THE DESIGN SPECIFICATION FOR SYRACUSE;
A MULTI-JUNCTION CONCENTRATOR SYSTEM COMPUTER MODEL

N.J.Ekins-Daukes[1], Y. Kemmoku[2], K.Araki[3], T.R.Betts[4], R.Gottschalg[4], D.G.Infield[4],, M.Yamaguchi[1].
1. Toyota Technological Institute, Tempaku-ku, Nagoya, 468-8511, Japan,
2. Toyohashi Sozo College, Toyohashi, Japan
3. Daido Steel Co. Ltd., Nagoya, Japan
4. CREST, Loughborough University, Loughborough, UK

ABSTRACT: The design specifications for a computer model that simulates the performance of multi-junction concentrator systems is described. The model will predict annual system power output as well as allowing detailed analysis of individual modules, the multi-junction cells and the component junctions themselves. Recent validation tests have shown that the model is able to reproduce experimental results from outdoor testing under clear sky conditions. The model will be valuable to scientists and engineers who are designing multi-junction concentrator systems, investigating unusual concentrator system behaviour or developing new multi-junction concentrator module designs.
Keywords: Modelling, Multijunction Solar Cell, Concentrators, III-V Semiconductors, Software

1. INTRODUCTION

Highly efficient III-V multi-junction solar cells have recently been incorporated into terrestrial solar concentration systems, promising high power density and potentially reducing the cost of photovoltaic power generation[1]. Field tests are currently underway on such concentrator modules and large quantities of valuable system data have been acquired. However it is sometimes difficult to extract detailed information regarding the performance of the concentrator system simply by inspecting the data. To obtain a greater understanding of the concentrator system in the outdoor environment, a computer model is under development that will simulate the concentrator system under realistic conditions. The computer model will become a useful tool for evaluating particular concentrator system designs, identifying problems as they become apparent, as well as calculating the annual power output under particular climatic conditions.

The outdoor testing of the concentrator system takes place at two locations in Japan, Inuyama and Toyohashi University of Technology [2]. Regular measurements of the system power output, IV profile and solar irradiation are made, together with meteorological measurements such as temperature, humidity and wind speed. The concentrator system employs double axis tracking and a Fresnel lens followed by a homogenizer to give a concentration ratio of 400 suns at the photovoltaic cell surface. The triple-junction $InGaP/In_{0.01}GaAs/Ge$ solar cell attains an efficiency in excess of 36% for concentration ratios between 100 and 500 suns [3] and has been incorporated into two concentrator module designs. One module design has an average efficiency of 22% under a clear sky [4], and the other more recent 200Wp design has to date attained an average efficiency of 26.8±1.5%, also under clear sky conditions[1]. Figure 1 shows the second, 200Wp module and an example IV curve. It is clear that the fill-factor (FF) is not optimal for this module, suggesting some cells are shaded or badly current mismatched. However, to obtain a more quantitative information from the IV curve, a detailed model is necessary. This paper outlines a computer model that is being developed to improve the understanding of high-efficiency concentrator modules.

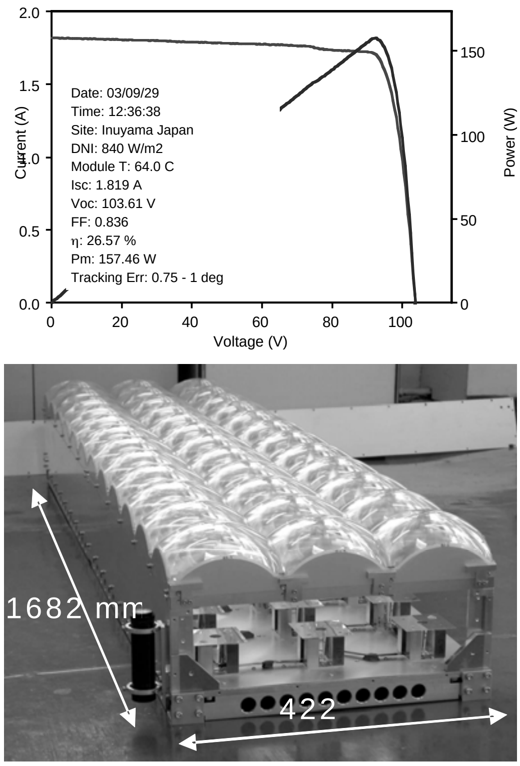

Fig. 1. 200Wp module assembly and a module IV curve where undesirable shading of some cells has reduced the FF.

2. DESCRIPTION OF THE SYRACUSE COMPUTER MODEL

The computer model, called Syracuse, is broadly composed of four components. The first is a spectral irradiance model that accounts for climatic variation in the sunlight, giving a realistic estimate of the spectral photon flux incident on the concentrator module. The second component is a photovoltaic device model that simulates the photogeneration and recombination in each of the component junctions in the multi-junction solar cell. The third component of the model assembles the photovoltaic device models into a circuit network representing the module and system configuration. Finally, the forth component solves the PV circuit network and the results are collected into a form in which they can be readily compared with the outdoors test data.

The Syracuse model is written in the Java programming language and is designed to be easy to use and the user input takes place through a series of forms and windows, making it straightforward to inspect parameters and set up simulations. All the user inputs are passed as appropriate netlist files to the freely available SPICE circuit network solver [5]. The resulting IV curves are returned to the Syracuse program for further analysis, graphing and comparison with experimental data. The experimental data and outdoor test conditions are held in a MySQL database, accessible across the internet. The general process is shown in figure 2.

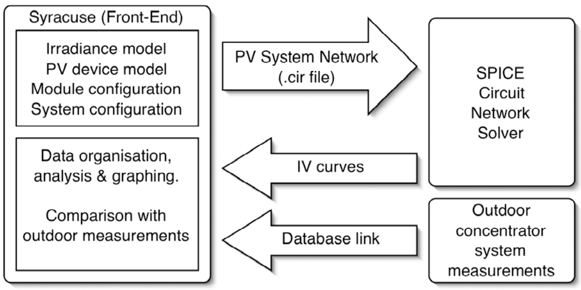

Fig.2. Schematic diagram showing how the Syracuse front end links with the SPICE circuit network solver and the outdoor measurement database.

The process of generating the SPICE netlist files is one of the valuable features of the Syracuse program. While SPICE is an excellent tool for solving circuit networks, none of the existing schematic capture tools are suitable for simulating photovoltaic systems and similarly the data analysis functions are not well suited for evaluating photovoltaic parameters. A further advantage of Syracuse is the ability to create batches of simulations, so for example, the performance of the concentrator system can be simulated at hourly intervals over many days or months. An important aspect of this batch mode is that the resulting IV curves are automatically collected and analysed, allowing large quantities of data to be handled with ease.

The process that leads to the generation of the SPICE netlist is shown in figure 3. There are three main processes, each drawing from various user inputs shown at the top.

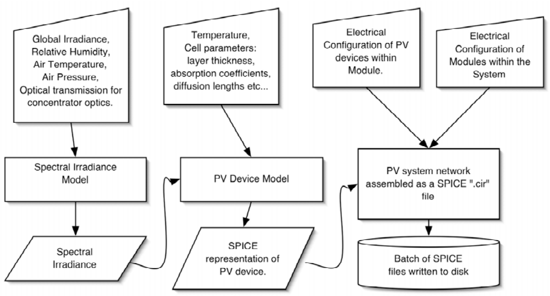

Fig 3. Process in the Syracuse front-end leading to the generation of SPICE netlist files. User inputs at the top and processes are represented by rectangles.

In any photovoltaic system model, it is crucial that the solar irradiance incident on the solar cell is determined accurately. In this case the multi-junction cell design also requires an accurate prediction of the spectral irradiance incident on the concentrator module. If the concentrator modules are located in a dry arid climate, with very little cloud cover then models such as SMARTS2 can be used to predict the spectral irradiance. However in many practical locations, including the Toyohashi and Inuyama test sites, there is significant cloud cover which complicates the task of predicting the spectral irradiance. Nevertheless, a spectral irradiance model that can account for cloud cover has been developed at the University of Loughborough. The model, called ASPIRE [6], requires only the global irradiance and some meteorological inputs to account for the effect of cloud cover and gives a good agreement with measured spectral irradiance in the UK. When applied to concentrator systems, the irradiance model offers a further challenge in that diffuse light cannot be collected by the concentrating optics, so the spectral irradiance model only considers the direct beam spectral irradiance.

The 400X concentrator module design consists of 36 multi-junction cells connected in series uniformly illuminated using dome shaped Fresnel lenses and a glass homogeniser. The receiver package [7] and module [8] design are discussed elsewhere at this conference.

A simple equivalent circuit for the multi-junction solar cell is used and is shown in figure 4. The photogeneration rates are calculated by integrating the convolved spectral irradiance and experimental cell quantum efficiency and lens losses. The diode/resistance parameters were obtained from extensive testing of individual sub-cells[9,10] at 25°C.

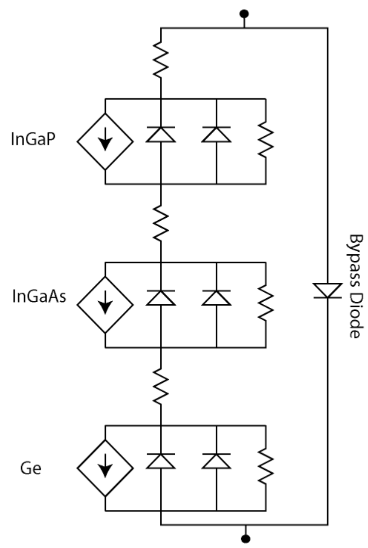

Fig.4 Equivalent circuit for a single multi-junction cell packaged with a bypass diode into a receiver [7]

The 36 multi-junction receivers are connected in series and the resulting IV-curve calculated. It is computationally advantageous to assume each cell in the module is similar, but one of the key features of the Syracuse model is to be able to distribute the parameters statistically to account for manufacturing tolerances. As a result, all 36 cells are simulated together as a module, allowing the effects of current mismatching to be simulated.

3. VALIDATION AGAINST EXPERIMENTAL DATA

At present the cell and module functions of the Syracuse model have been completed, allowing the model to be tested against experimental data.

Figure 5 shows the result of current mismatching in the module. With identical cells, the IV-curve is almost completely flat between 0 and 90V, whereas the mismatched cells show a slow degradation in current resulting in a lower fill factor. This behaviour is simply due to the bypass diodes which shunt the poorly performing cells at low module biases. At higher module biases the poorly performing cells become forward biased, so the bypass diodes no longer shunt the poorly performing cells, and the overall module current drops. Only a small distribution in short-circuit currents is required to give this effect and the distribution used is shown in figure 6.

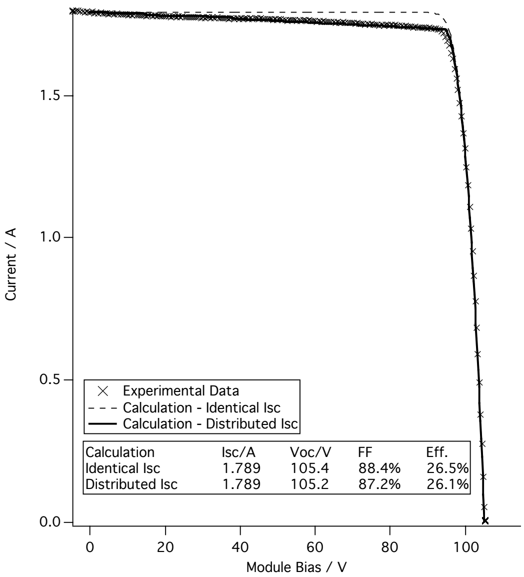

Fig 5. Experimental 400X module data and two simulated IV-curves, showing the effect of current mismatched cells.

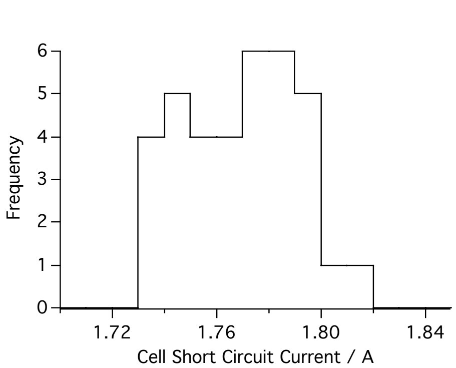

Fig. 6 The simulated variation in short-circuit current for each cell in the 36 cell module.

Using the SMARTS2 spectral irradiance model [11], the performance of the 400X concentrator module can be predicted on days with clear sky conditions. The predicted DNI for the Toyohashi test-site (34°45.996'N, 137°22.999'E) is compared with experimental data taken on a clear day in figure 7.

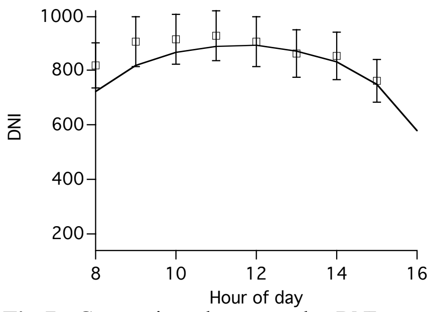

Fig 7. Comparison between the DNI measured on 16th October 2003 at the Toyohashi test site (squares) and that predicted by the SMARTS2 model (line).

The agreement between the measured DNI and predicted DNI is reasonable, considering that there is a 10% measurement error. Good agreement is also obtained between the short-circuit current predicted by the Syracuse model and the measured data, as shown in figure 8, although it seems likely that the calculated DNI is underestimated between 8am and 10am. Nevertheless, the DNI predicted by the SMARTS2 model is still a reasonable estimate of the actual DNI incident on the module.

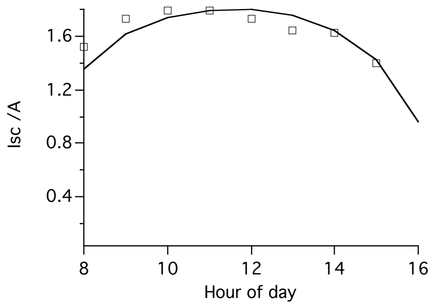

Fig.8 Comparison between the measured (squares) and simulated (line) short-circuit current.

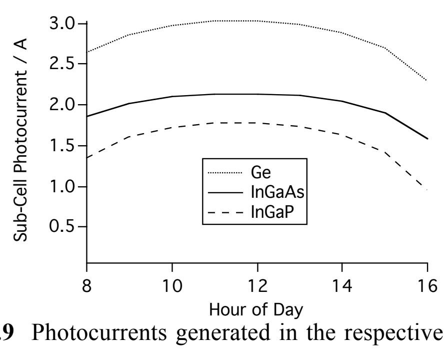

Fig.9 Photocurrents generated in the respective InGaP, InGaAs and Ge sub-cells.

Figure 9 shows the photogeneration in each sub-cell, showing that the InGaP/InGaAs/Ge cell is limited by the InGaP top cell. The cell is best current matched around midday, while in the morning and evening, the blue component of the spectrum is weak, and the spectral mismatch worsens. The effect of spectral mismatch can also be seen in the fill-factor, shown in figure 10. The fill-factor rises to partially compensate the spectral mismatch [12], showing a minimum around midday.

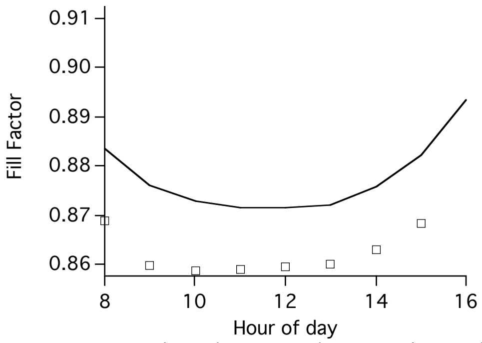

Fig. 10 Comparison between the experimental fill-factor (squares) and calculated fill-factor (line.)

The good agreement between the predicted module power output and the experimentally measured value shown in figure 11, suggests that providing the spectral irradiance can be predicted accurately, then the goal of predicting the annual power output from the module in different climates is attainable.

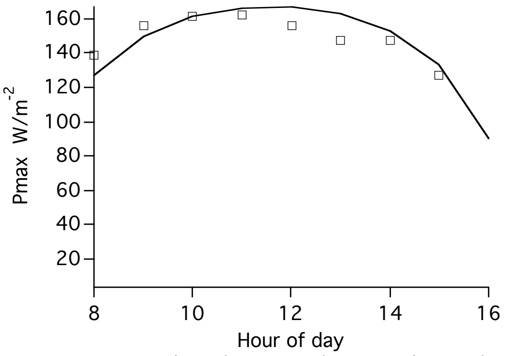

Fig..11 Comparison between the experimental power delivered by the module (squares) and that predicted by the model (line).

Other than working on an accurate model for the spectral irradiance, the temperature dependency of the module needs to be investigated more fully [13]. The simulations presented here assume a constant cell temperature of 50°C and that only the recombination parameters of the sub-cells change with temperature [14], reproducing the results of earlier studies[15]. The temperature dependency of the short-circuit current [16] will be included in the future. Also the model can be adapted to accommodate a multi-unit equivalent circuit, which may be necessary to model systems with substantial chromatic aberration or non-uniform illumination of the solar cell [10].

The Syracuse model is scheduled to be completed by the Autumn of 2004, at which point the model and the outdoor test database will become available to the photovoltaic community. News and eventual downloads will be posted at the web-site: www.syracuse-pv.webhop.org

4. CONCLUSION

The proposed computer model will allow users to analyse the performance of multi-junction concentrator systems. The model will predict annual system power output as well as allowing detailed analysis of individual modules, the multi-junction cells and the component junctions themselves. Recent validation tests have indicated that these goals are attainable and it is hoped that the model will become a valuable tool for designing multi-junction concentrator systems, investigating unusual concentrator system behaviour and for improving the design of multi-junction concentrator modules.

ACKNOWLEGEMENTS

This work was supported by the Incorporated Administrative Agency New Energy and Industrial Technology Development Organization (NEDO) under Ministry of Economy, Trade and Industry (METI). and partially supported by the Ministry of Education, Culture, Sports, Science and Technology as a Private University Academic Frontier Research Center Program "Super High-Efficiency Photovoltaic Research Center"

REFERENCES

1) M.Yamaguchi, et al., 5DP.1.3 Proc. 19th European PV Conference & Exhibition (2004)
2) Y.Kemmoku, et al., Proc. WCPEC 3 (2003) p2379
3) T.Takamoto, et al., Proc. WCPEC 3 (2003) p581
4) K.Araki, et al., Proc. WCPEC 3 (2003) p630
5) SPICE Homepage http://bwrc.eecs.berkeley.edu/Classes/IcBook/SPICE/
6) T.R.Betts, et al., Proc. WCPEC 3 (2003) p2182
7) K.Araki, et al., 8AV.3.15, Proc. 19th European PV Conference & Exhibition (2004)
8) K.Araki, et al., 5BV.2.20, Proc. 19th European PV Conference & Exhibition (2004)
9) K.Nishioka PhD thesis, NAIST, Nara, Japan.
10) K. Nishioka, et al., Jpn.J.Appl.Phys, 43:3 (2004) p.882-889
11) C.A.Gueymard, Solar Energy, 71:5, (2001), p.325-346,
12) M.Meusel et al., Prog. Photovolt. Res. Appl., 10, (2002), p.243-255
13) Y.Kemmoku et al., 5BV.2.40 Proc. 19th European PV Conference & Exhibition (2004)
14) G.Massobrio & P.Antognetti, “Semiconductor Device Modeling with SPICE”, 2nd Ed. McGraw Hill, (1993).
15) D.J.Friedman, Proc. 25th IEEE PVSC (1996), p89-92.
16) D. Aiken, Proc 29th IEEE PVSC (2002) p.828-831