A NETWORK OF ALL SKY IMAGERS (ASI) ENABLING ACCURATE AND HIGH-RESOLUTION VERY SHORT-TERM FORECASTS OF SOLAR IRRADIANCE

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Abstract

The Eye2Sky network is a measurement network in north-western Germany consisting of multiple all-sky imagers (ASI), meteorological and solar irradiance measurements. The network provides high temporal and spatial resolution data for meteorological and especially solar energy related applications. With increasing photovoltaic (PV) capacity in electrical grids fluctuations in solar irradiance due to changing cloud cover may have adverse effects on the grid stability. Within Eye2Sky, new technologies and methodologies facing the demand for more accurate solar irradiance forecasts are being developed. The ASIs used in Eye2Sky record 180° field of view hemispherical sky images from fish-eye lensed cameras. Accompanied with local measurements of solar irradiance components (global, direct and diffuse) a very short-term forecast of the solar resource is possible. These nowcasts provide minutely updated information up to 20 minutes ahead with 1-minute temporal and 50 m x 50 m spatial resolution. This approach shows more precise forecasting results for the next minutes ahead compared to traditional and less detailed methods based on satellite or numerical weather prediction models. In the network, multiple ASIs are used to enlarge the spatial coverage and the forecast horizon requested by many applications. Moreover, the forecast error can be reduced with a network of cameras. In this article, the Eye2Sky network, its research results and applications are introduced.

1 Introduction

The energy transition towards renewable energies leads to an increasingly penetration of electric power grids with photovoltaic (PV) power generation. The volatility of solar irradiance, in short-term periods caused dominantly by changes in cloud cover, can therefore be a critical issue for grid voltage and frequency and therefore the stability of the electrical grid. Additionally, regulatory limitations of allowed ramp-rates for PV plants are already effective or being discussed [1] .

Accurate nowcasts of the short-term PV-power generation will therefore support the integration of larger amounts of PV capacity. For low voltage distribution grids, they potentially enable higher PV penetration by utilizing short-term flexibility options and saving investments in the electrical grid [2,3] . For combined PV-battery systems nowcasts can support battery size optimization and management for ramp-rate regulations [4,5]. Moreover, short-term updates of energy production in PV plants assist energy traders by reducing deviations in predicted production and therefore saving money in intraday markets.

For these very short-term forecasts of solar resource variability, high resolution local cloud cover information from all-sky imagers (ASI) are the fundamental information source needed for accurate and reliable short-term forecasts of cloud cover and surface solar irradiance distribution.

ASIs provide high resolution images of the sky, recorded with cameras equipped with fisheye lenses providing a 180° field of view. ASIs are able to resolve small-scale cloud cover and cloud fronts, responsible for short-term solar resource fluctuations. They can therefore remedy the reduced spatial and temporal resolution of state-of-the-art solar forecasting methodologies like numerical weather prediction models or satellite image-based forecasting.

Eye2Sky is an operational network of ASIs installed and operated by DLR in northwest Germany. At 29 different locations, all-sky imagers record images every 30 seconds. At 12 locations, the images are complemented by solar irradiance and meteorological measurements. The Eye2Sky network covers about 110 km x 100km with a focus at the city of Oldenburg. It has a lower station density in rural areas and a higher density in the city of Oldenburg, thus providing an almost complete coverage of the city (Section 2). The network is under ongoing development since 2018 and already provides more than 3 years of sky images and high-quality measurements (Section 3).

The images and measurements from Eye2Sky are the basis for ongoing nowcast experiments at DLR (Section 4). These experiments investigate the potential of very short-term, high resolution and accurate predictions of solar irradiance in the upcoming minutes.

Due to the limited field of view of an ASI, the nowcast horizon and the spatial coverage for a single camera system are also limited. The average nowcast horizon of 20 minutes and the covered radius of 4 km (depending on cloud conditions) [6] is therefore extended by combining multiple ASIs of the Eye2Sky network.

In addition, a multiple data source approach using on-site irradiance measurements and satellite-based irradiance nowcasts together with ASI based nowcasts contributes to further improvements in accuracy, nowcast horizon and spatial coverage.

2 Network

The Eye2Sky network has been initiated with the first installations in 2019 and has been growing until today. In August 2022 in total 30 stations at 29 different locations in the city of Oldenburg and surrounding area were active (Fig. 1).

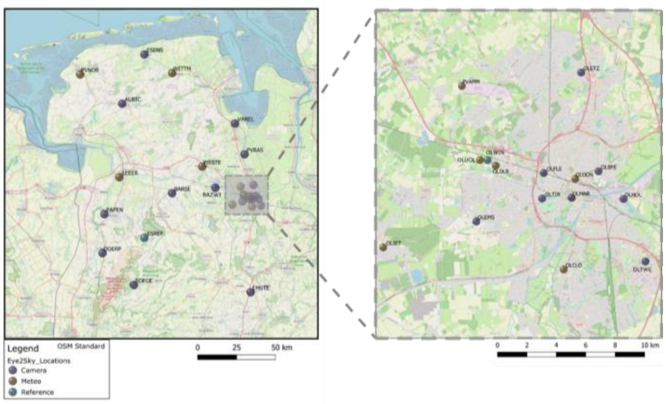

Figure 1: Distribution of ASI and meteorological stations active in August 2022. Two meteorological stations (Reference) are equipped with high quality solar trackers and additional meteorological instruments.

Additionally, 6 ceilometers (2 operated by DLR, 4 operated by German Weather Service DWD) supplement the network with cloud height reference data.

The instrumentation of the stations can be grouped in different types (Table 1). Every location is equipped with an ASI. 12 stations provide meteorological and irradiance measurements (Meteo). Two of them are reference stations used for validation and providing additional measurements.

Table 1: Number of active stations in the Eye2Sky network according to their instrumentation.

Area	ASI	Meteo	Reference	**Total**	Ceilometer
Rural	15	4	1	**15**	5
Urban	14	6	1	**15**	1
Total	28	10	2	**30**	6

The locations have been chosen based on a preselected distribution and the availability of suitable properties. The distribution should fulfill the following requirements:

- Fair coverage of the low-voltage electricity distribution grid of EWE (grid operator) between Oldenburg in the east and the Dutch border in the west and the North Sea coast in the north.
- High density of stations in the city of Oldenburg in order to have a good coverage of the urban area with high overlappings in between camera images
- A fair distribution of meteorological measurements for calibration and validation of solar irradiance analysis and forecasts.

Further, suitable locations need to offer safe access for maintenance, provide protection against theft and vandalism, electrical power supply, a sufficient 4G mobile network reception, as well as free field of view with as little as possible obstacles in the surroundings.

3 Instrumentation

The all-sky imagers (ASIs) of Eye2Sky are surveillance cameras of type Mobotix Q25 6MP color version with a fisheye lens providing 180° field of view. All cameras are equipped with an additional ventilation and heating unit preventing the lens from dust, dew, snow and ice. The cameras are calibrated geometrically describing lens distortion (intrinsic calibration) and external orientation after installation. The intrinsic calibration is performed by the provider of the ASI system (CSP Services) with a method developed by Scaramuzza et al. [7]. The external orientation, i.e. the azimuth deviation from geographical north, is calculated during full moon nights detecting the moons position relative to the cameras orientation as proposed by Blum et al. [8].

The meteorological stations have additional rotating shadowband irradiometers (RSI) and provide direct normal (DNI), diffuse horizontal (DHI) and global horizontal (GHI) irradiance (Fig. 2). The RSIs are of type CSP Twin-RSI [9]. Tilted pyranometers (LiCor200 and LiCor190) at 30° tilt angle pointing south (180° azimuth angle) measure global tilted irradiance (GTI) and tilted photosynthesis active radiation

(PAR). Ambient air temperature and relative humidity is measured with a combined sensor (Campbell Scientific CS125).

Figure 2: Intrumentation installed in a solar plant showing the ASI (left), the RSI (center) and the tilted pyranometers (right).

The reference stations provide irradiance data measured with a solar tracker along with additional meteorological measurements (wind, precipitation, air pressure) and guarantee high quality data.

Meteorological data acquisition is performed by a high-quality data logger (Campbell Scientific CR1000X) pushing data in real time to a central server. Real time data transfer is secured via 4G mobile network routers establishing a connection to a WireGuard VPN.

4 Database

Eye2Sky provides a large and increasing large data base of ASI images, in-situ meteorological and cloud height measurements since 2019. At present, camera images are stored every 30 seconds during daytime (Fig. 3-4).

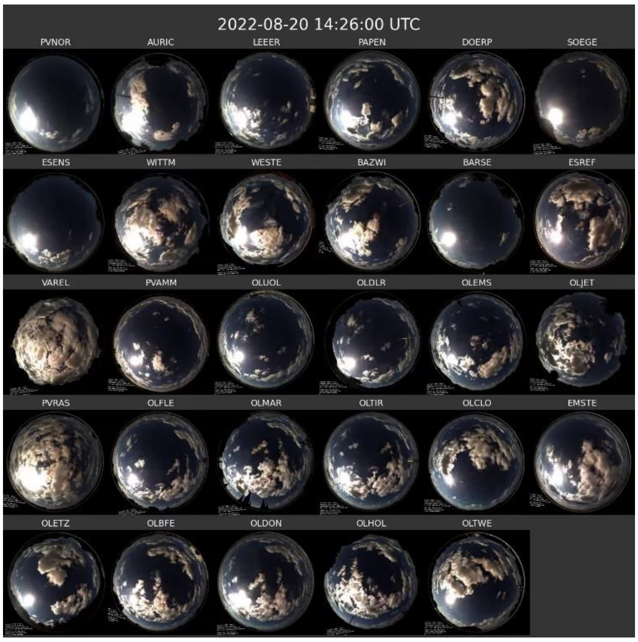

Figure 3: Example collage of 29 camera images taken at 20[th] August 2022 at 14:26:00 UTC.

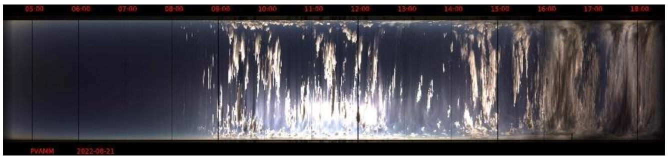

Figure 4: Keogram for ASI at station PVAMM showing concatenated vertical stripes of each sky image during a full day.

The meteorological measurements are provided as 1-min averaged and quality-controlled values.

Availability and quality of the data is optimized by a high-quality instrumentation, strong mobile network connection at each location and regular maintenance visits. Data quality checks based on existing standards are performed on 1-min averaged data [10]. Figure 5 shows a comprehensive evaluation of irradiance measurements at station OLUOL. Since both camera lenses and irradiance sensors are affected by atmospheric deposition (especially rain and dust) regular cleaning should be performed. The effort of regular cleaning intervals at remote stations is reduced by operational quality control of station data by comparison with reference sites in Oldenburg which underly at least weekly cleaning intervals.

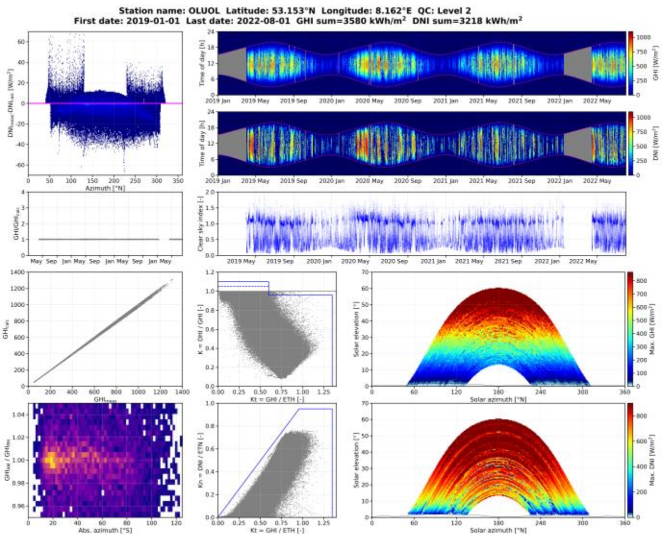

Figure 5: Comprehensive quality control (QC) of irradiance measurements at station OLUOL (located at University of Oldenburg) from April 2019 - August 2022. QC description and method from [10]

5 Short-term forecasting

The objective of short-term forecasting of solar radiation is to provide solar resource information for the next minutes to hours ahead for various stakeholders like plant and grid operators as well as energy traders at a very high accuracy. State-of-the-art forecasting technologies based either on numerical weather prediction models or satellite images combined with on-site monitoring systems still lack accuracy in terms of predicting short-term fluctuations and local ramps which is crucial for many applications. Statistical methods based on latest local measurements [11] can perform well but rely on a correlation between past and future conditions. Therefore, the usage of high-resolution information of local and nearby cloud coverage provided by all-sky imagers (ASI) is the key for reaching this objective.

3.1 ASI-based nowcasting

Short-term forecasting or nowcasting methods for global and direct irradiance (GHI/DNI) based on ASI systems are under development since more than a decade. Several scientific and commercial hardware and software solutions have been published (e.g. [6,12–17]).

The limitation in spatial coverage of a ground-based camera [18] is the reason why the majority of ASI-nowcasting systems focuses on local applications, e.g. single PV/CSP plants (e.g. [19]). Here, multi-ASI systems (with two or more cameras) in short distances to each other could already proof increased accuracy by deriving 3D cloud properties (e.g. cloud height) with stereographic approaches and also by reducing uncertainties introduced when using a single camera [20].

The Eye2Sky network introduces now the capability to utilize multiple distributed ASIs in order to gain a larger coverage (e.g. a region, city or distribution grid). Moreover, the forecast horizon for single sites can be enhanced since some cameras of the network capture cloud conditions at distant locations.

For the Eye2Sky network, the WobaS system ([6,21], Fig. 6) has been adapted and extended to combine multiple ASI for a network forecast.

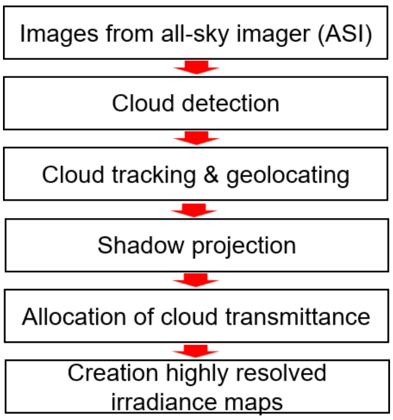

Figure 6: Flowchart of the basic processing steps inside the ASI-nowcasting system used for Eye2Sky.

For the city of Oldenburg (~10x12 km²), where 13 ASI cover the urban area, first results are present. Here, the usage of a network of cameras is reducing nowcasting errors by of up to 50% in highly variable conditions compared to the status quo of 2-ASI systems [22,23]. Additionally, Blum et al. [24] demonstrate more accurate cloud height estimations with the network of ASI in Oldenburg compared to pairs of ASI.

3.2 Satellite-based nowcasting

Satellite-image-based methods for cloud cover and irradiance forecasting for a few hours ahead have also been developed over years and are used operationally in leading solar forecasting technologies. For Eye2Sky, images from Meteosat Second Generation (MSG) satellites are used. A cloud motion vector (CMV) technique tracks clouds and enables predictions up to a 6 hours ahead [25]. MSG offers a spatial resolution of about 1-2 km per pixel and delivers images every 15 minutes. Satellite-based methods statistically combined with ground-based measurements show good performance under homogeneous conditions and in predicting cloud fronts resolved by the satellites. On the other hand, irradiance ramps or fluctuations caused by cloud features not resolved by the satellite cannot be predicted accurately in terms of amplitude, timing and duration. Fig. 7, showing predicted global irradiance based on ASI and satellite methods for the Eye2Sky region, illustrates the differences in spatial resolution and coverage.

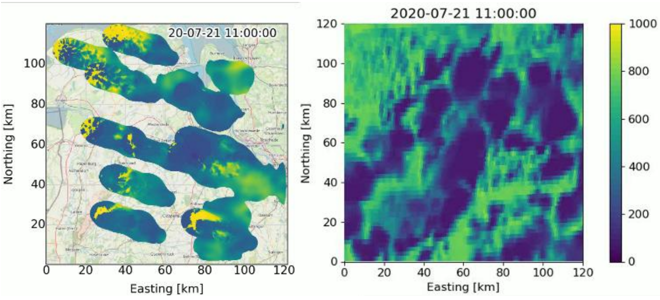

Figure 7: Comparison between ASI (left) and satellite (right) derived global horizontal irradiance (GHI) showing the difference in spatial resolution and coverage [26].

3.3 Hybrid forecasts

Advantages and disadvantages of the various data sources and technologies present lead to the development of hybrid and seamless forecasting technologies profiting of the strength of each input data source. The linear combination of ASI and satellite-based nowcasts (Fig. 8) trained on ground-based measurements is a first promising approach for the reduction of forecast errors. Multi-source approaches combining ground-based measurements, products from ASI and satellite systems with high resolution large eddy simulation (LES) and NWP models have been investigated in the European Union funded Smart4RES project aiming in development of next generation renewable energy systems (RES) forecasting models (www.smart4res.eu).

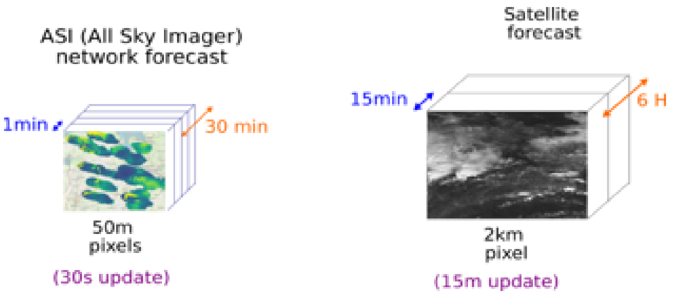

Figure 8: Data input for the linear combination model of ASI and Satellite forecasts.

6 Grid integration

Very short-term forecasts of solar resource variability can be used in a variety of applications, e.g. for increasing grid stability, dispatching backup capacities, optimizing storage management, load shifting, short-term trading or enhancing the PV hosting capacity in remote mini-grids (e.g. PV-Diesel hybrid systems). Overall, the information about short-term solar power output will increase the systems' reliability and efficiency.

Ramp mitigation, especially for large PV plants and depending on the underlying grid, is an important tool to increase grid stability when large and short-term drops or increases in PV generation are critical for balancing production and demand. One proposed method for ramp mitigation is linear down-curtailment of PV generation before a forecasted down ramp [27].

In combination with ramp mitigation battery storage management can benefit as well from very short-term solar forecasting by smart charging and discharging coupled with load- and market-pricing information. Smart algorithms incorporating generation and load forecasts can reduce the number of charging cycles and increase battery lifetime [28]. Increasing battery lifetime will in turn make the storage economically more feasible.

Nguyen et al. [29] studied the impact of high PV penetration on a distribution network and its hosting capacity by using sky imagers for a high resolution resource assessment with power system simulation. Here, a main advantage of the sky imager compared to a ground-based sensor network or metering installations is the reduction to a single or a few devices, which are able to reconstruct the cloud shadow distribution on a large area. When studying distributed PV or distribution grids respectively, high resolution solar forecasting can also be used for PV inverter control and storage management to optimize the distributed generation while reducing the impacts from high penetration on the grid.

In order to gain benefits through very short-term trading of PV power, market conditions have to be considered. When trading intervals and horizons will be reduced to intervals in the order of a few minutes and if update rates are increased, sky-imager-based short-term solar forecasting can contribute to smaller forecasting errors and therefore reduce overall system costs. Bilateral trading, e.g. between plant owners and consumers (e.g. industries with flexible loads, power to gas/heat facilities) or even between small-scale producers with rooftop PV capacities and neighbourhood consumers could contribute to better PV integration, e.g. in smart grids [18].

Samu et al. [30] summarize the usage of ASI-based nowcasting with power system modelling in mini-grids to increase the PV hosting capacity and to reduce costs. Ramp-rate control, predictions of spinning reserves, battery management and demand response management (DRM) have been highlighted as the major prospective applications. The authors point out, that in existing projects a reduction in battery size and diesel usage could be achieved.

7 Conclusion

The Eye2Sky network offers large potential for the development of novel very short-term forecasting methods for the integration of PV energy into electrical grids. Several studies already prevealed that the usage of multiple cameras in a network reduce forecast uncertainties compared to methods based on single or pairs of cameras. Multi-source approaches utilising the advantages of each data input (e.g. ground-based measurements, ASI and satellite based nowcasts, LES, NWP) will lead to a new generation of more accurate and seamless forecasting technologies for the very short-term horizon of 0-60 min ahead.

We are currently engaged in an intensive exchange with stakeholders like plant operators, grid operators and energy traders. Feedback from stakeholders on needs and requirements will support us to adapt nowcasting strategies to specific applications.

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