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Research Article

Assessing the Life-cycle Greenhouse gas (GHG) Emissions of Renewable and Fossil Fuel Energy Sources in Iran

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Abstract
Renewable power generation is known as a low emission energy source. However, it is extremely important to analyze the greenhouse gas (GHG) emissions of renewable energy power stations along the entire life-cycle to broaden the concept of sustainability to an environmental and economic point of view. The main objective of this study was assessing and comparing the GHG emissions within the life-cycle of solar and gas power generation in Iran. A further objective was to evaluate the external costs associated with carbon emissions. The life-cycle inventory was first analyzed. The output emissions inventoried in the study were carbon dioxide (CO_2). Then the CO_2 emission and social cost of carbon during every process in solar and gas technologies were calculated by energy and environment software. Gas power plants are found to have a life-cycle CO_2 emission of 658 g-CO_2/kWh, which is comparatively higher than solar power life cycles (5.9 g-CO_2/kWh). Life-cycle CO_2 emissions from solar and gas power generation systems, imposes 70.8 and 2883.6 million US dollars/year to compensate its social effects. Results of the present study showed that the solar power generation is the environmentally-friendly form of producing electricity when compared with gas power technology in terms of life-cycle CO_2 emissions. This makes solar power as promising solution to the Iran's cleaner power transition.
Keywords: Electricity generation, Life-cycle assessment, Solar energy, CO_2 emissions, Social cost

Introduction

Global demand for energy is rapidly increasing, due to the population growth and economic development (Ardestani et al., 2017). The burning of fossil fuels can cause serious environmental problems, such as climate change, global warming and air pollution (Benedek et al., 2018). Because of the aforementioned environmental consequences, renewable energy sources can play an important role across the global energy transition (Lee and Chang, 2018).

The share of renewable energy sources within the global power generation mix saw its largest annual increase ever in 2016, with an estimated 161 GW of capacity added. Total global renewable power capacity was up almost 9% compared to 2015, to nearly 2017 GW at year's end. Solar photovoltaic (PV) systems saw record additions and, for the first time, accounted for

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more additional power capacity (net of decommissioned capacity) than any other generating technology. Solar PV represented about 47% of newly installed renewable power capacity in 2016. Wind and hydro power technologies accounted for most of the remainder, contributing about 34% and 15.5%, respectively (REN21, 2017).

In Iran, by installing 14 new power plants (renewable energy units, diesel generators and distributed generation) with a total capacity of 2366 MW, the total nominal capacity of the Iran's power plants reached 78793 MW at the end of 2016, which reveals a 3.1% growth comparing with the previous year (Iran's Ministry of Energy, 2018). Table 1 shows the composition and the share of gross generation of different power plants types in Iran at the end of 2016. According to the Table 1, the overall nominal capacity of gas power plants reached 25919 MW and it contains 32.9% of the country's power plants. In 2016, renewable power plants participated with a nominal capacity of 13441 MW in the process of electrical energy generation and their share of installed capacity was equal to 17.1%.

Table 1. Composition of different power plants technologies in Iran (Iran's Ministry of Energy, 2018)

Energy source	Nominal capacity (MW)	Share of gross generation (%)
Steam	15829	20.1
Gas	25919	32.9
Combined cycle	23165	29.4
Hydroelectric	11953	15.2
Diesel	439	0.6
Renewables*	468	0.6
Nuclear	1020	1.2
Total	78793	100

*Wind, solar and other types of renewable energy (except hydro units)

The term “renewable power generation” is generally applied to those power generation resources that are reduce energy consumption and henceforth decrease pollution (Fu et al., 2015; Hosseinidoust et al., 2020). However, when considering the entire life-cycle of renewable power generation, from material cultivation to fabrication, construction, operation, maintenance and decommissioning, the energy consumption and pollution emissions should not be neglected (Peng et al., 2013; Behboudi et al., 2017). Life-cycle assessment (LCA) is a decision-making tool that can be used to evaluate the environmental impacts of renewable energy technologies from cradle-to-grave (Amponsah et al., 2014; Ludin et al., 2018).

Several literature studies considered LCA of renewable energy technologies. Hou et al. (2016) investigated the environmental impacts of grid-connected PV power generation in China using LCA. They calculated the greenhouse gas (GHG) emissions in the range of 60.1 to 87.3 g-CO_2eq/kWh, depending on the installation methods. They also reported that the 84% of the total GHG emission occupied during the PV manufacturing process. Nian et al. (2014) studied the life-cycle analysis on carbon emissions from nuclear power generation and they obtained a carbon emission factor of 22.80 t-CO_2/GWh. Siddiqui and Dincer (2017) assessed the environmental impacts of wind power plant in Ontario through a comprehensive LCA approach. The GHG emissions were found to be 12.05 g-CO_2eq/kWh. Wang et al. (2018) estimated the environmental impacts to be 3 .92 g-CO_2eq/kW over the entire life-cycle of the hydro reservoir facilities.

A negative externality, also known as an external cost, arises when the social or economic activities of one group of persons have an impact on another group and when that impact is not fully accounted, or compensated for, by the first group (Tol, 2011). A power plant that generates emissions of CO_2 across the entire life-cycle, causing damage to building materials or human health, imposes an external cost (Raeesi et al., 2020). So, assessment of public health effects associated with air pollution caused by various means of electricity generation is an essential consideration (Mohajeri et al., 2020). The social cost of CO_2 (SCC) has become a common metric in estimating the economic concept of uncompensated social or environmental effect. In other words, SCC is intended to be a measure of society's willingness to pay to prevent the future damages that would arise from an incremental unit of CO_2 being emitted in a given year (Wang et al., 2019).

A large number of LCA studies have been carried out on electricity generation technologies. The novelty of this work lies in the focus on Iran as an emerging manufacturing power in world industry. The current study was aimed to evaluate the CO_2 emissions within the life-cycle of the solar power stations compared to gas power technologies in Iran. Additionally, the external costs associated with CO_2 pollution will be estimated. Therefore, for these purposes information regarding the Iranian solar and gas industries was summarized. Then, the ranges of emission data for CO_2 and social cost of carbon emissions related to the solar and gas technologies were identified.

Material and Methods

Life-cycle CO_2 emissions of electricity generation sources

LCA approach evaluates the environmental impact of products and services across all life-cycle stages, describes their interaction with the environment and accounts for all steps from raw material extraction to final disposal (Bartolozzi et al., 2017; Yang et al., 2018). The LCA can be applied to assess the impact on the environment of power generation technologies and will allow producers and policy makers to make better informed decisions pertaining to environmental protection (Barros et al., 2020). Depending on the scope of the LCA study, life stages of power generation technologies may include all or part of fuel production (i.e., to also account for the non-consumable portion of the produced fuel) and transportation to the plant, facility construction, facility operation and maintenance, and dismantling (Nugent and Sovacool, 2014). There are many evaluation methods used in LCA analyses. In this study, Energy and Environment software was applied to calculated the life-cycle CO_2 emissions from solar and gas power plants.

Energy and Environment software which was developed by Iran's Ministry of Energy is a model for calculating air emissions from the energy sector. This software has the ability to estimate the emissions of air pollutants and calculate the external costs of each of the pollutants in five sections including power plants, households-commercial, agriculture, industry and transportation. A summary of the input information for the Energy and environment software is provided below.

The characteristics and current status of solar energy in Iran

Solar energy is the world's largest clean energy source and a huge potential of this energy is available in the global sunbelt which is greater than the demand of countries in the region. Considering the location of Iran in sunbelt from the viewpoint of energy harvesting amount and average annual sunny hours of more than 2900 hours, is one of the most proper world's countries and in some country's regions such as central desert areas of Iran and its neighbor cities, the average annual sunny hours reaches more than 3200 hours (Tavanir Holding Company, 2017). The installed nominal capacity of the solar power plants in Iran at the end of January 2019 is shown in Table 2. As stated in Table 2, the total nominal capacity of the Iran's solar power plants reached to 286.78 MW.

Table 2. Installed nominal capacity of the solar power plants in Iran (SATBA, 2018)

Power plant locations	Nominal capacity (MW)	Power plant locations	Nominal capacity (MW)
Alborz	0.63	Semnan	1.31
Chaharmahal and Bakhtiari	1.5	Sistan and Baluchestan	10
Fars	36.6	South Khorasan	11
Hamadan	45.4	Tehran	21.63
Hormozgan	10	Qazvin	2
Isfahan	11.45	Qom	11
Kerman	33.2	Yazd	58.5
Razavi Khorasan	0.31	Different provinces*	32.25
Iran			286.78

*Small-scale solar power plants in residential areas

The characteristics and current status of gas power plants in Iran

Installed nominal capacity of the gas power plants in Iran at the end of 2017 is presented in Table 3. As can be seen, total nominal capacity of gas power plants was 22.89 GW in 2017. The points which make gas power plants attractive are low price, increasing the efficiency (by converting them to combined cycle) and domestic manufacturing possibility of major part of this type of power plant (SATBA, 2018). Total operational capacity and gross generation of gas power plants was 22.44 GW and 76778 million kWh, with the utilization factor and average efficiency of 38.9% and 31.3% (Iran's Ministry of Energy, 2018).

Table 3. Installed nominal capacity of the gas power plants in Iran (Iran's Ministry of Energy, 2018)

Power plant locations	Nominal capacity (MW)	Power plant locations	Nominal capacity (MW)
Ardabil	960	Lorestan	60
Buhsehr	1193	Mazandaran	47.4
East Azerbaijan	164	Razavi Khorasan	1349.6
Fars	1991	Semnan	648
Golestan	972	Sistan and Baluchestan	1106.7
Guilan	120	South Khorasan	1665
Hormozgan	1871.8	Tehran	2675
Isfahan	1365.6	West Azerbaijan	1020
Kerman	739	Yazd	541
Kermanshah	748	Zanjan	648
Khuzestan	2096	Different provinces	916
Iran			22897.1

The main fuel used in the Iranian gas power plants is natural gas and gasoline is an alternative fuel for these power plants. In 2017, the amount of fuel consumption of gas power plants in Iran consists of 21.33 million m^3 of natural gas and 2.12 million liters of gasoline (Ministry of Energy, 2018).

Availability factor of power plants

The availability factor of a power plant is the amount of time that it is able to produce electricity over a certain period, divided by the amount of the time in the period. Availability factor of different types of power plants is presented in Table 4.

Table 4. Availability factor of different types of power plants (Manzoor and Rahimi, 2015)

Energy source	Availability factor (%)
Steam	91
Gas	91
Combined cycle	91
Hydroelectric	50
Solar	20
Wind	38
Nuclear	96

Results and discussion

CO_2 emissions and social cost of carbon in the life-cycle of solar power plants in Iran

In solar power system, the majority of CO_2 emissions are associated with electricity and fuel consumption during manufacturing (Gerbinet et al., 2014). Table 5 shows the CO_2 emissions and social cost of carbon in the life-cycle of solar power plants in Iran. According to the Table 5, Yazd (with total capacities of 48.5 MW), Hamadan (with total capacities of 45.4 MW) and Fars (with total capacities of 36.6 MW) are the largest producer of CO_2 in the life-cycle of solar power plants with the emission amounts of 502, 472 and 378 t/year, respectively. These solar power plants also have the highest external cost of CO_2 with the amounts of 12.05, 11.33 and 9.07 thousand US dollars/year. This is while Razavi Khorasan (with total capacities of 0.31 MW), Alborz (with total capacities of 0.63 MW) and Semnan (with total capacities of 1.31 MW) solar power plants are the smallest producer of CO_2 with the emission amounts of 3, 6 and 12 t/year, respectively. The social cost of CO_2 emissions in the life-cycle of Razavi Khorasan, Alborz and Semnan solar power plants is estimated to be about 70, 140 and 290 US dollars/year, respectively.

Table 5. CO_2 emissions and social cost of carbon in the life cycle of solar power plants in Iran

Province	CO_2 emission (t/year)	Social cost (US dollar/year)	Province	CO_2 emission (t/year)	Social cost (US dollar/year)
Alborz	6	140	Semnan	12	290
Chaharmahal and Bakhtiari	18	430	Sistan and Baluchestan	106	2540
Fars	378	9070	South Khorasan	112	2690
Hamadan	472	11330	Tehran	224	5380
Hormozgan	106	2540	Qazvin	24	580
Isfahan	118	2270	Qom	112	2690
Kerman	342	8210	Yazd	714	14590
Razavi Khorasan	3	70	Different provinces	336	8060
Iran				2977	70880

CO_2 emissions and social cost of carbon in the life-cycle of gas power plants in Iran

Gas processing, well venting, pipeline compressors and leaks in transmission and storage systems make up the vast majority of CO_2 emissions from the life-cycle of gas power plants (Navajas et al., 2019). The amount of CO_2 emissions in the life-cycle of gas power plants in Iran are shown in Table 6. As stated in Table 6, power plants in Tehran (with total capacities of 2675 MW) are the biggest emitter of CO_2 with the emission amounts of 14.03 million t/year followed by Khuzestan (with total capacities of 2096 MW) and Fars (with total capacities of 1991 MW) with the emission amounts of 10.99 and 10.44 million t/year. While Mazandaran (with total capacities of 47.4 MW), Lorestan (with total capacities of 60 MW) and Guilan (with total capacities of 120 MW) are produce the least CO_2 with the emission amounts of 0.24, 0.31 and 0.62 million t/year. Thus, Tehran, Khuzestan and Fars provinces have the highest external cost of CO_2 in the life-cycle of gas power plants with the amounts of 336.88, 263.95 and 250.73 million US dollars/year, whereas Mazandaran, Lorestan and Guilan have the lowest external cost of CO_2 with the amounts of 5.97, 7.55 and 15.11 million US dollars/year.

Table 6. CO_2 emissions and social cost of carbon in the life cycle of gas power plants in Iran

Province	CO_2 emission (million t/year)	Social cost (US dollar)	Province	CO_2 emission (million t/year)	Social cost (US dollar)
Ardabil	5.03	120.9	Lorestan	0.31	7.55
Bushehr	6.26	150.24	Mazandaran	0.24	5.97
East Azerbaijan	0.86	20.64	Razavi Khorasan	7.08	169.95
Fars	10.44	250.73	Semnan	3.4	81.61
Golestan	5.1	122.4	Sistan and Baluchestan	5.8	139.37
Guilan	0.62	15.11	South Khorasan	8.73	209.69
Hormozgan	9.82	235.72	Tehran	14.03	336.88
Isfahan	7.16	171.98	West Azerbaijan	5.35	128.45
Kerman	3.87	93.06	Yazd	2.83	68.13
Kermanshah	3.92	94.2	Zanjan	3.4	81.61
Khuzestan	10.99	263.95	Different provinces	4.8	115.35
Iran				120.04	2883.6

Life-cycle CO_2 emissions for the solar and gas power plants in Iran is presented in Table 7. As can be seen, life-cycle CO_2 emission for the solar power plants is 5.9 g-CO_2/kWh, compared to 658 g-CO_2/kWh for gas power plants. This shows that gas power plants have nearly 111 times more impacts when compared to solar power plants in terms of global warming potential and human health.

Table 7. Life-cycle CO_2 emissions for solar and gas power plants in Iran

Power plant	Life-cycle CO_2 emission (g-CO_2/kWh)
Solar	5.9
gas	658

Results of the present study showed that the total installed capacity of the solar power plants in Iran is 286.78 MW, with the availability factor of 20%. The life-cycle CO_2 emission for the solar power plants is 5.9 g-CO_2/kWh. Similar observation was reported by Sherwani et al. (2010) who assessed the life-cycle of solar PV based electricity generation systems in China. They found that the CO_2 emission of 100 MW poly-crystalline solar PV system with efficiency of 15.8% was 9.4 g-CO_2/kWh. In this regard, study fulfilled by Li et al. (2019) revealed that the 10 MW concentrated solar power plant with availability factor of 57% is estimated to have CO_2 emissions of 35 g-CO_2/kWh. This discrepancy could be related to the different manufacturing, installation location/time, and installation type, including rooftop and ground-mounted systems.

The overall nominal capacity of gas power plants is 22.89 GW with the availability factor and average efficiency of 91% and 31.3%, respectively. The life-cycle CO_2 emission for the gas power plants is 658 g-CO_2/kWh. Similar results were found by Agrawal et al. (2014) who studied the life-cycle CO_2 emissions and their impacts due to the gas power plant in India. They reported that the total CO_2 emission from the 350 MW gas power plant with plant efficiency and fuel share (natural gas) of 42% and 100%, was 548 g-CO_2/kWh. Also, the investigation on the life-cycle assessment of natural gas power plants in Thailand showed that the total CO_2 emission to the atmosphere from the 3689 MW gas power plant with efficiency of 44% was 528 g-CO_2/kWh (Phumpradab et al., 2009). The CO_2 emissions for gas power plants in Iran are slightly different from power plants in India and Thailand as a result of different power generation efficiency (i.e., 31.3%, 42% and 44% in Iran, India and Thailand, respectively).

The nominal capacity of the Iran's power plants has been on a steady increase. Considering the average annual growth rate, gas power generation capacity was predicted in the forecast period of 2019 to 2029 and shown in Figure 1. Figure 1 also depicts the life-cycle CO_2 emissions of this kind of power plants. As can be seen, Iran's gas power generation capacity in 2019 is 31.39 GW with the life-cycle CO_2 emissions of 164.75 million t/year. The power generation capacity and the life-cycle CO_2 emissions are projected to increase by 56.76 GW and 297.84 million t/year, respectively in 2029. It shows an average emissions growth rate of about 6% per year. Considering that the increased usage of fossil fuels to meet electricity demand have caused detrimental effects on the environment, development of renewable electricity generation sources should be noted and performed.

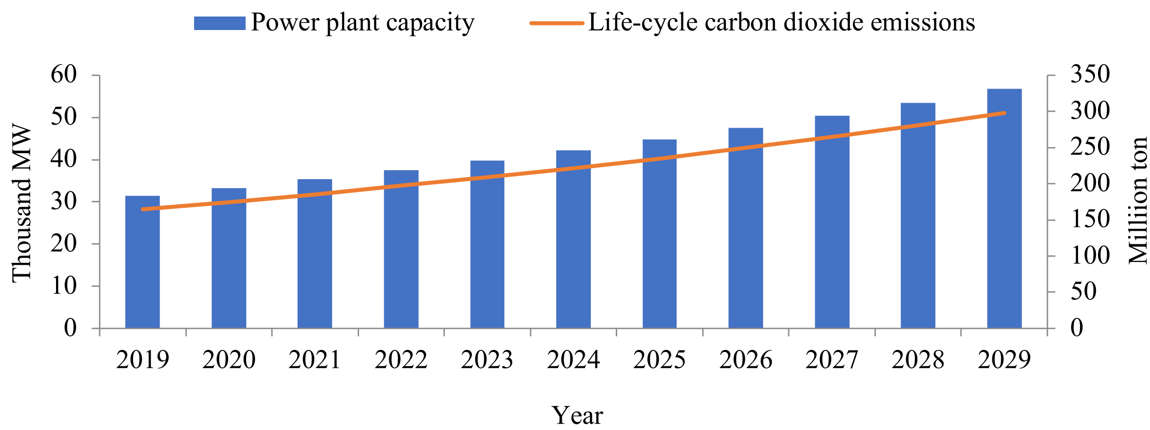

Figure 1. Projection growth of gas power generation capacity in Iran (2019-2029)

Conclusions

GHS emissions were generally estimated for the full operational life-cycle of each energy source from the manufacturing of the plant to full operation and dismantling of the system (i.e., cradle to grave). This paper focused on life-cycle GHG emissions of electricity generation from solar and gas energy sources. Emission factor for CO_2 was selected as a key indicator for environmental performance during electricity generation. Results showed that solar power is not a clean energy because of its serious pollutant discharge during different life-cycle stages. Although a certain amount of 5.9 g-CO_2/kWh is released during the entire life-cycle, the value will be much lower when compared with the CO_2 emissions from the life-cycle of gas power plants (658 g-CO_2/kWh). The LCA results show that solar technologies are already proved to be very sustainable and environmental-friendly in the state of the art. With the emerging of new manufacturing technologies, the environmental performance of solar technologies is expected to be further improved in the near future. Hence, development of more environmentally benign solar turbine construction methods is suggested.

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