Synthesis of DNI time series with sub-hourly time resolution

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Abstract

The output of a CSP plant shows a non-linear response to the incoming direct normal irradiance. Due to inertia of the various sub-systems and part-load effects for a proper modelling of their energy yield, information on the DNI with high time-resolution is necessary down to the one minute scale. As this type of data is only scarcely available, tools for the synthetisation of these sets have to be applied. We have adopted a respective procedure for the use in the context of yield prediction. The performance of the procedure is, on the one hand tested for the statistical similarity of measured and synthesised data. On the other hand, the applicability of the synthetic sets is checked by comparing the outcomes of a transient plant simulation model for both types of data. The paper gives results from these tests and draws conclusions concerning further improvements of the scheme for the synthesis.

Keywords: DNI, synthesis of solar irradiance data, high temporal resolution data, dynamic simulation of solar thermal power plants

1. Introduction

For a precise analysis of CSP performance the knowledge of sub-hourly fluctuations of the incoming direct normal irradiance (DNI) is required. Respective measurements are, however scarce and satellite derived data a mostly supplied in 60 min time resolution. Thus, there is a need of procedures to generate synthetic time series to be used as input for system simulations. Within the framework of the SESK-project on standardization of yield prognosis of solar thermal power plants (A research project funded by the German Ministry of Environment and Reactor Safety - BMU) a procedure has been set up. It is based on the knowledge of the statistical characteristics of sub-hourly fluctuation of the DNI, drawn from measurements at locations in Spain, oriented by the scheme laid out by Skartveit and Olseth [1].

2. Statistical characteristics of DNI series with time resolution of one minute

For the statistical characterization of time series of irradiance data, the separation of systematic and stochastic components of the fluctuations is beneficial. This is commonly done by normalization with the values expected under clear sky conditions. This results in series of the clear sky indices k* and the beam clear sky indices k*dir for the global irradiance and the direct irradiance respectively. In [1] a multilayered scheme for modeling the probability density of both types of sets is given, with distribution parameters of the k*dir values linked to parameters of the k* distribution. For the characterization of the time series properties of the data, the autocorrelation coefficient is used solely. With the knowledge on the probability density and the autocorrelation characteristics, a procedure to synthesize data sets may be set up. Concerning minutely data of global irradiance and illuminance data, respective tools had been developed and applied (see e.g. [2]).

For simulations in view of the synthesis of data sets to be used as input for the modeling of concentrating solar power (CSP) plants, we have adopted a simplified approach to the Skartveit and Olseth [1] scheme.

2.1 Probability distribution

Probability densities of the k*dir values have been extracted from empirical data series. The k*dir values are calculated on the basis of a simple clear sky model, tuned to give a reasonable envelope of the measured DNI values. Fig. 1 shows an example for clear sky and measured minute by minute values for one day.

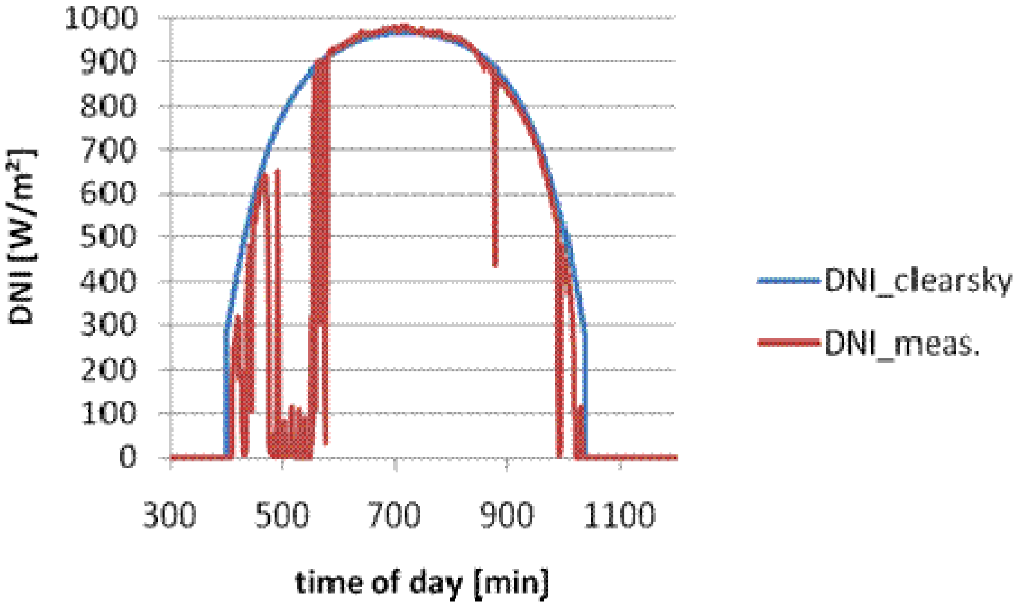

Fig 1: Series of measured DNI values with a time resolution of one minute together with a model for the values under clear sky condition.

Characteristic densities are gained for different sub-ensembles formed by data from different classes of hourly means characterized by k*dir. A class width of 0.1 is selected to achieve good separation. Fig. 2 gives the cumulative distributions of these sets.

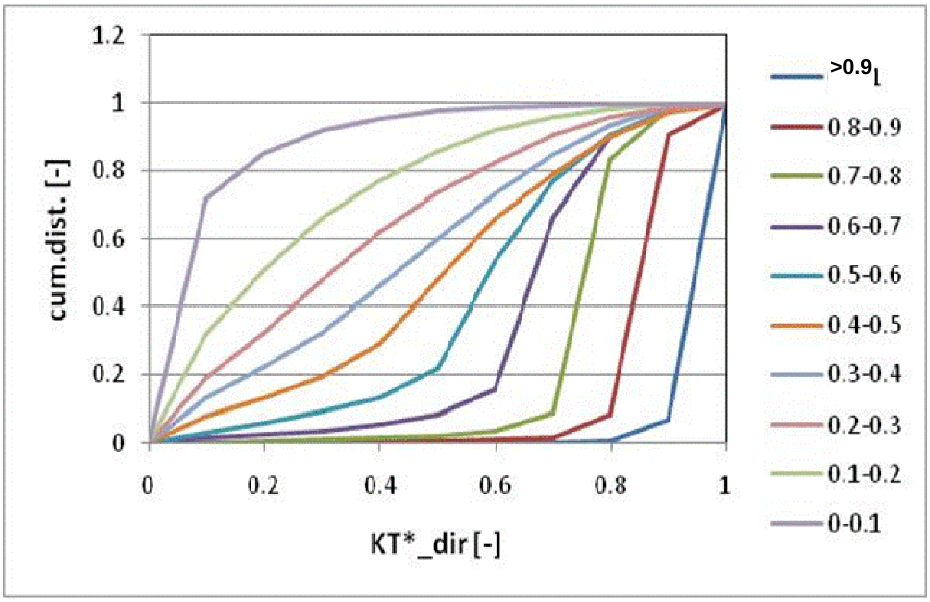

Fig: 2: Cumulative distributions of 1 minute values of the clear sky index. Curves refer to different classes of the hourly mean clear sky index (color labeling given on the right).

2.2 Time series characteristics

The autocorrelation coefficients are determined for the subsets as given above. Values of the coefficient range from < 0.6 for hours with a low hourly mean to values close to 1 for higher hourly means (see Table 1).

k*dir class	**0< k*dir < 0.1**	**0.1 < k*dir < 0.2**	**0.2 < k*dir < 0.3**	**0.3 < k*dir < 0.4**	**0.4 < k*dir < 0.5**	**0.5 < k*dir < 0.6**	**0.6 < k*dir < 0.7**	**0.7 < k*dir < 0.8**	**0.8 < k*dir < 0.9**	**0.9 < k*dir**
autoco. coeff.	**0.55**	**0.89**	**0.92**	**0.93**	**0.94**	**0.96**	**0.97**	**0.98**	**0.98**	**0.98**

Tab. 1: Autocorrelation coefficients for series of minutely k*dir values for different classes of hourly mean k*dir.

3 Data synthesis

Sets of synthetic DNI data are generated from synthetic k*dir sets together with the model of the clear sky DNI. The k*dir sets are synthesized using an autoregressive (AR1) process to establish a series with predetermined correlation characteristics. As this type of process results in a set of normally distributed values (with a target standard deviation of one), a subsequent mapping to a set with the desired probability distribution is necessary. This procedure (see Fig.3 for a scheme) is already used in schemes for the generation of sets of global clearness index data in different time domains. (see e.g. [2], [3]).

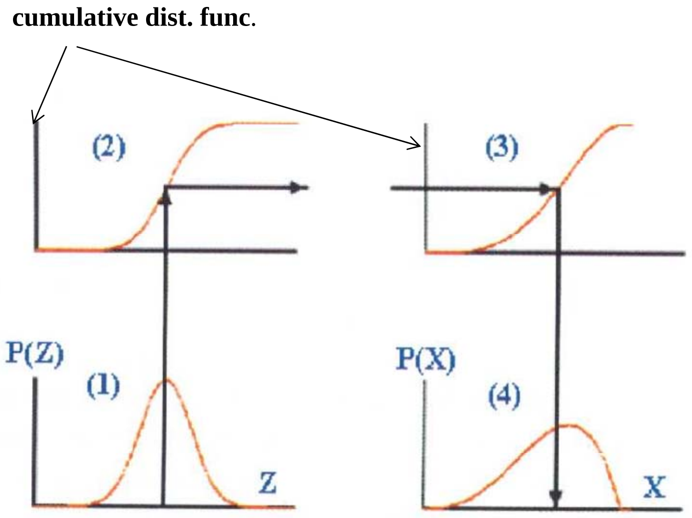

Fig. 3: Scheme for the mapping of data from a set showing a Gaussian distribution (left) to a set obeying a different distribution (right). Data are transferred according to the same rank in the cumulative distribution.

A respective tool, making use of the empirical distribution functions and autocorrelation coefficients, as shown above, is realized in a MATLAB application. Hourly mean k*dir values serve as input. It has to be remarked, that the synthesis has to be performed in a 'supervised' way in the sense that the new hourly sets are checked for their representation of the desired mean k*dir value and the intermediate normally distributed sets show a standard deviation close to one. To avoid extensive calculation time, for hours with mean k*dir values above 0.93, the procedure is suspended and all values are set to the hourly mean.

For the desired final use of the scheme, the hourly mean k*dir have to be taken from hourly data sets – either from ground station or satellite derived sources. This information has to go with an appropriate model for the respective clear sky values.

For the feasibility test of the proposed scheme, mean k*dir values are derived from the empirical sets , as shown above, and the resulting minutely k*dir sets are subsequently linked to the course of the clear sky DNI.. Fig. 4a and 4b show examples for empirical and synthesized sets of one minute DNI values.

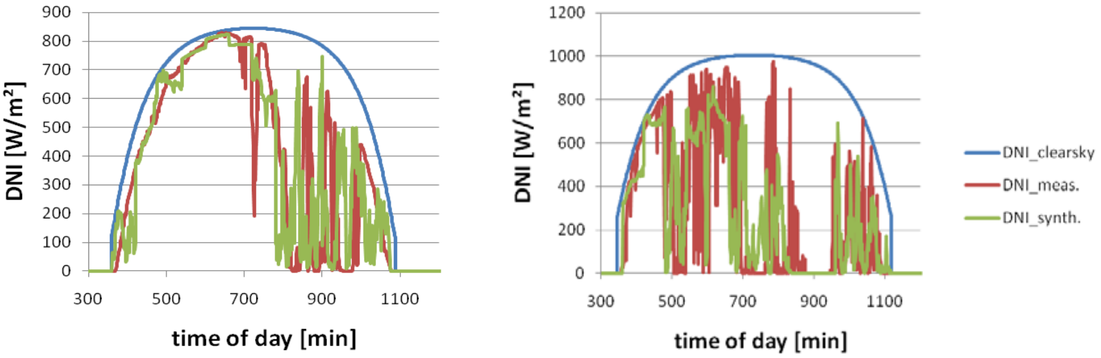

Fig. 4a,b: Time series of minutely DNI values. Shown are the course of the model for the clear sky DNI according to the model, the measured DNI values, and the synthesized sets. Synthesis is peformed on the bases of the hourly mean clear sky indices k*dir according to the measured set.

A closer view of the similarity of measured an synthetic sets is given by the comparison of the distribution functions of both sets. Fig.5 a-d give these curves for the DNI sets of four days. The accordance of measured and synthetic characteristics is mostly considered satisfactory. However, as can be seen in Fig.5d, major deviations may occur. Reasons for this may be traced back partly to the hourly resolution of the input to the synthesis process in conjunction with the intermittency of the fluctuation characteristics. This may call for a refinement of time series modelling beyond a homogeneous AR1 process.

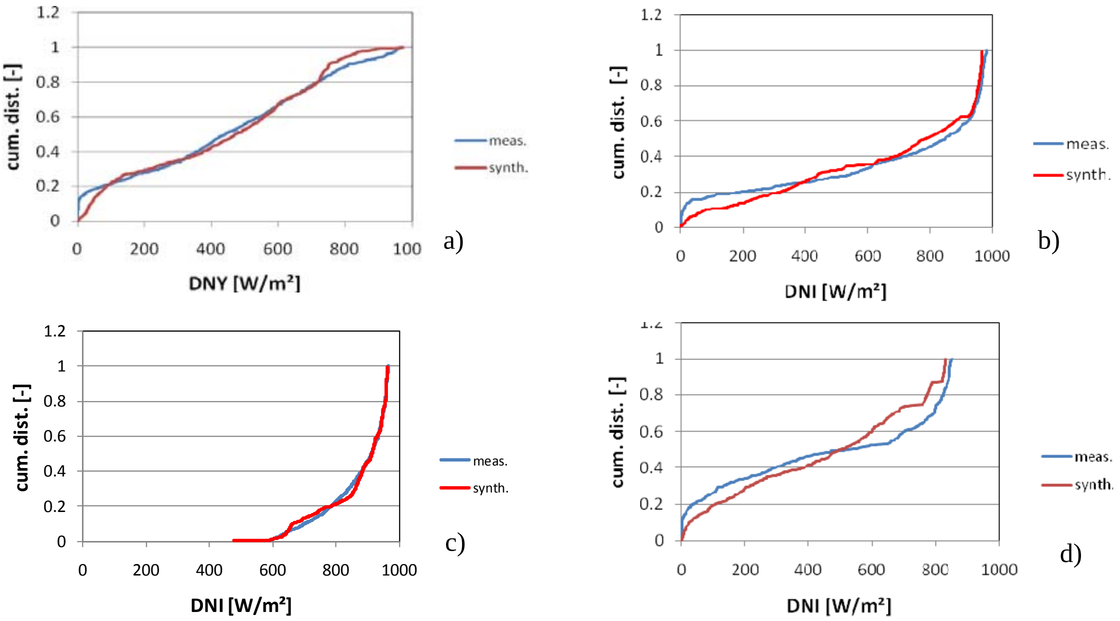

Fig. 5 a-d: Cumulative distributions of daily sets of measured and synthesized minutely DNI.

4. Validation

For a validation of this procedure in view of its intended final use, the synthetic sets are compared to measured sets by using both as input data for a dynamic model of a CSP plant. The plant model is built up in the Modelica/Dymola environment and is presented in the conference paper [5]. The model represents a plant, consisting of a solar field with152 loops with a total net aperture area of 492000 m² and a peak thermal output of 380 MW_{th}. The peak gross electricity production of the power block is 50 MW and the thermal energy storage providing a capacity for 7.5 nominal hours of plant operation.

From the high number of operation parameters of the plant, that are traced by Dymola, two key performance figures are selected as benchmark values for the comparison. These are the thermal energy gain from the solar field and gross electrical energy delivered by the plant. The second figure includes the production due to co- firing operation.

Runs have been performed using the data as described above. To get information of the sensitivity of the outcome to individual realisations of the synthetic sets, 3 runs of the data generation process have been performed for each day.

Fig. 6a,b give the time trace of the accumulated energy gains for one day (curves of the cumulative distributions of measured and synthesized data are given in Fig. 5a) : one for the measured set, 3 for the three synthetic realisations. In addition, the respective curve gained by a simulation run with hourly time resolution is given.

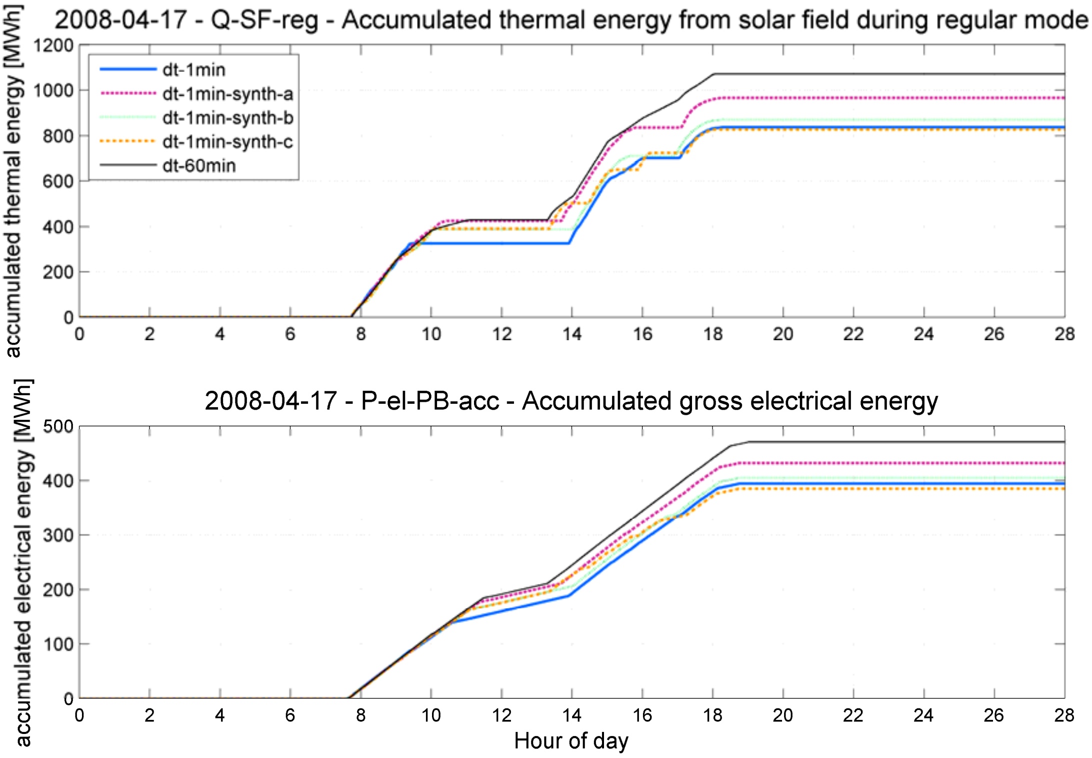

Fig. 6a (upper), 6b (lower): Daily time trace of the accumulated energy gain from the solar field (5a) and the accumulated electrical energy (5b) as simulated on the bases of measured and synthesized minutely DNI data sets and on a set with hourly time resolution. Data are for day 2008-04-17.

In that case the simulation based on hourly data overestimates both, thermal and electrical energy yield by about 20 %. The results for two of the synthetic sets are in close coincidence with the one for the measured data. The third synthetic sets shows an overestimation of the energy gains of about 15 %.

The same information for a second day are given in Fig. 7a and Fig. 7b. As for the previous case, calculation with hourly data leads to an overestimation of the energy gains (~20 %). In that case, all synthetic data fell short by overestimating the gains, however, less severe than for the hourly calculation. Looking on both, the curves for the cumulative distributions of measured and synthezised sets and the evolution of the DNI values over the day (Fig. 8) gives no direct hint for this general overestimation. Further analysis into the detailed time structure of the sets will be required to identify the cause of this incongruety.

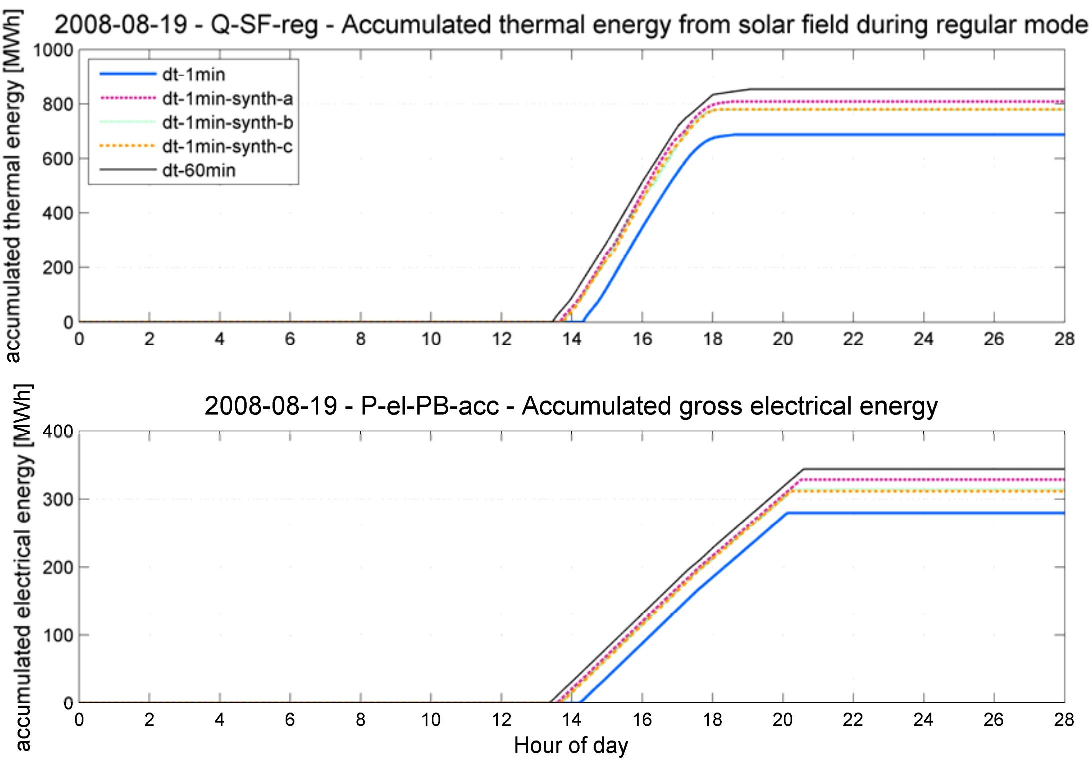

Fig. 7a (upper), 7b (lower): Same presentation as in Fig. 6a,b, but for day 2008-08-19.

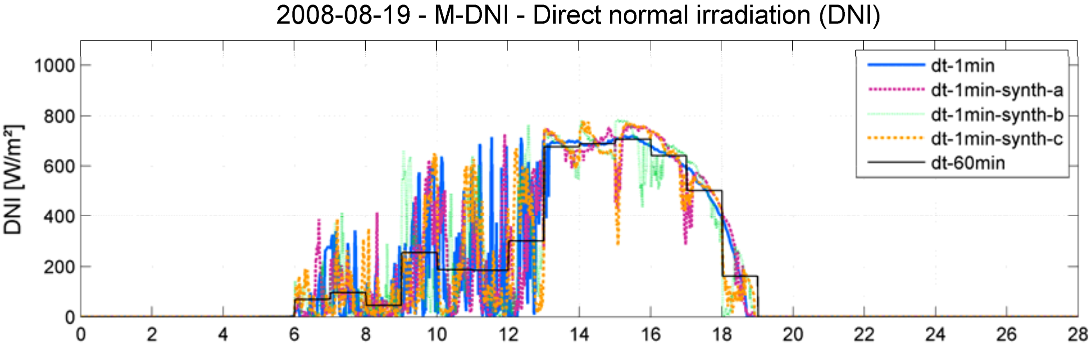

Fig. 8: Daily evolution of the DNI sets for 2008-08-19.

The results for a third example is depicted in Fig. 9a and Fig. 9b. As for the previous cases. calculation with hourly data leads to an overestimation of the energy gain (~25 % for the gain of the solar field and about ~10 % for the electrical energy). As for the example in Fig.6a and Fig. 6b, results for two of the synthetic set are close to those for the measured data. For the third synthetic set a underestimation of the energy gains occurs (~8 % for the solar gain, ~5 % for the electrical energy). Thus, no general conclusion on the sign of the deviaions due to the use of synthetic data can be drawn.

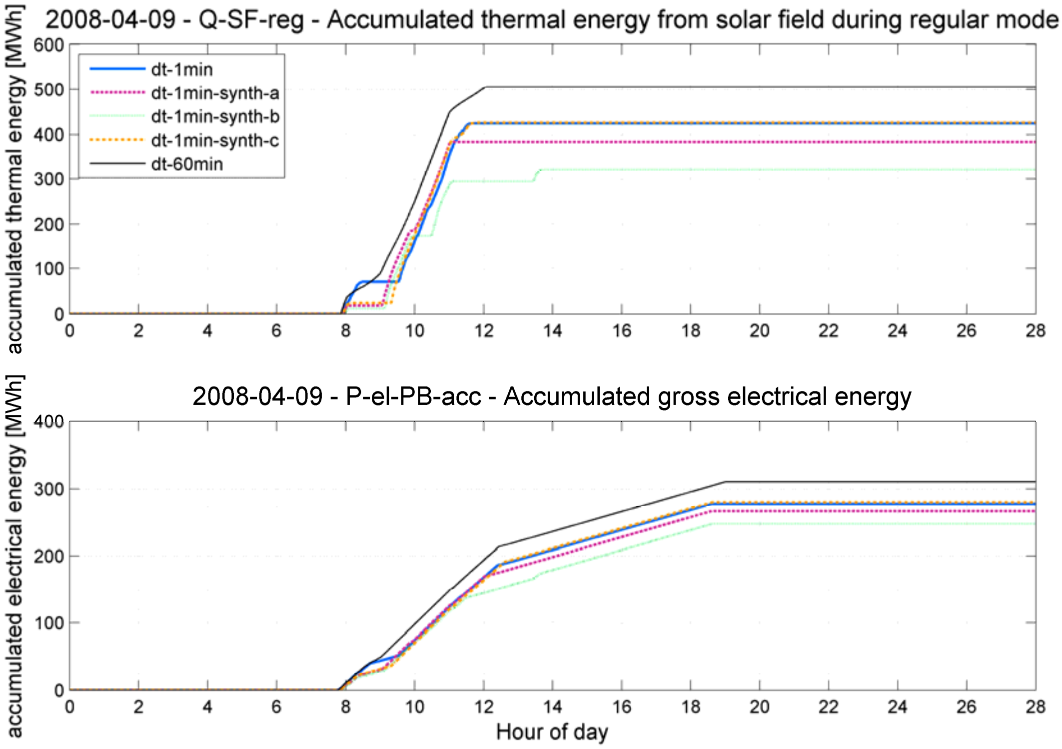

Fig. 9a (upper), 9b (lower): Same presentation as in fig. 6a,b, but for day 2008-04-09.

5. Conclusions

The examples indicate that the use of the synthetic sets of minutely DNI values may result in operation data that are close to the data determined from high resolution measurements. Notably, the respective difference is less than the difference to operation data gained from DNI sets with hourly time resolution.

To quantify the error resulting from application of synthetic instead of measured minutely DNI sets, the empirical data basis has to be extended. At the end, it must allow for the comparison of the performance data for a number of hours with similar hourly mean DNI and sun altitudes. The resulting information on mean and scatter of the operational data for statistically similar empirical inputs will give the correct benchmark for judging on the adequacy of the synthetic sets. Statements on a need for improvements of the scheme for the data synthesis – and hints for the type of improvements - may follow from this extended test.

Acknowledgements

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