Potential for renewable energy–assisted harvesting of potatoes in Scotland

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Abstract

Depleting energy resources, enhancing energy security and energy access and approaching climate change related challenges are some of the present day challenges. Against this backdrop, renewable energy (RE)-based farming has been a topic of serious discussion within Great Britain and Scotland. There are multiple advantages in the development and applications of RE micro-grids for farming communities as often they are located in areas that are quite remote and hence their energy sustainability provides security of supply. In the present article, a large-scale RE system that included solar photovoltaic and wind turbine has been critically analyzed with respect to its fractional contribution toward the total energy budget of a potato farm that produces 8000 tons of crops annually, with 4500 tons of the produce in cold storage for up to 8 months. The findings and recommendations from these case studies will help renewable energy practitioners in erecting and analyzing similar installations.

Keywords: energy payback time; renewable energy; wind energy; solar energy

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1 INTRODUCTION

The earliest sources of energy that humans exploited were wind and sun. The history of wind energy may be traced up to 2800 BC when the Egyptians used it to sail their ships [1]. Likewise, solar energy use has been recorded within the historical developments of the Greek civilization. Archimedes, a Greek physicist, allegedly used highly polished shields to focus the sunlight to burn down enemy ships. Later on in the 3000 BC, the Greeks and Romans were reported to harness solar power with mirrors to light their torches. Chinese civilization documented the use of mirrors for the same purpose later on in the year 20 AD [2].

Presently employed energy systems will be unable to cope with future energy requirements—fossil fuel reserves are depleting, and climate change has become a serious issue [3]. In the year 2019, the global average atmospheric carbon dioxide concentration was 409.8 ppm and these levels are higher than at any point in the past 800 000 years [4]. In fact, the last time the carbon dioxide concentration was this high was more than 3 million years ago when the temperature was 2–3°C higher than pre-industrial era and the sea level was 15–25 m higher than today [5, 6].

Fossil fuel and nuclear energy production and consumption are closely linked to environmental degradation that threatens human health and quality of life and affects ecological balance and biological diversity. Although available only in a diffuse quantity, renewable energy is abundant, inexhaustible and widely available. These resources have the capacity to meet the present and future energy demands of the world [7]. The cost of energy generated from these renewable sources has fallen by a factor of seven in the past 7 years [8]. On the other hand, the cost of fossil fuel–produced energy is in an increasing mode.

Over the past three decades, solar and wind energy systems have experienced rapid growth [8]. This is being supported by several factors such as declining capital cost; declining cost of electricity generated and continued improvement in performance characteristics of these systems. By the end of year 2020, the number of solar photovoltaic (PV) systems in the UK had exceeded 13 400 [9] and wind energy installed capacity had exceeded 22 GW as far back as year 2018 [10]. This pattern is being duplicated the world over.

The cost of electricity from offshore wind projects completed during 2012–2014 was UK pence 13.1/kWh compared to a wholesale price of UK pence 4–5/kWh. In 2017, the Financial Times [11] reported that new offshore wind costs had fallen by nearly a third over 4 years, to an average of 9.7 UK pence/kWh, meeting the government's target of 10 UK pence/kWh 4 years early. Later in 2017, two offshore wind farm bids were made at a cost of 9.7 UK pence/kWh for construction by 2022–2023. It is expected that

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a further 6 GW of clean energy is to be added to the grid by year 2025 at ∼4.7 UK pence/kWh at 2019 prices [12]. These figures are lower than current generation costs for fossil fuels.

Energy is the key to economic development and sustenance of future world. With rapid urbanization and increase in aspiration of majority of population, energy demand in developing as well as developed countries across the world is ever increasing and expected to grow in future.

2 THE GROWTH OF SOLAR AND WIND ENERGY IN THE UK

It has been reported that offshore wind has the technical potential to provide 36 000 TWh/annum of energy, which is more than the current global electricity usage [13].

The world's cumulative electric power capacity for solar PV and wind reached the respective figures of 634 GW [14] and 743 GW [15]. That milestone was achieved in the year 2020 for solar and the year 2021 for wind. The comparable installed capacities in the UK for solar and wind were 13.6 and 24 GW [16]. With the respective populations for the globe and UK at 7.674 billion and 66.8 million people [17], respectively, the per capita installed capacities for combined solar and wind installations are 179 and 563 W, respectively. Clearly, the UK is leading the rest of the world by a factor of 3. Despite the UK having a weak solar resource, the per capita installed capacity is 204 W, the comparative figure for the globe being 82 W. Once again, the UK is in the lead by a factor of 2.5. At this stage, a comparison is provided for the UK's average solar income (101 W/m^2) against that for mid and lower latitude countries such as Vietnam and India (western region) and those figures are 150 and 292 W/m^2, respectively. Hence, despite the odds, the UK has taken lead once again.

The UK offshore wind sector is due to expand fast as the government aims to increase its capacity from the current figure of 24 to 40 GW within a decade. That is evident by a number of ongoing activities such as follows: (a) the company Prysmian has won a contract to supply the submarine and land export cables for the Sofia wind farm, and (b) Prysmian is also constructing a submarine cable manufacturing facility in Wrexham, England, to supply the Hornsea 2 wind farm project [18]. The latter project will be constructed some 89 km off the Yorkshire coast and will be one of world's largest wind farm with 165 Siemens Gamesa 8 MW machines spread over an offshore area of 462 km^2. The project is due for completion in year 2022.

The reason for the acceleration of growth of solar and wind electricity generation technologies is the steep price drop as Table 1 indicates.

Here, a comparison of the generation cost of fossil fuel and renewable and nuclear power plants is provided. Note that over a decade, that is, from years 2009 to 2019, while the per kilowatt hour cost of solar PV and wind have dropped by a factor of 9 and 3.3, respectively, the cost for nuclear has actually risen and that for coal has remained stable. Table 2 presents the data on the ever-falling PV module price [19]. Table 3 provides information on the UK wind energy growth and performance statistics. The capacity factor data will be of particular relevance for this article. Furthermore, note that the capacity factor is on the increase as wind turbine installations move further offshore.

The solar cell was first used in space program over 60 years ago. Then a watt of PV module cost US$1865. Taking inflation into account, the price has now dropped by a factor of more than 3300! The price for wind energy generation has also dropped, but not on the scale of solar as shown in Table 2. Note that, for solar PV, each time installed capacity doubles, the cost of electricity

Figure 1. *Google map of Cononsyth, Arbroath, Scotland Latitude: 56.613304 North.*

Table 1. *Price comparison for electricity generation technologies, US cents/kWh*

Energy generation source	2009	2019
Coal	11.1	10.9
Gas	8.3	5.6
Geothermal	7.6	9.1
Nuclear	11.1	15.5
Solar PV	35.9	4
Wind, onshore	13.5	4.1

Table 2. *Solar PV module price, US$ per watt*

Year	Price
1976	106.09
1980	35.01
1985	14.85
1990	8.81
1995	5.83
2000	4.88
2005	4.24
2010	2.04
2015	0.6
2019	0.38

Table 3. *UK wind energy growth and performance statistics*

Year	Installed capacity, GW	Capacity Factor	Percentage of total electricity use
2016	16.2	26.3	12
2017	19.8	28.6	17
2018	21.7	30.0	18
2019	24.0	32.0	21

Table 4. *Cumulative installed wind power capacity in Scotland*

Year	MW
2008	1745
2009	2121
2010	2677
2011	3688
2012	3955
2013	4779
2014	5277
2015	5585
2016	6478
2017	7578
2018	8562
2019	9334
2020	9366

falls by 36% [20]. This relationship has also been observed for wind energy developments. The levelized cost of energy (LCOE) of onshore wind has fallen by 23% while capacity has doubled; for example, see [21]. For offshore wind, the cost has dropped by 10%. The International Energy Agency has determined that the cost of offshore electricity will drop 40% more by year 2030 [22]. On the other hand, the LCOE for nuclear power plants has risen by more than 60% in the past decade.

3 ENERGY DEMAND AND RENEWABLE ENERGY GENERATION IN SCOTLAND

Scotland has an installed wind power capacity of close to 9.4 GW and generates 31.8 TWh of electricity from renewable sources, with a population of 5.454 million that translates to the energy use of 5.83 MWh/year-capita. That is in contrast to the year 2014 world average of 3.13 MWh/year-capita. The bulk of the world electricity generation includes fossil fuel plants. Table 4 presents the rapid growth of wind power plants in Scotland.

Note that with an annual-average wind speed reaching 9 m/s Scotland has one of the best energy resource of nearly 1200 W/m^2. The solar resource is much more dilute though as the receipt is around 850 kWh/m^2-day compared to certain parts of Africa, which get over 1900 kWh/m^2-day. Despite the weak solar resource, the number of solar PV plants is on the rise in Scotland as shown in Table 5.

Table 5. *Cumulative installed solar PV capacity in Scotland*

Year	MW
2011	48
2012	95
2013	133
2014	175
2015	264
2016	326
2017	343
2018	344
2019	364
2020	378

The irony of the present situation is that those locations that have the most potential for capturing the two most promising sources of renewable energy—solar and wind—are lacking in their effort to exploit as shown via Tables 6 and 7. Those tables are based on material presented in reference [23].

4 PRESENT INVESTIGATIONS

Large parts of land in Scotland are used for agricultural purposes. The farmers have an important role to play within the Scottish economy. As the link between climate change and energy use is becoming increasingly evident, the farmers are in the process of installing solar and wind energy conversion systems. There are many research questions to be answered though and the main purpose of this article is to address a few of them such as:

a. Based on long-term measurements, what are the seasonal and annual capacity factor for solar PV and wind energy conversion?
b. To what extent are solar and wind resources complimentary?
c. Given the high latitude of Scotland what is the seasonal influence on the above resources?
d. In an agriculture perspective, what is the present day monetary cost of solar PV and wind energy conversion in Scotland?
e. What are the solar and wind generation associated Carbon emissions?
f. What are the long-term prospects of electricity storage?

5 SOLAR AND WIND TURBINE INSTALLATION ON A POTATO FARM

5.1 Cononsyth Farms

Cononsyth Farms (CF) houses ‘North Mains of Cononsyth’ and ‘Cononsyth Farm’ (see Figures 1 and 2). The farms are a medium- to large-scale agricultural farming entity located within rural East Angus (56.613304, −2.695326). The main business activities include the growing and processing of cereal crops, oilseed rape and potatoes over a 1500 acre geographical area. Note that an ‘acre’

Table 6. *Number of cities with high solar potential*

Percentile	Global horizontal irradiance, kWh/m^2-day	No. of cities in the dataset	No. of cities with renewable energy target	No. of cities with 100% target
Top 10	6.126	66	3	0
Top 20	5.851	248	17	6
Top 30	5.493	621	39	14

Table 7. *Number of cities in the world with high wind potential*

Percentile	Wind power density (W/m2)	No. of cities in the database	No. of cities with renewable energy targets	No. of cities with 100% target
Top 10	607	57	29	26
Top 20	457.7	206	88	80
Top 30	381.5	394	151	130

Figure 2. *Geometrical drawing of the detail of Cononsyth and North Mains at Arbroath, Scotland F1: North Mains of Cononsyth, T: Turbine, F2 Cononsyth Farm.*

is 4840 square yards or 0.405 hectare and is a measure of area that is widely used in the British farming industry.

The farm has diversified into commercial contract drying service for oilseed rape, peas, beans, oats, wood chip and pallet logs. Various food supermarket chains purchase the products grown and supplied by the farm. In order for a supplier of significant product volumes to trade with these supermarket chains, they must demonstrate that their processes align with their carbon emission reduction strategies.

CF has installed 2.939 MW of biomass heat production, 330-kWp wind turbine and 350-kWp solar PV electrical generation; these technologies have enabled a significant de-carbonization of its energy-demanding processes. The farm is also transitioning from combustion engines with investing in a fleet of EV forklifts, which are charged utilizing onsite generated renewable energy.

The gross owned landmass at CF is 500 acres, of which 100% is irrigatable. The business produces on average 8000 tons of potatoes annually on owned and rented ground in the County of Angus. Each year, 4500 tons of potatoes are stored in cold stores at 2.5–3.5°C for 6 to 8 months of the year.

The journey to renewables at CF began in 2008 when they were introduced to small-scale wind turbines. This initiated the idea of an 11 kW Gaia Turbine. CF investigated the possibility of a wind turbine and inquired into an early small scale renewable incentive scheme known as Renewable Obligation Certificates (ROCs). However, CF understood that to significantly reduce the farms' energy bills, a larger turbine would be required.

In 1 April 2010, a new UK Government–led renewable incentive scheme was introduced for generation of less than 5 MW rating. The scheme introduced is called the Feed-in-Tariff. From the launch of the scheme in 2010, the incentives were reduced by the process of degression until the closure for new applications in March 2019.

CF initially proposed a 500-kW turbine; however, it was advised that planning would be too high of a risk. The farm decided on a 330-kW turbine manufactured by a German company called Enercon. Enercon turbines were known to be of high reliability due to their non-gear generating technology.

Planning was submitted to Angus Council in June 2010 and was approved in December the same year. The turbine, which was one of the largest in Angus at the time, received no objection from 12 consultees. The application was seen to be consistent with the local development plan of the area, and no material considerations of sufficient weight would warrant the refusal of the application. The turbine was installed in 2012 and achieved an incentive payment of 23.5 p/kWh of electricity generated.

Also in 2010, CF enquired into the possibilities of roof-mounted solar PV. At the time, CF experienced difficulty getting Angus Council to agree to this principle as no roof-mounted solar PV system application had been submitted to them previously. The farm found a way around this by drawing panels on the roof of a new cold store warehouse extension. CF inadvertently got planning approval for the first 50-kW solar PV system in 2011, obtaining an incentive payment of 31 p/kWh generated. As it is index linked, the incentive payment is 38.5 p/ kWh. The installed JA Solar JAP60S01 270 W polycrystalline PV modules sit on the

Figure 3. *The 300kWp solar PV plant at Cononsyth, Arbroath, Scotland* ***Note:*** *The dull colored PV modules at the back of this picture were installed in year 2011. The brighter colored modules were installed in year 2019.*

roofs that are at an angle of 15 degrees from horizontal, with an aspect of 5 degrees East of South.

The de-carbonization of heat on the farm was initiated in 2013, with the installation of a biomass burner with floor-drying infrastructure to dry all the cereals grown by the business. Furthermore, biomass burners were installed in 2014, 2015 and 2016. CF identified a business opportunity for supplying dried woodchip to neighboring farmers with their own woodchip burners. CF was one of the only authorized suppliers in the area. The demand for woodchip lead to a gradual increase in biomass heat generation. March 2021 saw the installation a 900-kW woodchip burner. The farm now has 2.939 MW of heat generation from three units manufactured by an Austrian company ETA with thermal capacities of 199, 350 and 500 kW. Two other units in use were manufactured by German manufacturer Heizomat with respective thermal capacities of 990 and 900 kW.

The buildings at North Mains of Cononsyth are used for potatoes and potato box storage, grading and grain handling. The largest buildings are potato cold stores. The potato cold stores are energy demanding and operate for 6 to 8 months of the year. The stores have the capacity to store 1500 tons and maintain a temperature of 2.5–3.5°C.

All solar systems operate with no service fee; however, they are periodically reviewed to ensure performance is as expected. A service call out will be initiated if there is a notable decrease in energy generation.

In October 2012, CF installed a 330-kWp turbine after gaining planning consent in 2010. The turbine secured a Feed-in-Tariff of 23.5 p/kWh and paid back in just 4.5 years. The turbine generates electricity that is consumed directly on-site for the cooling demand of the 8000-ton crop grown annually. Although, the energy generation is 300% of the annual consumption of the farm, some 34% of the annual energy use is still imported. That is due to a lack of synchronicity between wind energy conversion and demand.

Figure 4. *The 330kWp wind turbine at North Mains of Cononsyth Date of installation: October 2012.*

The wind turbine is serviced under an agreement called Enercon PartnerKonzept contract. The annual cost of the service contract is €10 000 up to 7 years then €20 000 up to 15 years. Then after, the service fee is negotiable. As the turbine is now 8 years old, the service fee is now in the second phase.

5.2 Renewable energy generation at CF

In the year 2019, the North Mains solar PV plant was further enlarged, significantly, by addition of another 250 kW. That

Table 8. *Annual performance of the 330 kW wind turbine at Cononsyth potato farm at Arbroath, Scotland*

Year	2012*	2013	2014	2015	2016	2017	2018	2019
Average wind speed, m/s	9.1	6.8	6.3	7.0	6.3	7.0	6.6	6.6
Average power, kW	111	108	100	118	92	104	98	82
Capacity factor, ratio		0.33	0.30	0.36	0.28	0.31	0.30	0.25

*Records exist only from November 2012.

Table 9. *Monthly performance of the 330 kW wind turbine at Cononsyth potato farm at Arbroath, Scotland, for year 2015*

Month	1	2	3	4	5	6	7	8	9	10	11	12
Av. WS, m/s	7.4	8.1	6.5	7.4	5.4	6.5	5.8	6	5.9	8.3	7.8	8.6
Av. power, kW	130	90	106	107	63	80	76	79	74	144	147	147
Capacity factor	0.4	0.27	0.32	0.33	0.19	0.24	0.23	0.24	0.22	0.44	0.45	0.44

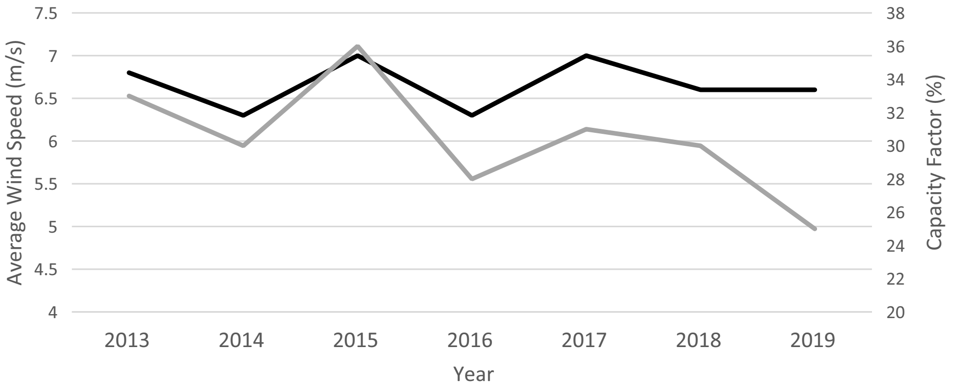

Figure 5. *Annual-averaged wind speed and capacity factor for the 330 kW Arbroath wind turbine* ***Note:*** *Average wind speed, black line; Capacity Factor, gray line.*

completed facility is shown in Figure 3. The total PV capacity at CF complex is thus 350 kW, split between Cononsyth (300 kW) and North Mains (50 kW). Each 15 minutes, the data-logger records the minimum, maximum and the average power output for the three power-plants. The three solar power-plants are the 50 kW each, installed in year 2011 at the Cononsyth Farm and the North Mains of Cononsyth, and the additional 250 kW installed in year 2019 at Cononsyth Farm. All PV plants are in good order, and their maintenance is backed up by a service contract.

The frequency of data collection from the wind turbine is 10 minutes, and among the parameters recorded are wind speed at the height of wind turbine nacelle (82 m), wind direction and minimum, maximum and average power output of the turbine and energy generation. Figure 4 shows graphical views of the CF wind turbine. It has to be reiterated that the turbine is in good order and its maintenance is backed up by a different service contract.

Tables 8 and 9 present performance of the wind turbine on an annual and monthly basis, respectively; the latter being for 1 year, 2015, which was most productive. The capacity factor is a good measure to assess the performance of a power plant. The capacity factor indicates the fraction of the time that the power plant was delivering at full capacity or the ratio of actual energy generated to the ideal value of energy that may be generated provided the plant ran at full capacity for the entire duration. While the capacity factor is of a high order, perhaps reaching a value of 0.9 for nuclear and fossil fuel plants, its value is much lower for renewable energy plants. It may be noted that in Table 8 no capacity factor has been reported for year 2012. This is due to the fact that the wind energy generation start date was 8 November 2012. Due to incompleteness of the year, the capacity factor for 2012 is not comparable to the corresponding value from other years. The average wind speed shown for year 2012 is also quite high (9.1 m/s) as the data are skewed heavily toward winter months with associated higher wind speeds. A few interesting points that may be picked up here are as follows: (a) in years 2015 and 2017, the average wind speed is identical, and yet the average power in year 2015 was 13% higher; (b) likewise, in years 2018 and 2019, the same phenomenon occurs, that is, identical wind speeds and yet year 2018 delivers power that is 19.5% higher; (c) compared to annual average, the two winter months of November and December have a wind speed average that is 37% higher.

The disparity of the energy yield for the years 2015 and 2017, and for the years 2018 and 2019 may be investigated further via Figures 5 and 6, and Figures 7 and 8, respectively. These four plots are explored furthermore. The first two plots, Figures 5 and 6, show the annual mean wind speed and capacity factor and a scatter plot that relates capacity factor to mean wind speed, respectively. Both figures indicate that for a given annual wind

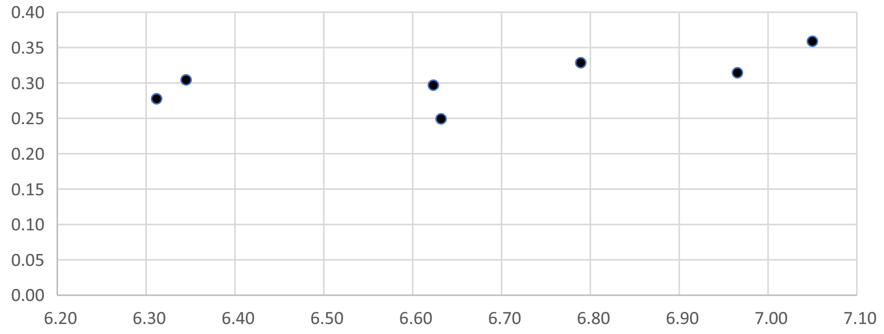

Figure 6. *Annual-averaged capacity factor versus wind speed for Arboath x axis: wind speed, m/s; y axis: capacity factor.*

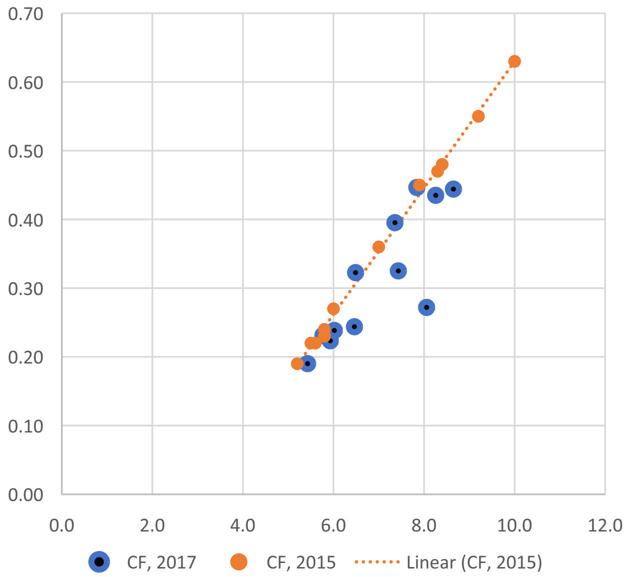

Figure 7. *Monthly-average wind turbine power versus wind speed for years 2015 and 2017 x axis: wind speed, m/s; y axis: capacity factor*

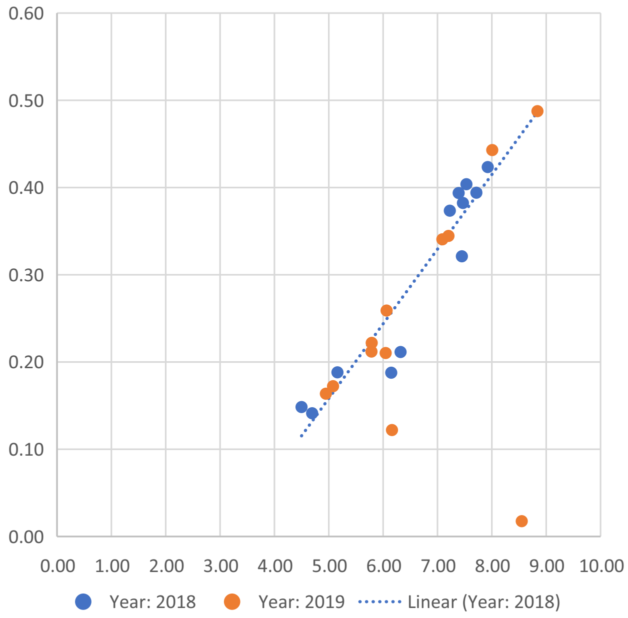

Figure 8. *Monthly-average wind turbine power versus wind speed for years 2018 and 2019 x axis: wind speed, m/s; y axis: capacity factor.*

speed the turbine delivers different values of capacity factor. That could be due to three reasons: (a) the mean wind speed is a combination of many instances of either low wind that lies below the cut-in speed of the wind turbine, which is around 4.5 m/s and that would reduce the capacity factor; (b) instances when the turbine was shut down due to storm conditions or mechanical breakdown; or (c) a combination of the latter two factors.

Close inspection of the dataset revealed that item (c) was the cause of the aforementioned phenomenon, that is, identical average wind speed and yet very different values of capacity factors. Note that the slope of the best-fit line for data from year 2015 (Figure 7) and year 2018 (Figure 8) indicates the same trend.

Hence, the conclusion is that the turbine is well maintained and has an annual high capacity factor of 0.36. Figure 9 provides further evidence in this respect, that is, the frequency of occurrence of a given wind speed is similar for the 2 years under discussion—2018 and 2019. The considerable departure of capacity factors for the latter two years is therefore mainly due to turbine downtime.

Tables 10 and 11 present data for solar PV performance in a manner similar to Tables 8 and 9. Once again note that the solar PV data were logged from 30 September 2011 onwards and hence in Table 10 no information is presented on capacity factor for that year. Furthermore, for the year 2021 the data were only available up to the month of April and hence the capacity factor is not available for the latter year. It is clear from the tabular information presented so far that at Arbroath the capacity factor for wind energy conversion is three times more compared to solar PV. That is on an annual basis.

On a monthly-averaged basis the wind/solar capacity factor ratio is much higher in winter months with low sun angle and shorter days. Hence, if a solar PV plant is to compete with wind turbine, the capacity of the PV plant ought to be at least three times more. Figure 10 presents such information for the combined total energy of a 330-kW wind turbine and 1-MW solar PV plant. Note that the energy delivery profile is now much more stable as

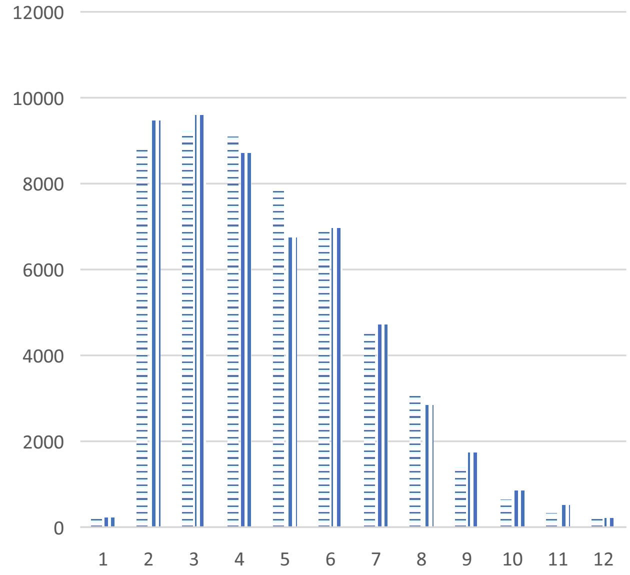

Figure 9. *Frequency of wind speed (m/s) for years 2018 and 2019.*

opposed to sole delivery from either a wind or a solar plant. The low performance of solar plant in winter months is subsisted by high wind energy delivery and vice-versa in summer.

That information is further enhanced via Table 12, which provides the average, the standard deviation and coefficient of variation (CoV) for solar, wind and combined plants. Note that for the combined plant the CoV drops to only a third of the value for solar and half of what the wind turbine offers, thus making it a stable entity.

The element of wide variation of energy delivery is inevitable in both solar and wind energy. Figures 11–13 present the daily variation of energy delivery from wind, solar and combined plants. The plots have been made for two months—January, a winter month, and September, a late-summer month. Once again, the advantage of the combined plant is obvious. The usefulness of such plots is that they enable design analysis of the storage that would be required for any given load profile. Renewable energy plants will need to overcome the intermittency related issues to become truly popular and useful. A great deal of work is ongoing with respect to battery and other forms of energy storage. That item shall be briefly explored in the following section.

Figure 14 provides a comparison of the turbine power delivery—the manufacturer's provided acclaimed performance is compared against measured power for two years, 2015 and 2019. The year 2015 presents data when the turbine was just over two years old, whereas 2019 data are for the machine when it was 7 years of age. No significant departure of actual power delivery is seen, thus validating the quality and maintenance of the machine.

6 EMBODIED CARBON ANALYSIS

With the rapid decline in the cost of PV modules and wind turbine electricity generation, the key decision parameter will be the emissions associated with any energy generation technology. Both solar and wind are in good stead as the present analysis will show.

In Lifecycle Assessment (LCA) studies, the energy payback time (EPBT) for any product is calculated as total primary energy used in the manufacture of the product divided by the annual energy generated by the product. For renewable energy products or systems the EPBT will be among other things, dependent upon the energy intensity of available electrical and thermal energy, and the climate as the latter will dictate the solar or wind energy resource. Within the context of the Scottish climate, Muneer *et al.* [24] carried out an LCA on an Edinburgh solar PV installation. Using the data provided in references [25–28], Muneer *et al.* [24] showed that the embodied CO_2 in the given solar PV system that included the mono-crystalline modules, inverters, cables and the supporting structure was 44 g CO_2/kWhe. The EPBT was found to be 8 years for Scottish climate.

More recent such work has been carried out by Kim *et al.* [29] and Ludina *et al.* [30].

Kim *et al.* [29] have shown that the EPBT for the mono-crystalline PV facility in South Korea was 2.97 years. The embodied CO_2 in the South Korean PV system that, once again, included the mono-crystalline modules, inverters, cables and the supporting structure was reported as 25 g CO_2/kWhe and the Carbon intensity of the mains electricity grid as 495 g CO_2/kWhe.

Table 10. *Annual performance of the 50 kW solar PV facility at Cononsyth potato farm at Arbroath, Scotland*

Year	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
En. Gen, MWh	3.2	39.4	41.1	43.5	48	45.6	44.8	46	46.3	47.7	6.8
Capacity factor		0.09	0.094	0.099	0.11	0.104	0.102	0.105	0.106	0.108	

Table 11. *Monthly performance of the 50 kW solar PV facility at Cononsyth potato farm at Arbroath, Scotland, for year 2015*

Month	1	2	3	4	5	6	7	8	9	10	11	12
En. Gen, MWh	1.3	2.5	3.9	6.7	6.8	6.7	6.2	6	3.9	2.5	1.1	0.5
Capacity factor	0.03	0.07	0.11	0.18	0.18	0.18	0.17	0.16	0.11	0.07	0.03	0.01

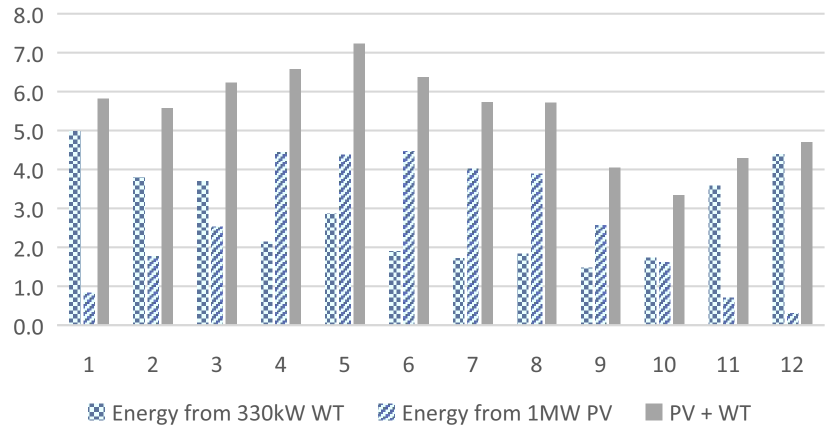

Figure 10. *Combined generation from 330 kW wind turbine and hypothetical 1 MW solar PV facility x axis: month number.*

Table 12. *Combined monthly performance of solar PV and wind turbine at Cononsyth farm for year 2015*

Month	1	2	3	4	5	6	7	8	9	10	11	12	Av.	SD	CoV
WT	5	3.8	3.7	2.1	2.9	1.9	1.7	1.8	1.5	1.7	3.6	4.4	2.8	1.2	41
PV	0.8	1.8	2.5	4.4	4.4	4.5	4	3.9	2.6	1.6	0.7	0.3	2.6	1.5	57
PV + WT	5.8	5.6	6.2	6.6	7.2	6.4	5.7	5.7	4	3.3	4.3	4.7	5.5	1.1	20

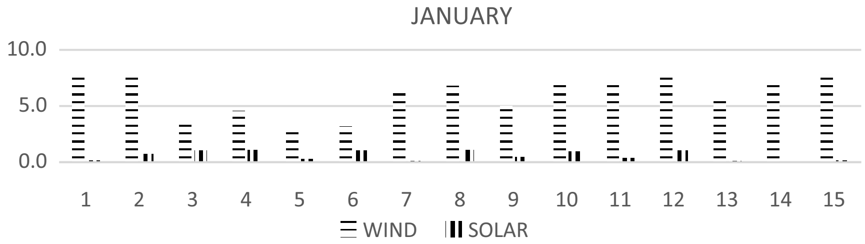

Figure 11. *Energy generation (MWh) of the 330 kW wind turbine and 1 MW solar PV plant for January 2015 x axis: day number.*

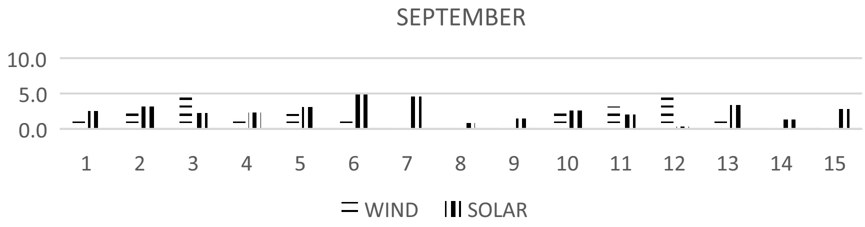

Figure 12. *Energy generation (MWh) of the 330 kW wind turbine and 1 MW solar PV plant for September 2015 x axis: day number.*

Ludina *et al*. [30] have provided LCA for rooftop mono-crystalline silicon PV in Southern Europe (solar irradiation of 1700 kWh/m^2/year). The reported EPBT was 2.5–3.0 years in year 2000 and 2.1 years in 2006, which decreased to 1.75 years in 2009. The gradual decrease is due to improvements in manufacture of PV modules that use less Silicon as time progresses. The latter EPBT figure of 2.5–3 years for Southern Europe ties closely with the 8 years EPBT for Scotland, reported by Muneer *et al*. [24]. The Scottish solar irradiation is 822 kWh/m^2/year, which is roughly half the receipt for Southern Europe, and hence the EPBT is doubled for Scotland.

Incidentally, Ludina *et al*. [30] have also quoted the GHG emissions data for wind power as having a range of 6.2–46 g CO_2-eq/kWh.

The work of Lenzen and Munksgaard [31] has shown that the capacity factor for wind turbines lie in the range of 10–50%,

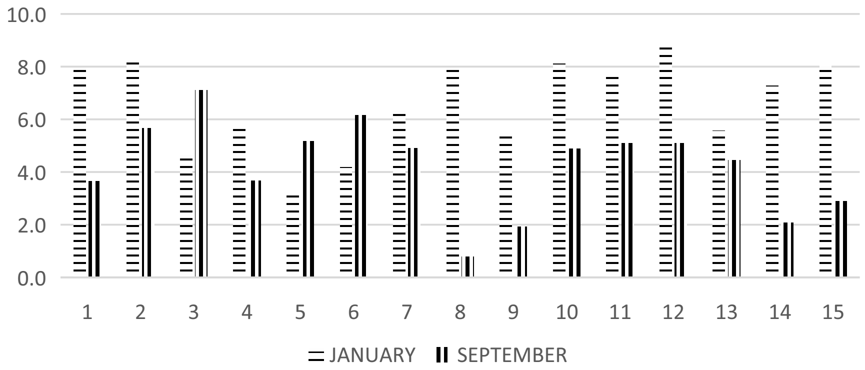

Figure 13. *Energy generation (MWh) of the combined 1 MW solar and 330 kW wind power plants for year 2015 x axis: day number.*

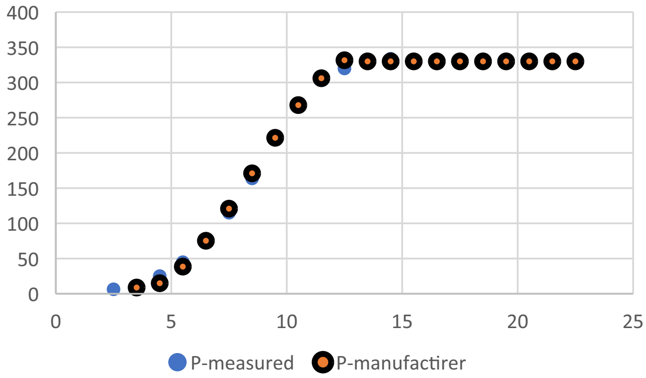

Figure 14. *Comparison of actual and manufacturer-claimed power delivery of the 330 kW wind turbine. X axis: wind speed, m/s; y axis, kW.*

although most modern machines have that range narrowed down to 20–35%. We have seen in the present analysis that under Scottish climate the capacity factor could be much higher, particularly during winter months.

Based on the works of Krohn [32], Gurzenich *et al.* [33], Schleisner [34] Ancona and McVeigh [35] and Wibberley *et al.*. [36], the lifetime of modern wind turbines has been shown to be between 20 and 30 years. Furthermore, work carried out under the aegis of Vestas wind turbine manufacturers [37] has shown that even after the latter time period the only components that may need replacement are the moving parts: generator, gearbox and blades. The 330-kW Enercon machine under discussion seems to validate the above claim with only the blade covering starting to show signs of wear and tear after 9 years of operation.

The works of Pick and Wagner [38] carried out for a 500-kW machine, and Tremeac and Meunier [39], for a 4.5-MW turbine have shown that respective embodied energy quantities are 3948 GJ and 70 152 GJ.

Research undertaken by Crawford [40] on the lifecycle audit of embodied energy of an 850-kW and a 3-MW wind turbine included a detail assessment of four major components—foundation, tower, nacelle and rotor. His results indicate that the embodied energy of the 850-kW machine was 34 574 GJ/MW and that for the 3 MW machine was 30 725G J/MW.

More recently, Smoucha *et al.* [41] carried out carbon analysis for 14 wind turbines that ranged from 50kW to 3.4-MW output suggests and confirms the works of Pick and Wagner [38] and Tremeac and Meunier [39], that is, the higher rated machines have higher carbon content per MW but the payback time drops with capacity. Smoucha *et al.* [41] found that the higher rated wind turbines had higher embodied Carbon per kW capacity, e.g. whereas an 80 kW machine had 58 tonne of Carbon, a 3 MW machine had 1,046 tonne embodiment. However, the latter research team has note that the payback time of larger machines was much shorter due to their higher capacity factors. That may be explained to the siting of higher capacity machines in open spaces such as offshore locations and higher hub height.

The work of Smoucha *et al.* [41] may be summarized with respect to embodied energy; thus, the embodied ton of CO_2 for 80-, 100-, 250- and 500-kW machines are 58, 61, 148 and 274, respectively, and their EPBTs expressed as a percent of the machine lifetime are 2.6, 2.2, 2.1 and 2. Interpolating for the 330-kW Enercon machine presently under discussion leads to an embodied 190-ton CO_2 and an EPBT of 3.1% of the lifetime.

7 LARGE-SCALE ENERGY STORAGE: PROSPECTS AND CHALLENGES

7.1 Electricity storage in electric batteries

The rapid rise of electric vehicle (EV) fleet around the globe presents an opportunity for large-scale storage of off-peak electricity from solar and wind. The trip efficiency of electricity storage and its reuse is very high, and thus this technology is appealing. On the downside, however, the large-scale mining of lithium and cobalt from a very limited number of countries in South America and Congo and the very serious environmental impact will be a big challenge. It is clear that off-peak storage will have to be via a number of alternate technologies.

In Scotland alone, with a population of 5.4 million people, the number of EVs is now over 7000. The average Li-ion battery has a 40-kWh capacity, and that figure is rising for newer models of

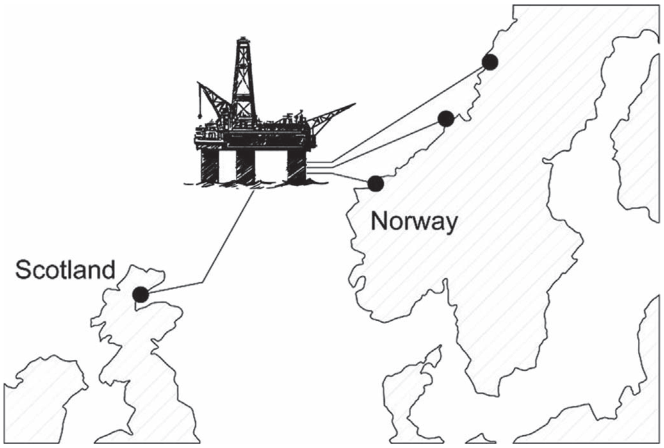

Figure 15. *Schematic for hydrogen production and transmission from Norway to Scotland*

vehicles that are appearing on the market. That translates into a storage capacity of 280 MWh that is available in the present time. However, by the year 2040, when most of the present automobile fleet of 3 million is replaced in favor of EVs, the storage capacity will exceed 180 GWh. The latter figure assumes an average battery capacity of 60 kWh for the EVs by year 2040. Note that the projected storage capacity of 180 GWh is over 40% of the daily electricity use in Scotland and should therefore suffice as a solution to the intermittency issue of renewable energy. However, there are other solutions available as well such as pumped hydro and hydrogen production via electrolysis of water. The pumped hydro is an established technology in Scotland with one of the first such schemes having been built in the year 1896 by Alcan for their aluminum smelter near Foyers, Inverness. Pumped hydro requires a large land area and further exploitation of this technology seems unlikely. However, hydrogen production is on the up and shall be discussed in the following section.

7.2 Electricity storage via electrolysis of water

The Scottish Port of Cromarty Firth is in the process of setting up agreements with the company Gen2 Energy of Norway to develop a project that will eventually lead to import of renewable electricity generated hydrogen into the UK. Figure 15 shows the schematic for hydrogen production and transmission.

The plans include setting up of an industrial scale electrolyser. The time scales demand that clean energy will be available by the year 2023. This will be demonstration of a large-scale, international project that will include the production, storage and supply of green hydrogen to Scotland, the rest of Great Britain and Europe. The plans include shipment of hydrogen by land and sea. Note that the thinly populated northern regions of Norway have an excess of renewable energy and present constraints on introducing that energy in the electricity network and thus the production and shipment of hydrogen presents a unique opportunity [24].

8 DISCUSSION

In Section 5, an initial analysis of the energy conversion performance of the 330-kW wind turbine and 50-kW solar PV facility on Cononsyth farm was presented. In this section further discussion is provided with the five research questions that were raised in Section 4 addressed expressly.

Tables 8 and 9 respectively presented data on annual and monthly wind speed, average power and capacity factor. Inter-annually, the wind speed is fairly consistent, varying between 6.3 and 7 m/s. The average and standard deviation of wind speed are 6.7 and 0.3 m/s, respectively. The average power delivered from the 330-kW machine varies between 82 and 118 kW. The corresponding capacity factor varies from 0.25 to 0.36 with mean and standard deviation of 0.33 and 0.03. Note that the ratio of standard deviation to mean is 10% on an annual basis. On the other hand, on a monthly basis, obviously, the variations are much more pronounced with a low capacity factor of 0.19 in September that rises to a high value of 0.63 in January, with a mean of 0.36 and standard deviation of 0.14 for the 12-month data. That is a reflection of the associated wind speeds in those months—5.2 m/s in September and 10 m/s in January.

The installed cost for the 330 kW Enercon wind turbine was £850 000. Reference [41] cites the life of modern wind turbines as 20–30 years. Assuming a 25-year life of the machine and referring to Table 8 for the energy delivery profile the monetary cost of the wind generated electricity works out as 3.56 UK pence/kWh or 4.03 US cents/kWh. The latter figure compares well with data provided in Table 1, which quote the cost of wind energy conversion as 4.1 US cents/kWh. The embodied EPBT for the wind turbine under discussion has been shown to be 3.1% of the lifetime (see Section 6).

Likewise, Tables 10 and 11 presented data for solar PV. On an annual basis the capacity factor has a range of 0.09–0.108, a mean value of 0.1 and standard deviation of 0.01. On a monthly basis, however, the variations for solar are much, much higher as would be expected for such a high latitude location as Arbroath—the capacity factor varying 0.01–0.18, a mean of 0.109 and a standard deviation of 0.063 for the 12-month data. The coefficient of variation (ratio of a standard deviation to mean) is now 58%. The corresponding figure for wind was 0.4, which indicates a much more stable resource.

Table 12 presented results for a hypothetical farm, which has the same 330-kW wind machine but with a much more enhanced solar PV facility of 1-MW capacity. In this case, the combined resource has a much more stable energy delivery with the coefficient of variation being only 20%. That is because of the complimentary nature of wind and solar—the former being a strong and stable resource in the winter months and vice-versa for solar. The latter is the case particularly at high latitudes with a large swing of availability of wind and solar throughout the year.

The actual installed cost quote that was received by the farm owners is £0.812 per watt. At the present conversion rate that is US$1.13 per watt. For the energy delivery profile shown in Table 10 and assuming a 20-year life of the PV installation, that works out at 4.54 UK-pence/kWh or 5.13 US-cents/kWh. That figure also compares well with data of Table 1, which showed a PV-generated electricity price of 4 US-cents/kWh. The embodied energy payback time for PV under Scottish climate was shown to be 8 years, which also has good agreement with reference [30].

In Section 7 two different technologies were presented for electricity storage that has to come into play given the intermittent nature of solar and wind resource. In view of the steep rise of EV sales and increasing amount of research being carried out on behalf of large corporations and governments on hydrogen generation and storage, the long-term prospects of electricity storage are indeed favorable.

9 CONCLUSION

CF is located near Arbroath in Scotland. In the years 2011/2012, the farm installed 50-kWp capacity of solar PV and a wind turbine of 300-kW capacity. Energy generation data were collected respectively at a frequency of 15- and 10-minute intervals. The following conclusions are drawn from the analysis of per 7 years of data.

The annual capacity factor for solar PV and wind energy conversion were in the range of 0.09–0.108, a mean value of 0.1 and standard deviation of 0.01 for solar PV and 0.25–0.36 with mean and standard deviation of 0.33 and 0.03 for wind. The monthly capacity factor for solar varies widely between 0.01 and 0.18. For wind the range of monthly capacity, factor was 0.19–0.63. It was found that the solar and wind resource in Scotland are advantageously complimentary with the output of the combined solar/wind plant having only a third of the coefficient of variation compared to solar or half of that for wind. The abovementioned wide variations in the monthly capacity factor are primarily due to the high latitude of Scottish locations.

A monetary energy and embodied carbon-related assessment was also carried out. It was found that the per kilowatt-hour cost of electricity from solar and wind were, respectively, 5.13 and 4.03 US cents. The payback time for wind turbine was found to be 3.1% of the lifetime of the machine or, in other words, 9.3 months. For solar PV the figure quoted was 8 years payback time.

Renewable energy plants will need to overcome the intermittency related issues to become truly popular and useful. A great deal of work is on-going with respect to battery and other forms of energy storage. A review of that work was presented and critically discussed.

9.1 Biographies of authors

Professor Tariq Muneer is a senior academic who is based at Edinburgh Napier University in Scotland. Professor Muneer has also been employed both by the government and industry as a consultant on a large number of engineering projects. Professor Muneer has been awarded several prestigious awards including the Royal Academy of Engineering Industrial Fellowship (2000–2002), the Royal Academy of Engineering Engineers Secondment Overseas (1995), the Leverhulme Trust (1989) and the University College, Oxford/General Electric Company, (1989) Research Fellowships. He is also the recipient of the Osmania University's Karamat Jung Gold Medal (1974), CIBSE Carter Bronze Medal (1990), CIBSE Napier Shaw Bronze Medal (1999), Millennium Commission's Fellowship Award (1999), Walsh-Weston (Society of Light & Lighting, London) Award (2002), Services to Industry Group's Proof of Concept award (2003) and the Scottish Green Energy, Highly Recommended Best Renewable Award (2006).

Professor Muneer is the author of 10 books and over 280 articles that have attracted over 4000 citations. He is also an editorial board member of the following three journals:

'Energies', published by the Swiss-based MDPI publishing house.

Sustainable Cities and Society, published by Elsevier.

Advisory Board Member: International Journal of Synergy in Engineering and Technology (IJSET).

Professor Muneer has also served as guest editor for the following three special issues of 'Energies' journal.

1. Recent Advances in Sustainable Buildings: Space Heating, Space Cooling and Lighting https://www.mdpi.com/journal/energies/special_issues/recent_advances_in_sustainable_buildings
2. Practice and Innovations in Sustainable Transport https://www.mdpi.com/journal/energies/special_issues/practice_and_innovations_in_sustainable_transport
3. Development of Sustainable Energy: Generation Technologies and Concepts https://www.mdpi.com/journal/energies/special_issues/generation_technologies_and_concepts

Professor Muneer is a visiting professor at the University of Granada, Granada, Spain and University of Maribor, Celje campus, Slovenia (2013–2023).

Rory Dowell has a Bachelor of Engineering degree in Energy and Environmental Engineering (Honors) from Edinburgh Napier University and a Masters of Sciences degree in Management from the University of Edinburgh. Rory is an energy consultant for a renewable consultancy in Edinburgh. Rory also works on renewable investment, engineering activities and project management. Rory has a strong interest and understanding of rapidly emerging renewable markets within the agriculture communities of Scotland and has spoken about his experiences at numerous events.

10 Author Contributions

Conceptualization, RD and TM; methodology, TM and RD; software, TM and RD; formal analysis, TM and RD; investigation, RD and TM; writing review and editing, TM and RD; supervision, TM.

REFERENCES

[1] 2008. *World Encyclopedia*2nd edn. Hampshire, UK: Geocenter International Limited, Basingstoke.

[2] Energysage. *The History of Solar Energy*. https://news.energysage.com/the-history-and-invention-of-solar-panel-technology/ (18 October 2021, date last accessed).

[3] Cuff D, Goudie A. 2009. *The Oxford companion to global change*. USA: Oxford University Press.

[4] Climate.gov. *Climate Change: Atmospheric Carbon Dioxide*. https://www.climate.gov/news-features/understanding-climate/climate-change-atmospheric-carbon-dioxide (18 October 2021, date last accessed).

[5] Scripps Institution of Oceanography/NOAA Global Monitoring Laboratory. June 2020.

[6] Climate.gov. www.climate.gov (18 October 2021, date last accessed).

[7] Asif M, Muneer T. Energy supply, its demands and security issues for developed and emerging economies. *Renew Sust Energ Rev* 2007;**11**:1388–413.

[8] Ramez Naam. Solar's Future is Insanely Cheap (2020). https://rameznaam.com/2020/05/14/solars-future-is-insanely-cheap-2020/ (18 October 2021, date last accessed).

[9] data.gov.uk. Solar photovoltaics deployment statistics. https://data.gov.uk/dataset/9238d05e-b9fe-4745-8380-f8af8dd149d1/solar-photovoltaics-deployment-statistucs (18 October 2021, date last accessed).

[10] Wikipedia. Wind Power in the United Kingdom. https://en.wikipedia.org/wiki/Wind_power_in_the_United_Kingdom (18 October 2021, date last accessed).

[11] Financial Times. Wind power has capacity to meet world's entire electricity demands. https://www.ft.com/content/7c36dd38-f69b-11e9-a79c-bc9acae3b654 (18 October 2021, date last accessed).

[12] Tim Clark. Government green lights 6GW of renewable energy schemes. https://www.newcivilengineer.com/latest/government-green-lights-6gw-renewable-energy-schemes-23-09-2019/ (18 October 2021, date last accessed).

[13] en:former. Offshore wind – the Made in Britain challenge. https://www.en-former.com/en/offshore-wind-the-made-in-britain-challenge/ (18 October 2021, date last accessed).

[14] statista. Cumulative installed solar PV capacity worldwide from 2000 to 2020. https://www.statista.com/statistics/280220/global-cumulative-installed-solar-pv-capacity/ (18 October 2021, date last accessed).

[15] Global Wind Energy Council. *Global Wind Report 2021*. https://gwec.net/global-wind-report-2021/ (18 October 2021, date last accessed).

[16] en:former. Why electricity from wind and solar is becoming ever cheaper. https://www.en-former.com/en/why-electricity-from-wind-and-solar-is-becoming-ever-cheaper/ (18 October 2021, date last accessed).

[17] Word Population Review. *2021 World Population by Country*. https://worldpopulationreview.com/countries (18 October 2021, date last accessed).

[18] Office for National Statistics. https://www.ons.gov.uk/ (18 October 2021, date last accessed).

[19] Orsted. Offshore wind cable contract sparks investment in Wrexham. https://orsted.co.uk/media/newsroom/news/2018/08/offshore-wind-cable-contract-sparks-investment-in-wrexham (18 October 2021, date last accessed).

[20] PV Magazine. Module Price Index – PV Magazine International. https://www.pv-magazine.com/2021/12/29/pv-module-price-index-the-price-spiral-winds-up/ (18 October 2021, date last accessed).

[21] International Renewable Energy Agency. *Solar Power*. https://www.irena.org/solar (18 October 2021, date last accessed).

[22] IRENA, 2020, Renewable Power Generation Costs in 2019, International Renewable Energy Agency, Abu Dhabi.

[23] Reuters Events. Offshore wind opex set to fall 40% by 2030 as suppliers dig deep. https://www.reutersevents.com/renewables/wind-energy-update/offshore-wind-opex-set-fall-40-2030-suppliers-dig-deep.

[24] Muneer T, Younes S, Lambert N *et al.* Life cycle assessment of a medium-sized photovoltaic facility at a high latitude location. *Proc Inst Mech Eng A J Power Energy* 2006;**220**:517–24.

[25] Kato K, Murato A, Sakuta K. An evaluation on the life cycle of photovoltaic energy systems considering production energy of off-grade silicon. *Sol Energy Mater Sol Cells* 1997;**47**:95–100.

[26] Jungbluth N. Life cycle assessment for crystalline photovoltaics in the Swiss eco-invent database. *Prog Photovolt* 2004;**13**:429–46.

[27] Jungbluth N, Bauer C, Dons R *et al.* Life cycle assessment for emerging technologies: case studies for photovoltaic and wind power. *Int J Life Cycle Assess* 2005;**10**:24–34.

[28] Kannan R, Leong KC, Osman R *et al.* Life cycle assessment study of solar PV systems: an example of a 2.7 kWp distributed solar PV system in Singapore. 2006. *Sol Energy*, volume 80, 5, 555-63.

[29] Kim J, Lee J, Kim K *et al.* Evaluation of the environmental performance of sc-Si and mc-Si PV systems in Korea. *Sol Energy* 2014;**99**:100–14.

[30] Ludina N, Mustafaa N, Hanafiahb M *et al.* Prospects of life cycle assessment of renewable energy from solar photovoltaic technologies: a review. *Renew Sust Energ Rev* 2018;**96**:11–28.

[31] Lenzen M, Munksgaard J. Energy and CO2 life cycle analyses of wind turbines – review and applications. *Renew Energy* 2002;**26**:339–62.

[32] Krohn S. 1997. The energy balance of modern wind trubines. In *Wind Power Note 16*. Copenhagen: Danish Wind Turbine Manufacturers Association.

[33] Gurzenich D, Mathur J, Bansal NK *et al.* Cumulative energy demand for selected renewable energy technologies. *Int J Life Cycle Assess* 1999;**4**:143–9.

[34] Schleisner L. Life cycle assessment of a wind farm and related externalities. *Renew Energy* 2000;**20**:279–88.

[35] Ancona D, McVeigh J. 2001. *Wind turbine – materials and manufacturing fact sheet*. US DoE: Princeton Energy Resources International for the Office of Industrial Technologies.

[36] Wibberley L, Nunn J, Cottrell A *et al.* LCA of steel and electricity production. Report no. B13. *BHP Research* 2001.

[37] Vestas Wind Systems, Life cycle assessment of offshore and onshore sited wind power plants based on Vetas V90-3.0MW Turbines report, Denmark, July 2006.

[38] Pick E, Wagner HJ. 2002. Cumulative energy demand (CED) and energy yield ratio for wind energy converters. In *Proc. of the World Renewable Energy Congress, VII* Wagner, H-J and Pick E, 2004, Energy yield ratio and cumulative energy demand for wind energy converters, Energy 2004;**29**:2289–95.

[39] Tremeac B, Meunier F. Life cycle analysis of 4.5MW and 250W wind turbines. *Renew Sust Energ Rev* 2009;**13**:2104–10.

[40] Crawford RH. Life cycle energy and greenhouse emissions analysis of wind turbines and the effect of size on energy yield. *Renew Sust Energ Rev* 2009;**13**:2653–60.

[41] Smoucha EA, Fitzpatrick K, Buckingham S *et al.* Life cycle analysis of the embodied carbon emissions from 14 wind turbines with rated powers between 50kW and 3.4MW. *J Fundam Renew Energy Appl* 2016;**6**:1–10.