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Validation of shading model in SolarMoves

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ABSTRACT

To understand the impact that vehicle integrated PV can have on the electricity grid requirements now and in the future the SolarMoves project is using a combination of detailed modelling and measurements to arrive at predictions for the European EV fleet and grid infrastructure requirements now and in 2030. The first phase of the project consisted of extensive modelling [1]. In this paper we take vehicle irradiance measurement results from phase two of the project to examine the validity of the seasonal shading model used in part one of the project. Measurement results indicate that shading losses can be somewhere between 5 and 20 %. Shading can have a significant impact on PV yield, especially on VIPV where the vehicle is moving through different terrains, including open spaces with little shading to very densely built up areas with a lot of shading. Taking account of this in an accurate way is a very important part of determining the possible PV yield.

1. Introduction

The transition from fossil fuel-based transport to electric transport is a crucial part of the energy transition. This shift will lead to a significant increase in electricity demand across all sections of the electricity grid, as vehicle charging will occur at home, on the street, in charging hubs and along highways. Consequently, this will necessitate grid reinforcements and a substantial increase in generated renewable energy to supply these charging stations with green energy. On the other hand, vehicle integrated PV (VIPV) will generate electricity where it is needed, reducing and in some cases eliminating the need for electrical infrastructure to charge the car.

In previous work for the SolarMoves project, TNO's Energy Flow Model (EFM) has been used to determine the energy needs of various vehicle types and use cases (archetypes). The set of archetypes was then used to construct a predicted European fleet of Electrical Vehicles and ultimately the impact on the European electricity grid was calculated [1,2]. In part 2 of the project a series of irradiance measurements are being made on vehicles across several locations in Europe and it is a subset of these measurements that are being used here to validate the shading model that has been used in the EFM.

Fig. 1 shows the workflow of the EFM. One of the key aspects is determining the incident irradiance that is used to calculate the generated energy from the VIPV. Using the location, time, sun position and meteorological data, specifically the global horizontal irradiance (GHI), the irradiance incident on the vehicle is determined, a shading loss, in our case a seasonal loss function, is applied and the generated PV energy can then be calculated.

2. VIPV irradiance shading model

Various approaches have been reported which are designed to quantify the impact of shading in the use of VIPV these include using measurements with fisheye cameras and irradiance sensors [3,4] or with simulations using digital surface models [3,5–7]. The shading model currently used in the EFM is based on the work of Cobbenhagen [5], with modifications that incorporate findings from Araki et al. [4]. Cobbenhagen's thesis [5] developed a sinusoidal seasonal distribution function of a daily average shading correction factor. The work was based on analysis using the Digital Surface Model (DSM) for surface heights in the Netherlands, the Actueel Hoogtebestand Nederland (AHN) [8] and historically measured irradiance data. Focussing on an area in Eindhoven, in The Netherlands the correction factor resulted in an annual shading loss of 27 %, but the function did not consider other types of routes or

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areas. The work of Araki et al. [4] reported a reduction in global horizontal irradiance on top of a vehicle of 3 % in open areas, 21 % in residential regions, and 48 % in built areas, with a variation depending on latitude, the work was based on results of the analysis of fisheye camera images for various types of areas.

For the SolarMoves project, the Cobbenhagen function was adjusted to get 3 different shading correction curves, depending on the terrain, Motorway, Semi-Urban, and Urban, which roughly correspond to the areas described by Araki et al., [4], however intermediate shading loss numbers were used to account for the latitude of the Netherlands, and for the fact that in the Netherlands there are hardly any completely open areas, and urban routes often consist of a mix between real city centres and more low-rise residential parts. The seasonal shading factors are shown in Fig. 2 showing an estimated average annual shading loss of: Urban: 35 %, Semi-urban 24 % and Motorway 15 %.

In this work we have used one month (33 days) of measured data, from July 5th to August 6th' 2024, to validate the shading model, with the date window shown by the red box in Fig. 2. In this time frame the model gives average losses for the three terrain types of: Urban, 25 %, Semi-urban, 17 % and Motorway 11 %.

3. Measurements

3.1. Measurement campaign

The measurement campaign for the Solar Moves project has been carried out by FhISE and uses sensors developed and used in the PV2Go project [9]. 23 Vehicles have been fitted with irradiance sensors that record irradiance and GPS coordinates. This campaign began in March 2024, and will continue for at least one year. The vehicles include trucks, buses, vans and passenger vehicles, travelling in various locations in Europe, including The Netherlands, Germany, Belgium, France, Slovakia and recently also Spain (Fig. 3).

For the purposes of validating the shading model a subset of the measurements has been used, taken from an E-Volvo truck, travelling mainly in the Netherlands (Fig. 4). While the truck has 3 irradiance sensors installed, one on the top and one on each side, only the top sensor has been used in this analysis, the side sensor data will be analysed and reported in future work. The analysed data set consists of 1 min values for GPS coordinates of latitude and longitude and 1 min mean values of the irradiance measured on the top of the vehicle. The data is further processed to include the direction of travel and comparative irradiance measured at nearby Dutch weather stations from the Royal Netherlands Meteorological Institute (KNMI) [10]. The measured latitude and longitude values are used to find the nearest KNMI weather station and the irradiance measured at that time stamp is collected. The KNMI data is based on 10 min average values and so the collected data has been interpolated to match the 1 min time stamp of the measured truck irradiance.

3.2. Analysis of measurement results

As a start for the irradiance model validation, all irradiance data from July 5 up to August 6 was used. The truck location for this time frame is shown in Fig. 4, these kind of routes resemble the regional distribution and long-distance driving reported in part 1 of Solar Moves [1], where a shading loss of semi-urban would have been selected. This would have resulted in a 17 % loss for the time frame given. Fig. 5 compares the total irradiance measured on the truck and at the nearby KNMI stations for this time frame. The total KNMI irradiance for the period was 167 kWh/m2. In the same period, the irradiance on the truck was 124 kWh/m2. This results in a total shading loss of 26 %. Which is higher than the shading loss of 17 % that would have been used in part 1 of the SolarMoves project. However, the measured irradiance loss includes the times when the truck was parked in the shade, which might not reflect the typical irradiance conditions of a truck with VIPV, and this kind of driver behaviour was not accounted for in the modelling.

3.3. Daily values

The shading model used by the EFM applies daily loss values and so further investigation into the data has been done on a daily basis.

Fig. 6 shows the daily driving distances of the vehicle. From this it is apparent that the truck is active on 19 out of the 33 days. It does not operate on the weekends and also not for one week from 22/7 to 29/7.

To remove the uncertainty of the vehicle being parked for extended periods in the shade, the analysis continues on the days when the truck is active. This is to reduce the 'driver behaviour' element with respect to

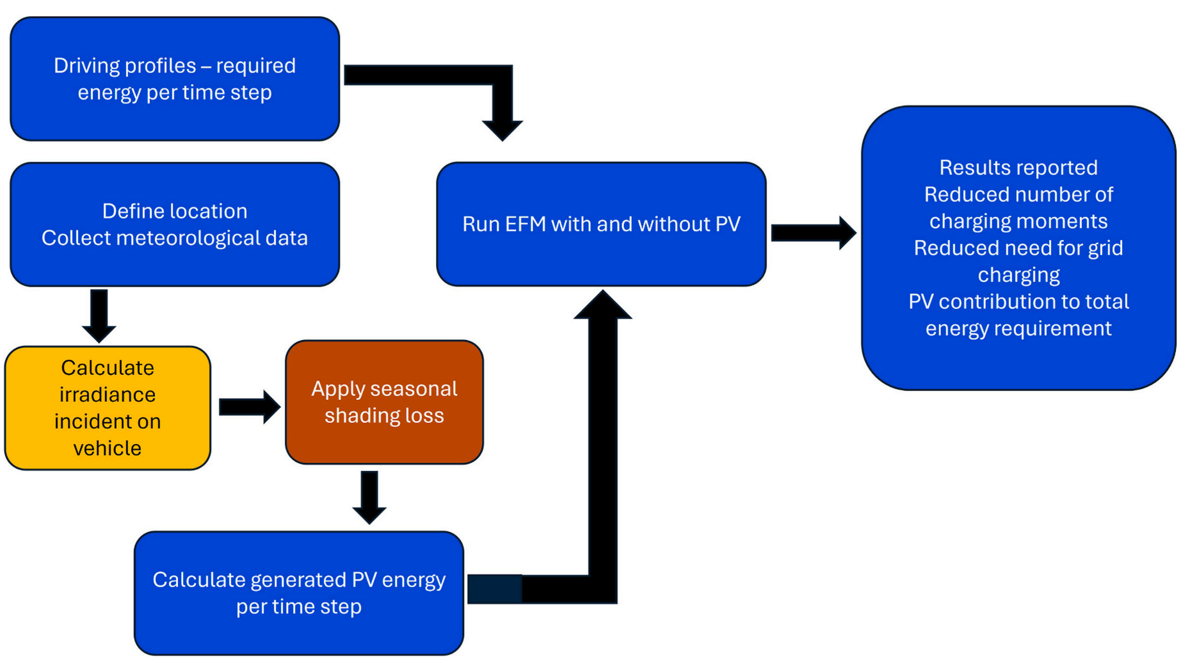

Fig. 1. Work flow to calculate the impact of PV on a given archetype highlighting the application of irradiance calculation and shading loss.

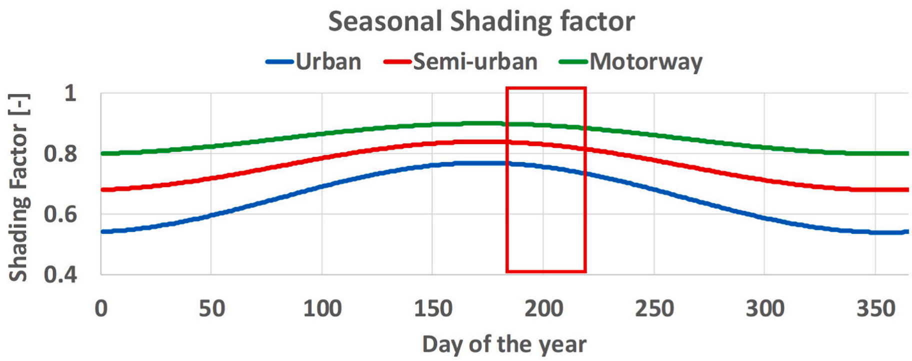

Fig. 2. Seasonal shading factor for different road types. The shading factor is the fraction of the solar light received by the VIPV during a trip on a certain road type in comparison to the amount of solar light received on a trip without any shading losses. The red box indicates the set of measured data dates used in this validation study.

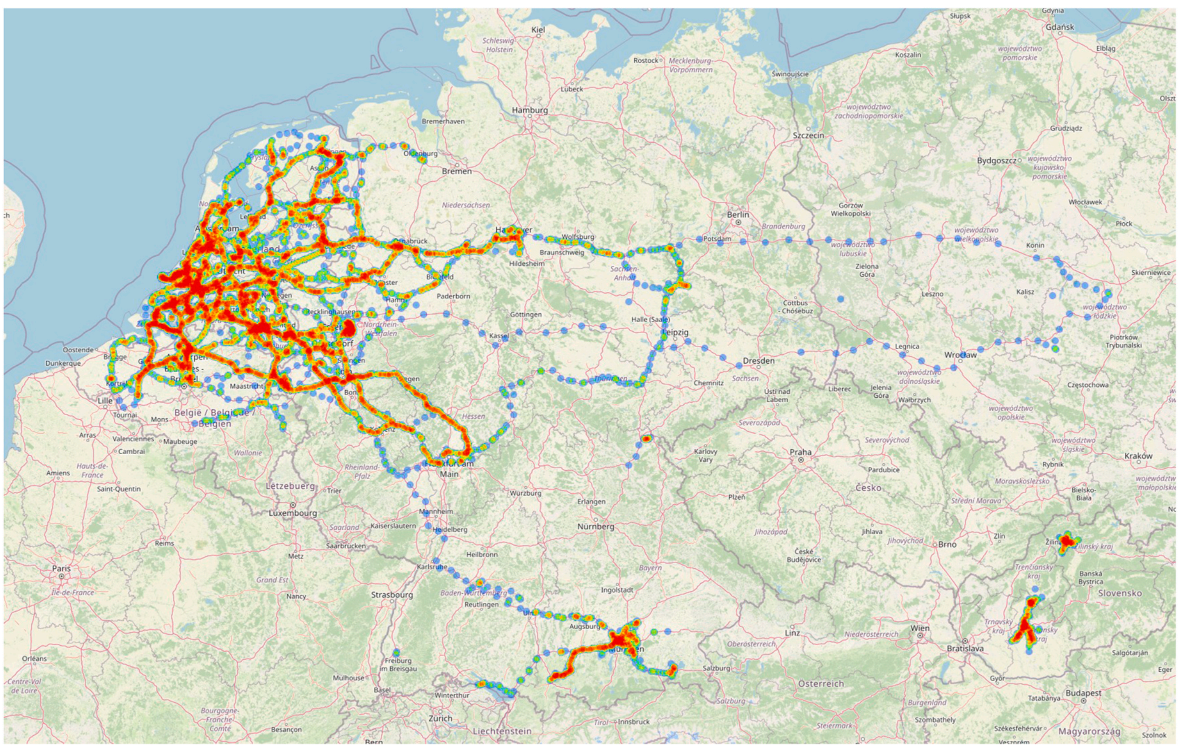

Fig. 3. Heatmap showing location of all irradiance sensors as of April 9th, 2025.

parking in the data, which we have no control over and was not included in the modelling. Looking at the daily measured irradiance for the days the truck was active and daily loss values, Fig. 7, it can be seen that there are two days where the loss is more than 20 %. It turns out that these are also days with very low irradiance and so it is a high percentage of a very low value, which have been considered outliers for this analysis. There are also two days where the truck irradiance is higher than the KNMI data, this is investigated further below. The average loss for the days when the truck is moving is calculated to be 11 %.

From the dataset, three days are shown below that compare the truck irradiance with KNMI irradiance data, namely July 9, 12 and 30. These days correspond to partly clouded, clouded and clear sky days respectively. Fig. 8, 9 & 12.

On the clouded and partly clouded days, July 9th and 12th, the irradiance fluctuates strongly due to passing clouds. As the KNMI sensor location is never precisely the same as the truck location it makes it impossible to directly compare the truck data with the irradiance data sets as passing clouds will pass at a different time. A daily average makes more sense and is also what was used in the shading model.

When looking at the sunny day, July 30th, the truck irradiance is 3 % higher than the KNMI irradiance, which is not expected.

Fig. 10 and 11 give an overview of the landscape the truck experienced on July 30. Fig. 10 shows the route for that day on top of the Bestand Bodemgebruik (Land use) map from the Bureau of Statistics (CBS) in the Netherlands [11]. Further analysis is given in Fig. 11 where the percentage of time spent in the different terrain areas is given for that day. This shows that for the specific time period, the truck was located in urban areas for 53 % of the time the remaining time in more open areas. This would fit best to the vehicle archetypes rigid truck with urban distribution or tractor-trailer with regional distribution in part one of SolarMoves [1], for which we have used the semi-urban shading function. For the time period under investigation, this function has an average shading loss of 17 % [1] the same as would have been applied to the whole data set for this truck mentioned previously. This is significantly different to the 3 % increase we see in the measurements.

Looking at the irradiance over the day, Fig. 12, we see that the truck

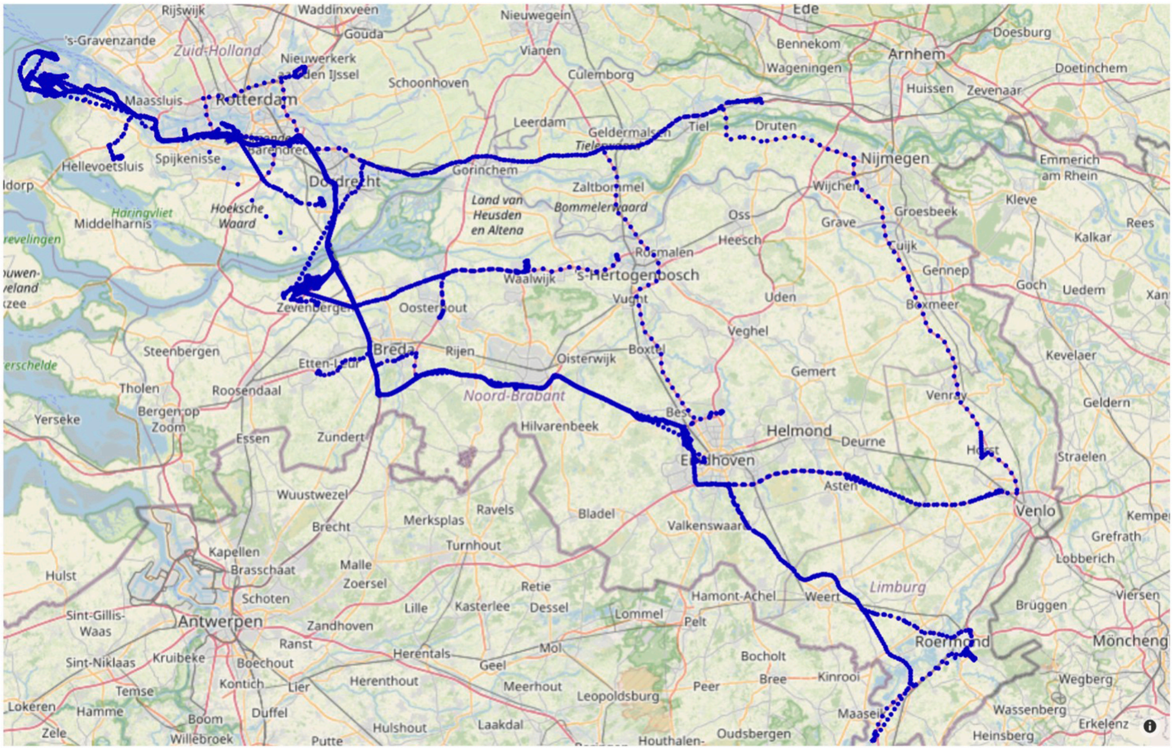

Fig. 4. Route of E-Volvo truck between July 5th and August 6th, 2024. All travel is in The Netherlands.

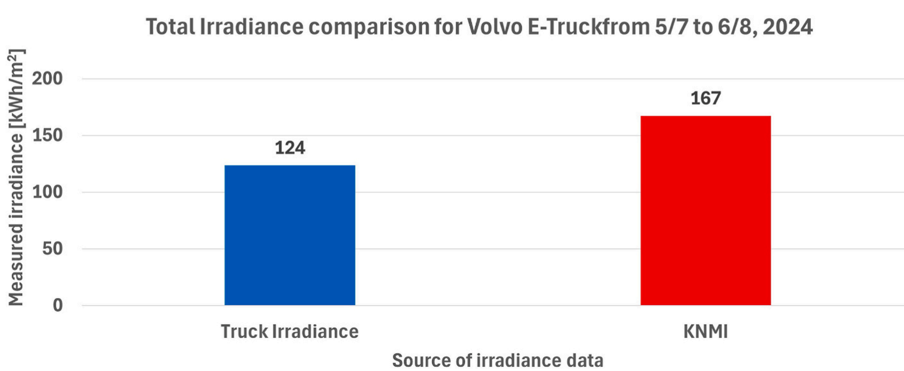

Fig. 5. Total irradiance measured on the truck and at KNMI weather stations between July 5th and August 6th. The results show a difference of 26 %.

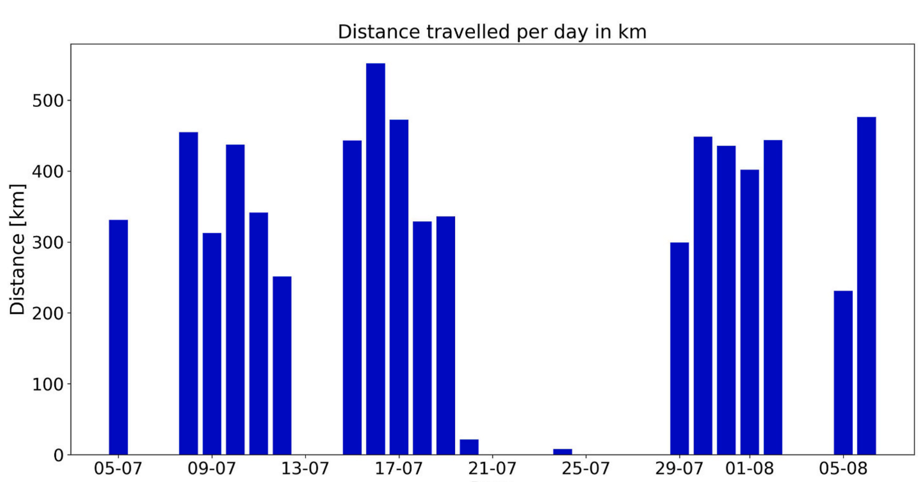

Fig. 6. Daily kilometres travelled by the Volvo Truck during the test period. The truck is not driven on the weekends or in the week between July 21 and 29.

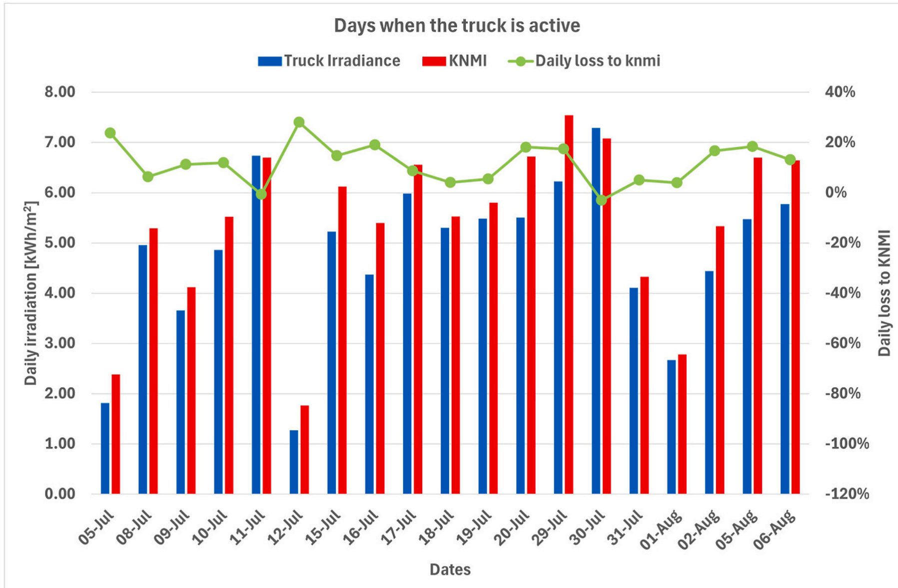

Fig. 7. Comparison of irradiance values when the truck is active, and on the right axis the daily loss (if negative it is a gain).

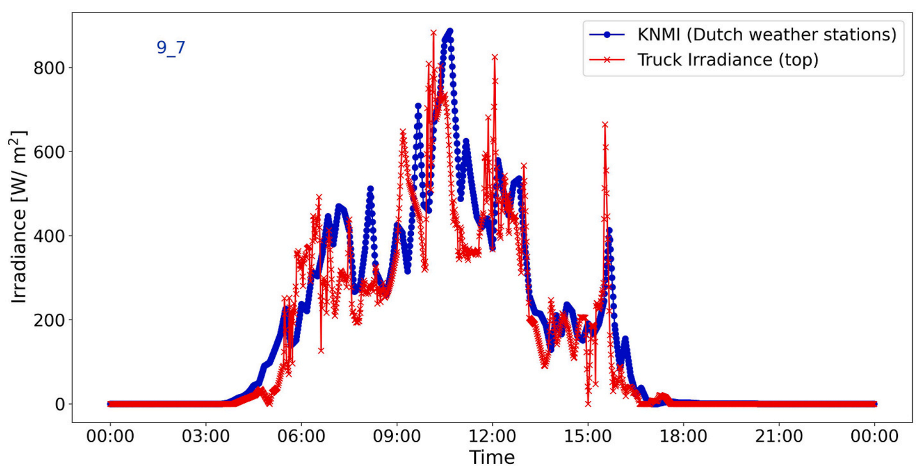

Fig. 8. July 9, 2024: KNMI and truck data on a partly clouded day the truck irradiance is 11 % lower than the KNMI data.

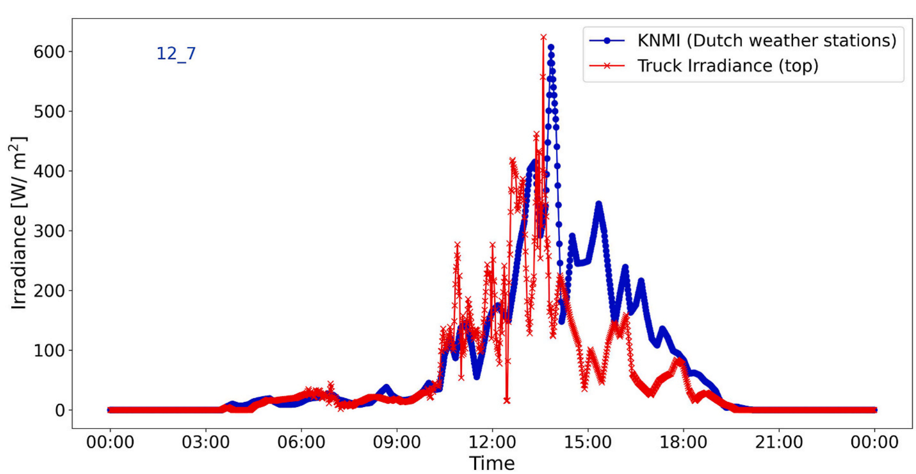

Fig. 9. July 12, 2024: KNMI and Truck data on a clouded day – here the KNMI data is more than 20 % higher than the irradiance measured on the truck. The truck is parked from 13:50 for the rest of the day and so the differences in irradiance can be due to building shade or moving clouds.

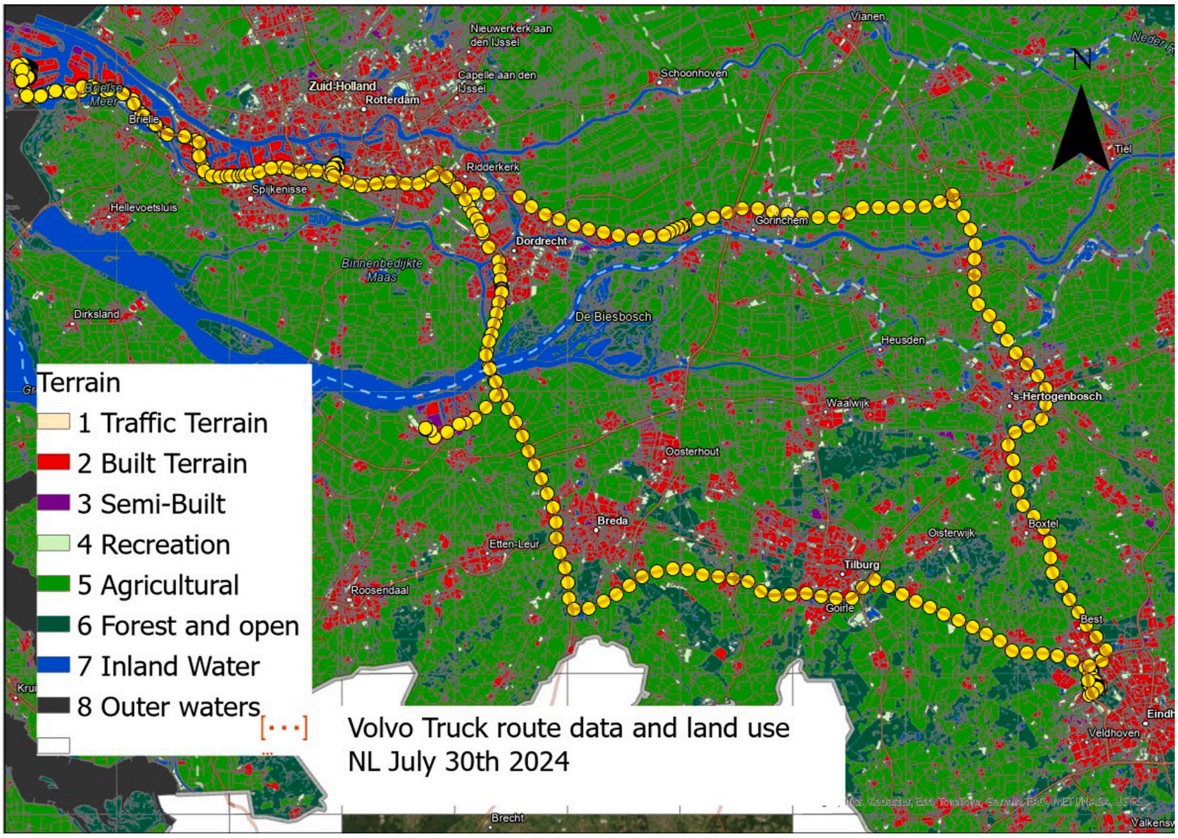

Fig. 10. July 30th Truck route, laid over the Land use map of the Netherlands [10].

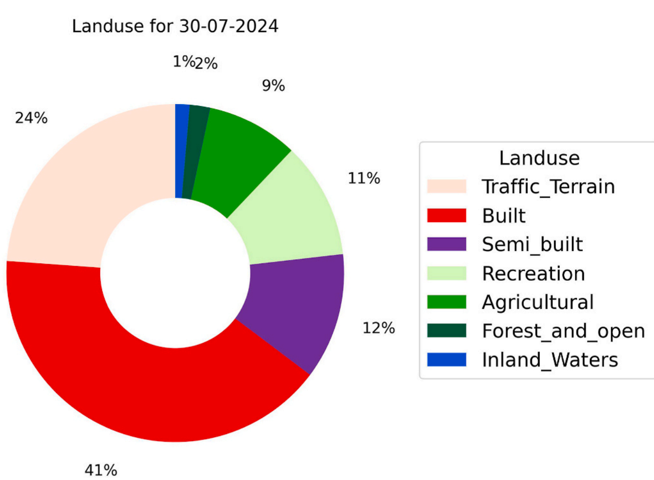

Fig. 11. Breakdown of Land use for the truck route on July 30th. 53 % of the time spent in built up or semi built up areas and the rest of the time in more open terrain.

irradiance is in fact higher than the KNMI irradiance in the morning and in the afternoon. Although there could be some extra reflection from nearby objects during the day, it is not expected that the irradiance will be higher for most of the day. One of the reasons for the higher irradiance appears to be the fact that the sensor on top of the truck is not mounted perfectly horizontally, but has an 11° tilt toward the direction of travel.

More insight has been gained by analysing the direction of travel of the truck. Fig. 13 shows data for July 30th. The figure shows the direction of travel for the truck as a function of time of day. The colour of the markers show when the truck irradiance is higher than the KNMI as blue tones, and the red tones show when the KNMI irradiance is higher than the truck. What is clear from this plot is that in the morning the truck is travelling east into the sun, and the markers are indeed blue. Around midday the truck travels mostly north, away from the sun, and the markers show KNMI is higher. Around 13:00 the truck travels west, also in the direction of the sun and the markers are again blue, whereas at 14:00 it is travelling east, away from the sun and the markers are red. The tilt of the sensor and these results give a clear qualitative explanation for the irradiance measured on July 30. Other days also showed this behaviour, higher truck irradiance compared to KNMI when travelling into the sun and lower truck irradiance while travelling away from the sun.

4. Validation of modelled values

The daily loss data from Fig. 7 is represented in Fig. 14 together with the shading model values that were estimated from a combination of the Cobbenhagen [5] and Araki [4] work. Ignoring the two outliers above 20 % and the two below 0 %, it can be seen that the majority of the Daily loss factors are somewhere between 5 and 20 %, which ranges from 'lower than the urban shading model' to 'roughly similar to the semi-urban shading model'. As mentioned above, based on the average terrain type the truck is travelling in, we would have assigned the semi-urban shading model, and thus would underestimate the irradiance (overestimate the daily loss).

The overestimation of the shading loss indicates that the initial estimate for the shading factor was reasonable, but slightly to high. On the other hand, the Araki [4] numbers, and thus our estimates, have been based on measurements on a van, whereas the data in Fig. 14 are the results of sensors on top of a truck. The height of the truck can also influence the results as it is to be expected that a higher vehicle will receive less shading from surrounding buildings, resulting in a lower shading factor.

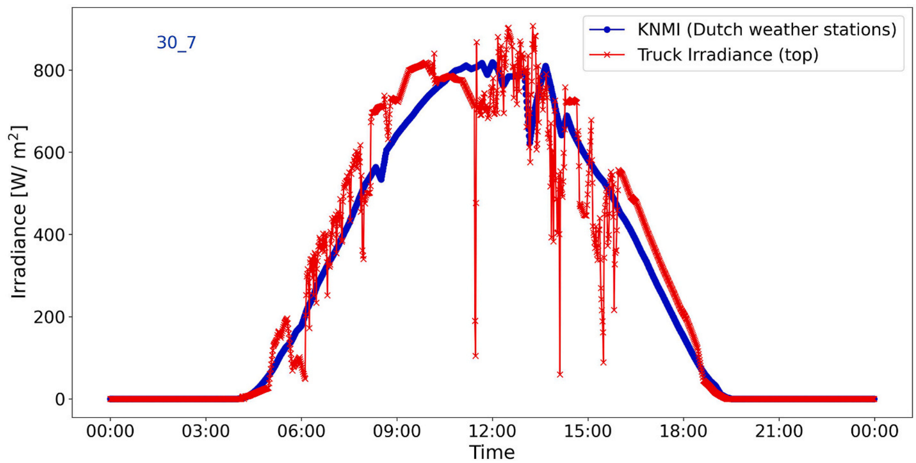

Fig. 12. July 30: KNMI and Truck data on a sunny day. The truck irradiance is higher than that measured by the local weather stations, in the morning and in the afternoon. This appears to be due to the fact that the sensor on top of the truck has not been placed horizontally.

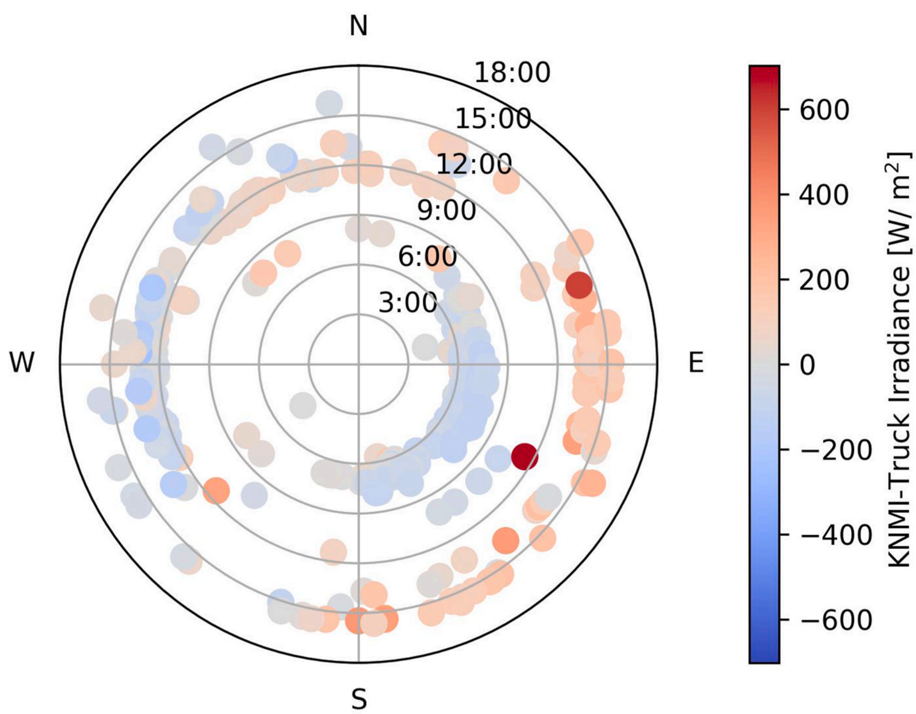

Fig. 13. Direction of travel vs time, showing when the Truck irradiance is higher than the KNMI, blue shade, and when KNMI is higher than the truck, red shade.

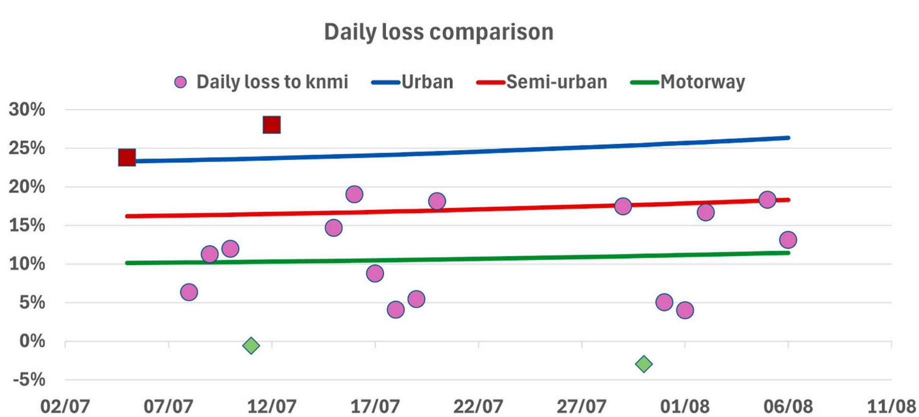

Fig. 14. Comparison of measured daily losses and the loss values applied from the shading model.

5. Conclusions

A detailed set of measured irradiance from a moving truck has been used to validate the shading model used in the EFM model in part one of the SolarMoves project. The measured data was first compared to local weather station data to obtain a loss or shading value, and then this was used in the comparison to the modelled loss values.

The model did not consider driver behaviour, or that the truck may be parked in the shade. However, this was seen in the measured data and is something to consider in further work. Because the truck was often parked and in the shade, a higher overall shading factor was seen in the measurements. However, reducing the data set to days when the truck was travelling, minimised that effect and gave a more reasonable shading result.

The sensor installed on the truck was slightly tilted, resulting in an occasional higher measured irradiance on the truck compared to the weather station, which related to the direction of travel. On very cloudy days with mostly diffuse light the tilt of the sensor is a lot less important.

In the next phase of this work more data will be analysed and compared to other vehicle archetypes.

CRediT authorship contribution statement

Anna J. Carr: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation. **Lenneke H. Slooff:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology. **Ashish Binani:** Software, Methodology, Investigation. **Christian Braun:** Supervision, Methodology, Investigation, Data curation. **Alexander Kleinhans:** Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation. **Ramakrishnan Kalyanasundaram:** Methodology, Investigation. **Ruud Derks:** Writing – review & editing, Supervision, Resources, Investigation. **Jan M. Kroon:** Supervision, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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During the preparation of this work the authors used Copilot in order check readability and language. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Data availability

The data that has been used is confidential.

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