DESIGN AND PERFORMANCE ASPECTS FOR LOW CONCENTRATION PHOTOVOLTAICS

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ABSTRACT: A review on the design and performance aspects of low concentration photovoltaics is presented in this work. In Physics Department at University of Patras, Greece optical and thermal performance of low concentration configurations have been studied regarding their effect to the electrical output. The experimental study confirms that the non-uniform distribution of solar radiation on the PV surface of concentrating photovoltaics reduces the electrical efficiency of them. This effect can be overcome combining the photovoltaics with low concentration devices that achieve uniform distribution of solar radiation on cell surface. The simpler and of lower cost mode is to apply diffuse reflectors instead of specular reflectors. The PV temperature reduction is also a factor for the electrical efficiency reduction and several modes for heat extraction can be applied according to the application requirements, using water or air cooled hybrid photovoltaic/thermal (PV/T) solar systems.

Keywords: Concentrators-1: Thermal performance-2: Cost reduction-3

1 INTRODUCTION

Several investigations result to lower the cost of photovoltaics increasing also their electrical efficiency, but their payback time has not been reduced enough to be considered cost effective. The combination of solar radiation concentration devices with PV modules is up to now the most viable method to reduce system cost, replacing the expensive cells with a cheaper solar radiation concentrating system. Besides, concentrating photovoltaics present higher efficiency than the typical ones, but this can be achieved in an effective way by keeping PV module temperature as low as possible. For PV cooling, a water or air circulation mode can be applied to extract the heat from it, avoiding the efficiency reduction due to the PV module temperature increase. The extracted heat can be rejected to the ambient or can be used to cover thermal needs of the application and these devices are the hybrid photovoltaic/thermal (PV/T) solar energy systems.

The concentrating solar systems use reflective (flat or curved mirrors) and refractive (mainly fresnel lenses) optical devices. These solar energy systems are characterized by their concentration ratio (CR) and can be combined with "linear focus" (2D) or "point focus" (3D) absorbers for low (CR<10X), medium (CR<100X) or high (CR>100X) CR, respectively. Concentrating systems with CR>2.5X must use a system to track the sun, while for systems with CR<2.5X, stationary concentrating devices can be used. The low concentrating ratio systems (CR<10X) are of particular interest for the photovoltaics as they are of linear geometry and thus one tracking axis is enough for their efficient operation.

The distribution of the solar radiation on the absorber surface (PV module) and the temperature rise of it are two problems that affect the electrical output. The uniform distribution of the concentrated solar radiation on the PV surface and the application of a suitable cooling mode contribute in all cases to an effective system operation, considering the achievement of the maximum electrical output. In this paper a review on low concentration photovoltaics is presented regarding the design and performance aspects of them. The experience from the research activities of Physics Department at University of Patras on low concentration solar energy systems is presented, discussing the results that are taken from laboratory experiments.

2 LOW CONCENTRATION PHOTOVOLTAICS

Among the first works on low concentration photovoltaics are the publications of Ralph [1] and Roy [2], with Luque [3] studying the advantage of static concentrators and Stacey and McGormick [4] giving performance results for low concentration photovoltaics. In the following, many works have been presented, which can be grouped regarding the used mode of concentration in V-trough reflectors, CPC (Compound Parabolic Concentrators) type reflectors, refractive concentrators and linear fresnel lenses, other concentrating systems and also systems with bifacial PV modules.

Regarding the V-trough reflectors, many works are referred to one or two tracking axis [5-15] using flat mirrors. The planar reflectors are used to increase solar radiation on PV module surface, with sun tracking to result in a uniform distribution of solar radiation on it. They are simple devices, achieving concentration ratios up to about two with east-west or north-south orientated reflectors. Low concentration CPCs is another category of devices that are coupled with PV modules [16-23], most of them are static concentrators (no movements to track the sun), but suffer from the non-uniform distribution of solar radiation on the surface of cells.

Bifacial cells are used [24-28] in order to adapt concentrating system geometry, reducing in this way cell material. Refractive concentrators [29-34], fresnel lenses [35,36] and colored diffused reflectors [37] are also optical devices that have been suggested for low concentration photovoltaics. In these systems the transparent refractive components are placed above cells and this results to optical losses by reflection and absorption of the incoming solar radiation.

3 LOW CONCENTRATION PV AND HYBRID PV/T SYSTEMS

Most of the absorbed solar radiation by solar cells is not converted into electricity and this has as result the increase of their temperature and the decrease of their electrical efficiency. The reduction of cell temperature can be combined with effective heat extraction by the use of the hybrid Photovoltaic/Thermal (PV/T) type systems, which convert simultaneously the solar radiation into electricity and heat. PV/T systems consist of PV modules and heat extraction devices mounted together, by which a circulating fluid of lower temperature than that of PV modules is heated by cooling them. Air heat extraction is considered a low cost mode and can be used for space heating of buildings mainly in medium and high latitude applications. Heat extraction by water circulation is more expensive, but it can be used for water preheating in low and medium latitude applications almost all year. Ambient air over 20^{o}C is less efficient in PV cooling and this limits the application of air type PV/T systems, mainly applied for natural ventilation of buildings and air preheating in agricultural and industrial processes.

Main concepts on hybrid PV/T systems have been presented in several works regarding heat extraction by water or air circulation [38-54]. The electrical and the thermal output of hybrid PV/T systems can be improved by using low concentration devices. In this field, have been presented words by Mbewe et al [55], Sharan et al [56,57], Al-Baali [58], Garg et al [59], Garg and Adhikari [60], Brogren et al [61,62], Fieber et al [63] and Helgesson et al [64].

Monocrystalline or polycrystalline silicon (c-Si or pc-Si) PV modules are almost double the cost per system aperture area than amorphous silicon (a-Si) PV modules. Therefore, the addition of the thermal unit is of lower relative cost for PV/T system based on c-Si or pc-Si (about 8%-10%) than of a-Si PV modules (about 15%-20%) of same size. In addition, the additional cost of the thermal unit must be offset by the corresponding increase in electrical efficiency and thermal output in order to make the PV/T system cost effective.

The PV/T systems can be characterized according to their operating temperature. The PV/T systems of very low operating temperature are referred to applications up to 30°C to 40°C, that are associated with air or water preheating, natural air ventilation, space heating, heating of swimming pools and heat pump applications. The plain and the low concentration PV/T systems can produce water or air of temperatures in the range 40°C to 60°C, and in medium temperatures between 60°C and 100°C for domestic water heating, space heating and cooling and other thermal needs. The low concentration PV/T systems can also provide heat above 100 °C for high temperature loads as desalination, cooling, steam production and other thermal applications, but so far there is no such known application.

The addition of a glazing increases significantly the thermal efficiency for a wider range of operating temperatures, but the additional optical losses from it reduce the electrical output of the PV/T systems. The electrical output is in most cases more useful than thermal output, as the cost of PV modules is several times higher than the thermal unit. In some applications where heat is a result of electricity then both electrical and thermal output are of equal value.

4 SEL ACTIVITIES ON LOW CONCENTRATION PHOTOVOLTAICS

In Solar Energy Laboratory (SEL) of Physics Department at University of Patras, Greece, low concentration photovoltaics using a-Si and pc-Si PV modules are studied. The work is mainly focused on the hybrid PV/T systems with water or air as heat removal fluid, aiming to improve their performance. The studies for air type PV/T systems [65,66] include several modes for the improvement of the air heat extraction from the PV modules. New PV/T system design based on dual (both water and/or air) heat extraction operation [67] have been proposed. Economical [68] and LCA [69] analysis comparing PV/T systems with standard PV and thermal systems give an idea about the cost and environmental benefits of concentrating PV/T systems.

Aiming to determine the effect of the additional solar radiation from the concentrator to the PV module surface we performed several tests using a module of a-Si cells. We tested outdoors the module to extract the I-V curve and to calculate the maximum power from it for several cell illumination modes due to shadow. We did experiments with variable shadow percentage, using for comparison a second same module without shade. The tests were performed for the two shading modes of the PV module according the geometry configuration of the cells and the obtained results were in a good agreement with those presented in study [70].

The electrical efficiency of the shielded module was reduced enough due to the non-uniform distribution of solar radiation on its surface. We tested also the PV module with a frame consisting of mesh type shield to have a smoother shadow and the results confirmed again the efficiency reduction, which now followed the mesh density.

Apart of PV shading we tested the a-Si PV module under concentrating solar radiation conditions, using low concentrating devices of reflective (flat and CPC curved mirrors) and refractive (linear fresnel lenses) type. These experiments showed that the electrical efficiency is also reduced, although the solar radiation intensity is increased on the module surface. This effect was more intensive in the case of CPC reflectors and fresnel lenses as higher peaks of flux were observed.

Considering the above results we estimated that is preferable (mainly by the cost side of view) and more effective (by the performance side of view) to use diffuse reflectors instead of specular reflectors and comparative outdoors tests showed the positive effect of them to the electrical behaviour of the used photovoltaics.

5 DIFFUSE REFLECTORS

In the concentrating solar devices the geometrical concentration ratio CR is determined by the ratio of the system aperture area to the absorber surface area. The increase of the electrical energy output of PV modules can be achieved by using diffuse reflectors as boosters, which give an almost uniform distribution of the reflected solar radiation on PV aperture surface [66,71]. The diffuse reflectors, in contrast to the specular reflectors that have to track the sun, can be stationary and are suitable mainly for PV module installation on horizontal building roof or ground plane, using effectively the space between the parallel rows of PV modules [66].

In SEL we have been involved in studying booster diffuse reflectors in combination with PV and PV/T systems. The tests are concerned with variable percentage of the additional reflected solar radiation on cell surface, with respect to its electrical efficiency as a function of the temperature. We notice that the additional solar radiation is not 100% uniformly distributed on the PV module surface and we can consider an effective concentration factor CR that corresponds to the solar radiation profile from the bottom to the top of the PV module surface.

We measured the effective concentration factor CR of a usual diffuse reflector (aluminium sheet) for several angles φ between the plane of the reflector and the plane of the PV module, as a function of the angle of incidence θ of solar radiation on the diffuse reflector. The angle φ=120° was observed that is an upper effective limit of the tested angles. The obtained results [66] depend on the used reflecting material and give an idea about the uniformity of the illumination. Values of CR>1.5 are not usually achieved in practice for stationary diffuse reflectors, because large size reflectors - compared to the PV module dimensions - are necessary. The booster diffuse reflectors are efficient mainly from spring to fall and are suggested to increase PV/T system total energy output (electricity and heat), using low cost additional system elements (cheap diffuse reflectors)

In case of PV/T systems with additional glazing, the negative effect of the reduction of the transmitted solar radiation on PV surface from reflection and absorption from the transparent cover, is balanced with the positive effect of the increased solar radiation input from the diffuse reflector.

6 CONCLUSIONS

Low concentration solar energy configurations combined with photovoltaics, as the flat or V-trough reflectors, the CPC reflectors and the fresnel lenses were reviewed regarding their effect to the PV electrical output. The non-uniform distribution of solar radiation on the PV surface of concentrating photovoltaics reduces the electrical efficiency of cells and this undesirable effect can be overcome applying simple and of lower cost diffuse reflectors instead of using specular reflectors. In addition, the increase of the absorbing solar radiation from the concentrator reduces cell electrical efficiency, but several modes for efficient and cost effective heat extraction can be applied and one can select the most appropriate according to the application requirements.

REFERENCES

1. E. L. Ralph, Solar Energy, Vol. 10, pp. 67 – 71 (1966)
2. A. S. Roy, Solar Energy, Vol. 21, pp. 371 – 375 (1978)
3. A. Luque, Solar Cells, Vol. 3, pp. 355 –368 (1981)
4. R. W. Stacey and P. G. McCormick, Solar Energy, Vol. 33, pp. 565 – 569 (1984)
5. J. Freilich and J. M. Gordon, Solar Energy, Vol. 46, pp. 267 – 273 (1991)
6. J. M. Gordon, J. F. Kreider and P. Reeves, Solar Energy, Vol. 47, pp. 245 – 252 (1991)
7. F. H. Klotz, 13th European Photovoltaic Solar Energy Conference, 23 – 27 Oct., Nice, Paris, pp. 372 – 375 (1995)
8. N. Fraidenraich, Progress in Photovoltaics: Research and Applications, Vol. 6, pp. 43 – 54 (1998)
9. M. Ronnelid, B. Karlsson, P. Krohn and J. Wennerberg. Progress in Photovoltaics: Research and Applications 8, 279-291 (2000)
10. V. Poulek, M. Libra, 16th European Photovoltaic Solar Energy Conference, 1–5 May, Glasgow, UK, 2453-2456 (2000)
11. A. Wheldon, R. Bentley, G. Whitfield, T. Tweddell and C. Weatherby, 16th European Photovoltaic Solar Energy Conference, 1–5 May, Glasgow, UK, 2622-2625 (2000)
12. F. H. Klotz, H.-D. Mohring, C. Gruel, M. Gasson, J. Sherborne, T. Bruton, M. A. Abella and P. Tzanetakis, 16th European Photovoltaic Solar Energy Conference, 1–5 May, Glasgow, UK, 2229-2232 (2000)
13. F. Dobon, J. Monedero, P. Valera, L. Acosta, G. N. Marichal, R. Osuna, V. Fernandez, 17th European Photovoltaic Solar Energy Conference, 22–25 Oct, Munich, 686-689 (2001)
14. F. Dobon, J. Monedero, P. Valera, L. Acosta, G. N. Marichal, R. Osuna, V. Fernandez, 17th European Photovoltaic Solar Energy Conference, 22–25 Oct, Munich, 664-667 (2001)
15. P. Valera, J. Enrile and R. Osuna, 19th European Photovoltaic Solar Energy Conference, 7-11 June, pp. 2656-2659, Paris, France (2004)
16. G. Almonacid, A. Luque, J. D. Aguilar, L. Almonacid and M. Lara, Solar and Wind Technology, Vol. 4, pp. 145 – 149 (1987)
17. A. Goetzberger, Proc. 20th IEEE Photovoltaic Specialists Conference, Las Vegas, pp. 1333 – 1337 (1988)
18. A. J. Chanumba, R. W. Bentley and G. R. Whitfield, The use of solar cells under 10X concentration. NORTHSUN 90, pp. 420 – 425 (1990)
19. I. Zanesco and E. Lorenzo, Progress in Photovoltaics: Research and Applications, Vol. 10, pp. 361 – 376 (2002)
20. R. Mohedano, P. Benitez and J. C. Minano, 2nd World Conference and Exhibition on Photovoltaic Solar Energy Conversion 6-10 July, Vienna, Austria, pp. 2241 – 2244 (1998)
21. T. Uematsu, T. Warabisako, Y. Yazawa, S. Muramatsu, 2nd World Conference and Exhibition on Photovoltaic Solar Energy Conversion 6-10 July, Vienna, Austria, pp. 1570 – 1573 (1998)
22. A. Parretta, P. Morvillo, C. Privato, G. Martinelli and R. Winston, Proc. of the International Conference, pp. 547-550, 7–11 Oct, Rome, (2002)
23. J. Nilsson, R. Leutz and B. Karlsson, 19th European Photovoltaic Solar Energy Conference, 7-11 June, pp. 2094-2097, Paris, France (2004)
24. U. Ortabasi, Proc. 26th IEEE Photovoltaic Specialist Conference, pp. 1177 – 1181 (1997)
25. S. Bowden, S. R. Wenham, P. Coffey, M. Dickinson and M. A. Green, Proc. 23nd IEEE Photovoltaic Specialist Conference, pp. 1068 – 1072 (1993)
26. B. Mayregger, R. Auer, M. Niemann, A. G. Aberle and R. Hezel, 13th European Photovoltaic Solar Energy Conference, 23 – 27 Oct., Nice, Paris, pp. 2377 – 2380 (1995)

27. M. Hernandez, R. Mohedano, F. Munoz, A. Sanz, P. Benitez and J. C. Minano, 16th European Photovoltaic Solar Energy Conference, 1–5 May, Glasgow, UK, 2394-2397 (2000)
28. M. Libra, 19th European Photovoltaic Solar Energy Conference, 7-11 June, pp. 2430-2433, Paris, France (2004)
29. I. R. Edmonds, I. R. Cowling and H. M. Chan, Solar Energy, Vol. 39, pp. 113 – 122 (1987)
30. K. Yoshioka, S. Goma, S. Hayakawa and T. Saitoh, Progress in Photovoltaics: Research and Applications, Vol. 5, pp. 139 – 145 (1997)
31. K. Yoshioka, S. Goma, K. Kurokawa and T. Saitoh, Progress in Photovoltaics: Research and Applications, Vol. 7, pp. 61 – 69 (1999)
32. A. Zacharopoulos, P. C. Eames, D. McLarnon and B. Norton, Solar Energy, Vol. 68, pp. 439 – 452 (2000)
33. N. C. Shaw and S. R. Wenham, 16th European Photovoltaic Solar Energy Conference, 1–5 May, Glasgow, UK, 2342-2345 (2000)
34. M. Hernandez, F. Bercero, R. Mohedano, P. Benitez and J. C. Minano, 17th European Photovoltaic Solar Energy Conference, 22–25 Oct, Munich, 623-625 (2001)
35. N. Kaminar, J. McEntee, P. Stark and D. Curchod, Proc. 22nd IEEE Photovoltaic Specialists Conference, Las Vegas, pp. 529 – 532 (1991)
36. W. R. Bottenberg, N. Kaminar, T. Alexander, P. Carrie, K. Chen, D. Gilbert, P. Hobden, A. Kalaita, J. Zimmerman, 16th European Photovoltaic Solar Energy Conference, 1–5 May, Glasgow, UK, 2141-2144 (2000)
37. A. Moehlecke, I. Zanesco, A. C. Pan, T. C. Severo and A. P. Mallmann, 17th European Photovoltaic Solar Energy Conference, 22–25 Oct, Munich, 785-787 (2001)
38. E.C. Kern Jr and M.C. Russel, Proc. of 13th IEEE Photovoltaic Specialists, Washington DC, USA, pp. 1153 – 1157 (1978)
39. S.D. Hendrie, Proc. of Int. Conf. ISES, Atlanta, Georgia, USA, May 28 – June 1, Vol.3 pp. 1865-1869 (1979)
40. L.W. Florschuetz, Solar Energy 22, pp. 361-366 (1979)
41. P. Raghuraman, Journal of Solar Energy Enginnering, Vol 103, pp. 291-298 (1981)
42. C.H. Cox III and P. Raghuraman, Solar Energy 35, pp. 227-245 (1985)
43. B. Lalovic, Solar Cells 19, pp. 131-138 (1986).
44. A.K. Bhargava, H.P. Garg and R.K. Agarwal, Energy Convers. Mgmt, Vol 31, No 5, pp. 471 - 479 (1991).
45. J. Prakash, Energy Convers. Mgmt. Vol 35, No 11, pp. 967-972 (1994)
46. K. Sopian, H.T. Liu, K.S. Kakac and T.N. Veziroglu, Proc. of ASME Int. Mech. Eng. Congress and Exhibition, Atlanta, USA, Nov.25-28, Vol.36, pp. 341 - 346 (1996)
47. T. Bergene and O.M. Lovvik, Solar Energy 55, pp. 453-462 (1995)
48. B.J. Brinkworth, B.M. Cross, R.H. Marshall and Hongxing Yang, Solar Energy 61, pp. 169-179 (1997)
49. Kalogirou S.A. *Renewable Energy*, 2001; 23: 247-260.
50. Sandness B., Rekstad J. *Solar Energy*,; 72, 1: 63-73. (2002)
51. Zondag H. A., De Vries D.W., Van Helden W.G.J., Van Zolingen R.J.C., Van Steenhoven A.A. *Solar Energy*,; 72: 113-128 (2002)
52. Zondag H. A., de Vries D.W., Van Helden W.G.J., Van Zolingen R.J.C., Van Steenhoven A.A. *Solar Energy,* 74: 235-269 (2003).
53. Coventry J.S., Lovegrove K. *Solar Energy*, 2003; 75: 63-72.
54. Chow T.T. *Solar Energy*, 2003; 75: 143-152.
55. D. J. Mbewe, H. C. Card and D. C. Card, Solar Energy, Vol. 35, No 3, pp. 247 – 258 (1985)
56. S. N. Sharan, S. S. Mathur and T. C. Kandpal, Solar and Wind Technology, Vol. 2, pp. 195 – 200 (1985)
57. S. N. Sharan, S. S. Mathur and T. C. Kandpal, Solar and Wind Technology, Vol. 3, pp. 281 – 285 (1986)
58. A. A. Al-Baali, Solar and Wind Technology, Vol. 3, pp. 241 – 245 (1986)
59. H.P. Garg, P.K. Agarwal and A.K. Bhargava, Energy Convers. Mgmt. 32, pp. 543-554 (1991)
60. H. P. Garg and R. S. Adhikari, Int. J. Energy Res., Vol. 23, pp. 1295 – 1304 (1999)
61. M. Brogren, M. Ronnelid, B. Karlsson, Proc. 16th Europ. PV Solar Energy Conf. Vol. III, pp. 2121-2124, 1-5 May, Glasgow, U.K. (2000)
62. M. Brogren, B. Karlsson, A. Werner and A. Roos, Proc. of the International Conference, pp. 551-555, 7–11 Oct, Rome, (2002)
63. A. Fieber, J. Nilsson and B. Karlsson, 19th European Photovoltaic Solar Energy Conference, 7-11 June, pp. 3040-3043, Paris, France (2004)
64. A. Helgesson, P. Krohn, B. Karlsson, L. Svensson and G. Broms, 19th European Photovoltaic Solar Energy Conference, 7-11 June, pp. 2223-2225, Paris, France (2004)
65. Y. Tripanagnostopoulos, Th. Nousia and M. Souliotis, Proc. 6th Europ. PV Solar Energy Conf. Glasgow, U.K. Vol II pp. 1874 – 1899 (2000)
66. Tripanagnostopoulos Y., Nousia Th., Souliotis M. and Yianoulis P. *Solar Energy,* 2002; 72, 3: 217-234.
67. Tripanagnostopoulos Y., Tzavellas D., Zoulia I. and Chortatou M. *In Proc. 17th PV Solar Energy Conference,* Munich, Germany, 22-26 Oct 2001; 2515-2518.
68. Tselepis S. and Tripanagnostopoulos Y. *In Proc. Int. Conf. PV in Europe* 7-11 Oct. Rome, Italy, 2002; 856-859.
69. Tripanagnostopoulos Y., Souliotis M., Battisti R. and Corrado A. Progress in Photovoltaics: Res. and Appl. 13, 3, 235-250 (2005)
70. W. Herrmann and M. C. Alonso, 19th European Photovoltaic Solar Energy Conference, 7-11 June, pp. 2685-2688, Paris, France (2004)
71. M. Hall, A. Roos and B. Karlsson, Progress in Photovoltaics: Res. and Appl.. 13, pp. 217–233 (2005)