Environmental Energy and Economic Research 2022 6(1): S027
DOI 10.22097/EEER.2021.298751.1213

Research Article

Effects of the Environmental Cost of Electricity Generation, Considering the LCOE Model

Seyedeh Mahsa Mousavi Reineh, Hossein Yousefi *

Faculty of New Sciences and Technologies, University of Tehran, Tehran, Iran

Received: 28 May 2021 /Accepted: 25 October 2021

Abstract
Human life is dependent on natural resources. Water shortage results from Climate change and population growth and societies worry about this complication. In addition to water supply in today's growing societies, energy provision and the consequences of their extraction are significant. The current study aimed to estimate the environmental costs of electricity generation and to analyze the impact of environmental costs on the price of electricity generation. The quantity of virtual water per kilowatt-hour of electricity generated from thermal power plants and renewable energies was estimated. Afterward, the quantity of particulate matter and greenhouse gases emitted from thermal power plants were determined. Within the final section, the price of electricity was computed by implementing the LCOE model under two different circumstances. The results reveal that the environmental costs of electricity generation affect the final price of electricity. Environmental costs of electricity generation, including the cost of fossil fuel, emissions, and virtual water costs in the steam turbine, gas turbine, and CCGT power plants are 3.03, 2.44, and 1.24 cent per kWh, respectively. The external cost of renewable energy is negligible. In alternative words, electricity from wind and photovoltaic keeps more than 10 million tons of particulate matter and greenhouse gases from emitting into the atmosphere each year. Therefore, to develop the Iran power industry, choosing the type of power plant and especially the type of cooling system has a key role in reducing water consumption. The results showed that the wind farms and photovoltaic energy are the most eco-friendly energy for controlling environmental issues.
Keywords: Electricity, Environmental cost, External cost, LCOE, Renewable energies, Virtual water

Introduction

The increasing population of the planet, finite energy resources, and the environmental impacts of fossil fuels have drawn the eye of all countries to differing kinds of energy sources. Therefore some countries have chosen to extend the employment of renewable energies like solar and wind powers (Mostafaeipour et al., 2016). There is an interdependency between the concept of energy and water typically known as the water-energy nexus. With increasing population and demand, decision-makers understand the importance of these two concepts. Just integrated planning for energy and water supplies can submit future demand (keller et al., 2010). Energy processes need water, these processes include electricity generation and the provision of fuel such as oil and natural gas, the extraction, purification, treatment, and disposal of heat and

* Corresponding author E-mail: hosseinyousefi@ut.ac.ir

wastewater. Also, energy is required for water treatment and supply (Delgado and Herzog, 2012). Certainly, these processes affect adversely on water resources. Actually, the water resources and the aquatic creatures of the regions suffer wherever the power plants are found (Averyt et al ., 2011).

Virtual Water in Electricity

Energy and water supplies are inextricably linked. Water excessive use is one of the most obvious environmental impacts of common power plants. With the increase of water withdrawal, the phenomenon of "embedded water" or "virtual water" that transfers in the process of electricity and energy trading between states or regions becomes important (Wang et al., 2015). During the time spent producing power, every single thermal cycle (coal, natural gas, nuclear, geothermal, and biomass) consumes water as a cooling liquid to drive thermodynamic cycles. In contrast, energy sources such as wind or solar, only require a little amount of water for cleaning equipment such as photovoltaic cells (Macknick et al., 2012). Hence improving the energy efficiency in using less water is important. By upgrading the existing cooling tower system overall energy efficiency can be increased by 1.5% (Jović et al., 2018). Another pressing environmental issue is regulating and minimizing the use of water in power generation systems (DeNooyer et al., 2016), (Savenije, 2020). Properly valuing water is difficult, and the green accounting of this natural resource isn't still complete and the dynamic and sensitive market of that isn't well developed. As a result, existing water price may not essentially represent a real worth for this resource (Dinar and Subramanian, 1998). Many studies calculate embedded water for generating electricity, such as Grubert and Grubert (2018), who assessed power plant water usage in the United States. The total amount of water which consumed and did not return to the source is equal to 10% of US freshwater. Important consumers are power plants based on: biofuels because of irrigation, injection and drilling oil wells, and hydropower through evaporation. Another conclusion of this paper was that in each of 300 power plants with once-through cooling system 70% of water usage related to this type of cooling system (Grubert, 2018).

Macknick et al. (2012) provide estimations about the concept and amount of water withdrawal and consumption through generating electricity in the United States. Major paper findings include: water extraction and consumption factors vary widely in various power generation technologies, but different types of cooling systems have a greater impact on water consumption. The maximum water consumption occurs when the cooling system is recirculating and the minimum occurs when renewable energies are replaced, such as photovoltaic and wind farm (Macknick et al.,2012).

Delgado et al. (2012) present a simple model for understanding the use of water in power plants. Especially for cooling, thermal power plants need large amounts of water. Various types of cooling systems require different amounts of water. The model estimates the use of water for the entire range of thermal power plants. One of the model's advantages is that it helps easily identify and understand what drives the use of water in a power plant. The design is also very useful in the development of water extraction and uses reduction strategies (Delgado et al., 2012).

In changing climate conditions, Gjorgiev and Sansavini (2018) concentrated on the impact of water policy restrictions on electricity generation. For the thermal power plant, i.e. once-through and wet tower cooling, two alternative cooling designs are tested. Finally, the analysis shows that once-through cooling systems are extremely sensitive to changes in water flow and temperature, which gives a chance to less sensitive technologies, i.e. wet cooling towers (Gjorgiev and Sansavini, 2018).

Zhang and Anadon (2013) use a mixed-unit multi-regional input-output and a life cycle impact assessment method based on the Eco-indicator to examine withdrawals, consumption, and wastewater of thermal power plants in china. 61.4 billion m^3 of water is withdrawn due to energy production. Another result was that the geographical disparity of fossil fuel reserves and water resources causes environmental effects. The environmental impacts of the consumption of water are concentrated in several northern China hotspots (Zhang and Anadon, 2013).

Externalities

Although generating electricity by renewable energy is more expensive than thermal power plants, they are more Eco-friendly and have negligible environmental impacts. Hence, one of the most important public policy reasons for promoting electricity generation from solar, wind, and other renewable resources is that they generate electricity without burning fossil fuels and emitting air pollution. One of the most important issues concerning the development and operation of energy systems is the production of greenhouse gas and pollutant emissions (Tavoni et al., 2007). External costs should be considered in evaluating energy sources (Parry et al., 1999).

Until 2010, thermal power plants that used fuels were economical owing to the subsidized fuels delivered by the government of Iran, and the price of electricity was controlled by the government. Over that period, the international price of fuel was upper than its internal level (Karbassi et al., 2007). The estimated subsidy on electricity prices was 1.5 US cent per kWh in 2010, implying that Iran's government has paid directly about 80 % of electricity generation cost as a subsidy. The low electricity price has a major role in environmental pollution because of the increasing rate of electricity consumption. The total amount of air pollutants produced by electricity generation, particularly CO_2, was estimated to be more than 128 million tons in 2009 (Mousavi et al., 2012). If continuous development and market introduction are achieved, renewable energy will make a substantial contribution to the reduction of global CO_2 emissions (Trieb et al., 1997).

The wind farm is an important sustainable supply of energy among renewable energy sources and countries pay more attention to sustainable development in recent years. The number of installed wind power plants is rising every year and several nations are planning to invest in wind energy soon (Keyhani et al., 2010). Solar energy is a strong renewable energy that is commonly used as an alternative to other energy resources by many countries. Many other countries, including Iran, continue to develop the infrastructure needed to utilize renewables (Mostafaeipour et al., 2016). Many governments and their policies tend to reduce environmental emissions which are gained by supporting renewable energies, but the high cost of investment in renewable energies is the most barrier to its development (Sen and Ganguly, 2017). The key obstacles and challenges to private sector investment and development in the renewable energy industry in Iran are high initial capital costs, lack of funding, lack of long-term government support, and low cost of electricity due to subsidized fossil fuels (Mousavi et al., 2012). Many studies have been conducted on externalities, for instance, Samadi (2017) has written a literature review on the cost of electricity generation technologies to decide which types of costs are important. The paper categorizes the relevant cost types, distinguishing them as the main categories between power plant level, system, and external costs. The results show that fossil-fuel technologies have more social costs compared to low-carbon technologies. More generally, the findings stress the importance of taking into account not only power plant-level costs but also system and external costs when comparing technologies for electricity generation from a societal point of view (Samadi, 2017).Feng et al. (2014) also calculated CO_2 emissions and water consumption by using Life Cycle Analysis, Input-Output Analysis and Water Stressed Index for carbon, gas, oil, hydro, nuclear, wind, photovoltaic, and hydropower plants. They showed that wind farms can save 80% CO_2 emissions and more than 50% of water consumption per kWh compared to the common technologies that use fossil fuels (Feng et al., 2014).

Levelized Cost of Energy (LCOE)

LCOE is a useful tool to compare the unit cost over its operational life (Szymański, 2021). The LCOE is a method of a power source that allows for a reliable comparison of various electricity generation methods (Szymański, 2021). Since electricity generation technology selection and design depends on the cost of producing energy, different technology costs need to be measured. Policy programs around the world for funding emerging clean energy technologies depend on reliable estimations of the Levelized Cost of Energy. Based on global reports, the LCOE analysis indicates that there is a wide cost range across renewable energy technologies. Hydropower and onshore wind are more mature technologies and the amount of their cost depends on the place they are located. If they locate in a suitable place, the costs will be the same as common technologies, but more emerging technologies such as marine tidal and wave are still in the early phases of cost discovery. The cost of generating electricity from a given technology should decrease overtime at a rate proportional to its degree of deployment. Over the past few years, LCOEs for photovoltaic (PV) and onshore wind have fallen dramatically as governments have provided financial support, these supports cause that these technologies deploy rapidly (Finance, 2017). A series of research from the different regions have looked at power plants to identify energy and economic potential.

AlderseyWilliams et al. (2019) revealed that LCOE estimates may be unreliable. They compared the LCOE of some offshore wind farms and one Combined Cycle Gas Turbine (CCGT) in the United Kingdom. The analysis shows that recent offshore wind projects display a significantly declining LCOE and that estimates of the cost of the public domain are unreliable (AlderseyWilliams et al., 2019). The LCOE model has been commonly used to estimate the costs of generating electricity. For example, IRENA (2012) estimated the cost of power generation across the world in 2010 (IRENA, 2012). Approximately 200 power plants in 21 different countries were investigated by OECD (2010) (Szymański, 2021).

Roth and Ambs (2004) present a full cost approach for determining the LCOE of 14 technologies for electricity generation. Internalizing "externalities", makes energy systems more sustainable and economical. This analysis includes the following externalities: air pollution damage, energy security, transmission and distribution costs, and other effects on the environment. Results indicated that internalizing externalities into the full cost strategy has a huge effect on the LCOE and the relative attractiveness of options for generating electricity. Findings suggest that renewable energies are more efficient and have negligible impacts (Roth and Ambs, 2004).

Mousavi et al. (2012) compare wind turbine as alternative energy competitiveness with existing ways of electricity generation in the Islamic Republic of Iran. For each type of technology, a LCOE strategy was carried out that included investment costs, operation and maintenance costs, fuel costs, and external pollution costs. Comparison of energy generation cost assessments reveals that wind power can be as economical as conventional power plants by taking into account global fuel prices and integrating air pollutant externalities (Mousavi et al., 2012).

Ouyang and Lin (2014) investigated the LCOE of renewable energy. This was one of the first studies on the LCOE of renewable energy in China. The conclusion showed that the Feed-In-Tariff (FIT) of Renewable Energy (RE) should be strengthened and modified dynamically based on the LCOE to better support RE's development. In China, the current FIT will cover onshore wind and solar PV at a discount rate of 5%. Except for biomass power, subsidies for renewable energy generation still need to be raised at higher discount levels (Ouyang and Lin, 2014).

Hulio and Jiang studied the output of the LCOE wind farm in Pakistan. Results showed that wind turbine efficiency was reduced by higher wind speed. The estimated levelized average energy cost for 1–10 and 11–20 years was US$ 0.11 and US$ 0.04/kWh, respectively. It makes it competitive with other energy technologies in terms of low production costs per kWh (Hulio and Jiang, 2018)

This paper aims to evaluate pollutants and greenhouse gas emissions that are resulting from fossil fuel power plants. The quantity of water consumption and water costs are also measured as virtual water of power generation. The effects of pollutant emission costs and the expense of water consumption in power plants are also investigated on the final price of electricity. The current study has been carried out in Iran in 2019. This paper is presented in four main sections: the introduction, the first section, deals with previous studies and provides an overview of study goals. Next, in the materials and methods section, the area under review, and the data sets and methods are added. Discussion and results, consisting of the main results and correlation with similar articles, and finally, the paper summarizes the findings in the last part.

Materials and Methods

The study area

Iran is a vast country (1.6 million km2), and its different types of climate are because of different topography, vegetation cover, and landscape. It is mild and quite wet on the coastal area of the Caspian Sea, continental and arid in the plateau, cold in high mountains, hot on the desert, southern coast, and the southeast. Generally, the Islamic Republic of Iran is not a humid country; but, within the west and also the north, the rain measure is a bit more than other areas. Because of that weather in Iran must be checked out regionally. In summer, the country's climatic situation is complicated.

The weather in the coastal areas of the Caspian Sea varies in summers due to high humidity. It's warm during the day, but it's relatively cool at night. Days are very hot in Iran's southern coastlines (Persian Gulf), and nights are relatively warm, with very high humidity (Keyhani et al., 2010). Countries know that climate is a crucial factor in development, growth, planning, and decision-making (Herbert et al., 2007).

Iran is located at 32°00'N and 53°00'E. The nominal capacity of the power plants in the country reached 76.5 GW in 2019. Of the total nominal capacity of the country's power plants, 20.7% belongs to the steam turbine, 36.4% belongs to the gas turbine, 25.5% belongs to combined cycle gas turbine, 15.1% belongs to hydropower and 2.3% belongs to other plants (nuclear, wind, solar, biogas and thermal recycling). The Ministry of Energy planned to increase the capacity of the country's electricity generation system, by new technology, combined cycle power plants, and renewable energy, in 2017. It aimed to secure local consumption and reduce distribution network losses and achieve higher efficiency in electricity generation (EnergyMinistry, 2016). The sample stations studied are indicated in Figure 1.

Research Methodology

To estimate the water usage of thermal power plants, a generic model is used in this paper. To illustrate the competitiveness of renewable energy, it is important to quantify levelized costs of energy. LCOE can be described as ‘‘a constant annually required revenue to recover all expenses over the life of a power plant’’ and is expressed as a price per kWh. Externalities are internalized by adding the external cost term to the LCOE equation that is used by the California Energy Commissions (Roth and Ambs, 2004).

Figure 1. Sample power plants in Iran

Virtual water consumption

A simple, generic model is introduced to predict water use accurately. The model's structure is given in equation 1, where water usage (I in L/kWh) is a function of the Heat Rate (HR) and other 3 parameters: A (L/kJ), B (kJ/kWh), and C (L/kWh) (Delgado and Herzog, 2012).

$$I = A(HR - B) + C \quad (1)$$

In equation 1 Parameter B shows heat flows that come out of the power plant. HR-B is the heat that is rejected by the cooling system. Parameter A is L/kJ and indicates the amount of water that is required through the cooling system. This depends on the kind of cooling system. This amount is different for once-through, wet cooling, or dry cooling. Parameter C is the amount of water which used in any process except the cooling system. Therefore, parameter I (the whole of water which cooling system using it to decreasing the heat), depends on C and A (3). The quantities of these parameters are shown in Table 1 (Delgado and Herzog, 2012), (Scott et al., 2011).

To represent the efficiency of power plants, HR is a common term used in power stations. There is an inverse relationship between the efficiency and the Heat rate of the power plants (a lower heat rate is better), and the efficiency at each power plant is a certain value. To calculate the Heat Rate, Equation 2 can be useful. HR depends on two factors: the type of fuel and the features of power plants. The lower the heat rate, the less cooling water is required per kWh (Delgado and Herzog, 2012).

$$Efficiency = {}^{3600}/_{HR} \quad (2)$$

LCOE

The LCOE is a helpful model to measure the unit costs over its operational life of different technologies. This model presents the levelized cost formula used to calculate lifetime (longrun) average levelized costs. The economics and methods behind estimating the average lifetime cost of each electricity-generating technology will be discussed. To calculate average lifetime levelized costs based on the costs for investment, operation, and maintenance, fuel, and external costs Equation (Delgado and Herzog, 2012) is used (Szymański, 2021), (Albani et al., 2020), (Ligus, 2015) and abbreviations may be found in Table 2.

Table 1. The relevant information of different power plants (Delgado and Herzog, 2012), (Comprehensive book on thermal power, 2018)

Type	Stations	Efficiency	Type of cooling	HR (kJ/kWh)	A (L/kJ)	B (kJ/kWh)	C (L/kWh)
Steam turbine	Montazeri	0.34	Dry	10588.2	0	5650	0.15
	Tous	0.37	Dry	9729.7	0	5650	0.15
	Ramin	0.36	Wet Tower	10000	0.0005	5650	0.15
	Iranshahr	0.31	Dry	11612.9	0	5650	0.15
	Rajaee	0.36	Dry	10000	0	5650	0.15
	Bistoun	0.38	Wet Tower	9473.7	0.0005	5650	0.15
Gas turbine	Sabalan	0.31	-	11612.9	0	5195	0.025
	Kashan	0.32	-	11250	0	5195	0.025
	Ferdosi	0.30	-	12000	0	5195	0.025
	Ofogh	0.27	-	13333.3	0	5195	0.025
	Chabahar	0.29	-	12413.8	0	5195	0.025
	Samangan	0.34	-	10588.2	0	5195	0.025
CCGT*	Zavare	0.48	Wet Tower	7500	0.0005	5650	0.18
	Neishabour	0.46	Dry	7826	0	5650	0.18
	Abadan	0.44	Dry	8181.8	0	5650	0.18
	Rajaee	0.32	Dry	11250	0	5650	0.18
	Shobad	0.33	Dry	10909	0	5650	0.18
	Paresar	0.50	Once-though	7200	0.00065	5650	0.18
Wind	Manjil	0.35-0.45	-	-	-	-	-
Photovoltaic	Persian Gulf	0.15-0.22	-	-	-	-	-

* Combined cycle gas turbine

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

The items of equation 3 can be described as follows.

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

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

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

$$C_{Ec}\left(\frac{\$}{kWh}\right) = Ef\left(\frac{g}{Btu}\right) \times HR\left(\frac{Btu}{kWh}\right) \times VED\left(\frac{\$}{g}\right) \quad (7)$$

As seen in Equation (Delgado and Herzog, 2012), the sum of capital costs, O&M costs, fuel costs, and external costs can be written as LCOE. To determine the external costs of CO_2, SO_2, NOx and other air pollutants released from power plants, the emission factor (EF), the value of environmental damage (US dollars per ton of pollutant), and heat rate (Btu per kWh) must be identified (Roth and Ambs, 2004). So the Equation 7 is a common form of calculation to estimate the C_{Ec} ($/kWh).

Table 2. Abbreviations (Aldersey-Williams et al., 2019)

Capital Cost	$/kWh	C_k
Depreciation Rate	%	DR
Total Plant Cost	$/kW	TPC
Construction Life	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

Data sets

To estimate the amount of virtual water consumption, efficiency, type of cooling, heat rate, and some parameters are required. The relevant information is given in Table 1. Many characteristics vary depending on the characteristics of power plants. For example efficiency, heat rate, and type of cooling system. Certain features differ for each type of cooling system, such as parameters A, B, and C.

In this analysis, cost estimations are conducted under two scenarios. In the first scenario, the specific fuel price of the power plant is subsidized, and the second scenario is based on the export price of fuel (35 cents per m3). The economic and technical characteristics of different power plants are presented in Table 3.

The economic parameters that were used in this study were derived from the economic studies carried out by the Iranian Energy Ministry and the Annual Energy Report of Iran (Mousavi et al., 2012), (Roumi et al., 2019), (EnergyMinistry, 2016).

To calculate External costs, Emission Factor (EF), and Value Of Environmental Damage (VED) are necessary. They are presented in Table 4. The values are extracted from the World Bank Report and Annual Energy Report (Mousavi et al., 2012; EnergyMinistry, 2016).

Table 3. Economic and technical characteristics (Mousavi et al., 2012), (Roumi et al., 2019), (EnergyMinistry, 2016).

Parameter	Value of Parameter				
	Steam turbine	Gas turbine	CCGT	Wind	Photovoltaic
HR (Btu/kWh)*	9700	11247	9480	-	-
PL	30	12	30	25	25
CL	5	2	5	2	2
CF (%)	89	62	76	30	18
TPC ($/kW)	1070	505	720	1900	4790
DR (%)	3.3	8.3	3.3	5	2
HY	6132	7358.4	7358.4	8497	8497
Discount rate (%)	14				
Escalation rate of O&M costs (%)	2			-	-
Escalation rate of fuel costs (%)	5			-	-
Cost of each unit exported fuel (natural gas) ($/MMBtu)*	9.92			-	-
Cost of each unit subsidized fuel (natural gas) ($/MMBtu)*	0.039			-	-

* Btu= 1055.05585 J, MMBtu= one million Btu

Table 4. Emission Factor and Value of environmental damage (Mousavi et al., 2012), (EnergyMinistry, 2016).

		CH4	CO_2	PM	SO_2	NO_x	CO	C
EF (gram/MMBtu)	Steam turbine	1.878	68757.829	13.831	449.899	102.579	485.425	56302
	Gas turbine	1.788	76733.462	12.998	103.144	118.148	18.561	63395
	CCGT	1.071	47565.503	7.674	55.148	72.601	17.73	41543
VED (cent/gram)		0.0335	0.00161	0.6923	0.2936	0.0965	0.00418	0.0006

Results and discussion

Quantity and Value of virtual water consumption

Depending on the type of power plant and the type of cooling system, the amount of water used in the power generation process is different. Choosing a cooling system will play a significant role in our future electricity mix growth. Differences between cooling systems can have significant environmental impacts on local water supplies and the need to obtain power generation water rights (Carter et al., 1979), (Reynolds, 1980), (Laws, 2000), (Scott et al., 2011).

The quantity of water consumed in each power plant was calculated using the information and parameters in Table 1. According to the sample stations in this study, the average virtual water consumption is presented in Table 5.

As the results show, it is possible to ignore water consumption in renewable energy sources. Whereas steam turbine with wet cooling system is high consumption. As a consequence, developing renewable energy technologies will help with conserving water resources.

In Iran, the price of raw water for industrial usage such as power generation is 0.02 cents per liter. It is therefore possible to calculate the economic value of water used in the production of electricity (Table 6).

Table 5. Virtual water consumption

Type of power plants	Type of cooling system	Virtual water consumption (L/kWh)	Virtual water consumption (m^3/year)
Steam turbine	Dry	0.15	854639
	Wet Tower	2.19	16360593
Gas turbine	-	0.025	54000
CCGT	Dry	0.175	919875
	Wet Tower	1.33	3938635
	Once-through	1.53	2502789
Wind	-	0.0	0
Photovoltaic	-	0.075	949

Table 6. Value of water consumed in electricity production

Type of power plants	Type of cooling system	Cost of virtual water (cent/kWh)	Cost of virtual water ($/year)
Steam turbine	Dry	0.003	170927.8
	Wet Tower	0.044	3272118.6
Gas turbine	-	0.0005	10800
CCGT	Dry	0.0035	183975
	Wet Tower	0.0266	787727
	Once-through	0.0306	500557.8
Wind	-	0	0
Photovoltaic	-	0.0015	189.8

Quantity of pollutant emissions

The amount of pollutions emitted by every single power plant is obtained by multiplying the relevant gas emission factor and the total production of that power plant. In the sample stations studied in this paper, the amounts of emitted gases were calculated and the results showed that thermal power plants produce more than 10 million tons of pollutants each year, including CH_4, CO_2, PM, SO_2, NO_x, CO and C. Table 7 shows the average of pollutants that are produced in each type of power plant. The amount of pollutants is estimated only at the stage of electricity production and the whole life cycle is not considered. Table 7 shows that 78% of the pollutants produced by thermal power plants belong to carbon dioxide, 21% belong to carbon and 1% belong to other pollutants.

Table 7. Quantity of pollutant emissions for each type of power plants (ton/year)

	CH_4	CO_2	PM	SO_2	NO_x	CO	C
Steam turbine	92	4368678	642.9	16560.4	14006.02	9573.71	1191460
Gas turbine	34.56	1665941	237.6	978.48	3587.76	81.16	454347
CCGT	46	2148806	1471.8	897.53	11930.35	269.81	586038
Wind	0	0	0	0	0	0	0
Pv	0	0	0	0	0	0	0

Results of LCOE model

The external cost of pollutant emissions was calculated according to Formula 7. External costs of different gases are listed in Table 8. The total cost of damages to air quality in this study is reported as external costs in Table 8.

Table 8. External costs of different gases (cent/kWh)

		CH_4	CO_2	PM	SO_2	NO_x	CO	C
External Cost (cent/kWh)	Steam turbine	0.0006	1.198	0.093	1.28	0.096	0.0197	0.328
	Gas turbine	0.0007	1.24	0.123	0.513	0.128	0.00087	0.427
	CCGT	0.0003	0.72	0.05	0.153	0.066	0.00072	0.2

LCOE model estimates the final cost of electricity under 2 scenarios. The first one is based on subsidized fuel cost and the second one is based on exported fuel cost, the findings are described in Tables 9 and 10 respectively. Graphical results are shown in Figure 4.

Table 9. LCOE based on First scenario (subsidized fuel cost)

	C_k	$C_{O\&M}$	C_{Fuel}	$C_{External}$	$C_{Virtual\ Water}$	Total cost (Cent per kWh)
Steam turbine	1.25	0.29	0.06	3.02	0.02	4.46
Gas turbine	1.27	0.22	0.09	2.44	0.00	4.03
CCGT	0.72	0.16	0.06	1.23	0.02	2.19
Wind	4.84	3.5	0	0	0	8.35
PV	7.14	4.27	0	0	0.00	11.41

As the results show in the first scenario according to the subsidized fuel conventional power plant electricity generation is cheaper than renewables, and it is not economical to build and produce electricity from renewable energy sources. The share of different costs of electricity generation is shown in Figure 2, this is based on the first scenario.

According to Figure 2, it is important to note that in thermal power plants the largest share of costs is related to external costs and in renewable power plants, the largest share is related to capital costs. In this scenario, the costs of fuel and virtual water can be neglected because the price of each unit of them is very cheap.

The price of fuel is considered equal to its export price in the second scenario and caused significant changes in the results. The share of different costs of electricity generation based on the second scenario is shown in Figure 3.

Table 10. LCOE based on the second scenario (exported fuel cost)

	C_k	$C_{O\&M}$	C_{Fuel}	$C_{External}$	$C_{Virtual\ Water}$	Total cost (Cent per kWh)
Steam turbine	1.25	0.29	16.05	3.02	0.02	20.63
Gas turbine	1.27	0.22	23.96	2.44	0.00	27.91
CCGT	0.72	0.16	15.68	1.23	0.02	17.81
Wind	4.84	3.5	0	0	0	8.35
PV	7.14	4.27	0	0	0.00	11.41

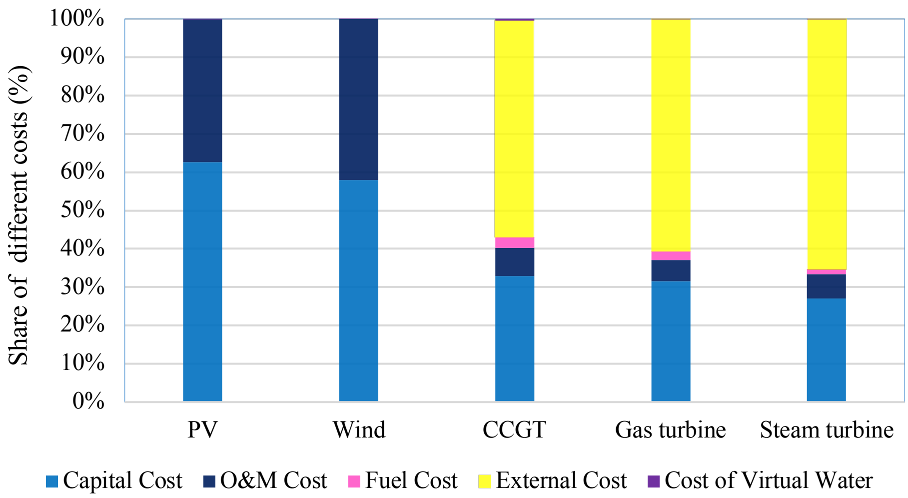

Figure 2. Share of different costs of electricity generation based on the first scenario (%)

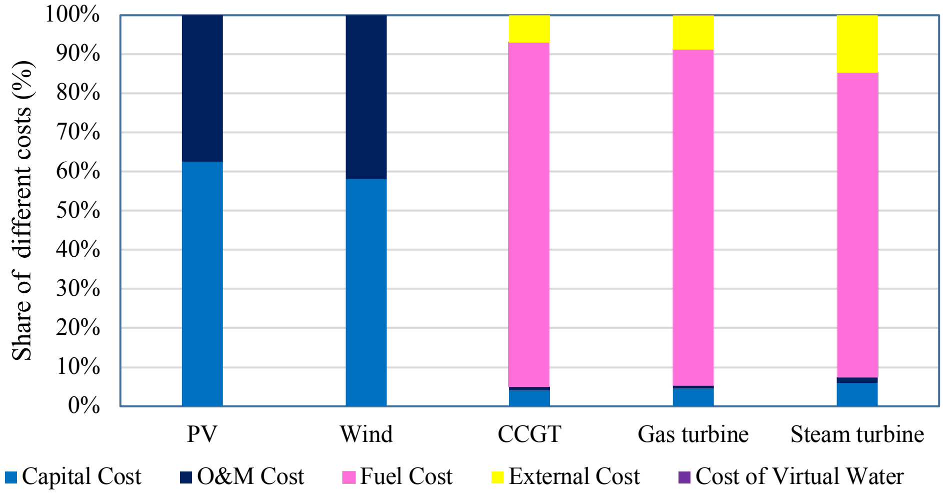

Figure 3. Share of different costs of electricity generation based on the second scenario (%)

The second scenario results show that generating electricity from renewables can be efficient if the fuel cost subsidies are excluded. In this condition fuel is expensive and it is better to be saved and instead of that renewable energy can be deployed easily. Figure 4 compares the LCOE of both scenarios.

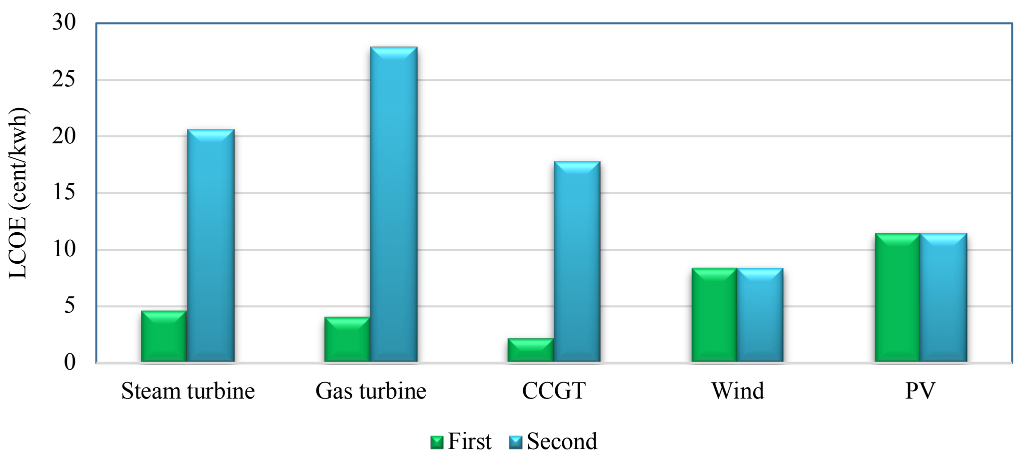

Figure 4. LCOE based on two different scenarios

According to the figures 2, 3 and 4, the difference between the final prices of the two scenarios in thermal power plants is related to the fuel cost.

Conclusion

The value of energy in today's world has led many countries to diversify energy sources and increase the share of renewable energy sources in their energy mix in addition to fossil fuels, which are the most popular and polluting energy sources in the world. Iran is a vast country with significant potential for both wind and solar energy sources. Using these resources can provide a major portion of the energy requirements of the country in the future. Unfortunately, little attention has been paid in recent years to the development of renewable energy. That is because Iran's gas and oil prices for thermal power plants are not a real fuel price, so electricity generation in thermal power plants is economical and renewable energy production is not economical. For instance, generating electricity from wind and photovoltaic power plants is not economical superficially. In the presented study, the cost of electricity generation in different types of power plants was investigated in two different scenarios. In the first scenario, where the price of each unit of fuel was determined based on the government rates, the results showed that the price of electricity generated in thermal power plants was more economical than the power provided by wind turbines and photovoltaic cells. But in the second scenario, by removing subsidies and considering the export price of the fuel used in thermal power plants, the cost of electricity produced at these plants will no longer be competitive and the use of wind and solar energy would compete with other sources of energy.

The absence of environmental costs of generating electricity is another advantage of wind and photovoltaic power plants over thermal power plants. Thermal power plants generate large quantities of pollution and greenhouse gases in the process of generating electricity by burning fossil fuels, causing irreparable damage to the planet. The environmental cost of generating electricity, including the cost of pollution of fossil fuels and virtual water consumption in the steam turbine, gas turbine, and CCGT power plants, is 3.03, 2.44, and 1.24 cent per kWh respectively. On the other hand, renewable energy (wind and photovoltaic) external costs are negligible. In other words, wind and photovoltaic electricity prevent more than 10 million tons of pollutants and greenhouse gases from entering the atmosphere and the environment every year.

The results of calculating the quantity of water consumed for the generating of each kWh showed that the quantity of virtual water consumed in various power plants depends on the type of power plant and the type of cooling system. The virtual water consumption rate for thermal power plants is between 0.025-2.19 liters / kWh, whereas the virtual water consumption rate for photovoltaic and wind turbines is between 0.07 and 0 liters / kWh. The average water usage is 2 million cubic meters in thermal power plants and 3,000 cubic meters per year in photovoltaic and wind power plants.

Water consumption in wind turbines was negligible in a study conducted by Macknick et al. (2012) and it was 0.09 liters per kWh in photovoltaic. According to Macknick's research, the Wet tower cooling system used 2.5 liters per kWh and 0.9 liters per kWh was used once-through the cooling system. In another study, Peter and Gleick (1994) examined the water and energy nexus. In that study, the amount of water used in various types of power generation technologies and types of cooling systems per kilowatt-hour of electricity production was investigated. The results showed that water consumption in renewable energies was negligible and water consumption in thermal power plants with wet tower and once-through was 2.6 and 1.1 liter per kWh respectively.

Therefore, to develop and grow the Iran power industry, choosing the type of power plant and especially the type of cooling system plays an important role in reducing water consumption. Although the cost of virtual water is negligible (0.02 cent/liter) due to the low cost of industrial raw water, the high water consumption in power plant processes for electricity generation indicates that by making conscious choices in the path of energy development, a significant amount of water loss can be prevented.

Based on second scenario, by removing subsidies and considering the export price of the fuel, wind and solar energy would compete with other types of technologies, so because of fuel subsidies, renewable energy can't develop quickly.

References

Albani, A., Ibrahim, M. Z., Yong, K. H., Yusop, Z. M., Jusoh, M. A., & Ridzuan, A. R. (2020). The wind energy potential in Kudat Malaysia by considering the levelized cost of energy for combined wind turbine capacities. Energy & Environment, 0958305X20937006.

Aldersey-Williams, J., Broadbent, I. D., & Strachan, P. A. (2019). Better estimates of LCOE from audited accounts–A new methodology with examples from United Kingdom offshore wind and CCGT. Energy policy, 128, 25-35.

Averyt, K. B., Fisher, J. B., Huber-Lee, A. T., Lewis, A., Macknick, J., Madden, N. T., ... & Tellinghuisen, S. (2011). Freshwater Use by US Power Plants Electricity's Thirst for a Precious Resource: A Report of the Energy and Water in a Warming World Initiative NREL Report No (p. 62). TP-6A20-5327 (Cambridge, MA: Union of Concerned Scientists) 62 p.

Carter, H. H., Schubel, J. R., Wilson, R. E., & Woodhead, P. M. J. (1979). Thermally induced biological effects caused by once-through cooling systems: A rationale for evaluation. Environmental Management, 3(4), 353-368.

Comprehensive book on thermal power. Holding Company in thermal power generation; 2018.

EnergyMinistry. Annual energy report of Iran. 2016.

Delgado, A., & Herzog, H. J. (2012). Simple model to help understand water use at power plants. Massachusetts Institute of Technology.

DeNooyer, T. A., Peschel, J. M., Zhang, Z., & Stillwell, A. S. (2016). Integrating water resources and power generation: The energy–water nexus in Illinois. Applied energy, 162, 363-371.

Dinar, Ariel, and Ashok Subramanian. "Policy implications from water pricing experiences in various countries." Water Policy 1.2 (1998): 239-250.

Feng, K., Hubacek, K., Siu, Y. L., & Li, X. (2014). The energy and water nexus in Chinese electricity production: a hybrid life cycle analysis. Renewable and Sustainable Energy Reviews, 39, 342-355.

Gjorgiev, B., & Sansavini, G. (2018). Electrical power generation under policy constrained water-energy nexus. Applied Energy, 210, 568-579.

Gleick, P. H. (1994). Water and energy. Annual Review of Energy and the environment, 19(1), 267-299.

Grubert, E., & Sanders, K. T. (2018). Water use in the United States energy system: A national assessment and unit process inventory of water consumption and withdrawals. Environmental science & technology, 52(11), 6695-6703.

Herbert, G. J., Iniyan, S., Sreevalsan, E., & Rajapandian, S. (2007). A review of wind energy technologies. Renewable and sustainable energy Reviews, 11(6), 1117-1145.

Hulio, Z. H., & Jiang, W. (2018). Assessment of the apparent performance characterization along with levelized cost of energy of wind power plants considering real data. Energy Exploration & Exploitation, 36(6), 1708-1728.

IRENA, (2012). Renewable power generation costs.

Jović, M., Laković, M., & Banjac, M. (2018). Improving the energy efficiency of a 110 MW thermal power plant by low-cost modification of the cooling system. Energy & Environment, 29(2), 245-259.

Karbassi, A. R., Abduli, M. A., & Abdollahzadeh, E. M. (2007). Sustainability of energy production and use in Iran. Energy Policy, 35(10), 5171-5180.

Keller, A. A., Tellinghuisen, S., Lee, C., Larson, D., Dennen, B., & Lee, J. (2010). Projection of california's future freshwater requirements for power generation. Energy & environment, 21(2), 1-20.

Keyhani, A., Ghasemi-Varnamkhasti, M., Khanali, M., & Abbaszadeh, R. (2010). An assessment of wind energy potential as a power generation source in the capital of Iran, Tehran. Energy, 35(1), 188-201.
Ligus, M. (2015). An analysis of competitiveness and potential of renewable energy technologies in Poland. Energy & Environment, 26(8), 1247-1269.
Laws, E. (2000). Aquatic Pollution 3rd edn (Hoboken, NJ)
Macknick, J., Newmark, R., Heath, G., & Hallett, K. C. (2012). Operational water consumption and withdrawal factors for electricity generating technologies: a review of existing literature. Environmental Research Letters, 7(4), 045802.
Mousavi, S. M., Ghanbarabadi, M. B., & Moghadam, N. B. (2012). The competitiveness of wind power compared to existing methods of electricity generation in Iran. Energy policy, 42, 651-656.
Mostafaeipour, A., Qolipour, M., & Mohammadi, K. (2016). Evaluation of installing photovoltaic plants using a hybrid approach for Khuzestan province, Iran. Renewable and Sustainable Energy Reviews, 60, 60-74.
Ouyang, X., & Lin, B. (2014). Levelized cost of electricity (LCOE) of renewable energies and required subsidies in China. Energy policy, 70, 64-73.
Parry, I. W., Williams III, R. C., & Goulder, L. H. (1999). When can carbon abatement policies increase welfare? The fundamental role of distorted factor markets. Journal of Environmental Economics and Management, 37(1), 52-84.
Reynolds, J. Z. (1980). Power plant cooling systems: policy alternatives. Science, 207(4429), 367-372.
Roth, I. F., & Ambs, L. L. (2004). Incorporating externalities into a full cost approach to electric power generation life-cycle costing. Energy, 29(12-15), 2125-2144.
Roumi, S., Parvin, M., & Yousefi, H. (2019). Financial and Environmental Analysis of Geothermal Heat Pump Utilization in Shiraz City of Iran. In Proceedings, 44th Workshop on Geothermal Reservoir Engineering (pp. 1-7). Stanford, CA: Stanford University.]
Samadi, S. (2017). The social costs of electricity generation—Categorising different types of costs and evaluating their respective relevance. Energies, 10(3), 356.
Savenije, H. H. (2020). Why water is not an ordinary economic good, or why the girl is special. Physics and Chemistry of the Earth, Parts A/B/C, 27(11-22), 741-744.
Scott, C. A., Pierce, S. A., Pasqualetti, M. J., Jones, A. L., Montz, B. E., & Hoover, J. H. (2011). Policy and institutional dimensions of the water–energy nexus. Energy Policy, 39(10), 6622-6630.
Sen, S., & Ganguly, S. (2017). Opportunities, barriers and issues with renewable energy development– A discussion. Renewable and Sustainable Energy Reviews, 69, 1170-1181.
Szymański, A. (2021). A brief history of the LCOE definition. Available at SSRN 3841428.
Finance, B. N. E. (2017). Global trends in renewable energy investment 2017.
Trieb, F., Langniβ, O., & Klaiβ, H. (1997). Solar electricity generation—a comparative view of technologies, costs and environmental impact. Solar energy, 59(1-3), 89-99.
Tavoni, M., Sohngen, B., & Bosetti, V. (2007). Forestry and the carbon market response to stabilize climate. Energy Policy, 35(11), 5346-5353.
Wang, Y. D., Lee, J. S., Agbemabiese, L., Zame, K., & Kang, S. G. (2015). Virtual water management and the water–energy nexus: a case study of three Mid-Atlantic states. Resources, Conservation and Recycling, 98, 76-84.
Zhang, C., & Anadon, L. D. (2013). Life cycle water use of energy production and its environmental impacts in China. Environmental science & technology, 47(24), 14459-14467.