Front. Energy 2016, 10(4): 375–381
DOI 10.1007/s11708-016-0426-6

RESEARCH ARTICLE

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Distribution and temporal variability of the solar resource at a site in south-east Norway

Abstract Globally, solar energy is expected to play a significant role in the changing face of energy economies in the near future. However, the variability of this resource has been the main barrier for solar energy development in most locations around the world. This paper investigated the distribution and variability of solar radiation using the a 10-year (2006 to 2015) data collected at Sørås meteorological station located at latitude 59° 39′ N and longitude 10° 47′E, about 93.3 m above sea level (about 30 km from Oslo), in south-eastern part of Norway. It is found that on annual basis, the total number of days with a global solar radiation of less than 1 kWh/(m^2·d) is 120 days while the total number of days with an expected global solar radiation greater than 3 kWh/(m^2·d) is 156 days (42.74%) per year. The potential energy output from a horizontally placed solar collector in these 156 days is approximately 75% of the estimated annual energy output. In addition, it is found that the inter-annual coefficient of variation of the global solar radiation is 4.28%, while that of diffuse radiation is 4.96%.

Keywords coefficient of variation, global solar radiation, diffuse ratio, albedo, PV energy systems

1 Introduction

Due to its geographical location, investment in solar energy conversion systems (SECS) is largely considered as non-economically viable in Norway. The reason for this is that Norway is located in a region with a low sunshine duration belt where solar radiation is generally low, especially during the winter season. Notwithstanding of this low solar radiation, interest in solar energy development is growing in the country. Until recently, the only major support scheme for renewable energy development in Norway is the green certificate scheme. However, the entrance fee for participation in this scheme is a minimum of NOK 15000 (about US$1715[1)]) which is generally considered to be too high for owners of small-scale photovoltaic (PV) system (especially, residential owners). However, in 2015, the government agency (ENOVA) introduced financial incentives to support individual home owners to install solar water heating and solar PV systems. For the solar PV installation, an individual can get up to 35% cash back of total investment cost depending on the size of the installation, while the owner of residential solar water heating installation can receive up to 25% [1]. In addition, residential house owners within municipality region of Oslo can receive 40% of investment support for PV installations [2].

On global scale, solar energy is expected to play a significant role in the changing face of energy economies due, in a large part, to the recent technological advances in the field and the significant decrease in cost. However, solar energy is a highly variable and unpredictable energy resource. These factors have been the main barriers for solar energy development in most locations around the world. The sound knowledge about the level of variability in solar radiation data are important for improving the design of solar energy conversion systems and for understanding of their performance [3–6]. In addition, the knowledge of the solar resource variability could provide valuable information for determining how long measurement is required to ascertain the reliability of the available data [5,6]. Furthermore, this knowledge can help forecast future yield of solar energy conversion systems and to secure the loan from banks to finance solar energy projects. Additionally, the knowledge of the local solar radiation variability is the basis of any climatic study and

Received May 6, 2016; accepted July 4, 2016

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1) Using exchange rate of 1 US$1 ≈ 8.75 NOK (http://www.norges-bank.no/en/Statistics/exchange_rates/currency/USD, 26/01/2016)

its various applications [7]. It could also be useful in estimating dynamic losses of solar energy conversion systems as well as thermal fatigue of materials due to variable solar radiation [8].

Globally, there are reported studies on the variability of solar energy resource and factors that cause this variability. Gueymard and Wilcoz [5] as well as Wilcoz and Gueymard [6] studied the spatial and temporal variability in solar resource in the United States of America and concluded that the solar resource in both time and space varied widely across the country. Santabàrbara et al. [9] reported the monthly variations in global solar radiation in Catalonia (Spain). Other studies on variations and trends of solar radiation include those of Zhang et al. [10] for locations in eastern China, De Souza et al. [7] for a location in Brazil, Tomson and Tamm [8] for a site in Estonia, and Hernández-Escobedo et al. [11] for locations along the Gulf of Mexico.

However, in Norway there is limited work in this area. Parding et al. [12] studied the variability of shortwave (SW) irradiance, clouds and temperature in Bergen on the west coast of Norway, while Grimenes and Thue-Hansen [13] investigated the reduction of global radiation in Ås (situated in south-eastern Norway) between 1950 and 2003. These studies focused mainly on the dimming and brightening effects of the atmosphere at the location of their respective studies. As individual and organization are starting to show more interest in solar energy development in Norway, one of the main concerns is the variability of the performance in solar energy conversion systems (especially on electricity generated by PV systems). This information is very important if developers plan to borrow money from the bank to finance their solar energy installations. It is also essential for system operators to know the expected variability of the electricity output in grid-tied solar PV systems (for better planning and forecasting). The aim of this paper is to investigate the variability of global and diffusion solar radiation in Ås (in south-eastern Norway) using the 10-year measured solar radiation data. The findings in this paper could help to account for error/uncertainty in the prediction of solar energy resource in this part of Norway and similar locations.

2 Methodology

2.1 Source of data

The daily global and diffuse radiations on horizontal surface as well as albedo (ground surface reflectance) measurements at Ås meteorological station (Sørås, Norwegian University of Life Sciences (NMBU), Ås, Norway) are analyzed. The global irradiance has been measured at this meteorological station since 1950, while diffuse irradiance has been measured since 1966. In addition, albedo measurements have also been performed since 1966. However, for the work presented in this paper, the global radiation, diffuse radiation and albedo data for 10 years from January 2006 to December 2015 are collected and analyzed. The station is located at a latitude of 59° 39′ 37″ N and a longitude of 10° 46′ 54″ E, about 93 m above sea level. The global irradiance and reflected irradiance are respectively measured with the Eppley Precision pyranometer while the diffuse irradiance is measured with the Eppley Precision pyranometer instrument with sunshade (to block the direct beam irradiance). Reflected radiation is the part of global radiation reflected from the ground. To measure the reflected radiation, the inverted pyranometer is mounted 2 m above the ground. The measurement uncertainty of these pyranometers is about 10%. The global and diffuse irradiance as well as albedo measurements are made at a frequency of 0.1 Hz while a mean value for every 60 s are stored in the database.

2.2 Data analysis

The daily, monthly and annual average as well as standard deviation of the global and diffuse radiations for the 10 years set of data are determined. The average radiation data are given as

$$H_{\mathrm{m},t} = \frac{1}{n}\sum_{i=1}^{n} H_i, \tag{1}$$

where $H_{\mathrm{m},t}$ is the average value of radiation (either global or diffuse), H_i is the radiation data (global or diffuse) at a given resolution (daily, monthly or annual) and n is the number of data.

The standard deviation σ_t, is expressed as

$$\sigma_t = \left[\frac{1}{n}\sum_{i=1}^{n}(H_i - H_{\mathrm{m},t})^2\right]^{1/2}. \tag{2}$$

The variability in the solar radiation within a given time frame is examined using the coefficient of variation (CoV). It is defined as the ratio of standard deviation to the average (or mean) of a given set of data [5,14]. The CoV shows the extent of variability in relation to the mean of the data set. It is expressed as [5]

$$\mathrm{CoV}_t = \frac{\sigma_t}{H_{\mathrm{m},t}}. \tag{3}$$

With the coefficient of variation, the variability between sets of data can easily be compared. A low value of coefficient of variation, which is generally desired, indicates a high-level cluster of data around the average value. In addition, the frequency distribution of the long-term average daily and monthly of the global solar radiation on horizontal surface is examined. The frequency distribution can be used to estimate the fraction of time for which a given solar radiation can possibly occur at a site.

3 Results and discussion

3.1 Frequency distribution of global solar radiation (GSR)

The frequency distribution is based on the ten-year (2006 to 2015) average daily global solar radiation data used in this study. The monthly and seasonal number of days when the global solar radiation on horizontal surface is within the specific range at an interval of 1 kWh/(m^2·d) are presented respectively, in Tables 1 and 2. Table 1 shows that the global solar radiation is less than 1 kWh/(m^2·d) every day in the months of January, November and December as well as some days in February and October. On annual basis, the total number of days with global solar radiation less than 1 kWh/(m^2·d) is 120 days. It can further be observed that there is no expected day with global solar radiation below 4 kWh/(m^2·d) in the months of June and July. In addition, the total number of days with expected global solar radiation greater than 3 kWh/(m^2·d) is 156 days (42.74%) per year. The potential annual energy from a horizontally placed solar collector is estimated using the mid-value of the global solar radiation (for instances, 0.5 kWh/(m^2·d) for 0–1 kWh/(m^2·d) range and 1.5 kWh/(m^2·d) for 1–2 kWh/(m^2·d) range) as the expected solar radiation within each range. Using this approach, the expected annual energy output from the collector is 954.5 kWh/m^2, which is 2.4% less than the summation of daily global solar radiation. The energy output of the solar collector in 156 days (with GSR > 3 kWh/(m^2·d)) is about 75% of this estimated annual energy output.

On seasonal basis (Table 2), there is no expected day with a global solar radiation above 2 kWh/(m^2·d) in the winter season (December, January and February) while in the fall season (September, October and November) the solar radiation is generally less than 4 kWh/(m^2·d) with most of the days in the lower ranges. However, in the summer season, there is no expected day with a global solar radiation below 2 kWh/(m^2·d). Furthermore, during the summer season, it is expected that the solar radiation within the range of 6–7 kWh/(m^2·d) could occur in 12 days. During the spring season, there are no days with a global solar radiation less than 1 kWh/(m^2·d) or greater than 6 kWh/(m^2·d). In term of energy output from a horizontally placed solar collector, the estimated seasonal output are 330.0 kWh/m^2, 441.0 kWh/m^2, 127.5 kWh/m^2 and 56.0 kWh/m^2 for spring, summer, fall and winter seasons, respectively. It should be mentioned here that the estimated energy output could be higher for all the seasons if the solar collector is optimal tilted and oriented toward the equator, which is commonly the case for solar heating and PV systems installed in the sites in northern hemisphere.

Table 2 Seasonal daily distribution of global radiation horizontal surface

GSR range /(kWh·(m^2·d)$^{-1}$)	Number of days				
	Spring	Summer	Fall	Winter	Total
0–1	–	–	41	79	120
1–2	9	–	26	11	46
2–3	24	3	16	–	43
3–4	19	18	8	–	45
4–5	30	32	–	–	62
5–6	10	27	–	–	37
6–7	–	12	–	–	12

3.2 Temporal variability of solar radiation

Figure 1 shows the long-term daily average of the global solar radiations on the horizontal surface and daily coefficient of variation. It can be observed from Fig. 1 that the minimum daily global solar radiation is 0.101 kWh/(m^2·d) while the maximum value is 6.959 kWh/(m^2·d). In general, as expected for this site (and other sites in Norway), the global solar radiation increases gradually from January and attains a peak value around June and thereafter, decreases gradually. The dashed line indicates the daily average global solar radiation of 2.55 kWh/(m^2·d). It is estimated that, on average, the daily global solar radiation is greater than this average value in 177 days in a year (or about 48.5% of the number of days in a year) from mid-March to mid-September. The average daily GSR in these 177 days in a year is 4.44 kWh/(m^2·d) with a potential total energy output of 769.39 kWh of the solar collector. This amount represents about 82.6% of the potential annual energy yield of the solar collector placed

Table 1 Monthly distribution of global radiation horizontal surface (kWh/(m^2·d))

GSR range	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
0–1	31	17	–	–	–	–	–	–	–	11	30	31
1–2	–	11	9	–	–	–	–	–	6	20	–	–
2–3	–	–	19	5	–	–	–	3	16	–	–	–
3–4	–	–	3	15	1	–	–	18	8	–	–	–
4–5	–	–	–	10	20	6	17	9	–	–	–	–
5–6	–	–	–	–	10	13	13	1	–	–	–	–
6–7	–	–	–	–	–	11	1	–	–	–	–	–

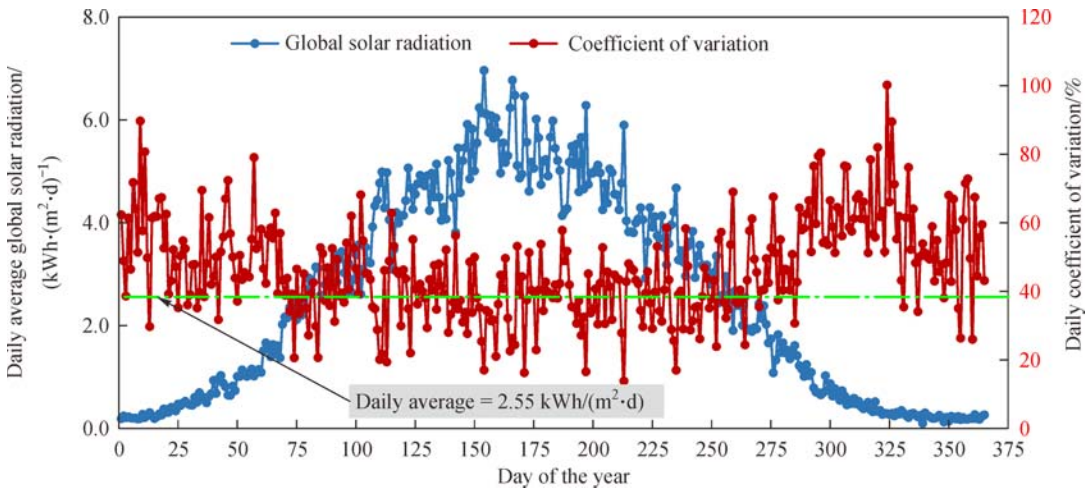

Fig. 1 Long-term daily average global solar radiation and coefficient of variation

horizontally in this location. The daily coefficient of variation in the global solar radiation ranges between 13.81% and 100.14% with an average value of 46.24%. In general, the variability of solar radiation is observed to be less pronounced in summer days when compared with fall and winter days.

Figure 2 presents the long-term daily average of the diffuse solar radiation on the horizontal surface and its daily coefficient of variation. The daily average diffuse solar radiation varies between 0.097 kWh/($m^2 \cdot d$) and 2.806 kWh/($m^2 \cdot d$) with an overall daily average of 1.189 kWh/($m^2 \cdot d$). Like the global solar radiation, the diffuse radiation follows the Gaussian distribution function but with a lower peak. The daily coefficient of variation in the diffuse solar radiation ranges between 9.92% and 84.02% with an average value of 35.70%. In general, the coefficient of variations of diffuse solar radiation is less than that of global solar radiation. This is caused by the relative stability in diffuse radiation when compared with global solar radiation. The global solar radiation is influenced by direct radiation which is subject to a strong variability as a result of momentarily stationary and moving cloud.

Figure 3 illustrates the long-term monthly daily average of the solar radiation on the horizontal surface. It can be observed from Fig. 3 that the monthly daily global solar radiation varies from 0.21 kWh/($m^2 \cdot d$) (in December) to 5.62 kWh/($m^2 \cdot d$) (in June). Likewise, the monthly daily diffuse solar radiation varies from 0.16 kWh/($m^2 \cdot d$) (in December) to 2.33 kWh/($m^2 \cdot d$) (in June). Also, presented in Fig. 3 is the monthly diffuse fraction (diffuse solar radiation divided by global solar radiation). The diffuse fraction ranges between 41.4% in June and 74.4 % in December (and 74.3% in January) with an overall average value of 54.7%. The value is within the range of diffuse radiation, between 50% and 60% of the global solar

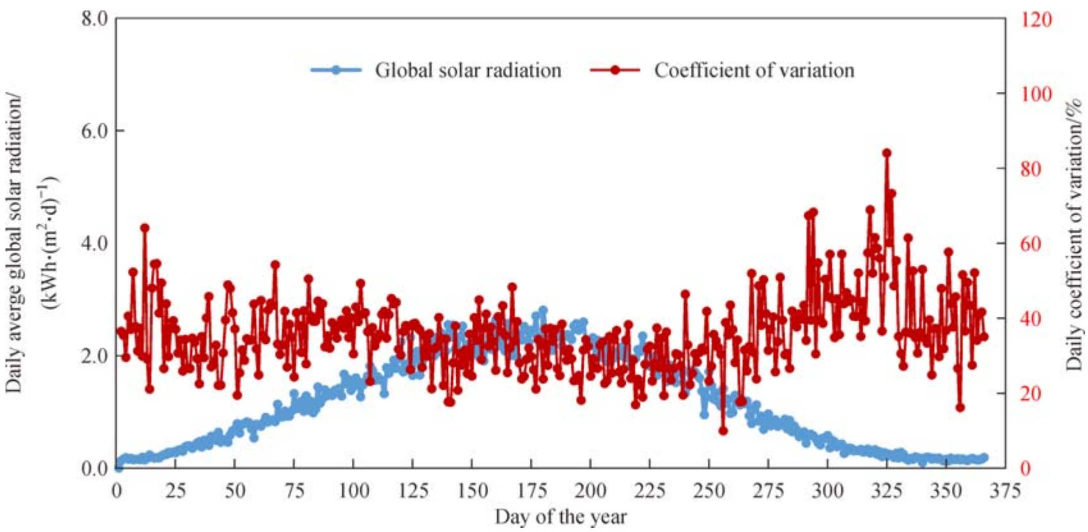

Fig. 2 Long-term daily average diffuse solar radiation and coefficient of variation

radiation, reported for locations in northern European [15]. The low fraction of diffuse radiation in June results from the relatively clear weather with high proportion of direct solar radiation while in January and December (as well as February and November) the weather condition is dominated by cloudy conditions with a low proportion of direct solar radiation.

Figure 4 shows the long-term monthly coefficient of variations. The monthly variability (that is, CoV) in the averaged daily monthly global solar radiation varies between 7.54% (in August) and 29.33% (in November) with an overall monthly average of 15.09%. This trend may result from the variability in cloudiness, which is more frequent during the winter and fall months than during the summer months. Furthermore, the diffuse radiation is observed to vary between 10.56% (in December) and 49.25% (in November).

Table 3 lists the summary of daily annual average of global solar radiation (kWh· $(m^2 \cdot d)^{-1}$), diffuse radiation (kWh· $(m^2 \cdot d)^{-1}$) and albedo. The long-term annual daily average of the global solar radiation is 2.55 kWh/$(m^2 \cdot d)$ with an overall standard deviation of 0.109 kWh/$(m^2 \cdot d)$. The variability in the inter-annual average daily global solar radiation ranges between –8% and 7.7% of the long-term average. In addition, the annual variability in the diffuse radiation ranges between −10.8% and 4.9%. Overall, based on the 10-year daily data examined in this paper, the coefficient of variation of the global solar radiation is 4.28%, while that of diffuse radiation is 4.96%. Hence, the global solar radiation in Ås can be said to be relatively steady and thus, predicting solar energy conversion systems performance in this site using the long-term annual average will only result in a manageable error.

The albedo which represents the reflected component of the global solar radiation can be used to estimate the total global solar radiation on an inclined surface. The long-term annual daily average of the albedo is 0.36 with a standard deviation of 0.040 and a coefficient of variation of 10.96%. On monthly bases (not shown), the values of albedo are 0.64, 0.74, 0.55 and 0.48 respectively for the months of January, February, March, and December (these high values are caused by the presence of snow in these months) while the rest of the months have an average value of 0.24.

To estimate the confidence level of the data, the

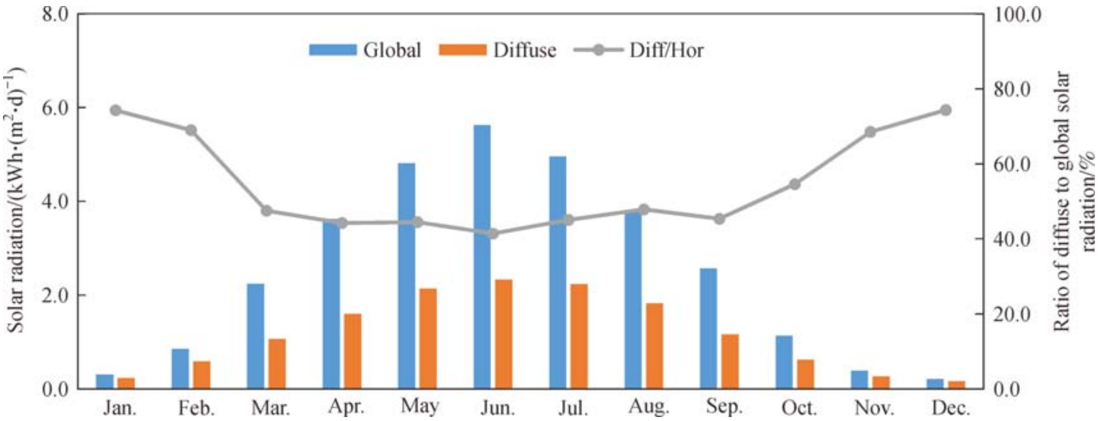

Fig. 3 Monthly average daily global solar radiation on horizontal surface

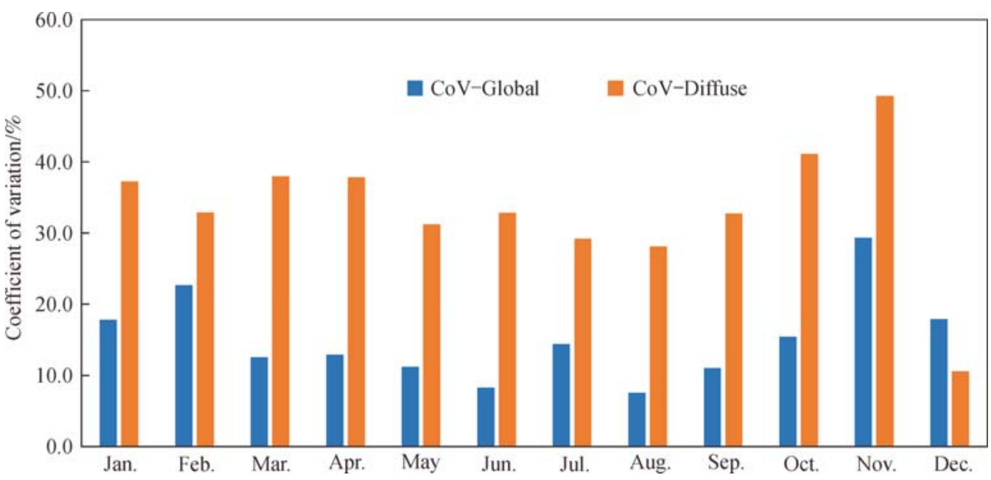

Fig. 4 Monthly coefficient of variation

Table 3 Summary of daily annual average of global solar radiation (kWh· $(m^2·d)^{-1}$), diffuse radiation (kWh· $(m^2·d)^{-1}$) and albedo

	2015	2014	2013	2012	2011	2010	2009	2008	2007	2006	Average	SD	CoV/%
Global radiation	2.74	2.58	2.55	2.46	2.51	2.55	2.62	2.63	2.34	2.48	2.55	0.109	4.26
Diffuse radiation	1.13	1.17	1.21	1.22	1.23	1.22	1.24	1.22	1.06	1.13	1.18	0.059	4.98
Albedo	0.32	0.30	0.37	0.35	0.38	0.44	0.39	0.37	0.33	0.37	0.36	0.040	10.96

difference between the individual yearly average global radiation and long-term average is divided by the long-term standard deviation. The results vary between $1.80\sigma_t$ and $-1.88\sigma_t$. Similarly, the diffuse radiation varies between $0.99\sigma_t$ and $-2.17\sigma_t$. Therefore, it can be concluded that there is a 95% likelihood chance that the individual yearly averaged of both global solar and diffuse radiations are within $H_{m,t}\pm2\sigma_t$ the range. For solar radiation data for applications in which the so-called "bankable data" are required, the use of the 95% confidence interval is recommended according to Gueymard and Wilcoz [5]. Therefore, based on the data analyzed in this paper, the variability in the solar radiation is within the acceptable limit imposed on the finance ability of solar energy projects.

4 Conclusions

The distribution of global solar radiation as well as temporal variability in solar radiation observations in Ås (about 30 km south-east of Oslo) Norway is investigated using the 10-year (from 2006 to 2015) measured data. The findings from this paper can be summarized as follows:

The total number of days with a global solar radiation less than 1 kWh/$(m^2·d)$ is 120 days while the total number of days with the expected global solar radiation greater than 3 kWh/$(m^2·d)$ is 156 days per year.

The inter-annual coefficient of variation of the global solar radiation is 4.28%, the diffuse radiation is 4.96%, and the albedo is 10.96%.

The coefficient of variability has low values during the summer months while the global solar radiation values are high during these months.

There is a strong likelihood of 95% that the individual yearly averaged of both global solar and diffuse radiations are within the $H_{m,t}\pm2\sigma_t$ range.

Overall, this paper shows that the long-term average of global solar radiation can be used for planning and prediction of the energy output of solar energy conversion systems in this part of Norway with a marginal error. In addition, since 80% the potential energy yield from a solar collector installed at this site can be achieved in 6 months (between mid-March to mid-September), the economic assessment of solar energy conversion systems at this location should be focused on the energy generated within this period.

Acknowledgements The author would like to thank Signe Kroken (Department of Mathematical Science and Technology, NMBU, Ås, Norway) for providing metrological data from the Sørås weather station.

References

1. Enova, Subsidies for electricity production (in Norwegian, 'Tilskudd for el-produksjon'). 2016–01–18, http://www.enova.no/finansiering/privat/enovatilskuddet-/
2. Linked in. Oslo (Norway) extends solar rebate program, 2016–01–18, https://www.linkedin.com/pulse/oslo-norway-extends-solar-rebate-program-grid-parity-concepts-europe?trkSplashRedir = true&forceNoSplash = true
3. Omran M A. Analysis of solar radiation over Egypt. Theoretical and Applied Climatology, 2000, 67(3–4): 225–240
4. Dahmani K, Dizene R, Notton G, Paoli C, Voyant C, Nivet M L. Estimation of 5-min time-step data of tilted solar global irradiation using ANN (Artificial Neural Network) model. Energy, 2014, 70(1): 374–381
5. Gueymard C A, Wilcox S M. Assessment of spatial and temporal variability in the US solar resource from radiometric measurements and predictions from models using ground-based or satellite data. Solar Energy, 2011, 85(5): 1068–1084
6. Wilcoz S M, Gueymard C A. Spatial and temporal variability of the solar resource in the United States. American Solar Energy Society–Proc. ASES Annual Conference, Phoenix, 2010
7. De Souza J L, Nicacio R M, Moura M A L. Global solar radiation measurements in Maceio, Brazil. Renewable Energy, 2005, 30(8): 1203–1220
8. Tomson T, Tamm G. Short-term variability of solar radiation. Solar Energy, 2006, 80(5): 600–606
9. Santabàrbara J M, Calbo J, Baldasano J M, Esteve J, Mitjà A. Month-to-month variation of global solar radiation in Catalonia (Spain). International Journal of Climatology, 1996, 16(6): 711–721
10. Zhang Y L, Qin B Q, Chen W M. Analysis of 40 year records of solar radiation data in Shanghai, Nanjing and Hangzhou in Eastern China. Theoretical and Applied Climatology, 2004, 78(4): 217–227
11. Hernández-Escobedo Q, Rodríguez-García E, Saldaña-Flores R, Fernández-García A, Manzano-Agugliaro F. Solar energy resource assessment in Mexican states along the Gulf of Mexico. Renewable & Sustainable Energy Reviews, 2015, 43: 216–238
12. Parding K, Olseth J A, Dagestad K F, Liepert B G. Decadal variability of clouds, solar radiation and temperature at a high-latitude coastal site in Norway. Tellus B-chemical & Physical Meteorology, 2014, 66(1): 25897
13. Grimenes A A, Thue-Hansen V. The reduction of global radiation in

south-eastern Norway during the last 50 years. Theoretical and Applied Climatology, 2006, 85(1): 37–40

14. Gil V, Gaertner M A, Sanchez E, Gallardo C, Hagel E, Tejeda C, de Castro M. Analysis of interannual variability of sunshine hours and precipitation over Peninsular Spain. Renewable Energy, 2015, 83 (680): 680–689
15. Mertens K. Photovoltaics: Fundamentals, Technology and Practice. John Wiley and Sons, Inc. 2014