The Photovoltaic (PV) Energy Conversion Chain: Irradiation to Grid Impact

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Abstract

The research presented in this thesis aims to enhance understanding of the influence of the inherent variability of solar irradiance on nationwide photovoltaic (PV) system performance. The spatial and temporal consistency of the solar resource is investigated. The case study area is the UK and the body of work presents nine publications written over four years with this objective in mind.

The key research theme is to produce national solar resource maps from ground-based measurements of solar radiation. Geographical Information System (GIS) techniques are utilised to build a UK map of irradiation from geographically sparse data, requiring development of new tools to both generate and verify the map data. With an augmented understanding of the solar resource, PV system dispersal is then investigated, allowing analysis and prediction of the impact on the electrical grid.

The papers describe: (1) determination of the most appropriate algorithm for interpolating ground-based irradiation measurements in the UK to countrywide coverage; (2) selection of solar irradiance component separation and translation models to obtain plane-of-array irradiation from the weather station global horizontal records; (3) justification of weather stations data as a fundamental model input; (4) statistical analysis of LiDAR data and application of GIS models to LiDAR data to obtain PV system tilts and azimuths as model inputs for (2); (5) conversion of solar irradiation to electrical output; (6) shading effects; (7) study of geographic divergence of generation; (8) aggregate grid variability; and (9) future installation scenarios.

There has been no previous study which commences with obtaining irradiation values for PV and proceeds through the entire modelling chain to assess cumulative impacts on grid transformers. This study may be adapted as a guide when undertaking equivalent research in other countries. Specifically, the work presented here is more extensively validated than that of previous authors. A nationwide analysis of spatial and temporal variation of PV output is delivered and current and future impacts on the National Grid are taken into consideration.

Acknowledgments

I would like to express my grateful thanks to my supervisor, Tom Betts, for his guidance, friendly advice and for encouraging me to undertake this Ph.D. Also to Ralph Gottschalg, who was my line manager for most of the time I have been at Loughborough, and who put the idea of a Ph.D. into my head in the first place.

I am grateful to my friends and colleagues Elena Koubli and Ian Cole. They have provided data for some of my publications, but more importantly explanation, advice and enthusiasm.

I would like to say thank you to all the members of the Applied Photovoltaic (APV) group in the Centre for Renewable Energy Systems Technology (CREST), past and present, and those who are a bit of both, with whom I have come into contact. You have given me companionship, feedback on my efforts and created a great environment in which to carry out research.

Lastly, I would like to mention my mother and sister, who are always there for me.

Nomenclature or List of Acronyms

BSRN	Baseline Surface Radiation Network
CAMS	Copernicus Atmosphere Monitoring Service
CRediT	Contributor Roles Taxonomy
CWOP	Citizen Weather Observation Programme
DBEIS	Department for Business, Energy & Industrial Strategy
DNO	Distribution Network Opera
FIT	Feed-in Tariffs
GHI	Global Horizontal Irradiation
GIS	Geographical Information System
IQR	Interquartile Range
Kt	Clearness Index
LiDAR	Light Detection and Ranging
LOOCV	Leave-One-Out-Cross-Validation
Met	Meteorological
MIDAS	Met Office Integrated Data Archive System
MLSP	Mean Sea Level Pressure
MWh/m^2/y	Megawatt hours per square meter per year
NIWE	National Institute of Wind Energy (India)
nMBE	Normalized Mean Bias Error
nRMSE	Normalised Root Mean Square Error
POA	Plane of Array
PV	Photovoltaic
REPD	Renewable Energy Planning Database
SAR	Synthetic Aperture Radar
SARAH	Follow-on system for the SAR-Lupe radar satellite constellation operated by the German armed forces (Bundeswehr)
Solargis	A company supplying weather data and software for solar power investments
TMY	Typical Meteorological Year
UK	United Kingdom of Great Britain and Northern Ireland
UKMO	UK Meteorological Office
US	United States of America
Wh/m^2	Watt hours per square metre
WOW	UK Met Office Weather Observations Website

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LIST OF NINE PUBLICATIONS:

	Title	Abbreviation
1	Interpolating and estimating horizontal diffuse solar irradiation to provide UK-wide coverage: selection of the best performing models	**KrigeP**
2	Satellite or ground-based measurements for production of site specific hourly irradiance data: Which is most accurate and where?	**GroundSatP**
3	Assessment of Potential for Photovoltaic Roof Installations by Extraction of Roof Slope from LiDAR Data and Aggregation to Census Geography	**Roof1P**
4	A GIS-Based Method for Identification of Wide area Rooftop Suitability for Minimum Size PV Systems Using LiDAR Data and Photogrammetry	**Roof2P**
5	Inference of missing data in photovoltaic monitoring datasets	**ThermElecP**
6	Detection of roof shading for PV based on LiDAR data using a multi-modal approach	**ShadeP**
7	Comparison of Solar Radiation and PV Generation Variability: System Dispersion in the UK	**VariabilityP**
8	The UK Solar Farm Fleet: A Challenge for the National Grid?	**FarmFleetP**
9	The future scope of large-scale solar in the UK: site suitability and target analysis	**FarmSiteP**

1 Introduction

1.1 Thesis by publication

Thesis by publication is permitted under the regulations of Loughborough University[1]. This thesis is based on 9 publications (8 journal articles and 1 conference paper), published between 2015 and the current date (2019). The papers have been published in journals and conference proceedings in the disciplines of renewable energy and photovoltaic science. These publishers have different author guidelines, so the papers vary in format, length and referencing style. A full list of the papers presented in this thesis is given in the appendix (Table A.1). This table also summarises the contribution of the thesis author, because one publication was as secondary author. A more detailed attribution statement for each paper, summarising the contributions of each researcher, is given with the paper's description in Section 6. The Contributor Roles Taxonomy (CRediT) (docs.casrai.org/CRediT) methodology for attributing contributions is used (McNutt et al, 2018). Only articles not previously published as conference papers and which directly support the theme of this thesis are included. Other relevant publications are listed in the appendix.

1.2 Structure of thesis

This chapter provides the context to, and an overview of, the 9 papers presented in this thesis. The following theses of authors who have recently fulfilled the requirements for the award of Doctor of Philosophy of Loughborough University via the Ph.D. by publication route were used as guidance for its contents and layout: Chakraborty, 2018; Gadd, 2017; Haines, 2014; King, 2017; Torrens, 2015. This chapter delivers the narrative theme which integrates the 9 papers into a coherent whole. Section 2 provides the background and justification for this research. The aims and objectives are specified in Section 3, before the steps in the research methodology are summarised in Section 4. Section 5 briefly outlines how each paper contributes to each research step. Section 6 elaborates on each research step in turn, the part played by each paper, and details the research premises and novelty. Further work not included in the papers and/or since their publication is described and suggestions for future improvements given. Finally Sections 7 and 8 draw overall conclusions and general recommendations for future research.

2 Background

Solar energy production capacity has grown rapidly in the UK in recent years, increasing more than 25-fold since 2010 (DBEIS, 2019). Most UK photovoltaic systems are grid connected. However, the National Grid is a centralised system, not originally intended for peripheral inflows from prosumers. There is the potential for reverse power flows, requiring intervention, leading to apprehension for the operational security of the power system. Very little factual data exists regarding the timing and location of PV electricity injection. Thus, PV system generation information is needed to investigate real grid impacts such as cable overload and network destabilisation. However, the changeable weather which is characteristic of the UK makes accurate local solar irradiance and output prediction a

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[1] http://www.lboro.ac.uk/services/doctoral-college/essential-information/code-of-practice/8-submission-publications/

demanding task. This research sets out to provide a sequence of detailed analyses, tool development and models to begin to address this problem. Whilst recognizing the significance of seasonal effects on PV performance, these are not discussed in any depth in this thesis. The focus is on hourly variability. The extent of this thesis is also limited to providing an overview of grid impacts. Detailed grid simulation with networks of nodes and power flow models is not utilised.

The data source is MIDAS (Met Office Integrated Data Archive System) from the UK Met Office (Met Office, 2006), from ground-based weather stations. This organisation has been recording hourly and daily global horizontal irradiation (GHI) for almost 70 years. Equipment has been upgraded and the number of weather stations has expanded significantly in the last 10 years, so this research focusses on the period 2005-2014. The distribution of the recording stations (88 in 2015) is somewhat uneven, ranging from less than 10 km apart in London to over 100 km between stations in Scotland. The locations reflect historical events and the transport network. There is no attempt at regular sampling (Figure 1).

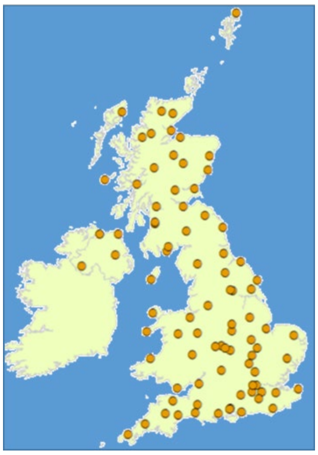

Figure 1: Location of MIDAS weather stations recording GHI in 2016

The decision was taken to use data based on ground-based measurements because these reflect actual environmental conditions. Satellite-derived solar radiation data is an alternative provision of solar flux. It is often quoted as being more accurate at distances greater than 25-30 km from a weather station (Perez et al., 1997). But UK weather stations are no more than 50 km apart in the more densely populated regions of the country, where energy demand is highest. Selection of ground station recordings as model input is justified further later in this thesis.

Evaluation of the electrical energy yield from PV systems provides information on the power balance at the distribution transformers, which may lack adequate spare capacity to incorporate the solar energy feed-in. It informs decision-making on system design and site selection, as well as performance evaluation and monitoring of PV systems. It also indicates whether or not investing in a PV system will be profitable and the length of payback period.

3 Research Aim

The aim of this research is:

> *To assess the influence of the spatial and temporal variation of irradiation on grid-connected PV system performance.*

This involves linking built-environment maps to a National Solar Profile, taking the UK as the case study (due to the funding sources of the projects that have supported the work, however the methodology can be applied to any location where data is available). The timing and location of photovoltaic output is then generated, so that effects on the distribution grid transformers may be ascertained.

In order to achieve this aim, this research presents a sequence of research steps, described in the constituent papers.

4 Methodological Research Steps

Hourly meteorological data from weather stations is the chosen input to the research sequence. This data is available as global horizontal irradiation only, for a relatively low number of sites in the case of the UK (compared to Norway and Switzerland, for instance). To produce photovoltaic yield data, plane-of-array irradiation is required. The object is to obtain output for any PV system, (domestic or commercial rooftop or solar farm) anywhere in the UK, and then to consider the impact of combined systems on National Grid substations. This is attained via the following sequence of steps (Section 4.1) and summarised in Figure 2. More details of the algorithms involved and the relationship between them is given pictorially in Figure A.1 in the appendix.

4.1 Steps in PV energy conversion chain through to ultimate impact on the electricity transmission system

1. Interpolate global horizontal irradiation data to fill the gaps in areas lying between meteorological station locations. Additionally, interpolate the secondary input required for PV output modelling: ambient temperature (also MIDAS weather station data).
2. Calculate the sun declination angle and clearness index, Kt.
3. Use the sun geometry and Kt from Step 2 to enable the split of the interpolated global horizontal irradiation values into their beam and diffuse components.
4. Determine azimuth and tilt angle (from pulsed laser LiDAR data) for rooftop or solar farm.
5. Translate beam and diffuse irradiation values into plane-of-array irradiation via separate algorithms using the azimuth and tilt angle from Step 4. Re-aggregate the tilt beam and tilt diffuse into total plane-of-array irradiation.
6. Calculate module temperature from calculated in-plane irradiation and interpolated ambient temperature.
7. Investigate possible reduction in output due to shading of the system.
8. Calculate electrical performance and yield.
9. Examine the collective effect of PV systems on the distribution system, temporally and spatially.

10. Explore the current and future geographic distribution of PV in the UK to determine whether the smoothing effect of amalgamation of output will change.

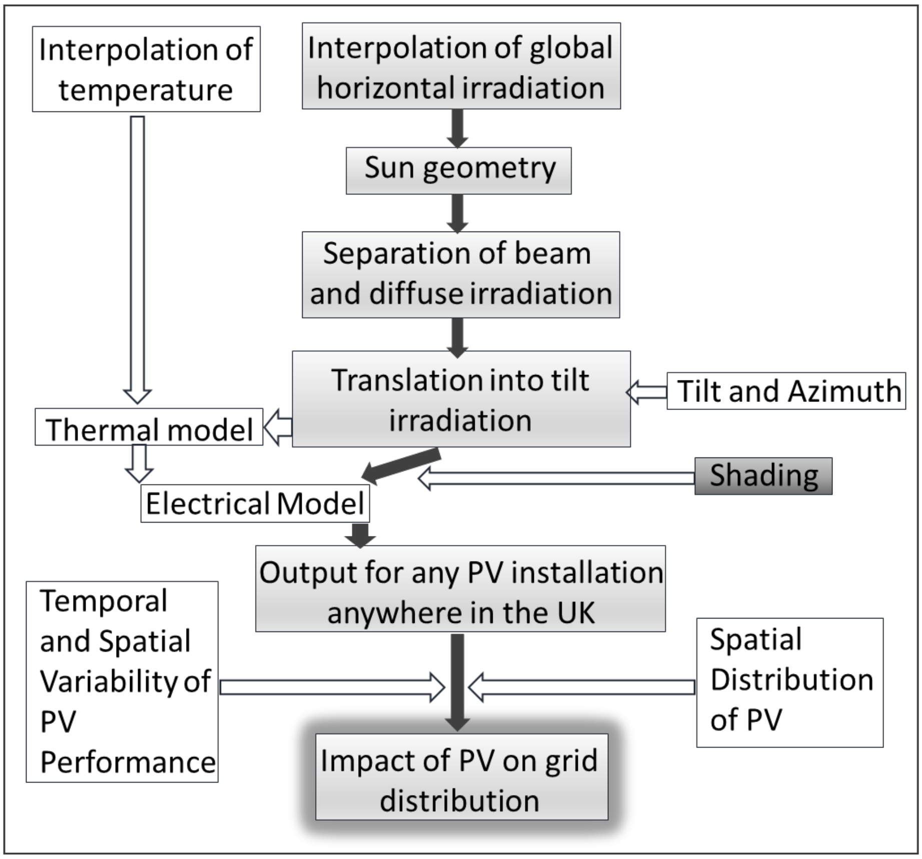

Figure 2: Steps in research sequence for conversion of global horizontal irradiation data to PV grid impact

5 Research Outline

The contribution of each of the papers contained in this thesis makes to each research step (Section 4) is itemised in the appendix (Table A.1). Moreover, this table gives the abbreviated name by which each paper will be known from here on. Figure A.2 in the appendix illustrates the linkage between the papers and steps in the research sequence in the form of a schematic diagram. Briefly:

KrigeP describes how global horizontal irradiation and temperature data may be interpolated to the point of interest. Next, it selects a separation model which is necessary prior to transforming this site-specific data into tilt irradiance. **Roof1P** summarises the interpolation step. It gives details of the sun geometry model employed prior to the separation step, of which it furnishes a synopsis. It then describes translation of the split irradiation components (beam and diffuse) into total plane-of-array irradiation. **GroundSatP** elaborates on the choice of source data (ground measurements) for interpolation. **Roof1P** (again) and **Roof2P** derive tilt and azimuth values required for the separation model and show how these values can be scaled up to regional/countrywide coverage. **ThermElecP** provides algorithms which generate PV output from the tilt irradiation. **ShadeP** evaluates models which detect potential losses due to shading. **VariabilityP** and **FarmFleetP** investigate how periodic and geographic aggregation of PV generation impacts on the grid.

Lastly, **FarmSiteP** studies PV distribution to ascertain whether transformer power balance is under threat from further deployment of solar PV.

6. The steps in the PV impact sequence

6.1 Interpolation

6.1.1 Determining the interpolation algorithm

KrigeP commences the sequence. It describes how to obtain accurate nationwide data for the most important input to any photovoltaic system: insolation itself. Accurate and geographically widespread data is essential because it is the available solar resource which has the largest influence on PV system yield. Uncertainty in solar irradiation assessment is the biggest contributor to uncertainty in energy rating of any PV system (Huld, 2011).

This first paper details how realistic solar irradiation data may be estimated countrywide, in places where it is not measured, by interpolation from surrounding measurement stations. Very little research has been published on the subject of selection of appropriate interpolation techniques for solar insolation in northern European conditions. There are more than ten existing spatial interpolation methods, each with up to ten parameters. Selecting the optimal choices for a given application can be challenging and is far from standardised. The presented research investigates theoretical, statistical and pragmatic procedures for deciding on options appropriate to the data and weather conditions of the case study. In the instance of the UK, the highest accuracy is achieved with ordinary kriging and an exponential semi-variogram. Although kriging is applied to the UK, the explanation of method selection can guide readers to apply kriging to other countries, even for quite dissimilar scenarios of climate and data availability.

Several methods were also trialled for determining the optimum output grid cell (pixel) size. This represents a compromise between being small enough for precision and not so small as to be computationally possible. Smaller grid size also increases the number of cells required to cover the country. This necessitates extra storage and increases data retrieval time when a specific location is requested.

The final problem when interpolating weather data is: how to display it for interpretation? Each kriged grid cell has a unique value of solar irradiation. These must be classified in order to create a meaningful National Solar Profile map. Too much data generalisation can result in a map which does not convey the intended information (Monmonier, 1996). Again a compromise must be reached, this time between capturing all weather patterns and legibility. Various techniques were tested to find a suitable number of classes. Examples of the resultant UK-wide GHI maps are given in Figures 3 and 4.

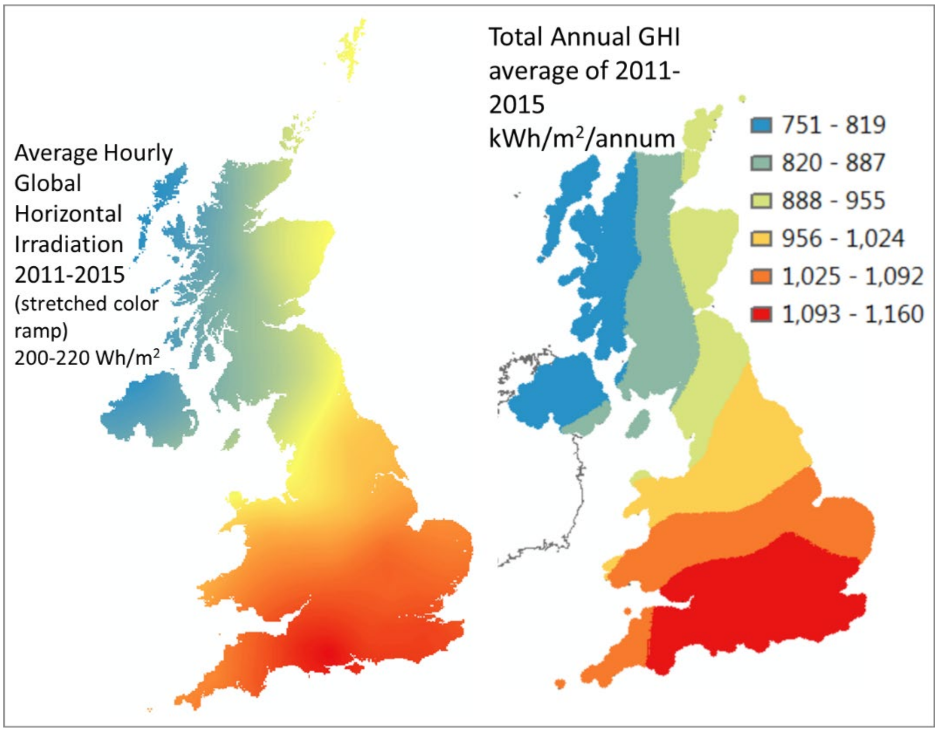

Figure 3: Kriged global horizontal irradiation for the UK. Average hourly value and average annual sum for five years.

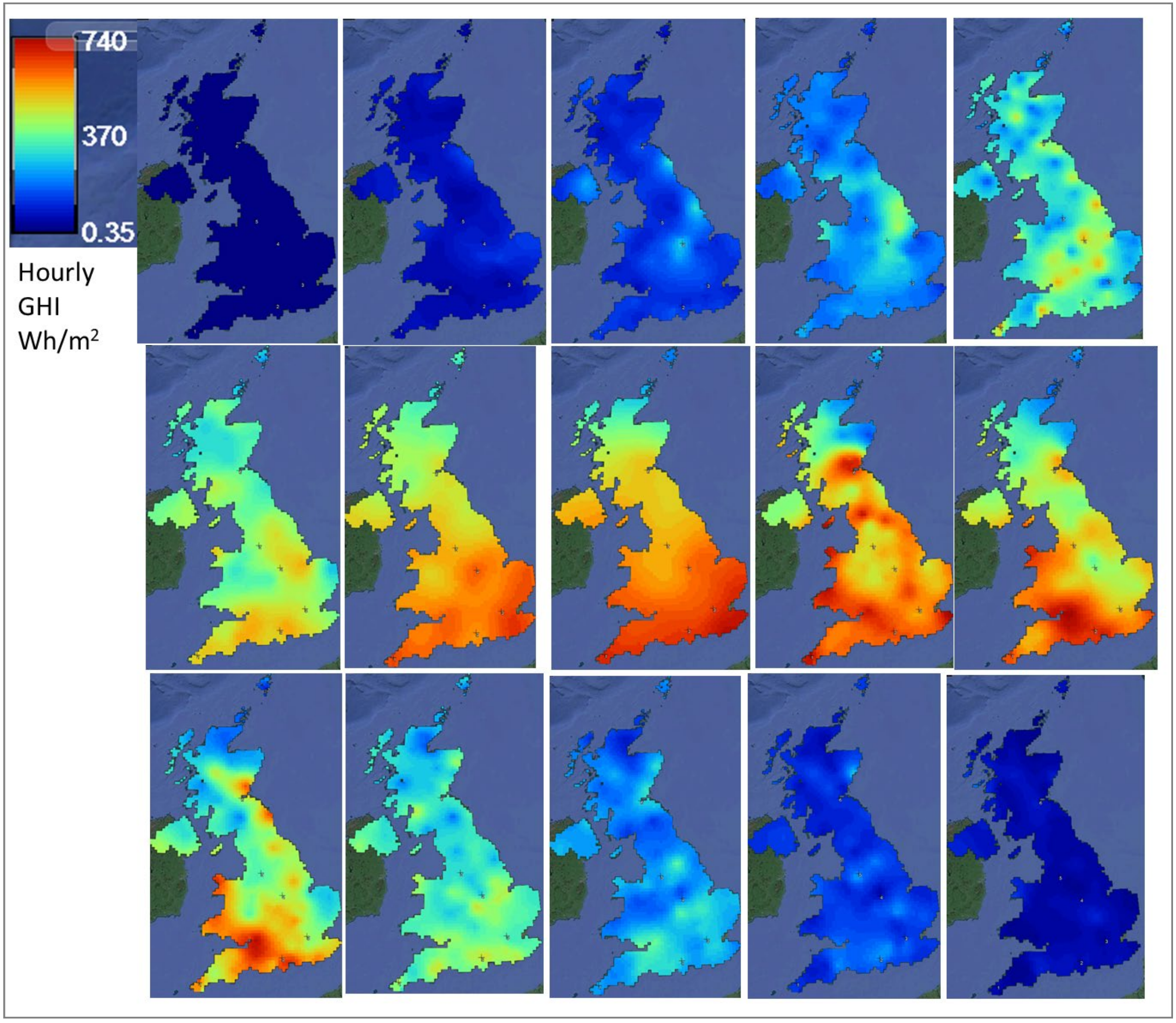

Figure 4: Kriged hourly global horizontal irradiation for 21 June 2016.

The procedures mentioned above were similarly used to select the kriging interpolation technique to produce location-specific temperature data for the PV energy conversion chain.

Contribution to Knowledge

KrigeP provides guidance on selection of the optimal interpolation technique for weather data for any country, in any climate zone, worldwide.

Division of Work

Author Contributions to **KrigeP**: Diane Palmer, Thomas Betts and Ralph Gottschalg conceived and designed the experiments; Diane Palmer carried out initial investigative work, analysed the data, developed the methodology and validated results; Ian Cole contributed data and analysis tools; Diane Palmer wrote the paper, supervised by Thomas Betts and Ralph Gottschalg.

Reasons for selecting the kriging method and the algorithm itself are additionally summarised in **ThermElecP** (see Section 6.6 for further details).

6.1.2 Initial Quality Control of UK Met Office Irradiation Values

Details of the prior quality control procedures applied by the UK Met Office to MIDAS data before release and further checks applied by the author are given in **GroundSatP** (featured in 6.1.4). The author carried out a review of outlier detection methods, summarised in Table 1, before determining on those applied in **GroundSatP** (numbers 3-5 in Table 1).

Table 1. Outlier Detection Methods for Global Horizontal Irradiance

No.	Method	Advantages	Disadvantages	Useful in this context
1	Linear Regression	Well-known	Removes many credible values	No
2	IQR - Upper limit: 3rd quartile + 1.5(3rd quartile – 1st quartile)	Well-known (Cairns, 2013)	Removes many credible values	No
3	Upper limit of 1,000 Wh/m^2 for hourly GHI: Before 10 am or after 4 pm	Simple	Arbitrary	Yes
4	GHI/extra-terrestrial irradiation < 1 if solar zenith > 2 degrees	Simple (Journee and Bertrand, 2011)		Yes
5	GHI/Clearsky irradiation <= 1.1 if solar zenith > 2 degrees	Functional (Journee and Bertrand, 2011)	Many different methods for clear sky irradiation. Can be 100 Wh/m^2 difference between the results of individual clear sky models.	Yes

In order to successfully apply Method 5, it was found necessary to use the maximum clear sky value each hour obtained from 4 different clear sky models:

- Adnot-Bourges-Campana-Gicquel (ABCG) (1979)
- Farber and Morrison (1977)
- Haurwitz (1945)
- Kasten–Czeplak (KC) (1980)

These models perform well at high zenith angles, as well as during midday hours and summer months when GHI is highest (Reno, 2012). Additionally, they are simple models and it has been reported that simple clear sky models are comparable in accuracy to more time-consuming and complex equations (Badescu (1997); Reno (2012)).

6.1.3 The accuracy of the kriging technique

The principal uncertainty indices employed (Normalized Mean Bias Error (nMBE) and Normalised Root Mean Square Error (nRMSE)) to select and report the accuracy of the kriging model are used correctly in **KrigeP** (Ramos and Bandera (2017)). These authors find that there is a wide range of articles, reports and theses in high impact factor journals containing mistakes in validation measurements.

Averaged over the period 2005–2014, the kriging process yields an average hourly leave-one-out-cross-validation RMSE of 56 Wh/m^2 (11%). Validation against an independent data source by comparison between kriged values and data obtained from the pyranometer in the outdoor measurement system at Loughborough University gives an RMSE of 80 Wh/m^2 (16%) (2015). Aggregation of values on annual and monthly bases also gives a good level of agreement between kriged values and those recorded in Loughborough (average annual nRMSE 26%, average monthly nRMSE 5%). Linear regression of hourly kriged/measured global horizontal irradiation and temperature values gives very favourable results: $R^2 = 0.95$ for GHI and 0.99 for temperature. Temperature is less spatially variable than GHI which is rapidly influenced by passing cloud.

Kriging data values closely follow the distribution of ground-measured irradiation values into bins. Figure 5 compares aggregate frequencies of MIDAS weather station values, kriged data, and three satellite databases for ten sites spread throughout the UK for one year (2104). It may be seen that the SARAH model differs from the ground measurements at low irradiation values and is therefore not performing well early morning/late evening and in cloudy conditions.

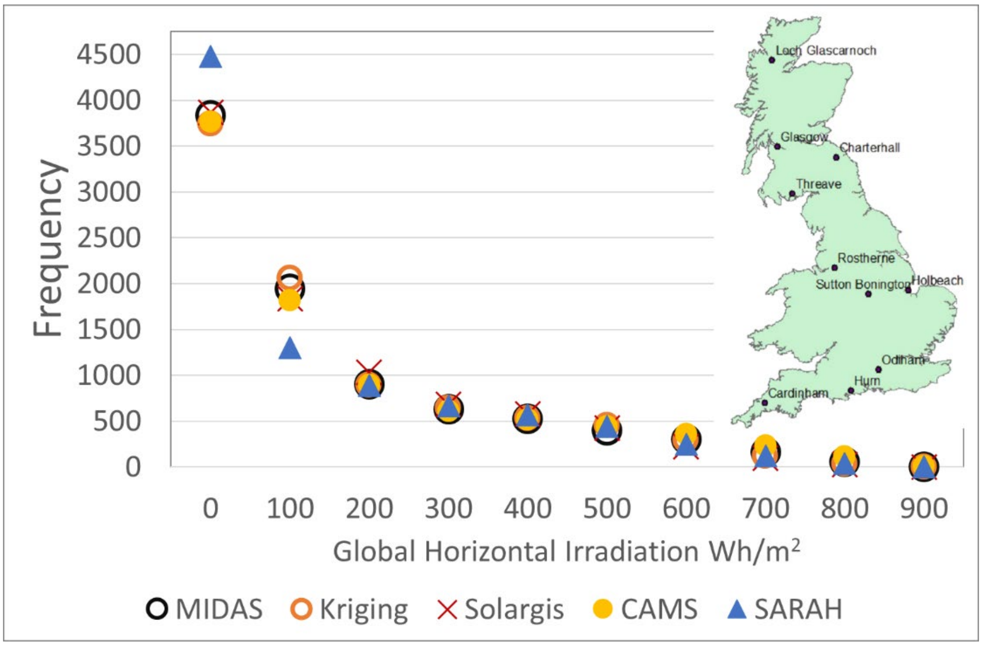

Figure 5: Kriging and satellite model variation for 10 sites in 2014.

When the total score of GHI within each bin is calculated (Figure 6), kriging tracks the ground measurements distribution closely across all bins, except 800 Wh/m^2. The CAMS model over-estimates at high values (too many high values). Solargis and SARAH tend to over-estimate in low-medium irradiation bins and under-estimate in high bins. These trends are reflected in the total net annual irradiation values for all ten sites. Kriging has the closest total GHI/y to MIDAS (Figure 6 insert).

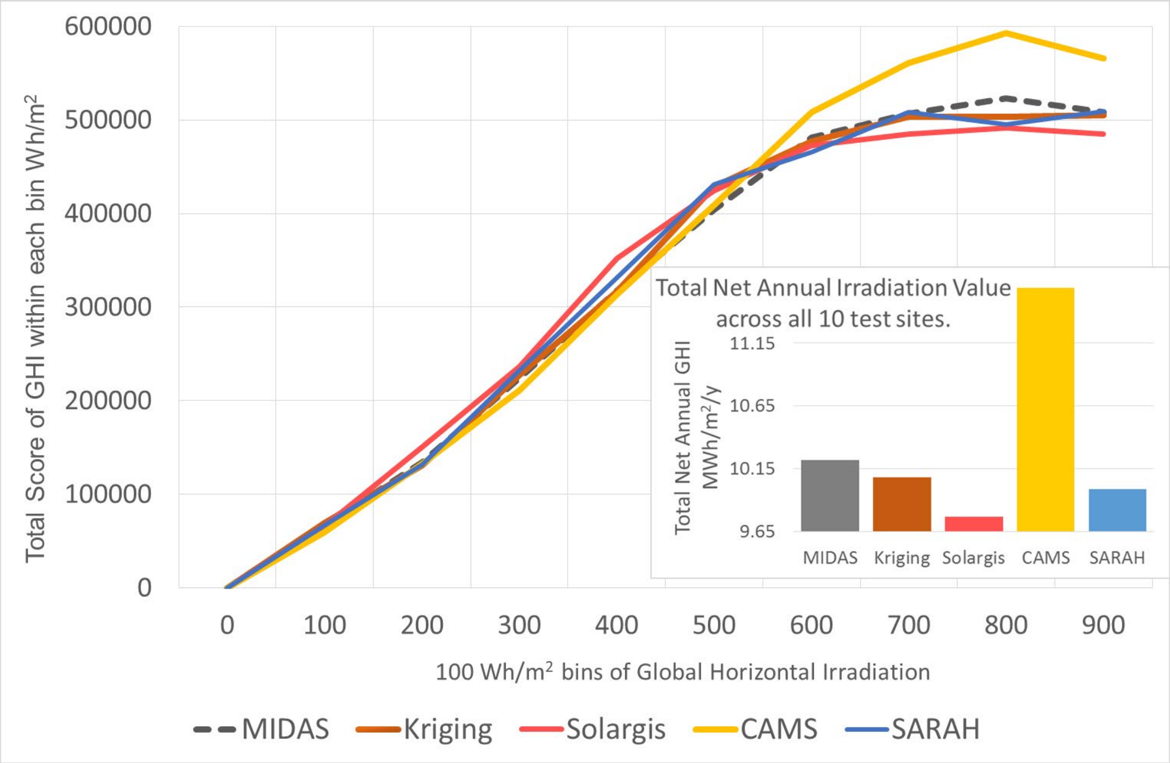

Figure 6: Total GHI per 100 Wh/m^2 irradiation bin for ground measurements, kriging and 3 satellite models for 10 sites in 2014.

A realistic distribution of values is of importance because this impacts on PV system behaviour. Different values of irradiance are converted into electrical yield with different efficiencies (Cole et al, 2017). One reason why kriging delivers a realistic distribution of values and does not omit low values (unlike satellite models) is that it has the ability to act as a gap-filler. Only 5 weather stations are required to report readings in any one hour in order to produce a countrywide grid of values. Fewer measurement stations report in for early morning and late evening hours. Whereas the accuracy of kriging increases as the number of input stations increases, the annual irradiation figure is accurate because it is less likely to have missing values.

6.1.4 Why choose ground-based measurements of solar irradiation?

GroundSatP elaborates why, given that there are two main sources of solar irradiation data (weather station and satellite), kriging of ground-based measurements is used in this thesis. As a rule, quality-controlled ground-measured data is accepted as more accurate than satellite-derived data (Stackhouse et al, 2015). MIDAS weather stations data is the most accurate source of global horizontal irradiation data licensed for academic use (open data as of 14 February 2019). The MIDAS network is relatively dense and extensive, so kriging errors are acceptable. In addition, satellite-modelled data has lower accuracy at latitudes greater than 50°, in coastal areas and in regions with continuously changing cloud (Suri and Cebecauer, 2014). Lastly, kriging of ground values in the UK provides the greatest accuracy in regions with higher irradiation, where solar installations are more likely to be located (Figures 3, 7, 8 and 9).

GroundSatP commences with a national assessment of the performances of different methods for assessing surface solar irradiation in the case of UK. The nearest neighbour extrapolation and kriging methods are studied using the available ground station observations. Three satellite based products are also investigated in this study. In the second part, the influences of different atmospheric/surface factors on the performances of each method/product are studied.

The extrapolation technique did not produce satisfactory results. This is because, although a solar farm may be close to a weather station, it may be separated from it by a large lake or mountains and therefore experiences very different weather conditions. That is, microclimatic effects and regional weather patterns rule out the simple nearest neighbour method as an accurate source of GHI data.

It is demonstrated that when the ground station distance is closer than 25 km, the kriging model outperforms the best satellite model. The other satellite models do not equal the accuracy of the kriging procedure until a distance of 100 km or more is reached, which in the UK is offshore. The average inter-station distance for UK Met Office sites recording irradiation is 40 km. In addition, kriging values are realistically distributed (Section 6.1.3). Therefore kriging of weather station values is selected for use in this research.

GroundSatP answers the following questions:

- What is the optimum number of solar radiation measurement stations in the area considered?

- Are these stations adequately arranged so as to describe the radiation climate of the area?
- How should the radius of influence be determined, which is defined as the average distance over which the spatial correlation has significant values?

Contribution to Knowledge

GroundSatP shows that choice of irradiation model is not as clear as the accepted paradigm of select satellite data at a distance greater than 25 km from a weather station (Perez et al., 1997). The decision depends on the accuracy of the satellite model employed and the number and distribution of GHI measurement stations in the region. Weather station density is the key factor for countries with similar climates to the UK. 3-6 weather stations per 100 x 100 km grid square or 2 neighbours in a 45-100 km distance band of each weather station produce more accurate regional coverage when the data is interpolated than satellite databases. The ranges are dependent on the satellite model used for comparison.

Furthermore, average breakeven distance is only an approximate guide to irradiation model selection. This is site dependant, and is influenced by weather systems, factors associated with latitude and topographical ruggedness. The error distribution of the various irradiation models across the UK is illustrated in Figure 7. RMSEs for each model are normalised zero to one. This means that the location of the highest and lowest errors for each model are indicated, rather than the size of errors between models. It may be seen that the lowest kriging errors (blue in Figure 7, left) occur in the Midlands and Southeast, where weather stations cluster and the land is relatively low-lying. The error distribution of the satellite models varies noticeably between models. One common feature is that the lowest errors tend to occur in the centre of mainland Britain, where the land mass of Ireland provides protection from prevailing southwest weather fronts.

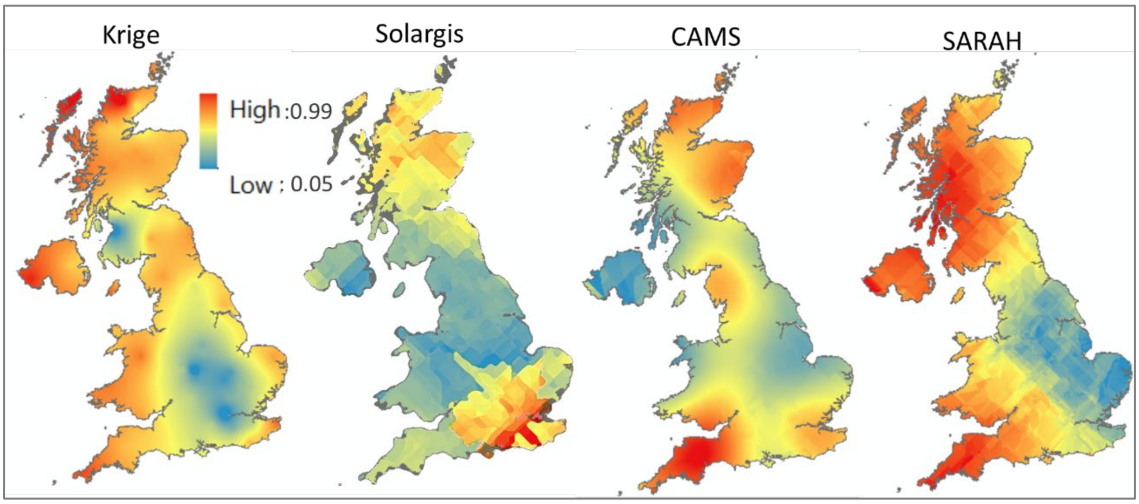

Figure 7: Normalised RMSE for kriging of UK Weather Stations measurements and 3 satellite models (based on GHI values for 2014).

Additional error distribution maps reveal that kriging of ground measurements and the best satellite model (Solargis) produce nRMSEs (this time normalised by mean) for GHI in overlapping ranges (22-56% for kriging, 28-37% for Solargis) but not in the same areas of the UK (Figure 8). Solargis outperforms kriging in the majority of the UK except for a region extending about 200 km north-south and 150 km east-west covering the northern Home Counties. (This is depicted by the pale pink area in left-hand map of Figure 8. Large blue stars representing larger Solargis errors may also be seen in this region on the right-hand weather stations map.) This region coincides with areas where many of the larger capacity solar farms may be found (Figure 9).

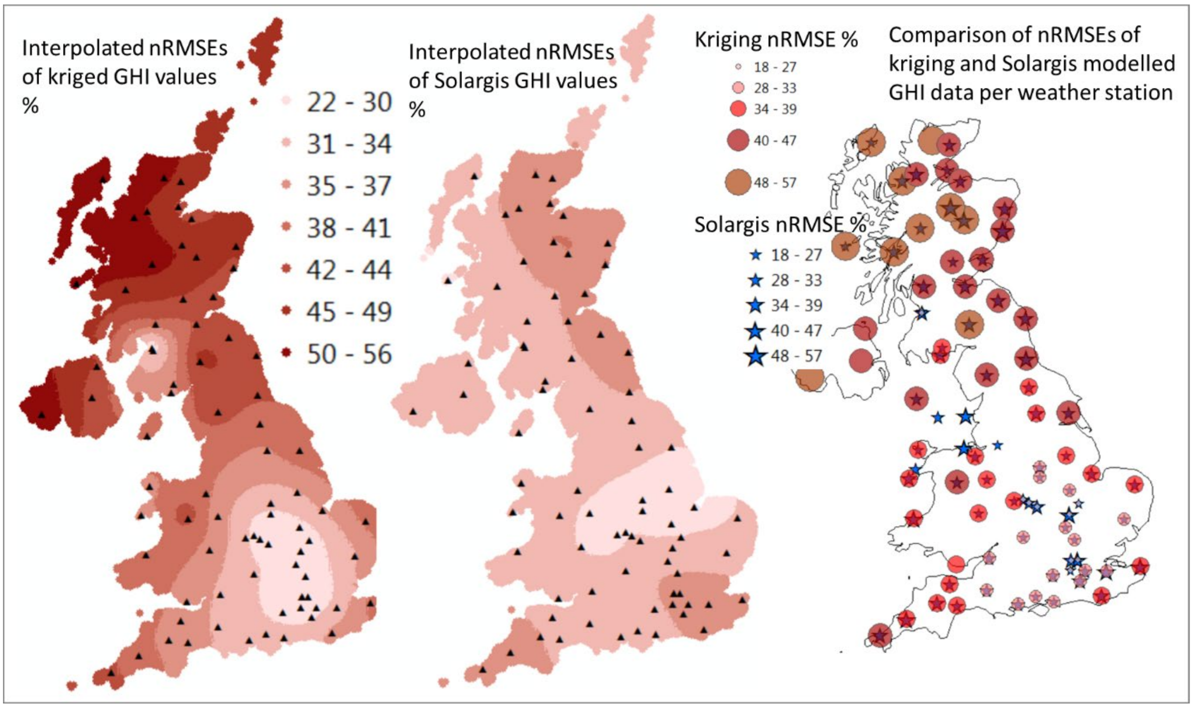

Figure 8: nRMSE (normalised by mean) for kriging of UK Weather Stations measurements and Solargis satellite model. Left and centre maps show interpolated errors, the right-hand map illustrates errors at actual weather station sites.

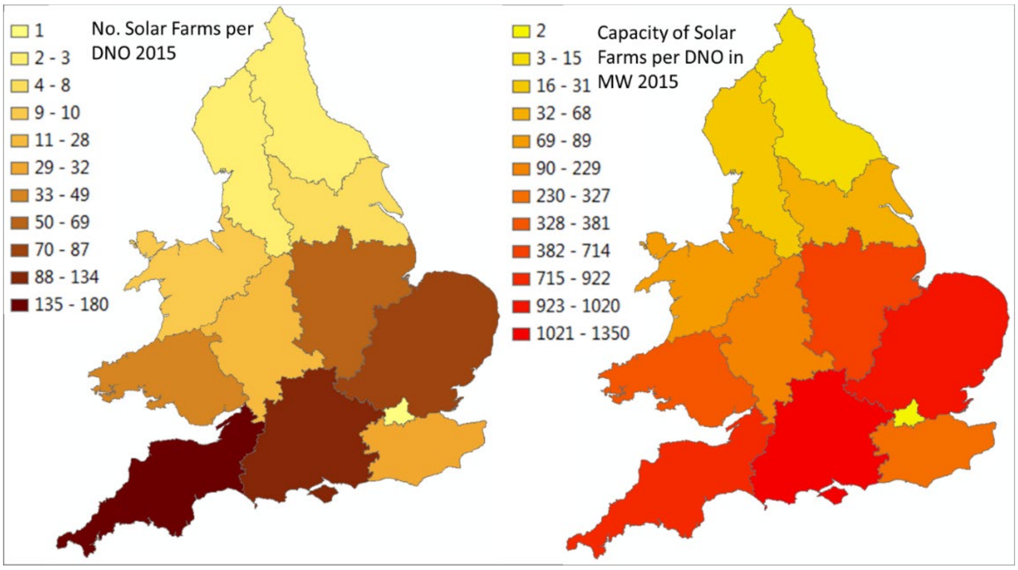

Figure 9: Distribution of solar farms per Distribution Network Operator Area (DNO) in 2015 (data from https://www.gov.uk/government/publications/renewable-energy-planning-database-monthly-extract)

The work is innovative in that influence of station network density has not hitherto been recognised in studies of solar irradiation. In addition, it investigates differences in accuracy of data derived from extrapolation/interpolation of ground-based sources and satellite-modelled data in distinct physiographic regions. The findings are applicable throughout global temperate zones. Other climate regions have less spatial variability and it is speculated that these will not require such a dense measurement station density for accurate interpolation. For instance, in arid plains, other authors report low MBE between weather stations and points at some distance (Ameen et al, 2018; Loghmari and Timoumi, 2017).

Division of Work

Author Contributions to **GroundSatP**: The research goals were devised by Diane Palmer, who also carried out the analysis, investigation and methodology. Elena Koubli and Ian Cole supported with background information. Tom Betts and Jose A. Ruiz-Arias advised on analysis and tools. Diane Palmer wrote the paper, supervised by Thomas Betts and Ralph Gottschalg.

6.1.5 Future Work on Interpolation Step

Further work on interpolation may include enhancing the accuracy by supplementing the UK Met Office MIDAS data with that from other sources, such as crowd-sourced or citizen observatories data from amateur weather station networks. The worldwide Citizen Weather Observation Programme (CWOP) (http://wxqa.com/lum_search.htm) (Figure 10) and UK Met Office's Weather Observations Website (WOW) (http://wow.metoffice.gov.uk/home) are examples of these. Use of supplementary measurement points will reduce kriging error but personal weather stations use less accurate (more affordable) instruments rather than the pyranometers utilised by national weather stations networks. It will be necessary to test whether the benefit of more observations for interpolation outweighs the disadvantage of the lower accuracy of the additional inputs.

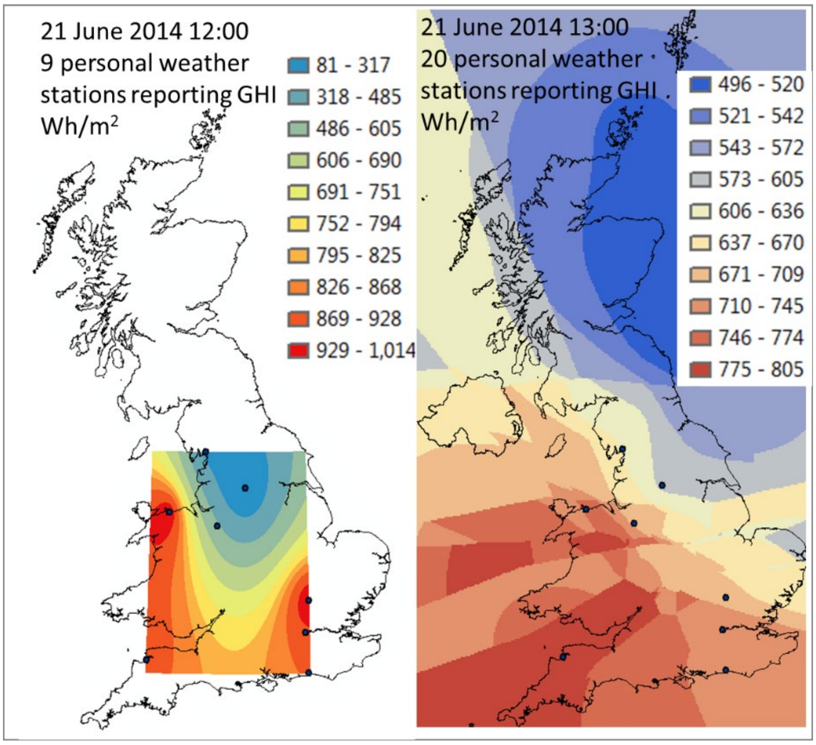

Figure 10: Hourly GHI maps interpolated from CWOP data.

Interpolated pyranometric stations data may also be enhanced by merging or fusion with satellite-derived irradiation data. A literature review has shown that the following techniques appear the most promising to augment hourly solar irradiation values:

- Kriging with External Drift (aka regression kriging) (Journee and Bertrand, 2010)
- Spatially interpolated additive bias between stations and satellite data (Journee and Bertrand, 2010)
- Kriging of Differences (Betcke and Beyer, 2004)
- Optimal Interpolation (Ruiz-Arias, 2015)

By experimenting with these methods, it is expected to discover if combining two datasets will result in a product which is better than either one individually. More than that, whether a better result is obtained, a better result only found where weather stations are more dense, or a better result achieved at certain times or seasons or irradiation levels.

GroundSatP revealed that mean sea level pressure (MSLP) impacted on solar irradiation. Combination techniques could additionally explore synergy between MSLP (and/or latitude which is related and easily obtainable) and solar irradiation, as well as incorporating satellite data.

It is planned to make the National Solar Profile maps and the data they represent publicly available. (The UK Met Office permits re-distribution of derived data supplied under an academic licence, as long as it cannot be re-engineered and is not being used for commercial gain. Reversal of kriging would not only be difficult, but would also require knowledge of the semi-variogram and number of input stations used per hour. This is not recorded when the algorithm is run.) Public supply of data creates challenges in terms of server storage and ease of selection. Experiments in reducing the size of the dataset, both temporally and spatially, will be performed. It is proposed to develop a Typical Meteorological Year, so that it is necessary to store only one year of data. Further empirical work on grid size in addition to the theoretical analysis already described in **KrigeP** will be undertaken. Preliminary results obtained by analysis of one year of data suggests 10 km may be a fine enough grid resolution to capture spatial variation in hourly solar irradiation. Figure 11 plots the leave-one-out-cross-validation (LOOCV) nRMSE at each MIDAS weather station against distance to nearest weather station, using 2014 values. Fitting and extending a linear trendline gives zero nRMSE% at 10 km distance. Future work will investigate how the prediction accuracy changes as grid sizes increases. Individual weather stations' measurements will be compared with data interpolated on grids of various sizes.

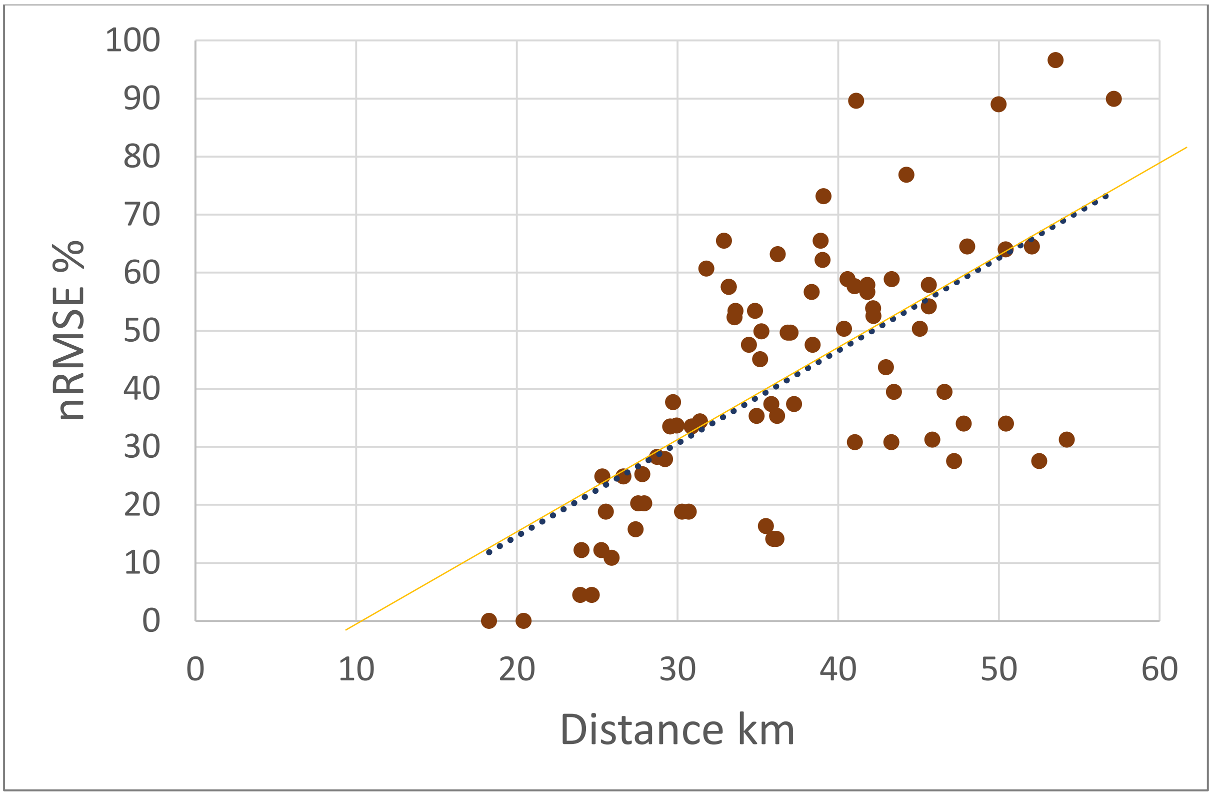

Figure 11: 2014 MIDAS data. LOOCV nRMSE% at each weather station against distance to closest weather station.

It is surmised that the kriging model, and the finding that it outperforms satellite data in regions with 3-6 weather stations per 100 x 100 km, is only applicable in temperate zones. It is proposed to examine the differences between the findings obtained in the UK and those of a new case study: India. India has a predominantly tropical climate, which has both dry and humid areas. Like the UK, weather in India is linked to a jet stream (south-westerly summer monsoons) which follows latitude. India has a new network of monitoring stations from which surface irradiation values are available (NIWE, 2014).

6.2 Sun Geometry

The sun geometry model employed in this research is described in **Roof1P**. The declination angle calculated by the model is used to compute the clearness index which is essential in the next stage. The Strous algorithm was chosen because it is fast, has good accuracy and is easy to use. Possibly, further research could determine how much eventual modelled yield is influenced by utilising higher levels of accuracy such as the Solar Position Algorithm (Reda and Andreas, 2004).

Division of Work

Author Contributions to **Roof1P**: Diane Palmer, Thomas Betts and Ralph Gottschalg formulated the research ideas. Diane Palmer applied the analytical techniques and developed the methodology. Ian Cole gave guidance on data visualisation. Diane Palmer wrote the paper, supervised by Thomas Betts and Ralph Gottschalg.

6.3 Separation of Beam and Diffuse Irradiation

KrigeP provides the next step in the sequence by selecting a separation model which divides the interpolated global horizontal irradiation data into its direct and diffuse components. Knowledge of irradiation composition can assist with the design of solar PV systems.

Contribution to Knowledge

Ground-based values of diffuse solar irradiation are currently available for two UKMO sites only in the UK. The algorithm chosen in **KrigeP** delivers countrywide coverage.

6.3.1 Future Work on Separation Step

MIDAS data is made available as sums of 60-minutely readings for each hour which are allocated a time of the hour end. For example, values between 11:00 and 12:00 are categorised as “12:00”. However, this is an over-simplification of the data. The actual end of observation time purports to be ten to the hour e.g. 11:50. However, an examination of the electronic timestamps of the data exhibits a range of observation end times. For instance, Sutton Bonington weather station may report at 11:52, Watford at 11:48, Prestwick at 11:37 and so on. There is not a constant time per weather station. That is, Sutton Bonington may report again at 12:58. Most weather stations transmit readings within a ten-minute band of nn:50, but cases of 40 minutes too early have been detected.

Calculation has shown that a difference of just ten minutes may have considerable impact on end results. The annual average POA irradiation was calculated at Sutton Bonington Met station from GHI for 10 years 2008-2017. If a timestamp of nn:30 is used (to take the centre of the hour), the greatest irradiation is computed for a tilt of 30^{o}, instead of the expected 38^{o} obtained with a timestamp of nn:20. Similarly, when the annual average POA irradiation is calculated per compass point at Sutton Bonington for ten years at a constant inclination of 38^{o}, the greatest POA irradiation is obtained for the southwest direction, rather than the expected south. Faulty timestamp can be confused with weather conditions such as morning clouds or fog, or condensation on the sensor.

Despite the differences in observation end times, the irradiation measurements are currently treated by this research as if they all occur at nn:50. This is because a minimum of five measurements per hour are required for the interpolation algorithm. The accuracy of kriging increases if at least 20-30 inputs are used. In future it is planned to correct all the hourly irradiation values to nn:50, rather than simply apportioning them to that time. This may be done by straightforward averaging in the first instance, although there are also more complex techniques. Hourly averaged data may be redistributed based on the clearness index (Gibson et al, 2016). One minute irradiance time series have also been recreated from hourly data by applying Markov chains to cloud cover data (Bright et al, 2015).

6.4 Translation into tilted-plane irradiation

Roof1P details the transposition model for generating tilt irradiation from the horizontal components. Plane-of-array (POA) or tilted irradiation is required to simulate the energetic performance of photovoltaic devices. Validation against Loughborough data has proved that this combination of algorithms delivers the best results for UK conditions, while it is acknowledged that different models may better suit other climates. Current decomposition models are based on empirical correlations. It has been reported that they have different biases based on location (Ineichen, 2008) and climate (Lave et al, 2015) because of differences in cloud cover. In addition, there are different values of air mass, high clearness index proportion, atmospheric aerosols and atmospheric turbidity between sites, for instance between Europe and Australia (Ridley et al, 2010).

Looking at electricity output prediction, the chief source of uncertainty lies in transforming GHI to POA irradiation (Koubli, 2017). There are very many decomposition and translation models, as researchers have continuously attempted to improve results. Translation to in-plane irradiation is usually accomplished by the two-step method described here. That is, separation into beam and diffuse components, followed by translation to a tilted plane. Yet, the fact that GHI to in-plane irradiation transformation is site-dependent makes it suitable for a neural network approach. This was undertaken using the interpolated GHI data furnished by this research by a co-author (Koubli, 2016). Measured and interpolated GHI were available for a PV system in Loughborough, together with calculated sun position and measured POA irradiation for training the neural net. This single-step approach shows reduced bias compared to the traditional two-step method, even with the best performing models, but would benefit from further work in cross-location validation.

Another way in which solar irradiation plane translation models may be improved would be to investigate the influence of albedo. This is the third, ground-reflected component of GHI, besides the beam and diffuse elements. The greater the tilt angle, the larger the effect of the albedo on the calculated POA irradiation (Mubarak et al, 2017). UK domestic systems have some of the steepest slopes worldwide, due to sharp roof pitches for rain runoff and the optimal PV angle resulting from high latitude. It has been variously reported that a constant albedo of 0.2 gives optimal results (David et al, 2013) and, in contrast, that use of a constant value leads to an increase in bias (Mubarak et al, 2017). The contradictory findings of these two groups of researchers are probably due to the selection of different test sites with dissimilar prevailing weather. Influence of albedo in the UK and selection of appropriate values would need to be empirically determined.

6.5 Tilt and Azimuth

The algorithms applied in the separation and translation steps require accurate values of collector plane tilt and azimuth in order to produce realistic results. Whilst these values are fairly standard for solar farms, they vary within a range for rooftop installations. Few records of roof tilts and azimuths exist for the majority of buildings. **Roof1P** and **Roof2P** describe how these values may be determined over large areas using data captured by laser from aircraft i.e. LiDAR (Light Detection and Ranging) data. The results are extensively validated.

Roof1P expands a method to obtain information about building roof features (tilt, azimuth and area). Building characteristics are extracted for a single city and statistically scaled-up based on property type to predict UK-wide parameters. It has the advantage of requiring LiDAR data and building outlines for a single urbanisation only for scale-up, and therefore can speedily produce results. **Roof2P** focusses on procuring more exact values of azimuth, in preference to categorisation into somewhat arbitrary compass directions. Usable roof areas for PV are extracted.

The wide-area analysis which these papers provide is useful for determining impacts on infrastructure which is one of the goals of this thesis.

Division of Work

Author Contributions to **Roof2P**: Diane Palmer originated and designed the research; assimilated the LiDAR data and maps; identified and applied appropriate tools; developed the methodology. Elena Koubli captured, cleaned and stored the housing database. Ian Cole advised on technical details. Diane Palmer wrote the paper, supervised by Thomas Betts and Ralph Gottschalg.

Contribution to Knowledge

Roof1P sets out a flexible method. It may be applied to any number of buildings of any type. The multiplier (which is used to expand tilt/azimuth results from a single city to nationwide) can be adapted to fit the datasets available, as described in the paper.

The work of **Roof2P** is novel because it takes an alternative approach to standard methods of capturing rooftop characteristics for photovoltaic installation. It does not try to accurately reproduce single house models or building plans, like the majority of existing methods. Instead the suitability of each roof for at least a minimum size photovoltaic system is assessed for wide areas e.g. cities or regions. The results are twice validated, firstly against aerial imagery and then against an installer’s database of 886 systems (the largest ground-truthing of any similar method to date). The first check discovers if any unsuitable roofs are wrongly selected. The second check determines whether any roofs already fitted with PV are missed.

6.5.1 Future Work on Tilt and Azimuth Step

Further work could include taking advantage of the installers' database used in **Roof2P** to train an artificial neural network to recognise homes suitable for domestic PV system installation. No prior assumptions at all about rooftop characteristics would be required. Appropriate roof tilts, azimuths, sizes, absence of shade and chimneys etc are recognised by the trained neural network. The building outlines of houses fitted with PV systems could be used to select LiDAR data. Machine learning could then be employed to identify patterns in the LiDAR similar to those houses with PV installations. Enhancements could include expanding the database with more rooftop systems recognised from GoogleEarth. The database comprises small two-plane houses. Addition of more domestic systems would increase the chances of distinguishing larger and more complex properties where PV could be deployed.

6.6 Thermal and Electrical Models

ThermElecP advances the PV impact sequence by providing thermal and electrical models. These generate PV output and performance ratio data from the POA irradiation values which **KrigeP**, **GroundSatP**, **Roof1P** and **Roof2P** furnish. The specific thermal and electrical models were selected because they only demand two inputs (POA irradiation and temperature), provided by this research. Above that, they accurately calculate power output for crystalline silicon modules, the most widely used photovoltaic technology.

Division of Work

Author Contributions to **ThermElecP**: Elena Koubli and Ralph Gottschalg drew up the objectives. Elena Koubli selected and executed the algorithms, devised the methodology and verified the findings. Diane Palmer supplied data inputs for the algorithms (interpolated in-plane irradiation and ambient temperature data) and advised on input data description. Elena Koubli wrote the paper, supervised by Ralph Gottschalg. Diane Palmer and Paul Rowley reviewed the paper.

6.7 Shading

An important consideration in modelling PV energy output is to determine whether or not a PV installation is shaded, to what extent and where the shade falls. Shade can be largely avoided for large commercial (ground-mounted) installations but perfect conditions for domestic rooftop deployment are rarely achievable, as noted in **Roof1P** and **Roof2P**. A shadow falling on a solar array has the following effects. The electrical yield of each single PV cell is reduced in proportion to the amount of shade falling upon it. Not only that, cells are connected in series, therefore output of the entire bypass diode-protected cell string (typically 20-24 cells) falls to the level of the shaded cell. Thus a long thin shadow, e.g. from a television aerial, falling diagonally across a solar array can reduce the output of every string substantially.

ShadeP reviews and scores several models which study the effect of shading on PV. These are: building shadow simulation, image analysis, hill-shading, ambient occlusion and ray-tracing. The inputs required, type of shading covered (i.e. self-shading from own roof and roof features; near shading from other roofs, trees etc; terrain shading; all of these types or a selection of them), speed and usability of the software are covered. Image analysis and hill-shading with ambient occlusion are additionally discussed in **Roof2P** for determining roof aspect. **ShadeP** gives a critique of the advantages and disadvantages of each model and acts as a guide as to which technique is appropriate in which circumstances (data availability, computing power available, personnel resources).

Contribution to Knowledge

The novelty of **ShadeP** is that it utilises approaches more commonly employed on terrain (i.e. hill-shading) for rooftop modelling.

Division of Work

Author Contributions to **ShadeP**: Diane Palmer planned and designed the research; obtained and prepared the data; categorised methods; utilised the GIS tools; analysed results. Ian Cole and Brian Goss implemented the skydome/ray-tracing model. Diane Palmer wrote and presented the published work, supervised by Thomas Betts and Ralph Gottschalg.

6.7.1 Future Work on Shading Step

It has been observed that modelled shadows can fall on either side of a roof during the course of an hour. In between the two timestamps the shadow must fall on the roof but this is missed due to the temporal resolution of the data. Hence, the research could be extended by developing a method to disaggregate the hourly MIDAS data to a higher temporal resolution (see Section 6.3.1 for a discussion of possible techniques).

The shadow models examined so for are based on either LiDAR data or aerial photography. Possibly improved results could be achieved by working out a procedure to analyse the 3D images obtained by combining these inputs. An example is given in Figure 12 which extracts building heights from LiDAR and drapes aerial imagery over the resultant model.

Figure 12: St Mary's Church and surroundings, Prestwich, Manchester. 25 cm LiDAR data draped with aerial photo (date flown 11 June 2015, time unknown)

6.8 Spatial and Temporal Variation of PV Performance

The models which have been identified, developed and employed up to this point, deliver PV yield for any photovoltaic installation (domestic/commercial/large-scale and roof- or ground-mounted) anywhere in the UK. At this point the overall effect of amalgamations of PV systems are explored. **VariabilityP** and **FarmFleetP** provide a picture of the complexity of the general research area. They put the challenges involved in assessing the impact of widespread photovoltaic installations on all levels of the power network into context.

6.8.1 System Dispersion and Aggregate Irradiation Variability

Output from individual solar farms may theoretically overwhelm transformer reserve capacity. It potentially may create instabilities in the power system due to variability or localized overload due to too high generation in specific areas. **VariabilityP** considers the production of all UK solar farms together. When one is generating at maximum capacity, its neighbours may not be. This lessens the overall impact on the national transmission system. The effect of size, number and cluster shape on irradiation smoothing for selected groups of solar farms is considered.

Variability of irradiation and therefore of electrical yield from a specific solar farm is less if viewed in aggregate with surrounding installations. If this regularizing effect is disregarded, unnecessary grid connection restrictions may be put in place. It is demonstrated that the current distribution of solar farms in the UK has a smoothing effect on collective variability in output. Combined, they mitigate the inherent fluctuations in PV output. This is useful from the point of view of ensuring the National Grid remains stable.

An exception to this situation is the case of the “blocking high” where high pressure over the UK gives dry, settled weather for days or weeks. This would lead to all solar farms in several adjacent grid supply point areas delivering maximum production simultaneously. No detailed studies of the frequency, length and spatial extent of such high PV events have been undertaken to date. However, the Met Office report that in July 2018 the blocked weather was accompanied by low wind speeds, as well as the heatwave. Thus, although PV production was high, the wind power supply was low (Dawkins, 2019). Weather stresses on the energy system are therefore complex. With climate change predictions suggesting more hot summers, further investigation of high PV events is necessary.

In common with many studies, this research uses mean hourly irradiation time-series as an input because of its availability. This hourly aggregation hides irradiance fluctuations which may occur at shorter time intervals and underestimates peak GHI. The interpolation method employed is also unlikely to predict obscuration of the solar resource by small-area clouds. Short-term fluctuations which could potentially result in ramps in PV output and grid problems are missed by modelling with hourly data (Bright et al, 2015). In the context of this paper, the mitigation of short duration variability within feeder areas is not detected. This is one of the limitations of this research (see Section 8 for a description of synthesis of higher temporal resolution data).

Contribution to Knowledge

VariabilityP offers an alternative method of investigating the variability associated with photovoltaic power. The influence of the various sizes of solar farms and their geographical dispersal is examined, alongside landscape features and weather patterns.

Division of Work

Author Contributions to **VariabilityP**: Diane Palmer and Elena Koubli originated the research. Elena Koubli produced the output data from GHI provided by Diane Palmer. Diane Palmer carried out the cluster and trend analysis. Ian Cole analysed wind direction. Diane Palmer wrote the paper, supervised by Thomas Betts and Ralph Gottschalg. Elena Koubli reviewed the paper.

Future Work on Dispersion Variability

This line of research could be continued by experimenting with scientific techniques for classification of clusters or groups of solar farms rather than the manual method currently employed. These methods include decision trees, hierarchical clustering and Principal Components Analysis.

The relationship between variability of output site clustering, regional weather and topography could be investigated further, for instance with multiple regression or random forest algorithms. Study of output variability patterns would also contribute to power distribution management decisions. Wavelets or Fourier Series are suitable analytical methods for this.

6.8.2 Impact on Transmission Systems of Solar Farms Output

In **FarmFleetP**, year-to-year and area-to-area variability of PV performance in the UK is studied. Generation from large-scale solar systems is investigated throughout the country. The work is useful in that it demonstrates that utility-scale solar installations are unlikely to cause fragility of the electricity system in the UK at the current time. The main message for network operators is that solar intermittency should not be a major concern. Attainment of nameplate capacity is also analysed. Few recent publications have investigated achievement of rated capacity by photovoltaic systems. Most have focussed on wind technology.

Contribution to Knowledge

There is no other nationwide analysis of spatial and temporal variation of solar farm yield throughout the UK. Furthermore, **FarmFleetP** points out the difficulty in planning for voltage control whilst array-to-inverter ratios remain unknown. The effects of inverter clipping due to array oversizing are discussed. Unfortunately, the impact of these on the annual output of the UK solar farm fleet cannot be analysed due to the deficit of publicly available information.

Division of Work

Author Contributions to **FarmFleetP**: The overall concept of the paper was the idea of Diane Palmer and Ralph Gottschalg. Elena Koubli produced the solar farms' output data from GHI provided by Diane Palmer. Diane Palmer surmounted research problems and analysed the research data at various levels of spatial aggregation, as well as for case studies. Diane Palmer wrote the paper, supervised by Thomas Betts and Ralph Gottschalg. Ralph Gottschalg reviewed the paper.

Future Work on Oversizing

More accurate modelling could be performed on oversizing/power limiting if information on solar farm inverter sizes becomes available.

6.9 Spatial Distribution of PV

Finally, **FarmSiteP** asks what form the future solar farm distribution in the UK will take. Knowledge of this distribution and yield calculated from kriged irradiation data will help model time and location of possible future PV power plant supply in the UK. This paper demonstrates the scientific selection of the most suitable sites for large-scale solar installations in the UK, using Geographical Information Systems (GIS) analysis. The objectives are: to determine how much large-scale solar can fit into the UK; and how much of this quantity will be installed in reality in the current economic circumstances. The approach presented may be applied anywhere with adequate spatial data inputs. Physical, technical, environmental and geographical requirements are considered, as well as economic viability.

More detailed grid modelling could provide information on load flow calculations for optimal operation of groups of PV generators. There are also energy system models, which may be used for the management, planning and expansion of the electricity grid to support the integration of PV. However, these models are beyond the scope of this thesis.

Contribution to Knowledge

FarmSiteP is innovative in that it investigates grid connection constraints. Previous authors have focussed on distance to high voltage grid only as a limiting factor. The impact of government policy on site selection is also examined. The case study is the UK which is a relatively high latitude region with a limited solar resource. Almost all previous studies have concentrated on countries with high average annual solar irradiation.

Division of Work

Author Contributions to **FarmSiteP**: Diane Palmer came up with the overall research goals and aims. She resourced the data, designed the experiments and evaluated the results. Diane Palmer wrote the paper, supervised by Thomas Betts and Ralph Gottschalg.

Future Work on Solar Farm Siting

FarmSiteP can be augmented by further examination of proximity of the coast to potential sites and how this influences suitability. Whilst this is very significant for the UK, other countries (e.g. the US) also need to consider coastal factors when installing PV. Large-scale solar deployment also needs to be continuously re-assessed, as land rents, government policies and subsidies change, and upgrades to the transmission system are carried out.

7 Overall conclusions

The research papers presented offer a range of insights in response to the over-arching thesis aim. That is, they investigate the spatio-temporal variability of the solar resource and its consequent impacts on national PV system performance. The GHI data source is selected, and the relatively sparse ground measurements chosen are interpolated to deliver countrywide coverage. The transformation process to convert the global horizontal irradiation values to the plane-of-array data needed for tilted solar array calculations is described. Details of PV system tilts and azimuths are obtained from LiDAR data. The meteorological figures are input into thermal and electrical models to deliver the desired PV yield information. Losses due to system shading are investigated. Lastly, the accumulated impact of large-scale solar systems output on the transformer grid is explored. The future distribution of utility-scale installations is also considered.

The research is innovative in that it illustrates the selection of the most effective interpolation technique and separation model for the UK. The guidance provided may be adapted to other countries. Evidence is presented that the choice between ground and satellite GHI values depends on the layout of the weather stations network and on the specific satellite model. It is not a simple choice that one is better than the other at a given distance. An achievable method, based on the available input data resolution, for determining rooftop PV systems tilt and azimuth is educed. Combined impact of nationwide PV systems on the National Grid has not been previously investigated. It is determined that the overall UK transformer power capacity is sufficient to assimilate all electricity injected by large-scale PV penetration at the present time.

This thesis advances knowledge in that, to date, such an integrated approach that covers all relevant factors (e.g. different array orientations, installation locations and sizes, regional weather differences, local grid infrastructure) has not previously been developed. Uncertainty when modelling the impact of relatively high penetrations of PV on local, regional and national power distribution systems may be lessened.

8 Recommendations for future research

There is wide scope for expanding this research, in terms of each individual step, and of the overall assessment of PV impact on components of the National Grid.

Looking at the separate sequence steps, interpolation of ground-based GHI values can be investigated in different climatic zones, as can appropriate separation algorithm adoption. Methods of improving interpolation results can be evaluated, for instance by incorporating extra alternative ground data sources, or by combination with satellite data. More sophisticated mathematical processes for ascertaining the influence of distributed PV on the transmission system can be examined.

Short-term irradiation forecasting of hourly GHI is another possibility, so that PV output will be modelled on forecast performance, instead of past performance. Prospective methods include K nearest neighbour or the relationship between irradiation variation and wind-speed at cloud height. (The UK Met Office provides wind data at height for pilots: https://www.metoffice.gov.uk/aviation/ga). The latest research is using combination of variously modelled GHI forecasts (Diagne et al, 2013).

Generation of sub-hourly irradiance data for PV impact modelling would also be helpful. Possible techniques are co-kriging of minute-interval Baseline Surface Radiation Network (https://bsrn.awi.de) GHI and hourly MIDAS data. Alternatively, there are stochastic models e.g. Richardson and Thomson (2012) or (Bright et al, 2015).

The thesis as a whole could be extended by contemplating the effect of *all* PV installations on the electrical network. So far, only solar farms have been analysed for capability to affect power balance at transformers. Notwithstanding, accumulated output of smaller systems could also engender reverse flow scenarios. The size, number and locations of current household PV systems are available until April 2019 under the Feed-in Tariffs (FIT) scheme (https://www.ofgem.gov.uk/environmental-programmes/fit/contacts-guidance-and-resources/public-reports-and-data-fit/installation-reports). Similar information regarding rooftop installations over 5 MW (industrial or commercial systems) may be found in the Renewable Energy Planning Database (REPD) (https://www.gov.uk/government/publications/renewable-energy-planning-database-monthly-extract). Thus, present impacts of domestic and commercial rooftop systems on the grid could be modelled utilising the methodology outlined in this thesis.

Future impacts will, of course, depend on the quantity and capacity of rooftop installations. Total national space for rooftop deployment may be estimated using the techniques described in **Roof1P** and **Roof2P**. However, the percentage of total possible roof area which will actually be used for PV is subject to a number of circumstances, encompassing socio-economic factors, ownership or rental of accommodation, rural or urban situation, and peer effects or social norms. These influences have yet to be fully investigated.

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Appendix

Table A.1: Relationship of Papers to steps in PV impact sequence

(Copies of all papers are available via Loughborough University's Institutional Repository at http://dspace.lboro.ac.uk)

∗ Author contribution: lead (L) or joint (J)

Citations (Google Scholar) as of June 2019)

	Reference	Abbreviation & Paper Type	∗	Research Step(s)	#
1	Diane Palmer, Ian Cole, Tom Betts, Ralph Gottschalg, 2017, Interpolating and estimating horizontal diffuse solar irradiation to provide UK-wide coverage: selection of the best performing models, Energies, Special Issue "Solar Photovoltaics Trilemma: Efficiency, Stability and Cost Reduction 2017", 10, 181; doi:10.3390/en10020181, URL: http://www.mdpi.com/1996-1073/10/2/181 https://dspace.lboro.ac.uk/2134/24167, https://hdl.handle.net /2134/24167.	**KrigeP** Peer-reviewed journal paper	L	Interpolation Separation	12
2	Diane Palmer, Elena Koubli, Ian Cole, Tom Betts, Ralph Gottschalg, 2018. Satellite or ground-based measurements for production of site specific hourly irradiance data: Which is most accurate and where? Solar Energy, Volume 165, 1 May 2018, Pages 240–255, URL: https://doi.org/10.1016/j.solener.2018.03.029 https://dspace.lboro.ac.uk/dspace-jspui/handle/2134/32399, https://hdl.handle.net/2134/32399.	**GroundSatP** Peer-reviewed journal paper	L	Interpolation	5
3	Diane Palmer, Ian Cole, Thomas Betts, Ralph Gottschalg, 2016, Assessment of Potential for Photovoltaic Roof Installations by Extraction of Roof Slope from LiDAR Data and Aggregation to Census Geography, IET Renew. Power Gener., vol. 10, no. 4, pp. 467–473, 2016. doi 10.1049/iet-rpg.2015.0388. URL: http://ieeexplore.ieee.org/abstract/document/7442743/ https://dspace.lboro.ac.uk/dspace-jspui/handle/2134/20065, https://hdl.handle.net/2134/20065.	**Roof1P** Peer-reviewed journal paper	L	Sun Geometry Separation Translation Tilt and Azimuth	6

4	Diane Palmer, Elena Koubli, Ian Cole, Thomas Betts, Ralph Gottschalg, 2018, A GIS-Based Method for Identification of Wide area Rooftop Suitability for Minimum Size PV Systems Using LiDAR Data and Photogrammetry, Energies, Special Issue “Solar Photovoltaics Trilemma: Efficiency, Stability and Cost Reduction 2018”, 11, 3506, doi 0.3390/en11123506, URL: https://www.mdpi.com/1996-1073/11/12/3506 https://dspace.lboro.ac.uk/dspace-jspui/handle/2134/36544, https://hdl.handle.net/2134/36544.	**Roof2P** Peer-reviewed journal paper	L	Tilt and Azimuth	1
5	E. Koubli, D. Palmer, P. Rowley, and R. Gottschalg, 2016, Inference of missing data in photovoltaic monitoring datasets, IET Renew. Power Gener.,vol. 10, no. 4, pp. 434–43. DOI 10.1049/iet-rpg.2015.0355. URL: http://digital-library.theiet.org/content/journals/10.1049/iet-rpg.2015.0355 https://dspace.lboro.ac.uk/dspace-jspui/handle/2134/20351, https://hdl.handle.net/2134/20351.	**ThermElecP** Peer-reviewed journal paper	J	Interpolation Sun Geometry Separation Translation Thermal and Electrical Models	9
6	Diane Palmer, Ian R Cole, Brian Goss, Thomas R Betts, Ralph Gottschalg, 2015, Detection of roof shading for PV based on LiDAR data using a multi-modal approach, in 31st European Photovoltaic Solar Energy Conference and Exhibition, 2015, p. 1753 – 1759, https://www.eupvsec-proceedings.com/proceedings?paper=32667 https://dspace.lboro.ac.uk/dspace-jspui/handle/2134/20083 https://hdl.handle.net/2134/20083.	**ShadeP** Organising committee reviewed conference paper	L	Shading	4
7	D. Palmer, E. Koubli, I. Cole, T. Betts and R. Gottschalg, 2016, Comparison of Solar Radiation and PV Generation Variability: System Dispersion in the UK, IET Renew. Power Gener., Volume 11, Issue 5, 12 April 2017, p. 550 – 557, DOI: 10.1049/iet-rpg.2016.0768 , Print ISSN 1752-1416, Online ISSN 1752-1424, URL: http://ietdl.org/t/iJLSVb https://dspace.lboro.ac.uk/2134/24168, https://hdl.handle.net/2134/24168.	**VariabilityP** Peer-reviewed journal paper	L	Temporal and Spatial Variability of PV Performance	5

8	Diane Palmer, Elena Koubli, Tom Betts and Ralph Gottschalg, 2017, The UK Solar Farm Fleet: A Challenge for the National Grid?, Energies 2017, 10(8), 1220; doi:10.3390/en10081220, URL: http://www.mdpi.com/1996-1073/10/8/1220 https://dspace.lboro.ac.uk/dspace-jspui/handle/2134/26255 https://hdl.handle.net/2134/26255.	**FarmFleetP** Peer-reviewed journal paper	L	Temporal and Spatial Variability of PV Performance	2
9	Palmer, Diane; Betts, Thomas; Gottschalg, Ralph, 2019, The future scope of large-scale solar in the UK: site suitability and target analysis, Renewable Energy, Volume 133, April 2019, Pages 1136-1146. URL: https://doi.org/10.1016/j.renene.2018.08.109 https://dspace.lboro.ac.uk/2134/34804, https://hdl.handle.net/2134/34804.	**FarmSiteP** Peer-reviewed journal paper	L	Spatial Distribution of PV	1

Figure A.1: First Part of Research Sequence: Measured Irradiation to PV Output

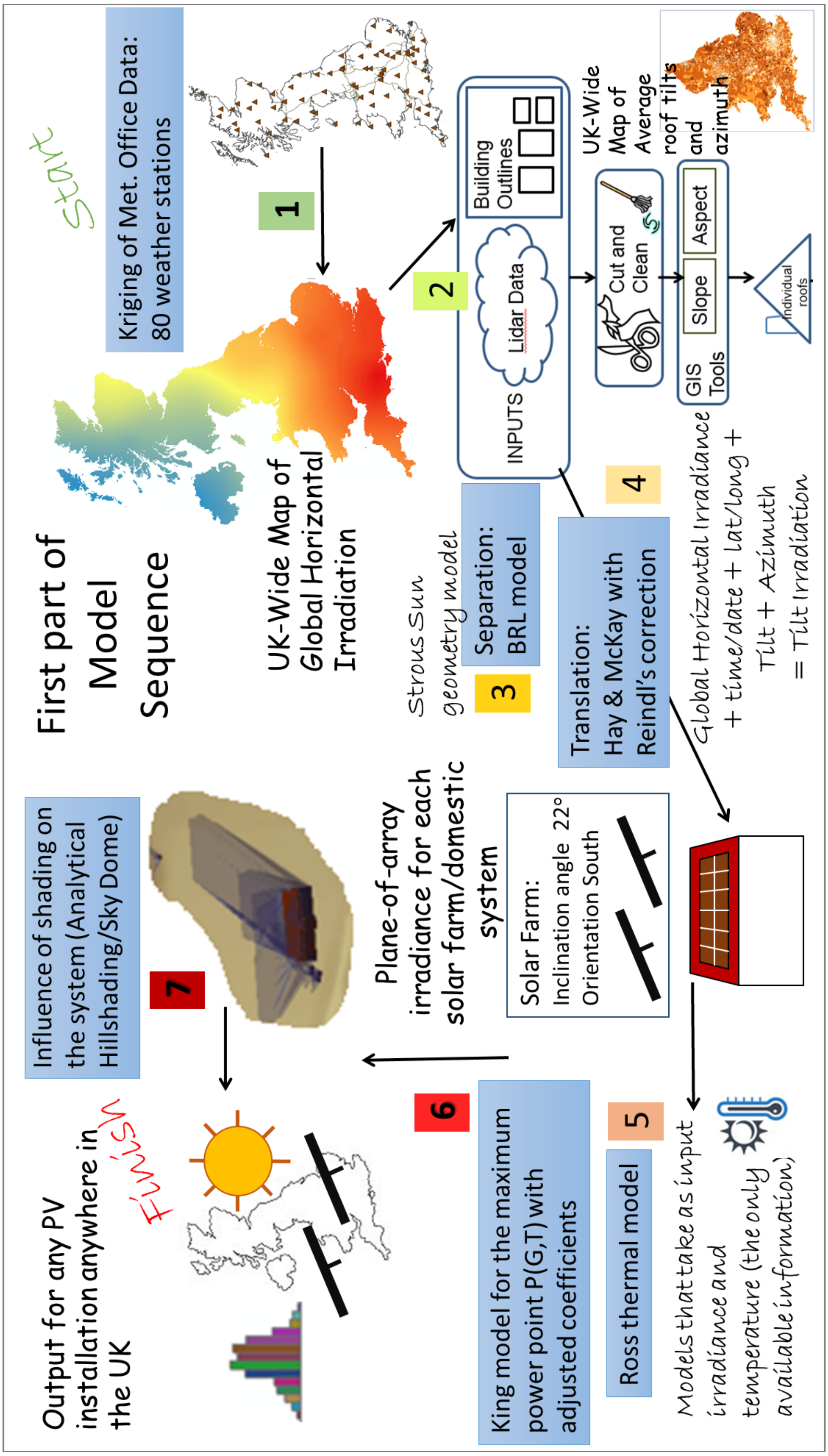
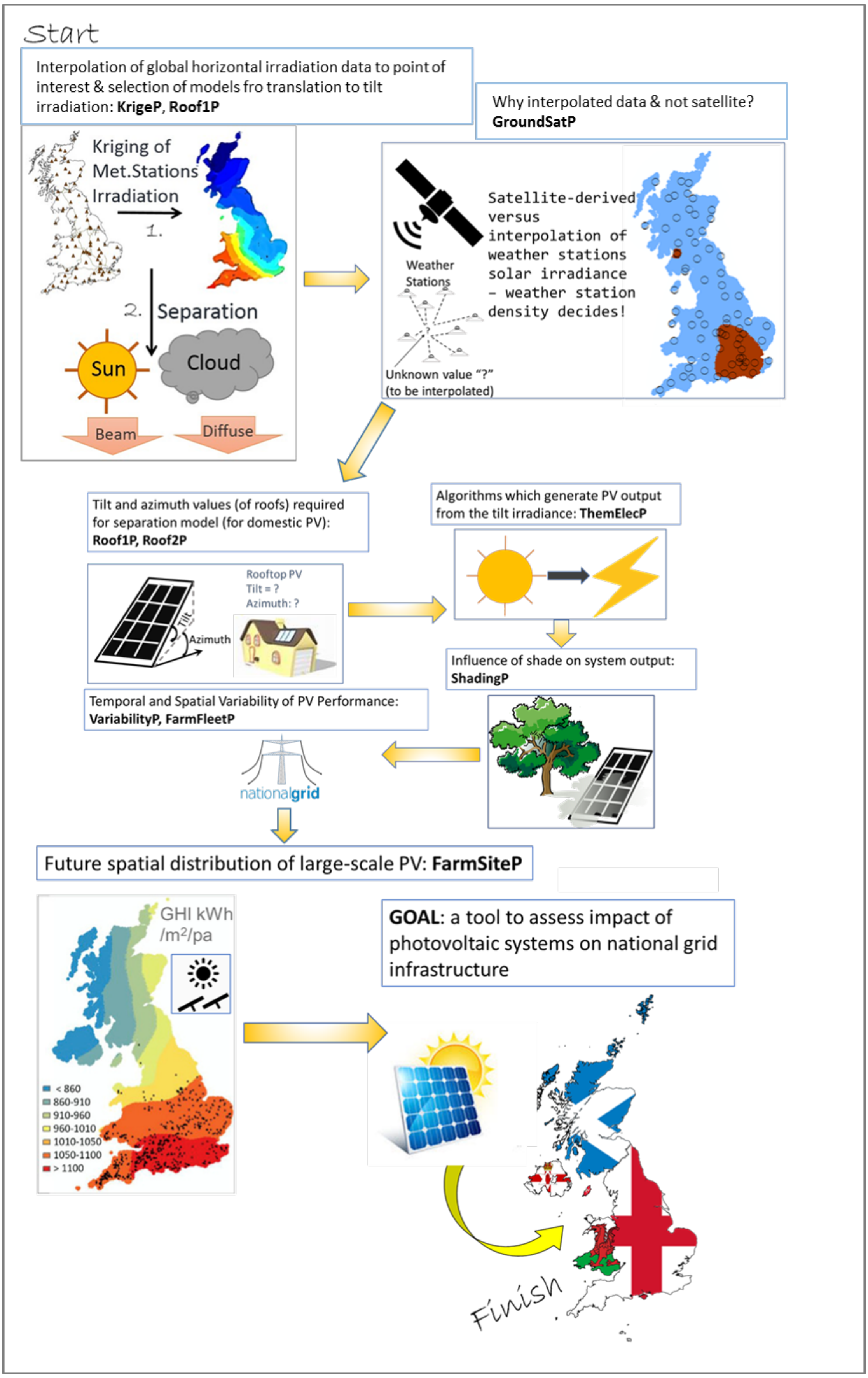


Figure A.2: Linkage of papers to PV energy conversion chain and grid impact



Interpolation of global horizontal irradiation data to point of interest & selection of models fro translation to tilt irradiation: **KrigeP**, **Roof1P**

Why interpolated data & not satellite? **GroundSatP**

Tilt and azimuth values (of roofs) required for separation model (for domestic PV): **Roof1P, Roof2P**

Algorithms which generate PV output from the tilt irradiance: **ThemElecP**

Influence of shade on system output: **ShadingP**

Temporal and Spatial Variability of PV Performance: **VariabilityP, FarmFleetP**

Future spatial distribution of large-scale PV: **FarmSiteP**

GOAL: a tool to assess impact of photovoltaic systems on national grid infrastructure

List of further relevant publications

Lead author on 1, 2, 6, 9 and 14.
Supplied data and wrote sections of (4) and (10).
Supplied interpolated global horizontal irradiation or plane-of-array irradiation data, interpolated temperature data and/or prepared LiDAR data for 3, 5, 7, 8, 11, 12, 13, 15 and 16.

1. Diane Palmer and Tom Betts, "Comparison of Typical Meteorological Year and On-site Measurements for Solar PV Site Selection", in Proceedings 15th Photovoltaic Science, Applications and Technology Conference, 2019
2. Diane Palmer, Ian Cole, Tom Betts and Ralph Gottschalg, "Estimating Rooftop Capacity for PV: Are we asking the right question?", in Proceedings 14th Photovoltaic Science, Applications and Technology Conference, 2018
3. Cole I.R., Palmer D., Goss B., Koubli E., Betts T.R., Thomson M., Gottschalg R. Impact Analysis of Irradiance Dataset Selection on Photovoltaic System Energy Yield Modelling. 1st Int. Conf. Large-Scale Grid Integr. Renew. Energy India, Bombay. 2017, URL: http://regridintegrationindia.org/wp-content/uploads/sites/3/2017/09/GIZ17_030_posterpaper_Ian_Cole.pdf
4. B Goss, IR Cole, E Koubli, D Palmer, TR Betts, R Gottschalg (2017), Chapter 4: Modelling and prediction of PV module energy yield, in Nicola Pearsall, The Performance of Photovoltaic (PV) Systems : Modelling, Measurement and Assessment. Pages 103-132, Woodhead Publishing Series in Energy (105). Elsevier, Amsterdam, 183 - 208. ISBN 978-1-78242-336-2
5. Ruben Urraca, Ana M Gracia-Amillo, Elena Koubli, Thomas Huld, Jörg Trentmann, Aku Riihelä, Anders V Lindfors, Diane Palmer, Ralph Gottschalg, Fernando Antonanzas-Torres, 2017, Extensive validation of CM SAF surface radiation products over Europe, Remote Sensing of Environment, Volume 199, p. 171-186, URL: https://doi.org/10.1016/j.rse.2017.07.013
6. Diane Palmer , Elena Koubli, Ian Cole, Tom Betts and Ralph Gottschalg, "Satellite or Ground-based Irradiation Data: which is closer to reality?", in Proceedings 13th Photovoltaic Science, Applications and Technology Conference, 2017
7. E. Koubli, D. Palmer, Paul Rowley, and R. Gottschalg, "Remote monitoring and failure detection for distributed small-scale PV systems", in Proceedings 13th Photovoltaic Science, Applications and Technology Conference, 2017
8. E. Koubli, D. Palmer, P. Rowley, T.R. Betts and R. Gottschalg, "Inference of Missing PV Monitoring Data using Neural Networks", in Proceedings 43rd IEEE PVSC Conference, Portland, Oregon, 2016. URL: http://toc.proceedings.com/32232webtoc.pdf
9. D. Palmer , E. Koubli, T.R. Betts and R. Gottschalg, "Space and Time Analysis of Irradiation variation across the UK: A 10 Year Study of Solar Farm Yield", in Proceedings 12th Photovoltaic Science, Applications and Technology Conference, 2016
10. E. Koubli, D. Palmer, P. Rowley, T.R. Betts and R. Gottschalg, "Comparison of Solar Radiation and PV Generation Variability with System Dispersion in the UK", in Proceedings 12th Photovoltaic Science, Applications and Technology Conference, 2016
11. E. Koubli, D. Palmer, P. Rowley and R. Gottschalg, "Investigating Two Thousand PV Rooftop Systems in the UK: Performance Analysis and Fault Diagnosis", in Proceedings 12th Photovoltaic Science, Applications and Technology Conference, 2016

12. I.R. Cole, D. Palmer, T.R. Betts & R. Gottschalg, ”A Fast and Effective Approach to Modelling Solar Energy Potential in Complex Environments”, in Proceedings 12th Photovoltaic Science, Applications and Technology Conference, 2016
13. E. Koubli, D. Palmer, P. Rowley, T. R. Betts, R. Gottschalg., 2015. Assessment of PV system performance with incomplete monitoring data. IN: Proceedings of 2015 31st European Photovoltaic Solar Energy Conference (EU-PVSEC), Hamburg, 14-18 September 2015, pp. 1594-1597. URL: https://www.researchgate.net/publication/284021958_ASSESSMENT_OF_PV_SYSTEM_PERFORMANCE_WITH_INCOMPLETE_MONITORING_DATA
14. D. Palmer, T.R. Betts and R. Gottschalg, “Assessment of Potential for Photovoltaic Roof Installations by Extraction of Roof Slope from Lidar Data and Aggregation to Census Geography”, in Proceedings 11th Photovoltaic Science, Applications and Technology Conference C97, 2015
15. E. Koubli, D. Palmer, P. Rowley and R. Gottschalg, “Replenishing Deficient Datasets in PV System Monitoring”, in Proceedings 11th Photovoltaic Science, Applications and Technology Conference C97, 2015.
16. Paul Rowley, Philip A Leicester, Diane Palmer, Paul Westacott, Chiara Candelise, Ralph Gottschalg, Thomas R Betts, 2015. Multi-domain analysis of photovoltaic impacts via integrated spatial and probabilistic modelling, IET Renew. Power Gener., Vol:9, ISSN:1752-1416, Pages:424-431, DOI: 10.1049/iet-rpg.2014.0374, URL: http://digital-library.theiet.org/content/journals/10.1049/iet-rpg.2014.0374

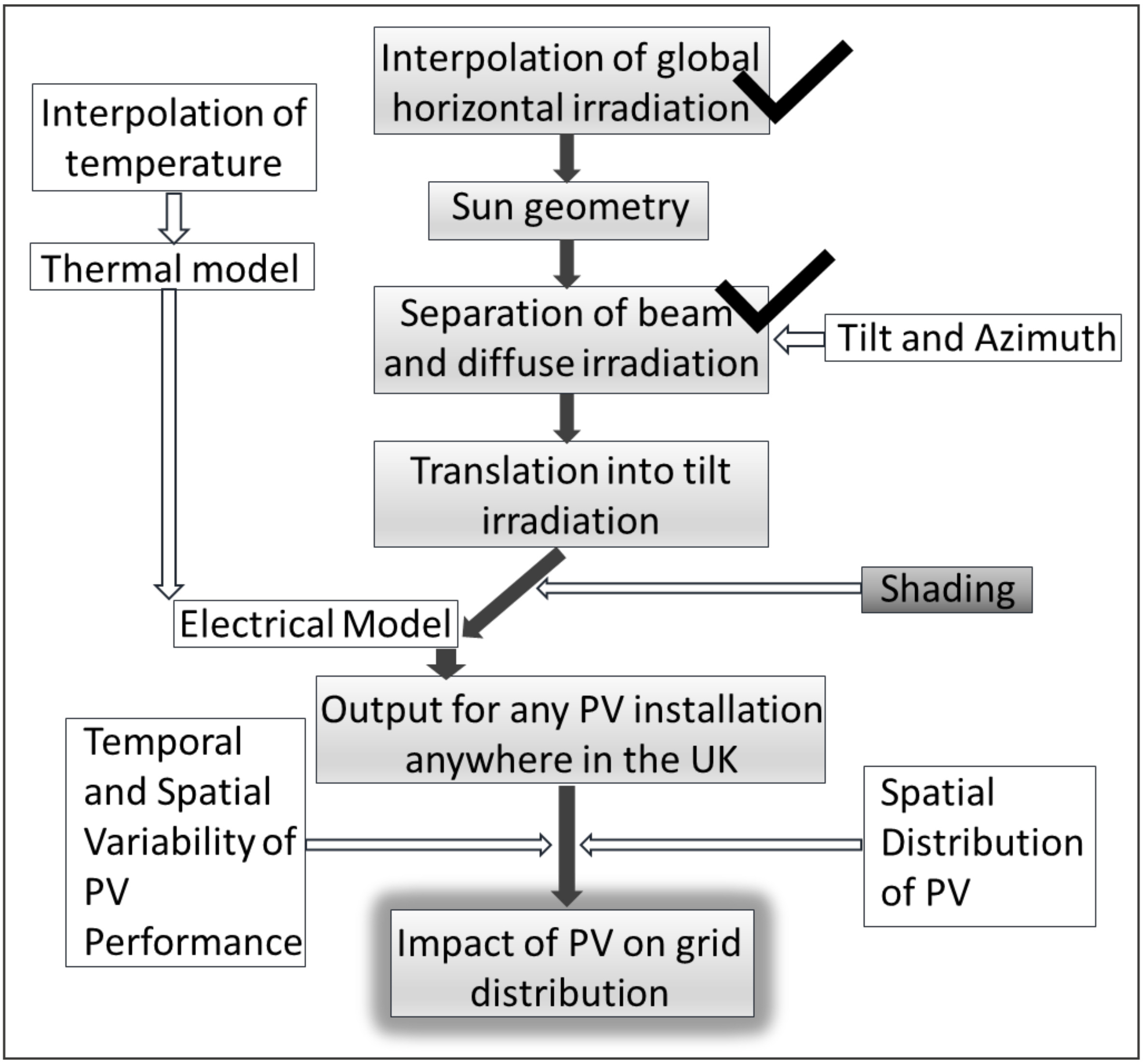
Nominations

- Runner-up for the best paper award in the Proceedings 14th Photovoltaic Science, Applications and Technology Conference (PVSAT-14), London, 2018 for the paper with title: “Estimating Rooftop Capacity for PV: Are we asking the right question?”
- Runner-up for the best paper award in the Proceedings 11th Photovoltaic Science, Applications and Technology Conference (PVSAT-11), Leeds, 2015 for the paper with title: “Assessment of Potential for Photovoltaic Roof Installations by Extraction of Roof Slope from Lidar Data and Aggregation to Census Geography?”

Nine Publications

Copies of all papers are available via Loughborough University's Institutional Repository at http://dspace.lboro.ac.uk and http://www.handle.net/.

KrigeP



Interpolation of global horizontal irradiation
Interpolation of temperature
Sun geometry
Thermal model
Separation of beam and diffuse irradiation
Tilt and Azimuth
Translation into tilt irradiation
Shading
Electrical Model
Output for any PV installation anywhere in the UK
Temporal and Spatial Variability of PV Performance
Spatial Distribution of PV
Impact of PV on grid distribution

KrigeP

Diane Palmer, Ian Cole, Tom Betts, Ralph Gottschalg, 2017, Interpolating and estimating horizontal diffuse solar irradiation to provide UK-wide coverage: selection of the best performing models, Energies, Special Issue "Solar Photovoltaics Trilemma: Efficiency, Stability and Cost Reduction 2017", 10, 181; doi:10.3390/en10020181, URL: http://www.mdpi.com/1996-1073/10/2/181, https://dspace.lboro.ac.uk/2134/24167, https://hdl.handle.net /2134/24167.

Author Contribution: Lead Author

Diane Palmer, Thomas Betts and Ralph Gottschalg conceived and designed the experiments; Diane Palmer carried out initial investigative work, analysed the data, developed the methodology and validated results; Ian Cole contributed data and analysis tools; Diane Palmer wrote the paper, supervised by Thomas Betts and Ralph Gottschalg.

Step(s) in PV Impact Sequence: Interpolation and Separation.

Originality

Very little research has been published about selection of appropriate interpolation techniques for solar insolation in northern European conditions.

Contribution to Knowledge

1. Provides guidance on selection of the optimal interpolation technique for weather data for any country, in any climate zone, worldwide.
2. Ground-based values of diffuse solar irradiation are currently available for two sites only in the UK. The algorithm chosen in KrigeP delivers countrywide coverage. The guidance provided may be adapted to other countries.

Purpose

1. Determination of the most appropriate algorithm for interpolating ground-based irradiation measurements in the UK to deliver national coverage.
2. Selection of separation model to obtain plane-of-array irradiation from the weather station global horizontal records.

Design

This research experiments with a wide range of methods to logically determine the most accurate interpolation and separation algorithms. These include investigating mathematical properties, experimentation and leave-one-out-cross validation. The accuracy of the techniques under scrutiny is assessed via Normalized Mean Bias Error (nMBE) and Normalised Root Mean Square Error (nRMSE).

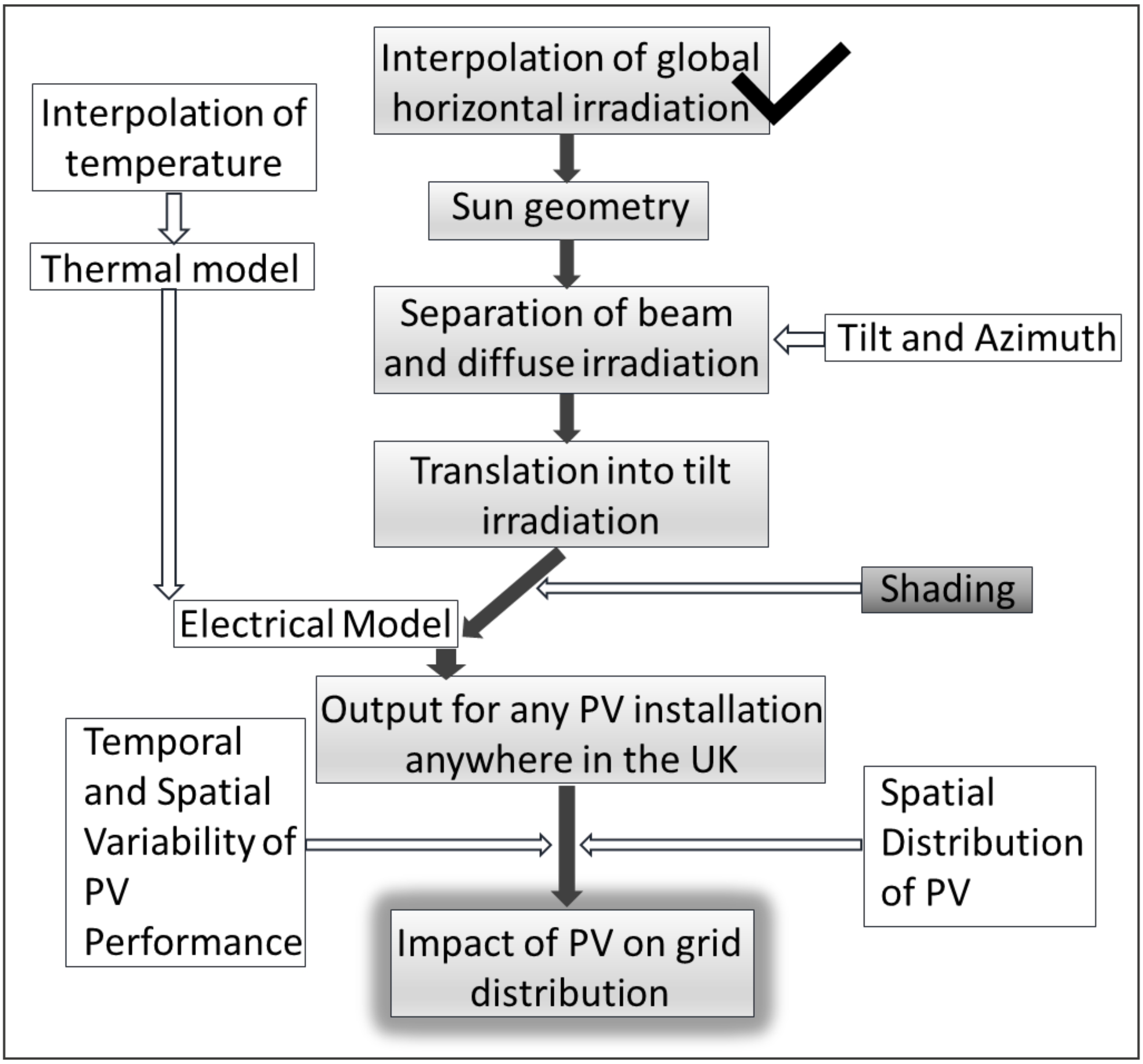
Findings

In the instance of the UK, the highest interpolation accuracy is achieved with ordinary kriging and an exponential semi-variogram. There is little difference between separation procedures but the Ridley, Boland, Lauret equation (a universal split algorithm) consistently performs well.

Conclusions/Interpretation of results

There are many possible models and model parameters for both the interpolation and separation stages. This work describes how to make a scientific selection.

GroundSatP


Interpolation of global horizontal irradiation
✓
Interpolation of temperature
Sun geometry
Thermal model
Separation of beam and diffuse irradiation
Tilt and Azimuth
Translation into tilt irradiation
Shading
Electrical Model
Output for any PV installation anywhere in the UK
Temporal and Spatial Variability of PV Performance
Spatial Distribution of PV
Impact of PV on grid distribution

GroundSatP

Diane Palmer, Elena Koubli, Ian Cole, Tom Betts, Ralph Gottschalg, 2018. Satellite or ground-based measurements for production of site specific hourly irradiance data: Which is most accurate and where? Solar Energy, Volume 165, 1 May 2018, Pages 240–255, URL: https://doi.org/10.1016/j.solener.2018.03.029, https://hdl.handle.net/2134/32399.

Author Contribution: Lead Author

The research goals were devised by Diane Palmer, who also carried out the analysis, investigation and methodology. Elena Koubli and Ian Cole supported with background information. Tom Betts and Jose A. Ruiz-Arias advised on analysis and tools. Diane Palmer wrote the paper, supervised by Thomas Betts and Ralph Gottschalg.

Step(s) in PV Impact Sequence: Interpolation.

Originality

The work is innovative in that Influence of station network density has not hitherto been recognised in studies of solar irradiation. In addition, it investigates differences in accuracy of data derived from extrapolation/interpolation of ground-based sources and satellite-modelled data in distinct physiographic regions. The findings are applicable throughout global temperate zones.

Contribution to Knowledge

GroundSatP shows that choice of irradiation model is not as clear as the accepted paradigm of select satellite data at a distance greater than 25 km from a weather station. The decision depends on the accuracy of the satellite model employed and the number and distribution of GHI measurement stations in the region.

Purpose

Justification of ground-based weather stations recordings as a fundamental model input to the PV energy conversion chain.

Design

Assesses the performance of different methods of obtaining surface solar irradiation throughout the entire UK. These methods comprise: nearest neighbour extrapolation and kriging of ground station observations; and three satellite-based products (one commercial, two publicly available). Furthermore, physiographic influences on the performances of each method/product are studied. Validation is by nMBE and nRMSE.

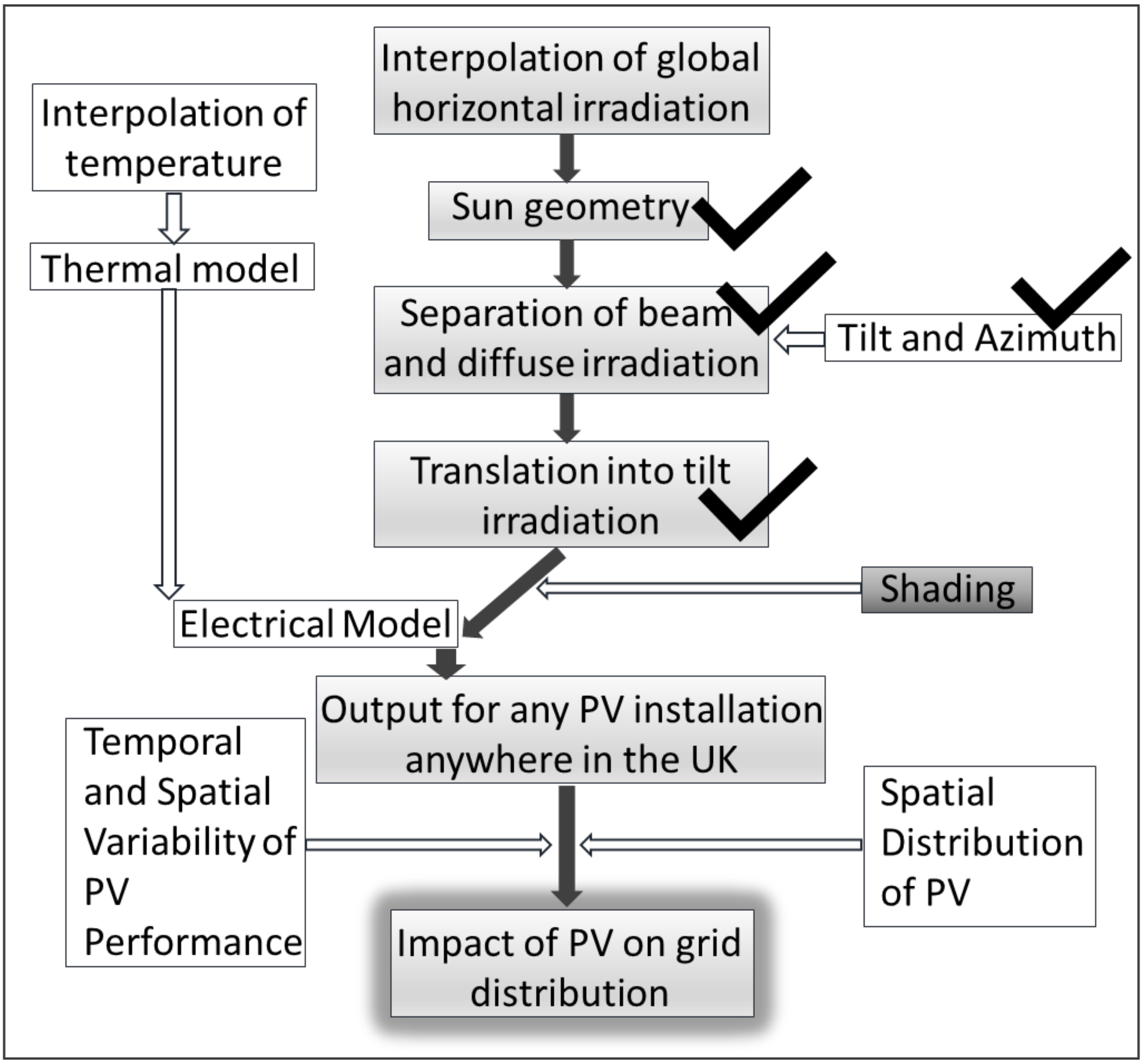
Findings

It is demonstrated that when the ground station distance is closer than 25 km, the kriging model outperforms the *best* satellite model. The other satellite models do not equal the accuracy of the kriging procedure until a distance of 100 km or more is reached.

Conclusions/Interpretation of results

The decision between satellite and ground-based irradiance data based on accuracy is not straightforward. It depends on the exactitude of the selected satellite model and the concentration of pyranometric stations.

Roof1P


Interpolation of global horizontal irradiation
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Tilt and Azimuth
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Output for any PV installation anywhere in the UK
Temporal and Spatial Variability of PV Performance
Spatial Distribution of PV
Impact of PV on grid distribution

Roof1P

Diane Palmer, Ian Cole, Thomas Betts, Ralph Gottschalg, 2016, Assessment of Potential for Photovoltaic Roof Installations by Extraction of Roof Slope from LiDAR Data and Aggregation to Census Geography, IET Renew. Power Gener., vol. 10, no. 4, pp. 467–473, 2016. doi 10.1049/iet-rpg.2015.0388. URL: http://ieeexplore.ieee.org/abstract/document/7442743/, https://hdl.handle.net/2134/20065.

Author Contribution: Lead Author

Diane Palmer, Thomas Betts and Ralph Gottschalg formulated the research ideas. Diane Palmer applied the analytical techniques and developed the methodology. Ian Cole gave guidance on data visualisation. Diane Palmer wrote the paper, supervised by Thomas Betts and Ralph Gottschalg.

Step(s) in PV Impact Sequence: Sun Geometry, Separation, Translation, Tilt and Azimuth.

Originality

Supplies wide-area analysis which can be used to study impacts on regional and national voltage networks.

Contribution to Knowledge

Roof1P sets out a flexible method. It may be applied to any number of buildings of any type. The multiplier (which is used to expand tilt/azimuth results from a single city to nationwide) can be adapted to fit the datasets available, as described in the paper.

Purpose

1. Specify sun geometry algorithm to calculate the sun declination angle and clearness index, Kt.
2. Use the sun angle and Kt to separate global irradiation into beam and diffuse components.
3. Determine azimuth and tilt angle (from pulsed laser LiDAR data) for rooftop or solar farm.
4. Adopt an appropriate translation algorithm to transform beam and diffuse irradiation numbers into plane-of-array irradiation using the azimuth and tilt angle.

Design

Roof1P determines upon the solar algorithms (sun geometry, separation and translation) employed by this research. Results are corroborated by comparison with pyranometric data from Loughborough University measurement station. This article additionally describes a method for the automated extraction of roof characteristics from aircraft-based LiDAR (Light Detection and Ranging) data. Validation of roof tilt with site measurements is undertaken by four different methods (inclinometer, trigonometry, photo trigonometry, installers' database).

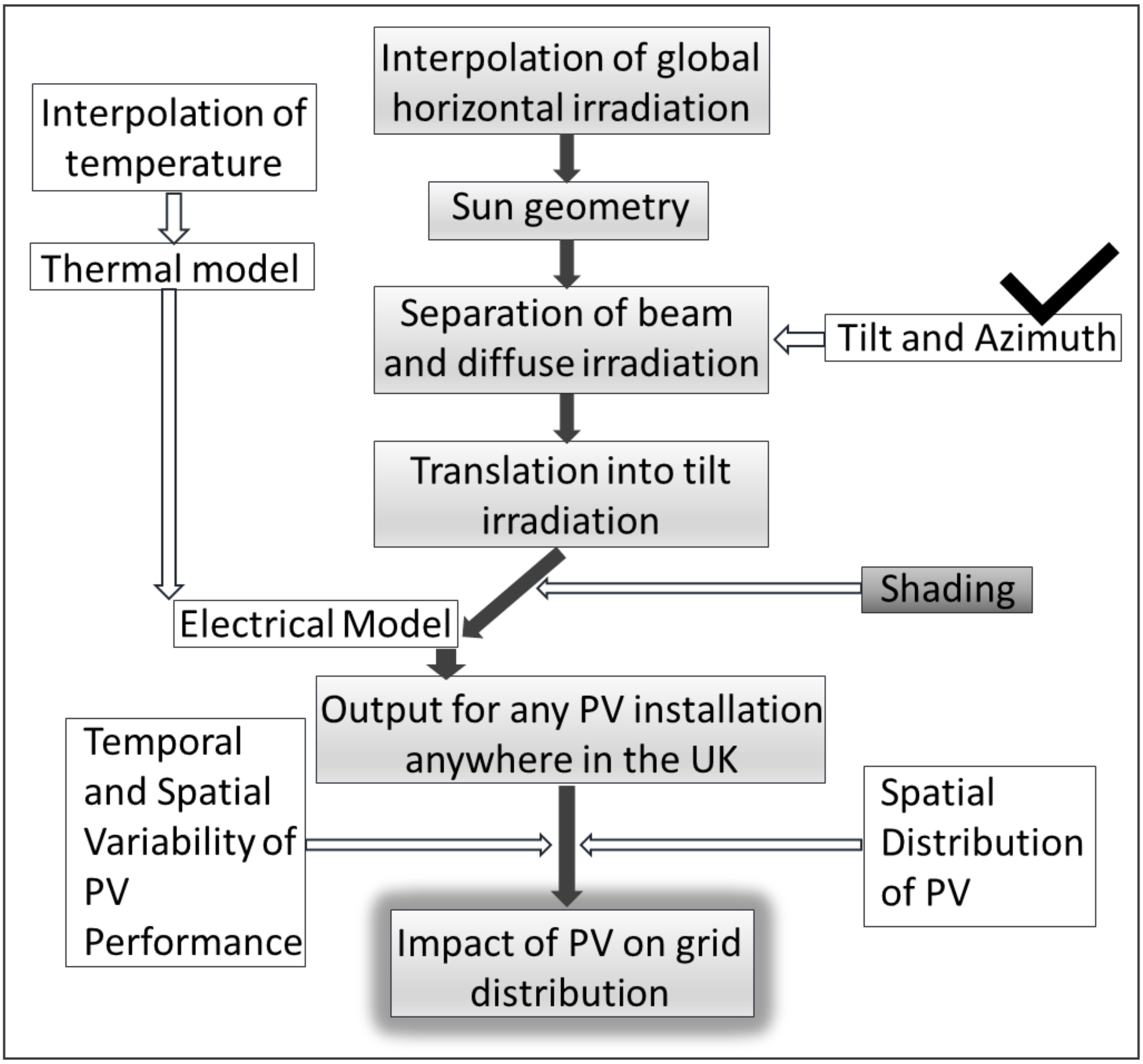
Findings

Roof1P expands a method to obtain information about building roof features (tilt, azimuth and area). Building characteristics are extracted for a single city and statistically scaled-up based on property type to predict UK-wide parameters.

Conclusions/Interpretation of results

This research describes how the required roof characteristics may be obtained together with expected percentage errors. It has the advantage of requiring LiDAR data and building outlines for a single urbanisation only for scale-up, and therefore can speedily produce results.

Roof2P


Interpolation of global horizontal irradiation
Interpolation of temperature
Sun geometry
Thermal model
Separation of beam and diffuse irradiation
Tilt and Azimuth
✓
Translation into tilt irradiation
Shading
Electrical Model
Output for any PV installation anywhere in the UK
Temporal and Spatial Variability of PV Performance
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Impact of PV on grid distribution

Roof2P

Diane Palmer, Elena Koubli, Ian Cole, Thomas Betts, Ralph Gottschalg, 2018, A GIS-Based Method for Identification of Wide area Rooftop Suitability for Minimum Size PV Systems Using LiDAR Data and Photogrammetry, Energies, Special Issue "Solar Photovoltaics Trilemma: Efficiency, Stability and Cost Reduction 2018", 11, 3506, doi 0.3390/en11123506, URL: https://www.mdpi.com/1996-1073/11/12/3506, https://hdl.handle.net/2134/36544.

Author Contribution: Lead Author

Diane Palmer originated and designed the research; assimilated the LiDAR data and maps; identified and applied appropriate tools; developed the methodology. Elena Koubli captured, cleaned and stored the housing database. Ian Cole advised on technical details. Diane Palmer wrote the paper, supervised by Thomas Betts and Ralph Gottschalg.

Step(s) in PV Impact Sequence: Tilt and Azimuth.

Originality

Roof2P focusses on procuring more exact values of azimuth, in preference to categorisation into somewhat arbitrary compass directions. Usable areas for PV are extracted.

Contribution to Knowledge

The work of Roof2P is novel because it takes an alternative approach to standard methods of capturing rooftop characteristics for photovoltaic installation. It does not try to accurately reproduce single house models or building plans. Instead the suitability of each roof for at least a minimum size photovoltaic system is assessed for wide areas e.g. cities or regions. Few previous studies are as extensively validated.

Purpose

Statistical analysis of LiDAR data and application of GIS models to LiDAR data to obtain PV system tilts and azimuths.

Design

This paper begins by reviewing and testing a range of existing techniques for identifying roof characteristics. A new method, based on selection of LiDAR pixels within half a standard deviation of the azimuth mode, is then presented. The results are twice validated, firstly against aerial imagery and then against an installer's database.

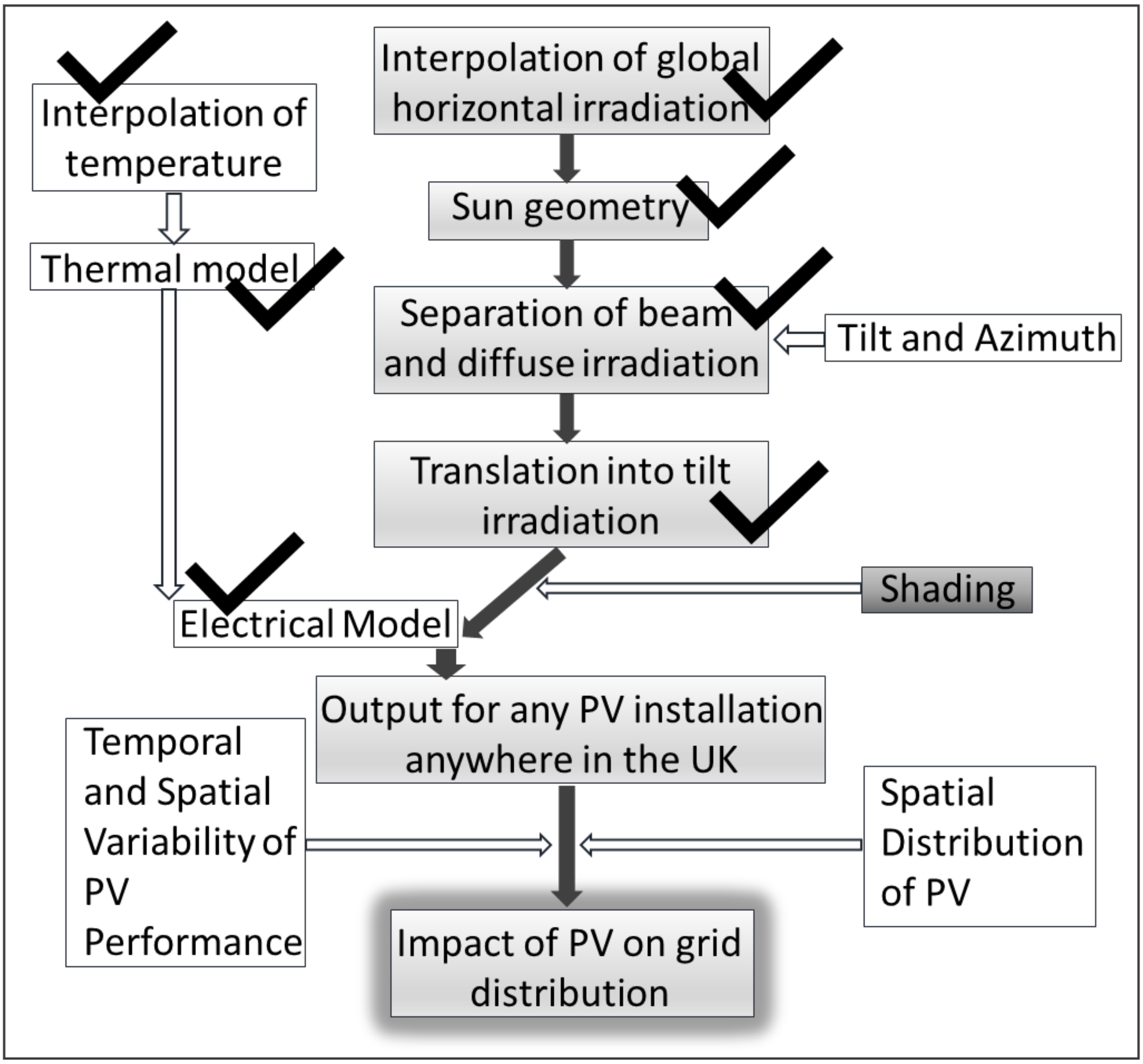
Findings

This is a versatile approach to handling non-ideal data, where standard peak finding algorithms cannot cope with the noise. The end result is a map of roofs suitable for PV system installation; size at least 1kW, known tilt and azimuth.

Conclusions/Interpretation of results

The tool developed here can be a powerful resource for investigating the deployment of rooftop PV. It can assist network operators in understanding how much energy the UK's potential minimum number of solar panels can produce and improve the efficiency of the electricity network.

ThermElecP


Interpolation of temperature
Thermal model
Interpolation of global horizontal irradiation
Sun geometry
Separation of beam and diffuse irradiation
Tilt and Azimuth
Translation into tilt irradiation
Shading
Electrical Model
Output for any PV installation anywhere in the UK
Temporal and Spatial Variability of PV Performance
Spatial Distribution of PV
Impact of PV on grid distribution

ThermElecP

E. Koubli, D. Palmer, P. Rowley, and R. Gottschalg, 2016, Inference of missing data in photovoltaic monitoring datasets, IET Renew. Power Gener.,vol. 10, no. 4, pp. 434–43. DOI 10.1049/iet-rpg.2015.0355. URL: http://digital-library.theiet.org/content/journals/10.1049/iet-rpg.2015.0355, https://hdl.handle.net/2134/20351.

Author Contribution: Secondary Author

Elena Koubli and Ralph Gottschalg drew up the objectives. Elena Koubli selected and executed the algorithms, devised the methodology and verified the findings. Diane Palmer supplied data inputs for the algorithms (interpolated in-plane irradiation and ambient temperature data) and advised on input data description. Elena Koubli wrote the paper, supervised by Ralph Gottschalg. Diane Palmer and Paul Rowley reviewed the paper.

Step(s) in PV Impact Sequence: Interpolation, Sun Geometry, Separation, Translation, Thermal and Electrical Models.

Originality

Synthetic performance data is generated based on interpolated environmental data.

Purpose

Conversion of solar irradiation to electrical output:

1. Calculate module temperature from calculated in-plane irradiation and interpolated ambient temperature.
2. Use calculated in-plane irradiation and module temperature to estimate electrical performance and yield.

Design

The specific thermal and electrical models were selected because they only demand two inputs (POA irradiation and temperature), provided by this research. Above that, they accurately calculate power output for crystalline silicon modules, the most widely used photovoltaic technology.

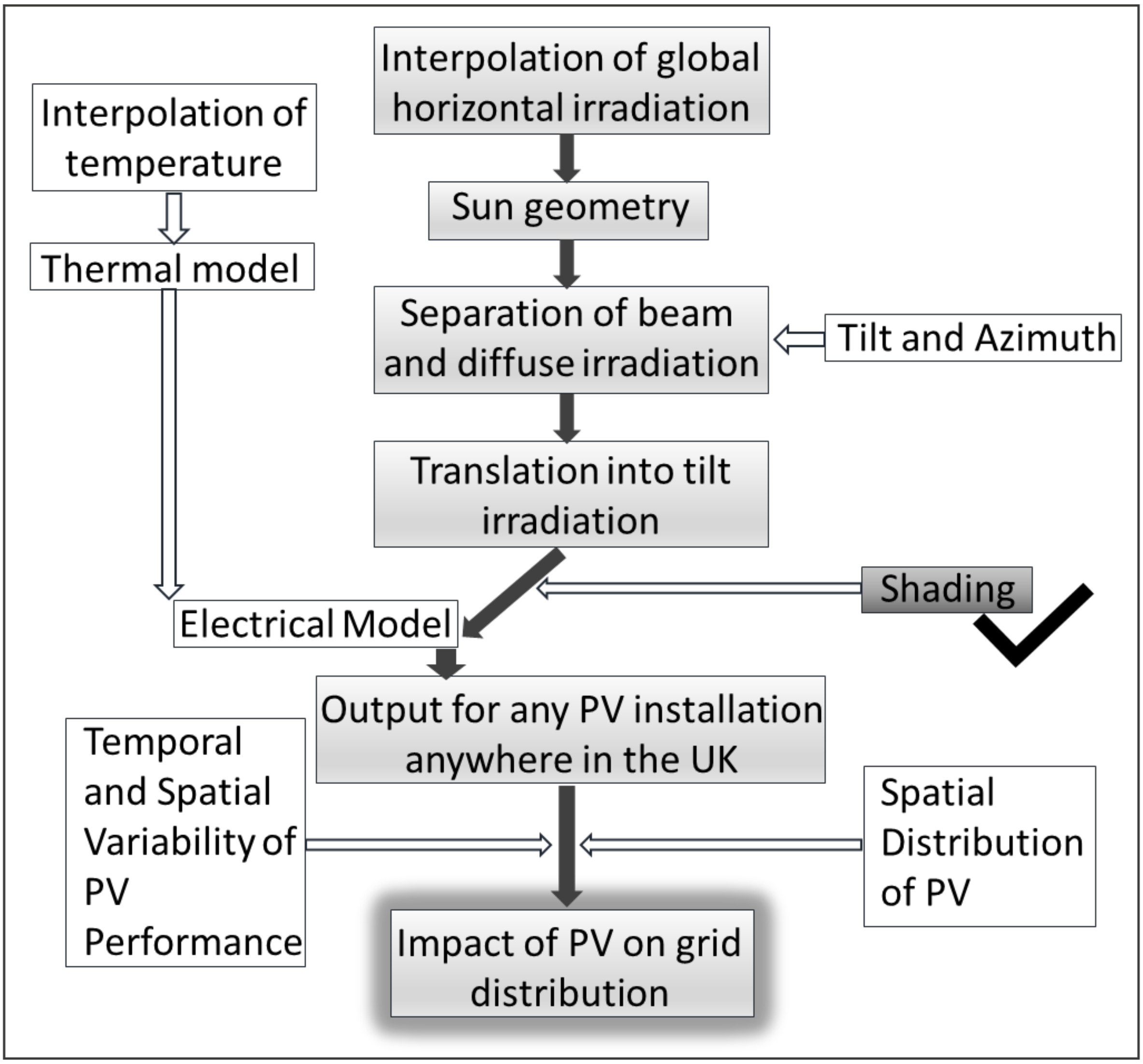
Findings

The highest random error is seen on days of low irradiation and partly cloudy days. Lower irradiation values give a higher percentage RMSE but this does not greatly influence absolute energy yield.

Conclusions/Interpretation of results

The results depend strongly on the climatic profile of the location.

ShadeP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ShadeP

Diane Palmer, Ian R Cole, Brian Goss, Thomas R Betts, Ralph Gottschalg, 2015, Detection of roof shading for PV based on LiDAR data using a multi-modal approach, in 31st European Photovoltaic Solar Energy Conference and Exhibition, 2015, p. 1753 – 1759, https://www.eupvsec-proceedings.com/proceedings?paper=32667, https://hdl.handle.net/2134/20083.

Author Contribution: Lead Author

Diane Palmer planned and designed the research; obtained and prepared the data; categorised methods; utilised the GIS tools; analysed results. Ian Cole and Brian Goss implemented the skydome/ray-tracing model. Diane Palmer wrote and presented the published work, supervised by Thomas Betts and Ralph Gottschalg.

Step(s) in PV Impact Sequence: Shading

Originality

The novelty of ShadeP is that it utilises approaches more commonly employed on terrain (i.e. hill-shading) for rooftop modelling. A model is sought which includes near, far and self-shading of roofs.

Purpose

To investigate possible reduction in output due to shading of the system.

Design

Evaluates models which detect potential losses due to shading.

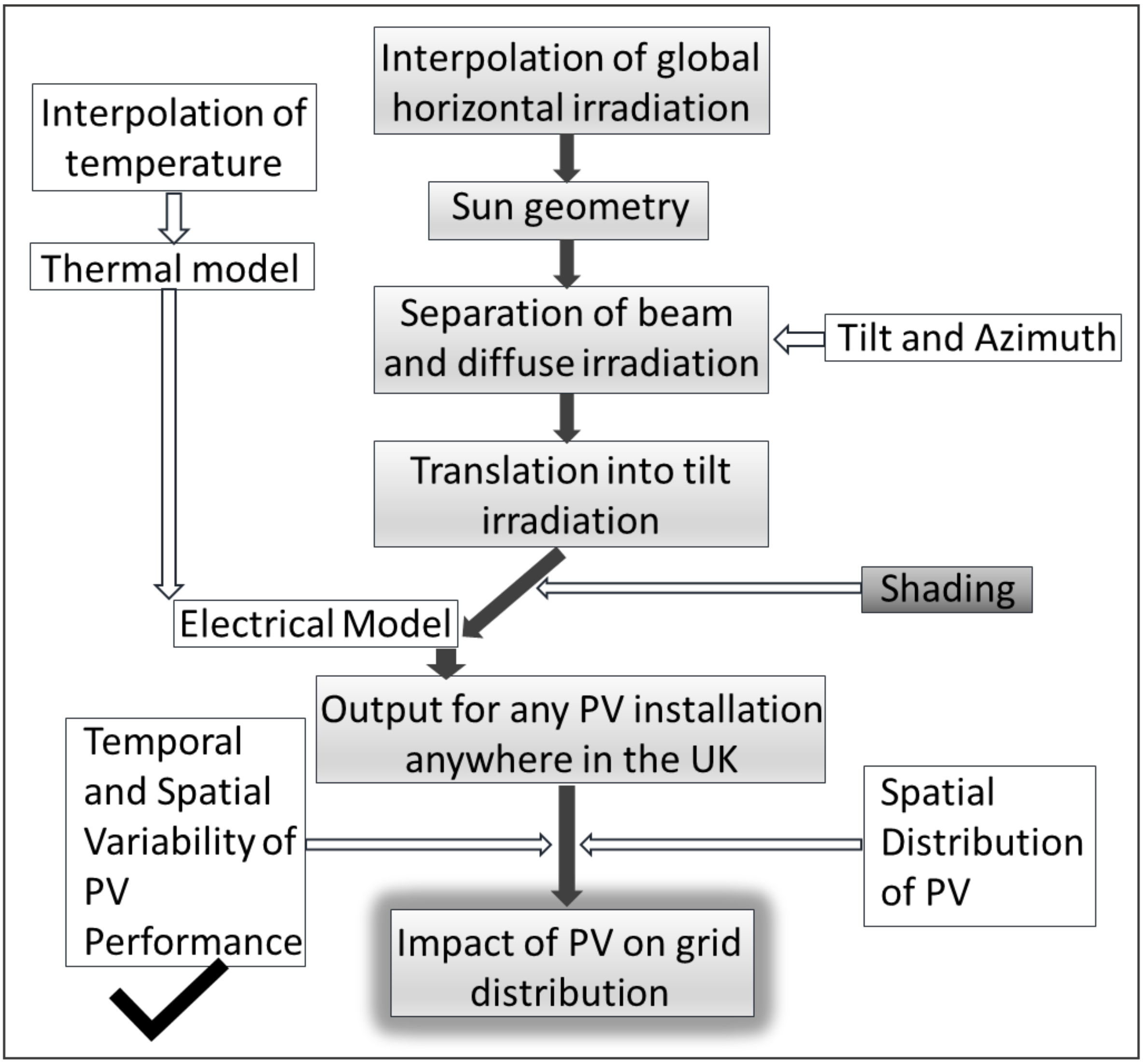
Findings

A shadow simulation model is useful where data is limited. Ambient occlusion produces lifelike results, but ray-tracing has the greatest accuracy.

Conclusions/Interpretation of results

Choice of shading model depends on: user ability, data availability and access to computer resources.

VariabilityP



VariabilityP

D. Palmer, E. Koubli, I. Cole, T. Betts and R. Gottschalg, 2016, Comparison of Solar Radiation and PV Generation Variability: System Dispersion in the UK, IET Renew. Power Gener., Volume 11, Issue 5, 12 April 2017, p. 550 – 557, DOI: 10.1049/iet-rpg.2016.0768 , Print ISSN 1752-1416, Online ISSN 1752-1424, URL: http://ietdl.org/t/iJLSVb, https://hdl.handle.net/2134/24168.

Author Contribution: Lead Author

Diane Palmer and Elena Koubli originated the research. Elena Koubli produced the output data from GHI provided by Diane Palmer. Diane Palmer carried out the cluster and trend analysis. Ian Cole analysed wind direction. Diane Palmer wrote the paper, supervised by Thomas Betts and Ralph Gottschalg. Elena Koubli reviewed the paper.

Step(s) in PV Impact Sequence: Temporal and Spatial Variability of PV Performance

Originality

Investigates the yield of UK solar farms in aggregate.

Contribution to Knowledge

VariabilityP offers an alternative method of investigating the variability associated with photovoltaic power. The influence of the various sizes of solar farms and their geographical dispersal is examined, alongside landscape features and weather patterns.

Purpose

To study geographic divergence of generation.

Design

Examines the collective effect of PV systems on the distribution system, temporally and spatially, in terms of variability reduction. Size, number and spatial relationships of solar farms are investigated, together with the effects of regional weather and topography.

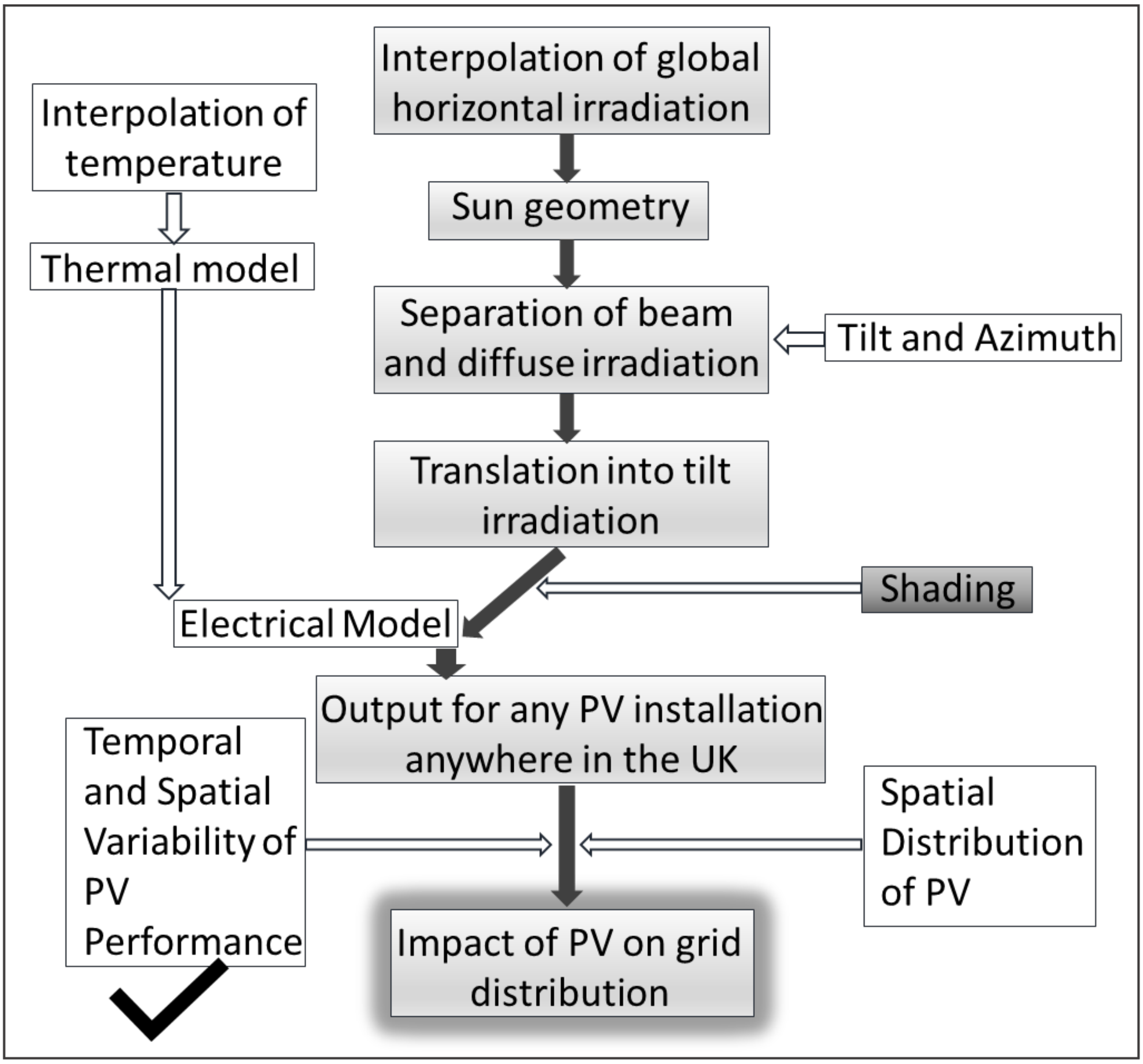
Findings

Spatial dispersion of solar systems reduces the variability of energy generation. Reduction in variability of output from solar farms results from a complex relationship between pattern of site clustering, proximity to coast, terrain and weather fronts.

Conclusions/Interpretation of results

The current distribution of solar farms in the UK has a smoothing effect on collective variability in output. This mitigates fluctuations in PV output.

FarmFleetP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✓

FarmFleetP

Diane Palmer, Elena Koubli, Tom Betts and Ralph Gottschalg, 2017, The UK Solar Farm Fleet: A Challenge for the National Grid?, Energies 2017, 10(8), 1220; doi:10.3390/en10081220, URL: http://www.mdpi.com/1996-1073/10/8/1220, https://hdl.handle.net/2134/26255.

Author Contribution: Lead Author

The overall concept of the paper was the idea of Diane Palmer and Ralph Gottschalg. Elena Koubli produced the solar farms' output data from GHI provided by Diane Palmer. Diane Palmer surmounted research problems and analysed the research data at various levels of spatial aggregation, as well as for case studies. Diane Palmer wrote the paper, supervised by Thomas Betts and Ralph Gottschalg. Ralph Gottschalg reviewed the paper.

Step(s) in PV Impact Sequence: Temporal and Spatial Variability of PV Performance

Originality

FarmFleetP points out the difficulty in planning for voltage control whilst array-to-inverter ratios remain unknown. The effects of inverter clipping due to oversizing are discussed.

Contribution to Knowledge

There is no other nationwide analysis of spatial and temporal variation of solar farm yield throughout the UK. Little work has been presented on temporally and spatially resolved generation and its link to existing infrastructure.

Purpose

To investigate how periodic and geographic aggregation of PV generation smooth combined photovoltaic output.

Design

Generation from large-scale solar systems is investigated throughout the UK, year-by-year and in different regions.

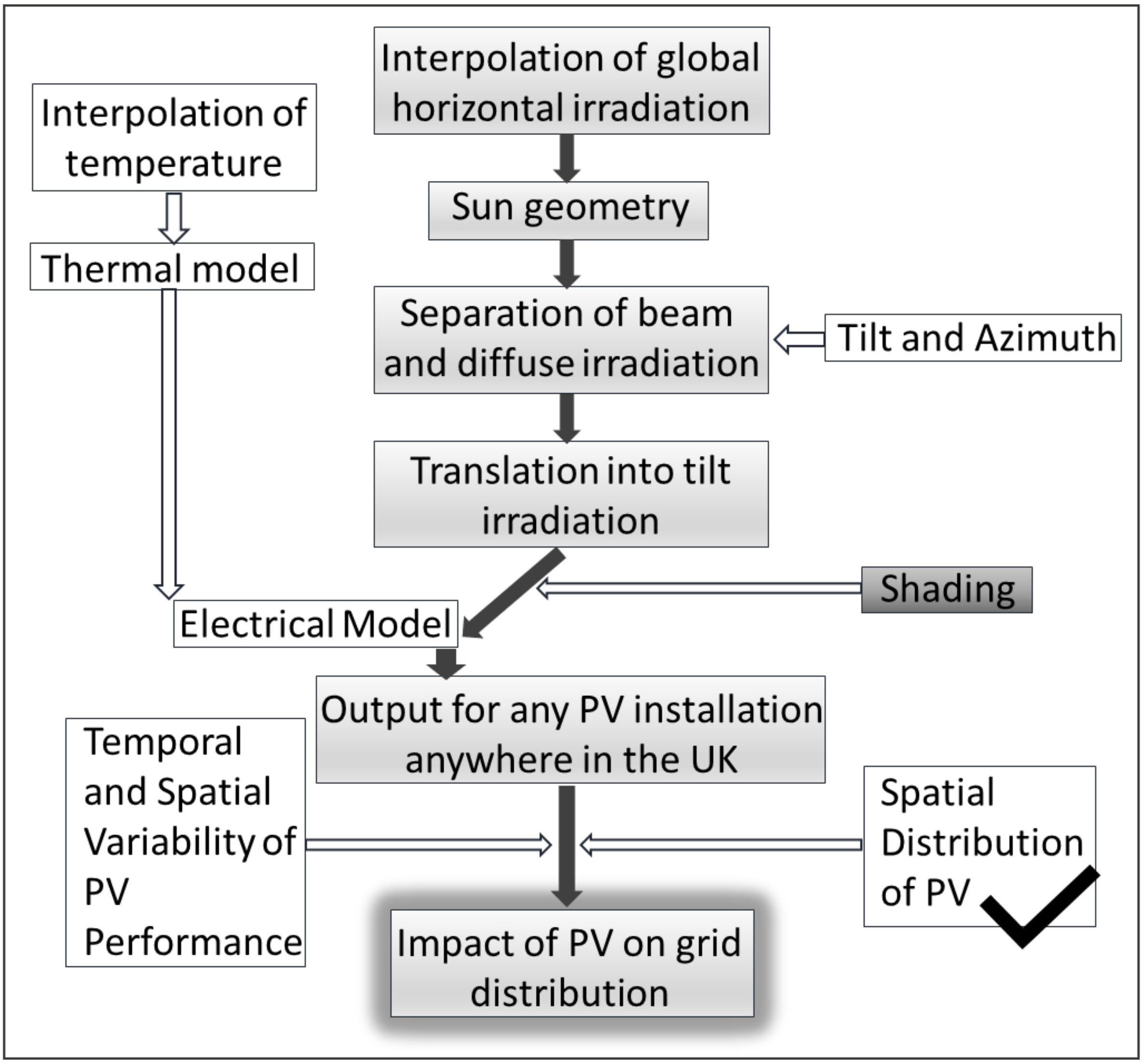
Findings

Output and demand are not well matched, as regards location. However, maximum yield occurs at predictable times. The existing grid infrastructure is shown to have sufficient capacity to handle electricity flow from large scale PV. Full nameplate capacity is never reached by the examples studied.

Conclusions/Interpretation of results

Utility-scale solar installations are unlikely to cause fragility of the electricity system in the UK at the current time.

FarmSiteP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Spatial Distribution of PV ✓
Impact of PV on grid distribution

FarmSiteP

Palmer, Diane; Betts, Thomas; Gottschalg, Ralph, 2018, The future scope of large-scale solar in the UK: site suitability and target analysis, Renewable Energy, URL: https://doi.org/10.1016/j.renene.2018.08.109, https://hdl.handle.net/2134/34804

Author Contribution: Lead Author

Diane Palmer came up with the overall research goals and aims. She resourced the data, designed the experiments and evaluated the results. Diane Palmer wrote the paper, supervised by Thomas Betts and Ralph Gottschalg.

Step(s) in PV Impact Sequence: Spatial Distribution of PV.

Originality

The case study is the UK which is a relatively high latitude region with a limited solar resource. Almost all previous studies have concentrated on countries with high average annual solar irradiation.

Contribution to Knowledge

FarmSiteP is innovative in that it investigates transformer loading constraints. Previous authors have focussed on distance to high voltage grid only as a limiting factor in large-scale solar installation. The impact of government policy on site selection is also examined.

Purpose

To explore the future geographic distribution of utility-scale PV in the UK to determine whether the presently observed smoothing effect of amalgamation of output will change in future installation scenarios.

Design

This paper demonstrates the scientific selection of the most suitable sites for large-scale solar installations in the UK, using Geographical Information Systems (GIS) analysis.

Findings

The greatest impediment to utility-scale solar expansion in the UK is the solar energy resource. Also, any suitability map which does not heed planning permission and transformer capacity will overstate potential solar farm area by up to 97%.

Conclusions/Interpretation of results

This research finds sufficient suitable land to meet Future Energy Scenarios (UK National Grid outlines for the coming energy landscape). The current pattern of UK solar farm siting is unlikely to change significantly, since all new potential sites were discovered in the south and southeast.