clean technologies

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Techno-Economic Analysis and Modelling of the Feasibility of Wind Energy in Kuwait

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Abstract: There continues to be significant attention and investment in wind power generation, which can supply a high percentage of the global demand for renewable energy if harvested efficiently. The research study is based on a techno-economic analysis of the feasibility of implementing wind power generation in Kuwait for 105 MW of electricity generation based on 50 wind turbines, which is a major requirement for clean energy. The study focused on three main areas of analysis and numerical modelling using the RETScreen software tool. The first area involved evaluating the performance and efficacy of generating wind power by collecting, analysing, and modelling data on observed wind levels, wind turbine operation, and wind power generation. The second area comprised an environmental impact report to assess the environmental benefits of implementing wind power. The third area involved economic analysis of installing wind power in Kuwait. The analysis was undertaken to determine the energy recovery time for wind energy and determine the mitigation of global warming and pollution levels, the decrease of toxic emissions, and any cost savings from implementing clean energy systems in Kuwait. Additionally, sensitivity analysis was undertaken to determine the impact of certain variables in the modelling process. The results were used to estimate that the energy price would be $0.053 per kWh for a power generation capacity of 105 MWh based on an initial cost of US $168 million and O&M of $5 million for 214,000 MWh of electricity exported to the grid. Moreover, the wind turbine farm will potentially avoid the emission of approximately 1.8 million t of carbon dioxide per year, thereby saving about $9 million over 20 years spent through installing carbon capture systems for conventional power plants. The wind farm is estimated to have a payback time of 9.1 years.

Keywords: techno-economic analysis and modelling; wind energy; RETScreen; Kuwait power generation

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Citation: Khajah, A.M.H.A.; Philbin, S.P. Techno-Economic Analysis and Modelling of the Feasibility of Wind Energy in Kuwait. *Clean Technol.* **2022**, *4*, 14–34. https://doi.org/10.3390/cleantechnol4010002

Academic Editor: Davide Astolfi

Received: 9 November 2021
Accepted: 13 December 2021
Published: 10 January 2022

1. Introduction

Economic and industrial development can be gauged by knowing how much energy a country produces [1]. There are currently economic and environmental advantages to reducing energy dependence and the negative consequences of traditional energy sources, including gasoline, natural gas, and coal, by adopting renewable energies, including wind, solar, biofuels, oceanic and tidal energy [2,3]. In a number of countries, electricity production is increasingly becoming dependent on wind energy, which is one of the most well-known kinds of renewable energy available to nations. This renewable energy source has much potential, and wind power production will likely increase significantly in the future. In 2000, the installed global wind power capacity was 17.4 GW, but by the end of 2019 [4], it had risen to 651 GW across the world. Wind capacity will potentially grow by 355 GW between 2019 and 2024, which means that the number of new wind turbines installed each year will exceed 71 GW of capacity by 2024 [4]. To have a sustainable energy source in the future, it is critical to formulate sound policy recommendations and implement sustainable energy practices. Sustainable energy policy is a multi-faceted endeavour and many researchers have focused on the development of renewable energy policy. Indeed, the use of renewable energy has been encouraged in a variety of ways by governments around the world. Studies also imply that renewable energy systems (RESs) should contribute more to energy production than conventional sources [5].

According to Kalair et al. [6], in the 21st century, energy engineers and researchers have shown a strong interest in green energy that minimises the negative consequences of a substantial rise in global energy consumption. Conventional fuels are projected to be the key energy source as they are consumed in conventional power plants to turn their chemical energy into heat used to produce electricity expected to release harmful pollution into the environment, primarily in greenhouse gasses (GHG) and contribute to climate change. This unsustainable reliance on conventional fuels to produce vast quantities of electrical energy has led to a decline in their resources that could prevent future generations from producing enough energy to meet their needs [7].

Moreover, the unit price of energy rose dramatically because of the unsustainable increase in energy use. Energy resources can be divided into three major groups. Nuclear resources are used in nuclear reactions to create heat that generates superheated steam. Then steam turbines generate electricity. Second, coal, natural gas, and crude oil come from a purely natural process. They are the fossilised remains of plants and animals that lived on Earth millions of years ago. The third group is renewable energy, which comes from sunlight, wind, waves, rain, and geothermal sources. Renewable energy is regarded as pollution-free, and it can generate power without polluting the air. So, it will play an essential role in energy use in the future. Renewable energy is used in many applications, such as cooling or heating air and water, generating electrical energy and transport. The use of energy on the planet is now shifting toward renewable sources [8].

According to Coherent Application Threads [9], wind energy is assumed to be one of the most important renewable energy sources. There is kinetic energy in the wind. Wind turbines apply an energy conversion process to convert kinetic energy into mechanical power, which AC generators convert into electricity. It is worth mentioning that wind power relies on air density, wind speed, and the turbine's swept area. Moreover, the height of the turbine hub has a strong influence on the energy output of the wind turbine, as wind velocity increases at higher altitudes [10,11].

1.1. Aims and Objectives

The proposed research has three main areas of study. The first is assessing the performance and efficacy of wind power generation by collecting, analysing, and modelling engineering data. The proposal includes an environmental impact report, an economic and financial review, and a life cycle assessment (LCA) of all three primary application fields. The main goals for the evaluation are as follows:

(i) To assess the energy recovery time for wind energy,
(ii) To determine the possibilities for mitigating global warming and reducing pollution in the form of toxic emissions,
(iii) To identify cost savings from implementing a clean energy system in Kuwait.

The main steps taken throughout the study are as follows:

- The most suitable sites for wind energy in Kuwait were selected and evaluated.
- RETScreen software was employed to estimate the efficacy of the selected wind turbine system in Kuwait.
- The analyses of the environmental, economic, and financial impact and a life cycle assessment (LCA) were completed to determine the energy payback time for the designed wind farm that includes determining the decrease of global warming and pollution levels and the decreases in toxic emissions, and any cost savings from adopting a renewable energy system in Kuwait.

1.2. Status of the Current Technology

According to Reve [12], the wind is an abundant natural resource that can be converted to electric energy using wind turbines. Environment-conscious jurisdictions, including the state of Kuwait, are actively exploring efficient options for raising the profile of wind energy in their mixes of the three significant groups of energy resources. Wind energy is gaining popularity worldwide because it creates minimal pollution and superior operational, economic, and financial performance. Figure 1 presents the global annual additions of wind power capacity and the world totals between 2009 and 2020.

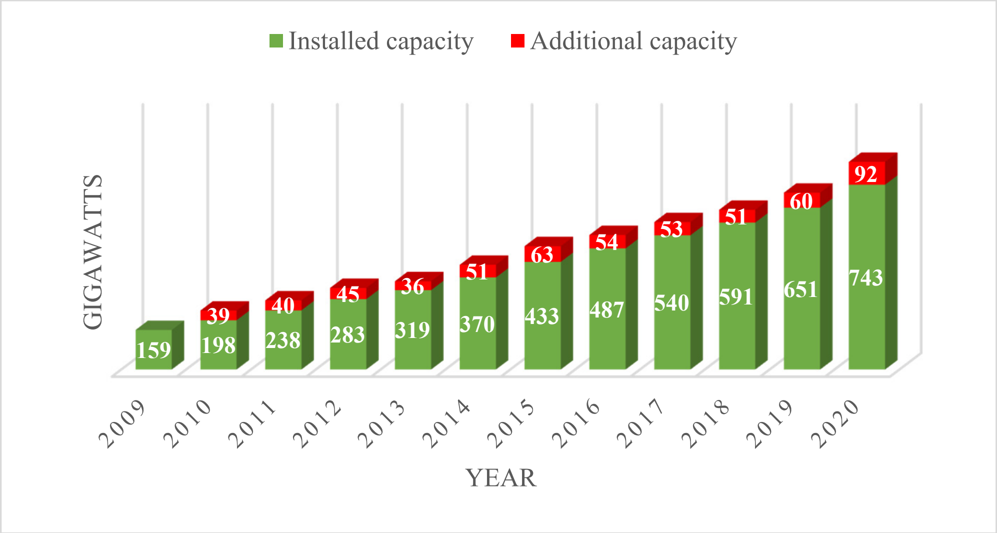


Figure 1. Accumulative global capacity of installed wind power between 2009 and 2020 [12].

1.3. *The History of Wind Energy*

Wind energy has invariably been used throughout human history to perform simple tasks such as winnowing to more complex energy-intensive tasks such as propelling ships [13]. The use of wind energy to grind cereals or raise the height (pressure) of irrigation water dates back to 200 BC, with the vertical windmills of the Persian–Afghan border. They were followed by the horizontal-axis windmills of the Mediterranean and the Netherlands from around 1300 to 1875 AD. These systems were perfected to pump water in the United States during the 19th century. Charles F Brush invented a low-speed and high-solidity wind turbine (WT) in Cleveland, Ohio, in 1888, which was a significant achievement in wind power generation. Another watershed moment in wind energy technology came from the US government's involvement in wind energy research and development following the 1973 oil crisis. Increased investment in wind energy technologies during the 1970s accelerated wind turbine commercialisation. As a result, the market evolved from primary domestic and agricultural uses to interconnected wind farm applications for electric utilities. In the 1980s, the technology spread to northern Europe, where wind resources are abundant. This created a small but steady market for wind energy. Nonetheless, wind energy development in other countries, including Kuwait, occurred much later, with significant achievements made in the last two decades [14].

1.4. *Performance Assessment*

Most wind turbines have a maximum power efficiency of 59.3%, known as Betz's limit. It describes the efficiency with which kinetic energy is converted into mechanical energy. The difference in efficiency is due primarily to the nature of wind turbines, not the inefficiency of the generator [15–18]. To achieve 100% efficiency, wind turbines should convert 100% of the wind; however, doing so would necessitate solid disc blades, which would prevent the rotor from turning because of their great weight, and no kinetic energy would be converted. The maximum power efficiency must be considered when engineering requirements, turbine strength, and durability are decided. Other inefficiencies in turbine systems, such as the generator, bearings, and power transmission, reduce overall efficiency to 10–30%. Horizontal axis wind turbines are more efficient than vertical axis wind turbines. However, wind direction does not affect vertical axis turbines, so they save a lot of time and energy that would otherwise be wasted chasing the wind [19]. As a result, when the wind direction changes rapidly in turbulent conditions, the vertical axis turbine generates more electricity despite its lower efficiency.

The major wind power plants in Kuwait are in the Shagaya area, with a total capacity of 10 MW and a lifetime of 25 years. The project ensures that the Kuwait Environment Protection Authority (K-EPA) is followed. The site was evaluated according to the guidelines established by Environmental Protection Law No. 42. The site is an open desert with no vegetation, inland water bodies, or coastal wetlands. The land use nearest the project is approximately 20 km away. In its assessment, the Geotechnical Inspection Company found no groundwater table within a depth of 30 m [20]. The area is also quiet, with no reports of earthquakes.

Soil samples analysed at Kuwait University had no metal contamination. The study area was designated a high-wind-energy desert. The site is vulnerable to high-quality sand encroachment [21]. Pollutants in the air exceed the air quality standards of the K-EPA, and gases are within allowable limits. The noise in the area is primarily natural, and it does not exceed the K-EPA standards. However, wind turbines have a significant negative impact on wildlife (avifauna), and they have sound and visual impacts that are a concern for public health and safety. The adverse effects on the soil, topography, land, water, and air quality are short-term, so they have little impact on the environment.

Negative environmental impacts can thus be mitigated, eliminated, or reduced during the project's construction, operation, decommissioning, and maintenance phases. The project also has the added benefit of creating employment and commercial opportunities in the surrounding areas. In the long run, the project will reduce greenhouse gas emissions, lower electricity costs, reduce the consumption and costs of fuels, promote alternative energy sources and increase tourism. According to one assessment, the project has no significant adverse environmental impacts; instead, it benefits the economy, health, and local climate [21].

The Kuwait Institute for Scientific Research conducted an economic and financial analysis to determine whether clean energy could contribute significantly to Kuwait's power and environmental protection needs over the next 20 to 40 years. According to the findings, renewable energy will have a cost-effectiveness index of 11% of electricity generated in Kuwait by 2030. Because of the fuel cost savings from using renewable energy technologies, wind energy and other renewable sources of energy will have a netback value of $2.35 billion [22].

The life cycle assessment has four stages: goal definition, scope analysis, inventory impact assessment, and result interpretation. Wind turbine environmental performance varies depending on the methods used to manufacture each part, the mode of transportation to the site, construction, operation, and maintenance, and the shape, size, and method for discharging waste residues [22]. Low wind speeds in Kuwait reduce the capacity factor of turbines, increasing their life cycle emissions. A turbine's lifecycle has been calculated to be 20 years.

1.5. The Cost of Installing Wind Energy

The initial costs of installing a wind turbine tend to be high, as with any renewable energy technology. This project's installation costs are based entirely on fixed costs, also known as 'CAPEX'. The costs associated with installing wind turbines and purchasing towers constitute approximately 84% of the total fixed costs. This very high cost has become a deterrent for individuals to invest, as there is no possibility of price fluctuations once the wind turbines are in operation [23].

Wind energy project costs can be divided into four categories [23].

- Turbine cost: includes the cost of the blades, the tower, and the transformer.
- Civil works: the cost of infrastructure, construction wages, planning, and foundation costs.
- Grid-linking costs are incurred when purchasing and installing transformers and mini-stations and the costs of purchasing cables and connecting them to distribution lines.

- Other costs, such as consulting fees, monitoring and evaluation fees, and maintenance fees.

The cost of turbines includes nacelle components such as gear transformer and power converter gearbox, the rotor blades, and the tower cost. The estimated cost for wind turbine components is shown in Figure 2. As depicted, the generator, transformer, converter, and gearbox accounted for approximately 23%, and the remaining 77% was paid for other related items such as wiring, rotor hub, rotor shaft, rotor blades, and the tower. The disparity in component costs between countries comes from differences in the price of turbines, location specifications, and other relevant expenses [23].

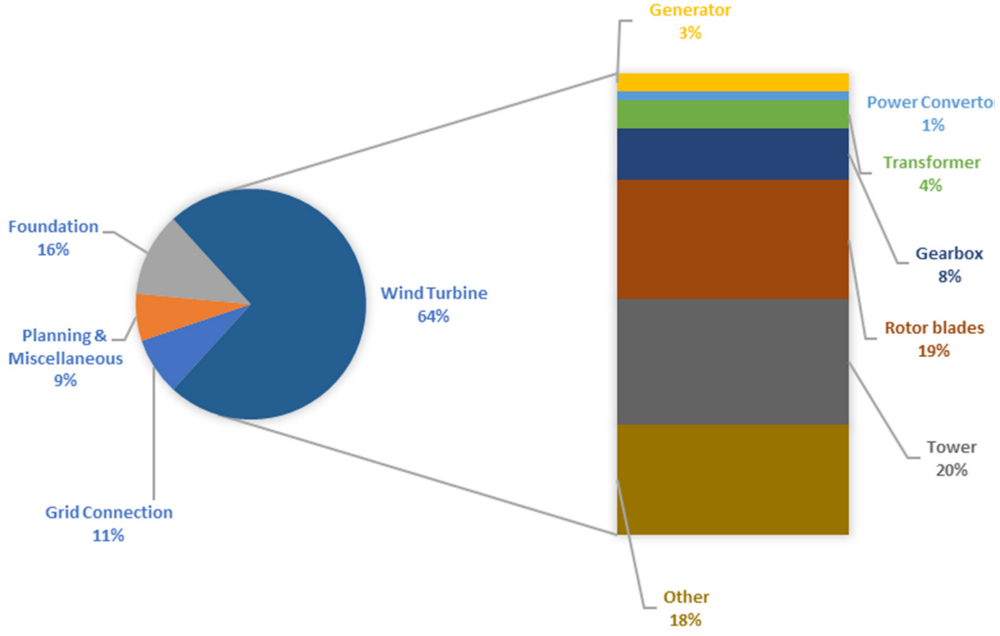


Figure 2. Accumulative global capacity of installed wind power between 2009 and 2019 [23].

The reasons for the high costs mentioned above include the following:

- The cost of raw materials (steel and copper). These two metals are critical for building, accounting for approximately 20–40% of construction costs.
- In Europe, offshore developments raise average installation costs. Moving from the surface market for water, which is dominated by Denmark, to the inner depths of water research in both Germany and the United Kingdom can raise costs.
- Because of the rapid increase in the production of advanced systems, consumer demand has outpaced supply. The human capacity to meet demand has also encountered many challenges in meeting shortages of unique parts, such as bearings, engines, gearboxes, and towers. These components' increasing complexity and design and production have also contributed significantly to the high prices.

1.6. Potentials of Wind Energy

Wind power is recognised because it depends entirely on the precision derived from wind power maps. As a result, significant effort is being made to update maps with current information on the world's wind resources. Much work is being done, and more tasks will be required to improve wind resource forecasts. Inadequate data on developing countries has been a significant impediment to exploring wind energy, particularly in countries at altitudes of more than 80 m. Many parts of the world have strong winds, both on and off the coast, but they are dispersed unevenly and often in suitable locations. Progressive, comprehensive research has provided finer details on general wind energy for for-profit and non-profit industries, with sufficient data on potential wind energy locations. This makes it easier for project advocates and policymakers to understand how the resources can be used based on precise site measurements. Wind energy capacity includes several variables, including meaningful assumptions and mean wind velocity. Some assumptions must be made about the size of the turbine, the strength of the turbine, the size of the rotor, the cost of research in various areas, and the availability of the unused land given the climatic conditions that the wind resource is near or otherwise required. Regardless of the unpredictability of the deciding factors, there are many advantages to onshore wind, and it can meet the need for electrical power for extended periods. About 39,000 TWh can be produced by combining highly sustainable onshore and offshore sources [24].

Wind energy capacity is determined by a variety of variables, including meaningful assumptions and mean wind velocity. Some assumptions are the size of the turbine, the strength of the turbine, the size of the rotor, the cost of research in various areas, the transport jam, and the availability of the new farm given the climatic conditions that the wind resource is near or otherwise required. Regardless of the unpredictability of the determining factors, it is evident that there are many advantages to onshore wind, and it can meet the need for electrical power for extended periods [24]. About 39,000 TWh can be produced by combining highly sustainable onshore and offshore sources [24].

1.7. Investment Opportunity

Significant research has been conducted to bring the cost of wind turbines into an affordable range, and this is expected to encourage investors and decision-makers to consider this sector. Several analyses have produced quantitative results. Many studies have been conducted on the offshore wind regions to estimate the cost savings that can be achieved in the onshore areas. Most of these studies have focused on ways to reduce wind farms' initial and ongoing costs by improving the designs of designated wind farms [25].

Another factor influencing the fixed cost of a wind turbine is using an appropriate process to select a geographic location with a high mean wind velocity. Wind efficiency improvements can help to lower the LCOE (levelized cost of electricity) of wind energy by increasing the mean ability impact. With offshore wind, cost reductions in other gas and oil industries and offshore underground transmission lines can benefit wind. Increases in product prices, particularly for copper, cement, and steel, affect wind energy costs based on the inflation rates [25].

To reduce the cost of each component of the wind energy project, a great deal of attention is given to lowering the LCOE. Such efforts are required to improve the outputs generated by collecting wind energy. The following are the main stages of a process to reduce the overall cost of installing wind turbines in onshore and offshore systems [25]:

- Project management and decision-making.
- Foundations.
- Wind blades.
- Grid linking and wiring.
- Installation.

2. Materials and Methods

The techno-economic analysis in this study compromise different steps. Figure 3 illustrates the main phases of the framework. The first part of the model includes four categories: Site selection; mathematical modelling; choosing a proper wind turbine and collecting turbine specifications; and acquiring the information needed for financial analysis, which includes annual interest rate, GHG reduction credit rate, electricity export rate, installation costs, the cost for the land, operation and maintenance costs, and electricity exporting to the grid expenses.

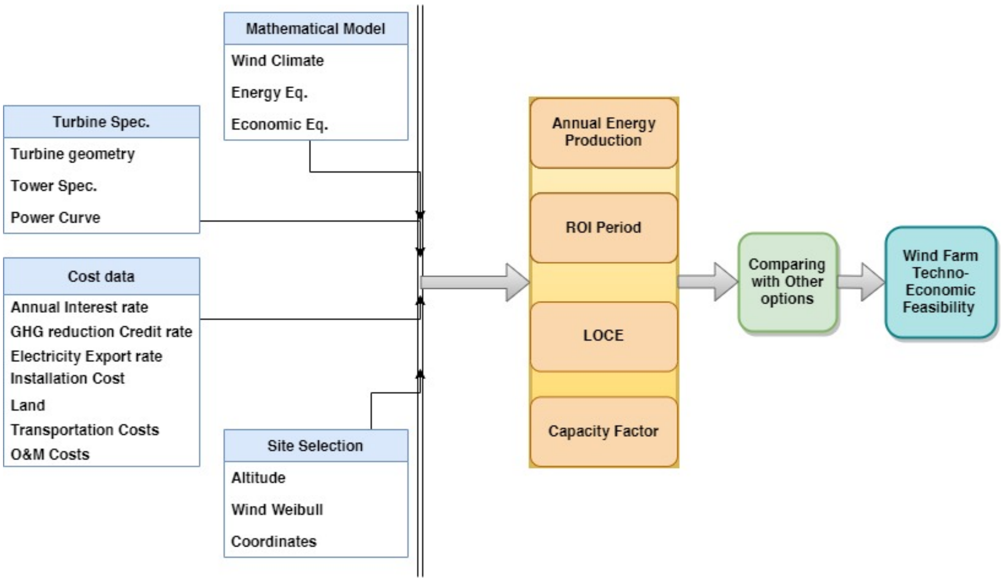


Figure 3. Proposed Model for Techno-Economic analysis of the Wind Farm.

The required data about the wind speed and geological properties of the selected locations in Kuwait are found from Global Wind Atlas and RETScreen Software database. The initial evaluation of the mean wind speed plot shown in Figure 4 reveals an outstanding potential of Kuwait for a wind farm and shows the selected sites for the location assessment.

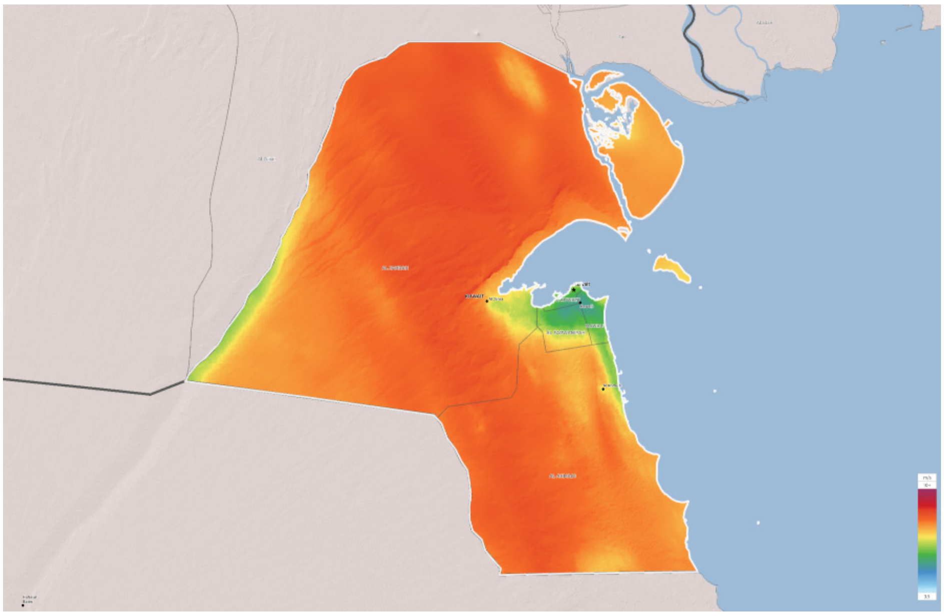


Figure 4. Mean Wind Speed at 100 m elevation in Kuwait [26].

2.1. Assumptions

As demonstrated in the proposed model in Figure 3, the analysis requires some initial data and specifications in terms of the technical specifications of the turbine, wind speed of the sites, and economics information. Table 1 shows the initial values and inputs of the model which was used for the analysis.

Table 1. Initial and assumed parameter values.

Parameter	Value	Source
wind speed (m/s)	Seasonal	[27]
The capacity of the plant	100 MW	Assumed.
The energy production cost	0.053 $/kWh	[28]
Average wind speed at 10 m	4.35 m/s	Calculated by software
Average air temperature	33.7 °C	Calculated by software
Average ambient pressure	101 Kpa	Calculated by software
Wind turbine capacity	2100 kW	Based on the database in RETScreen
Number of wind turbines Total capacity	50 105 MW	Capacity found by multiplying number of turbines by the capacity of each turbine
Array losses Airfoil losses Miscellaneous losses	4% 2% 6%	[29] [30] [31]
Availability	96%	
Electricity export price	0.054 $/kWh	[28]
Land price	$\$4/\mathrm{m}^2$	[32]
Discount rate	9%	[33]
GHG decrease credit rate	65 $/t CO_2	[34]

For the present value of future cash flows, a percentage discount rate of 9% is utilised. The weighted average cost of capital (WACC) is typically considered to be the most acceptable rate for a firm. A company's cost of capital is more than just the interest rate it should pay on long-term loans. To put it another way, the cost of capital is a wide term that encompasses the expenses of all types of investment funds—debt and equity—into one. As part of the financial viability assessment of a specific project, the "required return on investment" or "hurdle rate" is utilised as the discount rate. There are discount rates ranging from 3 to 18 percent for North American electric utilities, with 6 to 11 percent being the most commonly used figures.

Also, the model employs the discount rate to determine the MIRR (modified internal rate of return) and yearly life cycle savings. Negative cash flows are considered to be funded at the discount rate when computing the MIRR.

2.2. Numerical Modelling

Economic analysis of wind energy projects in specific locations is undertaken to determine the profitability and viability of the project. To quantify the time it will take to reimburse the initial capital investment, a simple payback calculation considers both revenue and expenses. Equation (1) indicates the formula for estimating the time needed for the return of investment [35,36].

$$SPP = \frac{C}{AEO \times P_e} \tag{1}$$

in which C represents the project's initial investment, including all expenses of turbine equipment and components, technicians' expenses, and the costs for the tower constructions and component transportation to the wind farm location [37]. AEO is the annual energy output (kWh/year). P_e is the electricity export rate ($/kWh). If the payback time of investments is less than the anticipated service life, then the investment is justifiable.

CRF and $C_{om_{life}}$ are the investment return factor and the present value of the annual cost over the lifespan of the wind turbine. CRF and C_{om} are provided by Equations (2) and (3) [38].

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \tag{2}$$

$$C_{om_{life}} = \frac{c_{om}}{i-e}\left\{1 - \left(\frac{1+e}{1+i}\right)^n\right\} \tag{3}$$

where C_{om} denotes the operation and maintenance expenditures for the first year and is estimated 20–30 percent of the annual cost of the turbine, which is the price of the machine divided by its life span, e is the increment rate of maintenance and operation, I is the rate of interest, and n is the practical life of the turbine [39]. These systems need investment, and a return of investment (ROI) study is necessary to evaluate their financial advantages. The ROI is provided by Equation (4) [40].

$$ROI = \frac{PVB - PVC}{PVC} \tag{4}$$

where PVC is a predicted cost of the project, and PVB is a prediction of the profitability of the project execution [38].

3. Results and Discussion

The analysis was completed employing RETScreen software. The findings are summaries and reported in the following section.

3.1. Wind Speeds at the Considered Locations

Three locations across Kuwait were chosen for the analysis. The primary parameter considered for the site selection was the wind speed throughout an entire year. Table 2 shows that the locations are estimated to provide different performance levels because of fluctuations in the weather.

Table 2. Selected locations wind speed comparison.

	Wind Speed (m/s)			
	Average	**Min.**	**Max.**	**SD**
Al-Ahmadi	4.69	0.17	14.14	1.98
Al-Jahraa	4.54	0.08	13.63	2.11
Umm Qasr	4.33	0.15	13.49	2.09

The monthly wind speed for 12 months was determined using the NASA climate data source. Figure 5 shows the distribution of the wind speed throughout an entire year. As evident, the high wind velocity is expected during June and July, and in other months a relatively constant wind speed is anticipated.

The seasonal average wind speeds for the two years and their mean are shown in Figure 6. According to this figure, the highest wind speed for both years occurred during summer, with values of 3.63 and 3.25 m/s. Also, the lowest wind speed for both years occurred during winter, with a value of 2.59 m/s.

The Weibull and Rayleigh probability density functions (WPDF & RPDF) and cumulative density functions (WCDF & RCDF) were calculated and compared with actual data histograms in Figures 7 and 8 for 2019–2020 and 2020–2021.

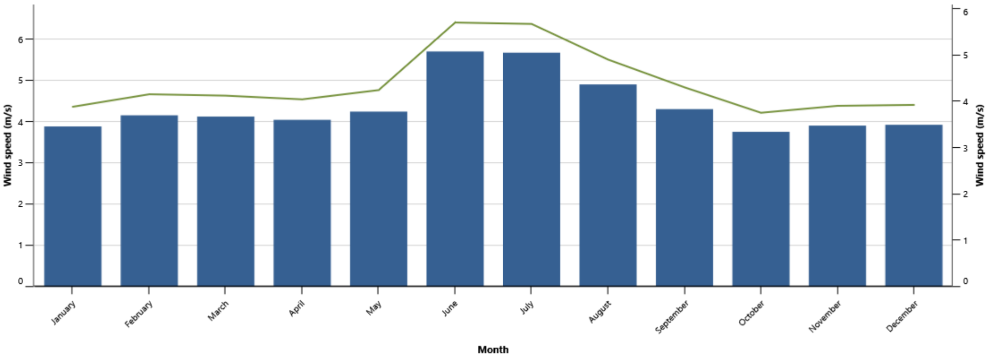


Figure 5. Average wind speed for each month of the selected site Al-Ahmadi.

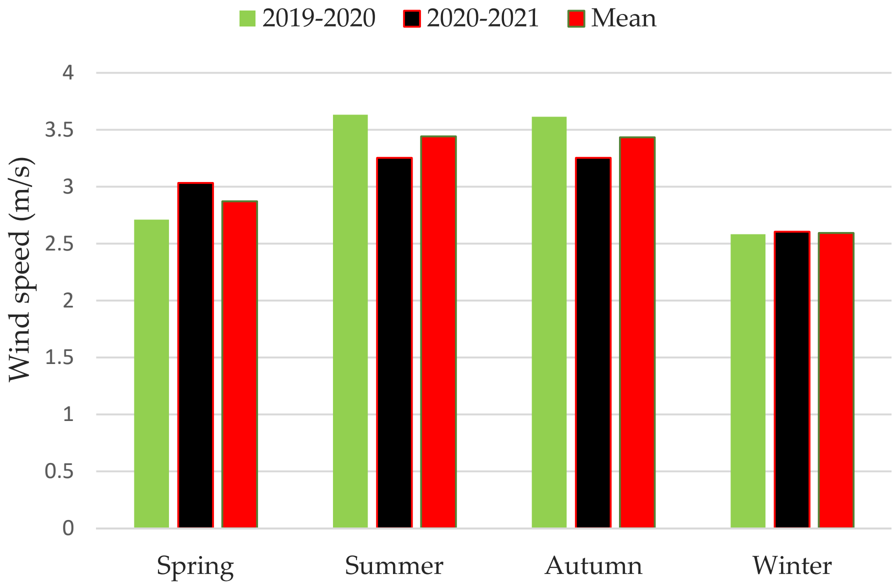


Figure 6. Seasonal–mean wind speeds for the year (2019–2021).

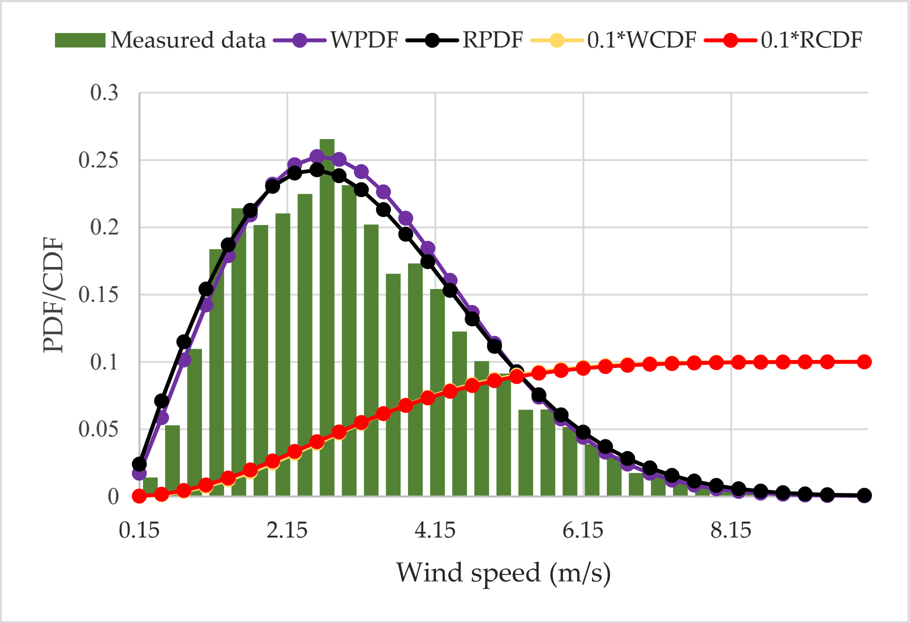


Figure 7. Wind speed frequency distribution analysis for 2019–2020. Source of Data: [41].

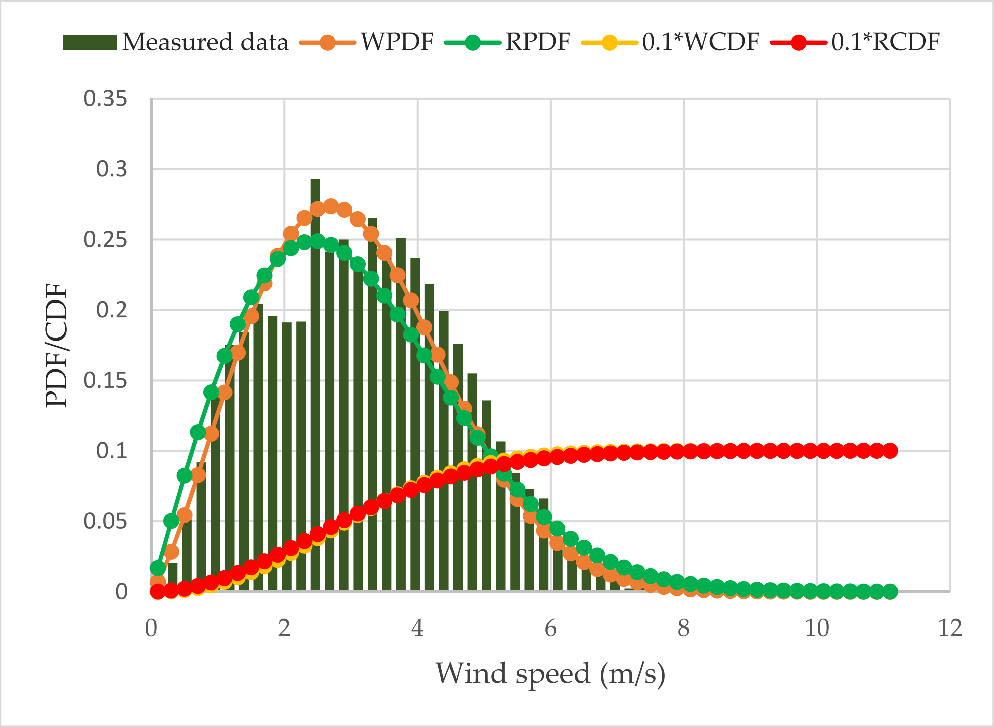


Figure 8. Wind speed frequency distribution analysis for 2020–2021 source of data: [41].

The distribution plots show a relatively high availability of the turbines over a year. Although Kuwait climate analysis shows a high probability of sandstorm probability, the new turbine models have additional filters to prevent entering dust in a nacelle compartment and operate in scorching climate areas. An example of this type of wind farm was installed in Oman in 2018 [42]. Although the deposition of dust on the blades will reduce the efficiency of the wind turbine, the impact of sandstorms and dust deposition was not included in the current study.

3.2. Wind Turbines Technical Analysis

The power curve and energy curve for the selected wind turbine are illustrated in Figure 9. The wind turbine chosen is the Suzlon model S.88/2.100–100 m. It was decided that 50 turbines would be installed, and they would generate 105 MW of electricity. The power curve shows that the power generated from each turbine at the turbine hub altitude previously assumed 100 m is around 850 kW at an average wind speed of 6 m/s. However, the power capacity of each turbine is approximately 2.1 MW at a 15 m/s windspeed. The cost of energy generation is $0.053/kWh, and the plant would generate about 105 MWh. The wind turbine farm is estimated to occupy the same area (325,000 m^2), increasing fixed cost.

Technical details of the Wind Turbine are shown in Table 3. The parameters were determined using the RETScreen database.

The technical analysis of the wind farm with 50 turbines and the specifications mentioned above resulted in the outcomes reported in Table 4.

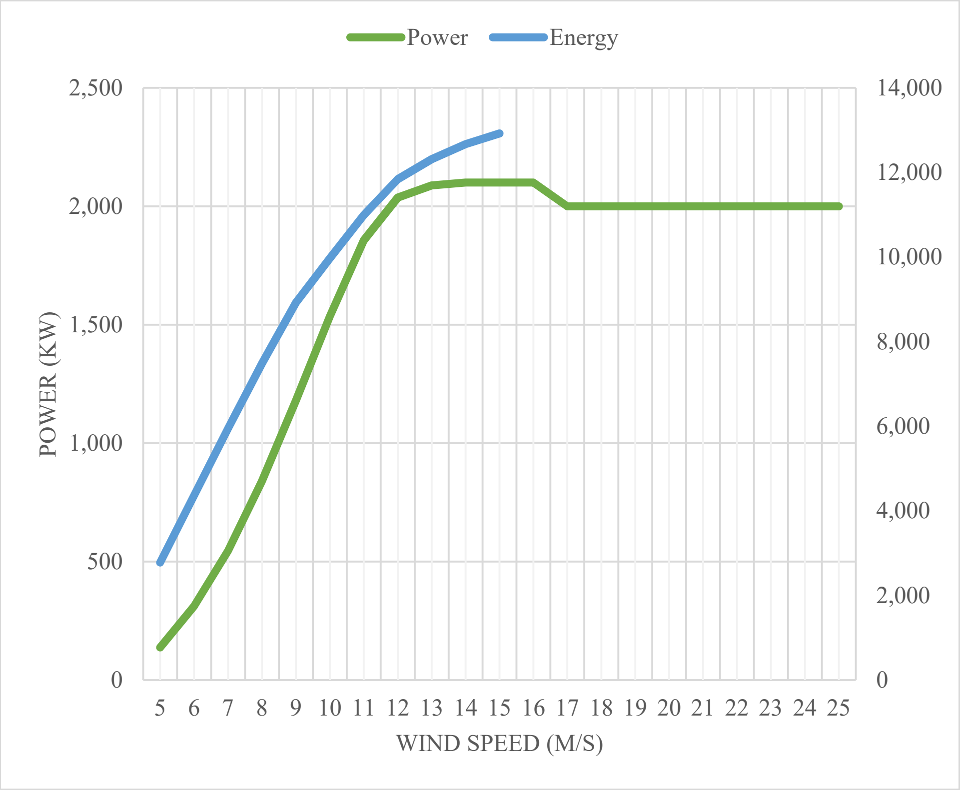


Figure 9. Power and Energy curve for the selected turbine.

Table 3. Technical Specifications of the turbines.

Wind Turbine Parameter	Value	Unit
Power Capacity per turbine	2100	Kw
Manufacturer—Model	Suzlon—S.88/2.100	
Number of turbines	50	
Power Capacity	105	Kw
Hub height	100	m
Rotor diameter	88	m
Swept area	6082	m^2
Shape factor	2	

Table 4. Technical analysis results of the wind farm.

Parameter	Value
Capacity Factor	20.4%
Electricity exported to the grid	214,372 MWh
Unadjusted energy production per turbine	4509 MWh
Gross energy production per turbine	4329 MWh
Losses coefficient per turbine	0.87
Specific yield per turbine	617 kWh/m^2

3.3. Wind Turbines Financial Analysis

Several parameters need to be considered for the financial analysis of the designed wind farm. The main cost elements are determined and shown in Table 5.

Table 5. Financial analysis results of the wind farm.

Parameter		**Wind Farm**	
Initial costs			
Initial cost		99.20%$	175,000,000
Land		0.80%$	1,400,000
Total initial costs		**100%$**	**176,400,000**
Yearly cash flows—Year 1			
Annual costs and debt payments			
O&M costs (savings)	$		5,333,333
Debt payments	$		0
Total annual costs	**$**		**5,333,333**
Annual savings and revenue			
Electricity export revenue	$		10,024,234
GHG reduction revenue—20 years	$		11,804,668
Other revenue (cost)	$		0
CE production revenue—20 years	$		2,784,509
Total annual savings and revenue	**$**		**24,613,411**
Net yearly cash flow—Year 1	**$**		**19,280,078**

3.4. Environmental Benefits

In terms of environmental benefits, it was estimated that the designed wind turbine farm would reduce CO_2 emissions by approximately 185,316 t per year as shown in Table 6, because electricity was harvested from the environment. After 20 years of operation, this represents savings of roughly $8,778,410 that would have been spent on constructing carbon capture systems in conventional power plants.

Table 6. GHG emission reduction.

Case Studied	**Emission Reduction**	**Unit**
Base Case	199,265.20	tCO_2
Proposed Case	13,948.60	tCO_2
Gross Annual GHG emission reduction	**185,316.60**	$\mathbf{tCO_2}$

According to the RETScreen database, each produced MWh of Electricity in Kuwait results in 0.7872425 t of CO_2. This rate was used to investigate the designed plant's environmental advantages, assuming that the electricity transmission line is 10%. As a result, Kuwait's greenhouse gas emissions will be 0.8747 per MWh of Electricity produced. Carbon capture systems have recently been used to prevent CO_2 from being released into the atmosphere and accumulating. It is assumed that preventing each tonne of CO_2 from being released into the atmosphere costs $65 and that the project will last 20 years. The revenue from decreasing GHG is $8 million.

The reduction of GHG emission is equivalent to 17,044.3 Acres of forest absorbing carbon or 79,625,389 L of gasoline not consumed.

3.5. Economic Viability Analysis

Common financial indexes, including NPV and IRR, were used to evaluate the project's viability. Based on the project's annual cash flow and initial investment price, the project's simple payback was calculated at 9.1 years. Details of the feasibility study are reported in Table 7 in terms of simple payback and equity payback.

Table 7. Financial viability analysis of the wind farm.

	Unit	Value
IRR—equity	%	8.7%
MIRR—equity	%	8.9%
IRR—assets	%	8.7%
MIRR—assets	%	8.9%
Simple payback	yr	9.1
Equity payback	yr	9.3
Net Present Value (NPV)	$	−4,388,900
Annual life cycle savings	$/yr	−480,789
Benefit-Cost (B-C) ratio	%	0.98
GHG reduction cost	$/tCO$_2$	2.65
Energy production cost	$/kWh	0.135

The cumulative cash flow diagram illustrated in Figure 10 shows a simple payback of 9.1 for the proposed project.

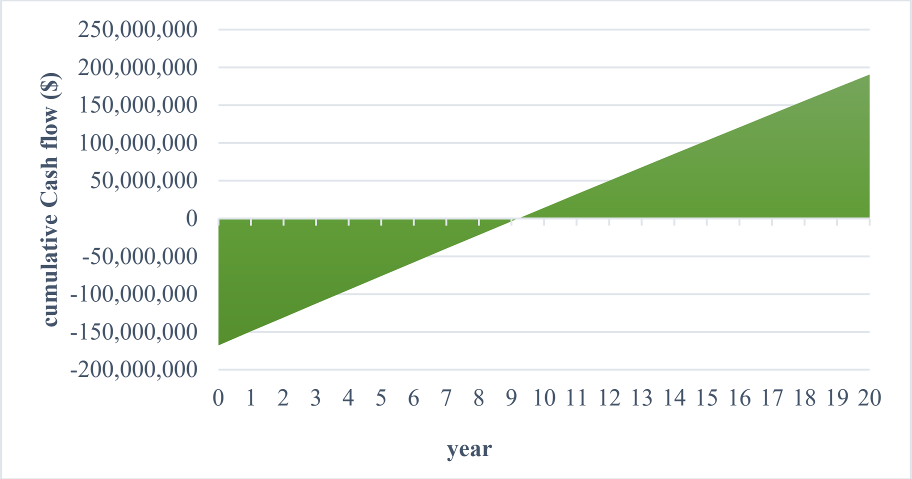


Figure 10. Cumulative cash flow.

3.6. Risk and Sensitivity Analysis

The risk analysis was implemented based on the project's pre−tax IRR−assets. Figures 11 and 12 show the results of the impact risk analysis and distribution analysis.

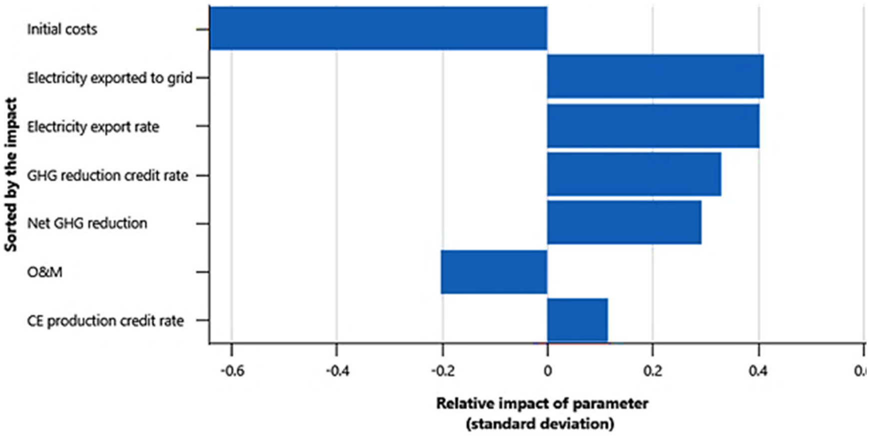


Figure 11. Impact−Pre−Tax IRR−assets analysis.

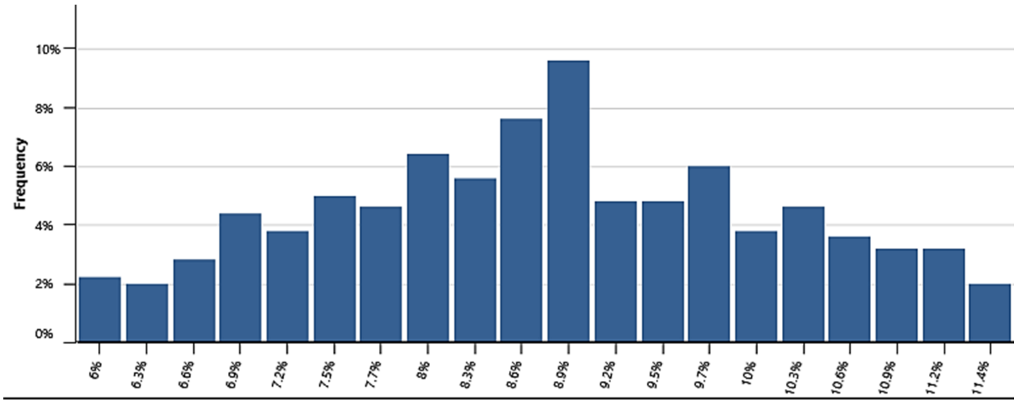


Figure 12. Distribution Pre−Tax IRR−assets analysis.

The impact graph depicts the relative variation of the financial indicator as a function of the degree of uncertainty in each significant parameter. At the bottom of the chart, there are no units on the X−axis. Instead, it shows the relative strength of each parameter. The stronger the input parameter's influence on the financial indicator's variability, the longer the horizontal bar is for that particular input parameter. The financial indicator's influence on the input parameters is automatically sorted. The economic indicator's variability is primarily influenced by the top (Y−axis) input parameter, whereas the bottom (X−axis) input parameter has a minor influence. User input parameters can be identified using this "tornado graph" if a more in-depth examination is needed. It is possible to determine the link between an input factor and an economic indicator based on its horizontal bar orientation (positive or negative). When the value of an input parameter rises, the value of a financial hand also increases. Since reducing expenses would raise the net present value (NPV), there is frequently a negative connection between initial expenditures and the NPV as demonstrated in Figures 13 and 14.

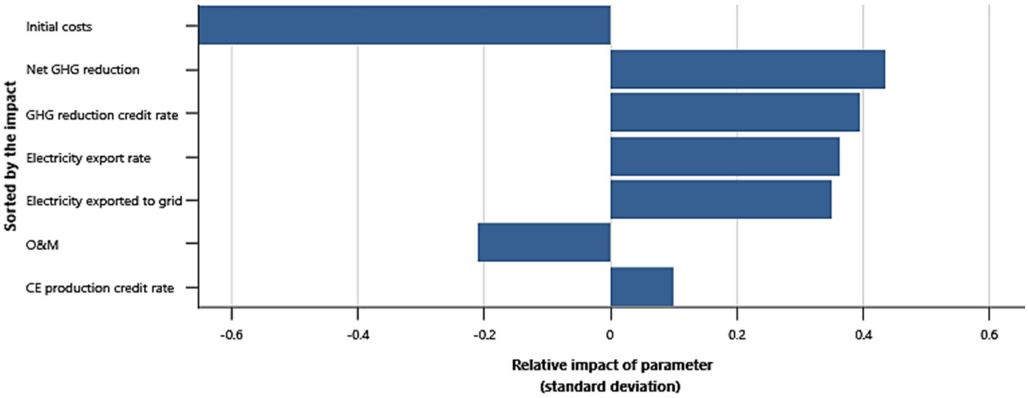


Figure 13. The relative impact of parameters on NPV analysis.

The sensitivity analysis was implemented using RETScreen software with a range of 25% and for the project's IRR-Pre-Tax asset and NPV. Results are shown in Figures 15–17.

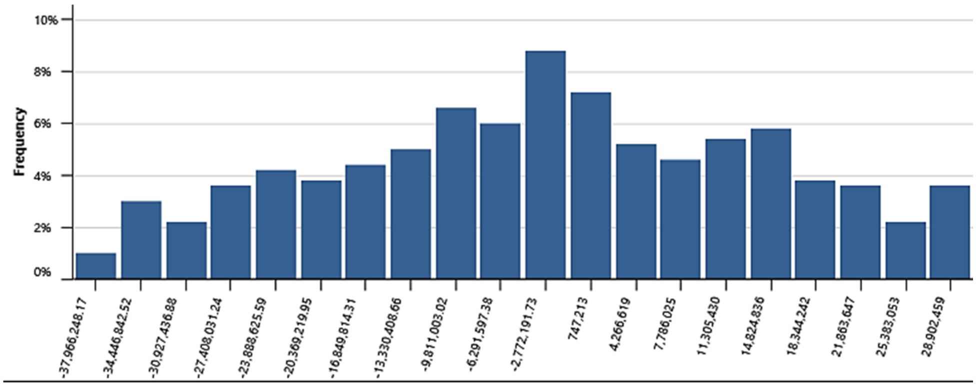
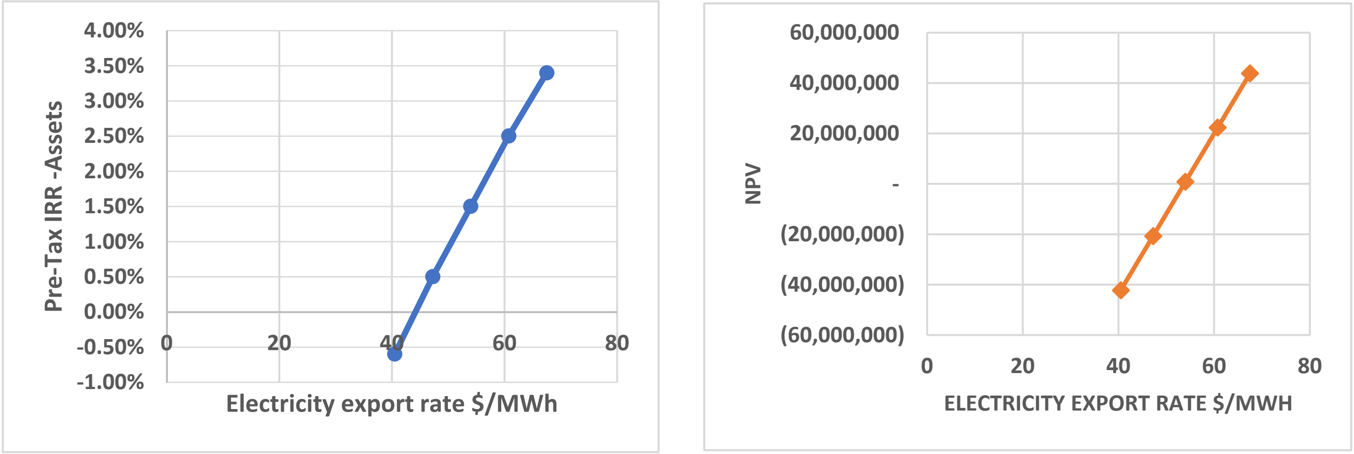
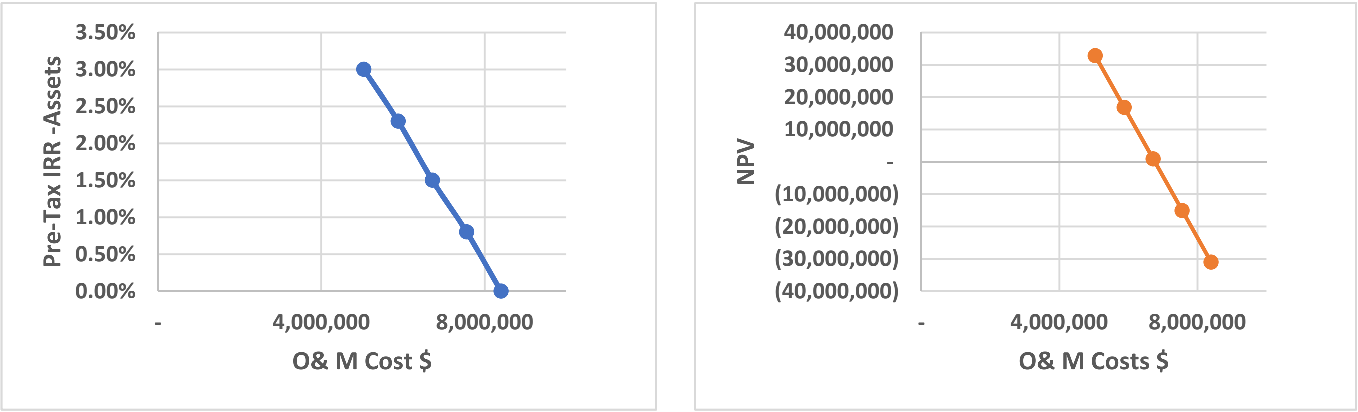


Figure 14. Distribution of NPV analysis.



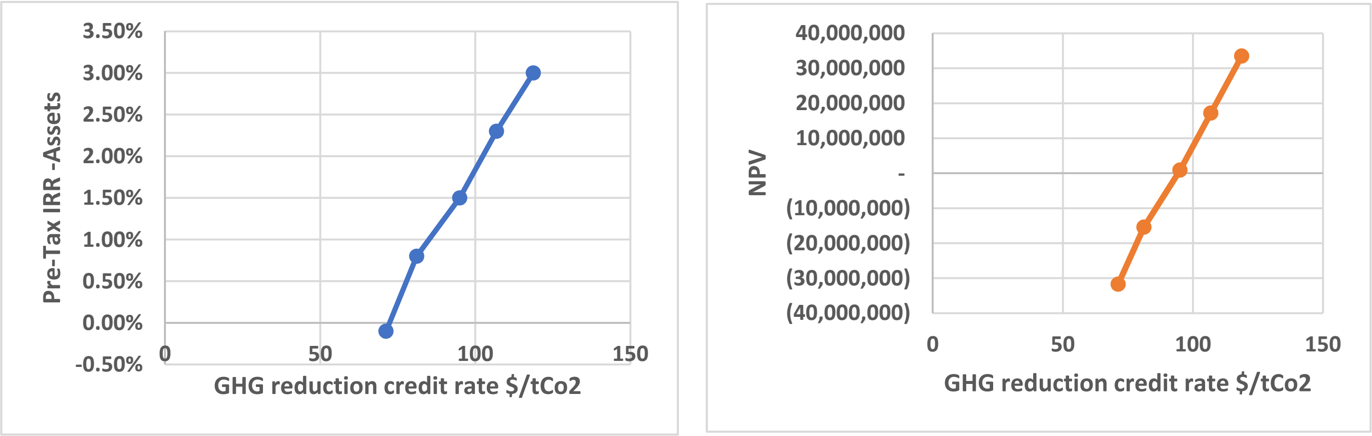
(**a**) (**b**)

Figure 15. Sensitivity Analysis of Electricity Export rate for (**a**) Pre−Tax IRR Asset analysis (**b**) NPV analysis.



(**a**) (**b**)

Figure 16. Sensitivity Analysis of O&M Costs for (**a**) Pre−Tax IRR Asset analysis (**b**) NPV analysis.



(**a**) (**b**)

Figure 17. Sensitivity Analysis of GHG reduction credit rate for (**a**) Pre−Tax IRR Asset analysis (**b**) NPV analysis.

The summary of the Risk and sensitivity analysis is shown in Table 8.

Table 8. Risk analysis summary of the wind farm.

Parameter	Unit	Value	Range	Minimum	Maximum
Initial Cost	$	176,400,000	25%	132,300,000.00	220,500,000
O&M	$	5,333,333	25%	4,000,000	6,666,666
Electricity Exported to the grid	MWh	185,633	25%	139,225	232,041
Electricity Export rate	$/MWh	54.00	25%	40.50	67.50
Net GHG reduction—Credit duration	tCO2	3,632,206	25%	2,724,155	4,540,258
GHG reduction credit rate	$/tCO2	65.00	25%	48.75	81.25
CE production credit rate	$/kWh	0.02	25%	0.01	0.02

4. Conclusions

Power engineers and academics have shown a strong interest in green energy and reducing the negative consequences of significant increases in energy consumption worldwide. In general, conventional fuels are estimated to be the primary energy source as they are consumed in traditional power plants to transform their chemical energy into heat used to generate electricity. This releases toxic materials and greenhouse gases (GHG) (such as carbon dioxide) into the atmosphere thereby resulting in climate change. Moreover, the unsustainable dependence on conventional fuels to generate large amounts of electrical energy has decreased the level of hydrocarbon resources that are available. This further diminishes the capacity of future generations to produce enough energy to meet essential needs. In this context, it is important that appropriate attention is focused on the development of renewable energy sources in connection with the decrease in the use of fossil fuel, which is an important area for researchers, policymakers, and industry to actively engage in developing viable solutions and implement relevant technologies, such as those associated with wind power generation.

Unit energy prices have risen significantly because of the unsustainable increase in energy demand. Wind energy is often considered to be one of the most important sources of renewable energy. The kinetic energy that exists in the atmosphere can be used to produce electricity using wind turbines. The operating theory depends on the use of wind turbines to implement the energy conversion mechanism as wind's kinetic energy is transformed into mechanical energy. The created mechanical power can then be converted to electricity by AC generators. It is worth noting that wind power depends on the air density, velocity, and the turbine's swept area. Moreover, the height of the turbine hub dramatically affects the energy performance of the wind turbine since the wind speed rises at a comparatively higher altitude. Wind is an abundant natural resource that can be transformed into electrical energy by wind turbines. Environmentally responsible jurisdictions, including the State of Kuwait, are aggressively pursuing successful options for enhancing the profile of wind energy in their renewable and overall energy mixes. Wind energy is gaining popularity worldwide because it creates minimal pollution and superior operational, economic, and financial performance. The research study adopted the techno-economic assessment (TEA) approach, which is a recognised form of modelling that allows researchers to estimate numerically the technical and economic performance of the proposed energy project. For example, see the work of Thomassen et al. on the use of TEA applied to assessing emerging green technologies [43], the study by Ortiz based on the TEA of the use of supercritical processes for the production of biofuel [44], and the research by Schnuelle et al. on the adoption of PV (photovoltaics) and wind power to enable dynamic hydrogen production through TEA [45]. In this present study, the TEA approach was applied to the case of developing a renewable energy system based on wind power in the state of Kuwait. The study serves as evidence based on the examination of the technical and economic viability of wind power production by calculating the performance of the power generation system, as well as the economic basis for investment in such a capability. The approach is particularly useful when applied to evaluating renewable energy systems for a specific region or country [46–50].

The research study consisted of three critical areas, including assessing wind power output and efficiency through collecting, analysing, and modelling engineering data. Furthermore, the study included an Environmental Impact Analysis, an Economic and Financial Review, and a Life Cycle Assessment (LCA) of all three primary application areas. This was done to calculate the energy recovery time for wind energy, evaluate the mitigation of global warming and pollution levels, and decrease toxic emissions and any cost savings resulting from introducing a renewable energy system in Kuwait. The study has validated the adoption of wind power and the findings are consistent with other TEA-based evaluations of wind power adoption, such as the work of Hulio et al. [51], Mostafaeipour et al. [52], and Kassem et al. [53].

The results from this TEA based modelling study support the following findings relating to the proposed adoption of wind power in the state of Kuwait:

- The energy price from wind power generation would cost about $0.053 per kWh, while the entire plant would produce 105 MWh. The proposed wind power plant is estimated to occupy an area of 325,000 m^2, which contributes to the fixed cost.
- The results are based on an initial cost of US $168 million and O&M of $5 million for 214,000 MWh of electricity exported to the grid.
- The proposed wind turbine farm will have the effect of avoiding the emission of carbon dioxide by approximately 1,848,086 tons per year as the produced energy was obtained from the kinetic energy available in the atmosphere. This would result in savings of approximately US $8,778,410 after 20 years of service that would be spent on the installation of carbon capture systems in conventional power plants.
- Sensitivity analysis was implemented with a range of 25% and for the project's IRR-Pre-Tax asset and NPV. It is important that such an analysis includes the O&M (operations and maintenance) costs as wind power facilities will, like other energy production facilities, carry such ongoing costs.
- The payback time of the wind power plant is estimated to be 9.2 years.
- It should be noted that the findings of this numerical modelling study are subject to the boundary conditions as specified in Section 3.

The recommendations for policymakers are as follows:

- There is a need to consider optimising the geographic locations of wind turbine farms and to avoid overly expensive sites. This has a strong influence on the payback time of the wind farm and the economic and environmental advantages of the locations selected.

- Wind turbine farms are characterised by high aerodynamic performance and short payback time. This needs to be further considered in any study of the feasibility of building a renewable energy plant in Kuwait.
- The types of wind turbines and the manufacturer's specifications are estimated to be the most critical parameters to be considered during the selection process for turbine installation.
- It is worth monitoring the performance of implemented wind turbines to ensure a stable and efficient energy-generation process is adopted.

In regard to future research areas, a number of potential avenues have been identified. Firstly, it is suggested that the viability of wind power generation in Kuwait is further evaluated through an empirical investigation of an installed small-scale facility. In this regard, an engineering feasibility study should be conducted to determine the realised level of power generation and economic characteristics of the facility. This research will build on the findings of this present TEA-based study and allow real-world data to be gathered on wind power adoption. Secondly, further research needs to be conducted on the impact of desert conditions (including sand and sandstorms in countries such as Kuwait) on wind power facilities. Thirdly, research is recommended that determines the optimal energy storage systems (such as batteries or other facilities) that are required to complement the adoption of wind power and especially when ambient conditions are not adequately windy.

Author Contributions: Conceptualization, S.P.P.; Formal analysis, A.M.H.A.K.; Investigation, A.M.H. A.K.; Methodology, A.M.H.A.K.; Project administration, A.M.H.A.K.; Resources, A.M.H.A.K.; Software, A.M.H.A.K.; Supervision, S.P.P.; Visualization, A.M.H.A.K.; Writing–original draft, A.M.H.A.K.; Writing–review & editing, S.P.P.; visualization, A.M.H.A.K.; supervision, S.P.P.; project administration, S.P.P.; funding acquisition, S.P.P. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Acknowledgments: The authors would like to gratefully acknowledge the insightful comments provided by the reviewers, which have helped to substantially improve the quality of the article.

Conflicts of Interest: The authors declare no conflict of interest.

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