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PERFORMANCE OF AMORPHOUS SILICON DOUBLE JUNCTION PHOTOVOLTAIC SYSTEMS IN DIFFERENT CLIMATIC ZONES

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ABSTRACT

To date the majority of investigations into the performance of amorphous silicon photovoltaic systems have been limited to single sites, and therefore the conclusions from such studies are unlikely to be as generic as they might at first appear. This paper compares data collected from different systems across the world in Brazil, Hong Kong, Spain, Switzerland, and the United Kingdom. All systems have been operating for a number of years, and are employing double junction amorphous silicon devices of a similar age manufactured by RWE Solar.

The data are analysed for performance variations reflecting the different climatic zones, and the variations are explained on the basis of operating temperature, incident irradiation and seasonal spectral shift.

INTRODUCTION

Recent times have seen the increased introduction of thin film amorphous silicon (a-Si) photovoltaic systems. The seasonal performance of these devices is markedly different from devices employing the more common crystalline silicon technology. The maximum efficiency occurs during summer, rather than winter, see e.g. [1]. This effect can, in some climates, be attributed almost entirely to variation in the incident solar spectrum [2,3]. Other researchers have, we believe wrongly, attributed this effect exclusively to a seasonal recovery pattern [4]. This improved summer performance is clearly of interest when investigating the energy yield of these devices and judging their quality. Previous investigations have often been hampered in that they were based on measurements at only one location. In this work, a number of systems from a single manufacturer (RWE Solar, Division Phototronics) are compared. A wide variety of climatic conditions are covered in this study by analysing data from sites as widely located as Brazil, Hong Kong, Spain, Switzerland, and the United Kingdom.

SYSTEMS UNDER INVESTIGATION

The five systems under investigation are summarised in Table 1. Some of these are in fact sub-systems of a larger installation. Sub-arrays with non-optimal roof pitches, and those producing unreliable data have been neglected.

It can be seen that a wide variety of operational con-

<table>
<thead>
<tr>
<th>System</th>
<th>Location</th>
<th>Country</th>
<th>Environment</th>
<th>Longitude</th>
<th>Latitude</th>
<th>Start of Operation</th>
<th>Installed Capacity</th>
<th>Orientation</th>
<th>Inclination</th>
<th>Inverter</th>
<th>Modules</th>
<th>Installation</th>
<th>Sampling Interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Florianopolis</td>
<td>Brazil</td>
<td>sub-tropical, south American</td>
<td>-48W</td>
<td>27S</td>
<td>16 Sep 1997</td>
<td>512</td>
<td>174</td>
<td>27</td>
<td>WE 500 NVR</td>
<td>PM6008A38N</td>
<td>Shading</td>
<td>4 min</td>
</tr>
<tr>
<td>2</td>
<td>Hong Kong</td>
<td>China</td>
<td>sub-tropical, East Asia</td>
<td>113E</td>
<td>22N</td>
<td>01 Oct 2000</td>
<td>2400</td>
<td>-85</td>
<td>90</td>
<td>Solwave 3090</td>
<td>PM6009A38N</td>
<td>Façade</td>
<td>10 sec</td>
</tr>
<tr>
<td>3</td>
<td>Mallorca</td>
<td>Spain</td>
<td>Mediterranean, south European</td>
<td>3E</td>
<td>39N</td>
<td>01 Oct 1999</td>
<td>578</td>
<td>-15</td>
<td>25</td>
<td>NKF OKE4</td>
<td>300G-UT</td>
<td>Roof-top</td>
<td>30 min</td>
</tr>
<tr>
<td>4</td>
<td>Neuchâtel</td>
<td>Switzerland</td>
<td>alpine, central European</td>
<td>7E</td>
<td>47N</td>
<td>10 Oct 1996</td>
<td>6440</td>
<td>25</td>
<td>33</td>
<td>TOPCLASS 2500/4</td>
<td>PM6008A58B</td>
<td>Roof-top</td>
<td>10 min</td>
</tr>
<tr>
<td>5</td>
<td>Oxford</td>
<td>UK</td>
<td>maritime, north European</td>
<td>1W</td>
<td>52N</td>
<td>01 Jul 2000</td>
<td>576</td>
<td>-5</td>
<td>13</td>
<td>NKF OKE4</td>
<td>300G-UT</td>
<td>Roof-top</td>
<td>30 min</td>
</tr>
</tbody>
</table>

Table 1. Overview of the systems under investigation.
ditions are covered by the systems under investigation. The climatic conditions and solar path in Florianopolis and Hong Kong are comparable, though one is southern hemisphere and the other is northern. The three European systems vary climatically due to sea exposure, of a Mediterranean influence, (Mallorca) and northern maritime climate, (Oxford) or land mass and high altitude, (Neuchâtel). Their different latitudes account for distinct seasonal differences, varying day-length through the year and the different angle and altitude of the sun's path. For both Hong Kong and Florianopolis, the peak summer solar radiation is directly overhead benefiting roof applications and penalising façade installations.

All systems are building integrated, either as façades (Hong Kong), as shading devices (Florianopolis) or as rooftop systems (Neuchâtel, Mallorca, Oxford). The common factor for all devices is the use of RWE Solar double junction (pin-pin, same bandgap) devices, thus differences due to different manufacturing technology are minimised. The 32Wp RWE Solar a-Si modules for grid-connected applications are offered in either 36V or 68V models, depending on whether the individual solar cells are patterned length-wise (less cells, thus V, = 36V), or width-wise (more cells, V, = 68V). The details of each installation are reported elsewhere, see [5] for the Florianopolis system, [6] for the Hong Kong system, [7] for the Mallorca and Oxford systems and [8] for the Neuchâtel system.

The oldest system is the one at Neuchâtel, which started operating in October 1996. The Florianopolis system started operation in September 1997 and the remaining systems in 1999 and 2000. There systems use different inverters, so this analysis concentrates on DC data as much as possible. There still is, however, an issue with possible sub-optimal maximum power point tracking of the systems adversely affecting the output of the arrays.

The technology is the same at each site, the difference in performance of the systems becomes apparent by examining the amount of time spent at different irradiance levels, as shown in Fig. 1. This difference is the major influence on the energy yields of these systems.

The influence of temperature and irradiance is investigated by sorting all available data into irradiance bins of 20 Wm⁻² and temperature bins of 1°C. The duration of time spent in each bin was summed for each site. The duration of time spent in each bin was summed for each site. Data were summed over the maximum number of whole years allowed by the size of dataset (e.g. Mallorca for 2 years from 01/01/00 - 31/12/01), and data was then normalised by the number of years to give a histogram of annual irradiance. Those sites that have been operational for longer, and those with shorter sampling times, such as Florianopolis, show less statistical scatter. The average daily yield was calculated in two stages. First, daily specific yields were calculated for each day at each site. Then average daily specific yields were calculated, by averaging all the daily specific yields in a given month.

All systems exhibit a seasonal variation of the energy yield, as illustrated in Fig. 2, where the average daily yield is illustrated for all systems. The Mallorca system outperforms the other systems, as it receives the greatest annual in-plane irradiance – a consequence of both climate and its optimal orientation. Conversely, the low yield of the Neuchâtel and Hong Kong system is purely due to their sub-optimal orientations. In particular, the vertical façade of the Hong Kong system deviates significantly from its ideal inclination.

It is interesting to see that, with the exception of the Neuchâtel and Hong Kong systems, the magnitude of the
seasonal yield difference is approximately linear with the
distance of the system from the equator. The minimum of
the yield for the Florianopolis system is in June, as is ex-
pected for a system in the Southern Hemispheres.

Fig. 3. Variation of the monthly efficiency.

Obviously, the magnitude of the irradiance is crucial
when looking at the daily yield. The picture changes
slightly when looking at the behaviour of the monthly av-
erage system efficiency, as shown in Fig. 3. There is a
seasonal trend observable for all devices, again with
Florianopolis exhibiting a minimum when the other sys-
tems exhibit a maximum. The drop in efficiency for the
Oxford system in the initial months is due to some teeth-
ing problems with the data acquisition equipment. All sys-
tems exhibit a relatively stable operation after the initial
degradation (as far as the degradational period was moni-
tored). The difference in magnitude is due to different
production periods and different orientations, which shows
in the Neuchatel system, as this system is split into one
east, one west and one south facing aspect. It is, how-
ever, interesting to see that the seasonal variation of the
systems in Europe follows the trend in the useful fraction
(UF), which we define as the fraction of irradiance in the
spectrally useful range of the device with respect to the
global irradiance. This indicates that the overall seasonal
variation is nearly exclusively caused by spectral effects.

The absolute loss in efficiency due to degradation
appears to be in the range of 20% of its initial value. This
was, however, mostly accounted for in the initial system
design. One should not forget that this is the average
monthly efficiency, and not the instantaneous efficiency at
STC. Thus, e.g. in the case of the Florianopolis system
which has a name plate efficiency of five percent, the per-
formance ratio is higher than 85%, which is impressive
considering that it is a warm and humid operating envi-
ronment and the age of the system.

The difference of the operating environments be-
comes very apparent when investigating how much of
the energy is generated in certain operating conditions. The
percentage of the annual yield in a given irradiance bin is
given in Fig. 4.

A significant difference is observed between the
Hong Kong and Oxford systems and the remaining sys-
tems. The Oxford system generates a significant amount
of its energy at low intensities. This effect is a direct result
of the high percentage of low irradiance operation shown
in Fig. 1. The shape of the results of the Hong Kong sys-
tem is due to the relatively steep angles of incidence of
the irradiance and thus a significant amount of reflection
can be expected. Furthermore, as this system is hardly
operating at high intensities, the low energy part is em-
phasised. The Mallorca system produces a slightly higher
percentage of its energy at irradiances around the 500
W/m² range, while the Florianopolis system produces
more at higher irradiances. This behaviour is partially due
to a slightly different variation of the system efficiency with
irradiance, as illustrated in Fig. 5.

On the extremes, the Mallorca system shows an in-
crease in operating efficiency for low irradiance levels,
whilst the Florianopolis system exhibits a decrease. This
can be due to different operating conditions, such as inci-
dent useful irradiance. A typical example of this might be
an increased diffuse component in overcast, low irrad-
iance conditions that typically would cause the light to be
bluer. All systems show that towards higher irradiance
levels, there is not a significant influence of irradiance
level on the system efficiency. The Oxford system is
slightly scattered at high irradiance but this is a statistical
effect due to the relatively small data set. In fact, the
rather than seasonal annealing. This paper concentrates on the energy production of the systems, future work will also include effects of these different environments on the degradation of these devices.

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The work at CREST has been supported by the Engineering and Physical Sciences Research Council (EPSRC) of the United Kingdom through contract No. GR/N04232. R. Ruther wishes to acknowledge with thanks the Alexander von Humboldt Foundation for sponsoring the Florianopolis PV installation. The array at HK was constructed with funding from the Hong Kong Electric Company Limited and Florrowity Architectural Metals Asia. The PV-Compare project, studying the Oxford and Mallorcan test sites, was funded by Solar Century, the BOC Foundation and the Charterhouse Foundation. Data collection at the Mallorcan site was undertaken by Nadav Voloj-Soffer and funded by the Avina Foundation.

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Fig. 6. Influence of operating temperature on efficiency.

The systems show, however, significantly different behaviours when looking at the temperature response, as shown in Fig. 6. The thermal coefficient appears to depend on the operating temperature. This is, however, not a thermal effect. Instead, this is due to the increase in irradiance responsible for this increase in operating temperature. The Hong Kong system confirms this with the efficiency still rising despite operating temperatures of up to 70°C.

All systems, except for the sub-optimally orientated Hong Kong system, show exceptionally good performance ratios, as shown in Table 2. The lower yielding Neuchâtel system, still operating above 75%, is not ideally placed and thus may suffer from high reflection losses. Furthermore, the Neuchâtel system is the oldest system in this investigation.

<table>
<thead>
<tr>
<th>Location</th>
<th>Lat</th>
<th>Energy Yield [kWh/kWp]</th>
<th>Irradiance [kWh/m²]</th>
<th>PR [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Florianopolis</td>
<td>27°S</td>
<td>1286</td>
<td>1497</td>
<td>86</td>
</tr>
<tr>
<td>Hong Kong</td>
<td>22°N</td>
<td>441*</td>
<td>650</td>
<td>68</td>
</tr>
<tr>
<td>Mallorca</td>
<td>39°N</td>
<td>1669</td>
<td>1715</td>
<td>97</td>
</tr>
<tr>
<td>Neuchâtel</td>
<td>47°N</td>
<td>989</td>
<td>1305</td>
<td>76</td>
</tr>
<tr>
<td>Oxford</td>
<td>52°N</td>
<td>927</td>
<td>1041</td>
<td>89</td>
</tr>
</tbody>
</table>

Table 2. Comparison of energy yield and performance ratio.

CONCLUSIONS

It has been shown that amorphous silicon systems operating in different climatic conditions can exhibit very high performance ratios, despite the high temperature conditions and high levels of irradiance. The importance of effective low irradiance operation as well as good thermal stability is clearly demonstrated, as in some climates that contributes significantly to the overall energy production. It is also likely that the observed seasonal performance pattern is largely caused by variations in the incident spectrum rather than seasonal annealing. This paper concentrates on the energy production of the systems, future work will also include effects of these different environments on the degradation of these devices.

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