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Impact of Wind Farms on Reduction of Power Plant CO_2 Emissions: A Real Case Study in Iran

M. Khatibi[1, 2*] and A. Rabiee[2]

1. Department of Power Grid Planning, Zanjan Regional Electric Company, Zanjan, Iran.
2. Department of Electrical Engineering, University of Zanjan, Zanjan, Iran.

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**Corresponding author: m_khatibi@zrec.co.ir (M. Khatibi)*

Abstract

Electricity generation through renewable energy sources such as wind energy has been growing in the recent years due to several reasons including the free and infinite resources as well as their considerable impact on the reduction of fossil fuel consumptions and CO_2 emissions. This paper aims to assess the impact of grid-connected large-scale wind farms in a region located in Iran on the reduction of natural gas (NG) as well as gasoil fuel consumptions in heat-cycle power plants and their related CO_2 emissions as a practical case study. The wind farms under study comprise about 51% of the total grid connected capacity of wind power generation in Iran by the end of March 2021. The total energy yielded by the studied wind farms are first extracted over a two-year period from April 2019 to March 2021 based on a detailed practical data, and then its impact is investigated on the reduction of NG and gasoil consumptions in a real heat-cycle power plant due to its practical fuel intake data. Finally, the reduction of CO_2 emission is calculated as a result of reduction in the NG and gasoil consumptions of the considered heat-cycle power plant. The results of this practical case study well-demonstrate the effective role of the wind farm energy yields on the reduction of fossil fuel consumption in heat-cycle power plants, and thus the significant reduction of CO_2 emission as one of the most crucial aspects of decarbonization and fossil fuel phase out plans.

Keywords: *Wind farm, Gas-cycle power plant, Fossil fuel consumption, CO_2 emission.*

1. Introduction

The use of renewable energy sources and clean energies including wind energy to generate electricity has always been of great importance due to the free and infinite resources as well as their significant impacts on reducing the consumption of fossil fuels such as coal, lignite, natural gas (NG), and gasoil (diesel), and consequently, the reduction of carbon dioxide (CO_2) and other pollutants [1]. Nowadays, in almost all regions of the world that have the potential of employing these resources, appropriate renewable energy-based power plants have been implemented or are underway. Moreover, several countries have planned to cover 100% of their load demands by renewable energies in a near future. In Iran, the generation of electrical energy from renewable energies (mainly including wind energy), given its very good potential in various regions of country, has been one of the key priorities of the Ministry of Energy in the recent years. Thus significant supports have been considered for the investment in this field such as long-term guaranteed electricity purchase agreements by the government with motivating feed in tariffs [2]. The role of wind farms in generating electrical energy can be studied from various viewpoints including the technical, economic, and environmental aspects. One of the important fields of studying renewable-based power plants is to assess their impact on savings of fossil fuel consumption in heat-cycle power plants, and consequently, reduction of environmental pollutions, especially CO_2 emissions, and various research works have been carried out so far in this field. In [3], the environmental impacts of wind energy has been studied including the problems, solutions, and suggestions as well as the positive and negative impacts of the wind energy. It has been concluded that wind energy will reduce the environmental pollutions and water consumptions. In [4], a case study has been presented in order to evaluate the potential environmental advantages of an increased shift from fossil fuels to renewable fuels for electricity generation in Oklahoma illustrating the explicit reduction that wind energy can have on the air quality and health benefits. A method of quantifying operational CO_2 savings from wind power generation has been described in [5] regarding the 2011 Irish electricity grid. Taking into account an emission model and 12-hour generation time-series for grid-connected thermal generators, it has been estimated that wind power saves 0.28 tCO_2/MWh, on average. In [6], the impact of wind energy and forecast uncertainty has been investigated on generator dispatch arrangements and CO_2 emissions. The results of this analysis show that a reduction of 17% in CO_2 emissions is reached at 30% wind penetration. An efficient literature review of wind farm life cycle investigations as well as the features related to CO_2 emissions have been studied in [7]. Power planning for Vietnam over the 2018–2030 period under CO_2 emission targets has been proposed in [8]. The results obtained show that by decreasing the 42.6% share of coal-fired capacity to 29% and 19% by 2030, the CO_2 reduction will be around 8% and 25%, respectively. The impacts of wind power generation for Ontario have been investigated in [9], resulting in an estimated benefit of 109 million USD by reducing CO_2 emissions via displacing thermal generations. Finally, various options to meet CO_2 emission targets in the Bahamas are studied in [10], considering the generation of 55% of total electricity by 2027 through renewable energy sources.

It is the purpose of this paper to investigate the effect of electrical energy generation by wind farms in a region located in Iran, as an actual case study, on the reduction of NG consumption in a real gas-cycle power plant, and thus reduction of CO_2 emissions. A two-year time period from April 2019 to March 2021 is taken into account. First, the amount of electrical energy yielded from the considered wind farms is calculated over the time period under study based on a detailed practical data. Then the saved amount of NG and gasoil consumption in a real gas-cycle power plant is calculated due to its practical fuel intakes. In addition, the related reduction of CO_2 emission is calculated.

This paper is organized as what follows. In Section 2, the total energy yielded by the considered wind farms is extracted. In Section 3, the reduction of fossil fuel consumption for both NG and gasoil fuel is investigated. Next, the impact of renewable-based energy generation on the reduction of CO_2 emissions is studied in Section 4. Finally, conclusions are presented in Section 5.

2. Electrical energy generated by wind farms

The area under study is one of the most potential regions in Iran in terms of wind energy resources, and so far, three large-scale wind farms with a total installed capacity of 163.72 MW, as summarized in table 1 [2], have been connected to the grid comprising about 51% of the total grid-connected capacity of wind farms in Iran and nearly 18% of the total renewable energy based generations by the end of March 2021 [2]. Figure 1 illustrates the monthly average electrical energy generation of the considered wind farms over the studied time period. It has been observed that from June to September, which is the peak demand interval in Iran due to the hot weather conditions, and hence, air conditioning load demands, the wind energy potential in this region is much better than the other months of the year. The capacity factor (CF) of a wind farm is defined as the actual electricity production of a power plant divided by the maximum possible electricity output over a period of time [11], [12]. In other words, it measures the actual generation of a wind farm compared to the maximum total it could generate in a specified period without any interruption [13]. The average CF of the studied wind farms over the studied two-year period is about 28%. The average CF of each wind farm is presented in table 1. The yearly CF of the studied wind farms are illustrated in figure 2, which depicts the suitable wind energy potential of the studied region.

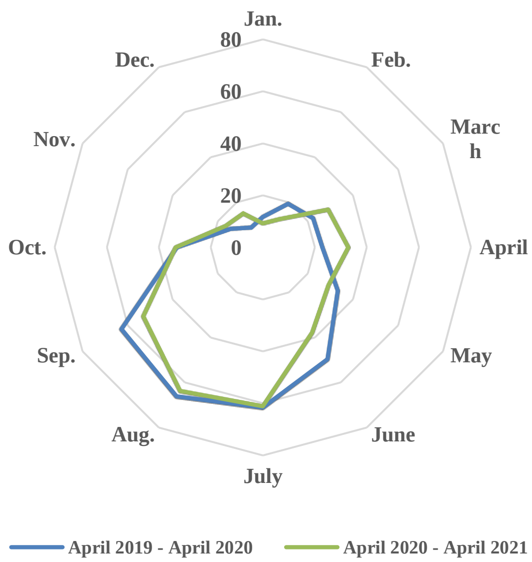

Figure 1. Electrical energy yields of the studied wind farms over a two-year period in GWh.

Table 1. Large-scale grid-connected wind farms in the studied region

Wind sarm	Installed capacity (MW)	Average CF (%)
Site 1	45.72	21.7
Site 2	55	32.2
Site 3	61.2	29.4
Total	163.72	28

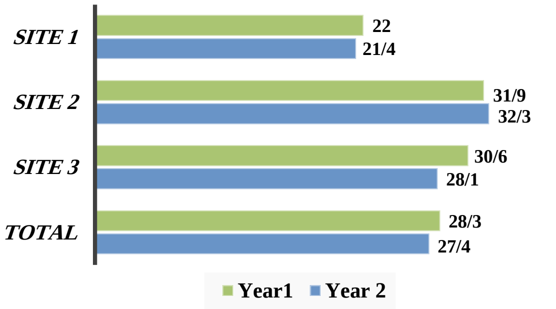

Figure. 2. Capacity factor of the wind farms in the studied area over a two-year period (%)

The electrical energy generated by the aforementioned wind farms over a two-year period from April 2019 to March 2021 is summarized in table 2, and the share of considered wind farms in the monthly generated energy is illustrated in figure 3 [14]. It has been observed that over the studied two-year period, a total amount of 799.2 GWh of electrical energy is generated by the wind farms under study, where 405.74 GWh is related to the energy yields from April 2019 to March 2020 and 393.46 GWh is associated with the energy yields from April 2020 to March 2021. The difference between the energy generations in the two 12-month periods may relate to the changes in windy hours, wind speed variations, out-of-service wind turbines, grid limitations, etc.

Table 2. Annual energy generation of the studied wind farms (MWh).

Time interval	2019-2020				2020-2021			
	Site 1	Site 2	Site 3	Total	Site 1	Site 2	Site 3	Total
April	6028.38	7169.72	9700.79	22898.89	7618.56	13567.63	11652.55	32838.74
May	7269.36	13382.46	12670.88	33322.7	7657.20	9608.52	11838.64	29104.36
June	9798.01	19867.33	19976.82	49642.16	7832.85	12429.06	17649.85	37911.76
July	12466.66	22377.43	26734.47	61578.56	11786.24	27071.95	22272.86	61131.05
Aug.	13528	25184.66	27494.12	66206.78	12189.49	26511.01	24993.6	63694.1
Sep.	13139.88	23629.02	25990.16	62759.06	11739.18	21385.44	19959.5	53084.12
Oct.	8232.54	11320.91	13422.64	32976.09	7688.03	13223.58	12586.04	33497.65
Nov.	3874.27	4932.00	5406.05	14212.32	3690.08	6811.05	5953.83	16454.96
Dec.	2448.16	1666.42	4715.12	8829.7	2262.92	9131.13	3693.24	15087.29
Jan.	3491.88	4230.96	3904.71	11627.55	1844.57	4660.3	2726.29	9231.16
Feb.	3135.89	9938.63	6311.66	19386.18	3028.55	4564.0	4842.05	12434.6
March	4742.04	9800.14	7753.01	22295.19	8274.31	8058.55	12654.43	28987.29
Total yielded Energy (MWh)	88155.07	153499.7	164080.4	405735.2	85611.98	157022.2	150822.9	393457.1

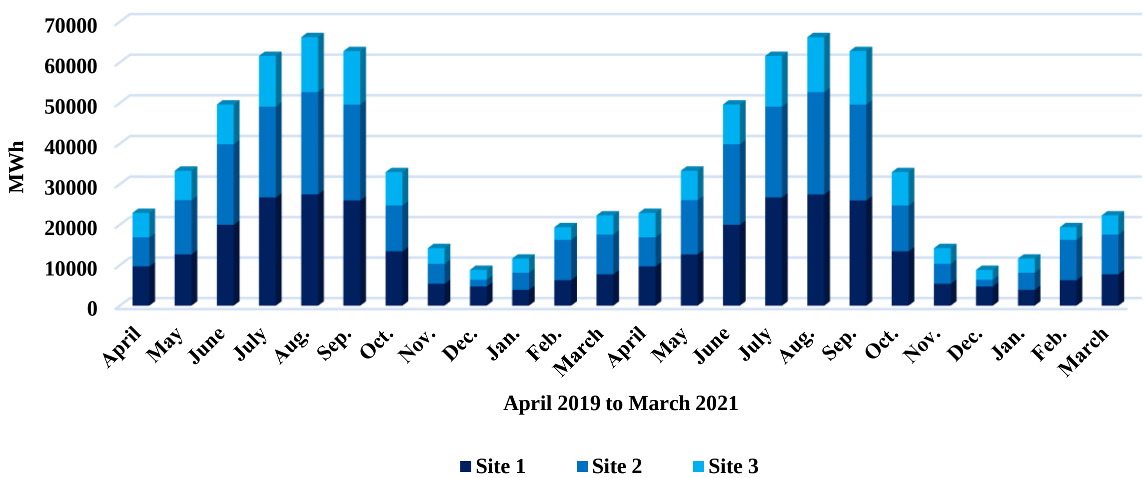

Figure 3. Share of studied wind farms in the monthly generated energy over the two-year period.

3. Reduction of fossil fuel consumption

In order to assess the reduction of fossil fuel consumption due to the energy generated by wind farms, the fuel intake of heat-cycle power plants must first be determined. The fuel intake in a power plant does not have a fixed amount, and it depends on various factors such as the plant life, type of prime movers, power plant efficiency, weather conditions, elevation of the power plant above the sea level, and heat content of the fuel, i.e. the amount of energy produced when it is burned [15], [16].

In this paper, in order to access the real amount of fossil fuel required to generate electrical energy in a heat-cycle power plant in the region under study, the actual fuel consumption data of a real gas-cycle power plant nearby the considered wind farms is considered. The reason for selecting this power plant for comparison is due to the fact that if the considered wind farms were not connected to the grid, this gas-cycle power plant would be in charge to generate the demanded energy. The considered gas-cycle power plant is elevated about 1800 m above the sea level, and its total capacity is 648 MW consisting of 4 gas units all put into operation in 2010 with an efficiency of about 31% [17]. It is operated by NG as its main fuel intake; however, it can also operate by the gasoil as the second fuel intake [18]. In addition, this power plant is designed to operate as a combined cycle but its steam cycle has not yet been constructed.

3.1. Reduction of NG consumption

In order to obtain the NG consumption in the studied gas-cycle power plant, its monthly NG intakes per MWh of electrical energy generation were employed, and then the yearly average of these values were calculated; an average of 0.3212 m^3/kWh was gained based on the existing practical data, meaning that in order to generate 1 MWh of electrical energy in the above-mentioned power plant with an efficiency of 31%, an amount of 321.2 m^3 of NG is required. As this power plant is only a gas-cycle type, its fuel consumption per MWh of electrical energy generation is higher than that of a combined-cycle power plant. It is worth noting that by grid connection of the steam cycle in the power plant under study, its efficiency will rise considerably, leading to a reduction in the fuel intake per generation of specific amount of electrical energy.

Regarding the 321.2 m^3/MWh for NG consumption in the studied gas-cycle power plant, the amount of NG savings per generation of total 799.2 GWh of electrical energy by the considered wind farms over the considered two-year period are summarized in table3. In addition, figure 4 shows the annual reduction of NG consumption as a result of energy generation by the considered wind farms.

Table 3. NG savings and related revenues due to the studied wind farms over a two-year time period.

Wind farm	NG saving (million m^3)	Related revenue (million USD)
Site 1	55.81	4.38
Site 2	99.74	7.83
Site 3	101.15	7.94
Total	256.7	20.15

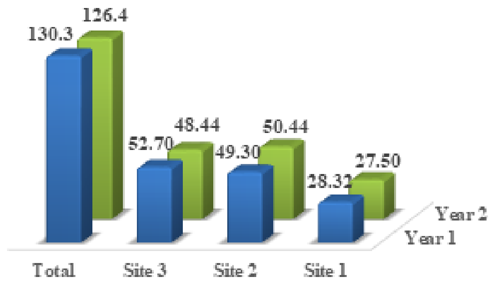

Figure 4. Reduction of NG consumption due to the energy yields by the studied wind farms (million m^3).

According to the results presented in table 3 and figure 4, if the 799.2 GWh of electrical energy yielded by the three studied wind farms over a 24-month time period were generated by a gas-cycle power plant with an efficiency of about 31% and NG fuel intake, an amount of 256.7 million m^3 of NGs would be burnt.

In addition, if this saved amount of NG was considered for export, given that the average heat rate of Iran NG is about 8600 kcal/m^3 [19] and regarding the average international price of NG over the past two years as about 2.3 USD per million BTU [20], its financial revenue would be about 20.15 million USD. (One million BTU is equivalent to 252000 kcal of energy, which requires 29.3 m^3 (29.3 = 252000/8600) of Iran NG to burn.)

3.2. Reduction of gasoil fuel consumption

The main fuel intake of the gas-cycle power plant taken into account in this paper is NG; however, it can also operate by the gasoil fuel intake as the second fuel intake. This is probable in the winter days due the NG shortages as a result of cold weather conditions, and thus the rising NG consumptions in the residential sector. Hence, in this section, the reduction of gasoil fuel consumption is also calculated regarding that if the total 799.2 GWh of electricity yielded by the wind farms over the studied two-year period were generated by the considered gas-cycle power plant with gasoil fuel intake, how much of this fuel type would be burnt. In order to calculate the gasoil consumption in this gas-cycle power plant, its yearly average of gasoil intake per MWh of electricity generation was utilized based on the practical data; an average of 322 Liter/MWh was gained [14]. Therefore, gasoil savings per generation of total 799.2 GWh of electricity by the considered wind farms in the studied two-year period are summarized in table 4. In addition, the annual reduction of gasoil consumption resulting from the electrical energy yielded by the studied wind farms is depicted in figure 5. It was observed that if the 799.2 GWh of electrical energy yielded by the considered wind farms over the studied two-year period were generated in a gasoil fueled gas-cycle power plant with an efficiency of about 31%, an amount of 257.34 million liters of gasoil would be burnt.

Table 4. Gasoil savings due to the studied wind farms and the two-year time period.

Wind farm	Gasoil savings (million liter)
Site 1	55.954
Site 2	99.988
Site 3	101.4
Total	257.34

Figure 5. Reduction of gasoil consumption due to the energy yields by the studied wind farms (million liters).

4. Reduction of CO_2 emission

The amount of CO_2 released when a fuel is burnt is a function of the carbon content in that fuel [16]. Different fuels emit different amounts of CO_2 based on the energy they produce when burnt, and the amount of energy produced is mainly determined by the carbon and hydrogen content of the fuel [16]. The CO_2 reduction related to the energy yielded by the studied wind farms is calculated in the following based on the considered real gas-cycle power plant with the fuel intakes of NG and gasoil fuel as well as taking into account its 31% efficiency.

4.1. CO_2 reduction based on NG

NG is primarily methane (CH_4), which has a higher energy content relative to the other fuels, and hence, it has a relatively lower CO_2-to-energy content [16]. Burning one million BTU (equivalent to 252000 kcal of energy) of NG releases about 53 kg of CO_2 [16]. Given that the average heat rate of Iran NG is about 8600 kcal/m^3, burning 29.3 m^3 of Iran NG will release 53 kg of CO_2. In other words, burning 1 m^3 of Iran NG releases about 1.81 kg of CO_2.

As mentioned earlier, in the considered real gas-cycle power plant with the efficiency of about 31%, 320 m^3 of NG is required to generate 1 MWh of electrical energy. Therefore, in this power plant, nearly 578.9 kg of CO_2 per 1 MWh of electrical energy generation will be released by burning NG. As a result, the reduction in CO_2 emission per 799.2 GWh of energy yielded by the wind farms in the area under study is summarized in table 5. It has been observed that by generating 799.2 GWh of electrical energy demand by the wind farms in the studied region and consequently, not generating this amount of energy in a heat-cycle power plant, the CO_2 emission is reduced by 464.34 thousand tons. The annual reduction of CO_2 emissions as a result of related reduction in the NG consumption due to the electrical energy generation by the considered wind farms is illustrated in figure 6.

Figure 6. CO_2 reductions due to the energy yields of the studied wind farms regarding the considered gas-cycle power plant and NG fuel intake (thousand tons).

4.2. CO_2 reduction based on gasoil fuel

The gasoil fuel is refined from crude oil at petroleum refineries. Burning 1 L of gasoil releases about 2.67 to 2.7 kg of CO_2 [16], [21]. As mentioned earlier, in the studied real gas-cycle power plant with the efficiency of about 31%, an amount of 322 L of gasoil fuel is required to generate 1 MWh of electrical energy. Hence, in this power plant, nearly 869.4 kg of CO_2 per 1 MWh of electrical energy generation will be emitted by burning the gasoil fuel. Consequently, the reduction of CO_2 release per 799.2 GWh of energy yielded by the studied wind farms is summarized in table 5.

Table 5. CO_2 reductions due to the studied wind farms over a two-year time period.

Wind farm	Reduction of CO_2 emissions (thousand tons)	
	In NG intake	In gasoil intake
Site 1	100.96	151.08
Site 2	180.42	269.97
Site 3	182.96	273.78
Total	464.34	694.83

Based on table 5, yielding 799.2 GWh of demanded electricity by the wind farms in the studied region, and therefore, not generating this amount of energy in a heat-cycle power plant with gasoil fuel intake, would result in the reduction of CO_2 emissions by 694.83 thousand tons, which is nearly 50% higher than the case of generating the same amount of electricity with NG fuel intake. figure 7 illustrates the annual reduction of CO_2 emissions as a result of related reduction in the gasoil fuel consumption regarding the yielded energy by the studied wind farms.

Figure 7. CO_2 reductions due to the energy yields of the studied wind farms regarding the considered gas-cycle power plant and gasoil fuel intake (thousand tons).

It is worth noting that considering the carbon tax savings due to the reduction of related CO_2 emissions will well-demonstrate the importance of renewable energy based power generations.

5. Conclusions

In this paper, as a real case study, we assessed the impact of grid-connected large-scale wind farms in a region located in Iran on the reduction of natural gas (NG) and gasoil consumptions in a gas-cycle power plant as well as the related reduction of CO_2 emissions. The studied wind farms comprised about 51% of the total grid-connected capacity of wind generation in Iran by the end of March 2021. As extracted based on a detailed practical data, a total amount of 799.2 GWh of electrical energy was yielded by the studied wind farms over a two-year period from April 2019 to March 2021. The impact of the renewable-based generated energy was then studied on the reduction of NG and gasoil consumptions in a real gas-cycle power plant based on its practical fuel intake data. It was observed that if the above-mentioned renewable-based energy was generated in a gas-cycle power plant with an efficiency of 31% and 321.2 m^3/MWh of NG intake, an amount of 256.7 million m^3 of natural gas would be burnt. The financial revenue of this saving in the NG consumption was estimated to be about 20.151 million USD based on the two-year average international price of NG. In addition, if the gas-cycle power plant had operated by the gasoil fuel intake, an amount of 257.34 million liters of gasoil would be burnt. Finally, the related reduction of CO_2 emissions as a result of generating 799.2 GWh of the demanded electrical energy by the considered wind farms and consequently, not generating it in a heat-cycle power plant, was calculated as 464.34 thousand tons in the case of burning NG regarding the average heat rate of Iran NG. The reduced amount of CO_2 in the case of burning gasoil was calculated as 694.83 thousand tons, which was nearly 50% higher than the case of NG fuel intake.

The results of this practical case study well-demonstrated the effectiveness of wind farm electricity generation on the reduction of fossil fuels consumption in heat-cycle power plants, and thus a significant reduction of CO_2 emissions as one of the most important features of decarbonization as well as fossil fuel phase out plans. The results of this paper also signified the role of renewable-based energy generation on the improvement of environmental issues, highlighting the importance of further motivating policies by the governments in order to increase the penetration of renewable-based energy sources for covering the demanded electrical energy. Moreover, in this paper, the impact wind farm energy yields on the reduction of NG consumptions in heat-cycle power plants and the related CO_2 emissions was investigated compared to a real gas-cycle power plant with an efficiency of about 31%. However, comparing the results of this paper with the fuel intake rate in a combined-cycle power plant, which generally have higher efficiencies, would be a field of interest for future research works.

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