

INTER-CONTINENTAL OPTIMISATION OF PHOTOVOLTAIC TECHNOLOGIES IN LARGE ARRAYS

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ABSTRACT: Photovoltaic systems are typically optimised for performance or cost. In order to evaluate the wider parameter space an extensive measurement campaign has been designed that will provide guidance on future system designs. Four near-identical, grid-connected 200kW_p PV systems are being installed onto IKEA home furnishings stores in four countries with different climatic classifications. The systems are integrated with comprehensive weather and power monitoring systems. This paper introduces the project and presents initial results.

Keywords: System Performance; Design; Energy Performance

1. INTRODUCTION

Many large industrial energy users still see on site renewables as part of their long term sustainability and energy efficiency strategies despite the current economic downturn and lower primary energy costs. However, large urban energy users are restricted in the choice of renewable energy sources they can use on site. Solar photovoltaic (PV) electricity generation is uniquely flexible for building added or integrated power generation due to a wide range of rooftop, façade and ground mounting options for PV arrays. Energy from solar PV has the advantages of being well aligned to commercial electricity demand cycles and having low maintenance requirements.

The key commercial objective in implementing solar PV generating capacity is to achieve a short return on investment. This may be in conflict with assumptions made in the technical community that the key objective is to achieve optimum electrical performance as this may come at a disproportionate cost.

There have been a number of previous medium to large scale PV comparison projects including:

- The UK “PV-Compare” Project [1] where several 1kW systems were compared site-by-site in Oxford and Mallorca.
- Collaboration between groups from Stuttgart, Cyprus and Egypt Universities, with arrays on the 3 sites [2, 3],
- IFSH (Emmerthal) compilation of performance data from 334 grid-connected PV installations (part of IEA PVPS Task 2 project (International Energy Agency: Photovoltaic Power Systems) [4]
- The Japanese Mega-Solar project [5-7].
- The BP-Solar summary of outdoor testing [8]

However, these tend to focus on performance alone, which is not the only requirement for PV system design.

2. THE NEED FOR MULTI-PARAMETER OPTIMISATION

Previous solar PV comparison projects have focused on output as a specific yield (kWh/kW_p) or performance ratio (PR). Comparison of kWh/kW_p is of limited value to consultants and designers without also showing the

relative costs. For example, the more efficient modules also tend to be more expensive, thus performance does not contain all required information for the actual cost of the electricity production by each module type. Nor does it allow a comparison of payback times. Research on costs of PV systems certainly exists, but independently of research on performance.

When designing systems for commercial buildings the system requirements are complex. Optimising for maximum efficiency might require excessive areas to be left around the panels to minimise shading. However, this approach might not offer the best value for money. If for example, the one-off costs such as grid connection, and structural approval are essentially constant, then compromising slightly on shading might actually give a lower cost per kWh or shorter financial payback time.

At present there are no models publicly available which enable performance and financial effects simultaneously, so that examining financial impacts of design decisions becomes a slow iterative process. As a result, there is a tendency for system designers is to design PV arrays for maximum energy production, without detailed analysis of the precise effect on the system economics.

The IKEA Group has a goal of using 100% Renewable Energy in all its buildings, under the ‘IKEA Goes Renewable Project’. Recently this has been achieved by purchasing ‘bundled’ renewable power, but the company also wants to generate Renewable Energy on-site, using solar, wind, and biomass [9]. Photovoltaic Power is an attractive option for IKEA, due to the large surfaces available on roofs, facades, and above parking lots.

Perpetual Energy Ltd (PE) has been contracted by the IKEA Group, to develop new processes for the design and implementation of commercial solar photovoltaic systems. The Centre for Renewable Energy Systems Technology (CREST) at Loughborough University is the research partner in the project.

This project is unique in taking a systems approach to solar photovoltaics. This will mean modelling, monitoring and analysing the system as a whole, and incorporating any interdependencies which may be overlooked by looking at individual parameters in a reductionist way.



Figure 1: Photograph showing micromorph PV modules on the Gent store.

3. TECHNOLOGIES

The PV modules of seven different manufacturers are being installed, including:

- poly-crystalline silicon (pSi),
- mono-crystalline (mSi),
- micromorph silicon (μ aSi),
- triple junction amorphous silicon (aSi),
- CIS (Copper Indium Diselenide).

The technologies are all configured as grid connected systems using identical inverters. Likewise the mounting system, array inclination and shading specifications are standardised across the technologies.

The systems are being installed on IKEA home furnishings stores at Latitudes from 37° to 54° north.

The sites and Köppen climate zones [10] are:

- Humid continental, bordering subtropical (Brooklyn, North –East USA).
- Oceanic (Gent, Belgium).
- Humid continental (Rostock, North-East Germany).
- Mediterranean (Seville, Southern Spain).

The systems will benefit from local feed-in tariffs or other incentives; hence a comparison of 4 different regulatory frameworks and solar incentives schemes will be possible. In particular, the project will compare financial performance between use of building integrated flexible amorphous panels, and the more traditional glass-based modules on elevated frames.

4. MONITORING SYSTEM

CREST and Perpetual Energy Ltd have developed a new monitoring system to achieve the data accuracy and resolution needed for verifiable research, which cannot be achieved with off the shelf systems.

Data currently being collected includes:

1. DC electrical parameters, where the voltage and current of each string is measured as well as the module temperature
2. AC electrical parameters, where the current and voltage of each inverter and the system as a whole are measured

3. Environmental variables, where in plane and horizontal irradiance, solar spectrum, ambient temperature and humidity, high-level and array level wind speed and direction and the current of reference modules of each module

Data is collected in one second intervals from each sensor on each of the four sites and is fed back to CREST in Loughborough using secure daily downloads.

CREST is developing new database algorithms to process the vast amount of raw data and generate regular performance reports.



Figure 2: Sensors measuring horizontal and plane-of-array irradiance and spectral distribution.

The DC power monitoring unit incorporates surge protection and fuses or diodes as appropriate, short term data buffering is also provided. The monitoring unit can monitor up to 16 strings and 2 inverters.

Power Monitoring Units (Figure 3 below) are also installed between the inverters and the AC Distribution Board, these monitor the AC Voltage and current from each inverter. Hence efficiency of the inverter can be analysed with respect to for example module power point or ambient temperature.



Figure 3: CREST / PE Power Monitoring Unit.

In addition to the high accuracy CREST/ PE monitoring system, the inverter manufacturer's off-the- shelf monitoring system is also used for instant access condition monitoring and fault diagnosis. In addition, a detailed real-time display of key parameters is provided at the store front for viewing by store visitors and customers.

This ensures that the energy production by all the modules can be accurately measured, and used to validate current models for energy production, for the key technologies.

5. RESULTS

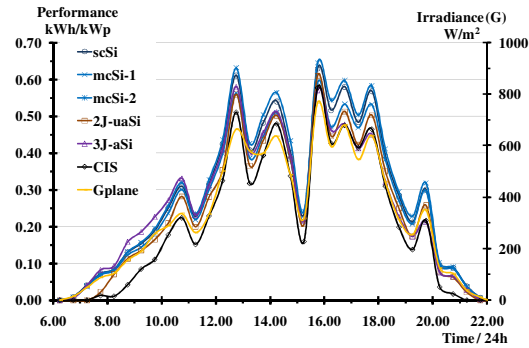


Figure 4: Performance (kWh/ kW_p) and plane of array irradiance for the 5 technologies at Gent for 19-07-2009 (a day with occasional cloud).

Figure 4 above shows the performance of the 5 technologies on typical day at Gent with patchy cloud, Irradiance measured in the plane of the array G_{PLANE} is shown for comparison

The triple junction amorphous plot shows improved performance earlier in the day which is due to the higher diffuse component of the light, as these devices typically benefit from such behaviour. The CIS (Copper Indium Diselenide) and micromorph silicon (μaSi), both show a delayed start of daily operation, this is due to these technologies having a lower string voltage, so that higher irradiance is required to achieve the minimum operating voltage of the inverter

A key limitation of comparing PV technologies as kWh/ kW_p, is that the rated P_{MPP} (W_p) of a module is specified at the time the PV module datasheet is published. Module manufacturers usually have to manufacture modules to this specification using available materials; this will often be batches of cells sourced from a cell manufacturer. As a result, there can be variations between the datasheet W_p and the actual W_p at STC of the modules as recorded when the modules are flash tested at the end of the production line. Further complexity is added by the different rates of outdoor degradation exhibited by different technologies.

There are a number of ways to exclude these deviations between datasheet and actual W_p at STC.

- i. Check factory flash test data for shipment against datasheet values.
- ii. Flash test a sample of modules in a lab
- iii. Carry out daylight IV test on array strings
- iv. Plot against area instead of W_p
- v. Plot against cost instead of W_p

i) *Variations between datasheet power and flash test power.*

Most manufacturers if asked, will provide flash test data for large shipments of modules, for smaller shipments purchased via distributors, this may be less straightforward.

When looking at performance at this level of detail it was necessary to note the difference between the actual module Power at STC (P_{MPP}), calculated as the sum of the I_{MPP} and V_{MPP} . This Power is usually rounded up or down to a tidy multiple of 5, as embedded in the model name.

	Gent	Rostock	Seville	Average
mSi	-0.31%	1.43%	-0.42%	0.23%
pSi -1	0.10%	0.73%	-0.15%	0.23%
pSi-2	1.21%	0.65%	-0.25%	0.54%
2J μaSi	1.85%	1.69%	1.30%	1.62%
CIS	1.30%	1.20%	TBC	1.25%
Overall average % deviation				0.74%

Figure 5: Deviation between flash test P_{MPP} and P_{MPP} embedded in model number

	Gent	Rostock	Seville	Average
mSi	-0.27%	1.39%	-0.38%	0.25%
pSi -1	0.06%	0.70%	-0.18%	0.19%
pSi-2	0.07%	-0.48%	-1.38%	-0.60%
2J μaSi	1.82%	1.66%	1.27%	1.59%
CIS	-0.38%	1.47%	TBC	0.54%
Overall average % deviation				0.38%

Figure 6: Deviation between flash test P_{MPP} and P_{MPP} calculated from datasheet: $V_{\text{MPP}} \times I_{\text{MPP}}$

From the above tables, one might assume that the batches of modules with greatest difference from the datasheet power are the batches with greatest variation within the batch, but that would be an incorrect assumption. For example the mono-crystalline batches had lowest % deviation from datasheet power, but the 2nd highest standard deviation of P_{MPP} within the batch.

	Gent	Rostock	Seville	Average
mSi	1.37	2.37	1.85	1.86
pSi -1	1.15	1.09	2.07	1.44
pSi-2	3.60	3.14	2.81	3.18
2J μaSi	1.03	1.51	1.41	1.32
CIS	1.42	1.22	TBC	1.32
Average standard deviation				0.38%

Figure 7: Deviation between flash test P_{MPP} and P_{MPP} from embedded in model name

iv) Plotting against module area against P_{MPP}

Option iv is shown in the graph below

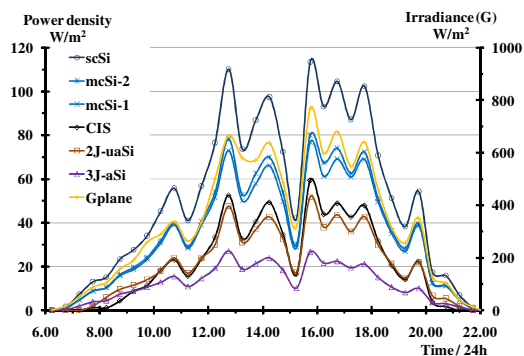


Figure 8: Power density at IKEA Gent (W/m^2) for the 5 technologies at Gent, for 19-07-2009.

Figure 8 above shows the power output per square metre for the same period as the previous Figure 4.

A possible source of error in the comparison is the difference between the power at STC quoted in datasheets and the manufactured power of the modules as provided in flash test data on delivery.

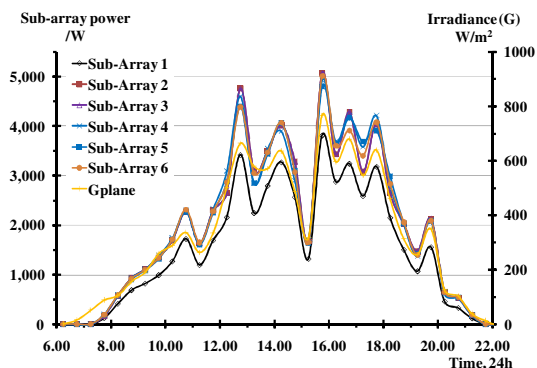


Figure 9: Power output plotted against time for 6 sub-arrays of micromorph silicon, for 19-07-2009.

5.1 Use of monitored data for detailed analysis of system anomalies.

The ability to Plot system performance at sub-array level provides a very useful diagnostic tool to analyse system performance issues.

Figure 9 above shows 6 sub arrays of the same technology in adjacent rows on the same roof.

Differences in power output between adjacent arrays may be attributed to the following issues:

Shading obstacles affecting adjacent strings, in particular this can be observed as a short time lag between output peaks as clouds pass across the panels,

Variations between plots with a longer time lag can occur as sun's trajectory is obstructed by rooftop obstructions

such as air handling units, parapets, stairwells, etc. For example the orange plot in **Error! Reference source not found.** above shows a temporarily poorer performance between 12:00 and 14:00 possibly because it is obstructed during this period. Similar but more subtle effects may be caused by slight variations in array pitch, where the array pitches follow pitches in the roof installed for rainwater drainage. This variation in array pitch is common with the more lightweight mounting systems used on commercial 'flat' roofs.

The micromorph array was more prone to variations due to shading than the other arrays for 2 reasons:

- The lower efficiency means more panel area is required for a given power output
- This particular thin film module has cells arranged in strips, this requires the panels to be orientated 'Landscape' rather than 'Portrait' so that the inevitable strip of dirt buildup along the lower aluminium frame of the module does not cause power mismatch between cells. (The matrix of 8 sided polygons in wafer based PV modules permits both portrait and landscape orientation).

Where one sub-array consistently performs worse than another, this is usually due to electrical variations. In minor cases this may be due to variations in manufacturing variations between modules, especially if the modules have been sorted into arrays of similar manufactured power. However due to the time required sort large quantities of modules according to manufacturers flash test data, it is more usual for modules to be randomly installed in strings.

Where an array consistently underperforms by more than few percent this is likely to be due to an electrical fault. For example the lower black plot in Graph 1 above has one string disconnected for maintenance, but the same disparity elsewhere could be attributed to a faulty string.

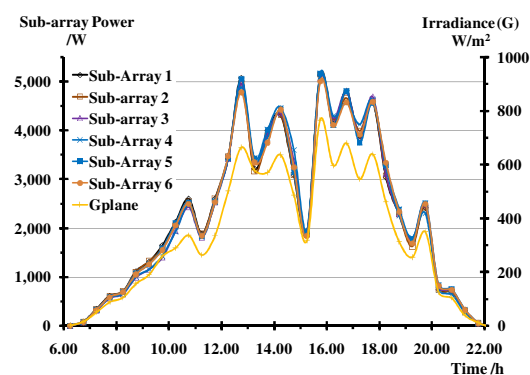


Figure 10: Power output plotted against time for 6 sub-arrays of mono-crystalline silicon, for 19-07-2009.

By contrast, Figure 9 above shows 6 sub-arrays of mono-crystalline silicon, the plots are more contiguous due to smaller manufacturing tolerances and greater packing density of panels on the roof.

6. CONCLUSIONS

A system for developing a detailed multi-parameter analysis has been developed. An extensive measurement campaign has been set up and installation is ongoing.

The PV systems at Rostock & Gent have now been generating electricity for use on site for 6 months, with all generated electricity exported to the local electricity network.

Initial results from the programme were presented and discussed. The visual analysis of the results provides an illustration of the possibilities of this project for analysis of the complex interactions in a large scale real world system. Full database operation for all 4 sites is expected to be completed within 6 months. Data will be recorded every 1 second for 24 months.

As the data is analysed in greater detail, from all sites and over a 12 month period, further papers will be published with the findings of the study.

7. ACKNOWLEDGEMENTS

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8. APPENDIX: DEFINITIONS

Parameter	Description	Units
AM	Air Mass in the earths atmosphere, through which sunlight passes.	(ratio)
G_H	Global Irradiance in the horizontal plane	W/m^2
G_P	Irradiance in the plane of the PV array	W/m^2
I_{MPP}	Module Current at the maximum power point and at STC	A
P_{MPP}	Maximum power at standard test conditions (STC) which are $G_H=1000 W/m^2$, $T_M=25^\circ C$ and $AM=1.5$	W_P
T_M	Module temperature	$^\circ C$
V_{MPP}	Module Voltage at the maximum power point and at STC	V

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