Pergamon

PII: S0360-5442(97)00102-3

Energy Vol. 23, No. 5, pp. 407–411, 1998

Printed in Great Britain
0360-5442/98 $19.00 + 0.00

MATERIAL CONSTRAINTS FOR THIN-FILM SOLAR CELLS

B. A. ANDERSSON,† C. AZAR, J. HOLMBERG and S. KARLSSON

Institute of Physical Resource Theory, Chalmers University of Technology and Göteborg University, S-412 96 Göteborg, Sweden

(Received 30 January 1997)

Abstract—Harnessing solar energy by using photovoltaic cells has the potential to become a major CO_2-free energy source. Materials requirements for the solar cells based on four types of thin-film photovoltaics have been estimated and compared with global reserves, resources and annual refining. The use of solar cells based on Cd, Ga, Ge, In, Ru, Se and Te as a major energy-supply technology has severe resource constraints. Other systems such as *a*-Si without Ge and crystalline silicon do not involve such constraints. For some of these metals, there is the risk of enhanced, environmentally deleterious concentrations in the ecosphere due to leakage from manufacturing, use or waste handling.

1. INTRODUCTION

The present global energy supply is primarily obtained from the use of fossil fuels. Emissions of the greenhouse gas CO_2 will inevitably lead to a change in the radiative balance of the earth and introduce changes in climate. The changes resulting from the greenhouse effect are considered by many to pose one of the most serious global environmental problems, even though considerable scientific uncertainty remains about the magnitudes of changes. A possible solution to mitigation of the escalating greenhouse effect is basing the energy system on renewable energy resources. Of these, direct harnessing of solar energy by photovoltaic cells has the potential to become a major source of energy supplies in a sustainable society. Solar insolation to the earth contains approximately 10,000 times more energy than what is currently used globally. A solar cell area of 5×10^5 km^2 (covering less than 10% of the Sahara) would be sufficient to generate the present global annual primary energy supply of 100,000 TWh.

Some promising solar cell technologies involve the use of chemical elements available from non-renewable and scarce resources. Several authors have studied environmental problems related to solar cells [1–8]. In some cases, resource scarcities were also noted. In this paper, we focus on resource and environmental constraints that a large-scale expansion of solar cells might encounter as a result of the use of scarce elements.

2. A RENEWABLE ENERGY SCENARIO BASED ON SOLAR CELLS

We assume a solar cell scenario in which the expansion rate is 1000 (TWh/yr)/yr on average during the next century. The solar cells will then generate 100,000 TWh/yr in the year 2100 and remain at that level thereafter. This scenario corresponds to a mean power of approximately 11 TW or about 1.1 kW per capita for a global population of 10 billion people. This level of solar power generation would make a significant contribution to future global energy supplies. The present primary energy supply in the world is approximately 100,000 TWh/yr or around 2 kW per capita. In the OECD countries, the mean energy use is about 6 kW per capita. Global primary energy requirements are expected to grow significantly over the next century as the population approximately doubles, the developing countries become industrialized, and the already rich countries become even richer. Thus, the assumed solar cell scenario alone is not likely to lead to stabilization of the atmospheric CO_2 concentration.

The proposed scenario can be compared to the intermittent energy supplies assumed in the global

†Author for correspondence. Fax: + 46 31 772 31 50; e-mail: frtba@fy.chalmers.se

energy scenarios developed at the Stockholm Environment Institute [9] and IIASA/WEC [10] (case C) and in the LESS scenarios [11], which are in the range of 40,000–120,000 TWh/yr by the year 2100. The higher value is for the SEI scenarios, whereas the two other scenarios lie in the lower range. However, they rely more heavily on biomass, which may turn out to be scarce because of constraints on land availability.

We make the assumption that there are no losses of materials during the transient expansion phase, i.e. both the degree of recycling and the utilization of refined materials are taken to be 100%. We consider only the materials requirements for the solar cells (not glass, frames or construction materials). For all of the cells, we assume an overall efficiency of 10% from solar insolation to electricity (which implies a module efficiency of approximately 12%). We choose an annual mean insolation of 2000 kWh/m^2 of solar cell area. These assumptions imply an impressive average expansion rate of 600 GW_p/yr.

3. MATERIALS REQUIREMENTS

Four different kinds of solar cells have been examined. Each of these technologies is tested separately against the supply scenario in order to investigate the limits for each technology. Of course, the future energy system will be made up of a mix of several different technologies.

Solar cells made of abundant silicon are not limited by the material resource constraints considered in this paper. Crystalline silicon cells have high efficiencies but are expensive. Amorphous silicon cells may be produced at low costs but have low efficiency. To resolve this dilemma, other technologies are under development. Here, we consider four different approaches. Two promising technologies require the polycrystalline materials cadmium telluride (CdTe) and copper indium gallium diselenide (CIGS). These have been proposed as the solution to the dilemma of having to choose between high cost and low efficiency [12]. One approach involves the use of a multiple-junction structure of amorphous silicon, in which one of the layers is a silicon–germanium alloy. A fourth alternative is to develop a photochemical cell that functions similarly to photosynthesis in green plants; the Grätzel cell is the first attempt to make such a cell.

The following materials requirements have been assumed for the four thin-film solar cells: (i) The amorphous silicon cell (*a*-SiGe) consists of a window layer of SnO_2, a triple junction structure based on *a*-SiC/*a*-Si/*a*-SiGe (0.35 μm) and a back contact of Al (1.0 μm) [7]. (ii) The CdTe cell is made of SnO_2 (0.12 μm), CdS (0.2 μm), CdTe (1.5 μm), Cu (0.001 μm) and one layer of Mo (1.0 μm) [4]. Mo is used as back contact in the reference cell we study here. In later versions of the CdTe cell, other materials are more commonly used. (iii) The CIGS cell consists of a layer of ZnO (2 μm), a layer of CdS (0.05 μm), a layer of $Cu(In_{.75},Ga_{.25})Se_2$ (2.0 μm) and a layer of Mo (1.0 μm) [13,14]. The Ga content is based on information from Granath (personal communication). (iv) The Grätzel cell consists of a layer of TiO_2 (10 μm) surrounded by two layers of SnO_2 (0.5 + 0.5 μm). The cell also contains a layer of Pt (0.002 μm) and 0.1 g/m^2 Ru in the pigment (Hagfeldt, personal communication). We have used figures that are representative of cells existing today. There remains the potential to lower materials use both in the contact and absorption layers. To absorb 90% of the photons, only 0.5 and 1.0 μm are needed for CIGS and CdTe, respectively [15]. The *a*-Si/Ge cell of van Engelenburg and Alsema [7] is stated to be a future device but the Ge content is roughly in accord with that of existing devices.

4. RESOURCE CONSTRAINTS

We have estimated (see Table 1) the required materials for each of the solar-cell technologies. The total and annual materials requirements for the scenarios are compared, respectively, with reserves and resources and annual refining (see Table 1).

All cells contain at least one element for which the requirement greatly exceeds the present reserve (column 3). Indium is the most critical of these elements and the requirement exceeds its reserve by a factor of 650. Other examples of such elements with requirement-to-reserve ratios in parentheses are Te (110), Ge (51), Se (30), Ga (25), Ru (7.5) and Cd (4.6). The stated reserves are defined by present prices and technologies. These may change rapidly given increased demand for these metals. As an

Table 1. Materials requirements and indicators for the solar cells in four solar energy systems, each based on a specific thin-film technology supplying 100,000 TWh/yr.

	Materials requirements (g/m^2)	Total material requirements[b] (Gg)	Total material requirements /reserves[c]	Total material requirements /max. resources[d]	Annual material requirements[e] /refined materials[f]	Potential losses[g]/ weathered amounts[h]	Material cost share[i] (%)
a-SiGe[a]							
Sn	3.3	1700	0.20	0.004	0.079	2	0.04
Ge	0.22	110	51	0.0003	21	0.1	0.5
Si	0.54	270	Negligible	Negligible	0.0031	0.000002	0.002
Al	2.7	1400	0.00032	Negligible	0.00075	0.00005	0.008
CdTe							
Sn	0.66	330	0.056	0.0009	0.016	0.4	0.008
Cd	4.9	2400	4.6	0.03–0.1	1.2	10–50	0.02
Te	4.7	2400	110	1–20	120	500–10 000	0.5
Mo	10	5100	0.93	0.01	0.47	6	0.1
CIGS							
Zn	9.1	4600	0.030	0.0003	0.0062	0.1	0.02
Cu	1.8	880	0.0017	0.00009	0.00098	0.04	0.008
In	2.9	1400	650	0.03–0.4	110	10–200	0.8
Ga	0.53	270	25	0.00007	48	0.03	0.4
Se	4.8	2400	30	0.3	12	100	0.1
Cd	0.19	95	0.18	0.001–0.005	0.048	0.4–2	0.0008
Mo	10	5100	0.93	0.01	0.47	6	0.1
Grätzel							
Ru	0.1	50	7.5	0.3–3	88	100–1000	0.09
Pt	0.05	25	0.83	0.01–0.1	2.4	6–60	1
Ti	1.2	600	0.0021	Negligible	0.0024	0.0002	0.03
Sn	5.5	2800	0.47	0.007	0.13	3	0.07

[a]In the SiGe-layer, the Ge:Si molar ratio is assumed to be 2:3 [18].
[b]Material requirement for solar cells generating 100,000 TWh/yr (insolation = 2000 $kWh/m^2/yr$ and system efficiency = 10%).
[c]Data for 1990 from Crowson [19]. Ru reserves from Renner and Tröbs [20]. Reserves for Ga have been set equal to 1% of the total amount of Ga in bauxite reserves, corresponding to the present refining percentage.
[d]The maximum resources are estimated, using average concentrations in the crust [21–28], as 0.01% of the total amount in the earth's crust down to 4.6 km below the surface [16]. This estimate is not applicable to abundant metals. When figures on crustal abundance differ by more than a factor of two, one upper and one lower bound are given.
[e]The annual requirement is calculated as 1% of the total material requirement for a 100 year build-up period, which implies 100% recycling rates.
[f]Primary metal refining from Crowson [19]. Data for Si refer to silicon metal.
[g]The potential loss is 1/30th of the total material requirement (assuming a lifetime of 30 years for the solar cells).
[h]Weathering is calculated using average concentration in the crust [21–28] and a global suspended sediment flux of 15 Pg per year in rivers [29].
[i]The material cost share has been calculated assuming a module cost of US$0.5/Wp and present metal prices [30].

example, there is a great deal of Ga in known mineral deposits that is not considered as a part of the reserves at the present price for Ga. For this reason, we have estimated the ratio of requirements to a rough estimate of the maximum resources (estimated as 0.01% of the total amount of each element in the earth's crust down to 4.6 km below the surface [16]). For some elements, the situation may be critical even from this perspective (column 4). This indicator is only a rough estimate of general scarcity. To establish a better measure of the maximum resources, each element must be treated separately. As examples, the geochemistries of Ru and Ga are rather different. Ultimately, supplies are limited by willingness to pay. For energy technologies this decision is also determined by the energy pay-back time.

We see from column 5 in Table 1 that all cells contain at least one element for which the prescribed expansion rate [1000 (TWh/yr)/yr] would require strongly increased refining rates over present levels. It should, however, be noted that the Ga and Ge contents of the annual production of coal ashes exceed their refining rates by two orders of magnitude [17]. The implications of increased demands are difficult to foresee since these elements are extracted as by-products from ores of more common metals. Refining rates will first approach mining rates, i.e. a larger fraction of the scarce metal contained in the base metal ore will be refined. Unless other sources are available, the demand for the base metal will thereafter constitute a severe constraint on the extraction rates of scarce elements. The present revenue from production of these scarce metals is a small fraction of the total revenue from a mining operation. Thus, a large price increase is needed to influence the mining rate strongly. The present costs of scarce elements account for not more than a small fraction of the module cost, even if the module cost is assumed to be as low as \$0.5/Wp (column 7). It is only in the case of Pt that the metal cost reaches 1%. This result indicates that the prices that could be paid for these metals in a large-scale development of solar cells may be substantially higher than current metal prices.

It would be of interest to investigate the geopolitical consequences of the geographical distribution of strategic metals. However, we do not elaborate on this aspect here.

5. ECOLOGICAL CONSTRAINTS

Column 6 provides an indicator of the potential environmental pressure of our large-scale solar cell scenario, given that sufficient resources are available. The indicator is defined in terms of the potential annual losses of materials from the solar cells divided by natural global weathering rates, where the potential losses are given by the annual turnover of the materials when the solar cells are replaced (1/30th of the total per year at the assumed lifetime of 30 years), and the natural weathering rate is defined as the global suspended sediment flux in rivers. For several elements, this measure is larger than unity. This result may be interpreted as an early warning signal that careful consideration must be given to potential environmental impacts.

6. CONCLUSIONS

Solar cells have the potential to become a large energy source in a sustainable society. However, we have shown that some of the most promising thin-film cells in terms of efficiencies and costs may meet severe resource constraints if they were to be employed on the postulated large scale, whereas other technologies, such as *a*-Si without Ge and polycrystalline silicon, do not have such constraints. For thin-film technologies based on scarce elements, it is important to create economic incentives, as well as an institutional and technological environment that facilitates a very high degree of recycling and utilization. From this perspective, it would be interesting to compare a centralized system composed of large-scale plants with a decentralized system with many small units. Finally, it is important to note that the potential for expansion could be increased by technological developments of thinner films and with improved efficiencies.

Acknowledgements—We thank K. Zweibel, T. Kåberger, K. Lindgren and J. Swahn for critical comments. Financial support from the Göteborg Energy Ltd. Research Foundation, the Swedish Council for Planning and Coordination of Research, and the Swedish Environmental Protection Agency is gratefully acknowledged.

REFERENCES

1. Eberspacher, C., Fthenakis, V. M. and Moskowitz, P. D., *Conference Record of the 25th IEEE Photovoltaic Specialists Conference*, May 13–17, 1996, p. 1417.
2. Tillman, A. M., *Energy and Environment*, 1995, **6**, 43.
3. Groetz, M., Vaucher, S., Tscharner, R. and Shah, A., *12th European Photovoltaic Solar Energy Conference*, April 11–15, 1994, p. 1229.
4. Hynes, K. M., Baumann, A. E. and Hill, R., *12th European Photovoltaic Solar Energy Conference*, April 11–15, 1994, p. 309.
5. Patterson, M. H., Turner, A. K., Sadeghi, M. and Marshall, R. J., *12th European Photovoltaic Solar Energy Conference*, April 11–15, 1994, p. 951.
6. Hill, R., in *Solar Electricity*, ed. T. Markvart. John Wiley and Sons, 1994, p. 165.
7. van Engelenburg, B. C. W. and Alsema E. A., *12th European Photovoltaic Solar Energy Conference*, April 11–15, 1994, p. 305.
8. Alsema, E. A. and van Engelenburg, B. C. W., *11th European Photovoltaic Solar Energy Conference*, October 12–16, 1992, p. 995.
9. Lazarus, M., *Towards a Fossil Free Future—The Next Energy Transition*. Stockholm Environment Institute, Boston, and Greenpeace International, Amsterdam, 1993.
10. World Energy Council and IIASA, *Global Energy Perspectives to 2050 and Beyond*. World Energy Council, London, 1995.
11. Ishitani, H. and Johansson, T. B., in *Climate Change 1995: Impacts, Adaption and Mitigation Options*, IPCC Working Group II. Cambridge University Press, Cambridge, 1996.

12. Service, R. F., *Science*, 1996, **272**, 1744.
13. Zweibel, K. and Barnett, A. M., in *Renewable Energy—Sources for Fuel and Electricity*, ed. T. B. Johansson, H. Kelly, A. K. N. Reddy and R. Williams. Island Press, Washington DC, 1993, p. 437.
14. Kapur, V. and Basul, B. M., in *Proceedings of the 21st IEEE Photovoltaic Specialists Conference*, 1990, p. 467.
15. Zweibel, K., *Harnessing Solar Power: The Photovoltaic Challenge*. Plenum Press, 1990.
16. Skinner, B. J., in *Resources and World Development*, ed. D. J. McLaren and B. J. Skinner. John Wiley and Sons, 1987.
17. Azar, C., Holmberg, J. and Lindgren, K., *Ecological Economics*, 1996, **18**, 89.
18. Antoine, A. M., Bruyere, J. C., Bullot, J., Drevillon, B. and Gauthier, M., in *Proceedings of the 7th Photovoltaic Solar Energy Conference*, 1987.
19. Crowson, P., *Minerals Handbook 1992–93: Statistics and Analyses of the Worlds Minerals Industry*. Stockton Press, 1992.
20. Renner, H. and Tröbs, H., *Metall*, 1988, **42**, 714.
21. Bowen, H. J. M., *Environmental Chemistry of the Elements*. Academic Press, 1979.
22. Greenwood, N. N. and Earnshaw, A., *Chemistry of the Elements*. Butterworth–Heinemann, 1984.
23. Ronov, A. B. and Yaroshevsky, A. A., Earth's crust geochemistry, in *Encyclopedia of Geochemistry and Environmental Sciences*, ed. R. W. Fairbridge. Van Nostrand, 1972.
24. Shaw, D. M., Geochemical distribution of the Elements, in *Concise Encylopedia of Mineral Resources*, ed. D. D. Carr and N. Herz. Pergamon Press, 1989.
25. *Ullman's Encyclopedia of Industrial Chemistry*, 5th ed. VCH Verlagsgesellschaft mbH, 1985–1995.
26. US Bureau of Mines, *Mineral Facts and Problems*, 1985.
27. Wedepohl, K. H., *Geochemistry*. Holt, Rinehart and Winston, 1971.
28. Wedepohl, K. H., *Handbook of geochemistry*. Springer–Verlag, 1978.
29. Nriagu, J. O., *Environment*, 1990, **32**, 7.
30. US Bureau of Mines, http://www.usbm.gov/mi/mcs1995/, February 6, 1996.