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RESEARCH PAPER

Impact Analysis of Internalizing Environmental Costs on Technical, Economic, and Environmental Performances for Power Plants

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Abstract
Electricity production has negative environmental effects. These effects cause costs (environmental costs) that are not considered in the calculation of the cost of electricity production. This study aimed to investigate the technical, environmental, and economic effects of internalizing these costs in total generation electricity costs. Accordingly, using historical data and the economic method of benefit transfer, the environmental costs associated with various methods of electricity generation were calculated for the environmental effects of existing power plants per kilowatt-hour of electricity generated. Then, the obtained costs were internalized into private electricity generation costs using mathematical modeling MATLAB software. The results showed that the environmental costs ranged from 0.052 to 0.135 C$/kwh in thermal power plants. Even though these costs were also present in renewable and clean energy power plants, they were relatively low. Also, internalizing these costs can change the electricity supply basket, with a predicted increase of 1.9% and 1.0%, respectively, in 2030 and 2050 in the share of clean and renewable technologies and decrease in fossil energy plants such as diesel. From 2017 to 2050, fossil fuel consumption is expected to decline by about 124 billion m^3 of natural gas equivalent, along with 136 $MTCO_2E$ reduction in pollutant and GHGs emission. Furthermore, the overall cost of producing electricity will decrease by 6337 billion dollars. Finally, it was found that the internalization of environmental costs would shift production away from power plants with higher investment costs and toward those with lower investment costs. However, thermal power plants, which produce an average of 85% for most electricity production. This is mainly due to other production costs, existing policies, and limitation on other sources of electricity production.

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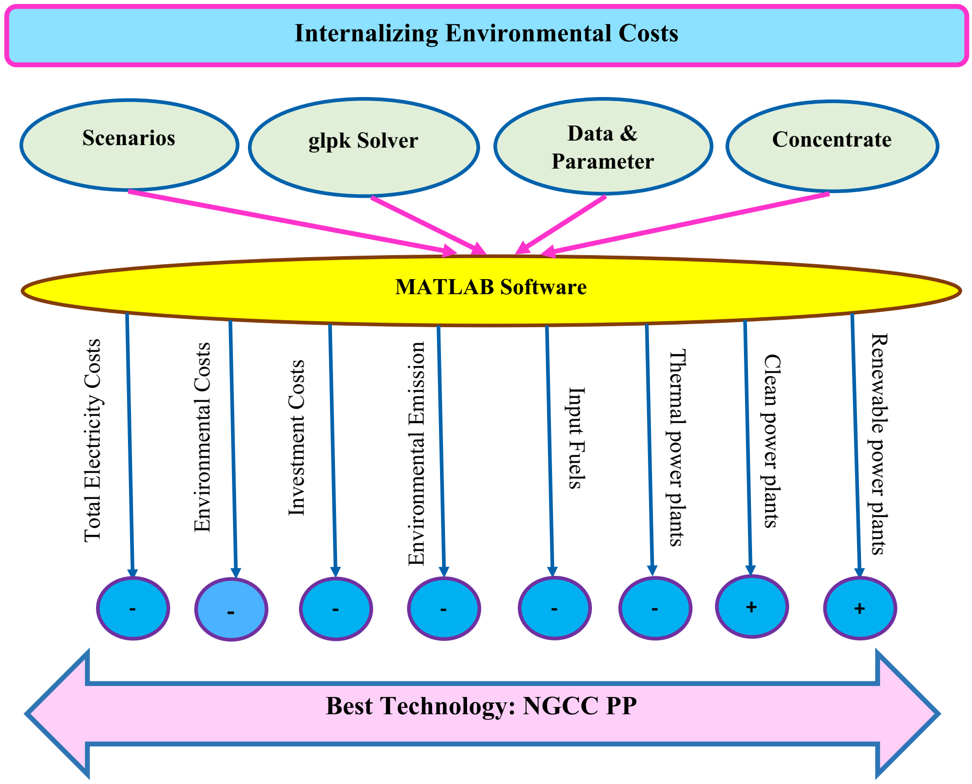
Graphical Abstract



Highlights

- Environmental external costs of all types of thermal power plants are higher than those of renewable and clean power plants
- Internalizing environmental external costs in the total cost of electricity production increases the share of renewable and clean power plants in electricity production.
- Internalizing environmental costs is expected to reduce greenhouse gas emissions and fossil fuel consumption significantly.
- Modeling the internalization of environmental costs is an efficient way to compare the technical, economic, and environmental performance of various electricity generation technologies and their current performance.

Keywords Environmental impacts · Electricity generation · Cost–benefit transfer method · Environmental costs · Electricity supply

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
WTP	Willingness to pay
GDP	Gross domestic product
MATLAB	Matrix laboratory
GLPK	GNU linear programming kit
GT	Gas turbine
NGCC	Natural gas combined cycle
WHR	Waste heat recovery
$MTCO_2E$	Million tones CO_2 equivalent
PP	Power plant
GHGs	Greenhouse gasses

Introduction

Various environmental pollutants with devastating effects enter the planet due to rapid population growth, increased dependence on fossil fuels, and overconsumption of natural resources (Rosen 2009a, b; Ediger et al. 2007). In the meantime, the consumption of fossil fuels worldwide is one of the main factors in the planet destruction and the adverse environmental impacts (Barbir et al. 1990; Rezafar and Behrooz 2014; Daragi and Bahrami Gholami 2012). Power plants, as one of the world's largest suppliers of electricity, are one of the major emitters of pollutants and greenhouses (Aboumahboub et al. 2020; EIA 2022; Kargari and Mastouri 2010, 2011), accounting for about a quarter of the world's total CO_2 emissions (EuroKAlert 2007). In addition to the emission of polluting and greenhouse gasses, power plants produce other pollutants, such as salts, particulate matter, heavy metals, fats, oils, fuels, organic and pathogenic materials, nitrogen oxides, sulfur, carbon, sludge containing heavy metals, calcareous materials, iron and aluminum, metal oxides, etc. (Gerlitzky et al. 1986; Munawer 2018; Saeeidi et al. 2005), leading to numerous environmental effects, such as pollution of water, soil, air, noise, etc. (Kumar et al. 2013; Van Zelm et al. 2016). There will be also changes in the quality of human life and the development of infrastructures due to the release of these pollutants and their subsequent effects, incurring costs (Bielecki et al. 2020), known as the external costs due to environmental pollutants, on society and individuals (Friedrich 2001, para. 18). Negative external environmental costs are those incurred by environmental damage to human health or the ecosystem, which are not calculated or included in production costs either by the electricity producers (power plants) or consumers ("EN35 External costs of electricity production" 2015, 2008; Sundqvist and Söderholm 2002; Koomey and Krause 1997; Friedrich and Voss 1993). It is noteworthy that these costs are significant and can lead to deviations in the economy (Sovacool et al. 2021).

Therefore, the electricity generation sector is currently facing two major global challenges: meeting the growing demand for electricity and reducing emissions of greenhouse gasses and pollutants, which adversely affect the environment (Gencer et al. 2020). The problems posed by these two challenges have forced governments, companies, investors, and even the people to produce sustainable electricity across the world to reduce the environmental impacts of these emissions and meet the needs for electricity generation.

Hence, different countries have developed and implemented various policies and legal measures based on their circumstances and concerns (Chang and Carballo 2011). Some of these programs include the use of renewable energies, increasing the efficiency of thermal power plants, increasing energy efficiency in all sectors of electricity generation and consumption, the use of systems and technologies to reduce pollution, approval of taxes and standards for emission, etc. (Hainsch et al. 2021; Eurelectric 2018; Towers 2010; Bielecki et al. 2020; Kusumadewi et al. 2017; IPCC 2019; Marion et al. 2001; UNEP 2016; Özer et al. 2013; Bygrave and Ellis 2003; Nebernegg et al. 2019; Zhang et al. 2020; Van de Graaf and Colgan 2016). However, many of these programs have not yielded significant results so far.

Global studies have mentioned several reasons for failure to achieve the emission reduction goals set by governments, including 1. Failure to consider the negative environmental impacts of electricity generation methods; 2. Implementation of long-term policies and programs of countries in electricity production regardless of environmental and economic considerations; 3. Low cost of fossil fuel generation compared to different clean and renewable electricity generation methods in some countries with cheap fossil fuel resources; and 4. Failure to consider the negative environmental costs of emissions and its internalization in the total costs of electricity generation and even the lack of appropriate methods to estimate these costs (Apt et al. 2007; Sundqvist 2004; Bohi and Toman 1993; Papadis and Tsatsaronis 2020; Ziyaei et al. 2021a, b; Jorli et al. 2018).

Therefore, internalizing negative environmental costs in the total cost of electricity generation is an effective policy tool to reduce the negative impacts of electricity supply (Fouquet et al. 2001; Sundqvist 2004; Klaassen and Riahi 2007; Karkour et al. 2020; Sundqvist and Söderholm 2002), and maybe one of the simplest available methods to change the power supply ("EN35 External costs of electricity production" 2015; Wang et al. 2016). We made these computations for the first time in the country and evaluated their cost, environmental, and technical effectiveness in power generation expansion plans by focusing on the cost-effectiveness policy in the electricity industry. This research provides a clear perspective on the environmental costs of power generation systems by in Iranian power plants in the electricity supply portfolio and developing a sustainable electricity generation system. Also, the integration of electricity generation costs with negative external environmental costs can be a comparative indicator for the evaluation of the economic, environmental, and technical performance of existing technologies. The qualitative consideration of these costs may show the loss and benefits associated with different power generation methods and contribute to a sustainable electricity supply. Additionally, its facilities the linkage between energy planning and policymaking in this area, which assists investors and government in choosing cost-effective methods of generating power that are technically, economically, and environmentally sustainable. This research also yields valuable insights for developing and even developed nations with similar power generation structures. The scenario-derived outcomes apply to other countries with gross fossil fuel resources and a high potential for renewable energy sources.

It also allows the identification and comparison of various technologies to determine the advantages and disadvantages of each. Therefore, this study was conducted to answer the following questions:

1. What are the environmental costs of different types of electricity generation methods?
2. What would happen to the environment and the economy if we do not internalize the negative environmental costs in the electricity generation costs for various electricity generation methods?
3. What benefits would environmental cost internalization offer?
4. What would be the consequences of internalizing the environmental costs of electricity generation on electricity supply?

The researchers conducted a review of the literature using appropriate support tools, such as models, software, and existing studies that are necessary and unavoidable when carrying out research (Aryanpur et al. 2019; Majumdar and Deutch 2018).

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

Literature Review

Many studies have pointed out the importance of calculating the environmental costs of electricity generation and its internalization in total production costs and its impacts on the development of electricity generation and the environment. Table 1 presents some of these studies.

It is noteworthy that only two studies conducted in 2007 were found in the review of the literature with a focus on the role of environmental cost internalization in electricity generation costs and its contribution to electricity supply, while there are many studies on the development of renewable energies. Another point about the studies presented in Table 1 and other related research is their significant limitations, such as the lack of a comprehensive and appropriate method to calculate external and environmental costs, the failure to consider all environmental effects (most studies have investigated the effects on human health), failure to take into account all pollutants produced by the electricity generation sector (mainly focusing on the air pollutants and greenhouses), standardization of study areas, etc. Thus, there is no comprehensive research on the role of the environmental cost internalization of electricity generation on the costs of electricity generation, investment, and supply, along with the environmental and technical issues simultaneously. Even if there are some studies, they have considerable limitations. In this study, it has been tried to make a complete review considering all the shortcomings.

Methodology and Data

The present study investigated a set of models and relationships for medium- and long-term planning of electricity generation development up to 2030 and 2050 using research scenarios with a mathematical optimization approach.

Area of Study

Iran is one of the countries with the largest fossil energy resources in the world (second in terms of gas and fourth in terms of oil resources) (IEA 2015; Ardestani et al. 2017). Accordingly, electricity generation in this country takes place mainly by fossil fuel power plants. According to statistics, about 92% of electricity in this country is generated by thermal power plants (the share of hydropower and nuclear and renewable power plants is 5% and 2.7%, respectively) (Tavanir 2017b), consequently producing large amounts of pollutants.

According to the statistics on electricity consumption in various sectors, the consumption has increased from about 184–237 thousand Gwh during the years 2010–2016 (Ministry of energy 2018), with a small share of clean and renewable energy in its production (Tavanir 2017a). Also, the electricity consumption of the country has reached about 306 thousand Gwh by the end of 2021. The share of clean and renewable power plants was around 1% (Ministry of Energy 2022).

The consumption of fossil fuels for natural gas, fuel oil, and gasoline was 69453 million m^3, 3770 million liters, and 4936 million liters, respectively, in this industry in 2016 (Tavanir 2017b), and by the end of 2021, it has reached 23,274 million m^3, 2142 million liters, and 10,392 million liters, respectively. Accordingly, the increase in electricity demand in future years will lead to an increase in the demand for these fuels. The current structure of fossil fuel and energy consumption in this industry is not pleasant and

Table 1 Summary of available studies on the internalization of environmental costs of electricity generation

Study	Results	References
Economical evaluation of electricity generation considering externalities	Wind power generation has the lowest cost, followed by power generation in combined cycle power plants. Even with external costs, photovoltaic solar power plants are expensive. Considering environmental costs, the production costs of solar power plants need to decrease by about 60% to be economically competitive with other power plants	(El-Kordy et al. 2002)
Environmental Externalities, Market Distortions and the Economics of Renewable Energy Technologies	The development of renewable energy depends on the proper pricing of fossil fuels and affects external impacts significantly	(Owen 2004)
Internalizing externalities of electricity generation: An analysis with MESSAGE-MACRO	Environmental cost internalization would decrease global CO_2 emissions from about 5% to 3%, and sulfur dioxide emissions will also reach the minimum. Besides, investment costs in electricity generation will increase from 0.2 to 1.2 cents per kilowatt-hour in 2010	(Klaassen and Riahi 2007)
Internalization of external cost in the power generation sector: Analysis with Global Multi-regional MARKAL model	Desulfurization methods in power plants and the reduction of nitrogen oxides have a significant impact on the external costs of electricity generation and reduction of local pollution	(Rafaj and Kypreos 2007)
EN35 External costs of electricity production	According to the external costs calculated in this study, coal-fired and fossil fuel power plants have the greatest environmental impact compared to renewable and clean power plants	("EN35 External costs of electricity production" 2008)
External cost of electricity generation in Baltic States	Environmental costs should be considered in addition to the costs of electricity generation and distribution to achieve the development of clean and renewable energies	(Streimikiene et al. 2009)
Incorporating life-cycle external cost in optimization of the electricity generation mix	If external costs are included in the modeling of electricity generation, the share of renewable energy, especially wind and hydropower, will increase; otherwise, gas power plants will be a priority. External costs also account for a significant percentage of total electricity generation costs	(Rentizelas and Georgakellos 2014)
Assessing the environmental externalities for biomass- and coal-fired electricity generation in China: A supply chain perspective	Renewable biomass power plants have 25–37% higher electricity generation costs than coal-fired power plants. If environmental costs are taken into account in the total electricity generation costs, the percentage will be 2–14% lower	(Wang et al. 2019)
	External costs are a practical tool for optimal prioritization of power generation options. It is also necessary to always consider the environmental costs of renewable power plants	(Karkour et al. 2020)

has many environmental impacts in addition to numerous economic and social effects.

There has been no attention to the negative external environmental costs due to various environmental effects of electricity generation methods so far, leading to considerable damage to industry, economy, government, and society. Therefore, it seems necessary to examine and predict the effectiveness of cost internalization as a good strategy for sustainable electricity supply and emission reduction. This is important as it provides a suitable perspective for the establishment of a sustainable electricity generation system through an increase in the share of renewable energy and other solutions.

Model of Study

The planning for electricity generation and supply aims to identify the best policies that can be achieved with all energy goals, including the optimal development of electricity generation, reduction of greenhouse gas emissions and other pollutants, development of the existing resources, increasing productivity through a reduction in fossil fuel consumption, production and investment cost reduction, etc., by defining various appropriate relationships and scenarios (Di Sbroiavacca et al. 2016).

The present study has the electricity generation planning model considering all the factors presented to investigate the role of environmental cost internalization in electricity generation costs.

Power generation planning shows what technologies use available resources to meet the demand for end-use electricity, given the various constraints, while minimizing the total discounted cost of the power generation system.

Therefore, this study defined and analyzed sustainable electricity generation scenarios according to the objectives presented in the previous sections as follows:

- Scenario 1: Identifying the situation of electricity generation and supply of the country in a probabilistic way and based on the changes in the existing trend by minimizing the costs of private electricity generation (Eq. 1).

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

- Scenario 2: Identifying the situation of electricity generation and supply of the country in a probabilistic way and based on the changes in the existing trend with the minimum total costs of electricity generation (Eq. 2).

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

In Eqs. 1 and 2, I, F, and V represent investment, fixed, and variable maintenance operation costs, respectively. E and S also show the environmental costs and residual values in the year y, determined based on the type of technology, operating hours, power generation capacity, emissions, etc.

Table 2 presents some initial assumptions and parameters used in Scenarios 1 and 2 in this study.

Table 2 The main and basic assumption for modeling

Technologies	Costs (c$/kwh)			Residual capacity (Kw)	Life (year)	CF	Eff (%)
	$V_{O\&M}$ ($/kwh)	$F_{O\&M}$ ($/kw)	Inv ($/kw)				
WHR	0.001	57.6	750	0	20	0.5	100
Solar (PV)	0.005	26.1	933	42800	20	0.22	100
Wind (onshore)	0.005	11.9	1100	191000	20	0.36	100
Hydro (mini)	0	16	1895	83300	20	0.38	100
Hydro (Large)	0	13.5	1500	1E+07	20	0.35	100
Geothermal	0	13.2	3830	0	20	0.85	100
Gasifier	0.03	0	3000	2000	20	0.73	28
Landfill	0.04	94.5	2407	1600	20	0.73	27
Nuclear	0.01	57.6	5530	915000	30	0.8	33
Diesel	0.0005	25	380	283800	30	0.75	35
Anaerobic digestion	0.04	23.1	2650	3000	30	0.73	28
Steam	0.0005	12.3	1100	1E+07	30	0.8	42
NGCC	0.0004	9.8	700	2E+07	30	0.7	65
GT	0.0006	13.2	450	2E+07	30	0.7	37

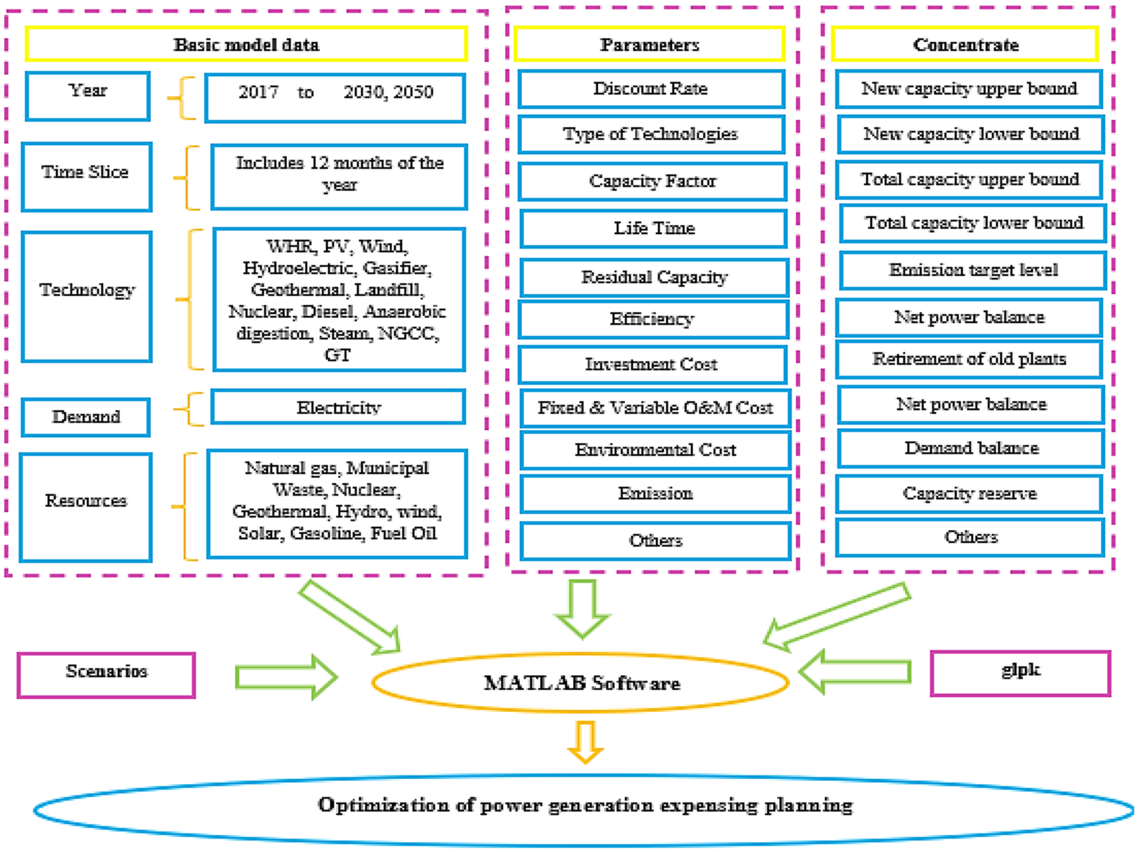


Fig. 1 Schematic representation of the research methodology

Other constraint functions considered in modeling include the maximum number of units to be established, the capacity of each technology, network reservation, net power generation, LOLE reliability, supply of electricity demand, limitation of renewable energy sources, retirement limitation of old power plants, limitation of fossil energy (fuel) supply.

Figure 1 provides a schematic representation of the research methodology.

It is noteworthy that an accurate prediction of electricity consumption is required to manage the sustainable supply of electricity in the long run (Zhang et al. 2020; Lee and Tong 2011), which needs the prediction of electricity demands (Khan et al. 2020; Lee and Tong 2011) using a significant volume of basic information and calculations (Fig. 1).

The required electricity demand until 2050 was estimated based on comprehensive studies conducted in the country and presented in modeling (Ziyaei et al. 2021a).

According to the estimated demand in this study, electricity demand will reach 411 thousand Gwh in 2030 and 1137 thousand Gwh in 2050 (electricity demand had an average annual growth of 4% compared to the base year 2017). Data of the study were divided into 4 categories of demographic, economic, technical, and other data collected based on information in the time series 2010–2017. Major consumer sectors also included the domestic, industrial, transportation, agricultural, commercial, and public sectors and street lighting (Ziyaei et al. 2023).

The calculation of environmental costs is required to examine and evaluate the effects of environmental cost internalization related to the electricity generation sector (Karkour et al. 2020; Mousavi Reineh and Sadatinejad 2020). This study has used a simple transfer-benefit method for estimations because the calculations are complex and difficult.

It is necessary to estimate the cost of damage caused by each of the released pollutants separately from a natural, human, or social disaster to accurately analyze and estimate environmental costs (Van den Bergh and Botzen 2015). The Extern E project conducted for the European Union from 1990 to 2005 is one of the most comprehensive efforts to estimate the external costs of electricity generation (Bickel et al. 2005). This study has calculated environmental costs considering the effects of pollutant emissions on products, materials, biodiversity reduction, soil acidification, nitrification, land degradation

Table 3 Important assumptions for the calculation of environmental costs

Title	Value	Explanation and References
GDP deflator index (Iran)	213.45	(Iran-GDP deflator), References: (Index mundi, 2019)
GDP deflator index (EU)	102.93	(GDP deflator: linked series (base year varies by country)-European union), References: (The World Bank, 2019)

for power plant construction, etc. for different pollutants, including ammonia, volatile organic compounds, nitrogen oxides, particulate matter, sulfur oxides, etc. Degradation and biodiversity reduction were assessed using the Willingness to Pay (WTP) method (Bickel et al. 2005).

Taking into account Eq. 3, the external environmental costs of various electricity generation methods for the country under study were estimated and presented in the table below:

$$WTP_p = WTP_s \times \left[\frac{D_p}{D_s}\right] \quad (3)$$

In this relation, WTP_p indicates the willingness to pay or the environmental cost of the study site (Iran), WTP_s is the estimated environmental cost in the EU, and D_P and D_S show the rate of GDP in Iran and the European Union, respectively. Table 3 presents important assumption for the calculation of environmental costs.

Given the methodology provided in Fig. 1 and considering the electricity demand, research objectives, and other functions, MATLAB software was used to predict and plan electricity generation and also internalize environmental costs in the cost function of electricity generation to decrease the resulting costs.

MATLAB is an optimization model used to plan long- and medium-term energy systems, analyze energy policies, and develop scenarios (MathWorks 2021).

The methodology of this model starts with writing a comprehensive code and continues as follows:

- Determining data and indicators (parameters and sets);
- Listing and defining titles, variables, relations, and equations (constraint and objective functions);
- Determining constraints, initial values, and special options;
- Introducing optimization solver and problem-solving (This model has used glpk solver and linear optimization.); and
- Representing the results and model output and analyzing the final results.

Results

According to the review of the literature and the presented methodology, the results of the research are as follows:

Environmental Costs

The environmental costs of electricity generation in Iran were calculated for various technologies and presented in the following figure. (Fig. 2).

As shown by the results (Table 1), these costs were higher in fossil energy sources than other sources and much lower or insignificant in renewable energy sources. Thus, the use of renewable energy sources seems necessary to deal with the environmental impacts of electricity generation. The highest environmental costs were related to diesel, steam, combined cycle, and gas power plants, respectively. Therefore, since these power plants account for the highest electricity

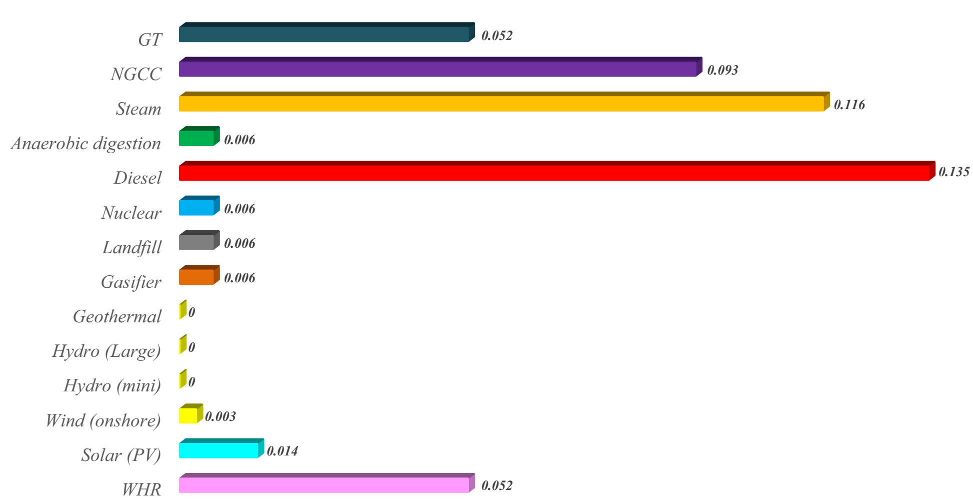


Fig. 2 The environmental costs of electricity generation in Iran by type of power plant (dollar cents per kilowatt-hour)

generation in Iran (about 92% of total electricity generation), the damage and possible costs imposed on society and the government would be very high. Also, the environmental impact of renewable power plants is mainly local, while the environmental impact of fossil fuel and nuclear power plants may be global, incurring costs on the whole world.

The initial investment costs of renewable power plants are higher than those of fossil fuels. Renewable energies are much more expensive and cannot compete with fossil energy sources in Iran because of a lack of appropriate technologies. However, if the environmental impacts and environmental costs of fossil energy sources are considered in the final cost of electricity, it may be possible to give them a priority.

It is also important to note that not all types of renewable energy are necessarily clean. Combustion in biomass power plants or gas emissions from the water behind dams and vapors in geothermal power plants are examples of emissions that incur environmental costs, although low. This issue has been taken into account in Fig. 2 and also in calculations.

Electricity Production

Modeling showed that the total electricity production according to its demand will increase from 254767.9 Gwh in 2017 to 411421.4 in 2030 and 963981.2 (3.8 times) in 2050.

Figure 3 presents the changes in electricity generation based on its demand in Scenario 2 and the internalization of environmental costs compared to scenario 1 (with no environmental cost internalization) by type of power plant.

As shown by the results, the electricity generation was the same in both scenarios according to the electricity supply and demand of the country. However, internalization of the environmental costs of electricity generation in the basic scenario leads to significant changes in the share of each power plant in electricity generation. The following table provides the share of each type of power plant in electricity generation in scenario 2 compared to the base scenario. Table 4 presents changes in the share of various power plants in electricity generation by environmental costs internalization compared to scenario 1.

According to the Table 4, the share of renewable power plants shows 5.3% and 2.3% growth in 2030 and 2050, respectively, by environmental cost internalization and minimizing the electricity generation costs compared to the baseline scenario. The decrease in the growth of the share of renewable power plants in 2050 compared to 2030 is related to the consideration of the technical and economic potential of renewable power plants in electricity generation in constraint functions when modeling. Meantime, the shares of wind, small hydropower (< 10 MW), and solar power plants are higher.

Also, the share of fossil fuel power plants (thermal, gas, combined cycle, and diesel) in the country's electricity generation decreases every year. Given that fossil fuel power plants considerably pollute and impose high environmental

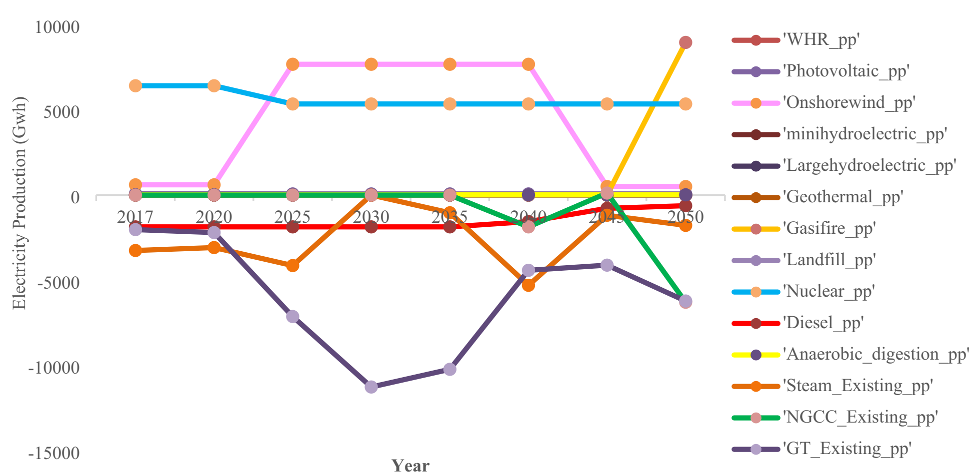


Fig. 3 Changes in electricity generation by environmental cost internalization compared to the baseline scenario

Table 4 Changes in the share of various power plants in electricity generation by environmental cost internalization compared to scenario 1 (%)

Power plant/year	2017	2020	2025	2030	2035	2040	2045	2050
Renewable	0.3	0.3	2.3	1.9	1.5	1.2	0.1	1
Large hydro electric	0	0	0	0	0	0	0	0
Nuclear	2.5	2.4	1.6	1.3	1.1	0.9	0.7	0.6
Thermal	− 2.8	− 2.6	− 3.9	− 3.2	− 2.6	− 2.1	− 0.8	− 1.5

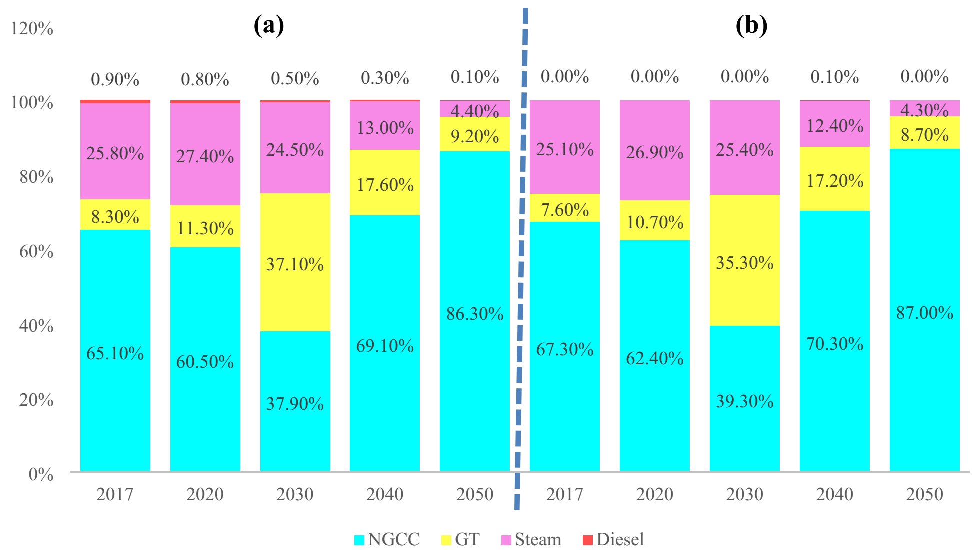


Fig. 4 Changes in electricity generation of thermal power plants by environmental cost internalization, Scenario 1 (**a**), Scenario 2 (**b**)

costs on the environment and society, the minimization of these costs in the objective function reduces the share of these plants. However, the share of this power plant in the country's electricity generation is about 82% in the base year and 92% in 2050, accounting for a large part of electricity generation. This is also because of the low costs of private electricity generation, including initial investment and fossil fuel supply costs (Iran has huge fossil fuel resources, and heavy subsidies are allocated to the fuel supply sector to generate electricity by thermal power plants) and the longer life of these technologies.

It is important to note that despite the high share of thermal power plants in electricity generation in this country, electricity supply by thermal power plants has changed under the effects of environmental cost internalization (Fig. 4).

As shown, the share of diesel, thermal, gas, and combined cycle power plants was 0.9, 25.8, 8.3, and 65.1%, respectively, in the base year in scenario 1. However, the same share was 0.0, 25.1, 7.6, and 67.3%, respectively, taking into account environmental costs in scenario 2.

Therefore, combined cycle power plants have the largest share in the base year in both scenarios, and their share in electricity generation will increase by 2% environmental cost internalization. Also, the largest share in both scenarios 1 and 2 was related to combined cycle power plants in 2050, accounting for 86.3% and 87%, respectively, while the share of other power plants will decrease due to pollution, except for gas power plants. The impact of environmental costs in the two scenarios has decreased in 2050 compared to the base year, which is due to the constraints imposed in the functions, including the minimization of electricity generation costs.

Input Fuels

Considering the practical capacity of the country's electricity generation, there is a need for huge capacity building for the country's electricity generation, which requires more fossil fuels due to the share of thermal power plants. The Table 5 shows the amount of fuel demand for electricity generation in the country.

As shown, fuel savings occur when environmental costs are applied to the electricity generation function by 124 billion m^3 equivalent to natural gas, leading to a reduction in the share of fossil fuels in electricity generation.

Meantime, the share of fossil fuels will be about 94%, while biomass and renewable fuels (including water, the solar, wind, and geothermal sources) will account for about 6%. Also, the share of nuclear fuel is almost zero, and the share of renewable and clean fuels will increase by environmental cost internalization. As these fuels must meet the shortage of production through fossil fuels, and the efficiency of these fuels is less than fossil sources, more renewable and clean fuel resources are required to generate equal amounts of electricity.

Environmental Emissions

Environmental cost internalization in total electricity generation costs will lead to a rapid reduction in environmental

Table 5 The fuel demand by the country's power plants in different scenarios (billion m^3 of natural gas)

Scenario	2017	2020	2030	2040	2050
1	1761.7	1914.3	3276.7	4596.2	6844.2
2	1760.5	1912.8	3223.0	4555.5	6817.5

Table 6 Reduction of environmental emissions in scenario 2 compared to scenario 1 per year by type of power plant (%)

Power plant/year	2017	2020	2030	2040	2050
Renewable	0	0	0	0	– 0.1
Large hydro electric	0	0	0	0	0
Nuclear	0	0	0	0	0
Thermal	– 99.9	– 99.9	– 99.9	– 99.9	– 99.8

emissions. The Table 6 shows the decrease in environmental emissions compared to Scenario 1.

As shown in the table, thermal power plants account for the largest reduction in environmental emissions in Scenario 2 compared to Scenario 1. The highest and lowest shares in the country's electricity generation among thermal power plants are related to the steam and diesel types, respectively (Fig. 5). Also, a very small amount (0.1%) of emissions from renewable power plants has decreased in 2050, which is related to biomass renewable power plants of the gasification type.

The results show a decrease in the emission of electricity generation pollutants during the period (2017–2050) by 135,856 thousand tons equivalent CO_2 (Table 7). This decrease is associated with the increase in the share of less polluting power plants (renewable and clean), the reduction in the share of steam and gas power plants, and the increase in the share of combined cycle power plants in electricity generation in thermal power plants due to lower pollution of combined cycle power plants than steam and gas ones. Table 7 shows reduction of environmental emission in scenario 2 compared to scenario 1.

Costs

The results showed that environmental cost internalization in the total costs of electricity generation would play a key role in the implementation of development policies in the long run. The impact of environmental cost internalization to assess the electricity generation costs in different technologies is as follows. (Fig. 5).

As shown, environmental cost internalization as a function of total electricity generation costs has led to a change in electricity generation costs from $ 5491 billion in 2017 to $19,041 billion in 2050 in scenario one and from $ 5286 billion to $ 18,752 billion in scenario 2. The total reduction in electricity generation costs is projected to be around $ 6337 billion over the entire period (Figs. 6).

The results also show that combined cycle and steam power plants have been the cheapest power plants in scenario 1 in 2017, with no consideration of environmental costs, and in 2030 and 2050 as well. The same was true for scenario 2 considering the environmental costs, which can be due to the low costs of construction, repair, maintenance, operation, and fuel in thermal power plants and the lack of necessary environmental penalties and strict laws to reduce environmental pollutants in this sector.

The following figures (Fig. 7) show the cost of initial investment in electricity generation in different years and various technologies in both scenarios.

As can be seen, the highest investment cost for electricity generation is related to gas power plants in 2017, in both scenarios, while it is related to the biomass power plant from anaerobic digestion type in 2030 and 2050 in scenario 1. However, the lowest investment cost compared to the actual electricity generation (dollars per kilowatt-hour) is related to thermal power plants of steam and combined cycle types.

Fig. 5 Emission of environmental pollutants in various types of thermal power plants (thousand tons equivalent CO_2)

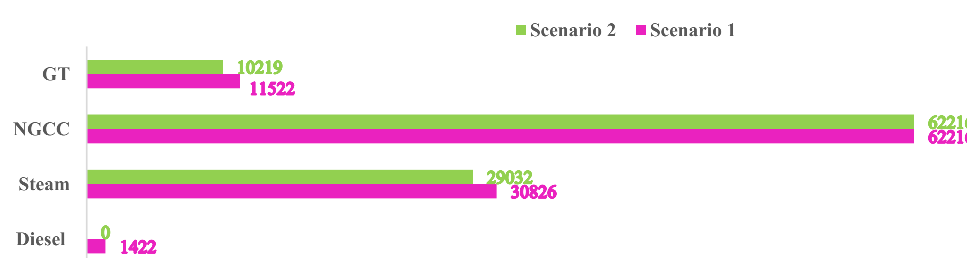


Table 7 Reduction of environmental emissions in scenario 2 compared to scenario 1 per year by type of power plant (thousand tons equivalent CO_2)

Power plant/Year	2017	2020	2030	2040	2050	Sum (2017–2050)
Renewable	13.1	13.1	10.9	10.9	2763.2	18001
Large hydro electric	0	0	0	0	0	0
Nuclear	0	0	0	0	0	0
Thermal	– 4519	– 4535	– 4050	– 3399	– 7537	#####
Sum	– 4506	– 4521	– 4039	– 3388	– 4774	#####

In Scenario 2, solar and biomass power plants of types landfill and nuclear had the highest investment costs in electricity generation in 2030 and 2050, and the share of other power plants increased compared to Scenario 1. This is because of the application of environmental costs of electricity generation in scenario 2 compared to scenario 1, leading electricity generation plans toward renewable and clean power plants with higher investment costs and lower production efficiency.

The table below (Table 8) also presents the role of environmental cost internalization in electricity generation on the initial investment cost of power plants compared to Scenario 1.

As the results show, the investment costs of power plants will decrease when environmental costs are applied to the total costs. This is because of changing policies of electricity generation from power plants with higher investment costs to those with lower investment costs taking the constraint of emission reduction and cost minimization into account. The total reduction in investment costs over the entire period is 155.7, 308.4, 2425.7, and 402,732 billion US dollars for renewable, large hydropower, nuclear, and thermal power plants, respectively. Thus, thermal power plants with fossil fuels have the largest share of the reduction.

Table 8 The role of environmental cost internalization in investment costs (US $ million)

Power plant/year	2017	2020	2030	2040	2050
Renewable	– 4.7	– 4.7	– 4.2	– 4.2	– 9.3
Large hydro electric	– 9.1	– 9.1	– 9.1	– 9.1	– 9.1
Nuclear	– 79.3	– 79.3	– 69.3	– 69.3	– 69.3
Thermal	– 5228	– 5637	– 9151	– 14452	– 22899

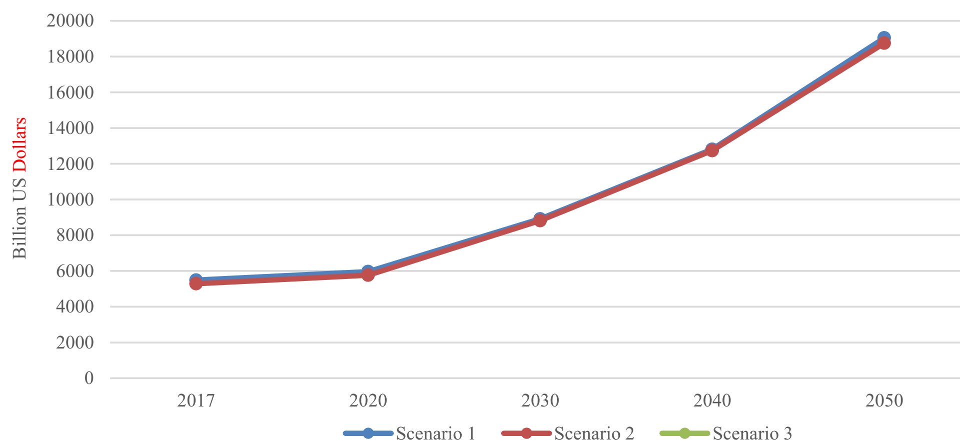


Fig. 6 The role of environmental cost internalization in the total cost of electricity generation

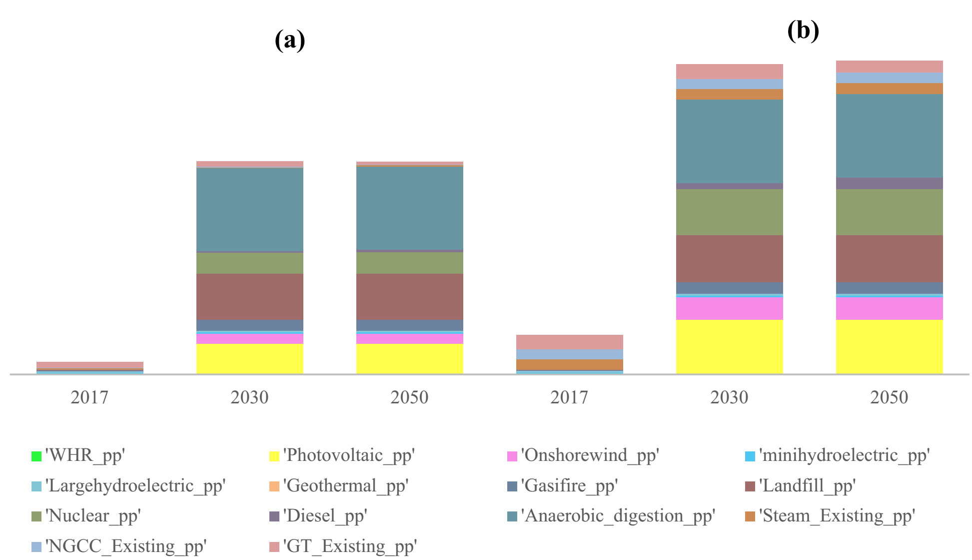


Fig. 7 Investment cost of electricity generation in different years by type of power plant Scenario 1 (**a**), Scenario 2 (**b**)

Discussion

Comparing the Results

This section presented a review of general findings from the previous section, followed by a comparison with the results of other studies.

Based on the results of this study, fossil power plants have 11 times higher environmental costs than renewable and clean power plants. So that the thermal power plants, renewable and clean power plants, and nuclear power plants contribute 60, 9, and 15% of the total power generation costs, respectively. In conclusion, thermal power plants generate private power at lower costs than renewable and clean sources. Also, the environmental costs of fossil energy sources are much higher than renewables. It was found that some renewable sources and clean sources have relatively negligible costs. Research by European Union 2003; Kåberger 2018; Machol and Rizk 2013; Nicoletti et al. 2015; Rabl and V. Spadaro 2016; Shahzad 2012; Sims et al. 2003, yielded similar results. It was found that environmental cost is associated with steam, combined cycle, and diesel power plants than gas power plants. These power plants use heavy residual fuel oil (like Mazut) rather than natural gas, which has less pollution. It was similar to the findings of Torki and Abedi 2011; Fouladi Far et al. 2016; Mousavi Reineh and Sadatinejad 2020, research. Furthermore, renewable power plants have higher private power generation costs (including initial investments, maintenance, and operation) than fossil fuel-powered thermal power plants. Biomass, geothermal, and small hydropower plants have the highest initial investment costs in constructing a renewable energy plant. Other researchers, such as Abbas et al. 2015; Longdon et al. 2022; Majdzadeh et al. 2016; Motahary et al. 2014; Nouchedehi et al. 2014; Ziyaei et al. 2021a, have reported similar results. There are several reasons for the high initial investment costs associated with constructing renewable power plants, including the lack of indigenous facilities and knowledge in producing equipment for the power plant manufacturing, Iranian sanctions, currency fluctuations, and other technical and political factors.

As a result of internalizing environmental costs and minimizing the power generation cost function compared to the base scenario, the share of power generation from renewable sources will increase in 2030 and 2050 (Tables 4, 5, 6 and 7 and Fig. 3). Wind, small hydropower, and solar power plants make up a significant share of this shift due to fewer environmental effects, higher potential, and country policies. The internalization of environmental costs (even a small percentage) significantly changed Iran's power supply portfolio and increased the share of renewable and clean power. Research results from streimikiene and Alisauskaite-Seskiene 2014; Nguyen 2008; Sener and Fthenakis 2014, support these findings. Additionally, thermal power plant shares were modified so that the diesel and steam power plant shares would reduce and the combined cycle power plant's share would increase. Meanwhile, gas power plants could not compete with combined cycle and other thermal power plants, even though they have lower environmental costs. Several factors contribute to this, including initial investments, maintenance, and operation costs, fuel accessibility, power generation capacity, infrastructure, and regional, national, and international policies. Other modeling functions take into account the mentioned items (Table 8).

Additionally, a significant proportion of fossil fuel consumption will decrease by internalizing the environmental costs of power generation. There is a direct connection between thermal power plant fuel consumption and environmental emissions. Results show that implementing the internalizing environmental costs policy has reduced emissions from fossil and renewable biomass power generation (gasification) by 100% in 2030 and 2050. The same result is presented in Jorli et al. 2018; Kousugi et al. 2009; Owen 2006; Nguyen 2008, studies as well.

Furthermore, taking the negative environmental costs of power generation into account, the total cost of power generation in 2030 and 2050 will reduce by 99 and 289 billion dollars (1 and 1.5%). Heat recovery, small and large hydropower and geothermal technologies will provide the most affordable power supply in 2050, among the other methods. However, they will only contribute 5% to Iran's power generation. Also, after the presented methods, fossil power plants of the combined cycle type generate power at the lowest cost, and approximately 87% of the country's power will come from them by 2050. Negative environmental costs and cost reductions in power generation were considered in this study. Despite the growth of the power supply portfolio, renewable and clean power plants are not a priority and cannot compete with combined cycle power plants.

The total power generation cost may have been miscalculated using the transfer-benefit approach in calculating environmental costs. As Jorli et al. 2018; Rabl and Spadaro 2016; Rabl et al. 2005; Sakulniyomporn et al. 2011; Spadaro and Rabl 2008, has shown, even with uncertain calculations, it's better to calculate and analyze them out than not. These calculations can justify policies to reduce environmental pollution emissions, replace renewable energy with fossil fuels, shift power supply portfolios, and generate power efficiently, sustainably, and environmentally friendly.

Overall, internalizing the negative environmental costs in the total power generation costs regardless of the method is an efficient and low-cost process to shift the power supply portfolio toward clean, renewable, and sustainable energy sources. In addition, it has been used to evaluate the current power generation efficiency and compare various technologies' technical, economic, and environmental performance. Fossil energy resources in Iran are used without considering the environmental impact and costs of different power generation methods. Also, fuel delivered to thermal power plants is subsidized in this country. It is, therefore, not enough to internalize negative environmental costs to change power generation methods and develop clean and renewable power plants. The country's energy sector will need profound changes to implement this policy, such as actualizing fuel prices and structural reforms. However, internalizing environmental costs may be an effective way of prioritizing power generation possibilities.

Limitation

In this study, all technical, economic, and environmental aspects are considered in modeling; however, there are limitations in this study, as described below.

Several limitations of the study can be attributed to the modeling process. Specifically, the technical components of the energy system are intricately interconnected with the political and economic parameters of the country. Therefore, analyzing policies that aim to reduce emissions and externalities and improve power generation techniques requires a macro- and multilateral approach. In addition, the outcomes should be viewed caution due to the inherent shortcoming of the two-objective optimal model in this study, which selects the outcomes of the most optimal generation technology based on production and externality costs when all modeling constraints are satisfied. Moreover, the modeling is accompanied by many uncertainties since it does not account for sudden and unexpected changes in the price or type of fuel consumed or variations in available resources or country policies. This may lead to differences between real conditions and model results. There are also the following limitations to the study:

1. Calculating the negative external costs of various electricity production methods is difficult, and there is no comprehensive method that can prevent deviations and errors in calculations. It is necessary to examine each country's external and environmental costs more carefully, primarily based on whether the study area is developed or developing. Other factors are also considered in the calculations of both contexts, such as population density, meteorological conditions, emissions from current electric generation, mortality rate, natural resources, and resulting impacts. Consequently, the calculated damages for each amount of produced pollutant mainly depend on the location and physical properties of the emission source, which are not considered in the present study and need more analysis.
2. The model is not analyzed for sensitivity or risk, which would provide insight into the weak and strong points of different types of energy sources.

The following are also limitations associated with Iran's policy:

1. Insufficient requirements for implementing environmental regulations and rules.
2. Lack of indigenous facilities and knowledge to manufacture equipment for renewable and clean power plants manufacturing;
3. Sanctions against Iran and fluctuations in the exchange rate;
4. Distorting the energy prices by assigning subsidies to the fuel even without considering negative environmental externality costs.

Conclusion

This study aimed to investigate the effects of internalizing the negative environmental costs of various electricity generation methods on total electricity generation costs. We used the simple benefit transfer method to calculate the environmental costs, which may also lead to deviations in the calculation results. According to the results, clean and renewable technologies cannot economically compete with the current technologies in the electricity market as the negative environmental costs of electricity generation are not internalized into the electricity price. Internalization of environmental costs into the total energy generation costs would undermine economic competitiveness. This is due to the model's sensitivity to the initial investment in technology and pricing and type of fuel. The subsidized fuel price in Iran, coupled with the lower investment and maintenance cost of thermal power plants, has prevented this country from developing renewable and clean energy sources.

While these calculations may deviate from the actual figures, the results of this study demonstrated lower environmental costs of electricity generation from renewable and clean energy sources. Accordingly, using clean and renewable energy sources is crucial to mitigating the negative environmental impacts of electricity generation. Even with higher initial investment costs in electricity generation, solar and wind energies can still compete with fossil fuels and become a priority, even for countries with abundant fossil fuels. Thus, minor changes in calculating these costs will not have little impact on this main objective, and internalizing electricity generation environmental costs into electricity generation costs can provide a sustainable environmental solution. Meanwhile, using other existing methods requires substantial investments and numerous new infrastructures, which are not easily achievable.

Ultimately, we suggest that appropriate methods (apart from benefit transfer) should be used to calculate quantitative external and environmental costs and the pricing of electricity generation costs, which can result in a sustainable electricity generation system. Therefore, establishing a reasonable and comprehensive cost accounting mechanism for developing the renewable and clean energy sector can play a crucial role in Iran. Besides, its internalization would also enable the country to take the necessary measures to develop renewable and clean energy, improving both the economic and environmental performance of the country's electricity generation sector through win–win policies.

Author Contributions The manuscript has five contributions including, SZ: Conceptualization, Data curation, Investigation, Methodology, Software, Formal analysis, Writing—original draft, Visualization. MP: Supervision, Investigation, Formal analysis, Writing—review and editing, Validation. DM: Formal analysis, Writing—review and editing, Validation. AK: Writing—review and editing. HG: Writing—review and 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.

Ethical Approval Not applicable.

Consent to Participate Not applicable.

Consent to Publish Not applicable.

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