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Graphical abstract

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Web tools concerning performance analysis and planning support for solar energy plants starting from remotely sensed optical images

Marco Morelli [a,*], Andrea Masini [b], Fabrizio Ruffini [c], Marco Alberto Carlo Potenza [a]

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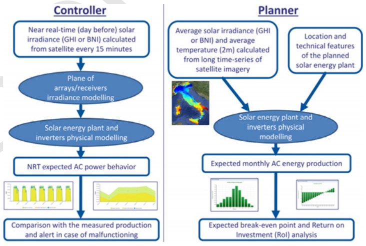

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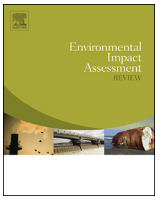

Highlights

Environmental Impact Assessment Review xxx (2014) xxx–xxx

Web tools concerning performance analysis and planning support for solar energy plants starting from remotely sensed optical images

Marco Morelli [a,*], Andrea Masini [b], Fabrizio Ruffini [c], Marco Alberto Carlo Potenza [a]

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- We developed an online service (Controller) dedicated to solar energy plants real-time monitoring
- We developed an online service (Planner) that supports the planning of new solar energy plants
- The services are based on the elaboration of satellite optical imagery in near real-time
- The validation with respect to in-situ measured hourly AC power data for three test solar plants shows a good accuracy: the overall Normalized Bias (NB) is −0.41%, the overall Normalized Mean Absolute Error (NMAE) is 4.90% , the Normalized Root Mean Square Error (NRMSE) is 7.66%, the overall Correlation Coefficient (CC) is 0.9538
- The maximum value of the Normalized Absolute Error (NAE) is about 30% and occurs for time periods with highly variable meteorological conditions

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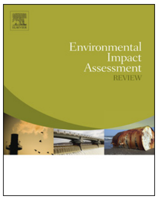

Web tools concerning performance analysis and planning support for solar energy plants starting from remotely sensed optical images

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ABSTRACT

We present innovative web tools, developed also in the frame of the FP7 ENDORSE (ENergy DOwnstReam SErvices) project, for the performance analysis and the support in planning of solar energy plants (PV, CSP, CPV). These services are based on the combination between the detailed physical model of each part of the plants and the near real-time satellite remote sensing of incident solar irradiance.

Starting from the solar Global Horizontal Irradiance (GHI) data provided by the Monitoring Atmospheric Composition and Climate (GMES-MACC) Core Service and based on the elaboration of Meteosat Second Generation (MSG) satellite optical imagery, the Global Tilted Irradiance (GTI) or the Beam Normal Irradiance (BNI) incident on plant's solar PV panels (or solar receivers for CSP or CPV) is calculated. Combining these parameters with the model of the solar power plant, using also air temperature values, we can assess in near-real-time the daily evolution of the alternate current (AC) power produced by the plant. We are therefore able to compare this satellite-based AC power yield with the actually measured one and, consequently, to readily detect any possible malfunctions and to evaluate the performances of the plant (so-called "Controller" service). Besides, the same method can be applied to satellite-based averaged environmental data (solar irradiance and air temperature) in order to provide a Return on Investment analysis in support to the planning of new solar energy plants (so-called "Planner" service).

This method has been successfully applied to three test solar plants (in North, Centre and South Italy respectively) and it has been validated by comparing satellite-based and in-situ measured hourly AC power data for several months in 2013 and 2014. The results show a good accuracy: the overall Normalized Bias (NB) is −0.41%, the overall Normalized Mean Absolute Error (NMAE) is 4.90%, the Normalized Root Mean Square Error (NRMSE) is 7.66% and the overall Correlation Coefficient (CC) is 0.9538. The maximum value of the Normalized Absolute Error (NAE) is about 30% and occurs for time periods with highly variable meteorological conditions.

Introduction

Context

One of the major global challenges in the near future is how to provide energy in abundance, and to be able to provide this energy from sources with a limited impact on the environment. The electricity consumption in the European Union has been estimated to rise by 50% from 2000 to 2020 (Eicker, 2003) and the exploitation of renewable energy in an efficient as possible way is fundamental to face the energy demand avoiding a strong increase of air pollution.

An effective and tangible approach to solve the energy production problem, used in Italy and in other countries, involves an improvement of the use of the solar energy solution. This could be also favoured by the introduction of specific laws. The solar energy production potentialities are well known, but they have begun to be fully developed only in recent years. Given the large variability, non-easily predictable, of the solar source, the planning and installation of new power plants require a careful a priori analysis. Therefore, the presence of services able to provide an accurate estimation of available energy sources is extremely important for the investors, that are given the possibility to evaluate the repayment plan when planning new plants. A service providing this kind of information can use standard techniques, such as in-situ measurements of the solar energy available in a certain location, but this kind of approach can be significantly expensive. On the contrary, cost reductions can be the strength of alternative approaches, such as planning support systems using data remotely sensed by satellites (Mueller et al., 2009).

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Furthermore, when the energy plant begins its activity, a service able to monitor the productivity of the plant so to improve it and increase the efficiency is necessary for cost reductions. An effective and low-cost approach is to use a service able to compare the power actual produced with the power predicted by a model. The model uses data from satellite to evaluate the environmental parameters needed to calculate the expected power production in well-functioning conditions.

"Planner" and "Controller" web tools

In order to face the problems related to planning and monitoring of solar energy plants described before, we developed two innovative web tools based on Earth Observation (EO) optical imagery: the "Planner" and the "Controller" services.

Both the services start from temporal series of solar GHI provided by the MACC Core Service, that is calculated from Meteosat Second Generation (MSG) optical imagery by means of the Heliosat-2 algorithm (Cano et al., 1986) and the ESRA model for clear-sky solar irradiance (Rigollier, 2000).

The "Planner" service consists of a web-GIS map showing average solar irradiance (Beam Normal Irradiance for CSP or CPV plants; Global Horizontal Irradiance for PV plants) and average air temperature, both obtained from historical satellite optical imagery archive (air temperature data lacks are filled by a spatial interpolation of the data provided by the meteorological stations of the Italian AirForce). The service shows the monthly averaged expected energy yield starting from site selection and planned plant technical features, providing also an estimate of the Return on Investment (break-even point and cumulative cash-flow).

The "Controller" service, instead, is in practice of an active solar plant production monitoring web-service that, starting from the near real-time calculation of the expected energy yield based on satellite-based incident solar irradiance, can provide a malfunctioning daily detection with an embedded email/SMS alerting system.

These services are currently available for PV, CSP and CPV plants. The spatial coverage comprises Italy, North-Africa and Qatar but it's going to be extended also to other regions (such as Brazil).

Methods

Both the "Planner" and the "Controller" web services are based on a similar scheme (as shown in Fig. 1): satellite-based irradiance data and air temperature data are set as inputs to a detailed physical model of the solar energy plant (PV, CPV or CSP) and of the inverters to calculate the expected AC power yield. The solar irradiance data have 4 km spatial resolution (in Italy) and 15 minute time resolution (following the MSG satellite resolution), whilst the air temperature data could have the same resolution if obtained from MSG or 30 km of spatial resolution and 3-hourly temporal resolution if obtained from Italian AirForce measured data.

The same scheme can be applied in the frame of the "Planner" service by using environmental data retrieved from historical long time-series of satellite imagery, whilst in the "Controller" service case the satellite-based data are elaborated in near real-time (i.e. with a maximum 24 hour delay and 15-min temporal resolution) to calculate the plant's performances for monitoring purposes. The plant's modelling part of the method, of course, is different depending on the type of solar energy plant of interest.

The interfaces of both services are based on web-GIS standards (such as GeoTIFF) and data are elaborated using also the PostgreSQL database with PostGIS extension.

CSP plants

A thermodynamic solar plant uses the direct solar radiation by reflecting it towards a concentrating point where a fluid is heated. The radiation intensity is hence a fundamental parameter for the plant planning and for its financial evaluation, but it is also a critical information in the operational mode of the plant, since it allows an accurate analysis of the plant performances.

The model has been developed in the frame of the FP7-ENDORSE project (Morelli et al., 2012) adapting existing approaches both for the modelling of the irradiance incident in the one-axis sun-tracking solar receivers (Perez et al., 1990) and for the performance analysis of CSP parabolic-trough plants (Qu et al., 2010; Powell and Edgar, 2012).

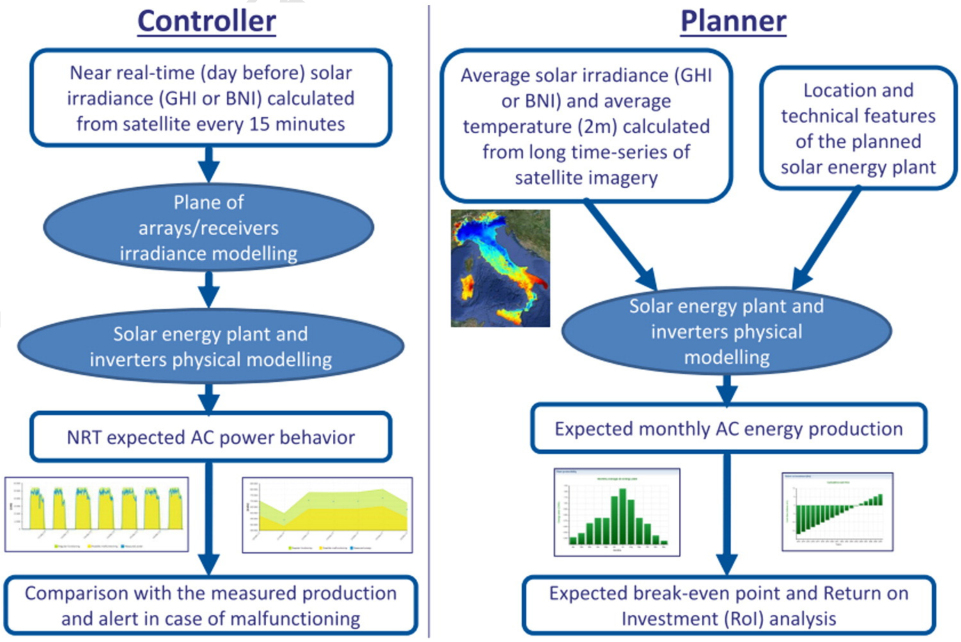

Fig. 1. General scheme of the "Controller" and "Planner" services dedicated to solar energy plants.

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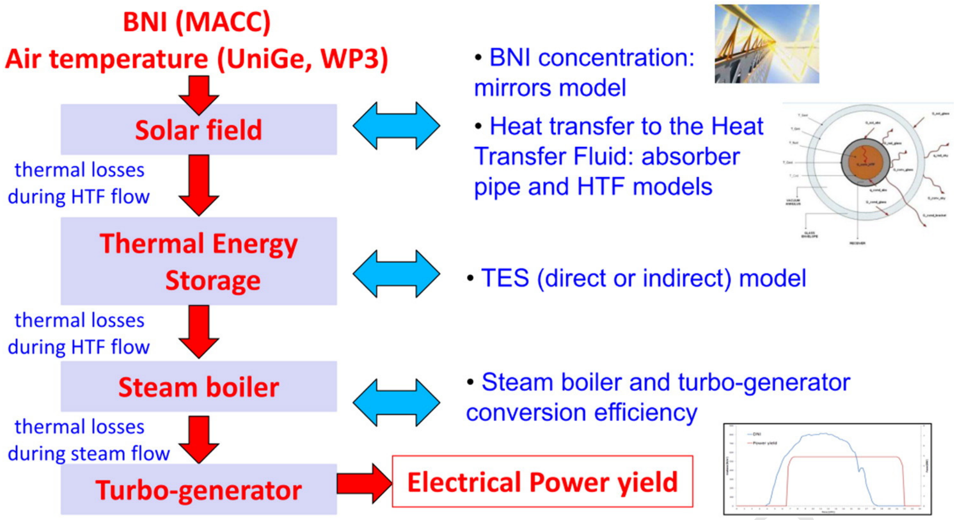

Fig. 2. Scheme of the model of parabolic-trough Concentrated Solar Power (CSP) plants used in the developed services.

The main parameters involved in the model are:

- the temperature and the flow rate of the heat-transfer fluid;
- the direct solar irradiance incident on the plane normal to sun rays (BNI) at ground level;
- the air temperature.

The algorithm (described schematically in Fig. 2) analyses the balance between the power absorbed by the fluid and the overall power losses, so the outputs of the whole modelling will be the following:

- The fluid temperature;
- The absorbed power;
- The power losses
- The instantaneous efficiency.

Other important aspects in the model are:

- Mirrors' optical characteristics (shape, reflecting properties);
- The film applied to the surface of the heat-concentrating pipe.

PV and CPV plants

The PV plants are typically composed by:

- Photovoltaic modules;
- Inverters.

The CPV plants are similar to the PV plants with the addition of:

- Reflecting mirrors or lenses concentrating the solar radiation on photovoltaic modules;
- Sun-tracking system to correctly orientate the reflecting mirrors.

In the case of these systems the environmental variable that mainly affects plant's performances is the solar irradiance absorbed by each PV module, that is proportional to the Global Tilted Irradiance incident on its plane.

Concentrating photovoltaic systems, instead, are usually divided into three categories: low, medium and high concentrations, based on the ratio between the effective area of the surface absorbing the solar radiation and the area of the modules where the radiation is concentrated. The photovoltaic systems with low concentration are the most used ones.

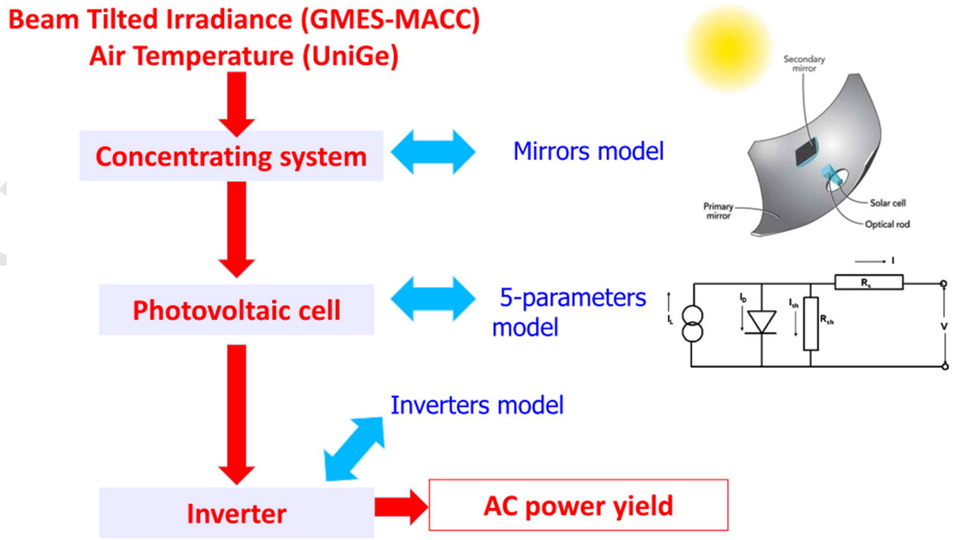

Fig. 3. Scheme of the model of Concentrating Photovoltaic (CPV) plants or Photovoltaic (PV) plants (avoiding the first part dedicated to concentrating system modelling) used in the developed services.

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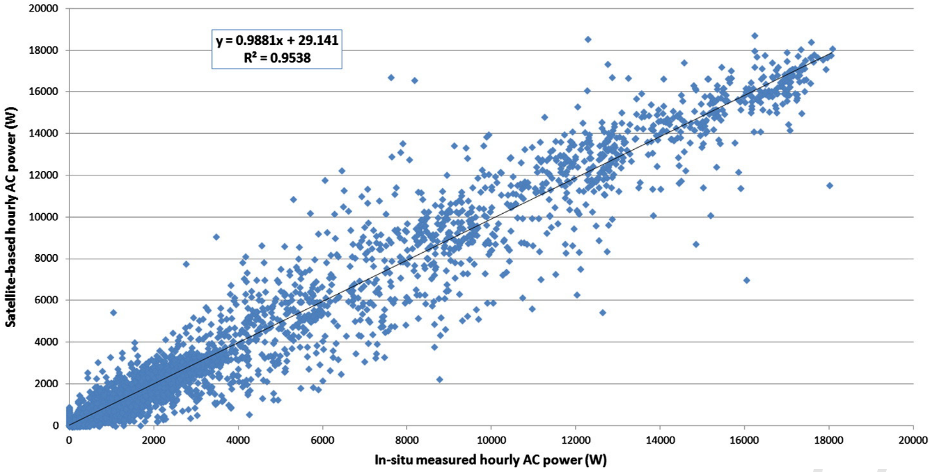

Fig. 4. Scatter plot comparing the hourly AC power produced by three different PV plants as calculated by the satellite-based method and as obtained from in-situ measured data. Source data are referred to a 4.86 kWp plant in Veneto (North Italy), a 3.89 kWp plant in Lazio (Centre Italy) and a 20.0 kWp plant in Sicily (South Italy). The considered periods are November 2013, January 2014, March 2014, May 2014, July 2014 and September 2014, for a total of 5383 time instants that range from 05:00 UTC to 20:00 UTC.

Similar to the CSP systems, the only solar radiation components that can be concentrated is the component direct incident on the plane normal to sun rays (BNI); the knowledge of this quantity is fundamental for planning and for financial evaluation of the costs, but is also a critical information in the operational mode of the plant, since it allows an accurate analysis of the plant performances.

The other two important aspects in the CPV plants are:

- the mirrors' shape;
- the photovoltaic modules.

Our modelling technique (schematically shown in Fig. 3) firstly models the Global Tilted Irradiance incident on the PV modules (PV case) or the Beam Normal Irradiance incident on the reflecting mirrors (CPV case) is following the approach described by (Perez et al., 1990) as above.

Then the solar energy plant is modelled in order to calculate the AC power yield. The PV modules used in the CPV plants are typically the same as the ones used in traditional PV systems and they have been modelled using an equivalent circuit with a (photovoltaic) current generator, connected in series with a resistance and in parallel with a diode and another resistance. This opto-electronic model of each PV cell has been taken from De Soto et al. (2006), whilst the modelling part concerning with the concentrating mirrors in the CPV case has been taken from Butler et al. (2012).

Results and discussion

We compared the hourly AC power (i.e. the hourly averaged AC power produced by the solar energy plant) calculated using the satellite-based methodology presented above and the in-situ measured one for three PV solar energy plants, respectively located in Veneto

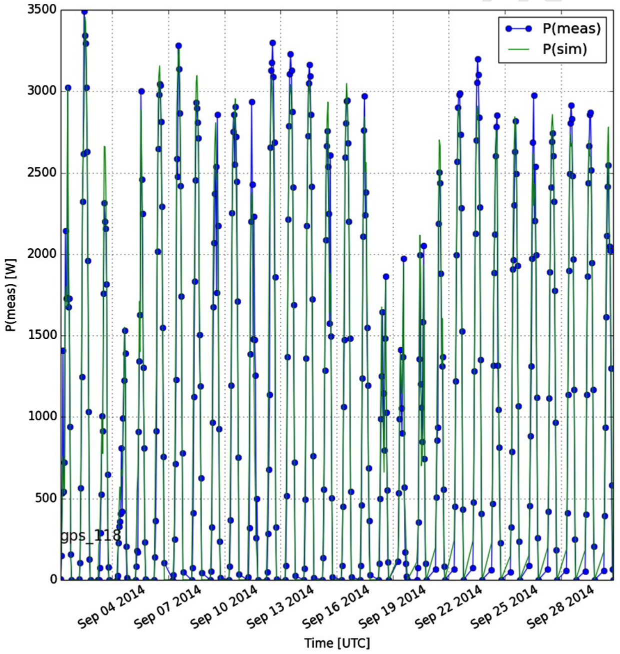

Fig. 5. Comparison between the behaviour of the satellite-based hourly AC power and the in-situ measured one. Data are referred to a single month (September 2014) for the PV plant in Veneto.

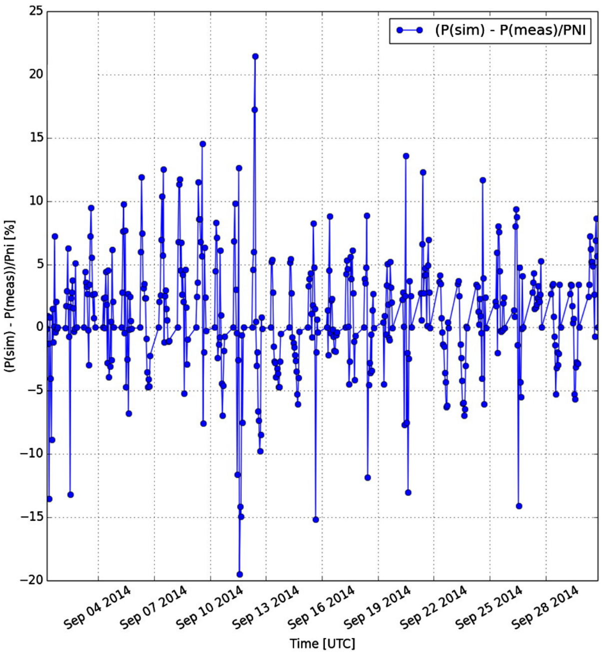

Fig. 6. An example of the behaviour of the NMAE resulting from the comparison between satellite-based and in-situ measured hourly AC power. Data are referred to a single month (September 2014) for the PV plant in Veneto.

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(North Italy), in Lazio (Centre Italy) and in Sicily (South Italy). We considered the hourly AC power data from 05:00 UTC to 20:00 UTC for November 2013, January 2014, March 2014, May 2014, July 2014 and September 2014 (considering all-seasons data). Since we have some lack of data, we considered a total of 5383 time instants.

The results obtained are shown in the scatter plot graph presented in Fig. 4. In Figs. 5 and 6 the results for one month for the Veneto plant have been reported, showing the comparison between the monthly behaviours of satellite-based and in-situ measured hourly AC power data (Fig. 5) and the related behaviour of the NMAE (Fig. 6) respectively.

The results show a good accuracy: the overall Normalized Bias (NB) is −0.41%, the overall Normalized Mean Absolute Error (NMAE) is 4.90%, and the Normalized Root Mean Square Error (NRMSE) is 7.66%. “Normalized” means that the statistical quantities reported here have been normalized with respect to the nominal power of each plant, i.e. 4.86 kWp, 3.98 kWp and 20.0 kWp respectively. The overall Correlation Coefficient (CC) is 0.9538. The maximum value of the Normalized Absolute Error (NAE) is about 30% and occurs for time periods with highly variable meteorological conditions.

The services are currently available online (an example of the web interface is shown in Fig. 7) and, in particular for PV plants, they have been already used satisfactorily by several customers (e.g. Enel Green Power, Martifer Solar, Global Power Service) in the last years.

Conclusions

The downstream services presented herein can be really useful for a great number of end-users like solar energy designers, building designers and solar energy plant installers and designers. Indeed the exploitation of satellite-based data could represent an optimal solution with lower costs and an only slightly lower accuracy with respect to solutions based on in-situ solar irradiance sensors (Forero et al., 2006; Papageorgas et al., 2013), avoiding also possible problems related to unpredictable malfunctions or dirtiness of sensors.

In particular the “PV-Planner” and “PV-Controller” services plants have been widely used and satisfied the end-users, whilst the web services dedicated to CSP and CPV are currently being provided in pre-market versions and will be launched on the market most probably in 2015.

Almost half hundred power plants in Europe have been constructed with the assistance of the PV-Planner (that in year 2011 has been used by more than 50,000 users) and currently more than 300 solar energy plants in Italy, Greece and South-Africa are being monitored by the PV-Controller system.

We found a great interest for these services, especially from the solar energy installers and designers, and we received generally good feedbacks. We received also a few suggestions for developing them further and to improve their usefulness.

The performances of these services could be further increased:

- improving the accuracy of the satellite-based irradiance data, in particular in highly variable meteorological conditions (e.g. forecasting the short-term cloud motion);
- including a ground albedo map with high accuracy and high spatial resolution;
- integrating a near-real-time map of air temperature (at surface) with high spatial and high temporal resolutions;
- knowing the intensity of each spectral component of the incoming solar radiation to modelling better the irradiance actually absorbed by the energy plant's solar panels/receivers.

Acknowledgments

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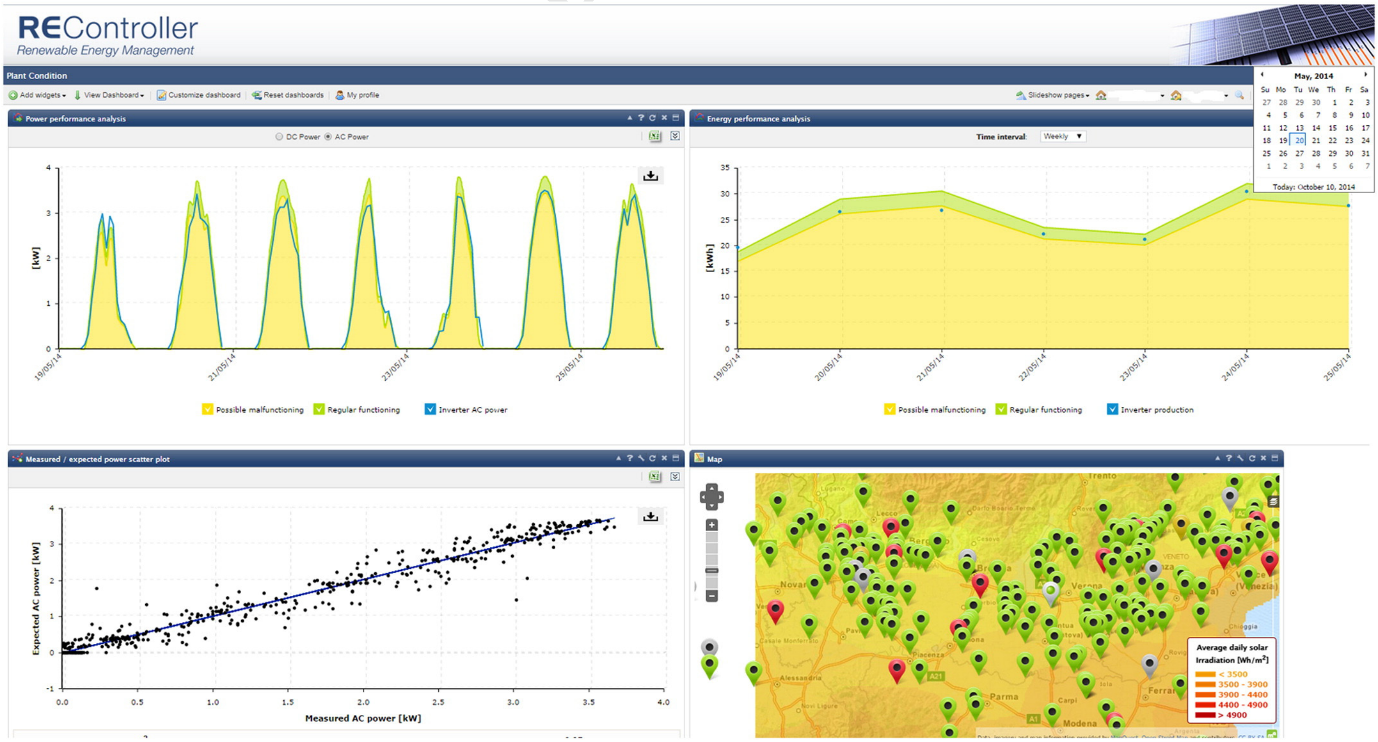

Fig. 7. An example of the web interface (dashboard) of the “Controller” service.

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data for east Sicily and the Italian AirForce (Aeronautica Italiana) for providing the air temperature data for the other regions covered by the service.

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