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Article

Assessing the Energy Generation and Economics of Combined Solar PV and Wind Turbine-Based Systems with and without Energy Storage—Scottish Perspective

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Abstract: Solar PV and wind energy conversion are now so economical that they compete head-on with all forms of fossil fuel and nuclear energy conversion. In view of climate change and the rising price of electricity due to wars, all governments are also facing popular policy pressures to rapidly switch to renewable energy. In this article, broad research questions are raised, and an attempt is made to provide answers in a logical manner. The questions may be categorized as being those related to the validation of fundamental data needed for the design of renewable energy (RE) systems, the long-term measured performance of those systems and the cost of RE electricity. Interest rates are rising rapidly in the current economic situation, and therefore, the present analysis is based on concurrent rates that are payable by borrowers. Measured data from a medium-sized solar PV and wind turbine facility that has been in operation for over a decade in Central Scotland has been used for this work. The main objectives of this article are: (a) to evaluate the manufacturer's acclaimed performance, (b) to evaluate capacity factors for PV and wind conversion, and complementarily of solar and PV resources, and (c) to obtain the cost of electricity generation of PV and wind. The primary source for undertaking the above exercise was a decade long, measured dataset from an agricultural farm located in Central Scotland. Commercial PV design software was also used to cross check the presently undertaken analysis. The main conclusion was that a community-based wind/solar plant is much more economical than grid-purchased electricity. The novelty of the present work is that all conclusions that were drawn are based on long datasets of measured wind/solar plants.

Keywords: climate change; energy modelling; electricity prices; wind and solar

1. Introduction

By the year 2023, while the worldwide cumulative solar PV capacity had reached the 940 GW mark, the UK had also reached 14 GW installed capacity. Per capita the UK, despite its poor solar radiation income is punching above its weight with the figure of 215 W which is in better contrast to the world per capita of 118 W. Likewise, a total capacity of 906 GW of wind turbines were installed worldwide by early 2023, the UK's share being 28 GW of which half were installed onshore the rest being offshore. That translates to 431 W/capita for the UK whereas the world average is 113 W/capita.

Presently, the United Kingdom has the sixth largest

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capacity for wind energy. Wind power generated about 25% of UK electricity, having surpassed coal in year 2016 and nuclear in 2018. It is the largest source of renewable electricity in the UK. Scotland now has the lion's share of wind turbines. That is only logical as it hosts a very healthy wind regime with even onshore annual capacity factors easily exceeding 0.35%. Solar energy is much more in dilute form within the UK in general and Scotland in particular with the annual capacity factor being around 0.12 for Scotland.

The UK government continues to support the deployment of renewable power right across Britain, with the Contract for Difference (CfD) scheme so far having awarded contracts to 52 projects in Scotland, which represents around 30% of all CfD projects and around 25% of total CfD capacity.

The scheme is designed to be fair and deliver low carbon deployment at low-cost to consumers – so that when wholesale electricity prices are higher than the price agreed in the CfD, generators pay back the difference. This will be passed on to energy suppliers and over time, is expected to translate to lower bills for consumers [1].

According to the Crown Estate report [2] in the year 2022 UK offshore wind farms generated 45 TWh of electricity, an increase on the 37 TWh of electricity generated during the year 2021. That energy is enough to meet the electricity needs of 41% of the UK housing stock or 11.5 million homes. The report also forecasts that offshore wind is on track to generate enough electricity to meet the needs of 47% of UK homes by the end of the year 2023 by adding an additional capacity of 8 GW of new wind turbine installation projects.

The present UK offshore wind capacity accounted for 24% of global capacity, second only to China. The UK Government's target is to have 50 GW of offshore wind capacity by the year 2030. Table 1 presents the declining profile of the carbon intensity of grid electricity for Scotland. Note that between the years 2010 and 2019, an 87% reduction was achieved.

Table 1. Declining profile of Carbon intensity of electricity generation in Scotland.

Year	Emissions Intensity, gCO_2e/kWh
2010	320
2011	238
2012	255
2013	216
2014	196
2015	151
2016	55
2018	43.1
2019	41.4
2021	26.9

Source: www.gov.scot/publications/climate-change-monitoring-report-2023.

The main aim of this article was to obtain the cost of electricity generation of PV and wind for Central Scotland. As a by-product, the complimentary nature of solar and PV resources was also investigated. It was found that the economics is in favor of wind/solar resources and also that the latter two resources are complementary to a fair extent. Details of presently found results and discussion follow.

The structure of this article is as follows. Following a review of the status of wind/solar farms in the UK and the economics of electricity generation with and without energy storage, the UK's present economic situation and the trend of domestic electricity demand, the article then presents measured data of wind/solar generation from an agriculture farm. A detailed statistical analysis of the data then follows and mathematical models for obtaining key information about the wind/solar resource evaluated.

2. Cost Data Ralated to Energy Farms Hosting Solar PV, Wind Turbine and Battery Energy Storage Systems (BESS)

2.1. Solar PV Farms in UK: Industry Reported Costs

The following costs are related to setting up a solar farm in the UK, all figures being provided by professional quantity surveyors. In view of the average annual UK solar income around 6–8 acres of land is needed to generate roughly 1 MW of peak solar power [3]. The above figure translates to 2.4 to 3.2 hectares/MW-peak power. There are currently over 1,000 solar farms in the UK, with a combined capacity of 8.67 GW. In the year 2022, a record number of new solar farm developments were approved in the UK with around 4 GW of capacity being approved, compared to 3.1 GW in 2021 [3]. Another source [4] quotes the land requirement of 10 hectares for a 5 MW solar farm. That is 2 hectares/MW-peak power and hence comparable to the above given figure of power density. Note that 1 hectare has an area of 10,000 m^2.

A 50 kW solar photovoltaic facility can cost about £30,000 in the UK both including installation and tax. A 200 kW agricultural solar PV system can generate enough power to run 40 homes and would cost around £180,000 [5]. Note that solar farm installation costs have dropped by 80% between the years 2010 to 2021. The quoted industry figures for installed costs are now 25 US Cents/W. The Abu Dhabi based International Renewable Energy Agency (IRENA) [6] has quoted the following figures for total installed PV costs: $4,808/$kW_P$ and $857/$kW_P$ for the years 2010 and 2021 respectively. As a result, the world-average Levelised Cost of Energy (LCOE) is reported to have dropped from 0.417 to

$0.048/kWh during the latter period.

2.2. Wind Farms in UK: Industry Reported Costs

Industry sources [7] provide the following costs related to setting up a wind farm of 1 MW capacity:

- Installed cost: $1.3 million.
- Operation and Maintenance cost: $42,000–48,000 per MW.

Payment to landowner: 5%–6% of annual turnover. In addition, the leasing cost of the land is between £850 and £1,100 per year.

The chosen site ought to have an annual average wind speed exceeding 6m/s. The International Renewable Energy Agency [6] provides the cost of wind turbine installation in the respective years of 2010 and 2021 and those costs are shown to have dropped from $2,042 to $1,325/kW. Likewise, the capacity factors have increased from 27% to 39%. As a result, the LCOE has dropped from 10.2 to 3.3 US Cents per kWh.

2.3. Industry Reported Cost of BESS

Cost data obtained from SMA Storage 134 kWh high voltage battery that delivers a peak power of 120kW indicate a capital cost of £135,000 ($169,000) inclusive of local tax [8]. Table 2 presents a digest of battery costs reported by the industry. We also note that the Netherlands-based Alfen group is deploying a two-hour-plus BESS in Belgium that will deploy a 24 MW/54 MWh system [9]. That project will be located in the Belgian town of Ostend and will have a discharge duration of 2.25 hours based on the power and capacity.

Table 2. Battery cost (number of life cycles = 6,000). Note: All costs provided are for entry level modules.

Seller	Capacity (kWh)	Cost	Type	DoD
Tesla	13.5 kWh	£5,700	Lithium-ion	100%
SolaX	3.5 kWh	£4,010	Lithium-ion	95%
LG Chem	6.5 kWh	£3,043	Lithium-ion	90%
Powervault	4 kWh	£4,470	Lithium-polymer	100%
Powervault	8 kWh	£7,020	Lithium-polymer	100%

Source: https://www.greenmatch.co.uk/blog/2018/07/solar-battery-storage-system-cost.
Note that although utility scale BESS is now being deployed on an ongoing basis the technology is still not fully cost effective [10].

2.4. Review of Cost Data for Solar PV, Wind Turbine and BESS

Munoz et al [10] evaluated the economic benefits, if any, of PV and BESS installation for the case of a vehicle charging for a waste management depot. They explored two power connection scenarios: 0.15 and 0.6 MW. The total cost of BESS for a lifetime of 15 years was explored. For a 1 MWh capacity the capital cost was estimated to be £254,000 ($317,500), the Operation and Maintenance (O&M) cost was £37,500 ($46,875) and the total cost was £291,500 ($364,375).

An important conclusion from the above study was that for a storage-based EV charging system, 20% to 33% of the total cost comes from BESS. That study also inferred that BESS cost is still a major barrier to their wide-spread deployment. However, cost reduction projections of 28% to 58% are expected by the year 2030. Halidou et al [11] investigated the Life Cycle Cost (LCC) for three cases of generating energy for the residential sector of the energy-poor region of the Sahara. The three cases were: (i) Solar PV with BESS, (ii) BESS with diesel generator (DG), and (iii) Solar PV with BESS and diesel generator (DG). Their conclusion was that case (iii) has the total lowest cycle cost. The relevant data of the above cited work that is relevant to the present work is as follows.

- Capital cost of PV = $500/kW
- O&M cost = $2 per year per kW
- BESS energy capacity cost = $200/kWh
- BESS power capacity cost =$400/kW

The conclusion drawn from the above study may be summarised below.

For an annual electricity load of 1.74 million kWh a solar PV installation of 3.18 MW would generate 4.69 GWh. The design BESS system would need to have of power capacity of 554 kW and an energy capacity of 5884 kWh. The LCC for the above system would be $2.66 million which includes an O&M cost of $6359 which would result in a per kWh cost of 11.5 US Cents. Hevia-Koch and Jacobsen [12] have worked out the year 2019 wind turbine costs as €800/kW ($872/kW), O&M €8–10/MWh-year ($8.72–10.9/MWh-year). Note that the lifetime assumptions for wind turbines were 20–22 years in 2017. By year 2019 that life expectancy had increased to 25 years. The reported wind turbine capacity factor for onshore Danish sites for 330 kW machines was reported as 0.33 which is close to above quoted figure of 0.35 for Scotland's onshore systems. The reported LCOE for European climate with a capacity factor of 0.33 was reported as 6.54 US cents/kWh. The O&M cost spread over 25 years was taken as 25–30% of installed cost.

Moon et al [13] have investigated the cost implication of using solar PV within the residential sector using a reconditioned electric vehicle, lithium-ion (Li-ion) batteries in three Asian countries. An excellent survey of findings from countries around the world was presented with an overall conclusion that Li-ion batteries outperformed their lead acid counterparts. It was concluded that further reductions were however needed for BESS to become economical. Their overall conclusion was that residential solar PV and reused BESS offered 56% lower LCOE than the grid.

The cost model emerging from Moon et al [13] study may be summarised thus. Installed PV cost $1.2/W, O&M cost $0.012/W-year. The respective PV LCOE US Cents per kWh costs for The Philippines, and Indonesia, respectively were 6.4, 7.5, and 9.2. With the energy storage added, the PV and BESS cost in US Cents per kWh were 33.4, 37.7, and 49.8 for respective solar PV capacity factors of 21.1, 17.9, and 14.8%. For all the above three countries the daily load was taken as 9 kWh. Dabar et al [14] have presented wind energy based electrical generation costs for Djibouti. They monitored wind speed for five locations within the Republic of Djibouti, the annual average wind speed range being 5.52–9.01 m/s for the years 2015–2019. Their overall conclusion was that the lowest cost of energy, LCOE was 6.94–13.3 US Cents per kWh. They have also reported that Weibull distribution for frequency analysis of wind speed offered a good fit. In total, the performance of ten wind turbines was analyzed that ranged in power capacity from 500 kW to 4.5 MW. Their annual capacity factor (CF) was found to be in the range of 13.4 to 29.9%.

2.5. Bank of England Interest Rate

In any economic study, the bank lending rate is of vital importance in assessing the payback period and LCOE. In that respect, Figure 1 presents data obtained from the Bank of England which is the reserve bank within the UK and sets the relevant bank interest rate [15]. Wide fluctuations are seen in the latter figure demonstrating an uncertain economic outlook over the recent past. The following analysis summarises the minimum bank interest rate that is chargeable to borrowers who wish to install renewable energy systems, with and without BESS.

- Average lending rate = 9.1%
- First quartile, Q1 6%
- Second quartile, Q2 9.9%
- Third quartile, Q3 11.9%

Note that the second quartile of 9.9% is close to the average value of 9.1% and hence the average value of 9.1% may be used with confidence in the present economic calculations.

The compound interest-based payback period, ‘n’ may be calculated using Equation (1),

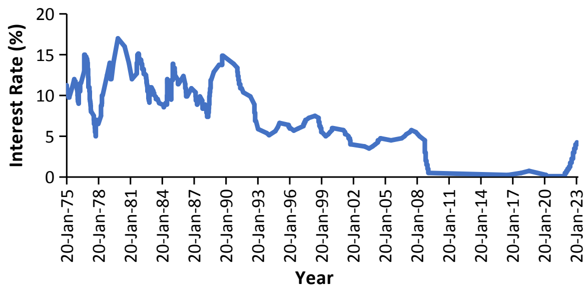

Figure 1. Historical base rate for interest rate set by Bank of England since year 1975.

$$P = m \times \left[\frac{(1+r)^n - 1}{r(1+r)^n}\right] \quad (1)$$

where P = borrowed principal sum of money to cover total installation cos t, m is the monthly repayment and r the lending bank’s interest rate. In the present work the per annum interest rate of 9.1% is used which is compounded monthly. Hence r = 0.091/12 = 0.007583.

3. Domestic Electrical Load in UK Residence

In the year 2003, a typical household in the UK consumed 11.8 kWh of electricity per day, the peak load being 7.18 kW [16]. Hence, a 5 MW farm would be able to support 1,220 homes. Note however that in view of the rising cost of energy and people becoming more conservation-prone, the average daily consumption is on a declining path. In that respect refer to Table 3. That information along with the one shown in Figure 2 shall be used in the energy simulation part of this work.

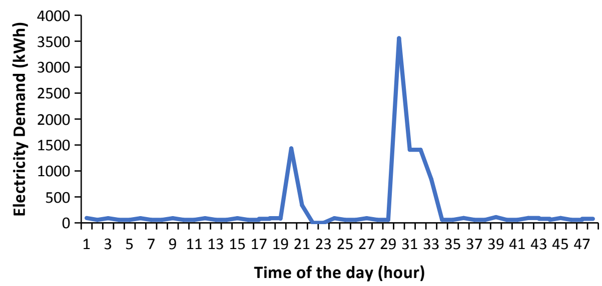

Figure 2. Half-hourly electricity demand in UK homes.

Table 4 presents the export price that homeowners may claim from electrical utility companies. There is a stark difference between the purchase and sale price of electricity that the large energy companies offer within the UK. One company, for example, buys electricity at US cents 8/kWh from homeowners and yet sells it for US cents 37.5/kWh.

In the United Kingdom between the years 2010 and 2020, electricity prices increased by 36%, then in October 2021 it increased by 12% and by a further 54% in April

2022. In October 2022 the price increased a further 80%. The overall conclusion is that the price increase from the year 2010 to early 2023 was by a factor of 4.5. The serious hike in electricity prices for the domestic sector has triggered a significant increase in the number of solar PV installations in residences. There is also a rapid deployment of wind turbines on farmlands.

Table 3. Declining pattern of UK domestic energy consumption.

Year	Daily Domestic Consumption, kWh
2007	18.11
2008	17.01
2009	17.2
2010	17.27
2011	16.36
2012	16.16
2013	15.28
2014	15.33
2015	14.73
2016	14.24
2017	14.12
2018	13.5
2019	13.16
2021	9.61

Source: https://www.gov.uk/government/statistical-data-sets/regional-and-local-authority-electricity-consumption-statistics.

Table 4. Energy export facility for the residential sector within the UK.

Energy Supplier	Price (p/kWh)	Price (US cents/ kWh)
Octopus (own customers)	15	18.8
Scottish Power (own customers)	15	18.8
Scottish Power	12	15.0
British Gas	6.4	8.0
EDF (own customers)	5.6	7.0
E.On (new solar accounts)	5.5	6.9
Pozitive Energy	5	6.3
So Energy	5	6.3
Octopus (non-customers)	4.1	5.1
OVO	4	5.0
SSE	3.5	4.4
Shell Energy	3.5	4.4
Utilita	3	3.8
EDF (non-customers)	3	3.8

Source: https://www.theecoexperts.co.uk/solar-panels/smart-export-guarantee.

4. The Arbroth Combines Solar and Wind Farm in Scotland

The Arbroath agricultural farm (Latitude = 56.6 degrees North, Longitude = 2.7 degrees West) is a potato growing entity. However, over a decade ago the farm owners made a strategic decision to install a large solar PV installation of 50 kW and an Enercon-330 kW wind turbine.

The 50 kW of solar PV system that are situated at the North Mains of Cononsyth in Arbroath were installed in October 2011 with a Feed Tariff (FiT) of 31.5 p/kWh. On average it produces 45,000 kWh per year. Due to inflation the Feed Tariff for this older facility was increased from 31.5 p/kWh to 40 p/kWh currently earning £18,000/annum. The solar modules have an average capacity factor from the year 2013 to the year 2018 of 11% for an inclination angle of 15°. Year-on-year, the capacity factor has been steady.

In March 2019 another 250 kW of solar PV modules were added against a capital cost of £201,600, which is equivalent to £806/kW or $1,006/kW. Figure 3 shows the older and newer solar PV installations at Arbroath.

The 330 kW-Enercon wind turbine was installed, way back, in October 2012 against a cost of £850,000. That is equivalent to £2,576/kW or $3,220/kW. However, according to the International Renewable Energy Agency report cited above [6] wind turbine installation costs dropped to $1,325/kW by the year 2021.

Figure 3. Arbroath, Scotland 350kWp solar PV plant.

The wind turbine produces 909 MWh annually. Due to inflation, the FiT has risen from 21.5 p/kWh to 23.93 p/kWh, currently earning £211,000 per year. The value of the feed-in tariff is index-linked, so it increases in line with inflation.

The turbine performance is analyzed by calculating its capacity factor for each of the six years: 2013 through 2018. Figure 4 shows the capacity factor plot. The average capacity factor is 31.5% which is above average for UK onshore wind.

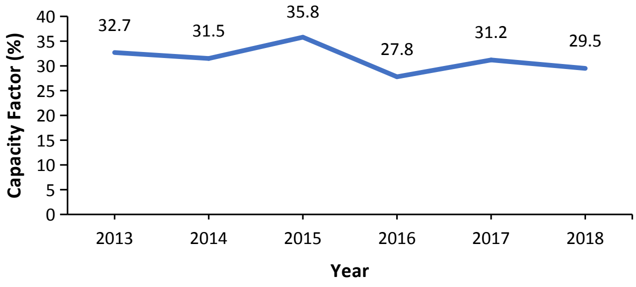

Figure 4. Arbroath wind turbine capacity factor for years 2013–2018. Average capacity factor = 31.4%.

In contrast to the wind turbine installation, the Arbroath solar PV plant delivers a capacity factor of only 10.4% compared to the UK average of 10.8% Note that Scotland has a solar radiation income of 800–1,000 kWh/m^2/annum, while the south of England has a solar radiation receipt of 1,100–1,300 kWh/m^2/annum. Figure 5 shows the capacity factor plot for the Arbroath solar PV plant.

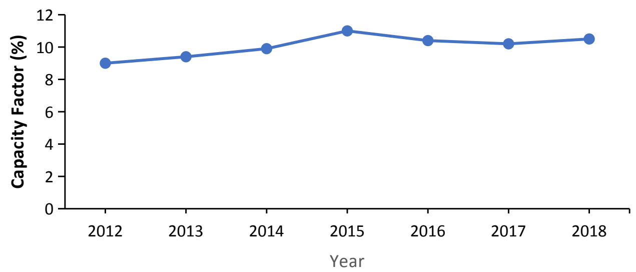

Figure 5. Arbroath solar PV plant capacity factor for years 2012–2018.

5. Research Questions

This article shall attempt to address the following seven research questions that are within the domain of this article's framework:

5.1 How reliable is renewable energy data that is freely available from web-based sources?

5.2 How valid are Rayleigh and Weibull models for determining wind speed frequency?

5.3 To what extent does the measured power curve of a medium-sized, mid-life wind turbine match the manufacturer's quotation?

5.4 What are the monthly capacity factors for solar PV and wind energy electrical conversion for Central Scotland?

5.5 If deployed in conjunction, how complimentary are solar and wind generation?

5.6 How accurate are energy generation predictions of solar PV commercial software?

5.7 What is the cost of deploying solar PV and wind turbines for Central Scotland?

6. Methodology

In Section 5 of this article, seven research questions were posed. Those questions may broadly be categorized as follows:

- Questions pertaining to fundamental data that is available from web-based sources. Questions 5.1 through 5.3 fall into that category. The research community has free access to such data, but the question is, how reliable is that data? Can one use such data with confidence? The present article addresses these important questions. The data from web sources were compared against measurements for this task.
- Question 5.4 is a key question, and presently the response is provided on the basis of long-term measured data, the latter being based on reliable records, having been backed up via industrial input through the instrument of service contracts. Using measured energy output from solar PV and wind turbines this research question was addressed.
- Questions 5.5 through 5.7 are research questions that will address cost queries related to solar and wind energy use and its short-term storage. Once again reliable, measured data is the basis for providing the answers. A combined solar PV and wind turbine system that is backed up by grid electricity is investigated. The entire system was digitally simulated on a high-performance PC and a number of variations of system parameters were investigated. A commercial design software (PV Sol) was also used for this task.

7. Results and Discussion

Following on from Sections 5 and 6 and after execution of the presently developed energy simulation code the results obtained regarding research questions 5.1 through to 5.7 are presented in numerical order.

Refer to Figures 6 and 7 which respectively present validation of data obtained from NASA [17]. The two renewable energy resources that are the subject of this work i.e., solar and wind energy now dominate the world energy market. It is a worthy question to ask how reliable is the data that is available free of cost? It was pointed out earlier that wind energy is a plentiful resource in Scotland with a much higher regime of wind speeds. In this respect refer to Figure 8 which presents measured wind speed data for Arbroath farm for the four seasons of winter (January), spring (April), summer (July), and autumn (October). It was also shown via Figures 4 and 5 that the capacity factors for wind and solar PV energy were respectively in the plentiful and poor categories. The wind speed regime in Scotland covers the full range that would be expected in a windy location. It was then found sufficient to validate NASA wind speed data using the downloaded dataset for Arbroath. However, due to the poor solar climate of Scotland, one needs to test NASA solar data for a much sunnier climate. Thus, to test NASA solar data the validation is performed via the use of measured data from Bahrain [18].

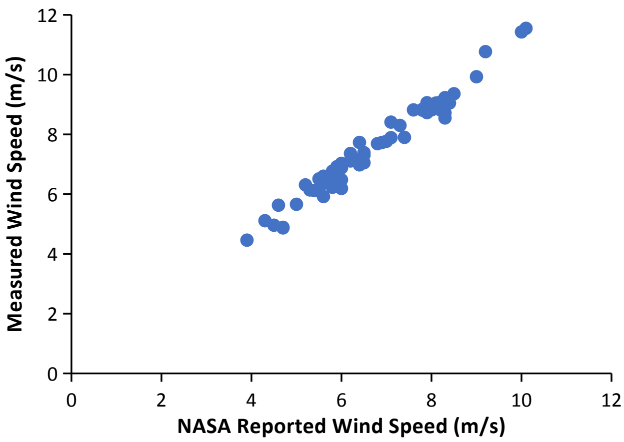

Figure 6. Correlation between NASA reported and on-site measured wind speed: Arbroath, Scotland (2013–2017).

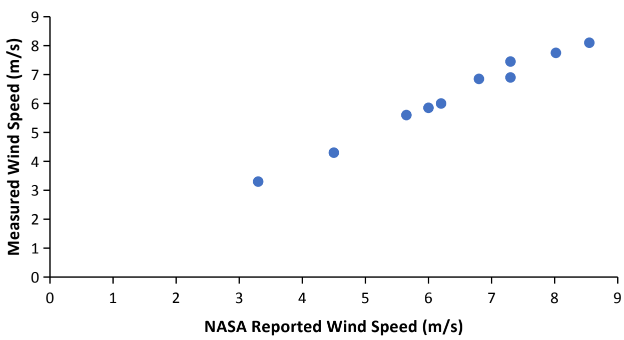

Figure 7. Correlation between NASA reported and on-site measured wind speed in Bahrain, Arabian Gulf (year 2001 data).

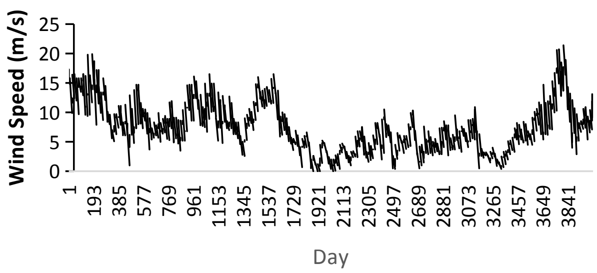

Figure 8. Wind speed recorded at Arbroath for the months of January, April, July and October. Note: only one week data has been plotted for each month.

The Rayleigh and Weibull distributions enable frequency assessment of wind speed. The respective models are presented in Equations (2)–(6) [19–22].

- *The Rayleigh distribution function for frequency of wind speed.*

A parameter, S is defined in terms of monthly- or annual-averaged wind speed, $\hat{U}$

$$S = \hat{U}\left(\frac{2}{\pi}\right)^{0.5} \quad (2)$$

The Probability Distribution Function (PDF) for the occurrence of wind speed P(u) will be,

$$P(u) = \frac{u}{s^2} exp\left(-\frac{u^2}{2s^2}\right) \quad (3)$$

The Cumulative Distribution Function (CDF) is given by,

$$CDF = 1 - exp\left(-\frac{u^2}{2s^2}\right) \quad (4)$$

- *The Weibull distribution function for frequency of wind speed.*

This PDF is a two-parameter model with shape parameter c > 0 and scale parameter $\delta > 0$:

$$\text{PDF} = \frac{c}{\delta^c}\hat{U}^{c-1}\text{exp}\left[-\left(\frac{\hat{U}}{\delta}\right)^c\right] \quad (5)$$

$$\text{CFD} = 1 - \text{exp}\left[-\left(\frac{\hat{U}}{\delta}\right)^c\right] \quad (6)$$

The following four steps highlight the computational procedure:

1. Find the sample average, $\hat{U}$
2. Find sample standard deviation, SD
3. Estimate shape parameter, c = 1.2785 ($\hat{U}$ / SD) – 0.5004
4. Estimate scale parameter, δ = $\hat{U}$ / (G(1 + 1/c)), where G(x) is the gamma function. The latter function is available in popular computing packages such as MS-Excel.

Using ten-minute measured wind speed data for six years (2013–2018), Figure 9 has been produced. Note that in Figure 9 'f-m' refers to the measured frequency, and f-Rayleigh and f-Weibull refer to predictions of those models.

The following inference may be deduced from the above-mentioned plot:

a. In the low wind speed regime, i.e., up to 12.5 m/s, the Rayleigh distribution provides a good assessment of wind speed frequency.

b. For wind speeds exceeding 12.5 m/s, though the Weibull is a much more accurate tool.

c. Note that the main power band for wind turbine is closer to 12 m/s and hence Weibull offers a better prediction facility.

d. However, note that Rayleigh requires only the average wind speed to kick start the calculation and hence offers an edge over Weibull in terms of simplicity. It is not always possible to obtain the standard deviation of wind speed data which is required for the Weibull model.

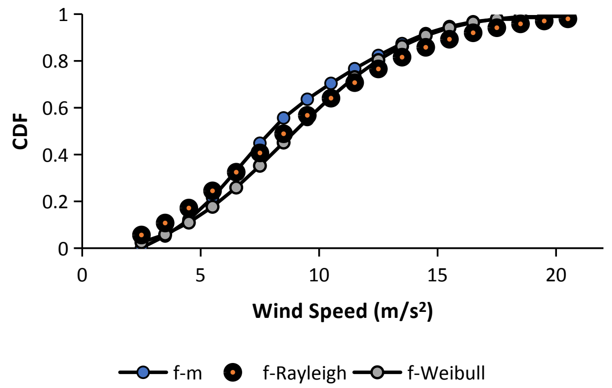

Figure 9. Cumulative frequency of wind speed, m/s: Model validation using measured Arbroath data.

Refer to research question 5.3, in that respect Figures 10 and 11 are presented which respectively show the power output of the Arbroath Enercon-330 wind turbine, each data point represents 10-minute averages and the comparison of the manufacturer-acclaimed power curve. In Figure 11 Pc refers to computed and Pm to measured machine output at a given wind speed, m/s. The measured averages for any given wind speed are also shown. There appears to be good evidence of validation.

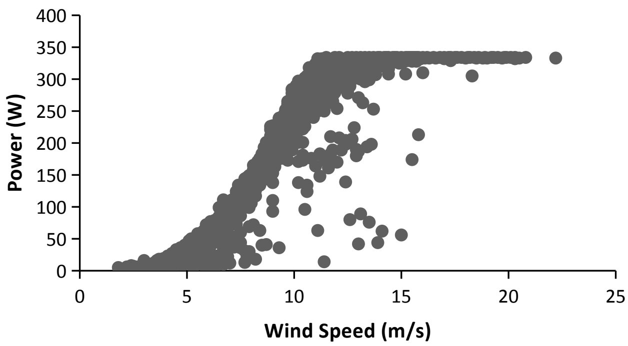

Figure 10. Power output of Enercon 330 kW wind turbine using one year's (2021) measured data. Data sampling interval: 10 minutes, number of recordings: 35,807.

Figure 12 shows power output data for the wind turbine for a period spread over 10 years. There seems to be no degradation of the power output for the period covering years 2013 to 2023, although 10 years had elapsed since the installation of the wind machine.

With reference to research question 5.4, Figures 4 and 5 were presented. The annual capacity factor for wind energy conversion varies from 27.8% to 35.8%. Those for solar PV conversion lie between 9% and 11%.

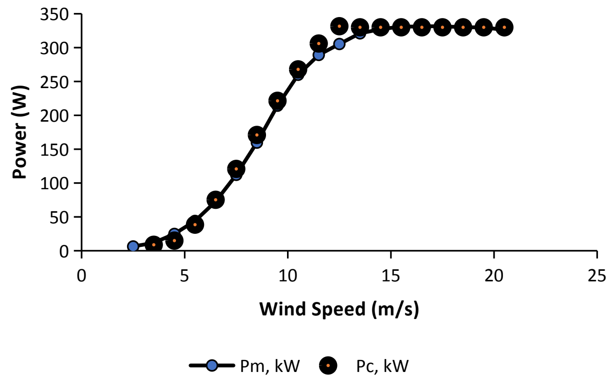

Figure 11. Evaluation of wind turbine performance.

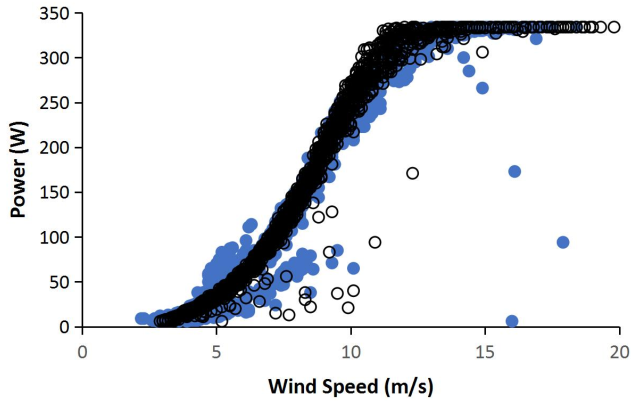

Figure 12. Comparison of Enercon wind turbine power output: Data from January 2013 (solid circles) and January 2023 (hollow circles).

Figures 13 to 14 are presented to address research question 5.5. As one would expect solar PV capacity factor would peak in summer and wind energy conversion in winter season respectively. That is demonstrated via Figures 13 and 14. The inter-seasonal variations are much more suppressed with the solar PV and the wind turbine capacity factor added together. Indeed, solar and wind appear to be complementary in nature.

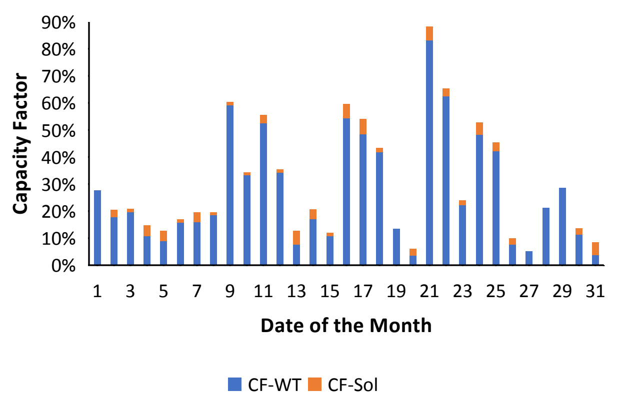

Figure 13. Daily capacity factors for wind turbine and solar PV installation for Arbroath – January.

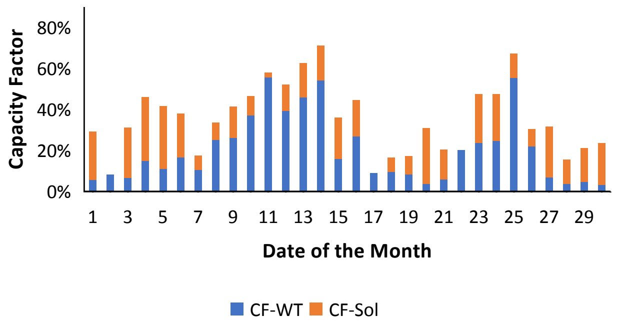

Figure 14. Daily capacity factors for wind turbine and solar PV installation for Arbroath – June.

Refer to Figure 15. This section of the article addresses research question 5.6. Herein a comparison is carried out between the simulated and measured energy yield, the simulation being carried out using a commercially available software, i.e., PV SOL.

An energy yield assessment summary for a 250 kW solar project for the designated location is presented. The site is Arbroath solar farm in Scotland, UK (56.6 N, 2.7 W). The energy yield study is conducted using solar PV simulation software PV SOL Premium 2023. PV SOL is a proprietary software widely used in industry and research sectors to design commercial-scale rooftop PV systems.

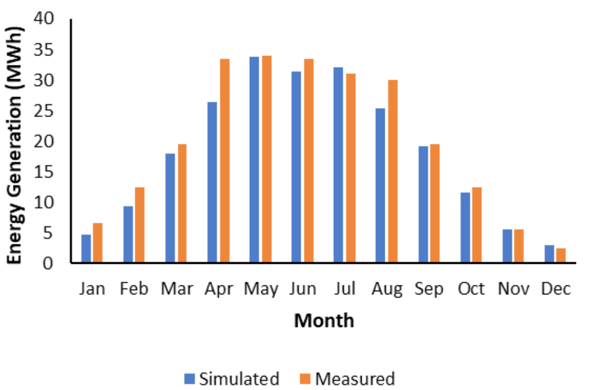

Figure 15. Yearly simulated and measured energy output of the 250 kWp rooftop system.

A fixed tilt system is built on the Arbroath solar farm using JA Solar 270 Wp modules. The modules are installed on a 15° pitched roof in portrait orientation. The energy conversion for any given location depends on the available solar resources of the designated area. The solar resources include Global Horizontal Irradiance (GHI), diffuse horizontal irradiance, and Global Tilted Irradiance (GTI). GHI is the total solar radiation received on a horizontal surface. This can be calculated as follows:

$$\mathrm{GHI} = \mathrm{DHI} + \mathrm{DNI} \cdot \cos(\theta_z) \tag{7}$$

Here Diffuse Horizontal Irradiance (DHI) represents irradiance coming from all directions of the sky per unit area of a surface. The Direct Normal Irradiance (DNI) is the total irradiance per unit area of a surface that directly comes from the sun is solar zenith angle. GTI is the solar irradiance that falls on the front side of the PV module's Plane of Array (POA). PVSOL uses the Hay and Davies model [23] to determine irradiance on a tilted plane (GTI). Meteonorm version 8.1 hourly weather data is used for the simulation. Meteonorm is a global climate database with a temporal resolution of more than ten years and a spatial resolution of about 3 km.

The simulation results are presented in Table 5. All data for this table has been sourced from the PVSOL software library. The annual GHI available for the given location is 919 kWh/m^2, and the average temperature is 9 ℃ . Three essential parameters in explaining the energy yield from a PV system are specific yield, performance ratio, and annual energy conversion. Specific or normalized energy yield refers to the amount of energy, E (kWh), produced for every kWp of manufacturer-specified standard test condition (STC) power of the module over a certain time.

$$\text{Specific Yield} = \frac{\mathrm{E\ (kWh)}}{\mathrm{P(kWp)}} \tag{8}$$

The specific yield of a PV plant depends on location, weather data, amount of irradiance falling on the PV, the performance of the module, including sensitivity at different temperature conditions, and module orientation. The specific yield of the PV system is 880 kWh/kWp/year.

The performance ratio presents the ratio between the actual energy produced and the theoretical maximum energy that would be produced if the system was running at STC efficiency. As per the IEC 61724 standard, the performance ratio of a PV system can be defined as:

$$\text{Performance Ratio, } \mathrm{P_R} = \frac{\mathrm{Y_{AC}\ (t)}}{\mathrm{E_{POA}(t)}} \tag{9}$$

Here $Y_{AC}(t)$ is the cumulative-specific energy yield of the PV system at a given period, and the unit of $Y_{AC}(t)$ is kWh/kWp. $E_{POA}(t)$ is the cumulative plane of array irradiation (kWh/m^2) simultaneously over the irradiance at STC (1000 kW/m^2). P_R of a PV system considers thermal losses, shading loss, cabling loss, inverter loss, mismatch loss and loss due to reduced efficiency at low irradiance. The performance ratio of the PV system is 87%.

The measured and simulated energy generation comparison is shown in Figure 15, which presents monthly produced results. The annual energy conversion is 220 MWh, and the actual energy conversion was 240 MWh, indicating the actual energy generation was about 9% higher than the simulated result. The peak conversion occurred during the summer months (April-August) at more than 30 MWh per month. The simulated results appear to be consistent with actual energy conversion. Overall, the measured data on-site showed strong agreement with the simulated results except in April, with a 7 MWh difference between actual and simulated data.

Table 5. PV Sol simulation parameters and output.

Site Location	Arbroath
Available Solar Resources	
Global horizontal irradiance (kWh/m^2)	919
Diffuse horizontal irradiance (kWh/m^2)	542
Average ambient temperature (℃)	9
PV System Components	
Module manufacturer	JA Solar
Module power (Wp)	270
No. of modules	926
Inverter manufacturer	SMA
Inverter capacity (kWp)	110 kW + 15 kW
No. of inverter	3
Simulation Output	
Total installed capacity (kW$_p$)	250
Declared net capacity (kW$_{ac}$)	235
Specific yield (kWh/kWp/year)	880
Generation (MWh/year)	220
Performance ratio (PR)	87%

The final research question, 5.7 queries the monetary cost of present-day solar PV and wind energy for Central Scotland. Note that Arbroath is a local town in Central Scotland. A simulation code was presently developed. Its algorithmic details are now provided.

In view of cost arguments presented in Section 2.4, BESS has not been included in the design renewable energy plant which consists of a single wind turbine and solar PV (Renewable Energy, RE) plant that are connected to a number of residences that predominantly use the local energy generated by the RE plant but in periods of insufficient RE grid electricity backup is available. The algorithm is basically an energy audit entity that for a given sub-hourly time-step will keep track of the wind and solar PV-generated energy as well as energy demand by the total number of residences in the local energy community. The time step chosen was 30 minutes as that is the lowest common multiple of 10 and 15 minutes, the latter being the time increments for which the wind turbine and solar PV output are available for the Arbroath RE farm.

For any given time step, if the total generation exceeds the demand and energy surplus is recorded, the energy is sold at the rate of US cents 8/kWh. On the contrary, in periods of a shortfall of energy, an energy deficit is recorded with energy bought from the grid at the premium rate of US cents 37.5/kWh.

In that respect, Tables 6 and 7 as well as Figure 16 are referred. Table 6 shows data pertaining to measured means of capacity factors and standard deviation for solar and wind resources. The high values of standard deviation when compared to the mean values indicate the highly intermittent nature of both wind and solar. Note, however, that while solar has an exceedingly low-capacity factor in winter, wind provides a much more stable base. Even in summer, wind provides capacity factors that are easily double that of solar. The annual mean capacity factors for wind and solar are 0.347 and 0.118 respectively. The ratio of the latter two capacity factors is 2.93. Thus, for this simulation exercise, a model renewable energy community is considered that would have a 357 kW wind turbine and 1,100 kW solar PV installation, thus maintaining a parity between wind and solar annual energy output.

Table 6. Seasonal measured capacity factor for solar PV and wind turbine at Arbroath. Shown below are the seasonal mean and standard deviation.

	Solar PV		Wind Turbine	
Month	Mean	Standard Deviation	Mean	Standard Deviation
January	0.03	2.54	0.57	0.50
April	0.19	1.35	0.40	0.81
July	0.19	1.23	0.10	1.13
October	0.07	1.86	0.32	0.94

Table 7. Simulation results for renewable energy generation, consumption, and export for Arbroath model community.

Number of Residences	520	100	40	12
Exported Energy, kWh	231	1636	4474	15586
Imported Energy, kWh	222	71	16	9
Income from Exported Energy, USD	18.5	130.89	357.94	1246.87
Payment for Imported Energy, USD	83.19	26.55	6.13	3.4
Electricity Cost, USD	64.69	–104.34	–351.81	–1243.47
Capital Cost Repayment, USD	23.38	121.59	303.98	1013.25
O&M Cost, USD	1.15	5.99	14.97	49.9
Total Cost, USD	171.3	43.8	–41.7	–226.82

Note: All energy and monetary cost figures provided above are for each residence per month. Energy quantities in kWh and monetary cost in USD.

Figure 16a–d shows the plots of total energy generated from solar and wind facilities for one week each in January, April, July, and October, thus representing the four seasons: winter, spring, summer, and autumn. The data used is energy generated during each half-hour. Four cases are considered with the number of residences connected to the renewable energy community being 520, 100, 40, and 12. We note that in the case of 520 residences a large amount of energy is imported on a number of occasions. This is also reflected in the data presented in Table 7. As the number of residences is decreased the net flow of energy is outwards, i.e., much more energy is exported than imported. The following data is the basis of LCOE calculation, all assessments being on the basis of the IRENA report [6]: capital cost of wind turbine \$496,875, capital cost of solar PV \$940,335, O&M costs = 0.5% of the total capital cost per year, lifetime of plant = 25 years. Imported electricity cost = US cents 37.5/kWh, Exported electricity cost = US cents 8/kWh, daily electricity load for each residence = 11.8 kWh.

Thus, the results of the simulation may be summarised as the cost of electricity, in USD, to each household for the cases of 520, 100, 40, and 12 residences being 171.3, 43.8, –41.7, and –226.82. The negative sign indicates that the household would be profiting from the plant, rather than paying for their electricity each month. That is due to the simple fact that the cost of grid electricity in the UK has shot up in the past year by a factor of between 3 and 4.5. Hence solar and wind electricity is now not just economical but profitable. Note that Figures 16 was plotted using the Microsoft Excel software.

8. Conclusions

Within the UK, in the past 12 years, electricity prices have shot up by more than a factor that ranges between 3 and 4.5. At the same time, the cost of installation of wind turbines and solar PV systems has dropped so low that renewable energy systems now compete head-on with grid-based electricity suppliers. The main research question addressed in this article was to find the cost of a combined wind/solar PV electricity generation plant, located in Central Scotland. Using more than a decade of measured data it was found that setting up of

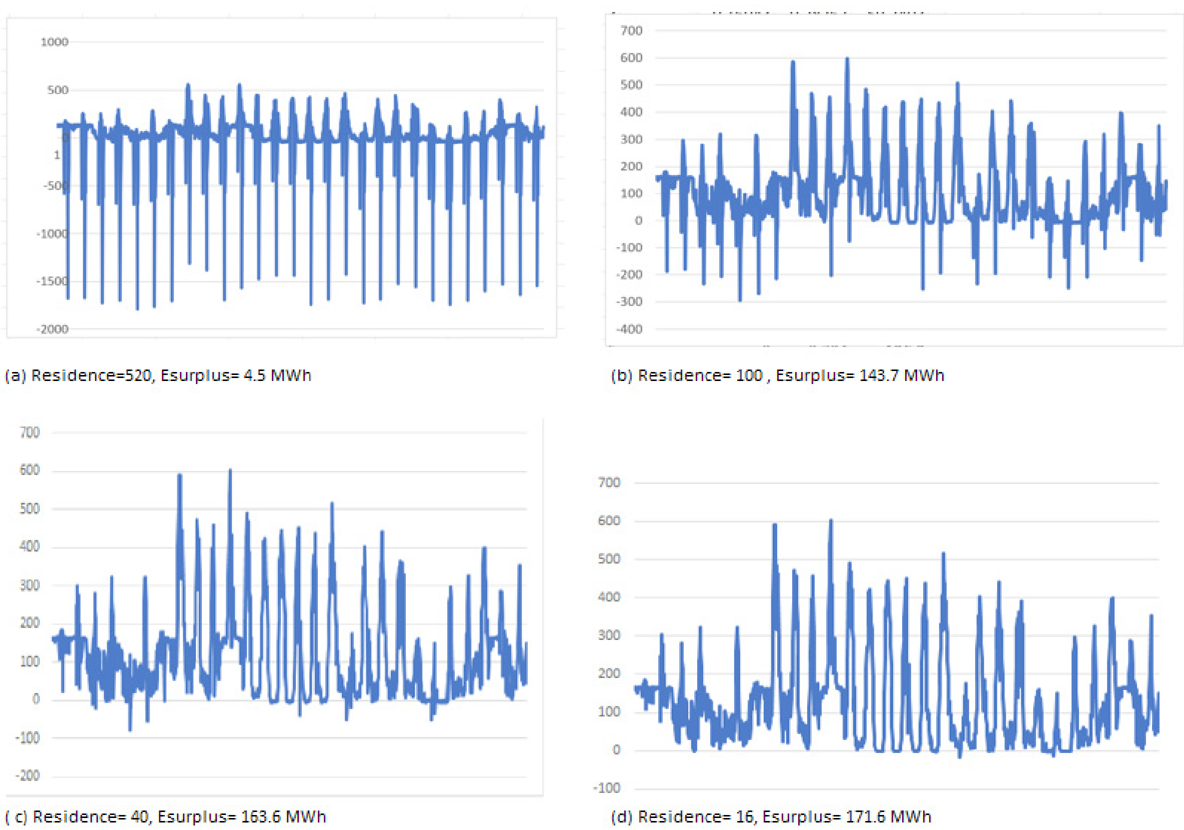

Figure 16. Energy simulation results for Arbroath renewable energy community residences. (**a**) Residence = 520, Esurplus = 4.5 MWh; (**b**) Residence = 100, Esurplus = 143.7 MWh; (**c**) Residence = 40, Esurplus =163.6 MWh; (**d**) Residence = 16, Esurplus = 171.6 MWh.

a community-based wind/solar plant is more economical than purchasing electricity from the grid. That is despite the fact that, currently, grid-electricity suppliers purchase electricity from energy farm owners at a cost that is less than a quarter of the price at which electricity is sold to residents.

This article also provides validation and quality evaluation of wind speed and solar radiation data that is freely available from web-based sources. Furthermore, validation is also provided for the conversion of the above datasets to predict energy generation from wind turbines and solar PV plants, thus completing the computational chain. The article is based on measured datasets from a medium-sized wind/solar electricity generation plant. The conclusions are obviously limited to (a) the location of the plant, i.e., Central Scotland, and (b) the size of the plant. The recent trend is to deploy larger wind machines that are much taller and more efficient. Furthermore, bifacial solar modules are now being used that enhance the output per square meter of installation. More studies are therefore needed, using data from northern and southern Scotland to develop a more complete picture of renewable energy prospects.

Appendix A

List of Acronyms

LCOE	Levelised Cost of Energy
LCC	Life Cycle Cost
CFD	Contract for Difference
BESS	Battery Energy Storage System
IRENA	International Renewable Energy Agency
PV	Photovoltaic
GHI	Global Horizontal Irradiance
GTI	Global Tilted Irradiance
DHI	Diffuse Horizontal Irradiance
DNI	Direct Normal Irradiance
RE	Renewable energy
PDF	Probability Distribution Function
CDF	Cumulative Distribution Function
DG	Diesel generator
CF	Capacity factor
FIT	Feed in Tariff
O&M	Operation and Maintenance
STC	Standard Test Condition

Author Contributions

Conceptualisation, T.M., M.A., R.D.; methodology, T.M.; software, T.M., M.A.; validation, T.M. and M.A.; formal analysis, T.M.; investigation, T.M., M.A.; resources, T.M., R.D.; data curation, T.M., R.D.; writing—T.M., M.A.; writing—review and editing, T.M., M.A. and R.D.; visualisation, T.M.; supervision, T.M.; project administration, R.D.; funding acquisition, R.D.

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Data Availability Statement

Due to confidentiality, no data was available at this time.

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Conflicts of Interest

The authors declare no conflict of interest.

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