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Original Article

Determining the Calculation and Application of Virtual Water in the Environmental Cost of Electricity Generation with Emphasis on Renewable Energy (Case Study: Iran)

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ABSTRACT

Background: The article evaluates techniques for estimating water consumption and environmental costs in power plants, highlighting the life cycle analysis approach as a comprehensive method. It aims to present a thorough method for calculating virtual water and its impact on environmental costs.

Methods: Therefore, this research used a non-probability sampling method to determine 50 different power plants in Iran that produce their electricity from thermal, gas, and combined cycle power plants. The study adopts a life cycle analysis to evaluate water consumption techniques and the environmental costs of power plants. Additionally, the Levelized cost of electricity was utilized to determine the final cost of electricity generated by all kinds of power plants. Also, two scenarios were introduced using the LCOE method for better decision-making by managers and were discussed.

Results: The analysis of the article indicates that the second scenario is the optimal choice for electricity generation, characterized by a decrease in carbon dioxide emissions and enhanced economic growth. It is imperative to augment capacity in the solar and wind sectors by 5% and increase the efficiency of power plants to specific levels for combined cycle, heat, and gas power plants, respectively, to perform the country's environmental commitments under the Paris Agreement.

Conclusion: The findings suggest that diversifying the energy portfolio through renewable resources not only mitigates greenhouse gas emissions but also contributes to economic growth by lowering the Levelized cost of electricity production.

Keywords: Virtual Water; Environmental Costs; Iran; Lifecycle; Levelized Cost of Electricity

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Introduction

Water Scarcity and Its Impact on Industries

Water scarcity has become a significant issue affecting various industries, especially electric power plants that require large quantities of water for their operations [1]. Water is deemed a fundamental constituent of life and represents one of the significant challenges of the current era, which may lead to several favorable and unfavorable global developments in the subsequent half-century. As the demand for water and energy continues to soar, the interdependence between these two resources is expected to deteriorate in the coming years [2].

The importance of the International Energy Agency report, which emphasizes the urgent nature of the global water crisis alongside increasing levels of carbon dioxide emissions, can be understood. The water stress index is employed to investigate this crisis, which commonly denotes the correlation between total water consumption and availability. Figure 1 illustrates the percentages of countries' water stress index, where high values signify a water shortage [3]. Water and energy are essential components that significantly influence food security, overall quality of life, and economic prosperity [4]. Addressing the water scarcity crisis demands either the creation and discovery of new resources or conserving the existing resources and their planned use [5].

Delbourg & Dinar [6] referred to the increase of local production (agricultural products) in places with insufficient access to water due to the lack of security, development, and harmful water management.

The Relationship Between Water and Energy

It is important to understand that the relationship between water and energy is a complex and multifaceted subject [7]. Energy is required to extract water from its sources, and all energy production processes depend on its existence. Water is an essential component in the equipment and technologies used in the energy production chain, including extraction, processing, purification, and conversion. Cooling towers, heat exchangers, and chemical reactors are some of the equipment that require water [8].

The cooling system is a critical factor that determines the amount of water used in power plants, with different systems varying in water consumption rates, initial costs, and annual expenditures [9].

Environmental Costs of Power Generation

However, the contribution of clean energy to electricity production is currently limited, with power plants that use wind, solar, heating, gas, and combined cycle technologies having high water consumption rates. These power plants also contribute to pollution and environmental costs, which can destabilize the electricity production system. To ensure transparency in the pricing mechanism within the energy sector, it is crucial to provide an accurate estimation of environmental costs and integrate them into the final cost structure [10, 11]. Environmental cost refers to expenses related to the production, transmission, transformation, and energy consumption of goods that affect society and the environment but are not included in the pricing of goods and services [11, 12].

We are looking for approaches such as increasing productivity or replacement because environmental damage assessment is a complex assignment. Therefore, paying attention to the Environmental consequences of manufacturing, industrial, and construction activities is not a luxury choice but a vital necessity [13]. For several

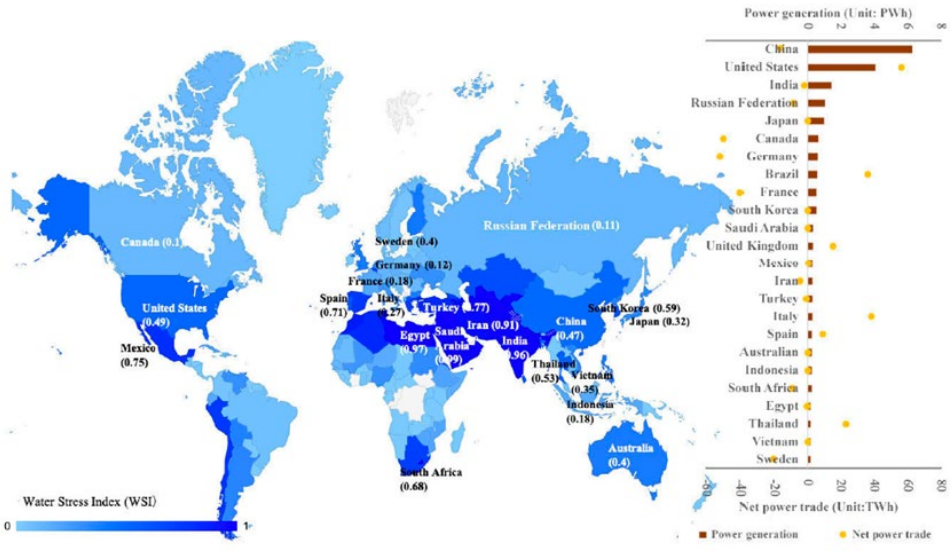

Figure 1: Global distribution of global water shortage, regional electricity generation, and net trade in 2017

years, awareness of social costs has been a concern of ministries and organizations. The health damage economic evaluation plan caused by air pollution in Tehran and the energy environmental survey project in the Islamic Republic of Iran have been carried out to determine the Environmental injury caused by Tehran's air pollutants [14].

Renewable Energy and Its Benefits

Renewable energy sources, such as solar power, wind energy, rainfall, tidal forces, wave energy, and geothermal power, encompass environmental costs within their operational frameworks [15, 16].

Electricity is an essential capital in modern societies, and is applied to meet basic daily needs. In addition, electricity is the economy backbone because is the manufacturing and service industries activity key [17]. Almost 400 power plants have been built in Iran by 2012. Moreover, natural gas was the highest fuel used in electricity production by 2009, with the largest electricity generation share done by steam power plants, while diesel power plants had the lowest production share. Annually, Iran exports 5.5 TWh of electricity to the seven neighboring countries of Afghanistan, Pakistan, Iraq, Turkey, Armenia, Azerbaijan, and Turkmenistan. The list of the power plants is mentioned in Table 1.

Creating the European electricity network as a virtual water trading network for countries with balanced pay electricity demand described by Chini & Stillwell [9]. Ram et al. [18] claimed renewable energies will be significantly cheaper than fossil and nuclear sources for electricity generation in G20 countries by 2030, and their benefits for economic development, improved welfare, environmental protection, and increased energy security more than.

Virtual Water

The concept of "virtual water" is of utmost importance in human life and plays a critical role in the electricity industry, particularly in thermal and solar power plants. Despite being rich in oil reserves, Iran has placed significant emphasis on the development of renewable energy due to the exorbitant price of power plant fuel. Economic analysis reveals that accounting for environmental costs and water footprint, electricity production from domestic renewable power plants can prove to be more cost-effective.

Kumar et al. [19] addressed the cost savings potential by adapting emissions trading in India and as well as, cited the absence of a carbon-emissions trading program associated with the increase in wind and solar energy production. Pischke et al. [20] examined renewable energy policies in five federal states and emphasized the coordination and effectiveness of policy instruments. Hosseini et al. [21] expressed that Iran is in third place in the ranking from the point of carbon dioxide gas emissions, and the government faces the challenges of lack of coordination in reducing energy consumption. Chen et al. [8] stated that international electricity trade is an opportunity to improve the allocation of world water resources with the virtual water concept and analysis of virtual water flow in the power grid system.

Challenges of Virtual Water Management

Virtual water calculations face several significant limitations and challenges that hinder their effectiveness in water management strategies. One major issue is the lack of standardized methodologies for calculating virtual water content, which results in inconsistencies across studies and complicates comparative analyses. Additionally, much of the existing research has predominantly focused on agricultural products, neglecting the virtual water embedded in industrial processes and services, thereby limiting a comprehensive understanding of water use across various sectors [22]. Furthermore, the socio-economic implications of virtual water trade are often inadequately addressed, with studies failing to explore how these flows impact local communities and economies. This oversight suggests a pressing need for interdisciplinary research that integrates economic, environmental, and social dimensions to fully grasp the consequences of virtual water trade. Lastly, environmental costs associated with water use in different sectors are not sufficiently reflected in current virtual water assessments, which can lead to policies that overlook ecological consequences [23, 9].

Many efforts towards sustainable development and facing challenges have increased in recent decades, and global environmental agreements and programs have been implemented.

Various concepts of sustainable development have been proposed since 1980 [24]. The development of greenhouse gas reduction protocols based on increasing the efficiency of power plants, use of renewable energy sources, energy management in-demand sectors, and participation in the Paris Agreement show Iran's actions to reduce greenhouse gases [25].

These measures help to reduce the effects of global warming and realize sustainable development in Iran [26]. Fthenakis & Kim [27] investigated water consumption in diverse types of power plants and showed that renewable energies are better options for reducing water consumption in electrical energy generation.

Virtual Water Calculations

Rabl & Spadaro, [28] evaluated the external costs of pollutants from fossil fuel combustion and concluded using the LCA method is beneficial for choosing low-impact electricity generation technologies. Y.-D. Wang et al. [29] addressed water resources management in sustainable electricity policies, which resulted in the reduction of regional water inequality in three states using sustainable energy standards and efficient resources. Streimikiene & Alisauskaite-Seskiene [30]

assessed the external costs of electricity production in Lithuania by 2030, leading to conclusions for future energy policy decisions.

Delgado Mart [14] expressed the importance of water consumption in power plants, especially in water-scarce areas, and that different variables affect water consumption in the cooling section of power plants. Mousavi et al. 2012 [31] conveyed that Iran's wind industry growth is a competitive option with conventional power plants, and the effect of the subsidy targeting law has a significant impact on the progress of the wind industry.

Policy Implications and Future Directions

A study representing the water consumption of the cement factory with 61.3 million cubic meters showed that we are facing the danger of the remains of the cement industry in dry areas [32]. Morteza Tahamipour Zarandi et al. [33] examined the virtual water trade in water resources management, emphasizing the virtual water crisis in Iran's trade with different countries. Fateme Bezaran and Neda Khosravani, [34] analyzed the emissions of carbon dioxide pollutants by households and economic sectors in Iran. Tahamipour Zarandi [35] took a look at the study of virtual water trading in water resource management, with an emphasis on reducing self-sufficiency from domestic water resources. Asadi et al., [2] compared the costs of geothermal electricity production with the Levelized cost method and its economic effects. The electricity production effect from renewable sources on carbon dioxide emissions reduction in Iran was evaluated [40]. Motahari et al. [36] introduced a study regarding the cost-effectiveness analysis of wind power plants compared to gas power plants by releasing the cost price of electricity. Wasfi Asfestani & Alishiri [37] dealt with external cost evaluation in power plants by considering variable differences in different countries.

This article presents a method for calculating virtual water and its application in estimating the environmental costs of electric energy production, focusing on renewable energy and international obligations. Additionally, the study seeks to optimize the use of selected renewable energies in electrical energy production in Iran, to achieve economic savings. The article seeks to answer several critical questions, including whether virtual water calculation is an effective way to determine environmental costs, whether the internalization of environmental costs, also referred to as external costs, of electricity generation from fossil power plants would lead to the growth of renewable energies, and the share of virtual water consumption in renewable and non-renewable energy in electrical energy generation. The purpose of this research is to explore the challenges that may arise from the country's commitment to the Paris Agreement. By providing insights into these issues, the article seeks to contribute to a better understanding of the environmental and economic implications of renewable energy production, which can inform decision-making processes.

The rest of this paper is organized as follows: Section 2 describes the fourth-step approach and the innovation concept for virtual water consumption evaluation; Section 3 presents studies in the field of evaluation and calculations of virtual water consumption in power plants and the environmental costs of the power industry; Section 4 introduces the scope of the study and then the calculation methods mentioned; Section 5 illustrates the results of the calculations includes the various Tables, Figures, and graphs; Section 6 the conclusion are presented, as well as suggestions to solve the current problems and improve the current situation.

Material and Methods

This article evaluates techniques for estimating water consumption and environmental costs in power plants, with a focus on the life cycle analysis approach as one of the most comprehensive methods available. By considering all stages of the energy cycle, this approach provides information on materials and environmental pressures related to each phase, as well as estimates of the health and environmental impacts of these pressures and the costs associated with them. However, one of the major challenges of this approach is the need for a wide range of data and information from all stages of the energy cycle, which can be difficult to collect.

To estimate the environmental cost of thermal electricity, we compare the country's GDP per capita to that of other countries. We obtain the mass of pollutants emitted by power plants based on numerical values of greenhouse gas emission factors and activity rates for each plant, allowing us to calculate the environmental cost of electricity generation according to the emission costs of each gas. Similarly, we compute the amount of water consumed by each power plant by calculating the water input to its various parts, without the need for detailed extraction data. By establishing a relationship between water consumption and the amount of removable heat generated by the power plant, we can accurately determine the consumed water.

Overall, this paper describes the information required for estimating the environmental costs of water consumption in power plants and provides a framework for calculating these costs. Additionally, we introduce the Levelized cost of electricity method as a tool for computing the final cost of electricity produced by various types of power plants.

Research Methodology

Input: A power plant-related dataset.

Output: Estimation of environmental expenses of

electric energy production.

Step 1: conducting an assessment on the status of virtual water in all types of power plants, including solar, wind, geothermal, heat, gas, and combined cycle power plants, is deemed a priority.

Step 2: it is imperative to evaluate the environmental costs associated with electricity production in diverse types of power plants. These expenses are primarily caused by the emission of polluting gases and the disruption of electricity production by virtual water.

Step 3: accounting for the actual cost of each kilowatt-hour of electricity produced is also on our agenda. The total cost of electric energy production varies according to the type of technology and consumption resources. Distinct techniques of electricity production have varied expenses, and these costs can vary according to the time of power use at different times. Costs include initial capital and ongoing operating, fuel, and maintenance costs, start-up costs, and remediation of any environmental damage, as well as.

Step 4: our research highlights the need to examine water resource allocation for all types of power plants in Iran, given its location on the land belt and suboptimal water situation. The paper recommends that carbon dioxide production should be reduced to 1850 million Tons by 2030. Accordingly, implementation solutions will be addressed in line with the Paris international agreement, based on the 4% and 8% scenarios.

EDN

A detailed outline of the conducting general process of this research is presented (Figure 2).

Research Location

Iran has a significant potential for generating renewable energy, particularly geothermal and wind, due to its favorable geographic conditions. The country's high energy consumption, excessive CO2 emissions, and the high cost of electricity derived from fossil fuels have led policymakers to encourage private investment in the renewable energy sector. Our research focused on a non-probability sampling technique, which identified 50 diverse power plants that produce electricity from thermal, gas, and combined cycle power plants. These findings underscore the importance of investing in renewable energy sources to meet Iran's growing energy needs while reducing its carbon footprint (Table 1).

Research Methods to Calculate the Electricity Costs

In this paper, various approaches for the economic evaluation of power plant construction projects have been examined. The entire cost of electricity consists of two parts: private expenses (direct) and external values (indirect). Direct prices include initial investment costs, repairs, maintenance, and fuel expenses. In addition, there are indirect or external costs that affect social welfare. For instance, the environmental costs caused by the emission of polluting substances in the electricity generation process have been evaluated, and virtual water consumption is also added to the amounts. This research calculates the external cost generated by air pollutants and water consumption and finally calculates the electricity cost.

Net Present Value Method (NPV)

One of the most common discount indices is the Net Present Value (NPV) index (1). To make the assessment, the revenues and costs must first be converted to present values and then the net present value of benefits should be gained from the difference between incomes and expenses [38].

$$NPV(i,n) = \sum_{t=0}^{n} \frac{R_t}{(1+i)^t}$$

where:

t is the time of the cash flow

i is the discount rate, i.e. the return that could be earned per unit of time on an investment with similar risk

R_t is the net cash flow i.e. cash inflow – cash outflow, at time t

NPV > 0: the project would add value to the firm, economic

NPV < 0: the project would subtract value from the firm, non-economic

NPV = 0: the project would neither gain nor lose value for the firm, this project adds no monetary value

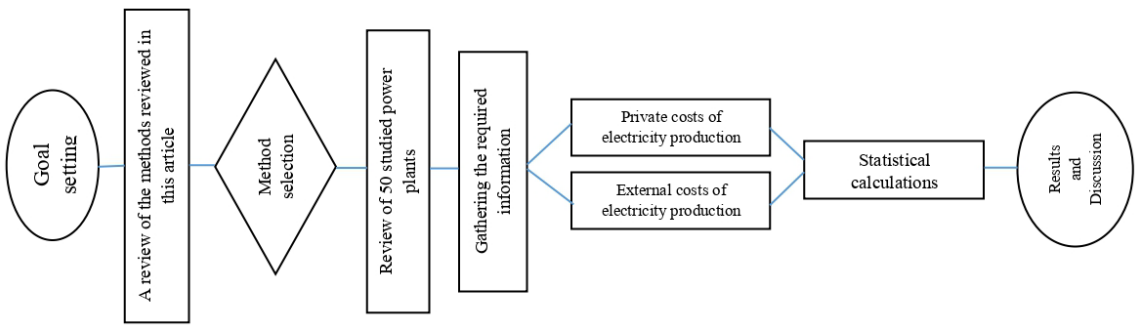

Figure 2: Research steps

Internal Rate of Return (IRR)

The Internal Rate of Return (IRR) is a financial metric used to evaluate the profitability of a potential investment (2). It represents the expected compound annual rate of return that an investment is expected to generate over its lifetime. The IRR is calculated as the discount rate at which the net present value of an investment equals zero. This means that the IRR is the rate at which the present value of the expected cash flows from an investment equals the initial investment. To calculate the IRR, the equation that sets the sum of all cash flows equal to zero is solved for the rate. Once solved, the obtained value is the internal rate of return of the project [39].

$$NPV(i,n) = \sum_{t=0}^{n} \frac{R_t}{(1+i)^t} = 0 \rightarrow i = r\% \qquad 2$$

When determining economic justification, the comparison between the discount rate and the minimum attractive rate or the minimum expected rate is essential.

Evaluation Approach

Life-cycle Assessment

The life cycle analysis method is a comprehensive tool for assessing the material and energy flows associated with each stage of a product or activity's life cycle. This includes the production of raw materials, their transformation, and the changes that occur until their final use and waste disposal. In the context of power generation systems, LCA considers all upstream and downstream processes of power plants, with a focus on parts of the fuel cycle that have significant impacts. The analysis also takes into account factors related to the production and consumption of construction materials and employees when they are estimated to be important sources of external effects.

The comprehensive life cycle assessment comprises three stages: life cycle inventory, life cycle impact assessment, and life cycle analysis. In the first stage, environmental effects are quantitatively expressed, such as pollutant emission rates and waste production. In the second stage, the environmental effects of each step are evaluated. Finally, the analysis considers

Table 1: List of Research power plants

Power plant type	Name	Province	Name	Province
heater	Sahand Thermal Power Plant	Eastern Azerbaijan	Mess Sarcheshmeh	Kerman
	Shahid Mohammad Montazeri Power Plant	Isfahan	Shahid Rajai	Qazvin
	Eslamabad	Isfahan	Zarand	Kerman
	Besat	Tehran	Bistoon	Kermanshah
	Tous	Razavi-Kharasan	Neka (Shahid Salimi)	Mazandaran
	Khorasan Petrochemical	Northern Khorasan	Shazand	Markazi
	Ramin	Khozestan	Bandar Abbas	Hormozgan
	Iranshahr	Sistan and Balouchestan		
Gas	Sufian	Eastern Azerbaijan	Chabahar	Sistan and Balouchestan
	Orumieh	Western Azerbaijan	Ofogh Mahshahr	Khouzestan
	Sabalan	Ardebil	Jahrom	Fars
	Kashan	Isfahan	Samangan	Kerman
	Ilam gas refinery	Ilam	Kalan Hydroelectric	Kermanshah
	Asaluyeh	Boushehr	Aliabad	Golestan
	Ray	Tehran	Dorud	Lorestan
	Shahid Kaveh	Southern Khorasan	Nowshahr	Mazandaran
	Ferdowsi	Razavi-Kharasan	Roodshour	Markazi
	Shirvan	Northern Khorasan	Bandar Abbas	Hormozgan
	Soltaniyeh	Zanjan		
	Shahid Bastami	Semnan		
Combined Cycle	Khoy	Western Azerbaijan	Shahid Rajai	Qazvin
	Zavareh	Isfahan	Qom	Qom
	Genaveh	Boushehr	Sanandaj	Kourdistan
	Martyrs of Pakdasht (Damavand)	Tehran	Shubad	Kerman
	Neishabour	Razavi-Kharasan	Pareh Sar	Gilan
	Abadan	Khouzestan	Neka (Shahid Salimi)	Mazandaran
Wind	Kazeroun	Fars	Sarv (Chadormalu)	Yazd
	Manjil	Gilan	Binalood	Razavi-Kharasan
Photovoltaic	Persian Gulf	Hamedan	Arca Solar Energy (Amir Kabir)	Kerman
Geothermal	Meshkinshahr	Ardebil		

available opportunities for reducing or mitigating the environmental consequences throughout the product or process's entire production cycle [40].The utilization of a suitable method for life cycle assessment (LCA) necessitates the inclusion of all stages of the energy cycle, gathering information about the flow of energy and materials, and assessing environmental pressures in each stage individually. In addition, it is imperative to have a mechanism in place to estimate the environmental and health effects caused by environmental pressures, as well as the costs of these effects. The initial step in LCA involves identifying a comprehensive list of all environmental effects during the lifespan of a product, which serves as the foundation for the LCA. However, it is often challenging to distinguish between inventory determination and LCA, and the process of evaluating the work-life cycle is both costly and time-consuming. The data collection and access to the required information are considered the most challenging phases of the LCA process. A lack of access to the necessary information and inadequate time and financial resources are among the most significant obstacles to conducting a proper LCA. Conducting this process does not guarantee the selection of a cost-effective and efficient product or process [41]. Considering the complexity of conducting this comprehensive assessment, our research aims to evaluate fossil fuels and water (system input) in the electricity generation phase (system boundary) and investigate the ramifications of fossil fuels on air quality.

Levelized Costs of Electricity Generation (LCOE) Method

The levelized cost method involves the conversion of costs into a uniform annual payment (3). In essence, this method equalizes costs to a fixed amount of income per sale of a product unit, which can cover all expenses associated with a project over its service life. The uniform or Levelized cost of energy method calculates the current value of investment and operation costs of electricity production throughout the project's lifetime. This method evaluates the production of one kilowatt-hour of electricity by dividing the current value of all costs incurred by the total electricity produced [42, 43]. The LCOE method has been utilized to compare the competitiveness of different electricity generation technologies, including heating, gas, combined cycle power plants, and renewable energy such as wind, solar, and geothermal. This method is not limited to a specific technology and can be deployed to compare costs across various domains [3, 41]. Equations 3 to 6 illustrate the formula for this index [22].

$$LCOE = C_k + \left[\sum_{t=0}^{PL} \frac{C_{O\&M} \times (1+e_{O\&M})^t}{(1+r)^t} + \sum_{t=0}^{PL} \frac{C_{Fuel} \times (1+e_{Fuel})^t}{(1+r)^t}\right] \times \frac{r(1+r)^{PL}}{(1+r)^{PL}-1} + C_{Ec} \quad (3)$$

The equation at hand involves the acquisition of the initial investment cost, maintenance cost, and fuel cost by means of the following set of relationships:

$$C_k = \frac{DR \times TPC(1+r)^{CL}}{HY \times CF} \quad (4)$$

$$C_{O\&M} = \frac{FOM}{HY \times CF} + VOM \quad (5)$$

Table 2: Adjustment of the parameters of the levelized cost equations

Name	Unit of measurement	Variable
Capital Cost	$/kwh	C_k
Depreciation Rate	%	DR
Total Plant Cost	$/kw	TPC
Total Plant Cost	Year	CL
Discount Rate	%	r
Hours Per Year	Hours	HY
Capacity Factor	%	CF
Total O&M Cost	$/kwh	$C_{O\&M}$
Escalation Rate Of O&M Cost	%	$e_{o\&m}$
Total Fixed O&M Cost	$/kwyear	FOM
Total Variable O&M Cost	$/kwh	VOM
Heat Rate	Btu/kwh	HR
Plant Life	Year	PL
Fuel Cost	$/Btu	FC
Escalation Rate Of Fuel cost	%	e_{Fuel}
External Cost	$/kwh	C_{Ec}
Value Of Environmental Damage	$/gr	VED
Emission Factor	gr/Btu	EF
Levelized Cost of Electricity	$/kwh	LCOE

$$C_{Fuel} = FC \times HR \quad 6$$

$\mathbf{C_{Ec}}$ which is the external costs caused by gaseous pollutants emitted from power plants, will be described in detail in the next section. As for the equations mentioned earlier, certain variables necessitate an intricate explanation, thus a detailed breakdown of Table 2 has been provided.

For the purposes of this study, the calculation of the capacity factor (CF) (7) of thermal power plants will be based on equation 7. This measure is used to assess the effectiveness of a power plant in generating maximum power [44].

$$CF = \frac{M}{rated\ capacity \times 24 \times 365} \quad 7$$

M: annual energy production of the power plant (MWh)
Rated capacity: rated capacity of the power plant (MW)

Selection of a Research Method to Calculate the External Cost (environmental damage)

Researchers have calculated the amount of environmental damage of electricity production and the resulting external costs using several methods. In the following, the techniques applied in this research will be introduced.

Environmental Economic Evaluation Method

The economic valuation of the environment is described based on two categories of demand-based methods and non-demand-based methods:

Demand-based Methods

Travel Cost Method: The economic value of clean air is calculated based on the costs incurred to use it [28].

Hedonic Pricing Method: the value of the environment in the market price of goods is evaluated using the price of houses in different areas concerning the environment [18].

Contingent Valuation Method (CVM): People's preferences about the environment are collected and valued through questionnaires or interviews [45].

Willingness to Accept Compensation (WTAC) and Equivalent Variation (EV): Economic value is obtained due to an unpleasant event and its impact on people's welfare [46].

Non-demand-based Methods

Dose-Response Approach: The value of the reduction in productivity of humans, plants, or animals caused by pollution is calculated based on their physiological changes [47].

Replacement Cost Method: The cost associated with repairing a damaged asset caused by pollution is supposed as the monetary value of the environment.

Adjustment or Compensatory Behavior Method: the behaviors that companies or individuals perform to compensate for damage caused by pollution, are calculated as the economic value of the environment [48].

Opportunity Cost Method: The process of calculating the economic worth of the environment does not involve the assessment of its environmental benefits. Rather, it relies on estimating the benefits derived from activities that tend to harm the environment [30].

Gross Domestic Product Ratio Method

This technique proves to be a valuable tool in estimating the external costs of countries with limited information. It entails comparing the GDP per capita of such countries to the average of those with readily available data, such as European countries. As an example, in the case of Iran, the estimation of external costs for electricity consumption and production is determined by considering the GDP per capita and the emission factor of polluting gases, in comparison to European nations [49].

$$\sum \frac{GDP_i}{GDP_c} \times Environmental\ pollutant\ cost \times Emission\ factor \quad 8$$

Where:
GDPi is equal to the gross domestic product of Iran
GDPc is equal to the gross domestic product in the selected country c
Environmental pollutant, the environmental cost of the pollutant in the country c and
Emission Factor, pollutant emission factor in Iran

The methodology employed yields a ratio that serves as an indicator of the external costs associated with Iran's electricity production in comparison to that of a number of benchmark countries. It should be noted, however, that such a ratio does not provide a comprehensive and isolated representation of the external costs attributed to Iran's electricity production.

Calculation of the Number of Pollutants Produced by Power Plants

The significance of clean air and the discharge of pollutants from power plants is a widely recognized fact. The computation of these pollutants' emission rate is determined based on the mass of pollutants or gases generated from combustion, per the quantity of electrical energy produced. This data is a crucial tool in monitoring air quality and formulating effective emission control measures [50]:

$$E = A \times Ef \times (1 - \frac{ER}{100}) \quad 9$$

Where:
E is equal to the emission rate of the pollutant (mass value of the pollutant)
A is equal to the activity rate (production rate of the industrial unit, for example, x kilowatt-hours of electricity produced)
Ef is equal to the emission factor (the amount of pollutant mass released per amount of product or activity rate)
ER is equal to the overall percentage of emission reduction, if pollutant reduction systems are not used, this value is zero [51, 52].

After the determination of the pollutant mass (E), the next step is to calculate the external cost of air pollution. To accomplish this, it is necessary to express the effects of reducing air quality in quantifiable terms. The US Environmental Protection Agency (EPA) provides useful information in this regard, which includes the cost of releasing each ton of pollutants. By multiplying the amount of pollutant produced by its emission cost, the cost of removing and controlling the target pollutant gas can be calculated. This approach allows for a quantitative assessment of the negative impact of power plant activity.

Calculation of External Cost CEc

In this approach, the external cost is equal to the amount of damage in physical units multiplied by the value of the damaged environment in dollars per unit of electricity produced:

The value of the damaged environment per unit of failure × amount of failure = external cost

The approach for calculating external costs involves converting them into legal units, such as kilowatt-hours (kWh), which represent the emission and distribution of damage. The emission index is a variable and complex metric determined by a range of factors including plant characteristics, fuel source, pollutant control, and operating conditions such as heart rate and temperature. This index is particularly relevant for power plants that use fossil fuels, as it allows us to assess the external impact of air pollution.

$$C_{External\ Cost}\left(\frac{\$}{kWh}\right) = Ef\left(\frac{g}{Btu}\right) \times HR\left(\frac{Btu}{kWh}\right) \times VED\left(\frac{\$}{g}\right) \quad 10$$

Where:
Ef = emission rate due to fuel consumption
HR = thermal rate
VED = value of damaged environment (damage)

It is crucial to acknowledge that the quantum of pollutant emission is contingent upon the type of fuel employed. The severity of temperature alteration is the primary indication of the deleterious impact of pollutant emissions on the environment. The magnitude of emission and the intensity of temperature modification are physical parameters that can be effortlessly gauged. However, the pivotal factor that significantly influences the estimation of this equation and holds paramount importance in policymaking is the extent of impairment inflicted on the environmental worth [37].

In the following, the method of calculating the amount of water consumed in electricity production will be discussed so that by considering the price of each unit of water, the external cost of electricity production will be fully and comprehensively available.

Calculation of Virtual Water in Power Plants

Determining the amount of water consumed in power plants is a complex process that involves calculating the water input to its various parts. The precise method used for each power plant takes into account the amount of heat that can be removed. This calculation involves applying a formula that incorporates parameters such as heating rate, water consumption per kilowatt hour of electrical energy produced, and other variable factors. Additionally, power plant efficiency has been proposed as a means of calculating water consumption and its impact on the final cost of electricity.

The relationship of calculating the amount of water consumed by the power plant is as follows:

$$I = A(HR - B) + C \quad 11$$

Where:
I in liters per kilowatt hour (L/kWh) is the amount of water consumed by the power plant in liters per kilowatt hour of electrical energy produced.

The HR parameter in terms of kilojoules per kilowatt hour (kJ/kwh) indicates the thermal rate or the amount of heat required from the power plant fuel in terms of kilojoules.

In order to generate one kilowatt of electric power for an hour, the efficiency of power plants and their thermal rate are inversely related. The efficiency of each power plant is a fixed value, and the calculation of HR can be determined by using the following formula [19]:

$$Efficiency = {}^{3600}/_{HR} \quad 12$$

Parameter B, expressed in terms of (kJ/kWh), denotes the total input heat rate from the fuel side of the power plant, excluding the input the heat rate to the cooling system. This parameter represents the entirety of heat flow emanating from the power plant, except for the heat flow rejected by the water in the cooling section. On the other hand, parameter A, expressed in terms of (L/kJ), quantifies the volume of water required to remove one kilojoule of heat from the system, which varies depending on the cooling system. Lastly, parameter

C, expressed in terms of (L/kwh), is indicative of the water consumption in other parts of the power plant, such as dust washing, except for the cooling part, which accounts for a much larger share of water use. Given the small magnitude of parameter C, its precise value is challenging to ascertain.

It is noteworthy that the quantity of water consumed by each power plant varies depending on the type of cooling system and the power plant configuration.

It is worth noting that the water consumption of a power plant can be determined based on its efficiency. The relationship between the two can be established by considering the amount of heat lost in the plant. It follows that a higher efficiency corresponds to lower water consumption and vice versa if the relationship is expressed linearly. In other words, the highest efficiency of a plant corresponds to the lowest water consumption, while the lowest efficiency corresponds to the highest water consumption. Therefore, the amount of water consumption of a power plant with efficiency η is calculated from the following equation:

$$I = I_{max} + \frac{I_{min} - I_{max}}{\eta_{max} - \eta_{min}} \times (\eta - \eta_{min}) \quad 13$$

Based on our review of prior research in this field, it has been found that the calculation of water consumption and environmental costs in power plants can be determined by using various methods. In the following section, we will explore how annual water consumption and pollutant gas emissions across all types of power plants can be calculated with the help of these methods. Additionally, the impact of external and virtual water costs on the ultimate electricity expenditure in different scenarios will be analyzed. This analysis will be presented in detail.

Pros and Cons of Methods

Internal rate of return and present value methods focus on profitability and initial value investment. Due to the importance of the total cost in government projects, the internal rate of return method is unsuitable for economic analysis, and the Levelized cost method has been used to evaluate environmental and virtual water costs. This descriptive-analytical research has used LCOE and CEc methods to calculate the social cost of electricity production and the effect of external costs and virtual water expenses on the total price of electricity.

Data Analysis

This section presents an analysis of water consumption and virtual water usage in power generation at power plants, followed by an evaluation of polluting gases released by these power plants. The study then investigates the cost of environmental damage and determines the total cost of producing one-kilowatt hour of electricity by considering external costs such as polluting gases and virtual water. The research prioritizes scenarios for reducing greenhouse gas emissions, in line with Iran's commitments to the climate change convention. The best scenario for reducing carbon dioxide in the electricity generation industry is identified. The findings of this study are presented professionally and respectfully, suitable for sharing with a boss or external audience.

Investigation of Virtual Water Consumed in the Electricity Industry of the Country

Securing water and energy resources is one of the most vital challenges facing the world today, with the ever-growing population and increasing demand for water and energy resources. The persistent gap between demand and supply is a pressing concern. While our research has analyzed the water consumption of power plants solely in their calculable parts, such as the production of electricity, we have not been able to conduct a comprehensive life-cycle analysis of water consumption. Nonetheless, our investigation has focused on water consumption in power plant facilities and offices, as well as water usage for the irrigation of green spaces within power plants.

Water in the Process of Generating Electricity

The current study provides an analysis of various types of power plants such as steam, gas, combined cycle, wind, solar photovoltaic, and geothermal, concerning their water consumption patterns. The amount of water consumed by thermal power plants is largely dependent on their water source, whether it be a pipe, well, seawater, or river, and their geographical location. As a result, water consumption in thermal

Table 3: Parameters related to the amount of water consumed by power plants

Power plant type	HR heat rate (kJ/kwh)	B heat output (kJ/kwh)	C Water required in other sectors (L/kwh)
Gas	7200	5195	0.025
Steam	9000-9500	5650	0.15

Table 4: The parameter related to the amount of water consumed by cooling systems

Type of cooling system	A water intake (L/kJ)	A water consumption (L/kJ)
Open water circulation	0.022-0.034	0.00045
Wet tower	0.00034-0.77000	0.00042
Dry tower	0	0

power plants can be quite significant. Conversely, renewable energy plants, such as wind, photovoltaic, and geothermal, consume minimal quantities of water. For instance, wind and photovoltaic power plants do not utilize water during their electricity production processes [53]. To estimate the virtual water consumption in thermal power plants, we employed formulas 11 and 12, a Table of the amount of water consumed by power plants, and information extracted from the comprehensive book on the management, development, and production of thermal power and related industries of power plants, 2016. The results of the calculations were as follows:

Gas power plants do not require a cooling system, while in thermal power plants, 40% of the cooling system is a dry tower, 40% is a tower, a wet tower, and the remaining 20% is an open water circulation or open cycle system. Moreover, this statistic is split into two parts in combined cycle power plants. The gas unit of the combined cycle power plants has no cooling system, and its heating unit is such that 85% of it belongs to the dry tower cooling system, while the remaining 15% belongs to the open water circulation system. Furthermore, depending on the power plant's geographical location, the water supply source required by the power plant may differ.

Based on the average water consumption in liters per kilowatt-hour, it can be concluded that the boiler power plant consumes the most water during electricity production, followed by the combined cycle and gas power plants, respectively (Table 5).

According to a research study, the type of cooling system utilized in power plants plays a decisive role in determining the amount of water consumed. It was found that gas power plants and gas units of combined cycle power plants that do not require cooling systems are the most water-efficient options. Conversely, power plants that rely on tower cooling systems are among the most water-consuming centers. In the realm of renewable power plants, wind power plants do not consume any water in the electricity production process [54], while solar photovoltaic power plants only require water to clean surfaces that absorb and reflect sunlight such as mirrors, heliostats, and photovoltaic panels [55]. Geothermal power plants require water for both development and electricity generation operations [56]. However, this research focuses solely on the water consumption in the sector of electricity generation operations.

Water Consumption in the Staff Department

According to the prevailing norm of daily water consumption per capita, we have calculated the amount of water required based on the working hours of the power plant, the number of personnel working, and their shifts [50]. It is worth noting that before initiating the calculation process, we identified and eliminated any outliers.

Water in the Irrigation Department of Green Spaces and Planted Trees

The present research examines the impact of power plants on water consumption in green space irrigation. As per the Clean Air Act, it is crucial to establish green spaces in power plants. The calculations indicate that thermal power plants are required to comply with this law. The study has estimated the water consumption for green space irrigation by thermal power plants in various climates and determined the effect of the average annual water requirement of pine and fir species on water consumption [29, 33, 35, 37, 57, 58].

The findings have revealed that water consumption in this domain is contingent on the area covered by each power plant. Hence, regardless of the type of power plant, the amount of water consumed depends on the size of the space dedicated to a power plant. According to the results, the Shahid Rajaei power plant (Steam unit), Bistun (Steam), and Shirvan (Gas) are the most significant consumers of water in this sector.

The Amount of Gaseous Pollutants Released from Thermal Power Plants

In 1996, the pollutant and greenhouse gas emission factor in the country's power plant sector decreased due to the increase in the share of natural gas, the decrease in the use of liquid fuels, and the change in the technology of converting the gas sector to a combined cycle. This reduction has happened based on the average emission of polluting and greenhouse gases in the country's power plant sector compared to the previous year. (g/kwh) [58, 59].

Considering the significant emission factor that Co2 and C have compared to others, these two gases are the main gases released as a result of one year of operation of the studied power plants. The results showed that in all three types of heating, gas, and combined cycle power plants, the percentage of CO2 and C emission is 78% and 21%, 79% and 21%, 70% and 30%, respectively (Figure 3).

Table 5: The amount of water consumed during electricity generation by types of coolers (author's calculation results)

Type of cooling system	Average water consumption (L/Kwh)
wet tower	2.59
dry tower	0.15
Blue open cycle	1.24
No cooling system	0.025

Renewable energy plants, including wind, photovoltaic, and geothermal, are a sustainable source of electricity production that does not require fuel consumption. In geothermal power plants, geothermal gases, primarily consisting of CO2, are released in the form of steam from the Earth's surface. According to Fridriksson et al.'s study in 2016, more than 95% of these gases comprise of CO2, with insignificant amounts of other gases. As a result, the study calculated the emission rates of only CO2 and SO2 (Table 6).

Levelized Cost of Electricity (LCOE)

The estimation of the levelized cost of electricity (LCOE) in Iran is based on the average cost of power plant operations over their lifetime. The calculations consider general assumptions and characteristics of the power plants, but do not include transmission and distribution costs. Emissions of polluting gases are evaluated only in the fuel combustion section, and other stages such as fuel extraction and distribution are not included. The costs are categorized into two parts: electricity production costs and environmental costs. The former includes initial investment, fuel, and repair costs, while the latter includes the costs of air pollution and virtual water consumption.

Initial or Private Expenses

The private costs involved in the construction, maintenance, and fuel for power plants are significant and require careful evaluation (Table 7) In our analysis, we have collected the technical-economic characteristics of the power plants from the 2013 report of the Electricity and Energy Planning Office of the Ministry of Energy. Additionally, we have evaluated the depreciation rate using the straight-line method or equal installments. The current value of costs has been calculated using a discount rate of 14% per year, taking into account the economic conditions and inflation prevalent in the country. We believe that this approach will enable us to make informed decisions regarding the costs and benefits of power plant operations and help us achieve our goals [59-62, 22, 36].

External Costs

In this study, our focus is on thermal and renewable power plants. We aim to calculate the external costs associated with the entry of polluting gases, suspended particles, and greenhouse gases into the atmosphere, as well as the costs of water consumption during the power plant's various processes, including production, staff department, administrative work, and green space irrigation. We first calculated the emission factor (EF) of gases released from thermal power plants in terms of grams per BTU. Subsequently, we estimated the cost of the environmental damage caused by the emission of gaseous pollutants from the power plant in cents per gram (Table 8).

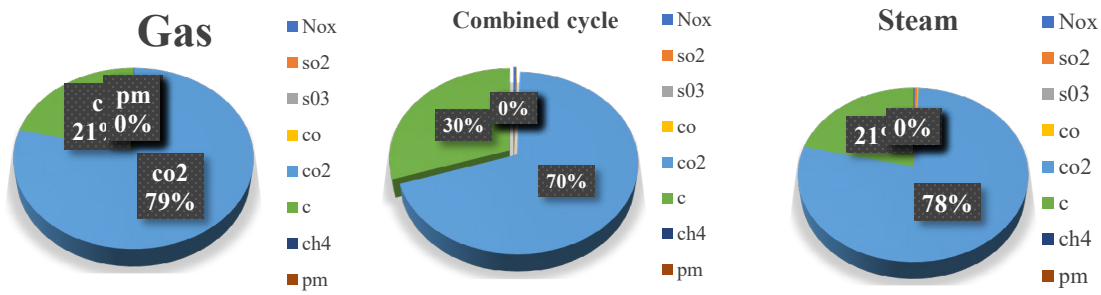

Figure 3: The average share of gases released from gas, combined cycle, and the steam power plants

Table 6: Investment, maintenance and fuel costs (c/kwh)

Power plant type	NO_x	SO_2	SO_3	CO	PM	CO2	CH_4	C
Gas	11180.61	15419.90	54.35	8431.67	491.47	333228	71.08	908926.34
Steam	2745.09	543.55	12.5	97.64	233.68	1849069.15	38.02	793166.88
combined	10627	592.31	15.57	334.2	263.68	1849069.15	38.02	793166.88
wind	0	0	0	0	0	0	0	0
Photovoltaic	0	0	0	0	0	0	0	0
Geotherma	0	34.16	0	0	0	44950.63	0	0

Figure 7: Levelized costs in the first scenario and different options of the second scenario in 2030 (Million Tons)

Power plant type	Steam	Gas	Combined	wind	Photovoltaic	Geotherma
Investment cost	1.74	2.74	1.14	4.89	8.21	3.67
Cost of repairs and maintenance	0.28	0.28	0.15	1.98	3.27	1.46
Fuel cost (current gas price)	0.22	0.28	0.22	0	0	0
Fuel cost (export gas price)	9.40	12.29	9.31	0	0	

The study conducted reveals that the cost of virtual water consumed is an important factor that should be included in external costs. As a result, the water tariff for non-domestic customers at the end of 2019 (cents per liter) and the volume of water utilization in all types of power plants across various sectors was calculated in terms of cubic meters per year.

The quantity of water consumed in power plants is primarily dependent on their technical features, such as the power plant type and cooling system employed. Thermal power plants utilizing a cooling tower system consume more water than other power plants. The type of cooling system used has a significant impact on water consumption. While the disposable system uses less water, it is important to note that the effects of thermal pollution and environmental impact should not be disregarded. The administrative sector's water usage is dictated by the number of personnel, while the irrigation sector's water consumption is determined by the power plant's surface area. Thus, based on the outcomes obtained, the total water utilization in all types of power plants can be summarized as follows:

Stream > Combined cycle > Geothermal > Gas > photovoltaic > wind

According to the dollar price in 2019 and the non-domestic water price tariff shown in Table 8, the external cost caused by the virtual water consumption of a power plant can be calculated (Table 9).

The results of the calculations performed to obtain the investment cost, repairs and maintenance, and current and export fuel costs are given in the Table below.

According to the value of each unit of water in the country in Table 8 and the amount of water consumed by a power plant in a year, it is possible to calculate the virtual water consumption of a power plant during operation.

The results of these calculations can be seen in the graph below (Figure 4).

In this section, before the final announcement of the total cost of electricity with different technologies using the LCOE method, it is necessary to introduce two scenarios and discuss the total cost in these two scenarios.

• First scenario: Calculate the Levelized cost of electricity by considering the price of subsidized fuel (the same price at which power plants currently buy fuel) and by considering environmental costs, including the cost of pollution and greenhouse gases and the cost of virtual water.

• The second scenario: calculating the Levelized Cost of Electricity by considering the price of export fuel (the same price that will bring income to the country if we export the fuel) and by considering the environmental costs, including the cost of polluting and greenhouse gases and the cost Virtual water.

Using LCOE, the Levelized Cost of Electricity was calculated in different electricity generation technologies under various scenarios, and the results shown in Table 11.

The cost analysis of electricity generation options is crucial for understanding the economic viability of different energy sources. The document provides various graphs and Tables that illustrate the Levelized Cost of Electricity (LCOE) and other cost components associated with different generation methods.

For instance, the LCOE Figures presented in the graphs indicate significant variations among the energy sources. The LCOE for renewable sources is shown to be lower compared to fossil fuels, suggesting a trend towards more cost-effective renewable energy solutions. This is further supported by the data which highlights the decreasing costs of renewable technologies over time, emphasizing their growing competitiveness in the energy market.

Additionally, the Tables provide a detailed breakdown of costs, including capital expenditures, operational costs, and maintenance expenses for each energy source. The relationship between these Figures reveals that while initial investments for renewable energy may be higher, the long-term operational savings contribute to a lower overall LCOE. This is particularly evident when comparing the operational costs of traditional fossil fuel plants with those of solar and wind energy systems, as noted.

Moreover, the analysis of emissions and environmental impacts, as discussed further reinforces the economic argument for transitioning to cleaner energy sources. The lower emissions associated with renewables not only contribute to environmental sustainability but also reduce potential future costs related to carbon pricing and regulatory compliance.

In summary, the cost analysis presented in the document illustrates a clear trend: while traditional energy sources may have lower upfront costs, the long-term benefits and decreasing costs of renewable energy options make them increasingly favorable. The data

Table 8: External cost due to polluting and greenhouse gases (c/kwh)

Power plant type	NO_x	SO_2	SO_3	CO	PM	CO2	CH_4	C	Sum
Steam	0.255	0.497	*	0.022	0.039	10.15	0.001	0.333	11.30
Gas	0.229	0.051	*	0.001	0.127	14.46	0.002	0.473	15.34
combined	0.284	0.021	*	0.001	0.115	1.2	0.001	0.282	1.91
wind	0	0	0	0	0	0	0	0	0
Photovoltaic	0	0	0	0	0	0	0	0	0
Geotherma	0	0.01	0	0	0	1.35	0	0	1.36

supports a strategic shift towards sustainable energy solutions, aligning economic and environmental goals.

The initial investment cost and the cost of repairs and maintenance in renewable power plants are much higher than in thermal power plants. Renewable power plants are more affordable because they do not have fuel

Table 9: Technical-economic specifications of thermal, wind, photovoltaic and geothermal power plants

Technical-economic components	Unit	steam	Gas	Combined cycle	Wind	Photovoltaic	Geothermal	Source
Initial cost	Dollar per kilowatt	1070	505	720	1900	4790	4100	(OECD, 2015; Asadi et al. 2015)
Construction time	Year	5	2	5	2	2	4	(Mousavi et al. 2012; Motahari et al., 2013) and (Amiri et al. 2021)
Depreciation rate	Percentage	3.3	8.3	3.3	5	2	3.3	(Mousavi et al. 2012; Motahari et al. 2013) and (Amiri et al. 2021)
Capacity factor	Percentage	89	62	76	30	18	85	(Average of sample power plants) and (Mohammadi et al. 2015)
Lifespan	Year	30	12	30	25	25	30	(Kost et al., 2018; Mousavi et al. 2012) and (Amiri et al. 2021)
Number of access hours	Hour	6132	7358.4	7358.4	8497	8497	7446	(Asadi et al., 2016; Motahari et al. 2014)
Fixed maintenance costs	Dollar per kilowatt	9.4	4.4	4.34	30	50	84	(Mohammadi et al., 2015)
Variable maintenance costs	Dollar per kilowatt hour	0.00049	0.00065	0.00042	0.008	0	0.129	(Mohammadi et al. 2015)
Fluctuations in maintenance costs	Percentage	2	2	2	2	2	2	(Mohammadi et al. 2015)
Thermal rate	BTU per kilowatt hour	9700	11247	9480	0	0	9000	(Average of sample power plants) and (Amiri et al. 2021)
Current fuel cost per unit (natural gas)	Dollars to Million BTUs	0.23	0.23	0.23	0	0	0	(Monitoring and Analysis of the Iranian Electricity Market, Iran Electricity Network Management Company 2010)
Cost per unit of exported fuel (natural gas)	Dollars to Million BTUs	9.92	9.92	9.92	0	0	0	(Yousefi et al. 2019) [61]
Fuel price fluctuations	Percentage	5	5	5	0	0	0	(Asadi et al. 2016) [2]

costs, and external costs are negligible or close to zero. Although, due to the small price of water in the country, the cost of virtual water is small and even in some cases close to zero, it should be noted that the majority of external costs are related to polluting gases released from thermal power plants (Figure 5).

Table 10: External cost due to virtual water (c/kwh)

Power plant type	The cost of the production process	The cost of the administrative department	Irrigation cost
Steam	0.005	0.000012	0.0000
Gas	0.000085	0.00006	0.0000
Combined	0.001	0.0000	0.0000
wind	0	0.000018	0
Photovoltaic	0.0003	0.00008	0
Geotherma	0.004	0.000013	0

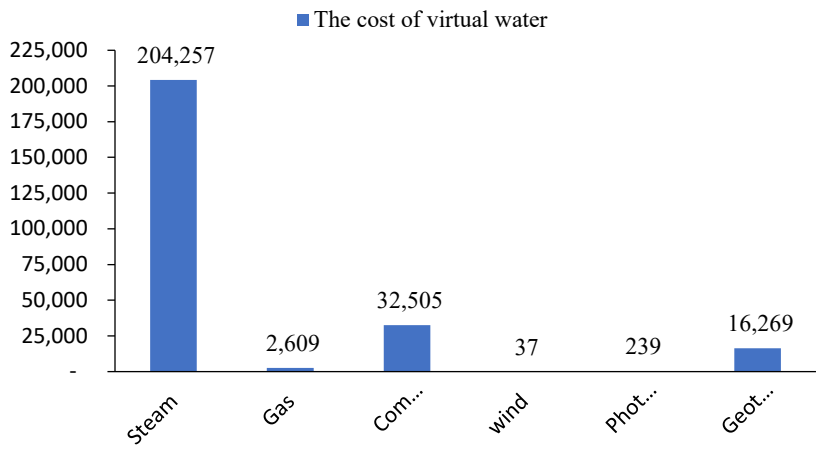

Figure 4: Virtual water costs (Dollars per year)

Table 11: The Levelized Cost of Electricity in different scenarios by power plant (c/ kwh) LCOE

Power plant type	The cost of the production process	The cost of the administrative department
Steam	13.78	28.96
Gas	18.86	35.98
combined	0.001	0.0000
wind	0	0.000018
Photovoltaic	0.0003	0.00008
Geotherma	0.004	0.000013

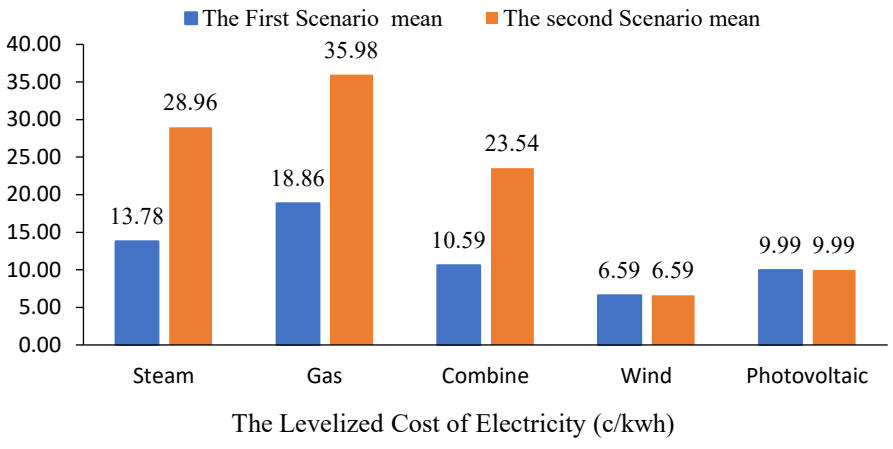

Figure 5: Comparison of scenario one and two in the Levelized final cost (c/kwh)

Policies to Reduce Greenhouse Gas Emissions

Among the international achievements in reducing greenhouse gas emissions, the drafting of the Kyoto Protocol, the Paris Agreement, the sixth development plan, and the national plan to reduce greenhouse gas emissions are mentioned. Since the government of the Islamic Republic of Iran joined the United Nations Climate Change Convention in 1996, it must act based on its commitments to reduce greenhouse gas emissions. On the other hand, the Islamic Republic of Iran's government is not included in any of the two main categories of this division and is committed to the general obligations of this convention. The general goal of this convention is to maintain the amount of greenhouse gas emissions caused by human activities.

The Obligations of the Government of the Islamic Republic of Iran under the Kyoto Protocol

In 1997, the first protocol in Kyoto was signed by the member states of the Climate Change Convention. This protocol set quantitative targets for the reduction of greenhouse gas emissions for countries in Annex 1 of the Convention. In Article 10 of the protocol, the non-annexed governments (including the Islamic Republic of Iran) are committed to preparing national lists of greenhouse gas emissions from sources and transfers through sinks without creating a new commitment and only in order to try to achieve general goals.

Obligations of the Government of the Islamic Republic of Iran in case of Joining the Paris Agreement

The Paris Agreement, ratified in 2015 with the consensus of 195 government entities, is implemented within the framework of the Climate Change Convention. The agreement aims to bring sustainable and global changes by reducing greenhouse gas emissions while setting national partnership targets for participating governments. During the COP21 conference in Paris, the participating countries agreed on the objectives of reducing emissions and maintaining safe temperature levels. Iran has also determined its national participation program as non-binding while adhering to national power and gas release scenarios. Iran has committed to increasing the emission reduction rate by 12% if potential obstacles such as sanctions, technology transfer, purchase of carbon certificates, and financial support are removed.

Law of the Sixth Development Plan

The electricity industry has been proposed as one of the strategies in the country's national energy strategic document, emphasizing the increase in the share of renewable energies in electricity production.

According to paragraph 50 of the Law of the Sixth Development Plan, the government is obliged to increase the share of renewable and clean power plants with the priority of non-governmental sector investment and also to reach at least 5% of the country's electricity generation capacity by the end of this program.

The sixth development program aims to install 20,000 megawatts of power plant capacity with an emphasis on combined cycle power plants, including renewable and fossil power plants, which is recognized as the last law in the country's national energy strategic document.

Vision document of Ministry of Energy

In line with the realization of the strategic goals of the vision document of the Ministry of Energy in the horizon of 1404 and the protection of national capitals, the reduction of environmental pollutants, and the economic production of electricity, the average efficiency of thermal power plants in the country has increased by at least one percent annually, and the country will be able to use and localize appropriate technologies to improve the efficiency of power plants.

Determining the Country's Energy Supply Scenarios and Options

The mentioned materials show that it is very significant to choose the right strategies to reduce the consumption of fossil fuels in electricity production and to replace renewable energies in reducing greenhouse gas emissions in the power plant sector. The two main approaches to reducing Iran's carbon emissions include improving the efficiency of power plants and using a variety of power generation technologies. Two main scenarios are considered for comparison:

First scenario: Continuance of the current situation in electricity production

The Second Scenario: replacing renewable energies with fossil fuels in electricity production, increasing the efficiency of power plants using existing capacities in the country, and programs to reduce greenhouse gas emissions.

Various scenarios have been investigated, and parameters such as fossil fuel consumption, share of renewable electricity, and the amount of greenhouse gas emissions have been examined. The importance of these evaluations was to determine the optimal scenario for electricity production in the future, and the emission of greenhouse gases is one of the determining factors for policymakers' decisions.

Results and Discussion

Analysis of Energy Supply Options and Scenarios

The "Results and Discussion" section presents a comprehensive analysis of various energy supply scenarios and their implications for carbon dioxide emissions and electricity generation costs. The key findings are organized around different scenarios, each exploring distinct options for energy supply by 2030.

Table 12: values of different parameters in the first scenario - Continuation of the existing process

Power plant type	Renewable and clean power plants		Fossil power plants			
	Photovoltaic	wind	Gas	Steam	Combined	Sum
CO2 released (mT) 2021	0	0	73.66	68.83	63.16	205.65
CO2 released (mT) 2030	0	0	105.38	98.47	90.36	294.2108
The share of each power plant in electricity production	0.01	0.07	25.8	29.3	37.3	
Each power plant's contribution to carbon emissions	0	0	%36	%33	531	%100
State fuel- Levelized cost (Million Dollars) 2021	3.43	15.82	16689.97	13848.76	13548.74	3.43
Levelized cost of exported fuel (Million Dollars) 2021	3.43	15.82	31840.14	29104.51	30116.84	355017.40
Levelized cost of Subsidized fuel (Million Dollars) 2030	4.90	22.64	23876.87	19812.21	19382.99	63099.61
Levelized cost of exported fuel (Million Dollars) 2030	4.90	22.64	45550.90	41637.27	43085.52	130301.22

Table 13: values of different parameters in the second scenario of the first option - Increasing the share of renewable energies up to 5% (25% solar and 25% wind)

Power plant type	Renewable and clean power plants		Fossil power plants			
	Photovoltaic	wind	Gas	Steam	Combined	Sum
CO2 released (mT) 2030	0	0	100.19	93.63	85.90	279.73
Levelized cost of Subsidized fuel (Million Dollars) 2030	1225.52	808.43	22701.54	18838.50	18426.84	62000.83
The share of power plants in the production of electricity and carbon dioxide emitted in 2030	%2.5	%2.5	%24.53	%27.86	%35.46	92.85
Levelized cost of exported fuel Million Dollars) 2030	1225.52	808.43	43308.66	39590.93	40960.12	125893.67

Table 14: values of different parameters in the second scenario of the second option

Power plant type	Renewable and clean power plants		Fossil power plants			
	Photovoltaic	wind	Gas	Steam	Combined	Sum
CO2 released (mT) 2030	0	0	105.38	98.46	90.37	294.20
Levelized cost of Subsidized fuel (Million Dollars) 2030	4.90	22.63	23875.89	19811.40	19384.32	63099.15
Levelized cost of exported fuel (Million Dollars) 2030	4.90	22.63	45549.03	41635.57	43088.47	130300.62

Table 15: Values of 20 different parameters in the second scenario of the third option

Power plant type	Renewable and clean power plants		Fossil power plants			
	Photovoltaic	wind	Gas	Steam	Combined	Sum
CO2 released (mT) 2030	0	0	91.45	85.10	76.81	253.361
Levelized cost of Subsidized fuel (Million Dollars) 2030	4.901	22.635	22179.52	17884.89	17572.18	57664.140
Levelized cost of exported fuel (Million Dollars) 2030	4.901	22.63	43840.00	39723.44	41166.51	124757.493

The first scenario
Continuation of the Existing Process

The first scenario examines the implications of maintaining the current energy supply strategy. The results indicate that fossil power plants, particularly gas and steam types, will continue to dominate electricity production, leading to significant carbon dioxide emissions. Specifically, the carbon emissions from gas power plants are projected to be 73.66 million tons in 2021, increasing to 105.38 million tons by 2030, while the Levelized Cost of Electricity (LCOE) for exported fuel is expected to be about twice that of government fuel in both years.

the second scenario - the first option
Increasing the Share of Renewable Energies

The second scenario emphasizes a shift towards renewable energy sources, aiming for a 5% increase in solar and wind energy contributions. This approach is projected to reduce carbon emissions by 14.48 million tons and save approximately 4407.56 million dollars in electricity production costs compared to the continuation scenario.

The second scenario - the second option

Efficiency Improvements in Thermal Power Plants

The second option within the second scenario focuses on enhancing the efficiency of thermal power plants by 1% annually. This strategy is expected to slow the increase in carbon emissions, with a potential reduction of 40.84 million tons by 2030 compared to the existing trend.

The second scenario - the third option
Combined Approach

The third option combines both efficiency improvements and an increase in renewable energy

Table 16: The amount of carbon dioxide reduction in fossil power plants per one percent increase in efficiency

Power plant type	Reduction of carbon emissions for one percent increase in efficiency
Combined	8.23 (g /kwh)
Steam	10/33 (g /kwh)
Gas	12/22 (g /kwh)

Table 17: Values of 22 different parameters in the second scenario of the fourth option

Power plant type	Renewable and clean power plants		Fossil power plants			
	Photovoltaic	wind	Gas	Steam	Combined	Sum
CO2 released (mT) 2030	0	0	86.96	80.92	73.02	240.8902
The share of power plants in electricity production in the second scenario of the fourth option of 2030	%2.69	%2.69	%26.42	%30.01	%38.19	%100
Levelized cost of Subsidized fuel (Million Dollars) 2030	1225.52	808.42	21088.59	17006.60	16704.21	56833.36
Levelized cost of Exported fuel (Million Dollars) 2030	1225.52	808.4	41683.68	37772.70	39133.09	120623.43

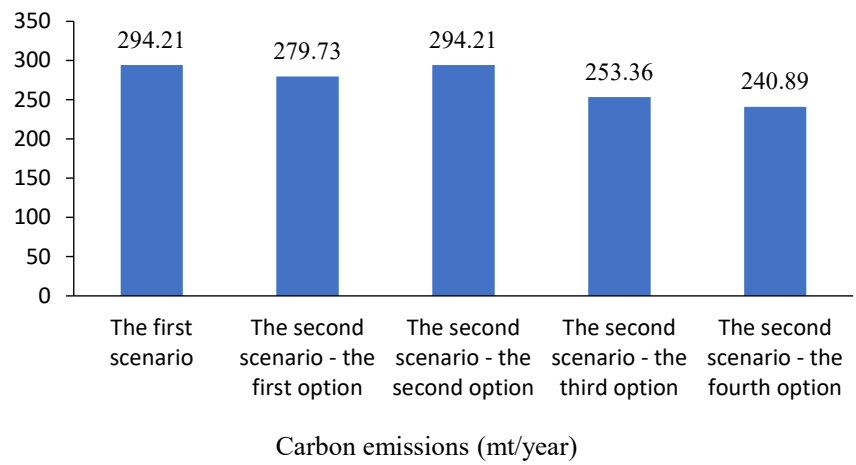

Figure 6: The amount of carbon dioxide emissions in the first scenario and the different options of the second scenario in 2030 (Million Tons)

share. This integrated approach is highlighted as the most effective in reducing carbon emissions and achieving economic savings, with a projected reduction of 53.32 million tons of carbon emissions compared to the continuation scenario.

The fourth option of the second scenario stands out as the most economically and environmentally favorable due to its integrated approach, which combines efficiency improvements in thermal power plants with an increased share of renewable energy sources. This strategy is projected to significantly reduce carbon emissions by 53.32 million tons compared to the continuation scenario, making it a compelling choice for meeting environmental commitments.

Moreover, the economic analysis indicates that this combined approach not only mitigates greenhouse gas emissions but also leads to substantial cost savings in electricity production. Specifically, it is expected to save approximately 4407.56 million dollars in production costs compared to the first scenario, which continues the existing energy supply strategy. The integration of renewable energy sources, such as solar and wind, further enhances the economic viability of this option, as these sources have negligible external costs associated with them.

Additionally, the fourth option emphasizes the importance of improving the efficiency of existing thermal power plants by 1% annually, which contributes to slowing the increase in carbon emissions and optimizing resource use. This dual focus on efficiency and renewable energy not only aligns with Iran's commitments under the Paris Agreement but also positions the country to achieve a more sustainable energy future.

In summary, the analysis underscores the importance

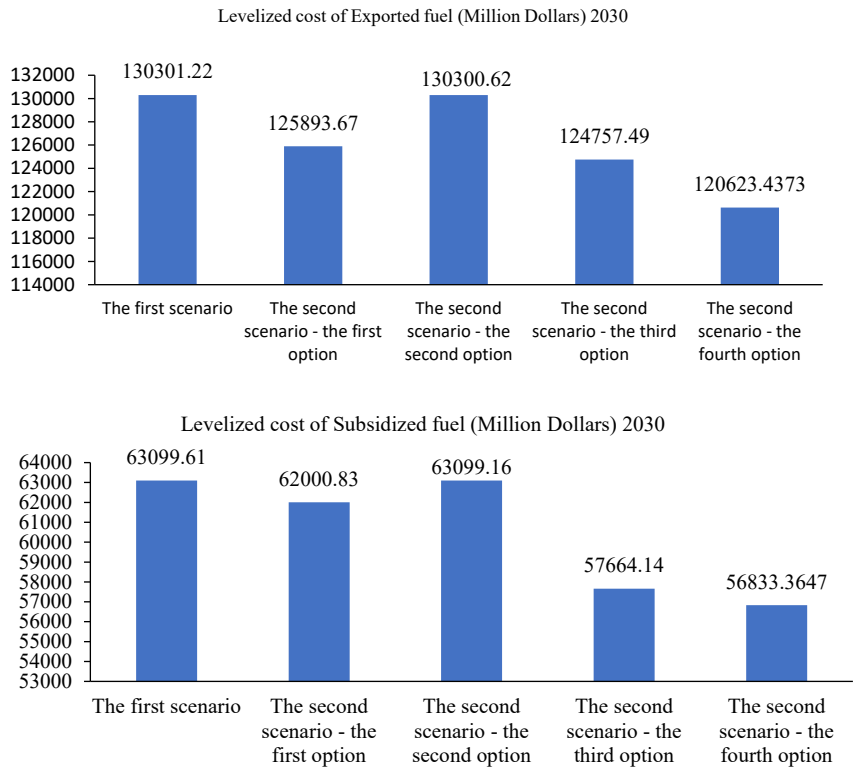

Figure 7: Levelized costs in the first scenario and different options of the second scenario in 2030 (Million Tons)

Table 18: A comparison between the results of various research and the aim of determining the cost price of electricity from different Technologies (Cent/kwh)

Results		Steam	Gas	Combined	wind	Photovoltaic
Current Research	Subsidized fuel	13.78	18.86	5.13	6.59	9.99
	Export fuel	0.28	0.15	1.98		
Mousavi, et al., 2012 (export fuel) [22]		11	13	9	9.5	-
Ram, et al., 2018 [62]		-	16.950	11.3	4	7
Asadi, et al., (export fuel) [2]		10	8	6	-	-
Report from International Energy Agency (China)		-	-	-	8.2	8.7
Motahari, et al., 2013 [36]	Subsidized fuel	-	7	-	8	-

of transitioning towards renewable energy and improving the efficiency of existing power plants to meet environmental commitments and reduce costs. The findings suggest that adopting a combined strategy will yield the best outcomes in terms of both emissions reduction and economic viability (Figures 6 and 7).

Final Cost of Electricity Generation

In an article titled "A Comparative Analysis of Electricity Generation Costs from Renewables, Fossil Fuels, and Nuclear in G20 Countries from 2015-2030," Ram and Child 2018 calculated the levelized cost of energy production using the LCEO method. The results showed that the average Levelized cost of energy production in combined cycle and gas-fired power plants is 11.3 and 16.95 cents per kWh of electricity generated, respectively.

The reason for the difference in the final cost in the above studies is the different initial information, including the price of each unit of fuel (government or export) and other technical specifications of the power plants. In the present study, the price of each unit of export fuel is 35 cents per cubic meter and the price of each unit of government fuel (with subsidies) is 0.139 cents per cubic meter. In the executive regulations of Note (14) of the 1396 National Budget Law No. 126375/T 54782 AH, the amount of 50 rials per cubic meter (or 0.139 cents per cubic meter) was set for the rate of various types of power plant fuel [63]. For this reason, in calculations based on the cost of government fuel, the cost price of electricity is lower than in other similar studies. Other studies that have made their calculations using information from years before 1396 have considered the price of government fuel to be 700 or 800 rials per cubic meter or more, depending on the year in question.

Conclusion

The findings emphasize that the optimal strategy for electricity production in Iran involves increasing the capacity of solar and wind energy by 5% and enhancing the efficiency of power plants. This approach is projected to significantly reduce carbon dioxide emissions by over 53 million tons compared to the continuation of the existing situation scenario, thereby fulfilling more than 75% of Iran's international emission reduction commitments under the Paris Agreement. The findings suggest that diversifying the energy portfolio through renewable resources not only mitigates greenhouse gas emissions but also contributes to economic growth by lowering the Levelized cost of electricity production. Additionally, the research highlights the importance of creating favorable conditions to attract private sector investment in renewable energy development, which is crucial for achieving both environmental and economic objectives.

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Competing Interests

The authors declare that there is no conflict of interest regarding the publication of this research paper.

Authors' Contributions

All authors contributed equally to this study.

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