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Influences on the energy delivery of thin film photovoltaic modules ☆

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ABSTRACT

The energy yield delivered by different types of photovoltaic device is a key consideration in the selection of appropriate technologies for cheap photovoltaic electricity. The different technologies currently on the market, each have certain strengths and weaknesses when it comes to operating in different environments. There is a plethora of comparative tests on-going with sometimes contradictory results. This paper investigates device behaviour of contrasting thin film technologies, specifically a-Si and CIGS derivatives, and places this analysis into context with results reported by others. Specific consideration is given to the accuracy of module inter-comparisons, as most outdoor monitoring at this scale is conducted to compare devices against one another. It is shown that there are five main contributors to differences in energy delivery and the magnitude of these depends on the environments in which the devices are operated. The paper shows that two effects, typically not considered in inter-comparisons, dominate the reported energy delivery. Environmental influences such as light intensity, spectrum and operating temperature introduce performance variations typically in the range of 2–7% in the course of a year. However, most comparative tests are carried out only for short periods of time, in the order of months. Here, the power rating is a key factor and adds uncertainty for new technologies such as thin films often in the range of 10–15%. This dominates inter-comparisons looking at as-new, first-year energy yields, yet considering the life-time energy yield it is found that ageing causes up to 25% variation between different devices. The durability of devices and performance-maintenance is thus the most significant factor affecting energy delivery, a major determinant of electricity cost. The discussion is based on long-term measurements carried out in Loughborough, UK by the Centre for Renewable Energy Systems Technology (CREST) at Loughborough University.

1. Introduction

The most critical factor determining the suitability of deploying photovoltaics is the cost of energy, or service, delivered and not the power rating of the devices. Energy is a commodity and thus the aim is to generate electrical energy, or services, as cheaply as possible. There are two major contributors to the final cost of electricity produced by a system: its specific energy yield and the costs of purchase, operation and maintenance. This paper concentrates on the first, the specific energy yield. The focus is on thin film technologies, namely different modules produced from amorphous silicon (a-Si) and Copper Indium Gallium Diselenide (CIGS), in particular on the energy yields of these devices which are susceptible to variations in the operating environment, have a wider design window and less availability of field experience data than conventional wafer-based crystalline silicon (c-Si) devices. There are a large number of performance studies reported, some with the aim of understanding the behaviour of a single type of device and some to compare the energy yields of different devices. This paper focuses on behaviour at module level, which may be built up to include system effects such as mismatch, interconnection and power conversion components.

PV modules are normally labelled with a power rating, which means the power measured at standard test conditions, STC, as defined in [1]. This is called peak-power, denoted as Wp. STC represent rather favourable operating conditions for most PV technologies as it is an unrealistic combination of a cold module temperature (25 °C) at a high irradiance (1000 W/m^2). Different modules, even of the same technology, generally have different rated powers and the energy yields must be made comparable in any inter-comparison study. This is achieved by using the specific yield (kWh/kWp). The specific yield is a key property of PV modules at a particular location and can be a major sales argument for competing PV module suppliers.

Many manufacturers use energy yield measurements to show the quality of their modules against those of competitors, see e.g. [2]. Some organisations, e.g. Photon, provide purportedly independent advice via the comparison of modules. There are also many

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independent investigations carried out by research institutes, e.g. [3–10], which also provide data sources to compare the energy yield of different technologies. The discussion is then often focussed on the determination of the 'best' technology and generalised claims on technologies are made as e.g. in [11]. The aim in the following is to show technology-specific differences, but does not claim to identify the 'best' technology or superior devices, since this tends to be specific to each installation. It is also shown that the differences between different devices within any thin-film technology group are so significant that it is virtually impossible to make a decision of which technology to use in a system purely on the basis of material.

The following demonstrates the differences in long term performance of different PV technologies, where 7 modules have been operated for more than 5 years in the current measurement system, with some having been operated for several years previously on another measurement system. The analysis is of the key influences on energy delivery of these specific devices and is not meant as a generalisation for any of the technologies in the test. In the case of amorphous silicon devices, the device structure, number of junctions, material of the junctions as well as manufacturing can impact on the energy yield significantly [12,13]. Similar differences are seen in the case of polycrystalline thin film devices [14]. These issues can be due to different manufacturing techniques or different device structures, where in the case of CdTe, for example, different window layers can result in significantly different quantum efficiencies [15]. The number of design parameters of thin film devices is larger and the production processes are less standardised than for c-Si, resulting in wide variation in the specific energy yield of modules of the same material technology.

One of the aims of this paper is to demonstrate the difference between optimisation for high module power and high specific yield. Optimisation for energy yield may not coincide with optimisation for STC rated power. As an example, the performance of a crystalline (c-Si) module is shown in Fig. 1 for a number of locations. A c-Si example is chosen because the performance of these devices is generally more familiar. The data used here is a matrix measurement as specified in [16] and the energy yield is calculated utilising an implementation of the proposed energy rating standard [17]. The effects of doubling the series resistance or halving the temperature coefficient are shown. The modifications are applied to the power measurement matrix and the annual energy yield for a number of locations is calculated by drawing on local meteorological data sets, as indicated on the map in Fig. 1. The overlay boxes indicate the specific yields and performance ratios for the different modules (described in the box in the centre of the graph entitled 'key').

The effects of the modifications in series resistance and temperature coefficients on the specific energy yield depend on the particular location environments and the device responses relative to STC. A practical example of such a modification is the number of front contact bus bars on wafer based technologies, e.g. changing from a two-bus bar design to a three-bus bar design for larger cells. The sub-optimal design, i.e. the one with two bus bars which causes a higher series resistance and thus high ohmic losses, typically has a lower power at STC but may have a higher specific energy yield than those with three bus bars due to relatively higher efficiency at lower irradiances. This is illustrated in Fig. 1 where the high resistance case delivers more energy for all sites but those with the highest annual irradiation. Thus the 'worse' device delivers a higher specific energy in the majority of locations. Similarly, an elevated temperature coefficient will have different effects in different locations, with relatively modest effects in cool to temperate climates. It can be seen that in certain environments the ranking in terms of performance ratio or specific energy yield changes for the different series resistances assumed or temperature coefficients.

The analogous situation to the variation in series resistance for thin films would be for e.g. the width of a cell (see e.g. [18]) or the change in the thickness of the transparent conducting oxide or any other factor that affects the series resistance in the cell. The cell geometry is crucial for thin film devices as it can change the series resistance and fill factor significantly [19]. The thickness (depth) of the device affects optical absorption but also degradation. Different window layers modify the spectral response and some devices undergo a shunt busting treatment, where all shunt paths are burnt out. Similarly, the temperature coefficient of more tuneable technology families such as CIGS can be influenced by the composition ratio of indium and gallium, i.e. a change of band gap, or simply material quality. This demonstrates the earlier point that devices of nominally the same material can have very

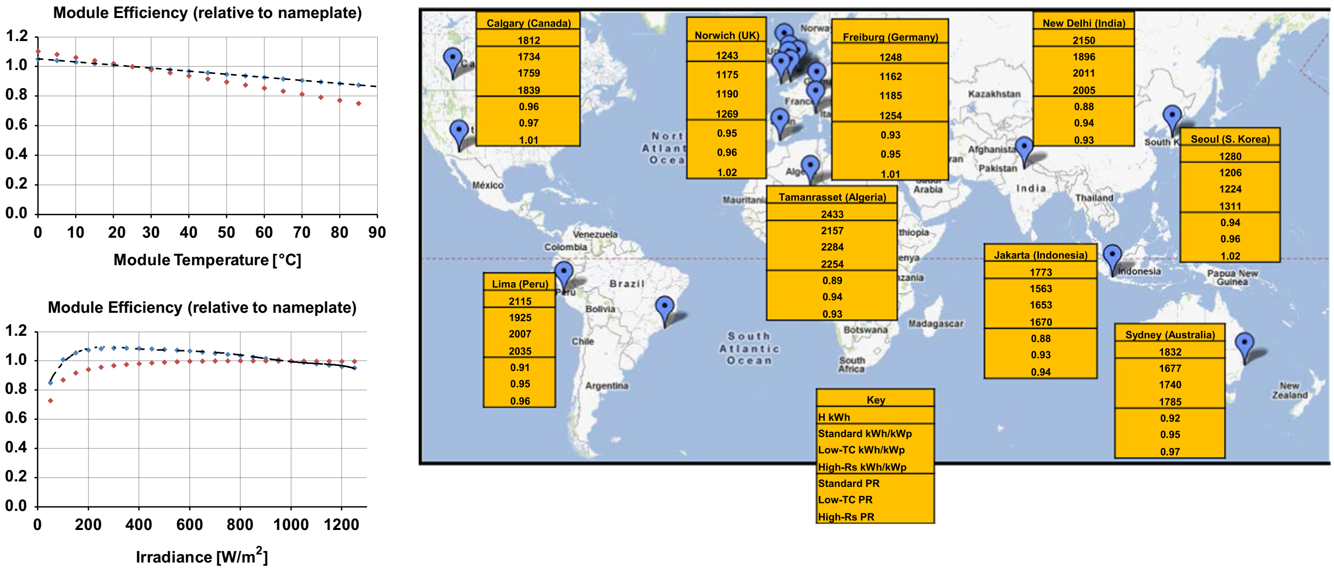

Fig. 1. Illustration of effects of temperature coefficient and high series resistance on power measurements and energy yield of devices. The underlying map was created in Google Maps. The upper figure on the left depicts the two different temperature coefficients used for the simulation, the lower picture depicts the underlying irradiance dependence as modified by the series resistance.