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Radial frequency diagram (sunflower) for the analysis of diurnal cycle parameters: Solar energy application

Marija Zlata Božnar [a,*], Boštjan Grašič [a], Primož Mlakar [a], Jacyra Soares [b], Amauri Pereira de Oliveira [b], Tássio Santos Costa [b]

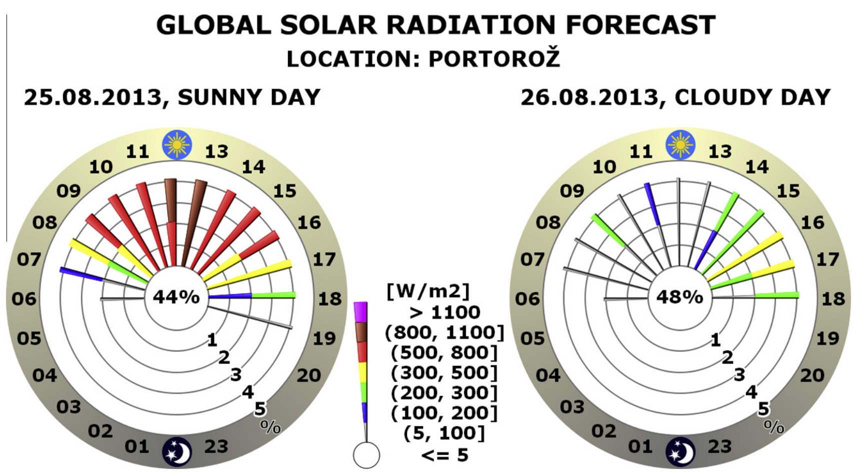
[a] MEIS d.o.o., Mali Vrh pri Šmarju, Slovenia
[b] Group of Micrometeorology, Department of Atmospheric Sciences, University of São Paulo, São Paulo, Brazil

HIGHLIGHTS

- The diurnal cycle of solar energy is important for the management of the electrical grid.
- A solar plant's average production depends on the statistical features of solar radiation.
- The new tool – the "sunflower", is proposed for solar energy availability representation.
- The sunflower identifies and quantifies information with a clear diurnal cycle.
- The sunflower diagram has been developed from the "wind rose" diagram.

GRAPHICAL ABSTRACT

A new type of graphical presentation showing diurnal cycle of solar energy forecast. The application is possible for other parameters related to weather and green energy production.



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ABSTRACT

Many meteorological parameters present a natural diurnal cycle because they are directly or indirectly dependent on sunshine exposure. The solar radiation diurnal pattern is important to energy production, agriculture, prognostic models, health and general climatology. This article aims at introducing a new type of radial frequency diagram – hereafter called sunflower – for the analysis of solar radiation data in connection with energy production and also for climatological studies. The diagram is based on two-dimensional data sorting. Firstly data are sorted into classes representing hours in a day. Then the data in each hourly class is sorted into classes of the observed variable values. The relative frequencies of the value classes are shown as sections on each hour's segment in a radial diagram. The radial diagram forms a unique pattern for each analysed dataset. Therefore it enables the quick detection of features and the comparison of several such patterns belonging to the different datasets being analysed. The sunflower diagram enables a quick and comprehensive understanding of the information about diurnal cycle of the solar radiation data. It enables in a graphical form, quick screening and long-term statistics of huge data quantities when searching for their diurnal features and finding the differences between the data for

* Corresponding author at: MEIS d.o.o., Mali Vrh pri Šmarju 78, SI-1293 Šmarje–Sap, Slovenia.
E-mail address: marija.zlata.boznar@meis.si (M.Z. Božnar).

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several locations. The results of the data analysis using the sunflower diagram show how daily or monthly-based patterns are identified within small or huge data sets. The paper demonstrates the sunflower diagram usefulness over a wide range of applications from green energy production to weather analysis.

1. Introduction

Many physical parameters are directly or indirectly dependent on sunshine exposure, having therefore, a natural diurnal cycle. The amount of sunlight reaching a certain area on the surface of the earth primarily depends on the time and location and secondarily on other atmospheric conditions (cloudiness, fog, particulate matter, photochemical smog, etc.). Time and location dependency can be calculated using a basic trigonometric analysis of the sun's position over the horizon. On the other hand atmospheric conditions form a complex nonlinear filter for sunlight that passes downward and scatters. All together these mechanisms result in complex diurnal cycles.

As a result of the solar diurnal cycle, solar power plants do not generate energy at a constant rate throughout the day, which makes it necessary to eventually purchase additional electricity from conventional sources. Namely, the solar diurnal cycle modulates the electricity price on the market according to the time of the day.

The object of our investigation is the daily pattern of solar energy availability and the seasonal variation of these daily patterns. For that reason, a straightforward representation of the solar diurnal cycle constitutes a useful tool for understanding the production and for planning the acquisition of additional electricity. Also, when deciding on locations for new solar power plants, a clear-cut graphical display of the natural conditions with regard to the availability of solar energy is an important tool for making an effective choice.

The results of the study can contribute to the community interested in solar radiation as an energy source, either directly, through solar collectors or panels, or indirectly, through the production of biomass on land (plants) or in aquatic environments (algae) for subsequent conversion to biofuel. In this context, finding a suitable method for the graphical display of temporal features of solar radiation is a critical issue.

Another question is the form in which solar energy reaches the surface; it is important to know whether the energy reaches the ground directly or as diffuse solar radiation [1,2]. Measurements or reliable weather forecasts can be used to estimate the predominant form of solar energy reaching the ground and this information can then be used to decide which type of solar panel technology should be used [3,4].

The main objective of this work is to introduce a new type of radial frequency diagram (sunflower diagram) for the analysis of solar radiation data in connection with energy production. Renewable energy production systems such as wind mills or photovoltaic plants for electricity production often have a non-uniform energy availability in time. As a consequence of this phenomenon a dedicated sophisticated control of spatial and temporal distributed electricity sources is required. The basic input information for such control is the description of the energy availability patterns. The sunflower diagram is a new possibility to present this description along two dimensions.

The sunflower diagram gives relative frequency information of the mean diurnal variability. The sunflower diagram is a relatively easy way to condense the graphical presentation of the time series with explicit frequency cyclic information. This paper concentrates on sunflower applications showing the diurnal cycle of time series but the new proposed method of graphical presentation is not limited to diurnal cycles. Sunflower presentations can also be generalised to other cycles such as weekly.

There are some other questions in the meteorological analyses that can be answered in a similar way as the question of solar energy availability daily patterns.

Related to climatology, the cloud cover can be displayed in a similar way as the diurnal cycle of global solar radiation. The sunflower representation can also be useful for tourism purposes to display detailed weather information on what a tourist can expect at a given location during the travel period. Another possible application is for traffic or vehicle planning and driver warning or a posteriori traffic analysis. Weather information and traffic analysis examples will be explained in detail in the following sections.

Another interesting potential application is in atmospheric pollution analysis. Not only atmospheric particulate matter and photochemical smog have a decisive effect on horizontal visibility [5] but they also affect the form of how solar energy reaches the surface [6]. Therefore, it is also proposed for the use of sunflower diagrams. Some examples of basic sunflower diagrams are provided in this work.

2. Data and methodology

2.1. Data – the sunflower testbed

The sunflower diagram was applied on a testbed, that contained measurements and model-based forecasts for atmospheric parameters in certain locations in Slovenia and Brazil.

The database contains half-hour average values of measured and predicted atmospheric parameters for the following locations in Slovenia: (i) rural areas over rugged terrain (Maribor, Brnik, Pustice), (ii) rural areas over flat terrain (Rakičan), (iii) coastal areas on rugged terrain (Portorož) and (iv) a town on rugged terrain (Celje). For an urban environment the aforementioned Sao Paulo station was used. The measurement data were provided by the Slovenian Environment Agency (ARSO), Slovenia, MEIS, Slovenia, and IAG, USP, Brazil. The model results were provided by MEIS [7] and created using the *Weather Research and Forecasting Model* (*WRF*) [8,9]. Detailed data about the station's locations and measurements are given in Table 1.

The meteorological stations provided statistically elaborated data every half hour for measurements at ground-level of air temperature, air relative humidity, wind direction and speed, global solar radiation, diffuse solar radiation (only available at some stations) and the Celje station additionally provides PM10, nitrogen oxides and ozone air pollution measurements.

Weather forecasts for complex terrain over Slovenia with fine spatial and temporal resolution (4 km, half-hour) were also prepared for the station locations using the WRF model.

All the results provided in this article are based on the data and tools of the MEIS testbed.

2.2. The phenomenon under investigation

The main question that we want to address with the proposed new analysis technique is the following: We have a time series of scalar values of a meteorological parameter (that can be also defined as a vector comprised of a scalar value and time stamp); What is the frequency distribution of the classes of the scalar within each hour of the day? In other words what is the pattern of this scalar value classes analysed according to its daily behaviour. Several meteorological parameters have a clear daily cycle that is important for many aspects of life and we describe a new possibility of condensing a two-dimensional presentation of the information on this pattern.

2.3. Methodology

The sunflower is a radial frequency diagram used to display the statistical frequency of the occurrence of different classes of a physical parameter, which exhibits a cyclic nature. The sunflower diagram assumes the dataset as a set of vectors; each vector consists of scalar values of solar radiation (measured or modelled) and the time within a day when the scalar value appears. The procedure of constructing a sunflower diagram consists of sorting these vectors firstly along the time elements into classes that represent each hour of the day and then within each hour class the vectors should be sorted into classes that represent the values of the solar radiation from small to maximum values. The results of sorting within each hour are then shown as colour and length coded sections of the corresponding radial segments.

This paper concentrates on examples of diurnal cycles where the periodicity is shown over the hours of the day. But the diagram itself can be generalised using any other independent variable instead of the hour of the day (such as other time periods like weeks, months; or such as longitude or wavelength).

A sunflower example is displayed in Fig. 1 for global solar radiation. Fig. 1 is made based on the measured global solar radiation at the standard meteorological station Pustice located in central Slovenia.

The diagram can be used for any size of dataset, ranging from at least one day to as many days as required. As can be seen in Fig. 1 all the statistics are calculated so that the whole is composed of the number of measurement intervals comprising a given time interval. Temporal resolution of the data should be better than one hour or at least one hour.

The sunflower diagram is divided into central and sector areas. There are 24 sectors – as many as there are hours in a day and at the centre-top, there is a symbol indicating noon, which can either be graphical or simply the number 12. Diametrically opposite this sign, at the centre-bottom, there is a symbol indicating midnight. The numbers 13 through 23 indicate the hours in a clockwise direction from noon to midnight and then again from 01 to 11 after midnight. The segments of the diagram display the relative frequency of the measured values in the time of day.

A legend of the solar radiation classes must be defined. The class representing the lack of solar radiation must be defined as having a measurement of 0. This class is followed by classes with greater values. It must be defined where class boundaries are closed and where they are open. The diagram in Fig. 1 uses a scale with eight classes. For other parameters the scale should be adjusted accordingly.

All known valid measurements are first sorted within the interval of all possible measurements so that all the measurements taken in a given hour of the day are collected in the corresponding segment. The measurements are then sorted within the segment into classes. The number of measurements within each class is then determined for each segment section and the relative frequency for all possible intervals is calculated. The relative frequency is expressed as a percentage. The relative frequency of the class with a measurement of 0 is also calculated separately. The relative frequency of this class is only calculated once for the entire time period (it is not calculated separately for each hour of the day).

The results are displayed in the form of a radial diagram divided into 24 sectors or segments. Each segment corresponds to a defined hour of the day, the measurements taken within which are used in the calculation of relative frequency. Segments should be drawn so that it is indicated between which boundary hours the measurements are used in the calculation, so that, for example, the segment is drawn inside between two separating boundary hours, leaning on one side on a boundary hour included in the interval and not leaning on the other side on an hour not included in the interval (closed and open time interval). At the centre of the radial diagram, there is a circle representing a class of null values. Segments are then drawn consecutively outwards from this circle, displaying in a colour scale the relative frequency of each class within a certain time interval. The lower class boundary is drawn first, then the rest until the last class (upper class boundary). Segment sections are drawn in the colours assigned to individual classes in the key defined by a legend. Only relative frequencies greater than zero are included in each segment. Concentric circles are used to define the segment length which constitutes 1% of all hourly intervals between the starting and ending intervals.

The colour scale for individual classes is given separately and it shows which boundaries are included and which are excluded. This can be done using the appropriate type of brackets. Values belonging to the class of zero values are also shown separately.

The text part of the image, in general, includes: (i) the name of the measurement location, (ii) the start and end intervals (iii) the

Table 1
Detailed description of the "sunflower" testbed.

Location	Coordinates WGS84	Elaboration period	Half hour average data available in the database					
			Global solar radiation	Diffuse solar radiation	Direct solar radiation	Wind	PM10	Relative humidity
Slovenia: available database 2012–2013 (except Pustice 2012–2015)								
Portorož	N45.4749 E13.6165	Aug. 2013	Yes	Yes	No	Yes	No	Yes
Rakičan	N46.6517 E16.1919	year 2012 Aug. 2013	Yes	Yes	No	Yes	No	Yes
Pustice	N45.9844 E14.5919	May 2013 Mar. 2015	Yes	No	No	Yes	No	Yes
Brnik	N46.2194 E14.4719	year 2012	Yes	No	No	Yes	No	Yes
Celje	N46.2345 E15.2625	year 2012	No	No	No	Yes	Yes	Yes
Brazil: available database 2012								
Sao Paulo	S46.7333 W23.5593	Sep. 2012	Yes	Yes	Yes	Yes	No	Yes

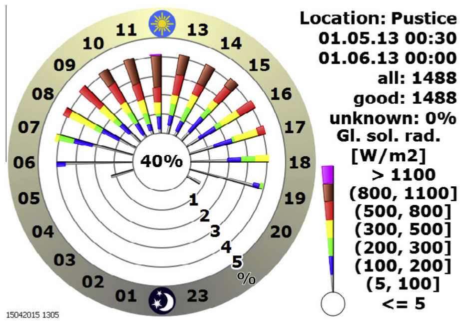

Fig. 1. Example of the sunflower diagram for global solar radiation for the automatic meteorological station Pustice for May 2013.

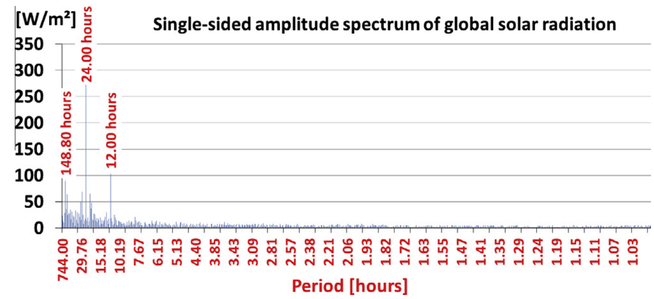

Fig. 2. The discrete Fourier Transform analysis result of the global solar radiation measured and statistically elaborated in ½ h time intervals for the Pustice station for May 2013, there are only three major peaks at 12, 24 and 148.8 h.

number of all possible measurement intervals, (iv) the number of all measurements received during this interval, (v) the number of good measurements within this interval (if measurements are evaluated individually in terms of quality or validity) and (vi) the name of the measured parameter and its unit.

It is practical to include the time stamp – the time of the creation of the diagram – to ensure the traceability of the origin of each diagram. It is particularly important when operating large databases, multiple editions or versions of individual documents containing multiple diagrams, etc.

2.4. Comparison with other methods for the analysis of the cyclic data time series

The most common graph to present the diurnal variation of the measured parameters is the line graph of the time series. However, the diverseness of the diurnal pattern becomes less apparent due to the graph's width limitations for each individual day. A line graph therefore does not allow the elaboration of huge data sets. Another option enabling statistical elaboration is using conventional one-dimensional histograms displaying the relative percentage or individual parts of the day averaged over any length period. This is a better representation method but it misses the diurnal cycle when there is transition between one day and another. A similar approach is also to average the values for the same daily hour for multiple days and then present these averages as a line graph [10]. Sometimes this averaging approach is used in meteorology also for the spatial averaging of the results for many locations for the chosen time intervals [11]. The main advantage of the sunflower over these methods is that it simultaneously presents the data frequency distribution in two dimensions and not only in one dimension.

For a more general elaboration of the periodic time series a well-known Fourier transform is used [12]. It is a transformation from a time domain into a frequency domain. The frequency components directly indicate the presence of the period in the basic time series. In case of solar radiation the basic component would be with the periods of 1 day and 12 h. Fig. 2 shows a discrete Fourier transform (DFT) of the same dataset as elaborated in Fig. 1. The DFT shows the transformation into periodic sinusoidal components of the wave lengths from 1 h to 744 h (31 days of May). In Fig. 2 the single-sided amplitude spectrum of the signal is shown for each wave length. The graph shows that the elaborated dataset has clear peaks of amplitudes at 12 h, 24 h and 148.8 h. A peak of 148.8 h indicates the synoptic scale disturbances. In comparison to this, the sunflower of the same dataset shown in Fig. 1 gives more and different information. Firstly, the dark part of the day is clearly shown and quantified. Then the colour coded segments' sections are showing the average pattern of the morning and afternoon transitions from low global solar radiation to peak and vice versa. The variability of the classes within each segment shows the expected weather related variability of the global solar radiation within each hour. Also the percentage of high global solar radiation classes can be easily estimated. All this information is of great interest for green energy production and other related fields of interest.

The Fourier transformation is mostly used in meteorology for analysing the energy components of wind with a changeable speed. The period of the gusts bearing significant energy is extremely important for viaducts' design [13].

The tendency of a graphical presentation instead of a tabular presentation of numeric values is obvious, also in two-dimensional (2D) presentations with a spatial component. The ground level isotherms shown over a map of a region are also well understood by the layman [14]. However, such a 2D presentation (of temperature, solar radiation or other scalar value) does not allow the presentation of statistics on the same plot (but it is still possible on multiple plots). Taking into account the geographic dimension prevents us from showing statistical information such as the relative frequency of a selected temperature interval.

Going back into the presentation of the statistically elaborated time series for a single point there can be found a wind rose diagram example [15–17]. It shows the relative frequency of wind speed classes in the sectors of the 2D circle where each sector represents a class of similar wind directions. In this way it shows the statistical elaboration of a vector with two components (wind speed and wind direction). Because of this feature, the wind rose was our source of inspiration for the sunflower. The generally used wind rose also correctly shows the transition from NW to N which is a similar problem as showing the transition from 23:00 time measurements to 00:00 and following 01:00. The wind rose is a useful diagram to present the statistically elaborated long-term characteristics of wind from standard ground level meteorological station(s). The wind rose prevails over the usage of histograms for the same information. Fig. 3 shows an example of a wind rose for 1 month of half-hour wind samples for the Pustice station.

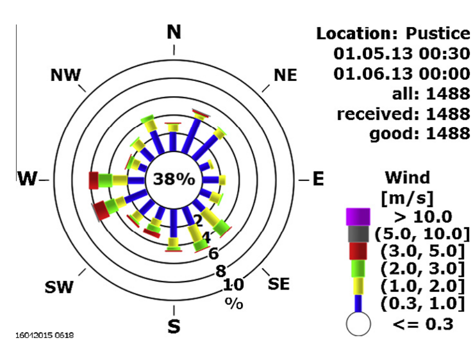

Fig. 3. Example of the wind rose for the automatic meteorological station Pustice for May 2013.

The sunflower can be used in a similar way. Therefore its prevailing usage over standard histograms is expected. The two components shown are for instance the meteorological parameter scalar value and the hour of its occurrence. Therefore the sunflower is fit for the statistical elaboration of all meteorological variables where the daily cycle is important.

In the presentation of weather forecasts several pictograms for 2 or 3 times per day are used. The pictogram itself does not contain the hour of the day information. Pictograms can be replaced by a sunflower weather presentation (as will be described in the following section) that on the contrary has precise timing information which is an important additional information.

2.5. Visualisation capabilities adapted to the human perception of graphic patterns

The essence of the representation using different colours and using segments of different lengths showing the relative frequency of a given class in a given hour of the day, is that the colour combination provides an unambiguous statistical display of the measurements. Comparing multiple diagrams to one another is relatively easy, as the differences in colour combinations are easily perceived. The differences of both the length of the day and the frequency of the individual classes are visible. The diagram can thus be used to display seasonal variations due to the changing seasons. Furthermore, it can be used to display variations within short periods, such as the differences between cloudy and sunny days, differences between foggy and non-foggy days, and is also very suitable for providing a straightforward graphical display of solar radiation forecasts as part of weather forecasts or energy harvesting potentials.

3. Results and discussion

Several different locations were chosen for the presentation of potential applications for sunflowers. The Sao Paulo station is located in the urban area of a Brazilian metropolis with millions of inhabitants, the Greater Sao Paulo [18,19,2]. The Rakičan station is set in a rural area of a flat continental region of Slovenia – the Pannonian Plain. The Portorož station is located by the shore of the Adriatic Sea in Slovenia; it is located on flat terrain, but is surrounded by very rugged terrain in the wider region. Some other locations Pustice, Brnik and Celje in the central part of Slovenia were also used.

3.1. The solar radiation sunflower

In this section we want to address the question on how to analyse the daily and monthly variations of solar energy availability in the form of global solar radiation. And secondly on how to analyse the availability differences between solar radiation components (global versus direct and diffuse).

Fig. 4 displays, respectively, the monthly variation of global solar radiation at the Rakičan station in the form of sunflowers within a period of one year. The images reveal the monthly availability of solar energy at the location. The differences between the four main seasons, the expected maximums for each month, the average day length for each month, and the speed and sharpness of the transition between day and night are clearly visible. Higher levels of global solar radiation (red, brown and pink) appear only from March to September. The proportion of the dark part of the day varies from 38% to 68% resulting from the seasonal variability of the location at this latitude. In winter months November, December and January the maximum global radiation hardly reaches levels up to 500 W/m^2 (yellow).

Global, direct and diffuse solar radiations are displayed for Sao Paulo (urban location) for 1 month (Fig. 5). Global solar radiation (left diagram) is a sum of the direct (middle diagram) and diffuse (right diagram) solar radiation. Diffuse solar radiation only rarely reaches over 300 W/m^2 while on the contrary the direct component contains the majority of the solar energy (yellow, red and brown classes). The diagrams also show that there is no solar radiation between 06:00 and 18:00 resulting in over 50% of all the intervals in darkness.

Sunflowers can also be drawn individually for shorter periods – for individual weeks or individual days. Fig. 6 displays three days from a randomly selected week at the Portorož location. Global solar radiation sunflowers clearly show the distinct difference between two sunny days followed by one cloudy day. According to the colour legend (from red to brown), bright sun was available from 09:00 until 16:00 on the 24th and from 08:00 till 16:00 on the 25th of August 2012. The following day, the 26th of August was a cloudy day and the sun was shining again (300–500 W/m^2) in the late afternoon from 15:00 until 17:00. Individual diurnal diagrams are useful for a detailed analysis of the weather situation.

3.2. Solar energy availability application as an example supporting green energy production

The Pustice station is located in the close vicinity of the "Frbežar" nursery garden that grows flowers for the market. The nursery garden has a photovoltaic solar power plant installed on the roof of the administrative building (see Fig. 7). During the late autumn and winter months the electrical energy produced is used to improve the illumination of the growing flowers. In other months the electrical power produced is sold on the market. In October, chrysanthemums are grown and therefore the availability of electrical power for each day is very important information. Fig. 8 shows one month's elaboration of global solar radiation, diffuse solar radiation and the calculated solar energy for the tilted plane for each hour of the day. Based on the sunflowers in Fig. 8 the photovoltaic solar power plant owner can estimate at which hour of the day in the elaborated period the solar plant will produce enough electrical power to enhance the growing flowers using the additional illumination. During the other hours the electrical energy for additional illumination should be purchased from the electrical grid distributors. The sunflower of solar energy on the tilted plane (right in Fig. 8) shows that the electrical power for additional illumination in March can only be produced from 10:00 until 16:00.

3.3. Wind energy availability application

Fig. 9 has been designed for the analysis of possible electric energy production using a small vertical wind turbine based on the wind speed forecast for a fictional location WindyStation in central Slovenia for a one year period starting from May 2012 and ending on April 2013. A derived function was used for the diagram – the wind intensity forecast for the chosen location was converted using the response characteristics of the wind turbine directly into the expected electric power output. The left sunflower shows the diurnal wind speed distribution that proves that strong winds are mainly available from 09:00 and 20:00. The energy production diurnal distribution using a wind turbine is presented on the right sunflower. It shows that energy production is only efficient when the winds are strong enough, therefore the best efficiency can also be achieved between 09:00 and 20:00. Grey (0-10 kW), blue (10-20 kW) and green (20-30 kW) classes of energy production show the periods of the day when the production of energy from wind is too low for economical exploitation. Unfortunately this is common for most

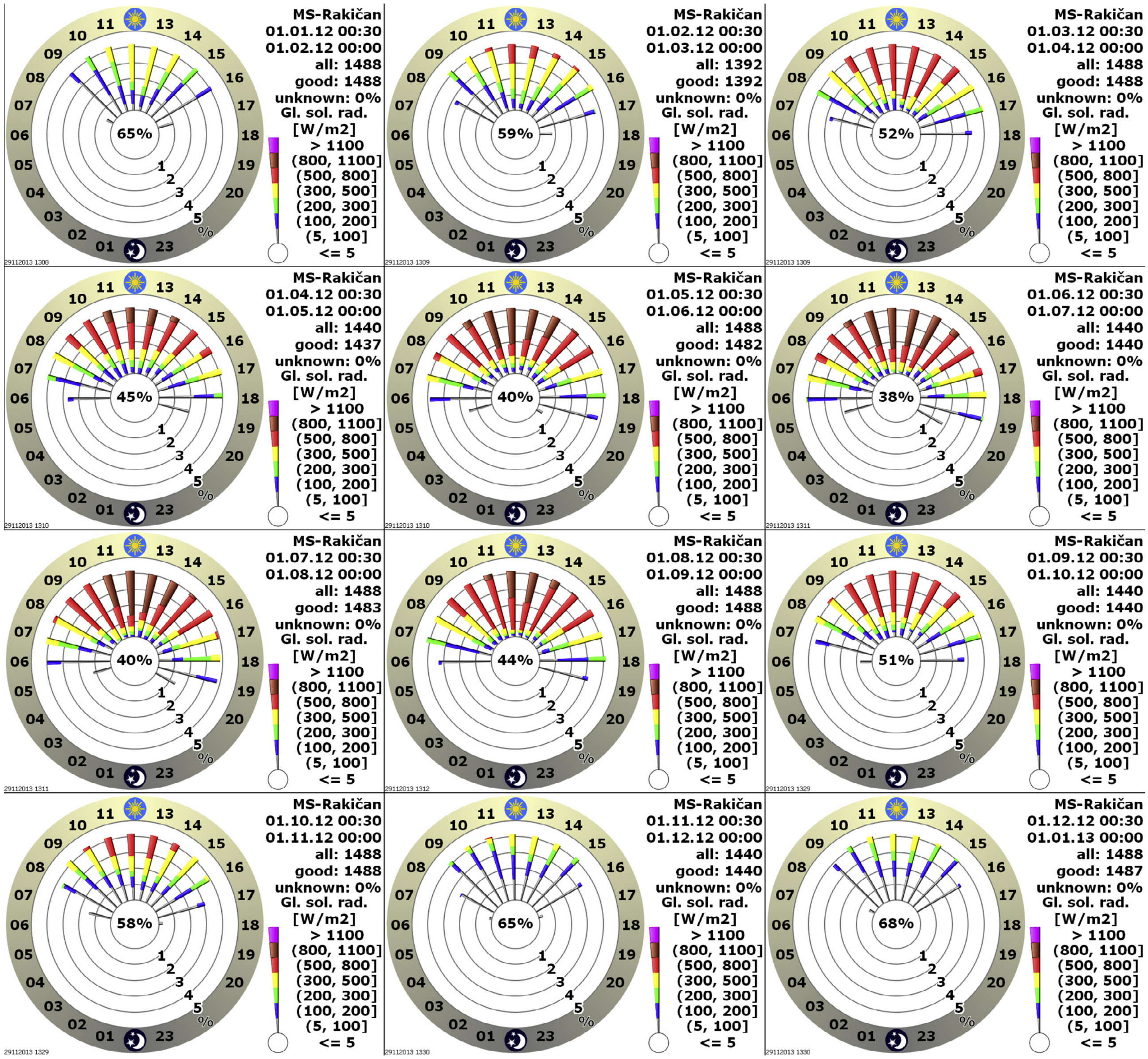

Fig. 4. Monthly variations of global solar radiation at the Rakičan station (near the town of Murska Sobota in Slovenia) in the form of sunflowers within a period of one year. Percentage of the dark part of the days following the sunrise–sunset yearly changes is clearly shown.

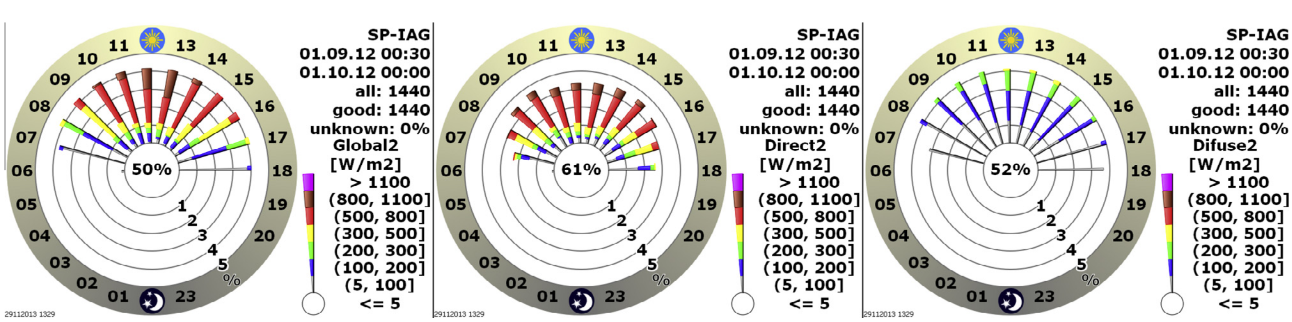

Fig. 5. Sunflowers of global, direct and diffuse solar radiation at the Sao Paulo station (Brazil) for September 2012.

cases at the WindyStation location, therefore this location is not suitable for the installation of a wind turbine. If there were no other available power sources for this location this kind of energy source would only be available between 10:00 and 18:00, but also at these times with a low probability of more than 30 kW.

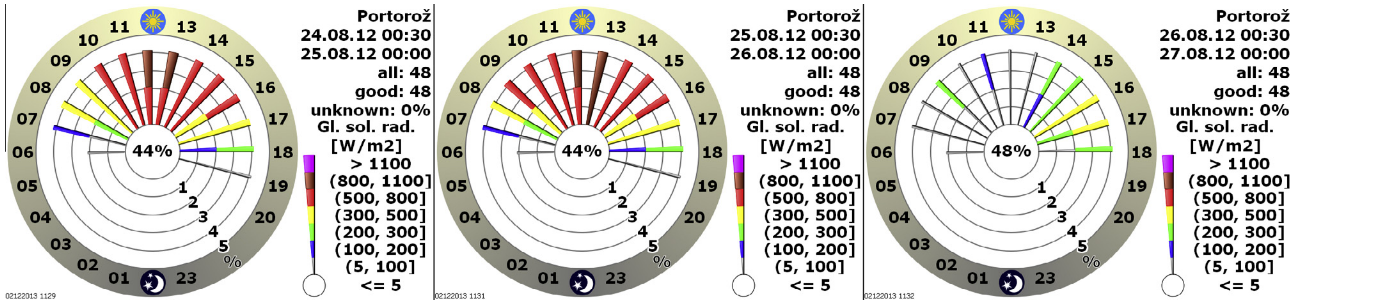

Fig. 6. Sunflowers of the global solar radiation for three consecutive days from a randomly selected week at the Portorož coastal airport location (Slovenia), 2 sunny and 1 very cloudy days.

Fig. 7. The photovoltaic solar power plant installed on the roof of the administrative building of the "Frbežar" nursery garden.

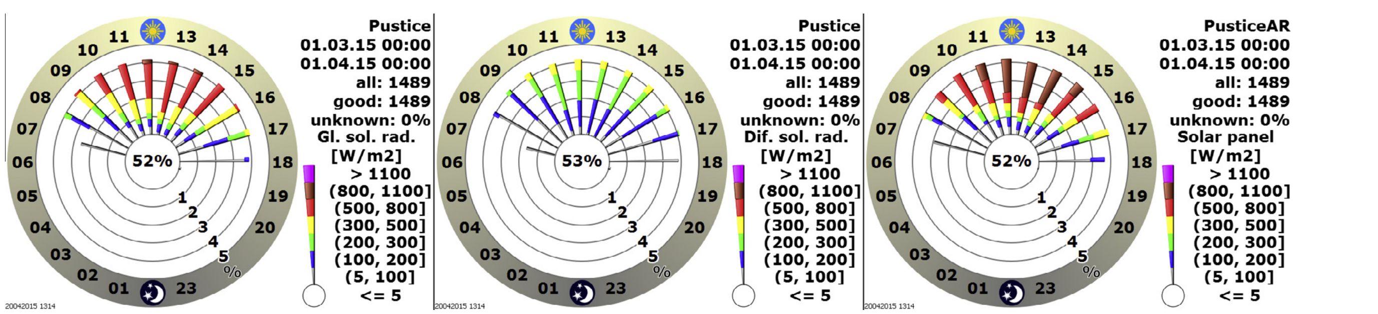

Fig. 8. A one month elaboration of the measured global solar radiation (left figure), the calculated diffuse solar radiation (middle figure) and the calculated solar energy for the tilted (45 degrees) plane facing south (right figure) at the location Pustice for March 2015. Energy on the square metre of the tilted plane is calculated as a sum of ¾ of the isotropic diffuse solar radiation and the scalar product of the unit vector of the position of the sun in the sky and the unit vector of the tilted plane divided by cosines of the zenith angle of the sun and multiplied by the direct solar radiation (based on a paper by Rakovec et al. [20]).

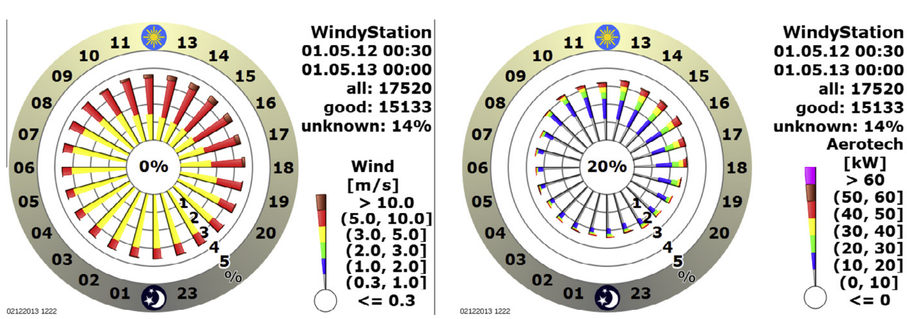

Fig. 9. Energy production forecast using a small vertical wind turbine. The sunflower of (a) wind intensity and (b) the Aerotech company wind turbine power as a hypothetical electricity production at a fictional location WindyStation.

3.4. Weather forecast presentation

The sunflower diagram is even more useful, however, for a clear-cut weather forecast display, as a single image can be used to display the diurnal variability of sun availability in detail, which is a key component for both detailed planning tourism and agricultural activities. The weather forecast example presented in Fig. 10 shows the precipitation, sun and cloud cover forecasts for the day 10.08.2013 for the location "Pustice" in the central part of Slovenia on a partially cloudy day. Between 03:00 and 05:00 in the morning there will be slight to moderate rain. Between 00:00 and 09:00 in the morning it will be moderately cloudy and between 09:00 and 14:00 only slightly cloudy. After 14:00 there will be clear sky and therefore the sun's intensity will be the highest between 09:00 and 16:00. MEIS's weather forecast system is documented in the paper by Božnar et al. [7] and available on-line at the web page http://www.kvalitetazraka.si/zasavje/index.php?lang=en.

3.5. Other atmospheric parameters presentation

The sunflower diagram can be applied to other atmospheric parameters that exhibit daily patterns. In such applications it enables finding the time dependent features of the phenomena under investigation. Examples of such analysis follow.

The sunflower can be used for various atmospheric parameters, green energy production or even the number of tourists visiting a determined place. The sunflower can be used to reveal the diurnal cycle characteristics for practically any quantity whose behaviour in individual hours of the day is of interest for study.

Fig. 11 shows the analysis of a one year (2012) diurnal cycle of the wind intensity at the Brnik location, where it is important to know the wind pattern due to the presence of an international airport. Winds in the brown class (above 10 m/s) are dangerous for aircraft landings because there is only one runway available. But in 2012 there were no so strong winds. Wind speeds in the red class (5-10 m/s) show a potential risk which will most probably occur between 12:00 and 17:00 and with a very low probability might appear in any other period of the day.

The monthly sunflower diagrams of the measured PM10 (dust) concentrations in the ambient air at the Celje location (a town in the rugged terrain of central Slovenia) during a one year period for 2012 are presented in Fig. 12. The analysis results for the months January, February, March, November and December show the appearance of concentrations greater than 50 μg/m^3 of PM10 during the whole day and a very small percentage of all measuring intervals (18%) of clean air (PM10 concentrations less than 10 μg/m^3). May is the only month when higher PM10 concentrations over 40 μg/m^3 are almost impossible. From the beginning of April until the end of October with the exception of May, higher concentrations of over 40 μg/m^3 can appear most probably in periods of the day from 06:00 until 11:00 and from 18:00 until 23:00.

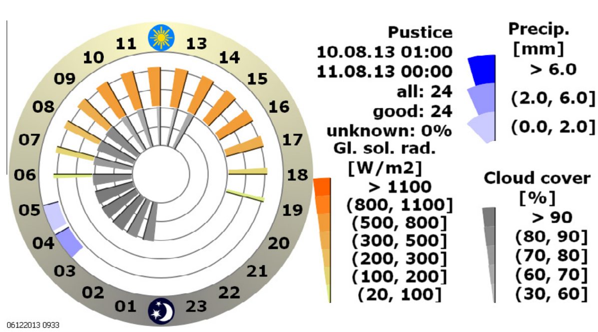

Fig. 10. Weather forecast example for the Pustice location on a partially cloudy day. On the same diagram, data about clouds, rain and solar radiation are combined.

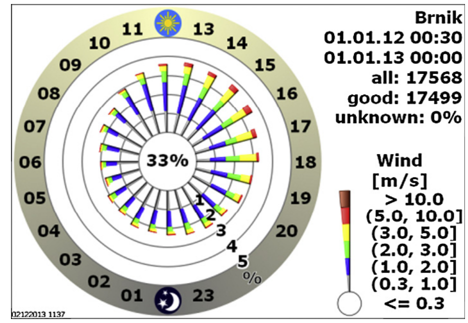

Fig. 11. A sunflower diagram of the wind intensity at the Brnik national airport location (Slovenia) for a 1 year period; calm within any hour is counted in the middle circle.

In other periods of the day the probability of clean air is much higher, so these intervals are very suitable for ventilating apartments and performing outdoor activities. Such presentations can be very useful for finding the relationships between air pollution and the related meteorological parameters (important questions of this kind are addressed, for instance, in a paper by Petelin et al. [10]).

The sunflower diagram for relative humidity data can be useful for agricultural and tourism purposes. The diurnal distribution of the measured relative humidity at the continental location of Rakičan and the coastal location of Portorož for August 2012 is presented in Fig. 13. A relative humidity above 90% only rarely occurs at the coastal location of Portorož. At the continental location of Rakičan such a high relative humidity represents a significant part of the measured relative humidity between 23:00 and 07:00. Between 09:00 and 12:00 a relative humidity above 60% is very rare for the coastal station while for the continental location this is a typical weather situation. According to all the measured values in August the portion of the measured relative humidity of the grey class (40–50%) is higher at the Portorož station than at Rakičan, while below 40% it is practically the same in both locations. From this it can be concluded that the coastal location is much drier than the continental location in August during the whole day.

3.6. Presentation of information for traffic and fuel consumption optimisation

An interesting "deviation" of the sunflower's usage can be made for traffic data presentation. Traffic is one of the world's most important energy usage process. Traffic smoothness significantly lowers the energy consumption. On the other hand traffic congestions increase energy consumption and also cause other negative effects such as air pollution.

Comprehensive information about traffic is a basic tool for drivers to adjust their route in such a way that it reduces the negative effects.

Fig. 14 shows a diurnal diagram of expected traffic for a fictional road A23 and the location "Zakotje" for 18 December 2013. Between 07:00 and 09:00 local time (LT) and between 14:00 and 17:00 LT a traffic congestion is expected that will be in the worst case more than 2 km long. At the same time the highest level of traffic is also expected which will reach its maximum between 08:00 and 09:00 LT and between 15:00 and 16:00 LT. Heavy vehicles' traffic shows a different diurnal distribution, only appearing between 06:00 and 24:00 LT, and its highest concentration is expected between 09:00 and 12:00 LT. After 19:00 LT the heavy vehicle traffic is significantly reduced. Such a presentation of traffic data has an important time dimension (hour of the day) which is missing in other traffic presentations such as the well-known Google Traffic application.

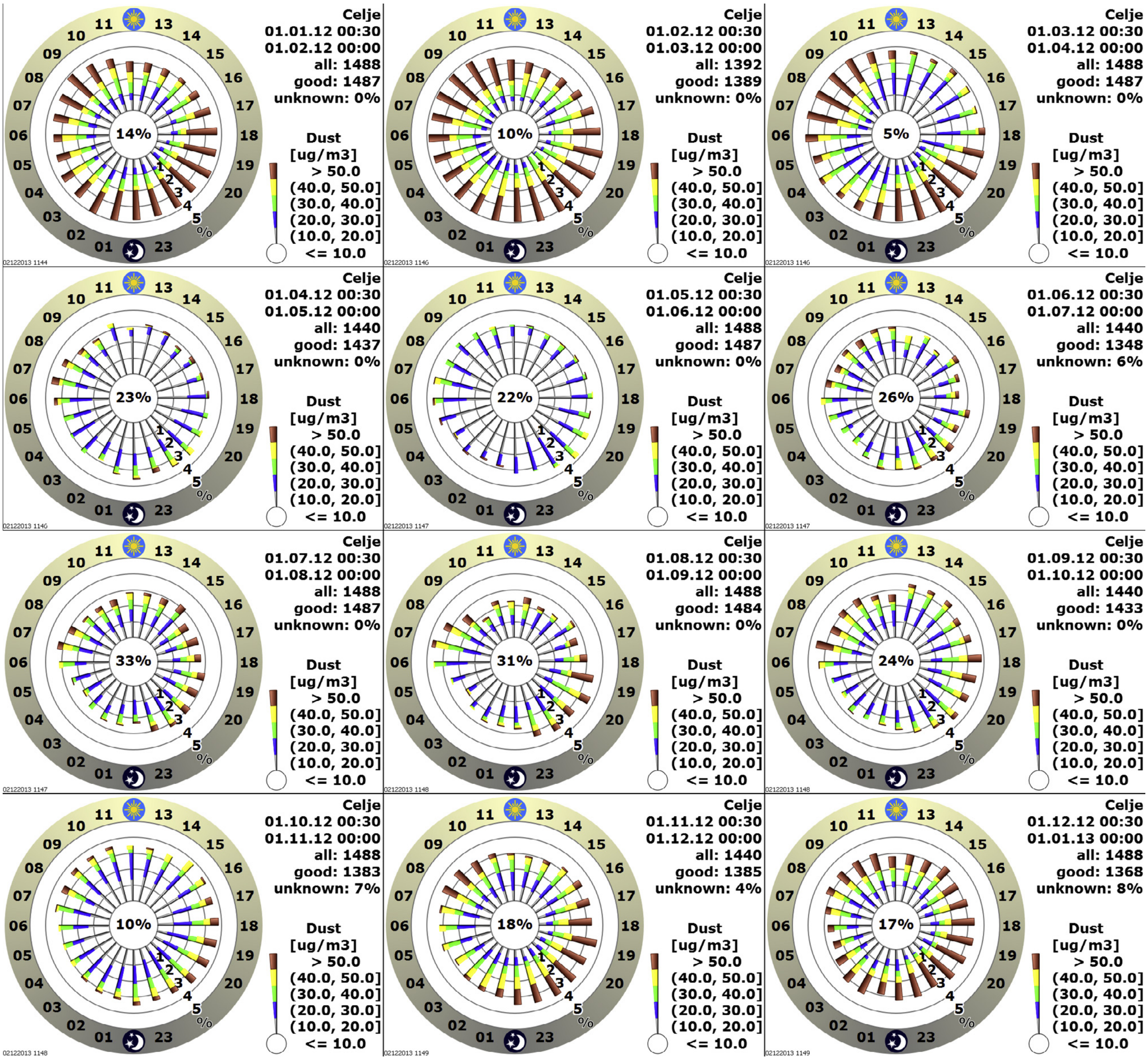

Fig. 12. Monthly sunflower diagrams of PM10 (dust) concentrations in the ambient air at the Celje location (a town in Slovenia) during one year. The diagrams clearly show at which time of the day people in the town centre can ventilate their apartments to get relatively clean air (the colour codes of the lower two classes indicate not so much polluted air, and the clean air of each hour is counted in the inner circle). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

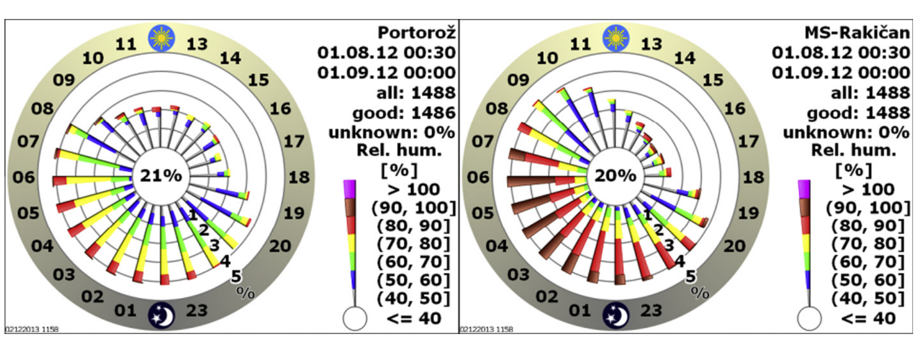

Fig. 13. A sunflower diagram of the relative humidity at the continental location of Rakičan and the coastal location in Portorož (Slovenia). The pleasant dry atmosphere of each hour is counted in the middle circle.

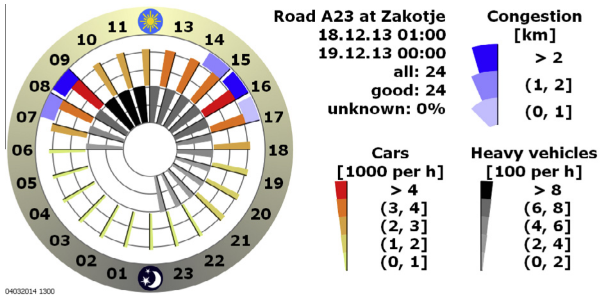

Fig. 14. The diurnal diagram of the expected traffic for a fictional road A23 and the location "Zakotje" for the day 18.12.2013.

3.7. Discussion of the sunflower used for solar and wind energy availability and atmospheric parameters analysis

In the 12 months' analysis in Fig. 4, it is shown how unique patterns representing global solar radiation availability vary within the months of the year. For each month, the time interval and percentage of the dark part of the day is shown. In addition, the distribution of the classes of high and low global solar radiation is easily comparable from month to month.

The information presented is a comprehensive way of presenting global solar radiation climatological features. Fig. 5 shows a monthly analysis of global solar radiation components (direct and diffuse). The relative frequencies of the composition are given for every hour of the day. The maximum nominal values that may be expected in each hour are presented. If a sunflower for global solar radiation is used for a single day's display as shown in Fig. 6 it is a new way of weather forecast presentation that shows one day's weather hour by hour in an intuitive way suitable for usage for the general public. Its upgrade with cloud and precipitation data is shown in Fig. 10. Both diagrams (Figs. 6 and 10) are suitable for usage for the general public instead of/or as complementary information to the current pictograms (picture of a sun with a cloud or rain droplets or snowflakes).

Its application in other atmospheric parameters (air pollution, relative humidity, wind) demonstrate the wide range of usage possibilities. Among the most important ones are the applications for green energy production such as wind turbines (Fig. 9) and photovoltaic solar power plants (Fig. 8). For green energy production, statistical information for short or long periods can be shown in a single sunflower diagram. Such a sunflower diagram shows the expected energy production in each hour of the day which is basic information for electricity grid control procedures and also for financial matters regarding the purchase of electricity.

An example of sunflower usage for traffic information presentation (Fig. 14) shows a more sophisticated way of how a sunflower diagram can contribute to lowering fuel consumption.

4. Conclusions

The sunflower is a radial frequency diagram used to display the statistical frequency of the occurrence of different classes of a physical parameter, which exhibit a daily cyclic nature. The diagram is based on two-dimensional data sorting. Firstly data are sorted into classes representing the hours in a day. Then the data in each hourly class is sorted into classes of the observed variable values. The relative frequencies of the value classes are shown as sections on each hour's segment in a radial diagram. The radial diagram forms a unique pattern for each analysed dataset. Therefore it enables quick features' detection and the comparison of several such patterns belonging to the different datasets being analysed.

The main characteristic of the sunflower diagram is that it provides information on the diurnal behaviour patterns of a chosen parameter in an intuitive and straightforward manner, even to those not familiar with mathematical periodic signal analysis tools.

In addition, the graphical representation enables the simultaneous comparison of a large quantity of parameters, as each parameter is displayed using a different diagram and a comparison of the diagrams can reveal subtle differences among the parameters or among multiple temporal diagrams for the same parameter.

The use and informative value of the sunflower has been illustrated using the example of an analysis of measured global and diffuse solar radiations for different locations (from rural to urban, from flat to rugged terrain) in Slovenia and Brazil. Its values, over the conventional methods such as the Fourier analysis or one dimensional histograms, were described and illustrated.

The display method is also useful for quickly screening measured or predicted parameters for quality assurance and quality control purposes. By systematically drawing all the known data or its subsets, it is possible to discover deviations from the expected or normal behaviour and find any potential extraordinary events and patterns, or errors. This method of searching for errors is especially suitable when dealing with large quantities of data which follow a diurnal cycle and which is difficult to examine using a line graph or through a consecutive numerical examination.

The sunflower is not only limited to energy, agronomy and atmospheric sciences, but it can also be useful in medical issues as the investigation of the diurnal cycle of a heart stroke [21,22] and social sciences, such as in studies on the characteristics of diurnal visits to tourist attractions or shops.

The sunflower display method can also be used for any physical or even any other parameter, such as the number of tourists visiting a popular attraction which exhibits diurnal variations and for which the display of an hourly variability is of interest. Sunflower diagrams are also important because they provide a straightforward graphical display of the behavioural similarities between different parameters. For example, a particulate matter air pollution diagram can be a complement to a diffuse solar radiation diagram.

Besides the solar radiation data there are different potential uses of sunflower variants in other fields, from climatology to tourism.

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References

[1] Furlan C, de Oliveira AP, Soares J, Codato G, Escobedo JF. The role of clouds in improving the regression model for hourly values of diffuse solar radiation. Appl Energy 2012;92:240–54.

[2] Soares J, de Oliveira AP, Božnar MZ, Mlakar P, Escobedo JF, Machado AJ. Modeling hourly diffuse solar radiation in the city of São Paulo using neural network technique. Appl Energy 2004;79:201–14.

[3] Kraemer D, Poudel B, Feng HP, Caylor JC, Yu B, Yan X, et al. High-performance flat-panel solar thermoelectric generators with high thermal concentration. Nat Mater 2011;10:532–8. http://dx.doi.org/10.1038/nmat3013.

[4] Zhou W, Lou C, Li Z, Lu L, Yang H. Current status of research on optimum sizing of stand-alone hybrid solar–wind power generation systems. Appl Energy 2010;87(2):380–9.

[5] Watson JG. Visibility: science and regulation. J Air Waste Manage Assoc 2002;52:628–713.

[6] Liepert BG. Observed reductions of surface solar radiation at Sites in the United States and worldwide from 1961 to 1990. Geophys Res Lett 2002;29(10). http://dx.doi.org/10.1029/2002GL014913.

[7] Božnar MZ, Mlakar P, Grašič B. Short-term fine resolution WRF forecast data validation in complex terrain in Slovenia. Int J Environ Pollut 2012;50(1/4):12–21.

[8] Skamarock WC, Klemp JB, Dudhia J, Gill D, Barker D, Dudhia M, et al. A description of the Advanced Research WRF Version 3, NCAR Tech. Note, NCAR/TN-475+STR 2008, 113pp.

[9] Hu XM, Nielsen-Gammon JW, Zhang F. Evaluation of three planetary boundary layer schemes in the WRF model. J Appl Meteor Climatol 2010;49:1831–44. http://dx.doi.org/10.1175/2010JAMC2432.1.

[10] Petelin D, Grancharova A, Kocijan J. Evolving Gaussian process models for prediction of ozone concentration in the air. Simul Model Pract Theory 2013;33:68–80.

[11] Ruiz JJ, Saulo C, Nogués-Paegle J. WRF model sensitivity to choice of parameterization over South America: validation against surface variables. Mon Weather Rev 2010;138:3342–55. http://dx.doi.org/10.1175/2010MWR3358.1.

[12] Cooley JW, Tukey JW. An algorithm for the machine computation of the complex Fourier series. Math Comput 1965;19(April):297–301.

[13] Saxton JL. Report on the Millau Viaduct. In: Proceedings of Bridge Engineering 2 Conference; 2007.

[14] DK Publishing. Complete atlas of the world. 2nd ed. New York, USA: Dorling Kindersley Publishing; 2012; 432p. ISBN: 978-0756689728.

[15] Greenhood D. Mapping. The University of Chicago, USA 1964; ISBN 0-226-30697-6.

[16] Lisac I, Zelenko B. Advantages and disadvantages of statistical wind rose analysis. In: Internationales Dr. F. Sauberer Gedichtnissymposium, Univ. f. Bodenkultur, Wien; 1985. p. 161–3.

[17] Zelenko B, Lisac I. On the statistical wind rose analysis. Theor Appl Climatol 1994;48(4):209–14. http://dx.doi.org/10.1007/BF00867051.

[18] Ferreira MJ, de Oliveira AP, Soares J, Codato G, Barbaro EW, Escobedo JF. Radiation balance at the surface in the city of São Paulo, Brazil: diurnal and seasonal variations. Theoret Appl Climatol 2012;107:229–46.

[19] Oliveira AP, Soares J, Božnar MZ, Mlakar P, Escobedo JF. An application of neural network technique to correct the dome temperature effects on pyrgeometer measurements. J Atmos Ocean Technol 2006;23:80–9.

[20] Rakovec J, Zakšek K, Brecl K, Kastelec D, Topic M. Orientation and tilt dependence of a fixed pv array energy yield based on measurements of solar energy and ground albedo – a case study of slovenia. In: Dr. Giridhar Kini (Ed.), Energy management systems. InTech; 2011. http://dx.doi.org/10.5772/18386, ISBN: 978-953-307-579-2.

[21] Argentino C, Toni D, Rasura M, Violi F, Sacchetti ML, Allegretta A, et al. Circadian variation in the frequency of ischemic stroke. Stoke 1990;21:387–9. http://dx.doi.org/10.1161/01.STR.21.3:387.

[22] Gyh L, Tan E, Lau C, Kamath S. Diurnal variation in stroke onset in atrial fibrillation. Stroke 2001;32:1443–8. http://dx.doi.org/10.1161/01.STR.32.6.1443.