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National Chair, Society for Sustainability and Environmental Engineering

Lorie Jones
Principal Environmental Engineer
Sinclair Knight Merz, Perth WA
Phone: (08) 9268 9626
Fax: (08) 9268 4598
Email: LJones@skm.com.au

For contributions to *The Environmental Engineer*, please contact

Julia Lamborn, Editor,
The Environmental Engineer
Lecturer
Swinburne University of Technology
Tel: (03) 9214 8344 (direct)
Fax: (03) 9214 8264
Email: jlamborn@swin.edu.au

For contact details of committee members in your State, please contact the Secretariat.

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Secretariat

Mrs Sarah Zelig, Committee Administrator
Institution of Engineers, Australia
11 National Circuit, Barton, ACT 2600
Tel: (02) 6270 6599
Fax: (02) 6273 2358
Email: szelig@engineersaustralia.org.au

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ENERGY PAYBACK OF ROOF MOUNTED PHOTOVOLTAIC CELLS

Colin Bankier and Steve Gale

Abstract

The energy payback time of photovoltaic (PV) cells has been a contentious issue for more than a decade. Some studies claim that the joule content of the energy and materials that were put into the process of making the PV cell, will be equalled by the joule content of the electrical output of the cell within a few years of operation. Other studies claim that the useful electrical energy output of the PV cell will never exceed the total amount of useful energy contained within all the inputs of the manufacturing, installation and lifetime operating processes of the PV cell. These studies are often loosely referred to as measuring the energy “payback” of the PV cell. This study undertook a literature review to determine the key assumptions and considerations included in PV Life Cycle Analysis (LCA) modelling. In addition, other forms of modelling such as embodied energy (EE) analysis have also been considered. This review has concluded that the likely energy payback of a typical domestic sized rooftop grid connected PV cell is approximately four years. In addition, it was estimated that larger utility PV cell power stations would have a much longer energy payback period.

Description of Abbreviations

sc-Si Single-crystalline silicon
 mc-Si Multi-crystalline silicon
 a-Si Amorphous silicon
 BOS Balance of System components (including mounting materials and structures, Inverters, cables and control electronic devices)

1. Introduction

Previously published estimates for the energy requirements of present day crystalline silicon modules vary considerably. As noted in Alsema (2000), these differences can partly be explained by different assumptions for process parameters, but they mostly appear to arise from estimates for the silicon purification and the crystallisation process. The majority of silicon solar cells are made from off-

spec material rejected by the micro-electronics industry, which introduces the question of whether to include process steps required for micro-

electronics wafers in the energy requirements for the PV modules. In order to attempt to draw some conclusions as to the actual energy

Table 1. Summary of energy payback periods found by reviewed literature

Author	Low Estimate (years)	Low Estimate Key Assumptions	High Estimate (years)	High Estimate Key Assumptions
Alsema (2000).	2.5	Roof mounted thin film module	3.1	Roof mounted mc-Si module
Alsema. & Nieuwlaar (2000)	2.6	Thin film module	3.2	mc-Si module
Battisti & Corrado (2005).	1.7	Hybrid photovoltaic / thermal module	3.8	Tilted roof, retrofitted mc-Si module
Jester (2002).	3.2	150W peak power mc-Si module	5.2	55W peak power mc-Si module
Jungbluth, N. (2005).	4	mc-Si module if emissions are not taken into account	25.5	sc-Si module if emissions are taken into account
Kato, Hibino, Komoto, Ihara, Yamamoto & Fujihara (2001).	1.1	100MW/yr a-Si, modules including BOS	2.4	10MW/yr mc-Si module including BOS
Kato, Murata & Sakuta (1997)	4	Sc-Si module. Excludes all processes required for micro-electronics industries.	15.5	sc-Si module. Includes all processes required for micro-electronics industries.
Kato, Murata & Sakuta, (1998).	1.1	a-Si module. Excludes all processes required for micro-electronics industries.	11.8	sc-Si module. Includes all processes required for micro-electronics industries.
Knapp & Jester (2001).	2.2	Production thin film module	12.1	Pre-pilot thin film module
Lewis & Keoleian (1996).	1.4	36.7 kWh/yr frameless a-Si module located in Boulder, CO	13	22.3 kWh/yr a-Si module with frame located in Detroit, MI
Meijer, Huijbregts, Schermer & Reijnders (2003).	3.5	mc-Si module	6.3	Thin-film module
Pearce & Lau (2002).	1.6	a-Si module	2.8	sc-Si module
Peharz & Dimroth (2005).	0.7	FLATCON (Fresnel-lens all-glass tandem-cell concentrator) module – 1900 kWh/(m ² yr) insolation	1.3	FLATCON (Fresnel-lens all-glass tandem-cell concentrator) module – 1000 kWh/(m ² yr) insolation
Raugei, Bargigli & Ulgiati (2005)	1.9	CdTe module including BOS	5.1	mc-Si module including BOS
Schaefer & Hagedorn (1992).	2.6	25 MWp a-Si module	7.25	2.5 MWp sc-Si module
Tripanagnostopoulos, Souliotis, Battisti & Corrado (2005).	1	Glazed Hybrid photovoltaic / thermal	4.1	Unglazed Hybrid photovoltaic / thermal

payback time of PV cells, several previous studies were reviewed. A summary of their findings is presented in table 1. These studies are all based on different assumptions, and evaluate different types of modules, and therefore cannot be directly compared. Some key assumptions of each study are shown. Please refer to the original articles for more detailed information.

2. Key Considerations

Many of the studies reviewed, such as Battisti and Corrado (2005) or Rauegi et al (2005) utilise accepted standardised methodologies such as Life Cycle Assessments (LCA), Embodied Energy (EE) analyses, Emergy Analyses, and Material Flow Accounting in their analyses. LCA methodology, for example, is governed by ISO (International Organization for Standardization). Some studies, however, use methods that are scientifically incorrect, for example attempting to treat different forms of energy as equal. In any embodied energy calculation, it is important to utilise realistic conversion factors when comparing one form of energy with another. The joule contents of differing forms of energy are not equal and the assumption of 100% conversion efficiency between energy forms is inaccurate. In order to adequately account for this, all energy sources need to be related on some common basis through accepted conversion factors.

The system boundaries for such embodied energy and LCA calculations can also become problematic to define. Many studies only consider electrical energy directly required for a particular process. However, when losses related to electrical generation, conversion and transmission are considered the energy actually required for the process might be considerably greater. Another factor that previous studies commonly fail to account for is human inputs, e.g. skilled education, labour, administration, maintenance etc. In order for any embodied energy calculation to be complete, all inputs must be accounted for.

This is an issue with the use of all LCA data. Care must be taken to ensure the user is comparing like with like within different studies and the boundaries of the study are the same. Ultimate certainty of inputs is not yet possible due to the wide uncertainties in environmental accounting. This

Table 2: Energy Payback Times found by Alsema

Module Type	Energy Requirement module only (MJ/m ² module)	Energy Requirement module with frame (Al), supports, and inverter (MJ/m ² module)	Payback Time (years)
mc-Si	4200	5400	3.2
Sc-Si	5700	6900	Not shown
Thin Film	1200	2400	2.7

paper deals with these issues by allocating a range within which the energy payback for PV systems is likely to occur.

3. Key studies influencing the debate

One of the studies reviewed, Alsema (2000), is a commonly referenced study claiming short energy payback periods. This study reviewed and compared ten previous studies to establish on which data there is reasonable consensus and how observed differences may be explained. Based on this review of available data, Alsema established a 'best estimate' of the energy requirement of multi-crystalline silicon (mc-Si), single-crystalline silicon (sc-Si) modules, thin film modules and balance of system (BOS) components. The study attempted to address several considerations outlined above. Key assumptions and methods used by Alsema are:

- Energy data is presented on a common basis as Equivalent Primary Energy units, that is the amount of primary energy (or fuel) necessary to produce the component.
- Electrical energy input is converted into primary energy requirements with an assumed efficiency of 35%.
- Process steps which are specifically needed for the micro-electronics wafers are disregarded
- Lower estimates for process energy consumption are used with the argument that lower quality requirements may lead to reduced energy consumption.
- Mc-Si, sc-Si and thin film modules are assumed to have efficiencies of 13, 14, and 7 percent respectively.
- The systems are assumed to receive an irradiation of 1700 kWh/m²/yr and have a performance ratio of 0.75.

Alsema's findings for different module types are shown in Table 2.

PV cells are estimated to have a lifespan of 25-30 years, therefore

repaying their embodied energy tenfold over their lifetime, according to Alsema's estimate. Alsema also predicts that payback times will decrease to 1-2 years by 2010, and even below this by 2020, based on technological advances.

Other studies, however, claim that the energy payback of PV cells is much lower than Alsema. For example, in contrast the most commonly cited (indeed possibly the only) study claiming that the energy payback time of PV modules exceeds their lifetime is Howard Odum's "Emergy" analysis of solar cells in his book Environmental Accounting (1996). No published studies were found that referenced Odum's work in relation to photo-voltaics, but his work is widely cited in less formal arenas such as web forums and has contributed to the view that PV modules are unable to payback their embodied energy over their lifetime. Emergy accounting has been shown to be an effective tool in whole-systems analysis and tries to evaluate the work previously required to generate a product or service. Odum evaluates a utility scale solar voltaic power installation in Austin, Texas, and concludes that the installation uses nearly twice as much "emergy" as it creates over its lifetime.

Upon scrutiny, there are two reasons why these findings can be rejected as indicating that PV modules are unable to payback their embodied energy over their lifetime:

- The installation was a large centralised power plant. The embodied energy in the concrete and other structures was greater than the PV cells themselves. Frameless modules mounted on existing structures or roofs eliminate the majority of this requirement and its associated embodied energy.
- The human labour of a team of highly trained engineers required to design, operate and maintain the plant were large portions of the energy requirement. De-centralised roof-mounted systems also eliminate

nearly all of this, as they require very low maintenance after installation. The embodied energy in design is also negligible due to amortization over lengthy production runs.

4. Analysis

Most published studies came to conclusions similar to those of Alsema (2000). There are, however, several important factors these studies neglect. Odum's (1996) methodology does at least attempt to account for embodied energy within a much larger system boundary, and to account for a wider range of inputs than other published studies. In order to come to our own estimate on the actual energy payback time, Alsema's findings were used as a basis and any factors not already accounted for were added to his figures.

The primary additional factor was human labour. Human labour associated with the construction and operation of the PV plant would be spread over thousands of PV modules, and would thus be negligible per m² of PV. It was decided, however, that labour for installation of each system would be significant and should thus be included. Based on Odum's (1996) Environmental Accounting, embodied energy of human service contributions can be handled in different ways. Two methods are presented - evaluating metabolic energy (usually giving insignificantly small figures), or national fuel share per person. Fuel use per capita (USA values - but estimated to be similar to Australian values) gave the highest value, so in the interest of caution this figure of 967 MJ per worker per day was used. It was estimated that one tradesman would require one whole working day to install a typical small roof-mounted system.

As previously mentioned, realistic energy conversion factors are another item commonly omitted from previous studies. Accurately including this however, is not simple. Exactly what is a realistic conversion factor depends on the energy generation and transmission system in question and a myriad of other factors that are difficult to define or to agree upon. Although it is acknowledged that some may view it as an overly optimistic figure, the 35% conversion efficiency used by Alsema was taken to be an acceptable simplification for the purposes of this study given that

Table 3. Adjusted Energy Payback Times

Module Type	Alsema: Energy Requirement module with frame (Al) , supports, and inverter (MJ/m ² module)	Adjusted: Energy Requirement module with frame (Al) , supports, inverter, and human labour (MJ/m ² module)	Alsema: Payback Time (years)	Adjusted: Payback Time (years)
mc-Si	5400	6400	3.2	3.8
Sc-Si	6900	7900	Not shown	
Thin Film	2400	3400	2.7	3.8

the average conversion efficiency of conventional Australian power stations is 35-38% (CSIRO).

The rated electrical output of the PV cells examined in Alsema's study were not quoted, so the energy payback time could not be re-calculated from scratch. Instead, the adjusted energy payback times were calculated using the ratio by which the total embodied energy increased. For example, it was assumed that if the embodied energy increased by 50%, the energy payback time would also increase by 50%.

The 967MJ required for one days labour was rounded to 1000MJ. This was added to the total embodied energy requirements for each type of module, and the new payback time was calculated accordingly. The results are shown in Table 3.

This estimate of four years may be seen to be optimistic by some, yet many of the figures used by Alsema are in fact cautious estimates. For example, Alsema's figures used in the study were based on 1999 technology. Alsema has forecast the embodied energy to dramatically reduce by 2010. They also include Aluminium frames on all modules, which account for a large amount of the embodied energy, and are no longer necessary in newer models. Taking these considerations into account, payback time for 2006 modules could be as low as 2-3 years. On the other hand, there are many factors that are difficult to fully account for. Taking a devils advocate stance even assuming double this payback time (6-8 years) still provides a significant energy payback over the proven minimum effective 25 year life of small scale PV systems.

5. Conclusions

Through evaluating a range of previously published studies claiming very different energy payback times, this study has attempted to draw some conclusion as to the actual energy payback time of PV modules.

Alsema's (2000) study provided a "best estimate" based on several other existing studies. Further embodied energy factors were added to Alsema's figures. An energy payback time of around four years was found for both mc-Si and thin film modules. Major limitations to the accuracy of this assessment are the difficulties in determining realistic energy conversion factors, and in determining realistic energy values for human labour. For this reason an allowance of up to 100% has been allowed, thus the range of payback is between 2-8 years. Thus small-scale roof mounted PV systems have a positive energy payback and are capable of contributing to a sustainable energy future.

6. References

- Alsema E. (2000). Energy Pay-back Time and CO₂ Emissions of PV Systems. *Progress in Photovoltaics: Research And Applications*, 8, 17-25.
- Alsema, E. Nieuwlaar, E. (2000). Energy viability of photovoltaic systems. *Energy Policy*, 28, 999-1010.
- Battisti, R. Corrado, A. (2005). Evaluation of technical improvements of photovoltaic systems through life cycle assessment methodology. *Energy*, 30, 952-967.
- CSIRO, Advanced Gasification Research Facility, Queensland Centre for Advanced Technologies, http://www.cat.csiro.au/3_4.htm
- Jester, T. (2002). Crystalline Silicon Manufacturing Progress. *Progress in Photovoltaics: Research and Applications*, 10, 99-106.
- Jungbluth, N. (2005). Life Cycle Assessment of Crystalline Photovoltaics in the Swiss ecoinvent Database. *Progress in Photovoltaics: Research and Applications*, 13, 429-446.
- Kato, K. Hibino, T. Komoto, K. Ihara, S. Yamamoto, S. Fujihara, H. (2001). A life-cycle analysis on thin-film CdS/CdTe PV modules. *Solar Energy Materials & Solar Cells*, 67, 279-287.
- Kato, K. Murata, A. Sakuta, K. (1997). An evaluation on the life cycle of

- photovoltaic energy system considering production energy of off-grade silicon. *Solar Energy Materials and Solar Cells*, 47, 95-100.
- Kato, K. Murata, A. Sakuta, K. (1998). Energy Pay-back Time and Life-cycle CO₂ Emission of Residential PV Power System with Silicon PV Module. *Progress in Photovoltaics: Research and Applications*, 6, 105-115.
- Knapp, K. Jester, T. (2001). Empirical Investigation of the Energy Payback Time for Photovoltaic Modules. *Solar Energy*, 71, 165-172.
- Lewis, G. Keoleian, G. (1996). Amorphous Silicon Photovoltaic Modules: A Life Cycle Design Case Study. National Pollution Prevention Center, School of Natural Resources and Environment, University of Michigan.
- Meijer, A., Huijbregts, M., Schermer, J. Reijnders, L. (2003). Life-cycle Assessment of Photovoltaic Modules: Comparison of mc-Si, InGaP and InGaP/mc-Si Solar Modules. *Progress in Photovoltaics: Research and Applications*, 11, 275-287.
- Odum, H. (1996). *Environmental Accounting: Energy and Environmental Decision Making*. John Wiley & Sons, New York.
- Pearce, J., Lau, A. (2002). Net Energy Analysis for Sustainable Energy Production from Silicon Based Solar Cells. Proceedings of Solar 2002 Sunrise on the Reliable Energy Economy June 15-20, 2002, Reno, Nevada
- Peharz, G., Dimroth, F. (2005). Energy Payback Time of the High-concentration PV System FLATCON. *Progress in Photovoltaics: Research and Applications*, 13, 627-634.
- Raugei, M. Bargigli, S. Ulgiati, S. (2005). *Energy and Life Cycle Assessment of Thin Film CdTe Photovoltaic Modules*. Energy and Environment Research Unit, Department of Chemistry, University of Siena, Italy.
- Schaefer, H. Hagedorn G. (1992). Hidden Energy and Correlated Environmental Characteristics of P.V. Power Generation. *Renewable Energy*, 2, 15-166.
- Tripanagnostopoulos, Y. Souliotis M. Battisti R. Corrado A. (2005). Energy, Cost and LCA Results of PV and Hybrid PV/T Solar Systems. *Progress in Photovoltaics: Research and Applications*, 13, 235-250.

SUSTAINABLE ENGINEERING & DEVELOPMENT A DECADE ON IN THE UK AND EUROPE

Eur Ing Professor Roger Duffell MSc PhD CEng FICE

Professor Emeritus Civil Engineering University of Hertfordshire and sometime Visiting Professor University College London

1. Context

At the time of writing this paper the Montreal Climate Conference has passed with limited progress¹, the future of Energy resources and needs in the United Kingdom (UK) is the subject of yet a further review with an implicit emphasis on the nuclear option and a major pollution incident is reported from China². The World Trade Organisation (WTO) concluded in Hong Kong with very little progress (the subsequent round in Geneva collapsed in acrimony in July.) Be it French farmers or American cotton farmers *et al*, protectionism still prevails and the sharing of the world resources is hardly touched. Almost two and a half decades on from Brundtland's definition of Sustainable Development, the global capacity for absorbing human activity is under even greater peril; will the system collapse within this 21st century? Is one optimistic or pessimistic?

One can look at pertinent data from a few countries of immediate interest



Roger Duffell

Table 1. choosing six factors and an index to illustrate the contrasts between them. They encompass 70% of world population at different stages of development. Some key statistics – selected by the author – are robust proxies for the human condition including the proxy for CO₂ emissions with the USA 7943 million tonnes of oil equivalent (mtoe) against the UK's 3824, France 4470 and China's 960. China currently comprises 20% of world population, and is 'enjoying' a phenomenal growth rate around 8%.

Lined up facing each other is France with nuclear electricity contributing 80% of its energy needs against the UK's nuclear 20% – and diminishing to less than 5% 20 years hence, The UK's 20 year moratorium on nuclear plants contrasts with the USA's 25 years+ since Three Mile Island in 1979, though this will change.

The 'green' movement is well mobilised in Europe, especially in the UK, led arguably by Friends of the Earth and Greenpeace. Though they and others are not 'luddities', they do ensure any new and regeneration infrastructure development proposals are rigorously challenged with inevitable long lead times to design and construction. There are still diametrically opposed views on the route for the bypassing of prehistoric celtic Stonehenge (2000BC circa) in the UK. The external costs of developments are not yet factored in (i.e. the earth is a free good) Twenty years after the Exxon Valdez oil spill (1989) in Alaska (3), there is no final

1. Communications developments has enabled the world to witness the fuel tank farm explosion (95 ha) near to where the author lived nigh on 20 years ago in Hemel Hempstead on the 11th December 2005. Reportedly the greatest explosion in Europe since World War Two, the fire was put out three days later. Amazingly there was no loss of life - it occurring at 6am on a Sunday morning. He now lives 5 miles from the site and understands it was 2.4 on the Richter scale. The damage estimate is reportedly £200m but what of the external costs borne by the local and regional economies, and the question - to rebuild or not rebuild?

2. The essence of this paper was delivered at the University of Adelaide on the 20th February 2006 and the Sydney Chapter of Engineers Australia on the 28th February 2006. It was subsequently delivered in five locations in New Zealand in March 2006.