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NTNU-SINTEF SolarNet: A solar irradiation monitoring network at high latitudes

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Abstract. This study presents a monitoring network for solar irradiation at high latitudes, called NTNU-SINTEF SolarNet. The network collects, with a time resolution ranging from seconds to hours, solar irradiance data, e.g. global horizontal irradiation, diffuse horizontal irradiation, direct normal irradiation, global tilted irradiation, solar energy generation, which are required in solar irradiation modelling in built environments. The network will be used for specific applications, such as (i) anomalies detection, (ii) influences of ground albedo, and (iii) ageing/degradation of solar modules, that are described in this paper. Some characteristics that make the NTNU-SINTEF SolarNet relevant for solar energy research at high latitudes are identified: short distances among the sensors, the ease of data accessibility, the use of the same sensor typologies, and different solar module technologies. The research holds the potential to boost the solar energy digitalization, impacting on several aspects such as predictive and adaptive control strategies for energy management, design of renewable energy system, multi-scale optimization and efficient exploitation of solar energy.

1. Introduction

In Norway, the interest in solar energy has significantly grown in the last decade as demonstrated by the constant increment of the installed solar power in the national energy grid: from 15 MW (2015) to 299 MW (2022), with a rapid doubling from 2021 to 2022 (source: nve.no). New technological solutions and innovative materials available on the market, e.g., building-integrated photovoltaics (BIPV), and bifacial photovoltaics (BPV) [1,2], have contributed to boost the exploitation of solar energy at building and neighbourhood scale. However, advanced applications like agrivoltaics [3] and floating PVs [4] are expected to be fully developed in the upcoming years. This will increase the need for robust decision-making tools and reliable solar irradiance data to optimal exploitation of solar energy potential, especially at extreme latitudes. This study presents a monitoring network for solar irradiation at high latitudes. Solar irradiance data, e.g., global horizontal irradiation (GHI), diffuse horizontal irradiation (DHI), direct normal irradiation (DNI), global tilted irradiation (GTI), solar energy generation (PV_{out}), required in solar irradiation modelling in built environments, are collected with a time resolution ranging from seconds to hours. The solar irradiation network established at

Gløshaugen Campus at Norwegian University of Science and Technology (NTNU) in Trondheim (Norway), called NTNU-SINTEF SolarNet, enables accurate monitoring of solar irradiation, and contributes to the solar energy digitalization (i.e., deployment of digital technologies for smart solar energy management) at high latitudes. The network has the potential to ease several tasks like the implementation of predictive and adaptive control strategies for energy management, design of renewable energy systems, multi-scale optimization and efficient exploitation of solar energy.

2. Methodology

2.1. Workflow

The workflow followed in this study concerns preliminary investigations to make use of data from the NTNU-SINTEF SolarNet. Data is used to perform solar analyses such as (a) anomalies detection, (b) influences of ground albedo, and (c) ageing of solar modules. (a) Through the observation of the GHI from different sensors, anomalies can be detected. The average value is compared against measurements from an unshaded sensor which is used as the reference to identify environmental shadowing, cloud enhancement and shadow, system failure, and snow accumulation on the other pyranometers. For this purpose, one-minute datasets are preferred. (b) The influences of ground albedo on the measured solar irradiation are evaluated by comparing the observations of GTI on the South façade of two research facilities, the Zero Emission Building (ZEB) Laboratory and the ZEB Test Cell Laboratory. Data used in this stage is collected by pyranometers installed at different heights (i.e., 3 m, 6 m), with the same tilt angle of the façade. (c) The ageing of the solar modules is evaluated by calculating the yearly efficiency as the ratio between the produced energy and the solar irradiation impinging on the module surface. This process enables to investigate the reduction of the performance level of solar systems operating at high-latitude locations. Solar irradiation variables considered in these tasks are reported in Table 1 together with time resolution, time interval, and sensor location.

Table 1. Solar irradiation variables, location of the sensor, and main characteristics of the datasets.

Variable		**Sensor location**	**Time resolution**	**From**	**To**
Global Horizontal Irradiation	$GHI_{tc,roof}$	ZEB Test Cell Laboratory	1 min	1/3/2022	1/3/2023
Global Horizontal Irradiation	$GHI_{tc,ws1}$	Ground weather station 1, ZEB Test Cell Laboratory	1 min	1/3/2022	1/3/2023
Global Horizontal Irradiation	$GHI_{tc,ws2}$	Ground weather station 2, ZEB Test Cell Laboratory	1 min	1/3/2022	1/3/2023
Global Titled Irradiation	$GTI_{tc,façade}$	South façade pyranometer, ZEB Test Cell Laboratory	1 min	1/3/2022	1/3/2023
Global Titled Irradiation	$GTI_{lab,façade}$	South façade pyranometer, ZEB Laboratory	1 min	1/3/2022	1/3/2023
Global Titled Irradiation	$GTI_{tc,roof}$	Tilted roof pyranometer, ZEB Test Cell Laboratory	Yearly	All	All
PV energy production	PV_{out}	ZEB Test Cell Laboratory	Yearly	All	All

2.2. NTNU-SINTEF SolarNet

The NTNU-SINTEF SolarNet consists of a network of sensors and monitored PV and hybrid photovoltaic/thermal (PV/T) modules that are integrated, installed, or applied on several research facilities and buildings of the NTNU Gløshaugen Campus (Figure 1). The sensors include a sun tracker and numerous pyranometers with different orientations. Such apparatus enables continuous collection of solar irradiation data with a high time resolution. The sun tracker is located on the rooftop of one of the buildings at the campus (named Sentralbygg 1), and it measures one-minute values of DNI, DHI, and GHI. At the ZEB Laboratory, eight pyranometers are integrated into the building envelope and the BPV pergola, allowing to measure the GHI and GTI on roof, façades, and the two sides (inwards and outwards) of the South-exposed pergola. Four pyranometers are installed in

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the ZEB Test Cell Laboratory, two monitoring GHI at the ground and at the roof level, and two collecting data on the tilted roof and on the South-exposed façade. The solar radiation is also monitored in the ZEB Living Laboratory with a sensor layout similar to the ZEB Test Cell Laboratory. Finally, NTNU-SINTEF SolarNet is completed with the monitored BIPV in the ZEB Laboratory; the PV and PV/T on the roof of the ZEB Test Cell Laboratory; the PV in the ZEB Living Laboratory; the dual axis solar tracking PV in the Sentralbygg 1; and the PVs installed with different orientation and tilt angles on the rooftop of the Elektrobygg.

Figure 1. Overview of the NTNU-SINTEF SolarNet at Gløshaugen Campus (Trondheim, Norway).

2.3. Ongoing research activities

2.3.1. Shading and other similar inter-building effects. Solar irradiation measurements from NTNU-SINTEF SolarNet sensors enable to investigate shading effects and other complex phenomena such as inter-building solar reflections within the built environment. In fact, the regularly recurring anomalies in monitored values with respect to the benchmark data can be interpreted as the evidence that a building or a vegetation element casts shadows or reflects solar irradiation towards the pyranometer.

2.3.2. Cloud enhancement. One-minute observations of solar irradiation allow detecting the cloud enhancement. Cloud coverage influences radiation scattering, and some changes in the cloud pattern can give a GHI measurement higher than in clear sky conditions. This can result in instantaneous peaks in the GHI and in irregular or recurring positive anomalies with respect to other sensors. Indeed, cloud enhancement is spatially limited, therefore, it is not detected by every sensor in the network.

2.3.3. System failure. The analysis of anomalies eases the detection of failures in system components. Sudden and continuous differences between observations and average values can prove the incorrect functioning of either the monitoring apparatus or the acquisition system.

2.3.4. Ground albedo. The observation of the vertically mounted pyranometers, allows evaluating the influences of ground albedo and inter-building reflections on the energy generation from the facades.

2.3.5. Soiling and snow accumulation. Monitoring different PV installations in the same network enables identifying soiling and snow-related issues that prevent the optimal operation of solar modules [5]. Weather data including snow depth, precipitation intensity, and wind velocity, pressure, and direction contribute to identifying the local environmental conditions in which snow or light-weight materials such as soil and dust tends to accumulate on PV panels. In addition, the visual inspection of the PV panels can be performed with semi-automated techniques to provide a quantitative estimation of the PV area obstructed by snow/soil. This information is correlated to weather data to calculate and forecast the reduction of PV production due to snow/soil deposits.

2.3.6. PV performance monitoring and prediction. Observations of PV modules allow investigating the degradation rate of the different technologies and their efficiency decay. Machine Learning-based (ML) methods are also implemented to correlate solar irradiation variables to PV power output.

2.3.7. Data quality filtering. Solar irradiation measurements from network sensors can be exploited to implement a data quality filter scheme which is specifically developed for high-latitude applications.

3. Results

3.1. Anomalies detection

Figure 2 shows GHI datasets from the NTNU-SINTEF SolarNet and their variation from benchmark data. From this, it is possible to identify shadow casting and other inter-building phenomena.

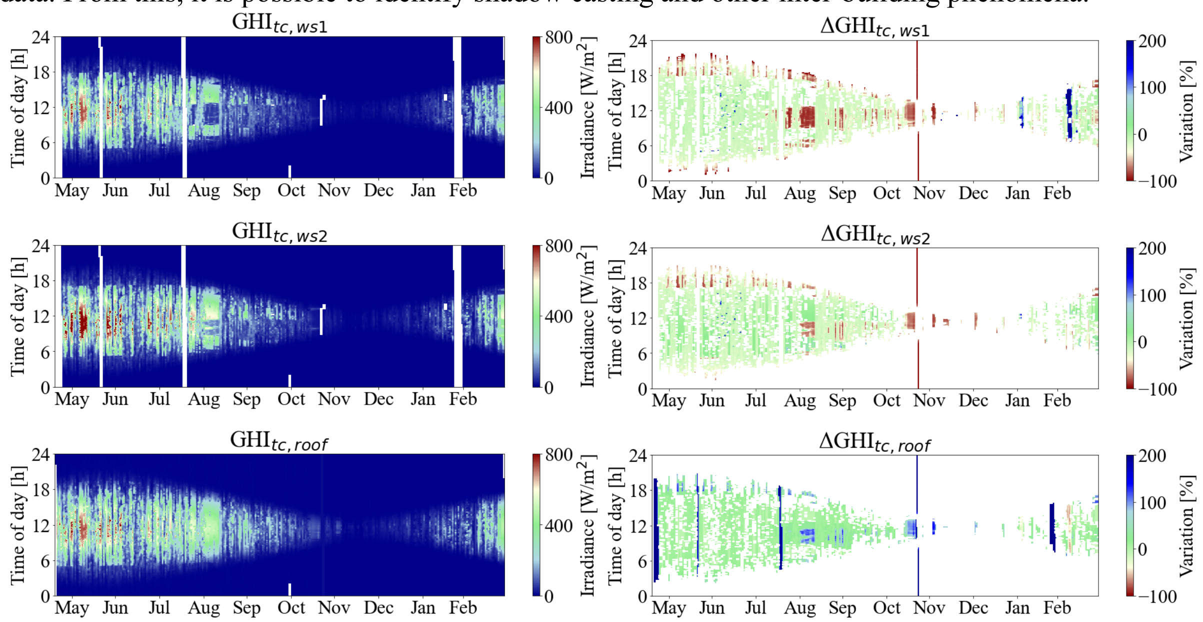

Figure 2. Heatmap visualization of GHI datasets and variation from benchmark data.

Figure 3 reported GHI$_{tc,ws1}$, GHI$_{tc,ws2}$, and GHI$_{tc,roof}$ observations between 5th and 7th September 2022.

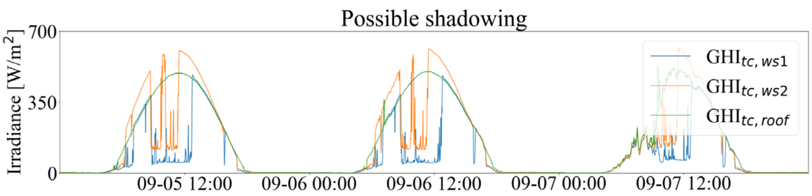

Figure 3. Observations of GHI from ZEB Test Cell Laboratory showing the presence of an element that shadows the ground sensors at around noon.

The graph highlights the presence of shadows that are casted from some element in the sensor's proximity. In fact, both GHI$_{tc,ws1}$ and GHI$_{tc,ws2}$ decrease with respect to GHI$_{tc,roof}$ at around noon every day, with the same magnitude. In Figure 4, GHI measurements from June 25th are outlined. Presence of clouds and changes in cloud pattern are identified at 5:00, 13:00 and 17:00. Also, clouds prevent a fraction of the solar irradiance to reach the sensors between 5:00 and 12:00, being GHI$_{tc,ws2}$ higher than GHI$_{tc,ws1}$ and GHI$_{tc,roof}$.

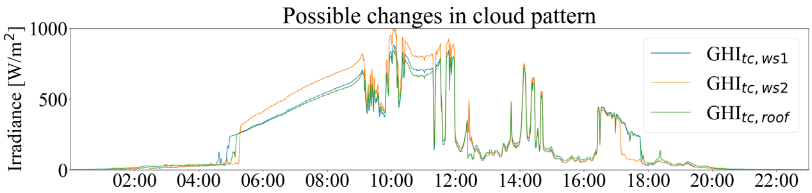

Figure 4. GHI profiles of June 25th, 2022: the presence of clouds and changes in the cloud pattern are clearly identified at 5:00, 13:00 and 17:00.

The days between 3rd and 5th February 2023 are exemplary for anomalies induced by snow deposits. In fact, there is a constant difference between the measured quantities throughout the day; therefore, the snow accumulation on top of the sensors is likely to be the main cause of it.

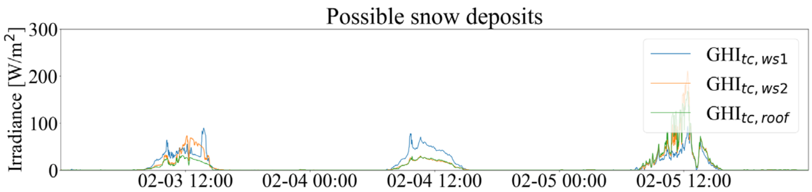

Figure 5. Observations of GHI from ZEB Test Cell Laboratory showing the presence of snow deposits on the pyranometers.

3.2. *Influences of ground albedo*

The influences of the ground albedo are here investigated in terms of variation of $GTI_{tc,façade}$ from the $GTI_{lab,façade}$ benchmark data (Figure 6). The visualization of results highlights that $GTI_{tc,façade}$ is usually lower than $GTI_{lab,façade}$ during morning hours, while being higher than $GTI_{lab,façade}$ in the afternoon.

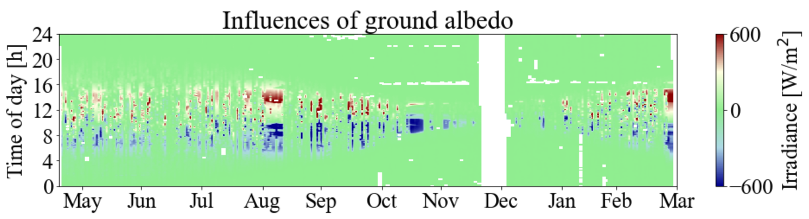

Figure 6. Variation of $GTI_{tc,façade}$ from the $GTI_{lab,façade}$. The white colour highlights the missing values in the dataset.

3.3. *Efficiency of solar modules*

The multi-crystalline silicon (mc-Si), the PV/T, and the CIS (copper indium selenide) thin film modules on the roof of the ZEB Test Cell Laboratory are considered to preliminary investigate the panels ageing in terms of efficiency (Figure 7).

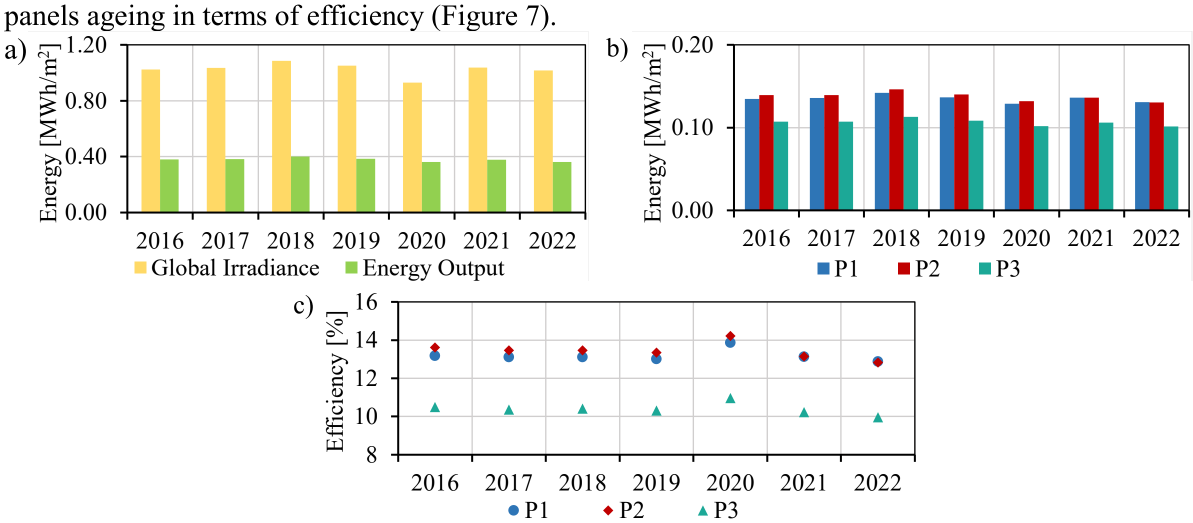

Figure 7. (a) Solar energy potential and energy output of solar modules at the ZEB Test Cell Laboratory; (b) energy production of mc-Si (P1), PV/T (P2), and CIS thin film (P3) modules; and (c) efficiency of the P1, P2, and P3 modules calculated throughout the monitoring period.

The rated efficiency is equal to 15.8% for the mc-Si modules, to 15.4% for the PV/T modules, and to 11.4% for the CIS thin film modules. Observations of cumulated produced energy and solar irradiation throughout the year are used. The monitoring campaign started in 2016. The measured efficiency was lower than the rated efficiency for every panel. In 2016, the mc-Si, the hybrid PV/T, and the CIS thin film modules showed an efficiency of 13.2%, 13.6%, and 10.5%, respectively. In 2022, the system efficiency is reduced due to ageing. The PV/T modules exhibit the highest degradation rate (-0.8% between 2016 and 2022), while the efficiency of mc-Si modules is almost constant throughout the monitored period. Similarly, the performance level of the CIS thin film modules is slightly decreased (-0.5%) in comparison to the initial value.

4. Conclusions

This study presents a monitoring network for solar irradiation at high latitudes: the NTNU-SINTEF SolarNet. Collected datasets enable detecting anomalies due to the clouds and shadows casting and investigating snow deposits, soiling and ground reflections. These aspects are relevant when estimating solar energy potential in the Nordics. Mutual shadowing of buildings often occurs at high latitudes that are characterized by low solar elevation angles for long periods. Similarly, snow deposits and ice accretion on the ground modify the ground albedo, affecting the GTI on building façades. The long duration of the monitoring campaign allows the analysis of the efficiency degradation of solar modules throughout their lifetime. This study describes the potentialities of NTNU-SINTEF SolarNet by highlighting the relevant characteristics of the monitoring network to conduct solar energy research at high latitudes such as the short distances among the sensors, the ease of data accessibility, the use of sensors with the same measurement accuracy, and the different solar module technologies that are monitored in the network. Future developments concern the implementation of semi-automated techniques which will detect anomalies exploiting ML. The solar irradiance database will be a basis of reliable data to be used to develop predictive algorithms for short-term forecasting of renewable energy production from PV modules.

Acknowledgements

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