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Preliminary assessment of the solar resource in United Kingdom

Abstract

Solar radiation resources data are the foundation of knowledge for programs of large-scale deployment of solar energy technologies. This paper summarizes the analysis of a new weather stations network in United Kingdom. The analysis used 3 years (January 2015 – December 2017) of data from 27 weather stations distributed across the country. The data comprises the Global Horizontal Irradiance (GHI), Diffuse Horizontal Irradiance (DHI), Direct Normal Irradiance (DNI), and the ambient temperature. Network design, implementation, and data quality assurance are described to document the network extent and quality. From all observed datasets, it was found that Plymouth city (located in southwest England) has the dominant GHI, and ambient temperature among all other 26 locations. The least GHI is observed for Aberdeen city (located in northeast Scotland) estimated at 77.3 kWh/m^2. The least average ambient temperature is equal to 9.1 ^{0}C, this data was detected by the weather station located in the capital of Scotland (Edinburgh city). Although continued measurements are needed to understand the interannual resource variability, the current study should have significant applications for preliminary technology selection, power plant modeling, and resource forecasting.

Key words: Solar resources; GHI; Ambient Temperature; United Kingdom.

1. Introduction

The United Kingdom estimates the country will need enormous energy assets in the coming decades for electricity generation, desalination, and process heat to meet the needs of a rapidly growing population and economy [1]. In order to use petroleum for higher value purposes and export, the United Kingdom is planning a sustainable energy mix that includes renewable energy based on local resources. Based on an expected large solar resource, solar energy has long been considered promising in the United Kingdom [2].

The department of energy & climate change in the United Kingdom is leading the renewable energy resource monitoring and mapping across the country [3], thus support of large increases to the country solar generation capacity, moving toward a sustainable energy technologies. As of February 2018 reports, the total installed capacity of solar photovoltaic in United kingdom reached 12,713 MW across 942,247 installations [4].

Whether globally, regionally, or locally in United Kingdom, successful solar technology development and power project applications relies, in part, upon understanding the available solar resource and its spatial, temporal, and spectral characteristics. For project deployment, characterization of the solar resource drives technology selection and project design, and characterizes the leading source of uncertainty in power project output estimates with implications for financing terms and returns on investments [5]. Thus, accurate measurements of the solar resource, along with environmental parameters such as ambient air temperature and dust levels, are critical to project arrangement. Furthermore, best practices in solar resource measurement are well-established, such as those documented by National Renewable Energy Laboratory (NREL) [6].

Various studies have already investigated the solar resources in various regions across the globe [7 - 12]. The assessment for the solar radiation resources in Saudi Arabia is presented by E. Zell et al. [7]. The valuation is based on the datasets collected from 30 stations distributed among the Saudi Arabia. The methodology is based on the analysis of the Global Horizontal Irradiance (GHI), Diffuse Horizontal Irradiance (DHI), Direct Normal Irradiance (DNI), and related meteorological parameters such as wind speed, and daily average temperature.

Furthermore, a feasibility study of solar energy in South Korea is presented by O. Nematollahi [8]. The solar assessment is based on the maximum, minimum, and average values of yearly horizontal radiation collected from 24 stations for a five-year period. Monthly and annual clearness indices for these stations were also calculated.

I.H. Rosma et al. [9] presented the development of an automatic solar station to measure the potential of solar energy resource in the unique tropical region like Pekanbaru City, Indonesia. Whereas, E. Abyad et al. [10] presented a unique models to estimate solar direct normal irradiance. The evaluation process were possible by comparing various dataset from different regions such as Boulder, USA.

Other advanced solar radiation forecasting widely presented in the literature. However, most recently, in 2018, S. Sun et al. [11] presented a decomposition-clustering-ensemble (DCE) learning approach for solar radiation forecasting. Authors verified the performance of the proposed DCE learning approach for a solar radiation datasets in Beijing, Chine. The results of the solar radiation forecasting show that the DCE learning approach produces smaller mean absolute percentage error (MAPE) rate of 2.83%.

Another interesting solar forecasting is proposed by A. Rohani et al. [12]. This model is based on a Gaussian process regression with k-fold across validation process, the biggest advantage of the proposed technique that it can be used with small data size. The model has been tested in Mashhad city, Iran, and the MAPE is equal to 1.97%.

In the United Kingdom, there is still a lack of assessment for already existing weather stations, and solar radiation methods. Previous work such as [13-15] evaluated the solar resources across the UK, But still, the solar irradiance and temperature assessment is based on small scale studied datasets, yet more, the assessment is based on a historical data set over short period of time (one year as a maximum). Additionally, the analysis of the solar radiation is usually taken from the solar irradiance data presented in Fig. 1.

In order to overcome this gap of knowledge found in the literature. We have established a data analysis tool to examine the behavior of various weather stations installed in different locations across the UK. Therefore, this paper summarizes the analysis of a new weather stations network, the analysis used 3 years (January 2015 – December 2017) of data from 27 weather stations distributed across the country. The data comprises the Global Horizontal Irradiance (GHI), Diffuse Horizontal Irradiance (DHI), Direct Normal Irradiance (DNI), and the ambient temperature. Network design, implementation, and data quality assurance are described to document the network extent and quality.

Additionally, the current study should have significant applications for preliminary technology selection, power plant modeling, and resource forecasting, not only in the region of UK, but internationally.

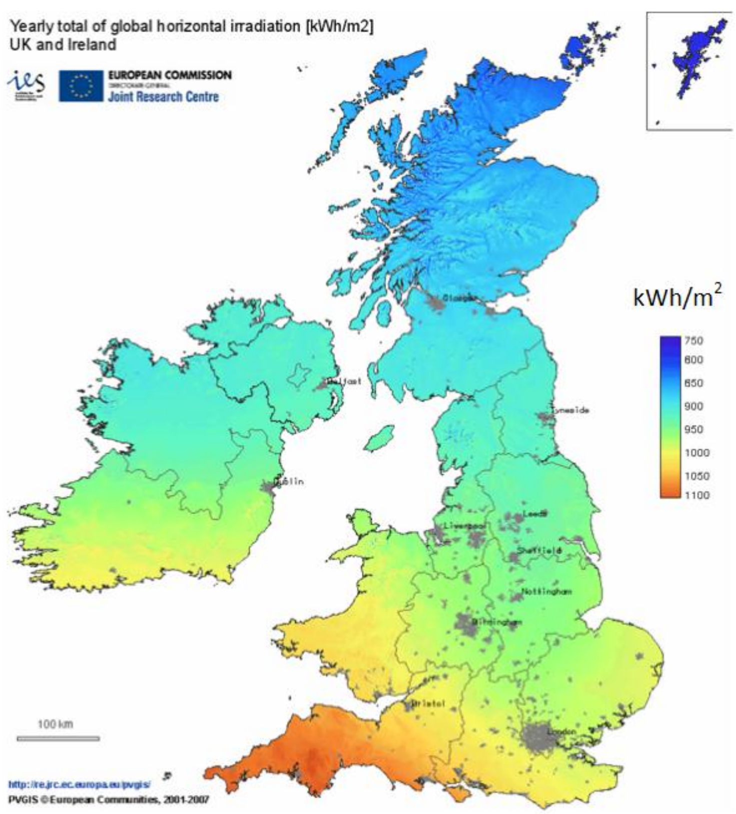


Fig. 1. Yearly total GHI in the United Kingdom – the map is taken from the European Commission Joint Research Center [16]

2. Data Gathering and Analysis Methods

The data used in this paper is based on three years of solar resource measurements (Global Horizontal Irradiance [GHI], Diffuse Horizontal Irradiance [DHI], and Direct Normal Irradiance [DNI]) and the average ambient temperature. The atmospheric data is collected by a subset of the weather stations distributed across the United Kingdom, since this is a modern network of weather stations, this section briefly describes the network instrumentation and design, along with the data collection process.

2.1 Weather Stations Network and Instrumentation

Multiple needs for accurate ground-based measurements of solar radiation and atmospheric parameters shaped the basis for the network architecture, to achieve the following objectives:

- Support the growth of analysis tools for evaluating and predicting solar resource levels and technology presentation characteristics
- Support instant prospecting by potential solar resource power project designers
- Support atmospheric studies into unique climate characteristics of the United Kingdom

Solar radiation can be transmitted, absorbed, or scattered by an intervening medium in fluctuating amount depending on the wavelength over the approximate range of 300 up to 3000 nm. The interactions of the Earth's atmosphere with inward solar radiation result in three fundamental components of interest to solar energy conversion technologies [17], these components can be illustrated as follows:

1. <u>Direct normal irradiance (DNI):</u> the direct radiation available from a 5° field of view across the solar disk on a surface oriented normal to the sun's position in the sky. Measurements of DNI are made with a Pyrheliometer mounted in a solar tracker. This solar component is of particular interest to concentrating solar technologies such as concentrating PV systems [18] and concentrating solar power [19].
2. <u>Diffuse horizontal irradiance (DHI):</u> the scattered solar radiation from the sky dome except from the solar disk (i.e., not including DNI) on a horizontal surface. Measurements of DHI are made with a shaded pyranometer [20]. Levels of DHI are generally lower under clear sky conditions than under cloudy sky conditions. DHI data are helpful for assessing the Plane-of-Array (POA) irradiance [21-22], and daylighting architectural design applications.
3. <u>Global horizontal irradiance (GHI):</u> total hemispheric or geometric sum of the DNI and DHI components available on a horizontal surface. GHI measurements are made with an unshaded pyranometer. GHI data represent the amount of solar radiation incident on horizontal flat plate solar collectors, and can be used to estimate the solar radiation on tilted flat plate collectors [23-24].

A total of 27 weather stations are in operation in the studied areas. The list of the stations and their locations are listed in Table 1. In this work, the locations have been studied in different parts of the United Kingdom, we have examined 15 weather stations in England, 2 weather stations in Wales, 3 weather stations in Scotland, and 7 weather stations in Ireland. The overall distribution of the weather stations shown in Fig. 2.

Table 1 Details on weather stations used in various locations

Site Location	Site Number	Site Name	Latitude	Longitude	Elevation
England	1	Plymouth	50.371	-4.143	17
	2	Exeter	50.726	-3.527	49
	3	Bristol	51.454	-2.597	15
	4	Oxford	51.752	-1.258	70
	5	London	51.507	-0.128	19
	6	Cambridge	52.203	0.125	20
	7	Norwich	52.629	1.292	26
	8	Nottingham	52.953	-1.149	45
	9	Liverpool	53.405	-2.981	41
	10	Manchester	53.479	-2.244	55
	11	Huddersfield	53.647	-1.782	93
	12	Hull	53.744	-0.339	9
	13	York	53.959	-1.082	21
	14	Sunderland	54.906	-1.375	28
	15	Whitehaven	54.547	-3.589	9
Wales	16	Cardiff	51.482	-3.179	17
	17	Aberystwyth	52.414	-4.082	6
Scotland	18	Glasgow	55.857	-4.244	29
	19	Edinburgh	55.950	-3.191	72
	20	Aberdeen	57.148	-2.093	53
Ireland	21	Cork	51.898	-8.471	9
	22	Carlow	52.841	-6.926	55
	23	Dublin	53.350	-6.260	13
	24	Galway	53.274	-9.049	14
	25	Athlone	53.425	-7.941	40
	26	Sligo	54.272	-8.475	17
	27	Belfast	54.597	-5.930	15

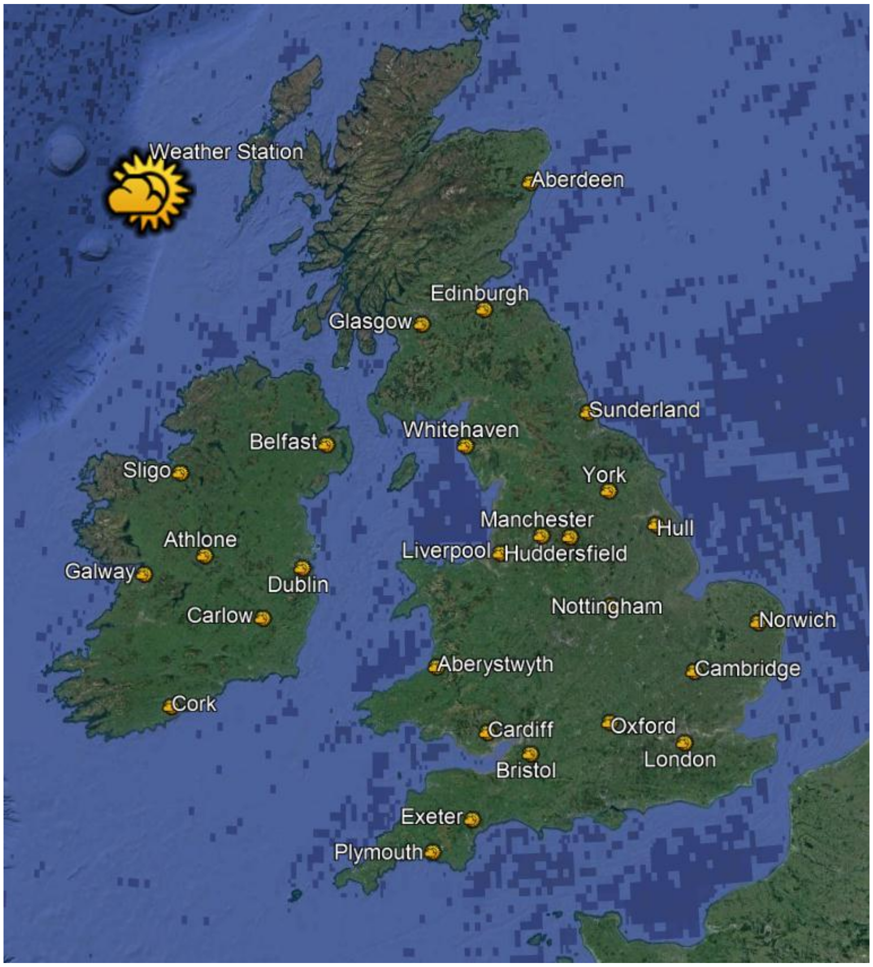


Fig. 2. Distribution of weather stations across the United Kingdom, map is retrieved from Google maps [25]

Each weather station comprises various sensors which measures the following environmental parameters:

i. Wind speed, range: 2 to 150 mile per hour (mph)
ii. Wind direction
iii. Temperature, range: -40 ^{0}C to 65 ^{0}C
iv. Relative humidity, range: 0% to 100%
v. Rainfall in mm or inches
vi. Solar irradiance (DNI, DHI, and GHI), range: 0 W/m^2 to 2000 W/m^2

The weather stations are wirelessly connected to a monitoring unit called Vantage Pro2 which is accessible using an IP address from Huddersfield site. The connection network is shown in Fig. 3(a). As can be seen, there are three main sub-stations which gather the data from different locations, the stations are Dublin, Oxford, and Edinburgh. All data is gathered at Huddersfield site, in which the data collection and the analysis process begins, this procedure is clearly presented in Fig. 3(b).

In fact, a proper operation and maintenance of the used weather stations, along with documentation of these practices, is critical for constructing reliable weather measurements. We have followed a procedure such that cleaning and maintenance are carried out twice weekly for the observed stations as per best practices developed by the U.S. Department of Energy's National Renewable Energy Laboratory [17]. Major tasks during cleaning and maintenance included cleaning all sensors and checking the wireless connections. Instrument calibration is planned to be conducted every three years as per manufacturer recommendations [26]; the instruments will be sent to the manufacturers to perform the calibration. No calibration was required during the three years for this study.

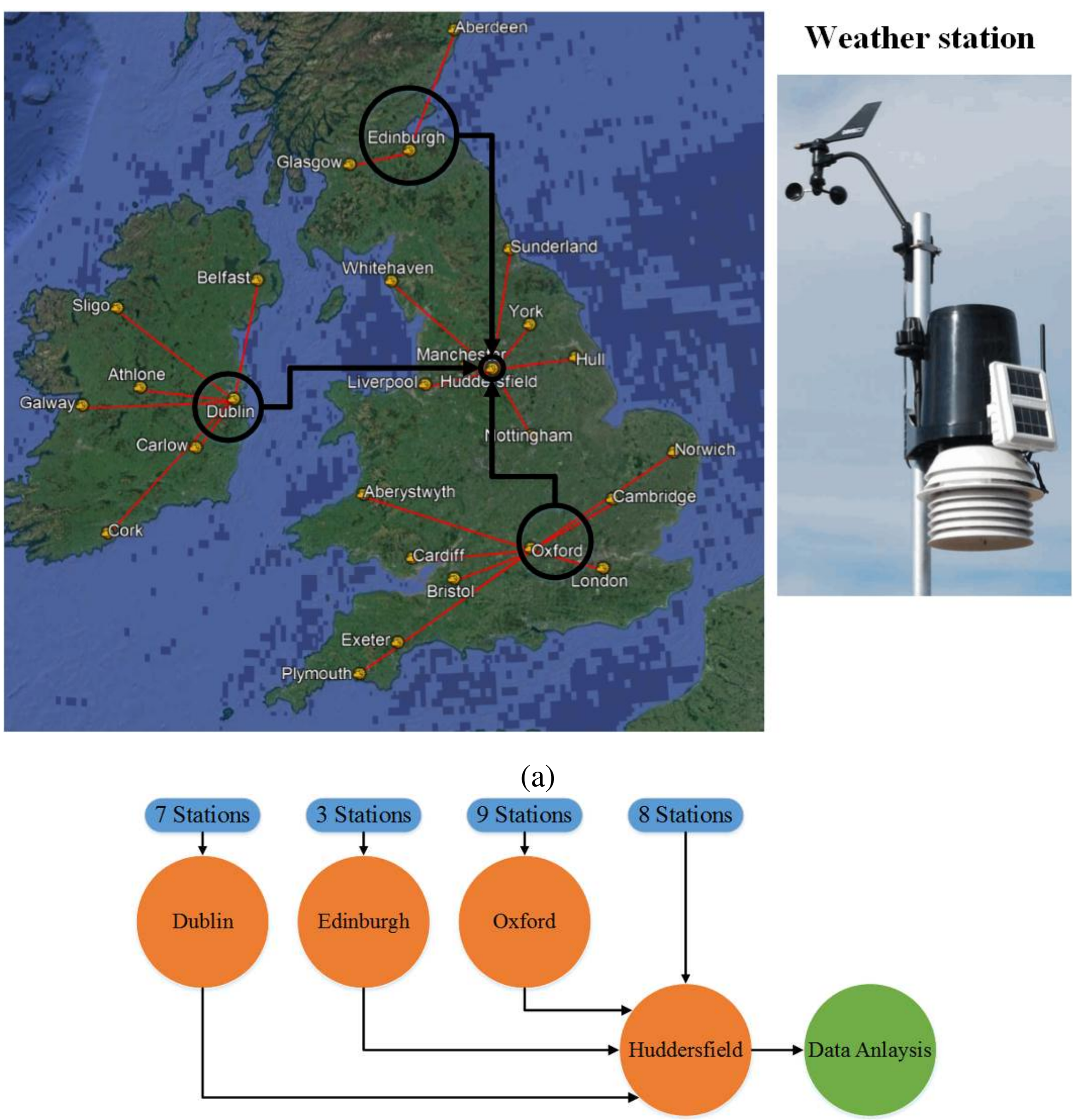


Fig. 3. (a) Connection network from all observed weather stations, (b) Weather stations allocation, where Huddersfield site procedures the analysis of the all measured data

The data gathered at Huddersfield site were analysed to determine trends and patterns by station and region. The yearly average solar radiation (in kWh/m^2) was calculated for GHI, DNI, and DHI, to assess the overall magnitude of the solar resource at each site and within each region, and in order to identify resource variability and temporal patterns.

Furthermore, the average ambient temperature data across all studied location were also examined, and the pattern of the temperature variations (increase or decrease) has been planned.

In this article, the data measurements for all weather stations were analysed, logged, and compared over the period from January 2015 to the end of December 2017 (3 years).

3. Results and Discussion

The analysis includes assessment of the monthly solar irradiation data from all studied weather stations, as well as the ambient temperature measurements.

3.1 Solar Irradiation and Ambient Temperature in England

In this section, the weather stations placed in various locations in England will be compared. As stated earlier in section 2, the data is captured over a period of three years (2015 to 2017). The yearly average GHI, DNI, DHI, and ambient temperature is reported in Tables 2 to 4; Table 2 summaries the measurements in 2015, Table 3 corresponds to data captured in 2016, and finally Table 4 summaries the measurement in 2017.

It is noticeable from Tables 2 to 4, that the maximum observed GHI is at Plymouth city, whereas London is ranked the second. The minimum irradiance level over the studied period (3 years) is observed for Huddersfield town with an average of 84.6 kWh/m^2 yearly. The second minimum GHI is observed by the weather station located in Sunderland city, where the average GHI over the studied period is equal to 85.6 kWh/m^2.

The highest average ambient temperature between 2015 and 2017 among all studied locations in England is obtained at Plymouth city (average temperature 12.2 ^{0}C). The second highest average temperature is found in Liverpool city, with an approximate of 11.7 ^{0}C. However, Sunderland city had the lowest average temperature between 2015 and 2017, with an average ambient temperature of 9.1 ^{0}C.

Table 2 Summary of the average solar irradiance and ambient temperature in England 2015

	Year 2015			
Location	Average GHI (kWh/m^2)	Average DNI (kWh/m^2)	Average DHI (kWh/m^2)	Average Temp. (^0C)
Plymouth	106	114	46	12.5
Exeter	96	87	52	12
Bristol	95	88	49	12
Oxford	92	83	51	10.9
London	98	94	50	11.6
Cambridge	91	84	51	11.4
Norwich	92	88	50	11.4
Nottingham	88	79	50	10.5
Liverpool	95	94	47	11.2
Manchester	85	73	51	10.8
Huddersfield	83	75	48	10.4
Hull	92	93	49	10.5
York	85	78	49	10.2
Sunderland	83	83	46	9.6
Whitehaven	93	94	44	11.2

Table 3 Summary of the average solar irradiance and ambient temperature in England 2016

	Year 2016			
Location	Average GHI (kWh/m^2)	Average DNI (kWh/m^2)	Average DHI (kWh/m^2)	Average Temp. (^0C)
Plymouth	102	106	47	12
Exeter	95	87	52	11.5
Bristol	93	88	49	11.5
Oxford	89	80	51	10.4
London	97	93	49	11.1
Cambridge	90	83	50	10.8
Norwich	93	88	50	10.8
Nottingham	90	82	51	10
Liverpool	96	97	48	10.5
Manchester	87	77	50	10.2
Huddersfield	87	80	49	9.8
Hull	95	99	49	10
York	88	84	50	9.7
Sunderland	88	94	46	8.9
Whitehaven	96	98	45	10.4

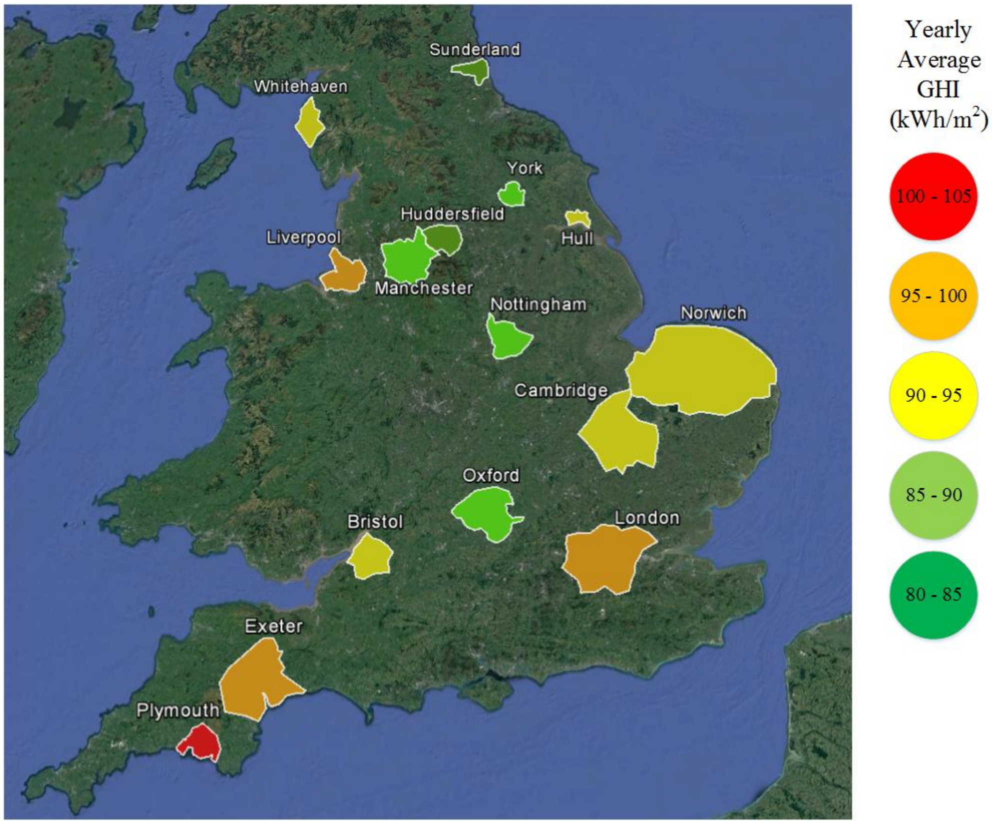
Table 4 Summary of the average solar irradiance and ambient temperature in England 2017

Location	Year 2017			
	Average GHI (kWh/m^2)	Average DNI (kWh/m^2)	Average DHI (kWh/m^2)	Average Temp. (^0C)
Plymouth	101	100	50	12.1
Exeter	95	85	53	11.6
Bristol	91	81	51	11.6
Oxford	89	78	52	10.3
London	95	88	51	10.9
Cambridge	90	82	51	10.7
Norwich	92	85	50	10.8
Nottingham	88	79	50	10
Liverpool	96	97	48	10.6
Manchester	86	76	50	10.3
Huddersfield	84	74	49	9.9
Hull	94	94	49	10
York	87	81	50	9.7
Sunderland	86	86	46	9
Whitehaven	94	94	46	10.8

In northern regions of England, the yearly GHI is relatively low, compared to southern regions. For example, York, Manchester, Huddersfield, and Sunderland have a yearly average GHI below 90 kWh/m^2. However, if we select southern locations such as Plymouth, Exeter, and London, the yearly average GHI is above 95 kWh/m^2. The map in Fig. 4(A) illustrates the geographical distribution of the yearly average GHI in all studied locations in England.

The annual average ambient temperature detected by the weather stations in England is geographically mapped and presented in Fig. 4(b). It is evident that Plymouth city has the maximum yearly average temperature competed to all other locations. In fact, the distribution of the temperature varies in different areas of England, for example, Sunderland city has an yearly average temperature of 9.1^0C, whereas Whitehaven is around 11.2^0C. Both cities are 144 km apart.

In conclusion, this section demonstrated the variations of the GHI, DNI, and DHI in all observed locations. The analysis is based on the GHI data since this parameter is usually used to study the sun irradiance impact on solar panels, solar thermal systems, and it is calculated using the addition of the DNI and DHI with respect to the incident radiation angle. On the other hand, yearly average temperature in England was presented, where a geographical map representation has been drawn to explain the variation of the temperature. It is also worth remembering that all presented data are captured over a period of three years (2015 – 2017).



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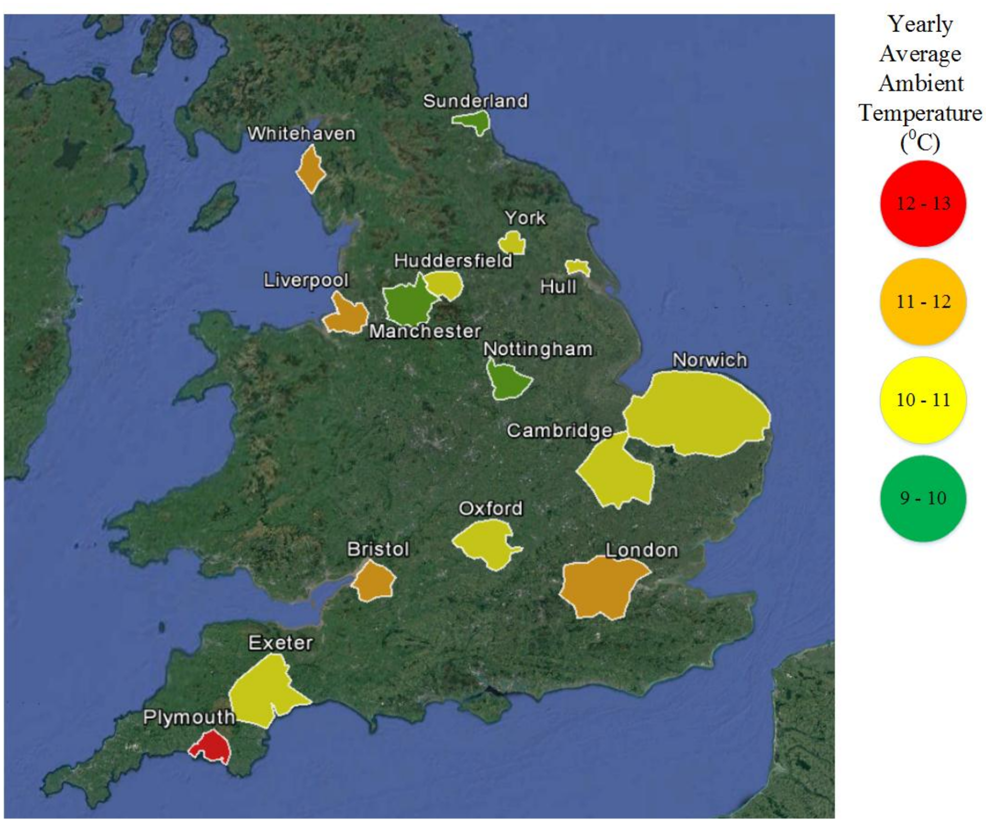


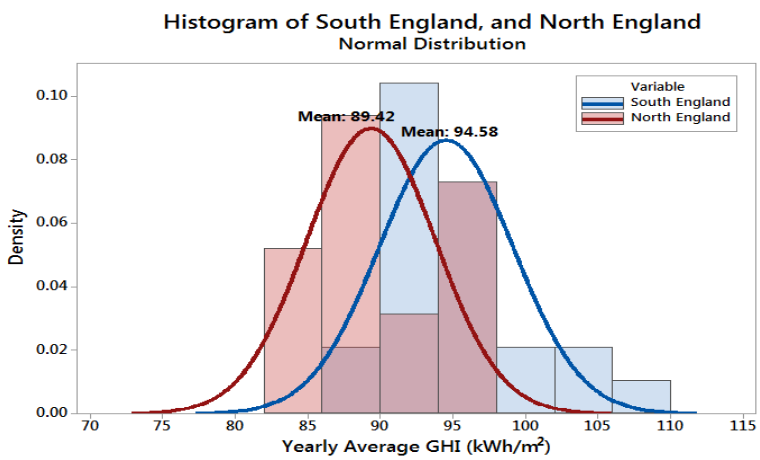
(b)

Fig. 4. (a) Distribution of yearly average GHI for the studied locations in England , (b) Yearly average ambient temperature in 15 different locations in England

As described earlier, north and south England does have variations of the yearly average GHI. It is evident from Fig. 4(a) that southern locations has higher GHI compared to northern locations. In order to explain the variations of the GHI in both northern and southern sites, a histogram including a normal distribution plot is plotted in Fig. 5(a).

It is evident that northern sites have lower yearly average GHI, where its mean is equal to 89.42 kWh/m^2. However, in southern sites the mean of all gathered samples for the yearly average GHI is equal to 94.58 kWh/m^2.

According to Fig. 5(b), south England has higher yearly average temperature compared to north England. As shown by the histogram and the normal distribution plot, the mean of the temperature for all locations in southern England is equal to 11.5 $^{\circ}$C, however, there is a drop by 1.33 $^{\circ}$C for the northern sites.



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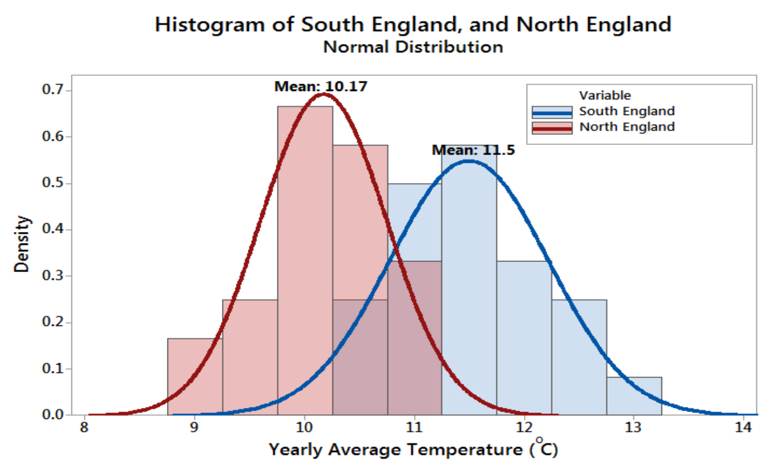


(b)

Fig. 5. Southern and northern England histogram and normal distribution plot. (a) Yearly average GHI, (b) Yearly average Temperature

3.2 Solar Irradiation and Ambient Temperature in Wales

In wales, two weather stations have been examined. The first is located in Cardiff city, whereas the second weather station is placed at Aberystwyth city. The distance between the weather stations is 92.4 km.

Data from both weather stations over a period of three years have been compared. A summary for the yearly average solar irradiance and ambient temperature are reported in Table 5. As can be noticed, Cardiff city has a higher yearly average solar irradiance over the last three years. In addition, the variations of the temperate is comparatively identical.

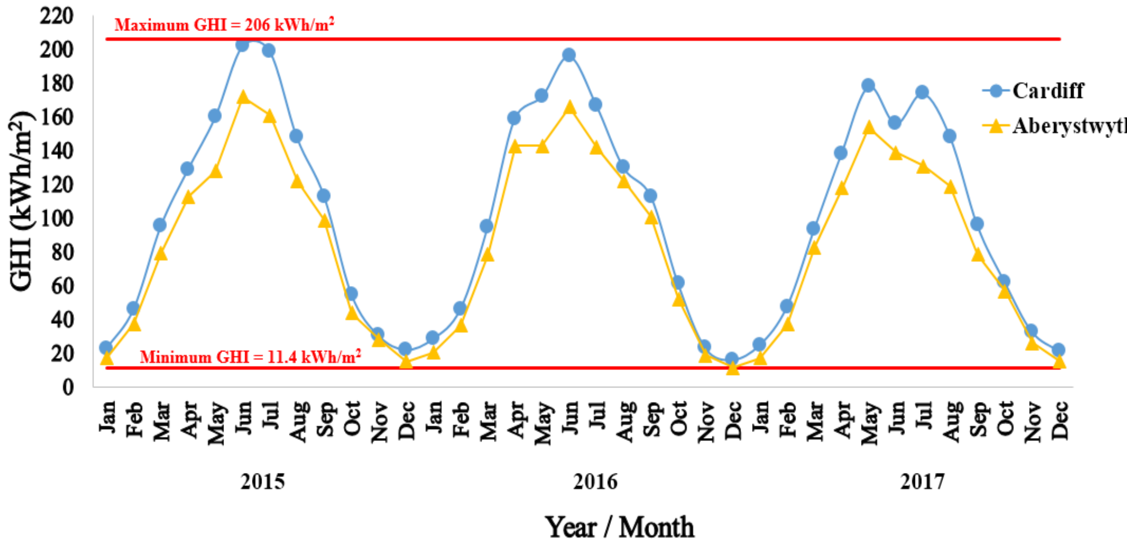
Table 5 Summary of the average solar irradiance and ambient temperature in Wales from 2015 to 2017

Year	Location	Average GHI (kWh/m^2)	Average DNI (kWh/m^2)	Average DHI (kWh/m^2)	Average Temp. (^0C)
2015	Cardiff	102	102	48	12
	Aberystwyth	85	69	49	12
2016	Cardiff	101	101	48	11.5
	Aberystwyth	86	75	48	11.5
2017	Cardiff	98	94	51	11.4
	Aberystwyth	81	63	49	11.6

For a better explanation, the monthly data of both weather stations has been acknowledged. Fig. 6(a) demonstrates the monthly average GHI for both stations. The maximum GHI is obtained for Cardiff city, in June 2015 at 206 kWh/m^2. In addition, the minimum GHI is equal to 11.4 kWh/m^2 detected in Aberystwyth, December 2016.

As show in Fig. 6(b), both locations approximately have the same average ambient temperature over the considered period. The maximum and minimum perceived levels for the average monthly ambient temperature is equal to 18 ^0C and 5.3 ^0C respectively; both levels are detected in Cardiff city in July 2015, and February 2016.

In fact, Cardiff city ranked the second in terms of the yearly average GHI compared to all other observed sites considered in this work (including England, Wales, Scotland, and Ireland), the first site which has the maximum yearly average GHI has been already shown, and discussed in the previous section, Plymouth city. This data will briefly be discussed in section 4.



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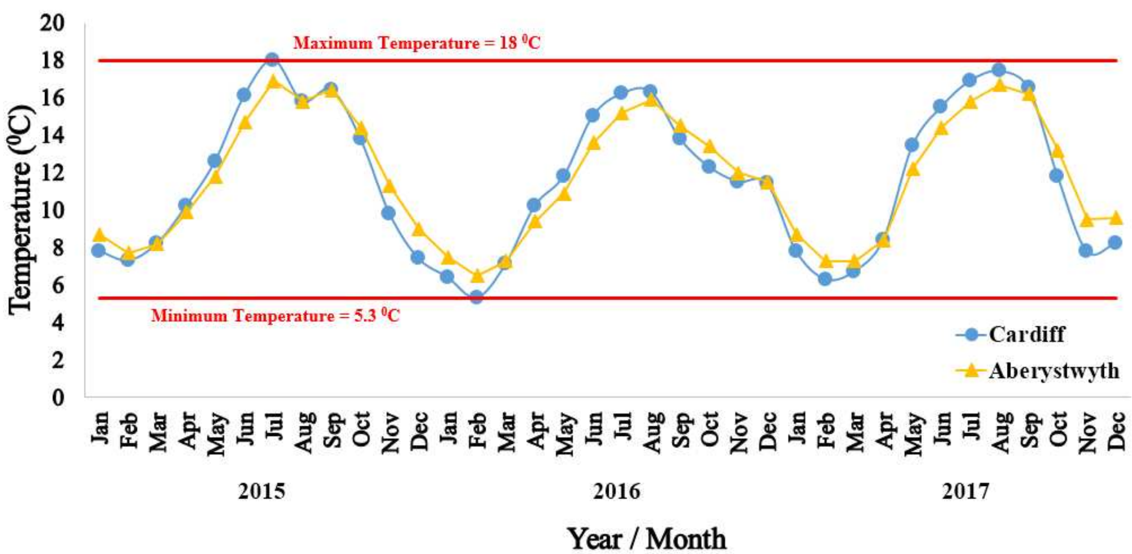


(b)

Fig. 6. (a) Monthly average GHI for both examined locations in Wales, (b) Monthly average ambient temperature

3.3 Solar Irradiation and Ambient Temperature in Scotland

In Scotland (north of the United Kingdom), three weather stations data have been inspected. The first is located in Edinburgh (capital of Scotland), whereas the second and third are located in Glasgow, and Aberdeen city. The distance between the weather stations between Glasgow and Edinburgh is around 70.4 km. However, the distance is much longer between both weather stations fitted in Edinburgh and Aberdeen; estimated distance 154.7 km.

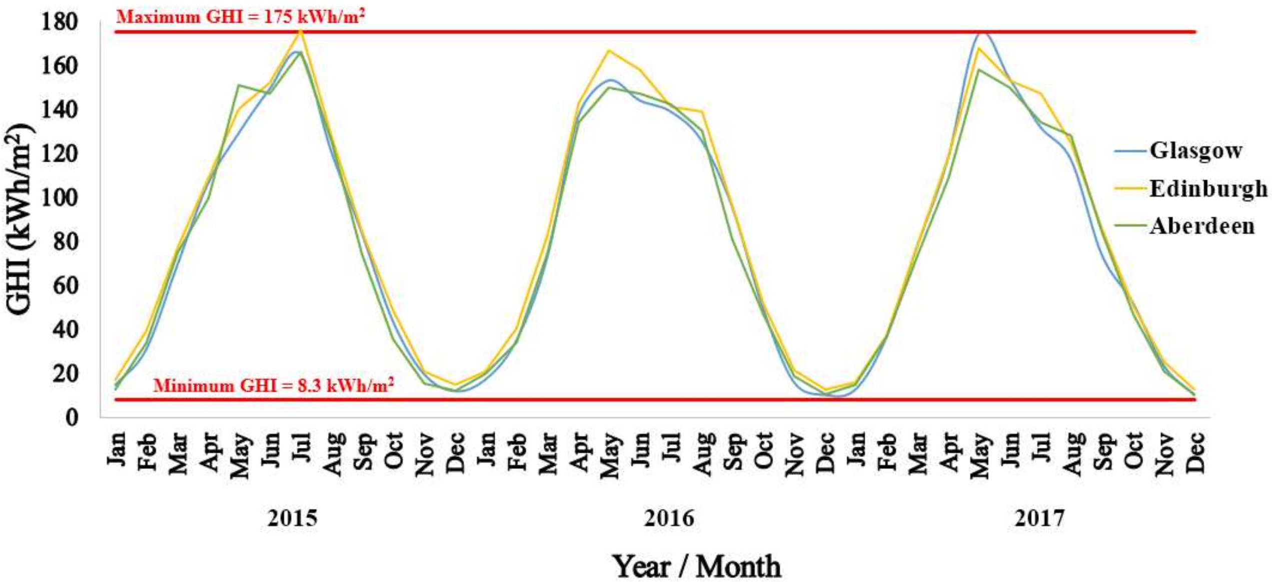
Table 6 summaries the solar irradiance and ambient temperature in the observed locations between 2015 and 2017. It is evident that Edinburgh has the highest yearly average GHI, whereas the second is Glasgow city. For more data remarks, Fig. 7(a) presents the average monthly GHI detected by the weather stations. From the observed data measurements, it was found that over the considered study period, Edinburgh and Glasgow reaches the maximum GHI at 175 (kWh/m^2), this data is presented in Fig. 7(a). Edinburgh weather station detected this data in July 2015, however, the weather station in Glasgow city detected this measurement last year in May 2017.

Table 6 Summary of the average solar irradiance and ambient temperature in Scotland from 2015 to 2017

Year	Location	Average GHI (kWh/m^2)	Average DNI (kWh/m^2)	Average DHI (kWh/m^2)	Average Temp. (^0C)
2015	Glasgow	79	67	48	10.1
	Edinburgh	84	94	48	9.6
	Aberdeen	79	84	44	9.7
2016	Glasgow	83	75	49	9.2
	Edinburgh	89	94	48	8.7
	Aberdeen	82	84	45	9
2017	Glasgow	82	73	49	9.6
	Edinburgh	85	82	48	9
	Aberdeen	71	78	46	9

Approximately all locations have identical average ambient temperature over the considered period. Fig. 7(b) illustrates the yearly average ambient temperature observed by the weather stations, which can be classified as follows (maximum to minimum):

- Aberdeen: 9.6 ^0C
- Glasgow: 9.2 ^0C
- Edinburgh: 9.1 ^0C



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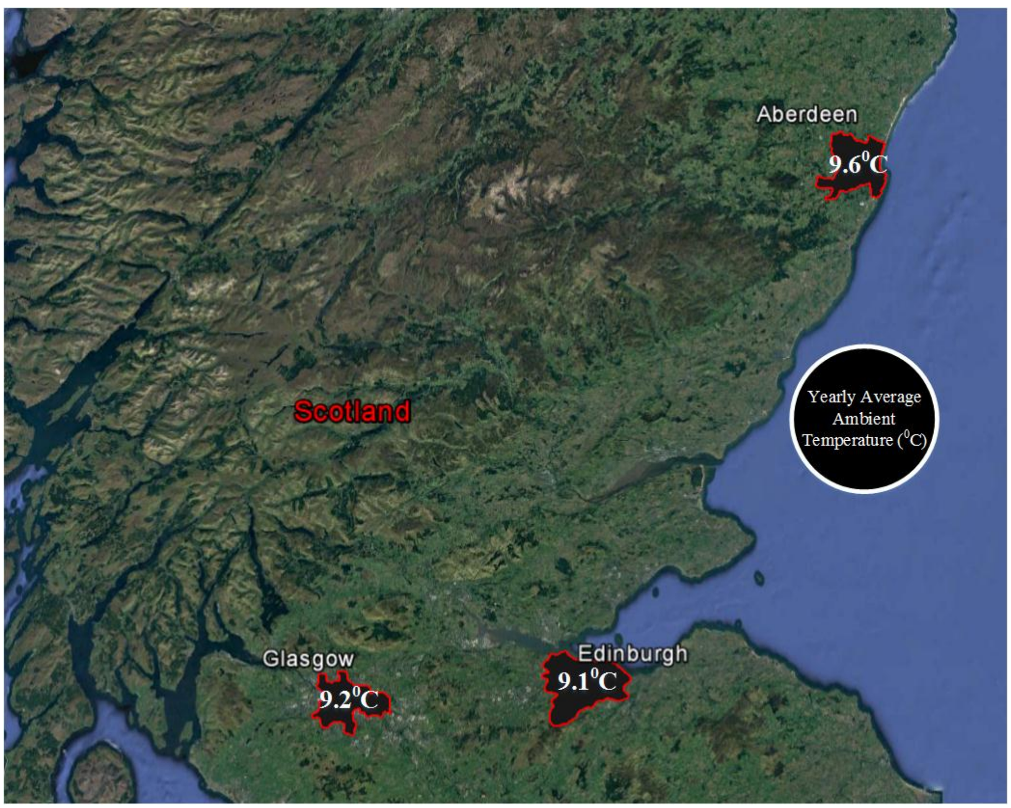


(b)

Fig. 7. (a) Monthly average GHI for three examined locations in Scotland, (b) Yearly average ambient temperature for the examined locations in Scotland

3.4 Solar Irradiation and Ambient Temperature in Ireland

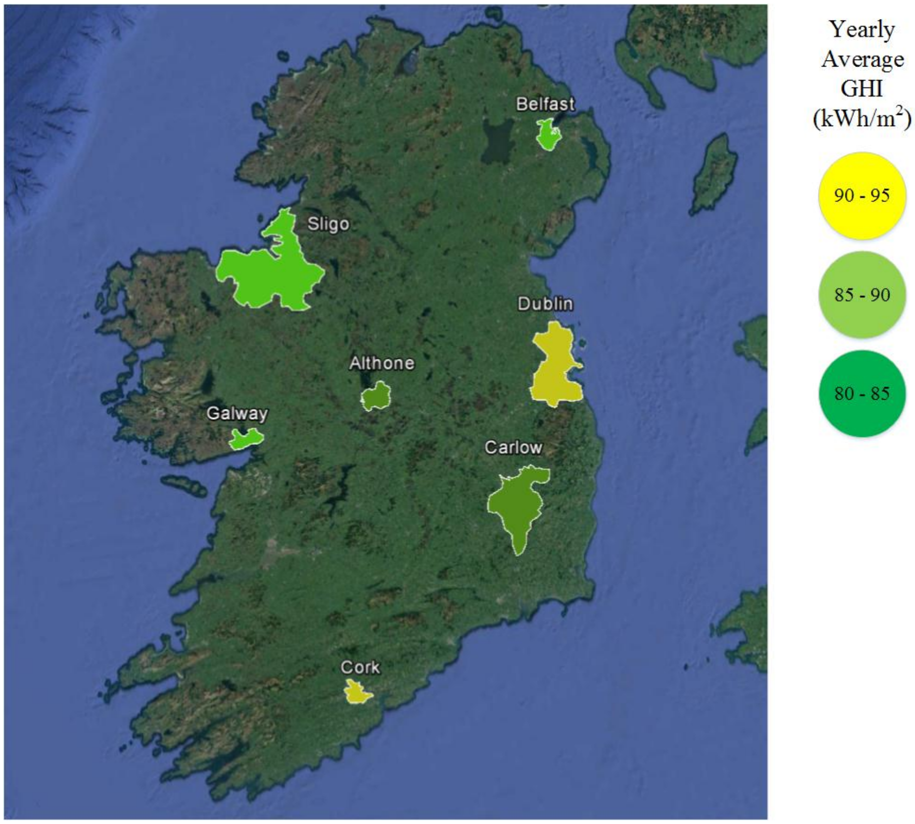
In this section, the weather stations sited in various locations in Ireland will be compared. The yearly average GHI, DNI, DHI, and ambient temperature is illustrated in Table 7 over a period between 2015 and 2017.

From the conducted results, Dublin city had the maximum overall yearly average GHI of about 91.7 kWh/m^2. The second maximum GHI is detected by Cork weather station, 91.3 kWh/m^2. The minimum GHI is observed in Athlone at 84.6 kWh/m^2. The distribution of all locations with the yearly average GHI is geographically mapped and analysed in Fig. 8(a).

On the other hand, Fig. 8(b) demonstrates the yearly average ambient temperature detected by all installed weather stations. Cork city has the extremist ambient temperate across all examined locations, where its annual temperature equals to 11.1 ^{0}C. The lowest annual temperature is detected in Athlone at 9.7 ^{0}C.

Table 7 Summary of the average solar irradiance and ambient temperature in Ireland from 2015 to 2017

Year	Location	Average GHI (kWh/m^2)	Average DNI (kWh/m^2)	Average DHI (kWh/m^2)	Average Temp. (^{0}C)
2015	Cork	93	86	52	11.2
	Carlow	85	72	52	10.7
	Dublin	91	88	49	10.9
	Galway	84	75	49	11
	Athlone	84	73	51	10
	Sligo	84	76	50	10.3
	Belfast	84	72	50	10.8
2016	Cork	93	86	52	11.2
	Carlow	86	72	52	10.2
	Dublin	94	96	49	10.4
	Galway	87	81	49	10.4
	Athlone	87	78	51	9.5
	Sligo	88	83	49	9.6
	Belfast	88	78	51	10.1
2017	Cork	88	77	52	10.9
	Carlow	83	70	52	10.5
	Dublin	90	85	50	10.6
	Galway	85	76	49	10.8
	Athlone	83	72	51	9.7
	Sligo	86	81	50	10
	Belfast	85	73	51	10.5



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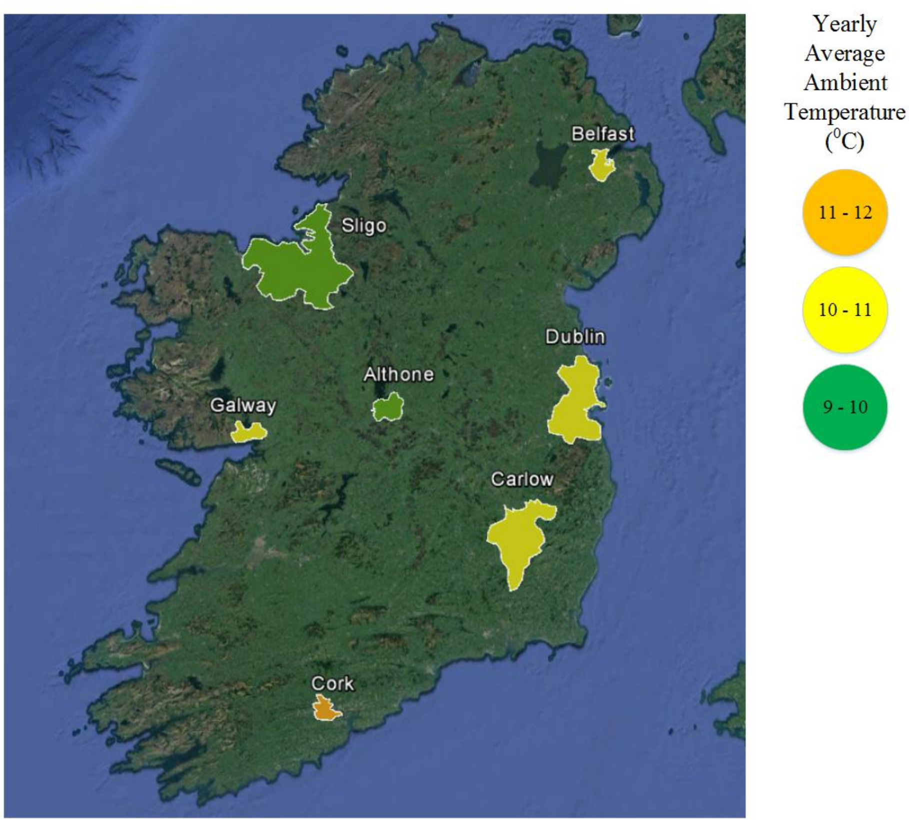

(b)

Fig. 8. (a) Distribution of yearly average GHI for the studied locations in Ireland , (b) Yearly average ambient temperature in 7 different locations in Ireland

4. Evaluating the Observed GHI and Temperature Datasets

In order to draw a relevant assessment for the results discussed earlier in section 3, all studied locations are compared and analysed based on the yearly average GHI and ambient temperature. For data comparison to be valid, the weather stations must have very similar exposure and be carefully set up. The set up criteria used in the developed weather network is similar to the weather stations placed across the country by the UK government, specifically, under evaluation and control by the UK Met Office [27].

The Met Office is the UK national weather service. It is an executive agency and trading fund of the Department of Business, Energy, and Industrial Strategy.

Fig. 9(a) presents a histogram and the normal distribution plot for the GHI in all observed locations. It is found that the yearly average GHI (kWh/m^2) is equal to (from maximum to minimum):

- South England: 95
- Wales: 92
- North England: 89
- Ireland: 87
- Scotland: 82

South England remains the highest GHI while in Scotland it is the lowest. Remarkably, the findings are consistent with the histogram and the normal distribution plot shown in Fig. 9(b), which displays the data taken from the UK government historical monthly GHI for meteorological stations [27]. The maximum difference between the observed data by the weather station network discussed in this article and the data taken form the Met Office is below ± 3 kWh/m^2.

According to the yearly average temperature. Fig. 9(c) shows the distribution of the temperature based on the analysed data previously discussed in section 3, whereas Fig. 9(d) shows the results obtained using the data taken form the Met Office [27]. The difference between the observed data from both resources are illustrated as follows:

- South England: 0.1 ^{o}C
- Wales: 0.2 ^{o}C
- Scotland: 0.1 ^{o}C
- Data for both Ireland and north England are identical

Comparable to the results obtained for the GHI, the yearly average temperature observed in the new weather station network discussed in this article is matching the results observed by the Met Office.

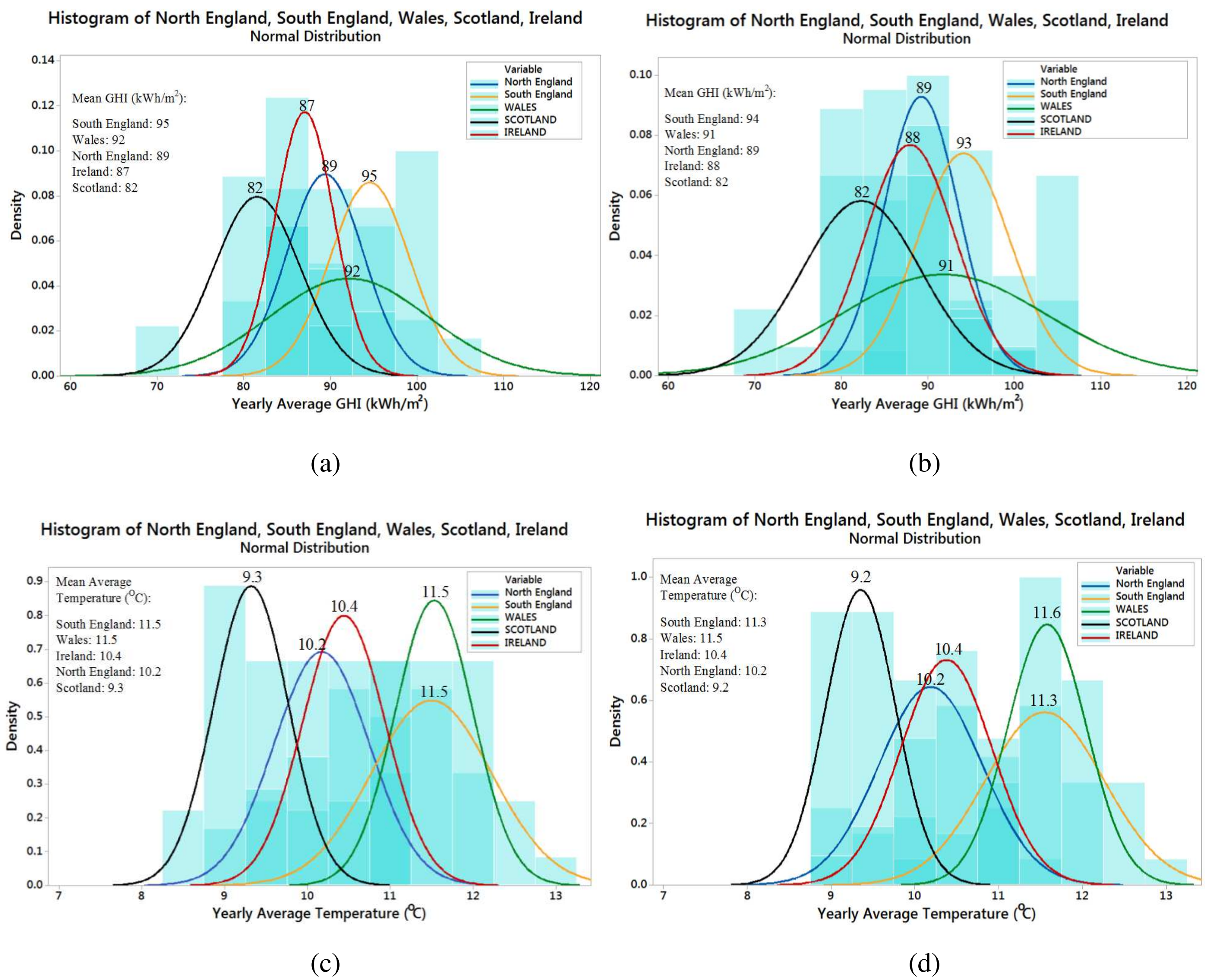

Fig. 9 Histogram and the normal distribution plots for the yearly average GHI and temperature in all studied locations across the UK. (a) GHI plot using the observed data from this article, (b) GHI plot using data taken from the UK Met Office [27], (c) Temperature plot using the observed data from this article, (d) Temperature plot using data taken from the UK Met Office [27]

5. Conclusion

This paper presents a detailed assessment for 27 weather stations installed at different locations in England, Scotland, Ireland, and Wales. This resource monitoring network has been specifically designed to meet the objective of improving available data and models of solar resources in the United Kingdom to support power project developers, researchers, and policy decision makers. To that end, the network has used the latest equipment and protocols for operations and maintenance, and tiered the station capabilities as appropriate to achieve spatial coverage and sufficient maintenance in remote locations.

This paper summarizes the data measurement over three years, specifically January 2015 to the end of December 2017. The data analysis has been carried out at Huddersfield Town site. A detailed assessment for the yearly average global horizontal irradiance (GHI) and ambient temperature is investigated and geographically mapped for each site.

It was found that Plymouth city (located in southwest England) has the dominant GHI, and ambient temperature among all other 26 locations. The least GHI is observed for Aberdeen city (located in northeast Scotland) which is approximately equals to 77.3 kWh/m^2. The least average ambient temperature has been analysed for the capital of Scotland (Edinburgh city), the observed average temperature by the weather station over three years is equal to 9.1 ^{0}C.

All observed data measured in England, Scotland, Ireland, and Wales have been compared to an actual measured data taken from the UK Met Office; the Met Office is the UK national weather service, it is an executive agency and trading fund of the Department of Business, Energy, and Industrial Strategy. After comparing both datasets, evidentially it was found that the maximum difference in the GHI is below ±3 kWh/m^2, whereas the maximum different for the yearly temperature is equal to 0.2 ^{o}C.

The data presented in this work will be very valuable for creating and validating solar resource forecasts to support utility scale plant operation and electric grid integration of solar-based power generation. Also the presented geographical maps could be used to analyse the impact of the irradiance and ambient temperature in each location, thus estimate the annual production of renewable energy resources, specifically Photovoltaic systems.

6. References

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