DYNAMICS OF OIL-BASED PARABOLIC TROUGH PLANTS - IMPACT OF TRANSIENT BEHAVIOUR ON ENERGY YIELDS

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Abstract

Most analyses of electricity yield for solar thermal power plants today are based on calculations of steady-state energy balances in hourly time-resolution. Start-up effects of plants can be considered based on simple energy balance approaches. But transient behaviour during cloudy situations is not well represented by today's performance models. Currently, Spain is the country, where most new solar thermal power plants are erected. The majority of the plants still follow the technology and experiences of the parabolic trough plants erected in California. But scattered clouds are much more frequent at the Spanish sites leading to high short-term variability of the thermal yield. Such interruptions due to broken clouds may cause significant losses compared to steady-state calculations. This paper describes a systematic correction method to consider dynamic effects in a quasi-static model. This model focuses on start-up procedure and periods of high solar volatility for oil-based parabolic trough plants. Since operation data have not been available for this project, a dynamic simulation model is used as the benchmark.

Keywords: parabolic trough, operation strategy, CSP performance model, dynamic model, steady-state model, transient effects, variability of solar resources, direct normal irradiance, DNI

1. Introduction

As other renewable energy systems like wind or photovoltaic, solar thermal power plants have to cope with fluctuations in the energy input. On top of the daily circle of the Sun come short-term variations caused by cloud fields. The reaction of the plant to these varying boundary conditions depends on the type of plant and its control. Simulation of such dynamic processes for such a complex system as a solar thermal power plant is demanding and requires substantial computational effort. For project development and financing purposes performance simulations shall cover at least a full year. Thus yield calculations for longer time-spans need to simplify the transient processes. Mostly they are performed by steady-state models, which today usually do not consider the influence of transient processes. For an accurate yield prediction of solar thermal power plants reliable methods, to consider these transient effects, are needed. The paper describes first approaches towards such a method. The dynamics of the plant is represented by a detailed dynamic simulation model including all relevant inertia of the system and a corresponding control system. The dynamic model is usually applied to simulate single days covering all operation modes like stand-still, start-up, regular operation, and shut-down [1]. With this model start-up processes and the reaction to short term fluctuations are analyzed. From the results, some methods to systematically include these effects in annual yield calculations are developed. Work on this aspect started within the SESK project [2] (standardization of yield prognosis for solar thermal power plants) and will be continued in a new SolarPACES activity within Task I [3, 4].

2. Method to consider the plant start-up

While the power block of a solar thermal power plant may not have to undergo daily start-ups due to thermal storage or fossil co-firing capacities, the solar system itself has to be heated up every morning. For parabolic trough fields with their large inventories of steel and heat transfer fluid this start-up energy is a considerable amount of the total energy collected (about 5% of the annual yield).

Starting from a plant cooled down to a certain temperature (index 0) the minimum energy required to start-up the field can be calculated as the sum of all energy differences in fluid, *i*, and steel masses, *j*, in the field,

$$\Delta E_{\text{min}} = \sum_i m_i * \left(h_i^{\text{final}} - h_i^0\right) + \sum_j m_j * c_j * \left(T_j^{\text{final}} - T_j^0\right) . \tag{1}$$

The final temperatures and enthalpies are those of the system in regular operation. This energy was needed if each component would individually be heated up in an infinitesimal short interval of time. In a real plant more energy is consumed during start-up since

- heat losses occur during the start-up period,
- heat has to be wasted (dumped) in certain stages of the process (e.g. waiting times).

In fossil fired plants one tries to control the heat production close to the heat consumption. For solar plants, it is only possible to reduce the available energy delivered by the sun to fit the tolerated heat consumption at every time instant of the start-up. A good start-up process is thus designed to use as much of the available energy as possible. The ratio of theoretically available energy during the start-up process to the minimum start-up energy is called start-up effort ratio

$$\psi_{\text{start-up}} = \frac{\Delta E_{\text{avail}}}{\Delta E_{\text{min}}} > 1 . \tag{2}$$

The available energy is defined as the usable heat that would be obtained if the plant was operated in regular, steady-state mode at each time instant. The state of the solar field in the morning depends on the number of night hours and the night-time ambient temperature. Thus, the start-up energy is different for each individual start-up. But, the start-up effort number is always similar and characterizes the quality of the start-up process. With the ideal process a start-up number of 1 would be obtained, realistic processes will show start-up numbers between 1.2 and 2. Since the start-up procedure realized at one specific day depends on the irradiation and temperature profile on this specific morning, the start-up effort number for the same plant shows a variation. Nevertheless, the start-up number approach with an average start-up effort number is useful for annual yield calculations. The required data can be obtained from

- operational data of a plant,
- dynamic simulations of the plant, or
- published reference values (not generally available today).

2.2 Start-up effort number derived from dynamic simulations

In absence of useable plant data the start-up behavior can be simulated with a dynamic simulation tool [5]. The tool itself is described in detail in a conjunct paper [1]. Only the main features are summarized here:

- transient mass and energy balance of collector row and header system
- simplified transient mass and energy balance for the power block
- operating modes including stand-still, solar field heating, start-up sequences of power block
- transition between different operating modes dependent on plant states
- no spatially resolved irradiance profile

With this model, start-up simulations for a number of selected days are performed. The cumulated available energy is recorded every minute and plotted against the minimum start-up energy for the corresponding time step. Fig. 1 displays the results together with the ideal start-up line. The regular operation point is found in the upper right corner. Starting from a point in the lower left corner the lines show how the start-up proceeds.

All curves are similar to each other with slight deviations in slope and offset. The behavior close to the regular operating point needs some explanation. In the start-up rules used for these simulations the solar field is heated up to an average temperature of about 370°C by recirculation before significant amount of heat is routed towards the power block. At this stage, the thermal energy content is higher than the one in regular operation and thus, the curves cross the 0 line. This overheating is not wasted but used for a faster power block start-up. With another start-up strategy the offset might be reduced. This diagram is therefore not only suited to determine the start-up effort numbers but also to identify optimization potential in the procedure.

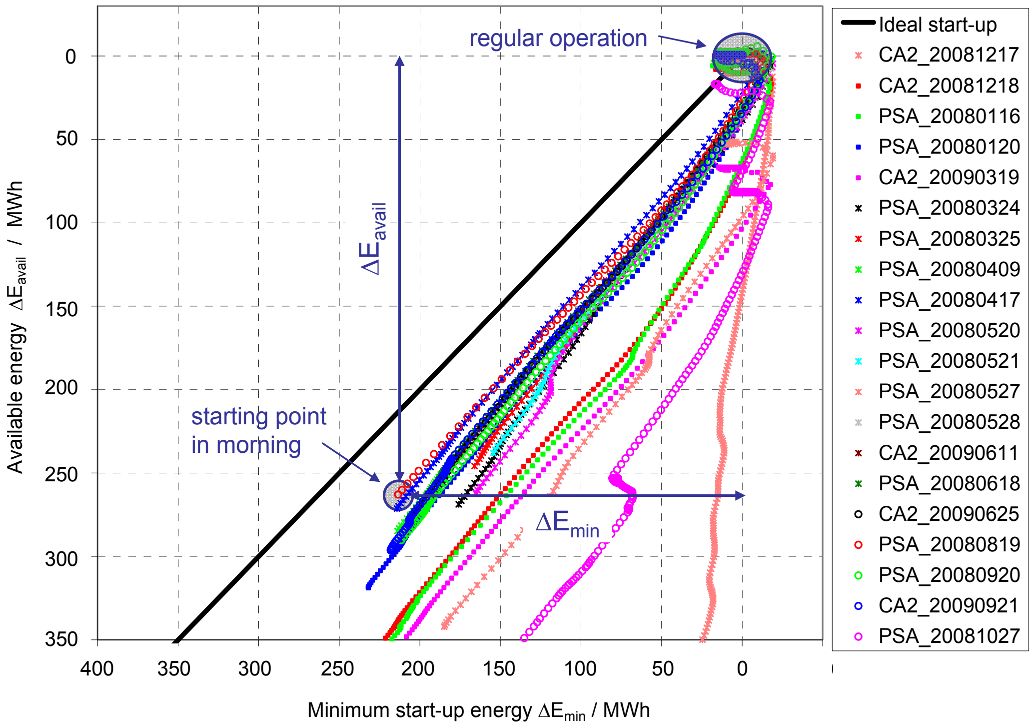

Fig. 1. Start-up diagram for various days obtained from dynamic simulation

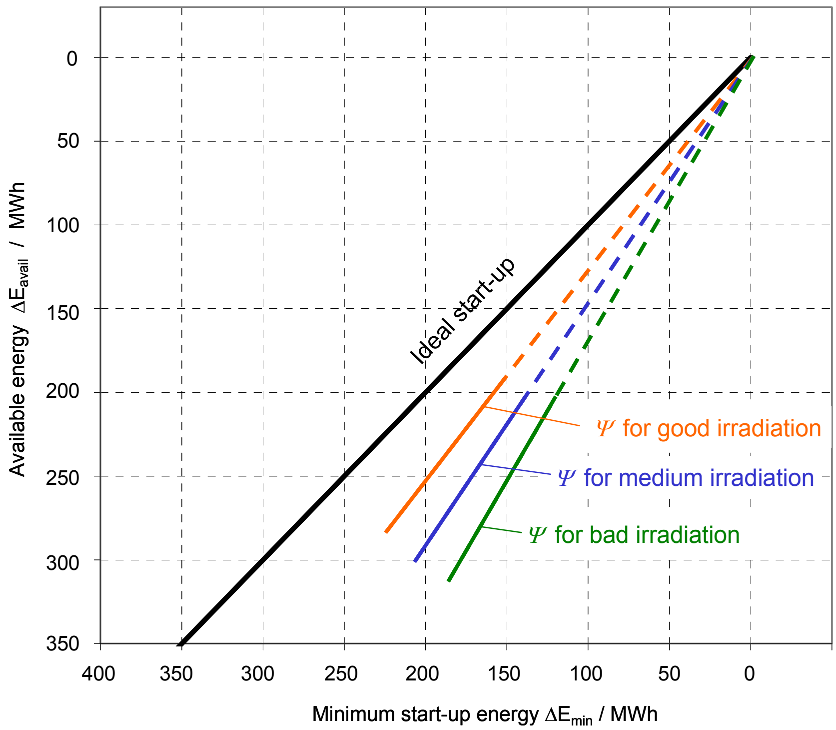

Fig. 2. Representative start-up curves

From analysis of individual days it turns out that the curves closest to the ideal line are obtained from days with good irradiation conditions. Curves below represent start-up during days with worse conditions, either caused by bad incident angles due to the season, or by low irradiation levels due to atmospheric conditions. The two lines far below the group were obtained for days with broken cloud situations. For these situation the start-up is frequently interrupted, takes longer, and thus the total energy consumption is higher. For days with such broken cloud situations the amount of energy required for the start-up may differ significantly since the start-up strongly depends on the specific irradiation profile. A sufficiently large number of start-ups has to be analyzed to find representative mean values. In general, it is recommended to categorize the start-up effort numbers according to the underlying irradiation profile. A reasonable number of groups could be 3 or 4 as illustrated in Fig. 2.

2.3 Options for real plants

The same approach as described for the data obtained from the dynamic simulation model can be applied to real operational data. For this purpose, a number of operation days have to be analyzed in order to identify the start-up effort numbers. The thermal state in the morning can be approximated based on the available temperature measurements and knowledge of the system. The regular operating state should be known to the operator and thus the energy difference $\Delta E_{\min}$ is easily identified. In order to determine the available energy during the start-up process a conditional expression for the end of the process has to be defined. Some effort has to be spent on a suitable selection since the real system is not as ideal as a simulation model. Exceeding a threshold temperature over a certain time interval can be an appropriate condition to define the end of the start-up process.

The available energy is then determined with a plant performance model based on the measured direct normal irradiation during the start-up period. To have a unique measure it is assumed that the plant operates at steady-state condition in each time step during the start-up process. For the steady-steady efficiency the one in regular operation is taken. An higher solar field efficiency due to lower field temperatures during start-up is not considered since these temperatures themselves would depend on the start-up process and are thus not suited as a reference. With these methods plots like the one in Fig. 1 can be generated and the corresponding groups can be derived. The more start-up data is available the higher is the reliability of the start-up effort numbers.

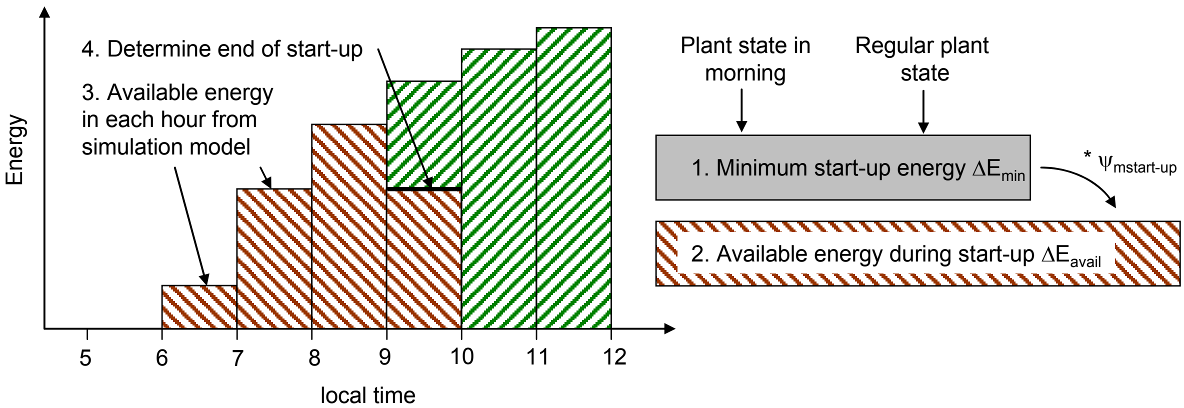

Fig. 3. Approach to consider start-ups in steady-state simulation models

2.4 Approach for start-up simulation

For annual yield calculations a detailed model for start-up is much too time-consuming. Today, combinations of thresholds for minimum required heat and time for the start-up phase are used in the models. Some models today already rely on simple energy balances between the morning and the regular operation state. Having the initial conditions determined from a plant cool-down curve the minimum start-up energy $\Delta E_{\min}$ can be calculated. If the start-up effort number is known for this kind of plant it directly follows the required heat input $\Delta E_{\mathrm{avail}}$. This energy can be subtracted from the calculated energies in the first hours of plant operation to finally yield a reduced heat and thus electricity consumption. The method is thus very well suited to be used in annual yield calculations. For high accuracy the user has to provide good guesses for the start-up effort number and the cool-down characteristic of his plant.

3. First approaches to consider short-time fluctuations

Performance models for CSP systems are usually based on a steady-state approach. In other words, for a certain boundary condition (irradiation and ambient parameters) one unique output is calculated. This reflects the reality as long as the boundary condition stays constant over a long period of time and thus, the process parameters are stable. In reality, solar plants undergo slow (hours) and fast (minutes) fluctuations of the irradiance. Caused by the large thermal inertia and the restricted possibilities for control actions the systems takes some time to reach again a stable, steady state operation. For slow fluctuations the transition between operating points is approximately linear since control action is slow and over- or undershoots can be avoided. During short-term fluctuations the control system is not in all cases able to stabilize the plant close to the set-point. Deviations of the real plant output from the theoretical prediction of the model may occur due to the following reasons:

- The real plant does not operate in the design point and thus efficiencies are reduced.
- More electrical power is needed due to intense control actions.
- Deviations from the tolerated process values may cause the security system to fall into safety mode. The consequences might include
    - solar power reduction by collector defocusing
    - a turbine trip and thus time and energy consuming restart of the turbine
    - temporary shut-down of the whole system

While the first two aspects will only cause slight deviations from the theoretical values the last one will be costly in terms of produced energy. To which extent short term fluctuations influence the electricity yield finally depends on the damping behavior of the physical system, on the quality of the control concept, and the deviations from the set-points tolerated by the components.

3.1 Transient behaviour of an oil-based plant

In order to study the impact of short-term fluctuations on the electricity yield, simulations with the same dynamic model as in section 2 are performed. The focus is now on regular operation over the day and not on the start-up behaviour. As an illustrative example the operation of an oil-based parabolic trough plant on April. 11, 2008 is simulated. The irradiance and temperature data are taken from a PSA meteo station in a resolution of 1 min. From this high resolution data, data sets of lower resolution (5 min, 10 min, 15 min, 30 min, 60 min) were derived by averaging over the 1 min data. The resulting DNI values are given in Fig. 4. Until 2 o'clock a rather smooth irradiation profile is given while the afternoon is characterized by some cloudy periods. If the 60 min data were taken as input to a simulation model a continuous operation of the solar power plant would be calculated with an expected part-load behaviour of about 50% during some time in the afternoon. Although not clearly visible from the plot a similar behaviour is obtained with 30 min data. When coming closer to the real irradiance data of this day by resolution of 15 min and below it is seen that the solar field will not be able to deliver energy between 15:15 and 15:45. This long period cannot be compensated by thermal inertia in the system, thus the solar field will fall into stand-by mode. Since recirculation over the field is maintained to be prepared for the return of the irradiation the temperature profile in the solar field can no longer be kept stable. The longer the period takes the more homogeneous the solar field temperature will get. In our case, a thermal storage system is available so the steam turbine can go on with operation. Nevertheless, the activation of the storage needs some time. So, the power production profile will undergo some break-ins, as shown in Fig. 4.

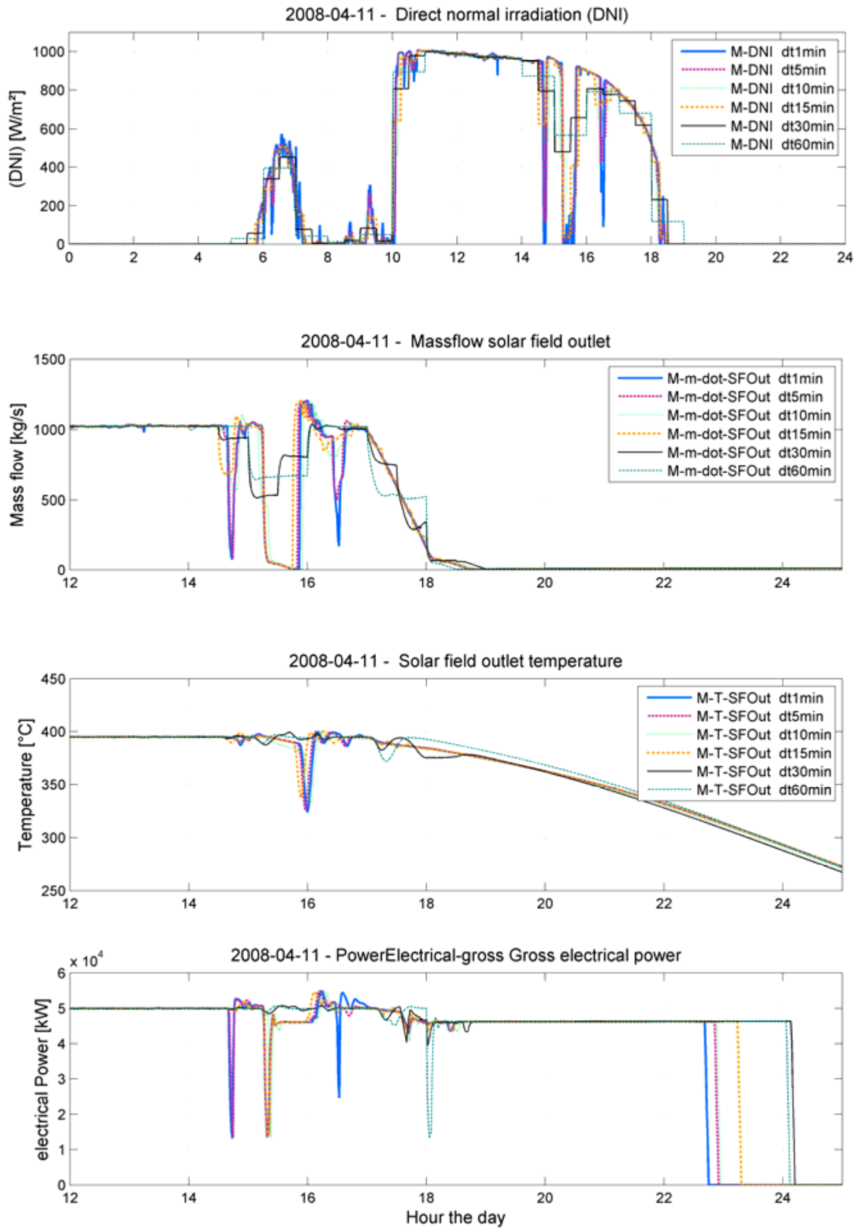

Fig. 4. Simulation results for April, 11th, 2008 on PSA for different temporal resolutions

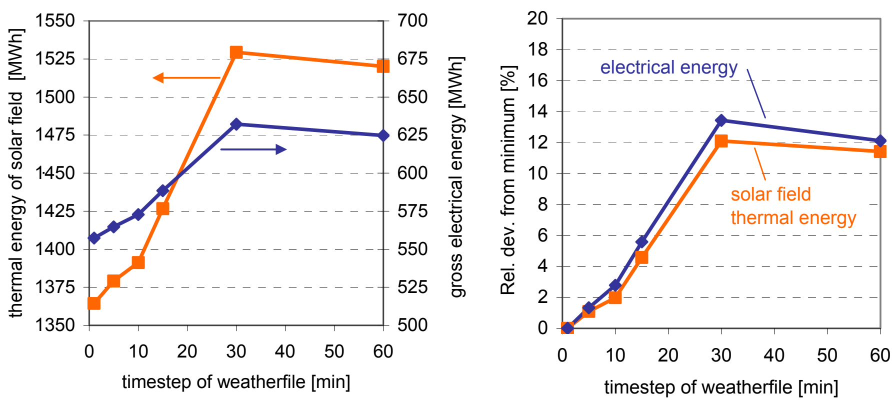

Fig. 5. Impact of weather data resolution on daily energy yields on April 11th, 2008

More severe in terms of the energy production is the fact that the solar field has to be brought into regular operation before connecting to the steam generator again. This process is characterized by a number of losses similar to the ones described in section 2. The produced thermal and electric energy depends on the temporal resolution of the weather data file. Fig. 5 illustrates that, for this day, large deviations of about 12% are observed in the thermal energy yield of the solar field and thus in the electrical production. The impact on the electricity yield can directly be seen from the power output in Fig. 4. For the 60 min resolution the plant produces electricity until about midnight while production ends at 22:30 for the 1 min resolution input.

The same studies have been performed for a number of other days. It has been found that the days with cloudy situations show great sensitivity to the temporal resolution. A unique factor cannot be derived since the conditions are too different. For the electricity yield calculations this impact of short-term dynamics has to be considered in order to come to good results. In general, electricity yields obtained on a basis of 60 min data will be higher than the ones for higher resolution. The next section drafts a method how these effects can be considered in annual yield simulations.

3.2 Characterizing solar irradiance

Today, in solar energy industry meteorological data still are often applied in hourly time-resolution. In this resolution short-term fluctuations of solar irradiance, caused mainly by broken clouds, is masked. Eventually, direct normal irradiance is either available at a high level or not available at, all due to clouds. Values in between, e.g. 500 W/m^2, require a very special cloud situation that is very rare. By using a clear sky model like the one of Bird [6], a clear sky index can be derived as

$$k^* = \frac{DNI}{DNI_{\text{clear sky}}} \tag{3}$$

A clear sky index close to 1 indicates a cloudless situation with low aerosol content of the atmosphere. It is not likely that significant cloud coverage is present for hours with high clear sky index. On the other hand, small clear-sky indices indicate nearly complete cloud coverage. A clear sky index in between is obtained for partial cloudy situations. Periods of high and low irradiance alternate. This shows that by means of the clear sky index some information on the character of the cloud situation can be derived. Based on this knowledge tuning factors for simulation model could be derived.

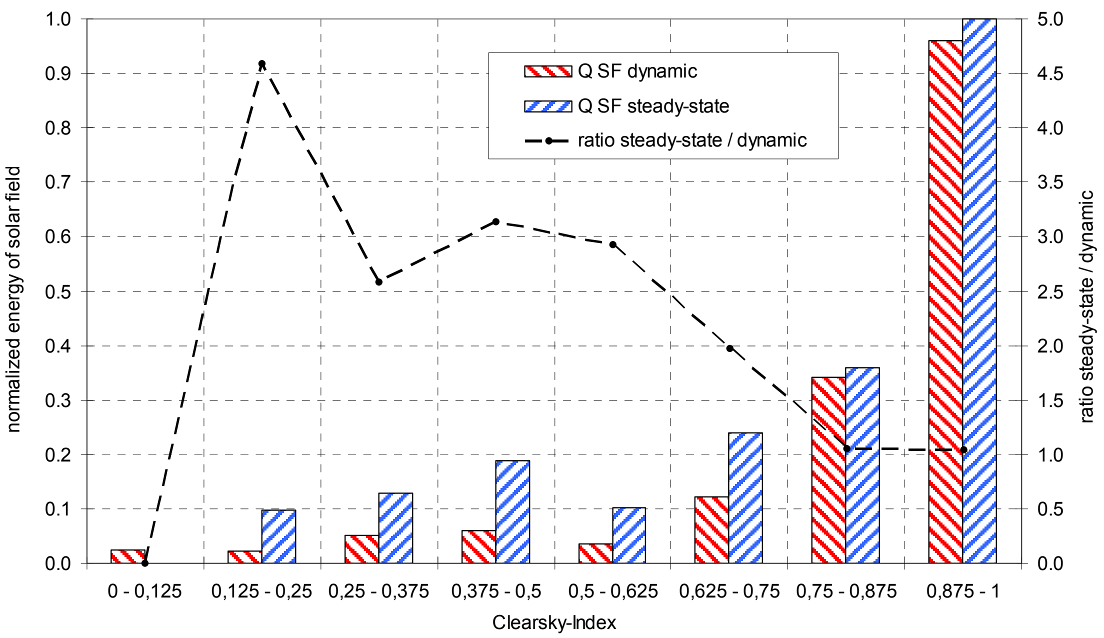

Fig. 6. Clear-sky dependency of outputs

Fig. 6 shows a comparison of thermal energy yields of the solar field calculated with the dynamic simulation model and a steady-state calculation model. The steady-state model has also been developed within the SESK project [2]. Simulations have been performed over a number of days including all kinds of cloud situations. The thermal yields in each hour were accumulated in groups according to the clear-sky index in the respective hour. The resulting values are normalized to the value obtained in the group with highest clear sky index. For better comparison the ratio between steady-state and dynamic results is plotted, too. By observing this diagram it becomes evident that good accordance is obtained for the high clear sky situations with a clear sky index above 0.75. For lower clear sky indices the output of the dynamic model is significantly lower than the one for the steady-state model.

An appropriate reduction factor for the steady-state model could be derived ones enough data are collected. In this study, the data base consists of 20 days. In addition, there are some minor differences between the steady-state and the dynamic model assumptions that would have to be corrected before final values can be derived. One should also note that the derived reduction factors would be only applicable for the present steady-state model. Other steady-state models that are used in industry and other research centres might already take into account transient effects.

4. Conclusions

The paper presents an approach for a method to account for impacts of transient behavior of solar thermal power plants in operational performance simulations with a quasi-static model, which is capable to simulate full years with low computational effort. The method introduces reduction factors for the start-up process and a reduction factor for regular operation under fluctuating irradiation. Simulation studies with a detailed dynamic model of a solar thermal power plant are conducted to demonstrate the relevant effects and to draft approaches for inclusion of their impacts. Work on this topic has been initiated within the SESK project. More studies on this field are foreseen to be part of a new SolarPACES task for standardized electricity yield calculations.

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