competitive with fossil energies. Such results have also been observed in foreign studies Sepulveda et al. (2018), Maradin (2021), Peidong et al. (2009), Arutyunov and Lisichkin (2017), and Munnich Vass (2017). However, it is worthy of note that the results of this study take all restricting factors into account in calculations, and the optimal portfolio is introduced considering all restrictions.

Table 5 Reduction of costs compared to the basic scenario in the optimal policy of sustainable power generation (million $USD)

Scenarios/year		Inv Cost	FO&M Cost	VO&M Cost	Env Cost
RE development		1340.9	469.0	-187.0	-1810.2
Efficiency	Convert GT to NGCC	1405.8	358.6	-202.6	-1739.2
	New technologies	1238.1	441.2	-214.8	-1697.0
	Steam repowering	1272.0	432.8	-208.7	-1807.8
GHG limit		1429.8	454.7	-202.0	-1730.3
Optimal policy		1959.7	450.4	-186.5	-1894.5

Table 6 Discussions on the results of the current study and other studies

References	Objective of the study	Results	Similarities	Differences
(Asadi et al., 2016)	The economic evaluation of the reduction of GHG emissions	Energy subsidies and not paying attention to the environmental damages of power plant pollutants are the main reasons for failure in sustainable power generation	Presenting the model of energy planning, economic consideration, and emissions of thermal power plants	No consideration of all renewable, nuclear, and hydroelectric power plants, no use of a long-term and quantitative planning model, technical and environmental indexes
(Aryanpur & Shafiei, 2015)	Determining the optimal share of renewable energies and their effects on the decrease of fossil fuel consumption and GHG emissions	Investment in the field of wind and solar renewable technologies is important	Considering the price of technology, determining the share of renewable energies, investigating GHG emissions, and estimating the demands	Considering the share of renewable energies in the consumption sector
(Ghadaksaz & Saboohi, 2020)	Investigating the decrease of GHG emissions by improving energy efficiency with the minimum cost	Energy efficiency is the most important factor for decreasing GHG emissions	Optimizing the energy system and considering all costs of power generation	Considering the scenarios of decreasing the consumption of fossil fuels and carbon tax

– Using customary and thermal power plants is a priority for power generation in all scenarios, even by considering environmental costs and the restrictions of GHG emissions, because the policies of decarbonization both in Iran and the whole world move toward a strategy that requires less investment costs. This issue has also been clearly explained in some studies, Ziyaei et al. (2021), Hirth and Steckel (2016), Khanna et al. (2019), Abolhosseini et al. (2014), Mirza et al. (2009), Plebmann and Blechinger (2017), and Aryanpour and Shafiei (2015). The investment cost reduction and prioritizing the use of different types of power plants in the scenarios of the study result from the price of fuels in variable costs. Customary thermal power plants in Iran generate power at a low price (a subsidy is paid for the fuel of power plants), and they are not easily competitive with other clean power plants, even with lower costs of repair, operation, and maintenance. Such results have also been observed in foreign study, such as Sepulveda et al. (2018), Ziyaei et al. (2021), Abdol Qadir et al. (2020), and Martins et al. (2019). However, a study by Heuberger et al. (2016) indicates that using some renewable energy sources is competitive with fossil energy sources in some areas of the world. Furthermore, they have led to decarbonization in this industry, with very lower costs, which is due to actual fuel costs in some countries, for example, Foster et al. (2017), Zeppini and Van den Bergh (2020), and Kaberger (2018).
– All studies indicate that energy policies in the power generation sector should focus on energy efficiency to decrease GHG emissions (decarbonization) because such policies bring in more remarkable results, with low costs. Similar studies were conducted by Abolhosseini et al. (2014), Masoomi et al. (2020), Sabeti et al. (2022), Emodi et al. (2017), and Cormos and Dinca (2021). Such strategies include the repowering of thermal power plants and constructing new combined cycle power plants with high efficiency. Therefore, an optimal supply system of sustainable power is created by increasing the share of renewable energies and increasing the efficiency of thermal power plants.

Limitations

As stated earlier, all studies compared here did not focus on the external and environmental costs of different types of power generation methods and some of the technical and environmental considerations. In the current study, such gaps are taken into consideration. However, there are some limitations in the current study and the existing policies. The limitations of the study are as follows: (I) lack of analyzing the sensitivity of the model and risk analysis, which makes it possible to show the weak and strong points of different types of energy sources; (II) lack of technical, economic, and environmental analyses of the scenario of carbon capture and storage in power plants, as a frequently used scenario for decarbonization; (III) lack of calculating the strategies of power demand management, which might have a greater contribution to decarbonization; and (IV) lack of considering the optimization effects on the power transmission and distribution system since this sector includes many losses in Iran and might influence the decrease of capacity building.

Policy limitations in Iran include the following: (I) lack of or limited financial support, such as giving government grants for efficiency and optimization strategies and feed-in tariffs, which might change power generation costs in the power supply sector into more suitable economic costs due to the decrease of investment costs and make it competitive with the customary power generation, and help to develop such strategies. (II) There are limitations and many obstacles to the strategies of increasing the efficiency in power plants, such as lack of knowledge, lack of executing the standards and regulations, distorting energy prices by assigning subsidies to the fuel, lack of technical facilities, sanctions, and lack of requirements for executing environmental rules and regulations.

Conclusion

Following the goal of reducing GHG emissions arising from power generation and presenting an optimal and sustainable portfolio, the decarbonization scenarios in this industry were defined in the current study. Besides, the quantities (considering the economic, technical, and environmental assumptions) were determined to prioritize, evaluate, and compare different types of power generation methods in each scenario.

The results showed that if the current status of power generation (the basic scenario) continues, supplying the demands by a cost-effective and environmentally suitable method will be a key challenge in the following years, and great capacity building will be required in the future. Moreover, the results in the power supply sector showed that the most promising option for decreasing the consumption of fossil fuels and emissions in the 2017–2030-time horizon is to take measures for improving energy efficiency, such as the repowering of steam power plants, among the scenarios of the study. Other measures include increasing the share of combined cycle power plants in all scenarios, through the strategies of converting gas power plants to combined cycle power plants and building new combined cycle power plants, with high efficiency. Considering the assumptions, the results of model implementation show that the combined or optimal scenario is the most suitable scenario of the study. If this scenario is executed in Iran, it will supply the demands and makes it possible to decrease fuel consumption by 31.5 billion cube meters of natural gas, decrease the emission of greenhouse pollutants by 77.6 million tons of CO_2, and decrease the environmental costs arising from power generation by 1894.5 million USD in the following years. Although the development of renewable energies is not cost-effective in this scenario, and it will not be competitive with fossil power plants, its development is an undeniable necessity, at least in terms of environmental issues and the security of power supply, which has high potential in Iran. Nonetheless, achieving this goal requires contextualization and providing many requirements such as obtaining the technical and technological knowledge for using this scenario.

Considering the limitations stated in the previous section, it is suggested to use renewable energy sources and strategies for energy efficiency in thermal power plants. Moreover, substantial attention should be paid to demand management strategies, exactly when the development of renewable energies and energy efficiency are costly and not economic. On the supply side, using the optimal policy for sustainability in power generation might play a role in sustainable power generation, but its execution might cause vulnerability due to such uncertainties as power supply fluctuations and high investment costs. Therefore, studies on risk management and analysis might contribute to achieving more suitable results. Furthermore, considering the role of other scenarios of reducing carbon, such as executing tax policies, using carbon reduction technologies, employing carbon capture and storage policies in power plants, and considering the role of financial mechanisms, might lead to more remarkable results, along with the scenarios proposed in this study.

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

Declarations

Conflict of interest The authors declare no competing interests.

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