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Assessing the impact of a solar eclipse on weather and photovoltaic production

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Abstract

With the strong expansion of the installed renewable energy over the last years, the relevance of weather forecasts for operating the German power system has considerably increased. In that context, rare but important events like the solar eclipse on the morning of 20 March 2015 pose an additional challenge when operating the power system, as it affects the photovoltaic (PV) power production by inducing strong gradients in the feed-in. In order to maintain grid stability, the uncertainties associated with the eclipse have been estimated in advance for planning necessary precautions. Especially the maximum gradients in PV-power were of importance for the provision of balancing energy. Numerical weather prediction (NWP) is very suited for this assessment, as it allows to consider the complex mechanisms occurring in the atmosphere. Thus the impact of the eclipse on meteorological parameters which affect the PV-power generation were evaluated. Sensitivity studies with NWP models have been conducted in order to assess the reduction in short wave radiation and temperature during the total solar eclipse months before the actual event. For this purpose, model simulations with the non-hydrostatic COSMO models from the German Weather Service (DWD) have been performed over Germany and Europe. As the weather situation and especially the cloud cover during the eclipse could not be known in advance, a realistic worst case (clear sky conditions) and a best case (overcast conditions) scenario were simulated over Germany. Thereof the PV-power production has been estimated and analyzed for the different scenarios. The NWP model data from the sensitivity studies are openly distributed (doi: [10.1594/PANGAEA.839163](https://doi.org/10.1594/PANGAEA.839163)). As near real-time NWP simulations considering the solar eclipse were conducted a few days prior to the event, they are herein validated with measurements. Furthermore, the actual PV-power production and actions taken by the TSOs during the solar eclipse are stated.

Keywords: solar eclipse, short wave radiation, photovoltaic power, numerical weather prediction

1 Introduction

A total eclipse is a rare and well understood astronomical event. It offers scientists an opportunity to verify and deepen their understanding of atmospheric processes. An overview of the diverse influences of a solar eclipse on weather is given by [ANDERSON \(1999\)](#). In literature, many studies assess these impacts by comparing observations during the solar eclipse to observations during non-eclipse days. Also, numerical weather prediction (NWP) models are used to understand the related processes in the atmosphere. Field observations during a solar eclipse have the disadvantage that they are dependent on local weather situations. NWP models, however, offer the possibility to simulate the effects of a solar eclipse for modified weather conditions by e.g. elimi-

nating existing clouds in the model. A solar eclipse simulation can also be carried out for different astronomical conditions and desired weather situations without the need to constrain model physics. The combination of all these complementary approaches helps to explain the processes during such a rare event. In contrast to atmospheric sciences, photovoltaic (PV) production on a grand scale is a relatively young scientific and economic sector. Simulations prior to, measurements during and intensive analysis after the solar eclipse on the 20 March 2015 help to deepen our understanding of the complex interactions in the atmosphere and their influence on PV-power production. Hence, the presented study describes this workflow and stresses the importance of collaborations in such an interdisciplinary field.

On 11 August 1999, scientists had the chance to study a total solar eclipse over Central Europe. The central shadow of the moon passed through the southern part of Germany. Despite of cloudiness in south-west

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Germany, [AHRENS et al. \(2001\)](#) could document the impact of the solar eclipse on the lower planetary boundary layer by means of routine observations. [VOGEL et al. \(2001\)](#) studied the solar eclipse and its influences on temperature and wind speed in the Upper-Rhine Valley with a non-hydrostatic model in which clouds were eliminated. [GROSS and HENSE \(1999\)](#) used the hydrostatic local forecast model that was at that time operational at the German Weather Service to review the effects of the total solar eclipse on mesoscale circulation. Instead of constraining model physics, they chose a differing date that provided the desired maximum insolation for assessing maximal influences of the solar eclipse. As the forecast quality of NWP models is improving progressively, forecasted weather conditions are also used as reference to assess the impact of a solar eclipse. [GRAY and HARRISON \(2012\)](#), for instance, used observations from the 1999 eclipse in the southern United Kingdom and compared these with the output of a high resolution NWP model ignorant of the eclipse.

A well documented solar eclipse outside of Europe occurred on 15 January 2010 over India under favorable weather conditions. [RATNAM et al. \(2010\)](#) and [SUBRAHAMANYAM et al. \(2011\)](#) compare surface observations during the eclipse with observations from preceding and subsequent days. The effect of the solar eclipse on the sea breeze were studied in [SUBRAHAMANYAM and ANUROSE \(2011\)](#). [KADYGROV et al. \(2013\)](#) summarize measurements taken at three different locations in Russia concerning three solar eclipses, respectively (29 March 2006, 1 August 2008 and 4 January 2011). In the United States (US) scientists and amateurs are currently planning and preparing for the total solar eclipse that will cross the US from north-west to south-east on 21 August 2017. The *American Astronomical Society* is organizing special workshops for this occasion, see [ARNDT et al. \(2012\)](#).

The last intensively studied total solar eclipse over Europe was on 29 March 2006. The open access journal *Atmospheric Chemistry and Physics* dedicated a special issue to this event ([ZEREFOS et al., 2007](#)). Therein, [GERASOPOULOS et al. \(2008\)](#) gives a multi-disciplinary overview of the conducted measurements and findings, including eclipse induced meteorological effects, but also effects on crops or marine life. [FOUNDA et al. \(2007\)](#) summarizes the effects of this total solar eclipse on meteorological variables across four stations in Greece. Additionally, the results of numerical simulations with the Weather Research and Forecast (WRF) model are compared with observations. For this purpose, the WRF model was run twice, once accounting for the solar eclipse and once without obscuration of the sun. [EMDE and MAYER \(2007\)](#) present results of a fully three dimensional simulation of the radiation transfer during this total solar eclipse. Also [KAZANTZIDIS et al. \(2007\)](#) studied the attenuation of global irradiance over Greece.

In recent years the contribution of renewable energy has gained in importance with regard to the power mix. In order to maintain grid stability, uncertainties

in power forecasts resulting from weather phenomena must be accounted for. For PV-power production, a solar eclipse represents such a challenging event ([MORRIS, 2014](#)). The total eclipse over Europe during the morning of 20 March 2015 was anticipated with great apprehension as it led to high gradients in power production. To ensure grid stability for this day, a long-term timetable was strictly adhered to by the TSOs. The early estimation of the possible maximum gradients was especially crucial for elaboration of measures. Thus studies for investigating possible effects of the solar eclipse in 2015 on the production of solar electricity in Germany have been conducted in advance, e.g., [WENIGER et al. \(2014\)](#); [WEINHOLD \(2014\)](#); [KÖHLER et al. \(2015\)](#); [KREIFELS et al. \(2015\)](#). The study by [WENIGER et al. \(2014\)](#) highlighted the chances of large gradients in accumulated PV-power in Germany. Power gradients on a sunny day were predicted to increase by 3.5 times during the eclipse ([WENIGER et al. \(2014\)](#); [WEINHOLD \(2014\)](#)). For the regional scale of distribution system operators (DSO), [KÖHLER et al. \(2015\)](#) studied the losses in load flows in the distribution grids of a testing ground during the solar eclipse, using the here presented NWP model simulation data. They point out that local gradients are in the same magnitude as experienced on cloudy days and thus are not critical on the smaller scale of DSOs.

The cloud cover posed one of the main challenges in predicting the effects of the solar eclipse. As the clouds can not be predicted months or even weeks in advance, assumptions had to be made which cover all aspects of possible solar radiation impacts. Additionally, the effect of the solar eclipse on ground temperature is of importance for the PV-power industry, as lower temperatures cause an increase in PV-panel efficiency ([KALDELLIS et al., 2014](#)). The study of [WENIGER et al. \(2014\)](#) provided a very good insight on the potential effects of the solar eclipse on the power system. Therein, as in common practice, several simplifications were adopted, i.e. the effect of the eclipse on the weather has been neglected and the reduction in irradiation caused by the eclipse has been assumed linear with the obscuration of the sun. Also, the temperature reduction and other atmospheric feedback mechanisms as induced by the eclipse are often neglected. Given the lack of knowledge on the effect of an eclipse on PV-power production, a calculation taking the effects of the eclipse on the weather explicitly into account is meaningful in order to reduce the overall uncertainty of this assessment. For these reasons, and also because the operational working chain of the system operators is based on NWP model data, the German Weather Service conducted NWP model simulations for the total solar eclipse well in advance for best and worst case situations ([KÖHLER et al., 2014](#)). The openly published data and insights were used by various power forecast providers as well as for an eclipse assessment of the Fraunhofer Institute for Solar Energy Systems ISE ([KREIFELS et al., 2015](#)). A detailed data description along with a retrospective look at the solar eclipse on the 20 March 2015 is presented in this work.

In the following, the solar eclipse of 2015 is assessed, inter alia, by use of NWP simulations. The solar eclipse and the reduction of the solar constant are described in Section 2 and 3, respectively. The COSMO model setup is explained in Section 4. In Section 5, an idealized worst case scenario simulation was conducted for Europe using the COSMO-EU (SCHULZ and SCHÄTTLER, 2011) under the assumption of clear sky conditions. Subsequently in Section 6, the COSMO-DE simulations are documented. In order to quantify the effect of the eclipse, a worst case scenario (cloud free) and best case scenario (cloudy) have been studied with the regional model COSMO-DE (BALDAUF et al., 2011b). The COSMO-DE simulations are based on real case studies, using the 20 March 2014 and the 16 March 2014 for studying worst and best scenarios, respectively. The weather situations and cloud characteristics for these days are described and the effects of the solar eclipse are quantified. The importance of the simulations for the power forecasts and thus for the German power system is highlighted in Section 7. Details on the openly distributed resultant data for the COSMO-DE and COSMO-EU including reference model runs without the solar eclipse are given in Section 8. In Section 9 a retrospective is given from the view of meteorologists and TSOs. The paper concludes with the summary of the results.

2 Solar eclipse on 20 March 2015

A solar eclipse is caused by the moon passing in between the sun and the earth. In a total solar eclipse the sun is completely obscured by the moon. Such a natural phenomena occurred on the morning of 20 March 2015. The path of the total solar eclipse and the location of the greatest eclipse is depicted in Figure 1 and is defined as the instant when the axis of the moon's shadow cone passes closest to the earth's center (ESPENAK, 2014a). The corridor of the moon's umbral shadow traversed from the North Atlantic north-eastwards over the Norwegian Sea. Over Europe this spectacle occurred between 7:45 and 11:45 UTC and effected Germany between 8:20 and 11:05 UTC. Germany was situated in the penumbra during this time and thus only experienced a partial solar eclipse. At 9:45 UTC, when the effect on solar radiation over Germany was largest, the region of maximum eclipse was above 64.2831° N, 6.8932° W (ESPENAK, 2014c). The umbra lay above the Faroe Islands. As the solar eclipse took place in the morning hours, the eclipse path and the sunrise had opposite cycles, i.e., the moons shadow passed over Europe from south-west to north-east, while the sun rose from south-east to north-west.

3 Parameterization of the eclipse

In order to determine the dimming effect of the solar eclipse, the positions of the sun and the moon have to be

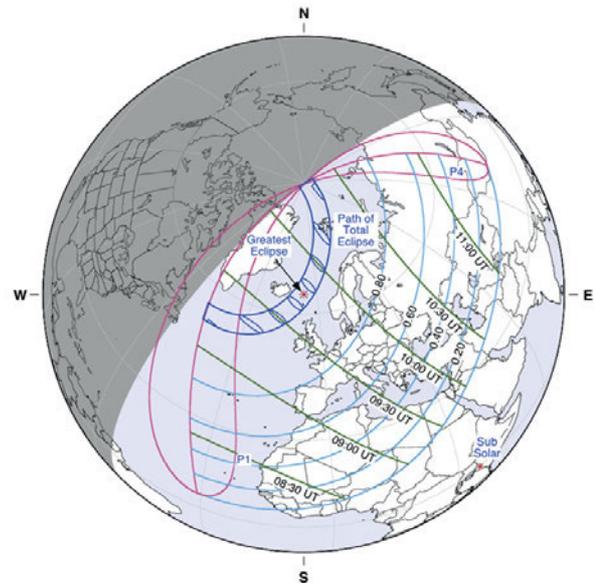


Figure 1: Visualization of the total solar eclipse path (in dark blue) and location of greatest eclipse (red asterisk) on 20 March 2015 (ESPENAK, 2014b).

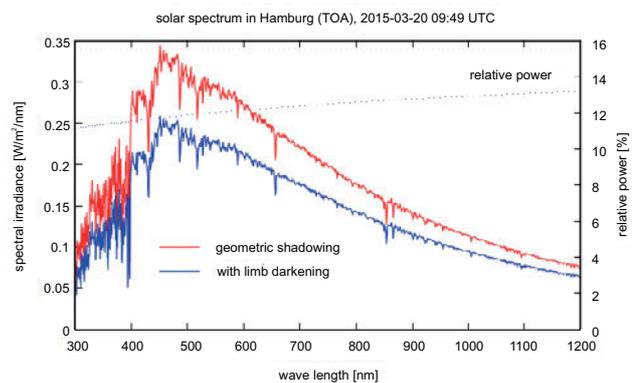


Figure 2: The simulated solar spectrum over Hamburg on 20 March 2015 at 9:49 UTC at the top of atmosphere (TOA) for different wavelengths. The spectral irradiance with geometric shadowing is marked by the red line and with additional limb darkening by the blue solid line. The dotted lines visualize the ratio of the spectral irradiance (TOA) and the reference spectrum.

known with high accuracy. The horizontal coordinates of the sun and the moon were calculated with the astronomy library of NinJo (JOE and FALLA, 2004). The ephemerides are based on DE405 provided by the Jet Propulsion Laboratory (STANDISH, 1998). The earth is treated as ellipsoid (WGS-84), whereas sun and moon are considered to be spherical. This simplification only has a marginal effect. It is far more important to take the limb darkening of the sun into account. This is done according to KOEPKE et al. (2001) with a reference spectrum based on GUEYMARD (2004). The calculation is limited to the wave length interval from 300 nm to 1200 nm, which covers the range of sensitivity of silicon cells as used in PV-panels. As the effect of the limb darkening depends on the wave length, Figure 2 compares approximated spectral irradiance based on simple

area calculations (geometric shadowing) with spectral irradiance that additionally considers the limb darkening over Hamburg on 20 March 2015 at 9:49 UTC for different wavelengths. The dotted lines display the ratio of the calculated spectral irradiance at the top of the atmosphere and of the spectral irradiance of the reference spectrum. The calculation of the spectral irradiance was performed on the COSMO-DE and COSMO-EU model grids with a time step of 15 minutes, corresponding to the time interval at which the radiation scheme is called. The spectral information is condensed to a single value, namely the reduction factor of the solar constant. This is the ratio of the calculated irradiance and the irradiance of the reference spectrum in the above mentioned wavelength interval.

4 COSMO model setup

The non-hydrostatic regional NWP models of the DWD are used in order to investigate the influence of the solar eclipse on the incoming solar radiation at the surface and the temperature near the ground. In the following the model setup for the COSMO-DE and the COSMO-EU are described. The convection permitting COSMO-DE has a horizontal resolution of 2.8 km and the COSMO-EU of 7 km. The operational setups for both models are documented in BALDAUF et al. (2011a) and SCHULZ and SCHÄTTLER (2011). As the incoming solar radiation is of main interest for the renewable energy sector during the solar eclipse, adaptations have been performed considering the radiation scheme for a higher accuracy in time and space. In the operational COSMO-DE setup, the radiation transmissivity is calculated every 15 minutes in the radiation scheme (RITTER and GELEYN, 1992). As this is numerically expensive, the radiation scheme is operationally called on a coarser grid with 2×2 grid boxes and the fluxes are subsequently downscaled to the COSMO-DE grid points. In the setup for the solar eclipse simulations, no averaging is conducted for the radiation scheme. The COSMO-EU simulations are performed in the same manner. While the radiation transmissivity is only calculated once per hour in the operational COSMO-EU, it is likewise updated every 15 minutes without horizontal averaging for this study. The operational model output of the short wave radiation variables is available every 15 minutes for the COSMO-DE since 9 April 2014 12:00 UTC. For the COSMO-EU only aggregated hourly averages are provided in the operational output. However, the published data set not only contains the 15 minute aggregated averages of the direct and diffuse downward short wave radiation at the surface but also their instantaneous values and the reduced solar constant. The conducted COSMO-DE simulations accounting for the solar eclipse use boundary data from COSMO-EU runs which also included the effects of the eclipse. Otherwise boundary effects are visible in the nested COSMO-DE domain. When using the distributed data please note that differences in the model

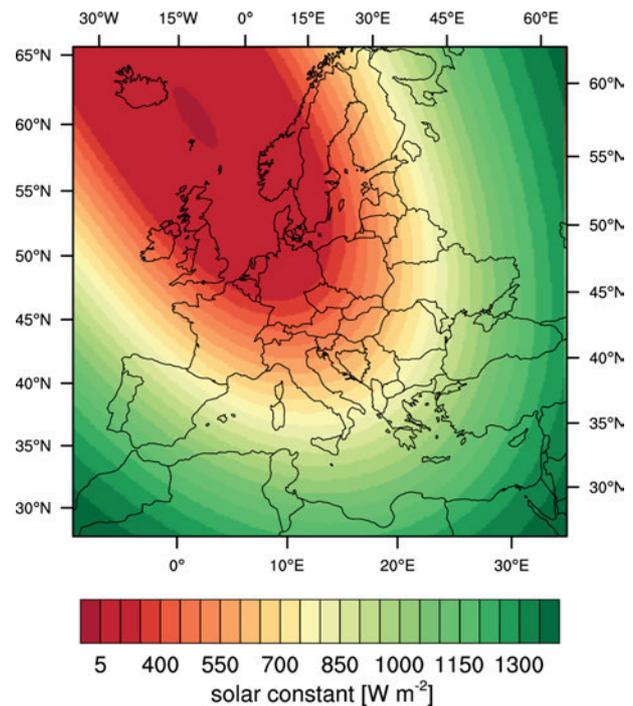


Figure 3: The solar constant at 9:45 UTC, as used in the COSMO-EU forecast for 20 March 2014 and initialized at 00:00 UTC.

configuration, in particular relevant choices for free parameters in the model physics, also lead to some differences in the results between COSMO-EU and COSMO-DE.

5 COSMO-EU simulations

The influence of the shadowing effects of a solar eclipse on the energy yield of photovoltaic systems is the largest on clear sky days. Such conditions are characterized by high atmospheric transparency and hence minimal extinction of solar radiation within the atmosphere, resulting in efficient photovoltaic energy production. For conducting the COSMO-EU simulations well in advance to the eclipse, 20 March 2014 was chosen as worst case scenario due to optimal astronomic conditions. In order to achieve a cloud free sky over the whole of Europe, the cloud cover for the calculation of the radiation fluxes is artificially set to zero in the COSMO-EU radiation scheme. Note that the cloud-free COSMO-EU simulations were solely used to assess potential maximum impacts over Europe but were not used as boundary data for any COSMO-DE runs. In Figure 3 the reduced solar constant for 9:45 UTC is shown. The umbra is clearly visible between the North Atlantic Ocean and the Norwegian Sea near the Faroe Islands.

The effect of the reduction of the solar constant during the total solar eclipse is clearly visible in the short wave radiation. In Figure 4, the COSMO-EU reference run (left), the COSMO-EU run accounting for the solar eclipse (middle) and their difference in the short wave radiation on the surface (right) is depicted

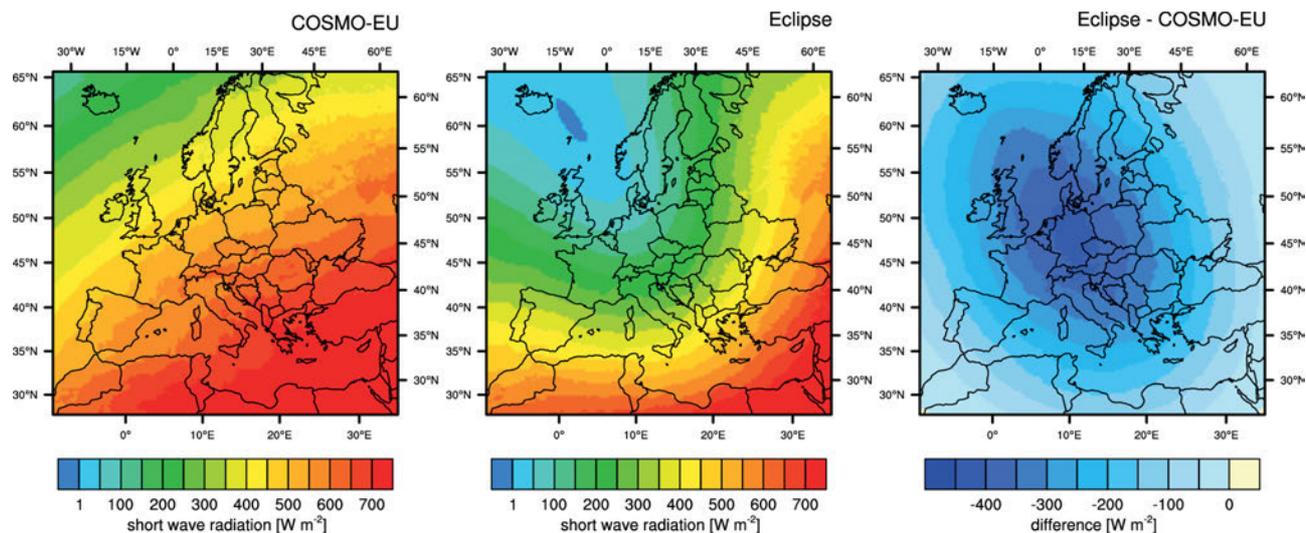


Figure 4: COSMO-EU with the cloud free setup at 9:45 UTC. On the left is the short wave radiation under clear sky conditions for the COSMO-EU, in the middle for the total solar eclipse COSMO-EU run, and on the right is the difference between the eclipse and operational COSMO-EU run.

at 9:45 UTC, when the solar eclipse reaches its peak. Regarding only the grid points above land, the mean difference is -182.36 W m^{-2} , resulting in a reduction of the incoming solar radiation of 31%. The effect of the two opposite movements of the umbra and the sun is clearly visible in the COSMO-EU domain plotted in Figure 4. The ellipse of maximum impact is directly centered over Germany.

6 COSMO-DE sensitivity studies

The COSMO-DE sensitivity studies were also conducted in summer 2014, well before the actual solar eclipse event. The studies were aimed to assess the possible maximal and minimal impact of the solar eclipse in 2015 on surface weather conditions and especially on solar radiation over Germany. A clear sky day with appropriate astronomical conditions was chosen as the worst case scenario for a realistic assessment of the maximal reduction of solar radiation at the ground over Germany: 20 March 2014. For comparison, a best case simulation is produced for a cloudy day, where the influence of the solar eclipse is expected to be minimal: 16 March 2014. For each case, the COSMO-EU and subsequently the COSMO-DE was run with and without the solar eclipse, respectively. The effect of the solar eclipse was then estimated by comparing the two model runs. Based on this study, these two days were equally used as best and worst cases in [KREIFELS et al. \(2015\)](#), for estimating aggregated PV-power.

6.1 Weather situations

The large-scale weather situations for the case studies are summarized in the following sections. For illustrating purposes, the objective weather pattern classification method of [JAMES \(2011\)](#) is used, which is based on the Hess and Brezowsky Grosswetterlagen (e.g. [HESS and BREZOWSKY \(1977\)](#)).

6.1.1 Worst case weather situation – 20 March 2014

The worst case situation is a good example of anti-cyclonic south-westerly flow (SWA). In Figure 5 the large-scale weather situation is visualized for this case. A vigorous low pressure system lies just to the south of Iceland, helping to advect a substantial body of warm air towards Central Europe, where a pronounced upper ridge has formed, moving gradually east during the day. A large surface high is centered over the Balkans, extending its influence to most of Germany, while frontal systems associated with the Icelandic low are crossing the British Isles and reached western France by the evening. Over Germany, the strongly anticyclonic nature of the flow, combined with sufficient insolation at the spring equinox and a relatively dry troposphere helps to break up any remaining layers of stratiform cloud quickly during the daytime, leading to largely clear skies.

6.1.2 Best case weather situation – 16 March 2014

Over Central Europe a strong north-westerly flow has formed between a high pressure system over Biscay and a large trough over Scandinavia. Germany is situated in a wide warm sector in which an originally warm and moist air mass has been advected around the Atlantic ridge with a long track over relatively cold sea surfaces. This warm advection results in the formation of an inversion layer in approximately two kilometers height above ground, which allows for low stratus clouds to persist over the whole day. The clouds only break up in the far south-west and westernmost parts of Germany, aided by lee-effects from neighboring hilly regions. Figure 6 illustrates the large scale weather situation for this best case simulation.

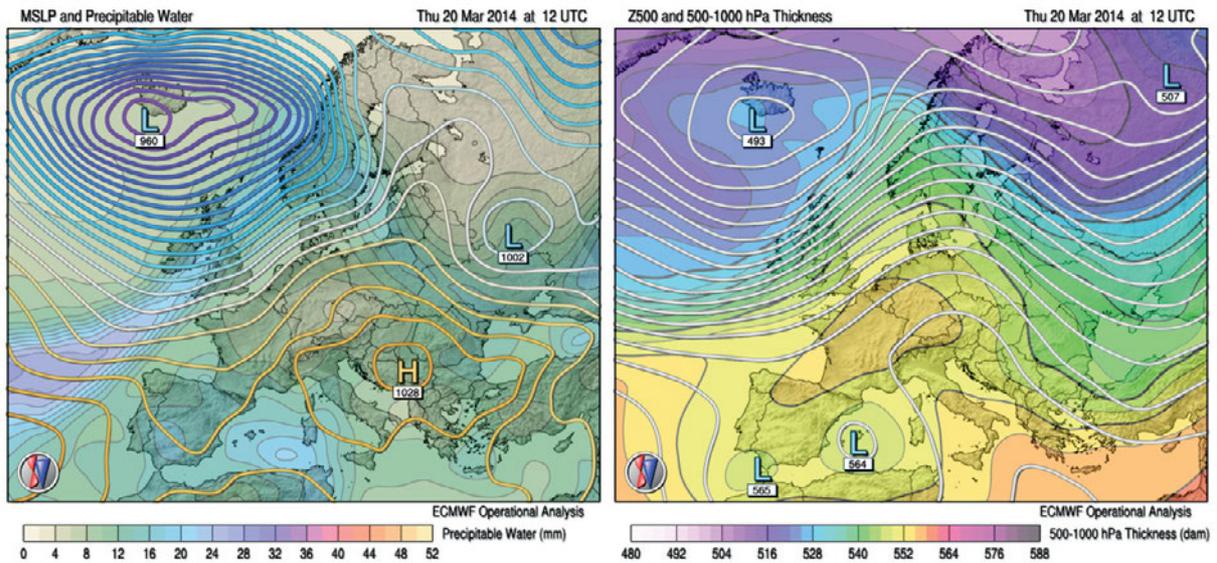


Figure 5: Visualization of the large scale weather situation for 20 March 2014 12:00 UTC, which can be categorized as an anticyclonic south-westerly pattern. On the left hand side, the mean sea level pressure in hPa (contour lines) and the precipitable water content (contour-filled field) are visualized. On the right hand side, the contour lines symbolize the geopotential of the 500 hPa level in dam and the shading indicates the relative topography between the 500 and the 1000 hPa level (provided by P. James, DWD).

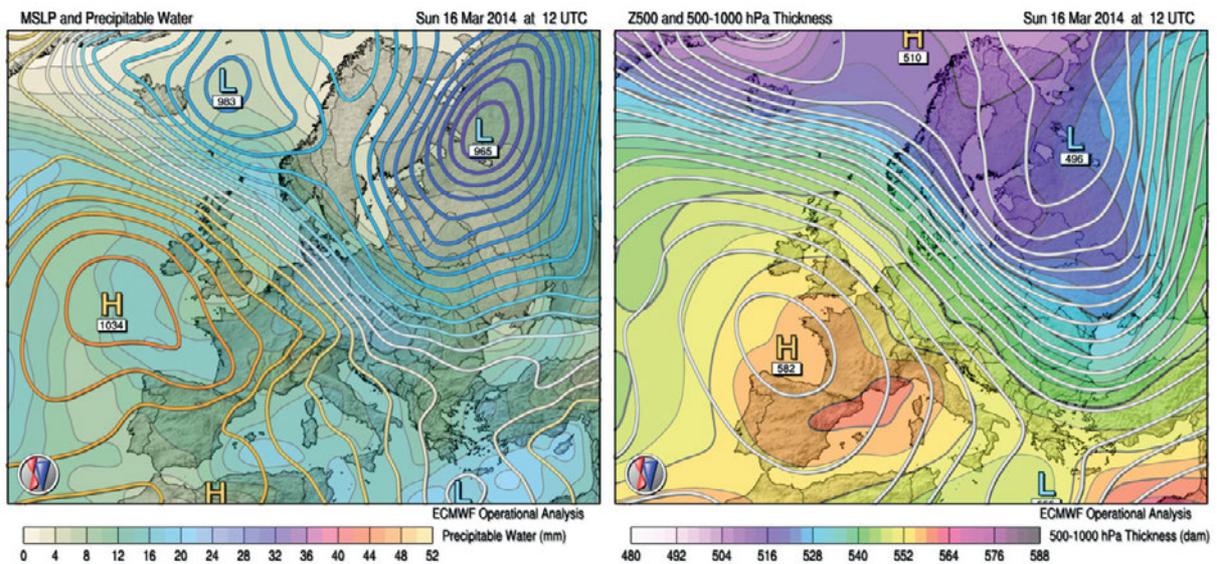


Figure 6: As Figure 5, but for the best case simulation of 16 March 2014 12:00 UTC. Subjectively, this weather pattern can be classified as a cyclonic north-westerly pattern.

6.2 Influence of the solar eclipse

Although the effects of the solar eclipse depend strongly on the local weather conditions and the time of year, the general impact on the lower troposphere can be summarized as follows. In daytime and cloud free conditions, the most pronounced effect is on the surface energy flux due to the dramatic reduction of incoming solar radiation. Temperature close to the ground drops as a direct response to the reduced surface energy flux. The lack of energy input cannot be compensated during the rest of the day and the temperature remains lower than it would under undisturbed (non-eclipse) conditions. With some

time lag, the modifications in the surface energy budget and near surface temperature effect the whole boundary layer through changes in the vertical transport of energy. During this process, the temperature profile is modified, which in turn impacts other variables such as wind and humidity. Noticeable intensification may be observed on (cool downslope) valley winds (Vogel et al., 2001) but also on larger scale wind circulations (Gross and Hense, 1999). Depending on local conditions such as orography or soil water content, the formation or dissolution of clouds may be affected (Anderson, 1999). Even low-frequency gravity waves caused by the travel of the moon's shadow at supersonic velocity can be ob-

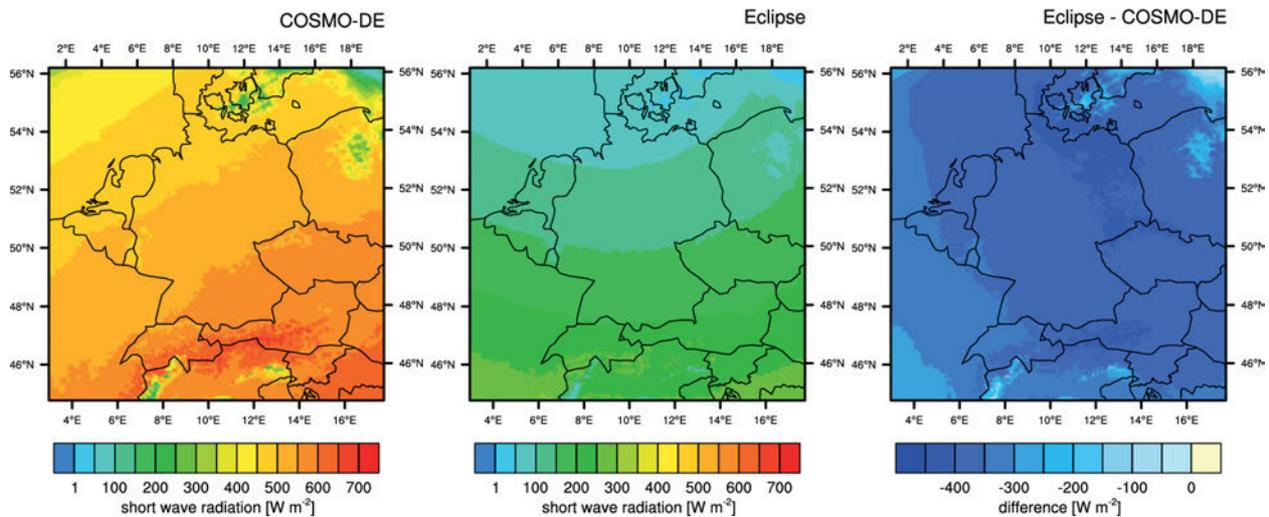


Figure 7: Comparison of the short wave radiation from the reference COSMO-DE run (left) and the COSMO-DE run considering the solar eclipse (middle). On the right is the difference between the model runs. The initialization time for the model simulation is 20 March 2014 00:00 UTC. The forecast for 09:45 UTC is shown.

served after the passage of an eclipse, not only in the stratosphere but also in measurements near the surface (MARTY et al., 2013).

In the following, the influence of the solar eclipse on radiation and temperature close to the ground as revealed by our study is presented. The worst and best case scenarios are considered separately.

6.2.1 COSMO-DE simulation – worst case scenario

For clear sky conditions, the reduction in the insolation during the solar eclipse is the most pronounced and thus represents worst case conditions. Cloud free and correct astronomical conditions are met on 20 March 2014, as thoroughly described in Section 5. In Figure 7 the influence of the solar eclipse on the incoming solar radiation on the surface as simulated by the COSMO-DE for 9:45 UTC is shown. The reference run is depicted on the left side, in the middle is the model run with the solar eclipse, and on the right side the difference in short wave radiation is plotted. The solar eclipse causes a dramatic reduction in the incoming solar radiation over the whole of Germany. The mean decrease in solar irradiance due to the solar eclipse (as computed with the COSMO-DE model) is 363.15 Wm^{-2} . This yields a reduction of 68 % when considering the average amount of incoming short wave radiation at the surface. Only model points over land are considered when computing these averages, as these pose the area of interest for photovoltaic energy applications.

Falkenberg is chosen for comparing the short wave radiation due to the existing measurement site there. In Figure 8 the influence of the solar eclipse on the short wave radiation and on the two meter temperature is shown using 15 minute instantaneous model output. For Falkenberg, the maximum deviation in the short

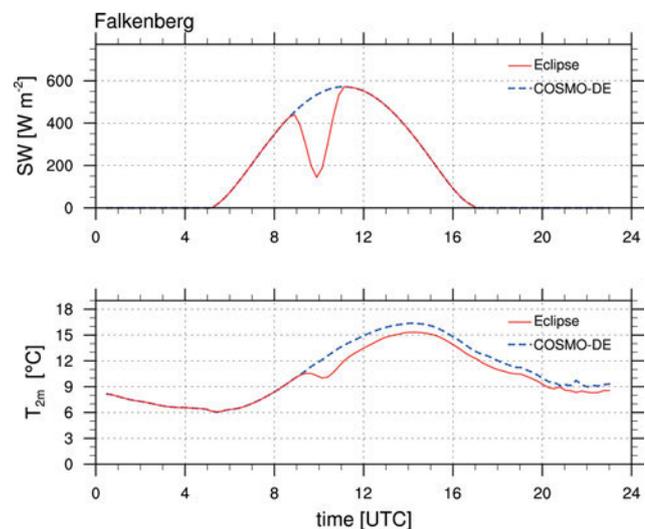


Figure 8: Short wave radiation (upper plot) and two meter temperature (lower plot) from the COSMO-DE simulation initialized on the 20 March 2014 at 00:00 UTC. The results are shown for Falkenberg in the operational COSMO-DE (dashed blue line) and the COSMO-DE run with solar eclipse (solid red line).

wave radiation is -389.56 Wm^{-2} and for the two meter temperature -2.47 °C . The drop and subsequent increase in two meter temperature (Figure 8) is in close correlation with the changes in short wave radiation. During the rest of the day the temperature close to the ground remains lower than it would for non-eclipse conditions. After the eclipse, the average temperature reduction of all land points gradually decreases from -1.19 °C at 12:00 UTC to -0.62 °C at 18:00 UTC (not shown). GROSS and HENSE (1999) and FOUNDA et al. (2007) indicate a mean temperature deficit of $0.5\text{--}1 \text{ °C}$ well after the eclipse in their numerical studies, although they consider eclipses under different astronomical conditions and use different study areas. The response in two meter tem-

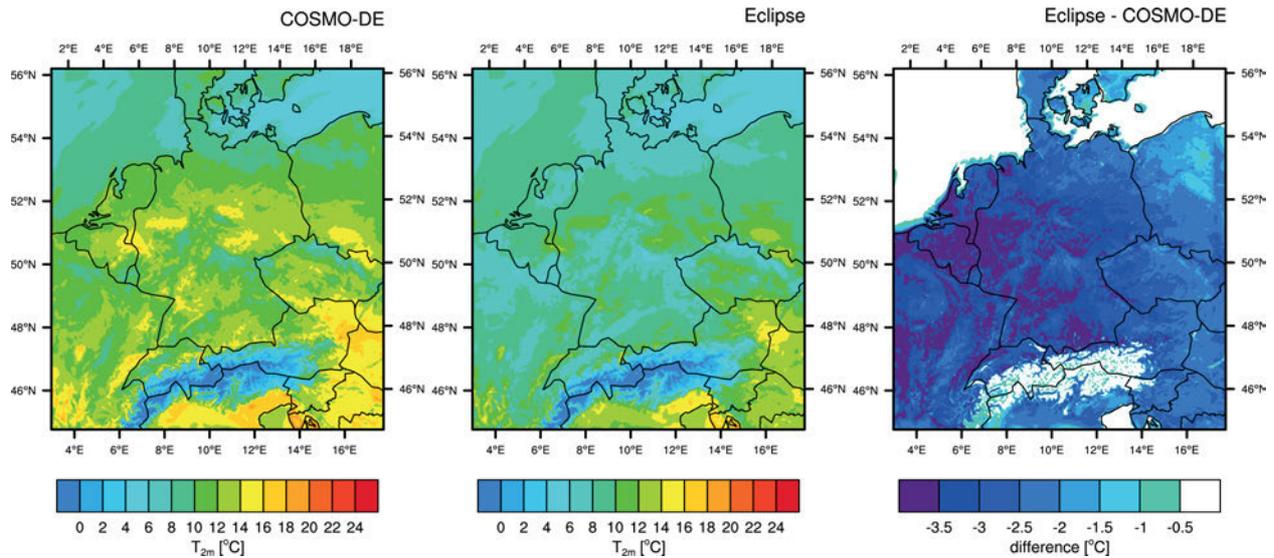


Figure 9: Comparison of the two meter temperature from the reference COSMO-DE run (left) and the COSMO-DE run considering the solar eclipse (in the middle). On the right is the difference between both. For the model runs, the initialization time is 20 March 2014 00:00 UTC and the 10 hour forecasts are shown.

perature also lags behind the signal in short wave radiation. Whereas the maximal reduction of solar radiation over the whole model domain is observed at 9:45 UTC (see Figure 7), the maximal mean reduction in two meter temperature is observed in the subsequent model output for 10:00 UTC.

Figure 9 illustrates the spatial variability in the eclipse-induced deficit of two meter temperature at 10:00 UTC. The mean difference for all land points is $-2.67\text{ }^{\circ}\text{C}$. For a small domain centered around Athens, [FOUNDA et al. \(2007\)](#) found a modeled average temperature response of $-2.7\text{ }^{\circ}\text{C}$ for land areas as consequence of the eclipse in March 2006. [GRAY and HARRISON \(2012\)](#) compared temperature observations during the eclipse in August 1999 in the United Kingdom with temperature forecasts on a 1.5 km grid from the Met Office Unified Model which did not consider the solar eclipse. They confirmed temperature decreases of up to $3\text{ }^{\circ}\text{C}$ in the transient eclipse zone. Due to cloudy conditions, their results reveal only a damped influence of the solar eclipse on two meter temperature. The amplitude of temperature reduction strongly depends on local influences, such as the local weather situation (e.g. cloudiness, advection), albedo, vegetation, or soil moisture. In the alpine region, the two meter temperature barely responds to the solar eclipse (see Figure 9). This is due to the high albedo and insulating effects of the snow cover which is simulated by the model.

6.2.2 COSMO-DE simulation – best case scenario

For the overcast best case scenario, the effect of the solar eclipse on the radiation and temperature is much less pronounced than for the clear sky simulation. The 16 March 2014 is chosen for these simulations for reasons described in Section 6.1.2. At the peak solar obscuration at 9:45 UTC, the average decrease in short

wave radiation above land points within the COSMO-DE domain lies at 148 Wm^{-2} . Yet this yields a relative reduction of 63%. The short wave radiation over Germany for the COSMO-DE run from 16 March 2014 is depicted in Figure 10. The reference COSMO-DE run is on the left, the COSMO-DE run with the solar eclipse is in the middle and the difference of both plots is shown on the right of Figure 10. While Germany mostly lies under thick low stratus clouds, the cloud cover breaks up in the south-western part, see Section 6.1.2. Thus, the solar eclipse reduces the incoming radiation by as much as 404 Wm^{-2} in the south-west, while reductions of only 4 Wm^{-2} are possible in the north-east. The same can be observed for the temperature near the ground. Only in the southwestern part of Germany, where the clouds break up, is a reduction in temperature of up to $2\text{ }^{\circ}\text{C}$ observed. For all land points within the model domain, the mean deviation in two meter temperature is $-0.91\text{ }^{\circ}\text{C}$ at 10:00 UTC.

Due to the thick cloud layer in the north, Falkenberg only has a peak in solar radiation of 40.69 Wm^{-2} in the reference run. The maximum difference to the eclipse model simulation occurs during the afternoon due to alterations in the cloud cover because of feedback mechanisms. Nevertheless, the influence of the eclipse on the two meter temperature is negligible (not pictured).

7 Impact on power forecast

With the increasing share of renewables in the German power mix the relevance of the weather forecast for the power system has increased. Due to a total installed capacity of 37 GWp on 1 Jul 2014, a special meteorological phenomenon like the solar eclipse of 20 March 2015 is seen as a challenging situation by system operators.

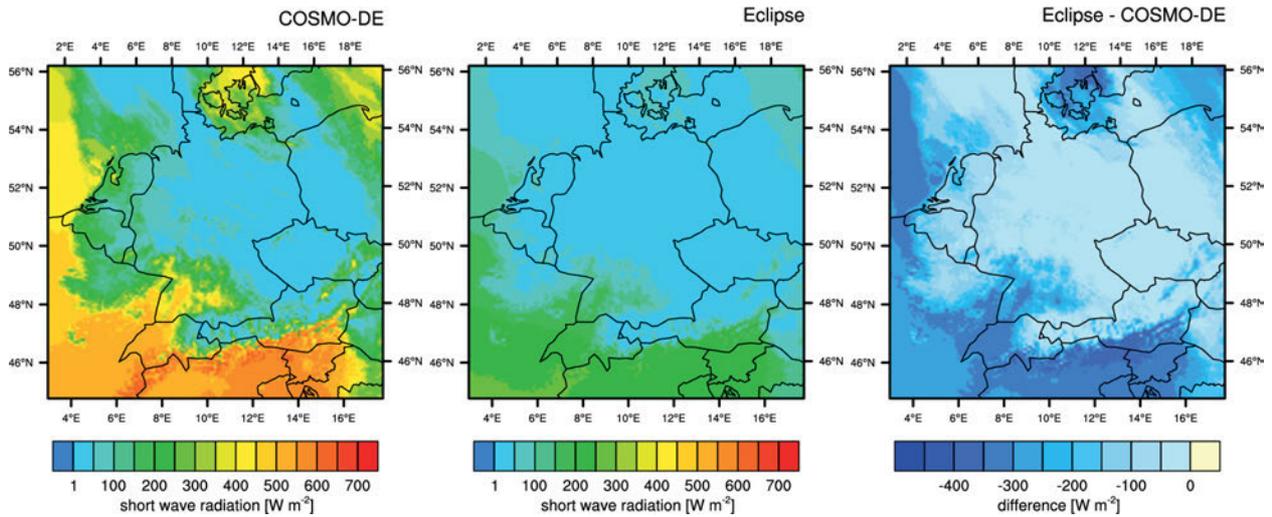


Figure 10: Comparison of the short wave radiation from the reference COSMO-DE run (left) and the COSMO-DE run considering the solar eclipse (middle). On the right, the difference between both model runs is shown. The initialization time for the simulations is 16 March 2014 00:00 UTC, the 9:45 UTC forecast is shown.

It directly impacts the electricity supply system (e.g. energy balance, power transmission) through its effect on the power production of the ca. 1.5 million installed photovoltaic plants. In this respect, an analysis of the effect of the solar eclipse on the irradiance, temperature and clouds is very important for system operators. The arising effect on the total PV-power production has to be equally considered. To address this issue, the PV-power production corresponding to the best and worst case scenarios has been evaluated. Two steps are necessary in order to calculate the reduction in PV-power production. In a first step, relevant PV-plant characteristics have been identified, e.g., PV-plant power curve, module azimuth and tilt angle. Probabilities of occurrence of all parameter combinations are then estimated as a function of the size of the plant as well as of its location. In a second step, the PV-power production is evaluated for each identified parameter combination. The expected PV-power is then estimated by a probability weighted average of power corresponding to the different parameter combinations. Finally, the results are scaled to the installed capacity and regionally aggregated.

The PV-power production estimated for Hamburg (arbitrarily chosen) is given in Figure 11a. The normalized PV-power is displayed as a function of time for the best and worst case COSMO-DE model runs with and without the solar eclipse. To assess the total effect of the solar eclipse on the German power system, PV-power time series have been aggregated over the whole of the country. The results are displayed in Figure 11b. Assuming an installed capacity of 37 GW_p, a maximal reduction resulting from the solar eclipse of 18 GW and 2.9 GW is observed at 9:45 UTC for the worst and best case, respectively. In addition, the solar eclipse causes a maximal power gradient of 6.20 GW (15 min)⁻¹ (worst case) and 1.12 GW (15 min)⁻¹ (best case) between 10:00

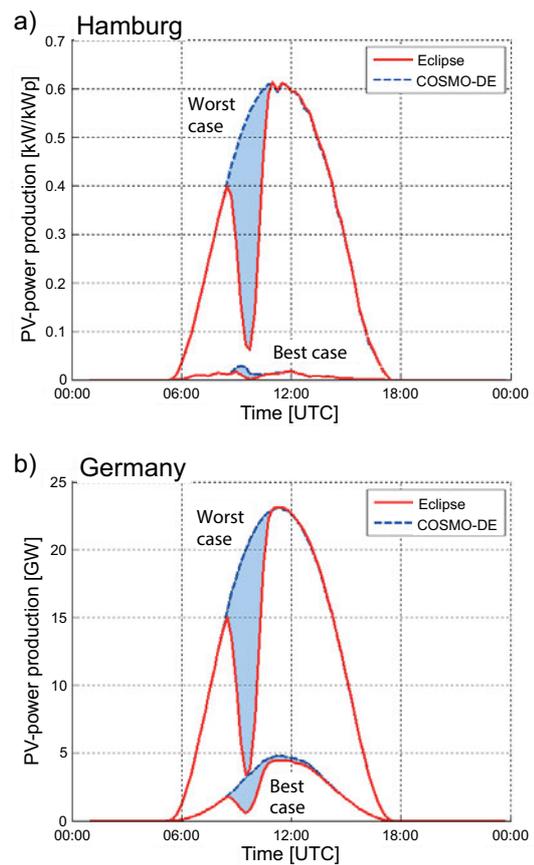


Figure 11: PV-power production estimated for a) Hamburg and b) Germany on the basis of the COSMO-DE simulations initialized on the 20 March 2014 (worst case) and 16 March 2014 (best case). The results are shown for the operational COSMO-DE (dashed blue line) and the COSMO-DE run with solar eclipse (solid red line). The effect of the solar eclipse is marked by a light blue area.

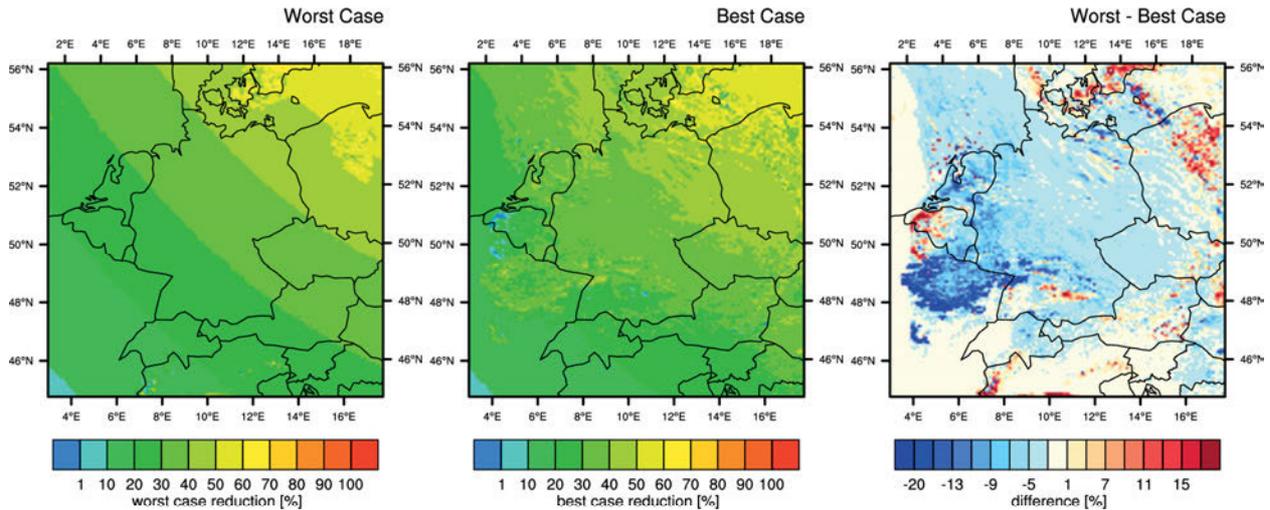


Figure 12: Percentage of difference in irradiance between the non-eclipse and eclipse COSMO-DE model run for the worst (left) and best (middle) cases along with their difference (right) for 10:15 UTC forecasts.

and 10:15 UTC. The maximum hourly gradient occurs between 9:45 and 10:45 UTC and yields 19.9 GW h^{-1} . These figures clearly show the relevance of the solar eclipse for the power system operation.

Additionally, in the best case scenario, a small reduction in the aggregated PV-power for Germany is visible in Figure 11b well after the eclipse. This reduction can be attributed to the change in cloud cover induced by the lack of energy input. As summarized in ANDERSON (1999), the response of clouds on the eclipse are versatile: while stratocumulus often increase horizontally and vertically, small scale convective clouds tend to dissipate. These effects are clearly visible in Figure 12. By comparing the COSMO-DE eclipse model runs to their reference runs, the reduction of the short wave radiation in percent is computed for the worst (left) and best (middle) case scenario. Their difference (right hand side in Figure 12) highlights the regions where the changes in cloud cover occurred. Thus, not using a physical NWP model for the PV-power calculation may lead to errors with a magnitude of 20% in areas with significant change in cloud cover (see west Germany, France).

8 Data description

The COSMO model data for the presented sensitivity studies is fully available. The data was published by PANGAEA, Data Publisher for Earth & Environmental Science, see KÖHLER et al. (2014). The supplementary data and further documentation are available at <http://dx.doi.org/10.1594/PANGAEA.839163>. The files are published in their original GRIB format and contain the model initial conditions, constants and forecast variables. The variable short names are specified in the model and database documentations by SCHULZ and SCHÄTTLER (2011) for the COSMO-EU data and by BALDAUF et al. (2011a) for the COSMO-DE. Boundary conditions for the model simulations can be made available on request.

9 Managing the actual solar eclipse

The real weather situation was better assessable the week before the actual solar eclipse occurrence. Precedingly, model runs with the COSMO-EU and COSMO-DE were conducted accounting for the eclipse. The model data was provided via an ftp server to the open public. A meteorological analysis, challenges for the TSOs, as well as the concerted actions amongst the four TSOs and support by the DWD are stated in the following.

9.1 Meteorologist's point of view

On the 20 March 2015, Germany was influenced by an upper air ridge with its center extending from Great Britain to northern Germany. During the preceding night, low stratus clouds had formed in the western and north-western parts of the country supported by the advection of moist air from the North Sea. Patches of this low level cloud cover were able to persist throughout the whole day, whereas elsewhere clear sky conditions prevailed. Only in the late afternoon northern Germany was influenced by an intensive upper level shortwave trough approaching the North Sea. The weather situation during the solar eclipse is very similar to the worst case scenario and led to comparable gradients in PV production, see Section 7.

The extent of the forecasted low cloud cover fields for the day of the eclipse varied during the model runs over the week before the actual eclipse. Whereas a clear signal was present at the beginning of the week, the predicted low cloud cover was not as distinct approaching the 20 March 2015. Additionally to NWP model forecasts, special weather reports were issued by the DWD synopticians of the operational forecast service. Having the low stratus clouds in the north-west, the numerical weather prediction in the control area of Amprion was

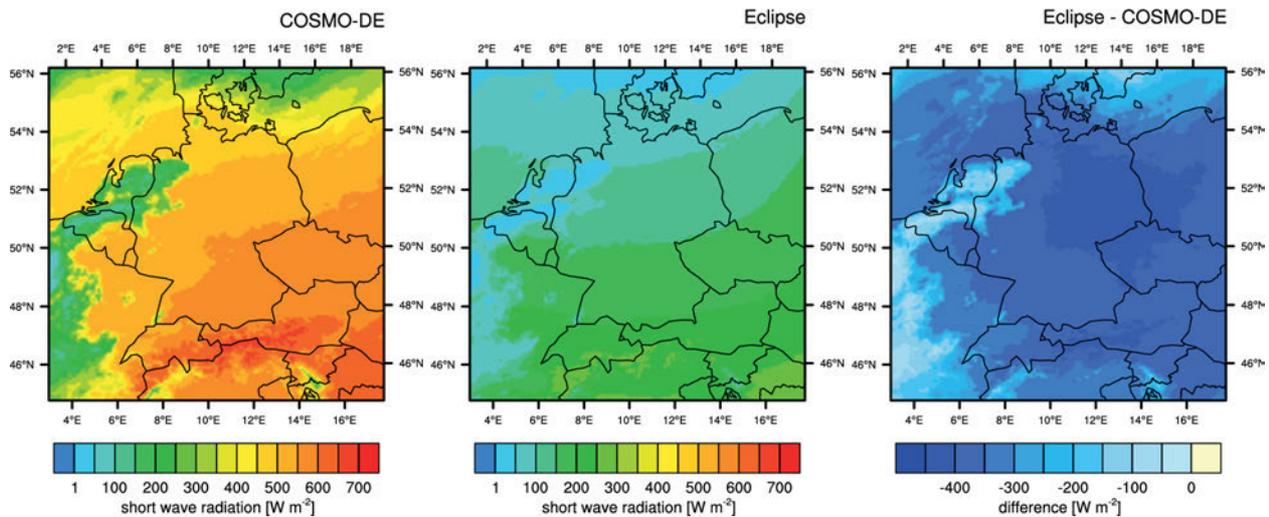


Figure 13: Comparison of the short wave radiation from the reference COSMO-DE run (left) and the operational COSMO-DE run considering the solar eclipse (middle). On the right is the difference between the model runs. The initialization time for the model simulation is 20 March 2015 00:00 UTC. The forecast for 09:45 UTC is shown.

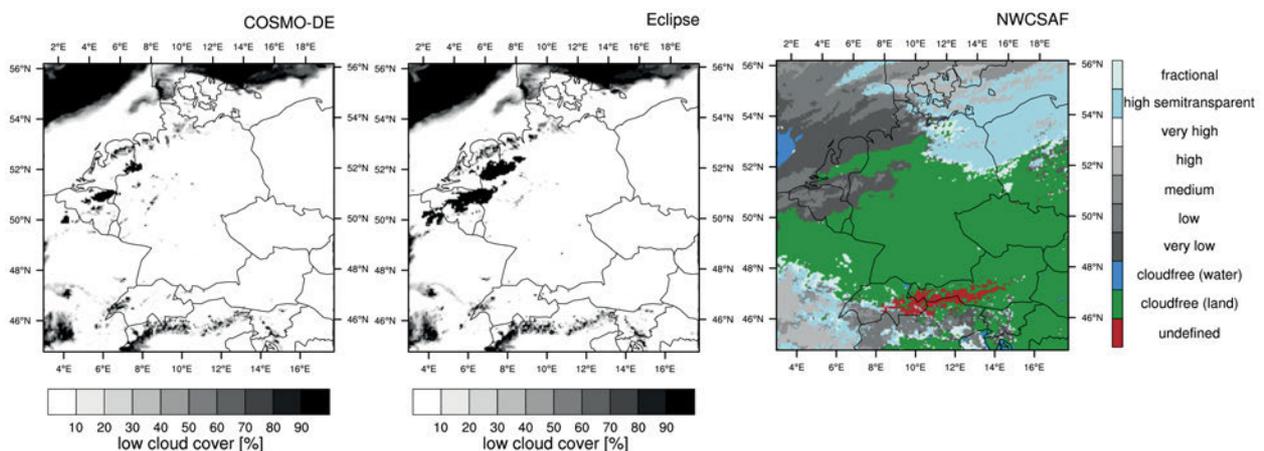


Figure 14: Comparison of the low cloud cover from the reference COSMO-DE run (left) and the solar eclipse COSMO-DE run (middle). On the right are the observed clouds based on the NWCSAF cloud classification. The initialization time for the model simulation is 20 March 2015 00:00 UTC. The forecast for 15:00 UTC is shown.

a challenge, while clear sky conditions dominated in the control areas of 50 Hertz, TenneT and TransnetBW.

The short wave radiation at the surface is shown in Figure 13 for the model run of the 20 March 2015 00:00 UTC and the forecast for 9:45 UTC. The operational COSMO-DE run, the COSMO-DE run accounting for the solar eclipse and their difference are depicted on the left, middle and right hand side, respectively. The solar eclipse causes a mean reduction in solar radiation over land of 336.06 W m^{-2} (68 %). This is consistent with the worst case simulations in Section 6.2.1. The maximal reduction in short wave radiation is 438.56 W m^{-2} .

The low clouds which formed in the north-east differ when regarding the two model runs. As stated in ANDERSON (1999) and discussed previously, the low cloud cover is intensified due to the lack of solar radiation in the model run with the eclipse. This phenomena is visi-

ble in Figure 14 in which the low cloud cover of the operational COSMO-DE (left) and the eclipse model run (middle) is shown for 15:00 UTC. As reference, a satellite based cloud classification product from Nowcasting Satellite Facility (NWCSAF, see DERRIEN et al. (2013)) is depicted on the right hand side in Figure 14. The increase in low cloud cover is 26 % at 15:00 UTC and the clouds continued to intensify. This persistence and evolution of the low cloud cover is consistent with the satellite information for low and very low stratus clouds.

After the solar eclipse, the Lindenberg Meteorological Observatory (Richard Aßmann Observatory) of the DWD evaluated the conducted COSMO forecasts against measurements from their Falkenberg site which are used and designed to monitor climate and environmental processes. In Figure 15, the model runs with the operational COSMO-DE setup (dashed blue line) and the COSMO-DE including the solar eclipse (solid red

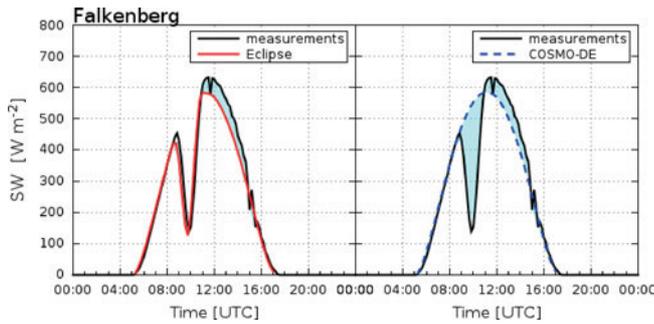


Figure 15: Comparison of the short wave radiation from the COSMO-DE run considering the solar eclipse (left) and the reference COSMO-DE run (right) with measurements for Falkenberg (black solid line).

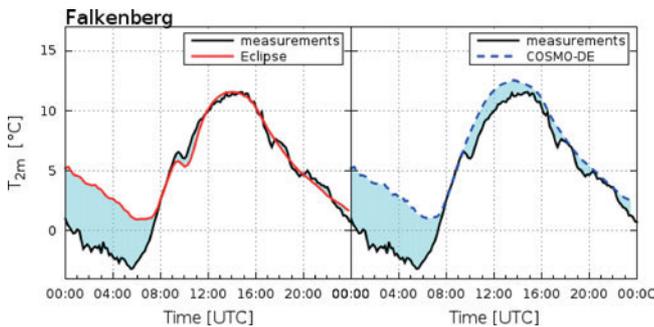


Figure 16: Comparison of the two meter temperature from the COSMO-DE run considering the solar eclipse (left) and the reference COSMO-DE run (right) with measurements for Falkenberg (black solid line).

line) are compared to pyranometer measurements for Falkenberg (solid black line) which have a temporal resolution of 10 minutes compared to the 15 minute time step of the model output. The comparison of the short wave radiation in Figure 15 reveals that the amplitude of the gradients induced by the obscuration and the subsequent increase in solar radiation after the eclipse are well captured. Only the maximum at noon in the measured solar radiation is not met by the COSMO-DE. A hypothesis for this shortcoming is the optically too thick atmosphere in the COSMO model which is likely due to the aerosols currently implemented (see HELMERT et al. (2007)).

In Figure 16 the modeled two meter temperature is compared to measurements (solid black line) for Falkenberg. The dashed blue line marks the operational COSMO-DE and the solid red line the COSMO-DE forecast including the solar eclipse. The effects of the solar eclipse are clearly visible by the reduction of the temperature which prevailed over the rest of the day. This is compliant with the findings in Section 6.2.1. Furthermore a note should be made on the large prediction errors which occur before sunrise with model temperatures higher than the measured values. Internal DWD verification studies of daily numerical weather forecasts from the DWD models versus measurements for the Falkenberg Boundary Layer Field site have been per-

formed. They indicate significant systematic forecast errors of the nighttime two meter temperature in the summer half-year especially in persistent high pressure situations with strong radiative cooling (as during the days previous to the eclipse). The two meter temperature in the COSMO models is derived diagnostically from the prognostic temperature in approximately 10 meters and from the surface temperature using a stability-dependent interpolation. Both these temperatures are typically too warm at night due to both enhanced vertical mixing in the lower boundary layer and increased vertical heat transport in the soil.

9.2 TSO's point of view

The event of the solar eclipse on 20 March 2015 presented a challenge due to the lack of experience with large gradients in PV-power feed-in. This experience was yet to be gained. Thus, a special operating concept among the four German TSOs for the solar eclipse 2015 was created beforehand. This concept had its focus on the German market and the security of the power grid and included establishing awareness amongst the market participants and coordination amongst the German TSOs. Most of the TSOs within in the ENTSO-E (European Network for Transmission System Operators for Electricity) were taken into account with several telephone conferences. Furthermore, the provision of balancing power was increased and repeatedly updated weather and power forecasts were gathered and disseminated amongst all participants.

A summary of the solar eclipse event is shown in Figure 17. In Figure 17a the extrapolated PV-power feed-in is shown. The gradients during the decrease of radiation reached $-2.7 \text{ GW}(\text{min})^{-1}$ and during the subsequent increase the maximum gradient $4.3 \text{ GW}(\text{min})^{-1}$ was observed. The total in controlling power used is depicted in Figure 17b and includes the secondary and tertiary control power as well as additional measures. The net frequency proved to be very stable, with power fluctuations continuously below $\pm 50 \text{ mHz}$ (see Figure 17c).

The lessons learned include that controllability of PV-plants needs to be reviewed for an effective future day to day business as the installed PV capacity is expected to increase further on. The market provided the necessary flexibility as the quarter-hourly intraday market proved to be very liquid given the corresponding supply and demand. Due to the good forecasts and a well planned marketing concept, the power control reserve was only used to balance the gradients within every 15 minutes.

10 Conclusions

This publication focuses on the total eclipse over Europe on 20 March 2015. The motivation for this work resulted from the needs of transmission system operators to anticipate the possible impact of such an event on

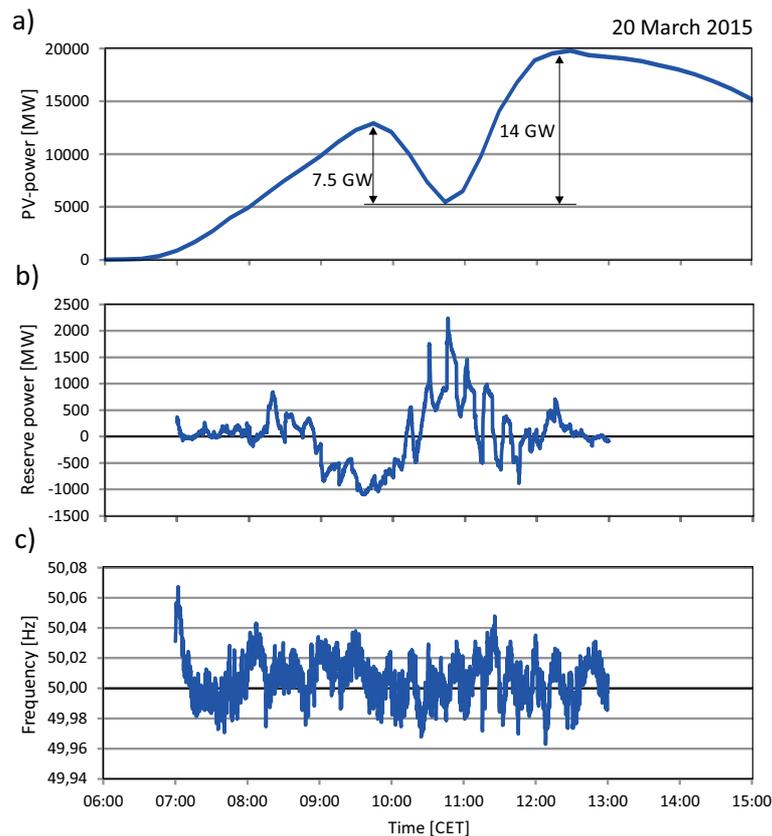


Figure 17: Shown in a) is the projection of the PV-power feed-in, in b) the total in reserve power, and in c) the net frequency for Germany on the 20 March 2015.

the power system, e.g. to increase the amount of reserve power. Months before the actual eclipse, sensitivity studies accounting for the greatest uncertainty factor, namely cloud cover, were performed with the non-hydrostatic COSMO model of the DWD in order to assess the potential maximal and minimal impact on solar radiation and temperature. These worst and best case NWP model simulations were used to assess an estimation of possible gradients in the German wide PV-power production during the solar eclipse. The gained experience helped to proactively prepare this special event. Days prior to the solar eclipse these NWP model setups were used to produce near real-time COSMO model forecasts. The actual weather situation during the eclipse was similar to the worst case scenario. Well planned precautions and cooperation amongst the various participants guaranteed that the power system stability was maintained throughout the event.

Real case scenario simulations were conducted well in advance using the non-hydrostatic COSMO models of the DWD. A clear sky scenario (20 March 2014) and an overcast scenario (16 March 2014), along with their reference model runs, were simulated in order to assess the worst and best case, respectively. Also, the 20 March 2014 was used for COSMO-EU simulations with artificially induced cloud free conditions. Therein the total solar eclipse taking place in the morning hours over northern Europe shows the highest impact over

Germany due to the opposite cycles of the eclipse and the rising sun. The strongest influence was found at 9:45 UTC under clear sky conditions. Considering all grid points over land in the simulations, the maximum mean reduction in short wave radiation at the surface over Europe yields 31 % in comparison to non-eclipse conditions. For the smaller domain of Germany the decrease yields 68 %. Due to thermal inertia, the two meter temperature decline is delayed. The mean difference over all land points is -2.67°C at 10:00 UTC. A reduction in temperature remained perceptible for the rest of the day in the model runs. These NWP sensitivity studies were openly distributed (KÖHLER et al., 2014) and served as the basis for some of the many assessment studies dealing with PV power gradients on the 20 March 2015, e.g., KREIFELS et al. (2015); KÖHLER et al. (2015). Also herein the NWP simulations were used to estimate the German wide PV power production. Due to the spatial nearly simultaneous and large scale drop in irradiance, the simulations suggest strong PV power feed-in gradients of up to $6.2\text{ GW (15 min)}^{-1}$ in the German power grid if clear sky conditions dominate the day of the eclipse.

During the eclipse actual near real-time NWP model simulations were conducted and provided to the open public. On the 20 March 2015, high pressure influence caused clear sky conditions over most parts of Germany. Only in the north-west (Amprion control area) persistent

low stratus clouds were perceivable throughout the day. These low level clouds also presented the biggest uncertainty factor for NWP model forecasts. The COSMO-DE run considering the solar eclipse showed a larger area of low stratus cloud cover in comparison to the control model run. The computed mean reduction in solar radiation over land for the day of the solar eclipse yielded 336.06 Wm^{-2} (68 %) which compares well to the worst case scenario. The modeled decrease in solar radiation and two meter temperature shows good accordance with ground measurements over Falkenberg. The NWP eclipse run also compares better to satellite observations concerning the representation of the before mentioned low stratus clouds.

The precaution measures taken by the TSOs lead to a stable power market during the day of the eclipse. Net stability was guaranteed at all times and power fluctuations continuously remained below $\pm 50 \text{ mHz}$. The actual maximum PV power gradients up to $4.3 \text{ GW (15 min)}^{-1}$ during the eclipse were well balanced.

The renewable energy community was well aware of the risks and uncertainties associated with the eclipse on 20 March 2015. From the view of a system transmission operator, the integration of renewable energies into the power system is a complex and challenging task, which depends strongly on the quality of the weather and energy feed-in prediction models. With the fact, that an absolute reliable forecast does not exist, it is important to identify extreme weather events, like the solar eclipse, that could influence the forecast error tremendously. The gained experience during the solar eclipse on the 20 March 2015 is of great importance considering future scenarios. Reaching the goal of German policy makers who envision a future installed PV-capacity of more than 60 GWp, such high gradients are to be expected for ordinary clear sky mornings (BURGES and SIKORA, 2014). Thus the created awareness and the interdisciplinary collaboration should be retained and pursued in order to successfully manage such challenging situations in the future.

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Disclaimer

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