Presented at the 21st European Photovoltaic Solar Energy Conference, Dresden,Germany, 4-8 September 2006

ENVIRONMENTAL IMPACTS OF PV ELECTRICITY GENERATION - A CRITICAL COMPARISON OF ENERGY SUPPLY OPTIONS

E.A. Alsema, e.a.alsema@chem.uu.nl, Phone +31 30 2537618 Fax +31 30 2537601
Copernicus Institute, Utrecht University, Heidelberglaan 2, 3584 CS Utrecht, The Netherlands
M.J. de Wild-Scholten, m.dewild@ecn.nl, Phone +31 224 564736, Fax +31 224 568214
Energy research Centre of the Netherlands ECN, Unit Solar Energy, P.O. Box 1, 1755 ZG PETTEN, the Netherlands
V.M. Fthenakis, vmf@bnl.gov, Phone +1 631 344 2830, Fax +1 631 344 4486,
National Photovoltaic EH&S Research Center, Brookhaven National Laboratory, Upton, NY 11973, USA

ABSTRACT: An overview is given of the environmental impacts of different PV technologies both at the present status of technology and for future technology. Crystalline silicon PV systems presently have energy pay-back times of 1.5-2 years for South-European locations and 2.7-3.5 yr for Middle-European locations. For silicon technology clear prospects for a reduction of energy input exist, and an energy pay-back of 1 year may be possible within a few years. Thin film technologies now have energy pay-back times in the range of 1-1.5 years (S.Europe). Greenhouse gas emissions are now in the range of 25-32 g/kWh and this could decrease to 15 g/kWh in the future. Therefore PV energy systems have a very good potential as a low-carbon energy supply technology.

Keywords: environmental effect, Life Cycle Assessment, c-Si, a-Si, Cu(InGa)Se2, CdTe

1 INTRODUCTION

In the last years considerable progress has been made in the assessment of environmental impacts from photovoltaic systems. In this paper we will give an overview of recent results, identify remaining gaps in knowledge and compare the environmental performance of PV energy generation with other (future) energy supply options.
The following issues are generally perceived as important when discussing the environmental impacts of PV technology:

- Energy Pay-Back Time
- Greenhouse gas (GHG) mitigation
- Toxic emissions
- Resource supply
- Health & Safety risks

We will focus on the first two subjects in this paper and touch briefly on toxic emissions. For a discussion of resource supplies we refer to [6,7]. Health and safety issues are being discussed in a separate paper at this conference [5].
After covering some methodological issues, we will discuss the environmental impacts of PV systems based on crystalline silicon technology. This is followed by a review of thin film technologies. Balance-of-System components are not discussed here, an extensive comparison of roof-top and ground-based BOS options is presented in [4].

2 METHODOLOGY

All environmental impacts results generated by the authors were obtained by a full Life Cycle Assessment, using the software SimaPro 7 and the database Ecoinvent 1.2. For PV *modules* the end-of-life phase was excluded from the analyses because only pilot recycling processes are available at present. An LCA study on one of these pilot process can be found in [9]. Waste issues are also not discussed in this paper.
Two impact types receive the most attention: primary energy requirement and greenhouse gas emission. The primary energy use is calculated by means of the method Cumulative Energy Demand (v. 1.03) as implemented in Ecoinvent. For presentation purposes all energy requirements, fossil, nuclear and renewable are summed into one primary energy figure. The greenhouse gas emissions are evaluated by means of the IPCC 2001 GWP 100a method (version 1.02).
Unless stated otherwise we use the following assumption for system location and performance:

- application type: grid-connected system, with modules installed in-roof (see [4] for details)
- location: either South-Europe with irradiation 1700 kWh/m2/yr, or Middle-Europe with irradiation 1000 kWh/m2/yr;
- system Performance Ratio: 0.75
- system lifetime: 30 years, except the inverter which has a 15 year life.

All electricity supplied to PV-specific production processes, except silicon feedstock production, is assumed to be supplied by the average electricity system for continental Europe (UCTE region, medium voltage level) as modelled in Ecoinvent. For silicon feedstock production which is a highly energy-intensive process and thus usually located at sites with low electricity cost, we assume a specific mix of hydro power and high-efficiency Combined Cycle gas turbines. Electricity generated by the PV systems is also assumed to *displace* the UCTE-average supply mix.

3. CRYSTALLINE SILICON TECHNOLOGY

With respect to crystalline technology the European CrystalClear project has provided the conditions for generating up-to-date Life Cycle Assessments. In cooperation with major European and US manufacturers a set of Life Cycle Inventory data has been collected covering the entire value chain from silicon production to module manufacturing. After averaging data from different sources (i.e. manufacturers) the data set has been made publicly available [3]. Based on these data a transparent and up-to-date analysis can be made of multicrystalline, monocrystalline and ribbon silicon module manufacturing. Probably the new LCI data will also be incorporated in the next official update of Ecoinvent, a much-used database for LCA studies [14]. In this way comparative analyses of PV will at least be based on data that really reflect the current technology status.

After initial publication of the data in December 2005 we have updated some elements of it in preparation of a full update, which latter is planned for end 2006. One major improvement is that we have included a recycling process for the sawing slurry, the cutting fluid that is used in the wafer sawing process. This recycling process, which is usually performed by the slurry supplier, is able to recover 80-90% of the silicon carbide and of the polyethylene glycol and thus realizes significant reductions in the environmental impacts related to these materials. Because of the cost savings it offers, the use of recycled slurry materials has probably been adopted by the large majority of wafer producers. On a module level the resulting impact reductions have been found to be as high as 15%.

One other area with updated data is the energy consumption of the Czochralski process for monocrystalline ingot production. We received new data from 4 European and one US mono-Si manufacturer that allowed us to make a new, more reliable estimate which turned out to be significantly lower than the previous value [2]. Note that wafer thicknesses have not been updated yet, although significant changes have occurred since the year of our previous data collection (2004). (Such an update is not trivial as we also have to account for changes in cutting yield). Neither have data for ribbon technology been updated, thus these figures still reflect the technology status for 2004.

In figure 1 a key result is shown in the form of Energy Pay Back Times for roof-top systems based on one of the three silicon technologies and located either in Middle- or Southern-Europe (for system assumptions see section 2).

Energy pay back time is now in the order of 1.5-2 years for systems installed in South-Europe and 2.7-3.5 years for Middle-Europe. In comparison with previous evaluations monocrystalline silicon results have come down significantly, due to improved data for Cz growing. Both mono- and multi-Si profit from inclusion of the slurry recycling process in our process flow scheme.

Within the CrystalClear project we do not look at present-day technology only. Evaluation of expected technology improvements in the field of silicon technology is performed regularly. Of course major advances are expected with regard to wafer thickness and cell efficiency, driven by cost reduction targets and (current) silicon shortages. We assume wafer thicknesses of 150 μm for our case study of future mono and multi-Si and 200 μm for ribbon silicon. In line with the targets formulated in the latest CrystalClear roadmap we have set cell efficiencies at 15%, 17%, and 19% for ribbon, multi- and mono-Si respectively.

Other technology developments that can significantly affect the environmental impacts are:

- New silicon feedstock processes, especially the deposition of polycrystalline silicon in a Fluidized Bed Reactor could reduce by at least 70% the electricity consumption in comparison with the (modified) Siemens process that presently dominates the market. Note however, that the cell efficiencies of 17% respectively 19% we assume for multi- and mono-Si have not been demonstrated yet with FBR material;
- Improved energy-efficiency in new ingot growing facilities. In the data we collected from various manufacturers we observe quite significant differences in energy consumption for both casting of multicrystalline ingots as for Czochralski growing of monocrystalline crystals, which can even amount a factor 3. However, careful consideration is always required if all data refers to the same unit output (i.e. with or without yield losses; before or after squaring, etc). Not surprisingly newer facilities appear to have lower energy consumption. We therefore assume for our evaluation of future production that today's best technology will become the standard.

Given the fast developments in crystalline silicon production we believe that most of these improvements may be realised within a few years.

Table 1 below summarizes our main assumptions for future technology and figure 2 shows the effects on energy input per m^2 module area. Observe that no changes for the energy input of the cell and module assembly process have been assumed here. If the assumed high efficiencies requires extended use and/or a higher class of clean room conditions for the cell line, this would increase energy consumption for the cell process. On the other hand the recent introduction of the new fast-cure EVA formulations will probably decrease energy consumption for the module.

Figure 3 shows the reduced impacts in terms of energy pay-back time and figure 4 in terms of GHG emissions.

Under the present assumptions all three silicon technologies could in the near future realize an EPBT below 1 year and a greenhouse gas emission of only 15 g/kWh. Differences in impacts between technologies tend to disappear as common processes and materials get an increasing share in the overall impact. Below we will compare the GHG emissions with those of competing low-carbon energy options.

4. THIN FILM TECHNOLOGIES

Currently thin film technology has a much smaller market share than crystalline silicon. Worldwide there are only a few commercial-scale production facilities. Therefore, only a few LCA studies of thin film industrial production processes exist. For the same reason publication of an LCI data set for major thin film technologies, following the recent example of c-Si industry, has not been possible yet. With the growing investments in thin film production facilities such an action should become easier though.

One of the best-documented thin-film LCA studies has been conducted by Fthenakis and Kim, on the production of CdTe modules by First Solar [1, 10]. Key results are depicted in figures 5 and 6, showing respectively the Energy Pay-Back Time and the GHG emissions. PV systems are as discussed in section 2, except that a ground-mounted installation was considered instead of a roof-top system. For module impacts, though, this makes no difference. Because these modules are produced in the USA the background database is also specifically chosen to reflect the USA production environment (Franklin

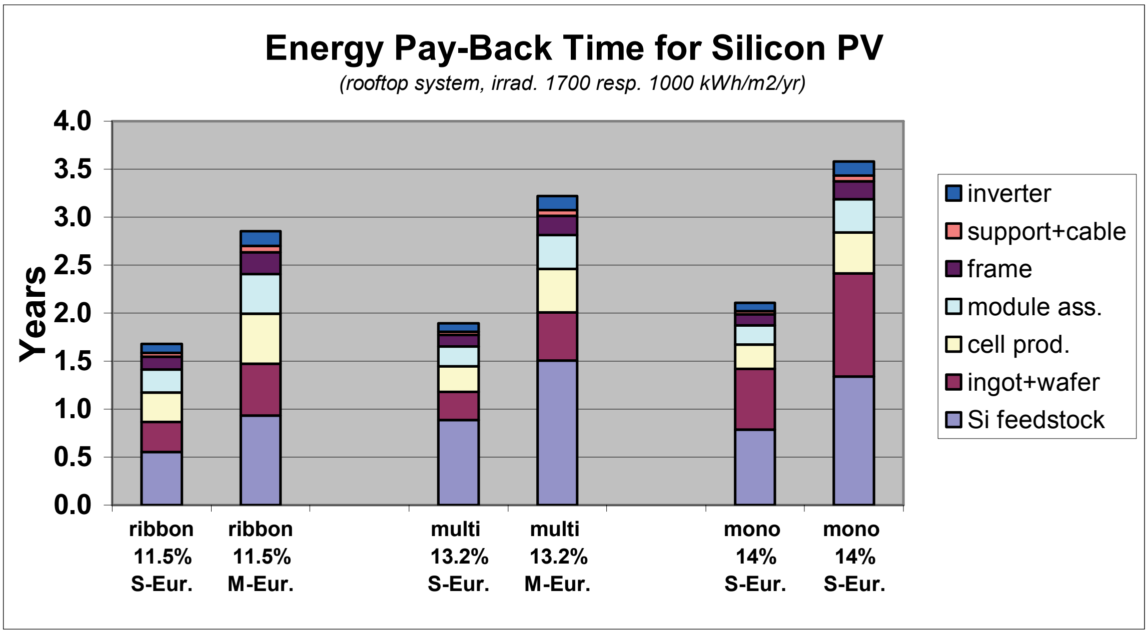


Figure 1: Energy Pay-Back Time (in year) of rooftop PV systems based on crystalline silicon technology at two different locations, South-Europe with 1700 kWh/m2/yr irradiation and Middle-Europe with 1000 kWh/m2/yr. Module efficiencies are shown for each technology; system Performance Ratio 0.75

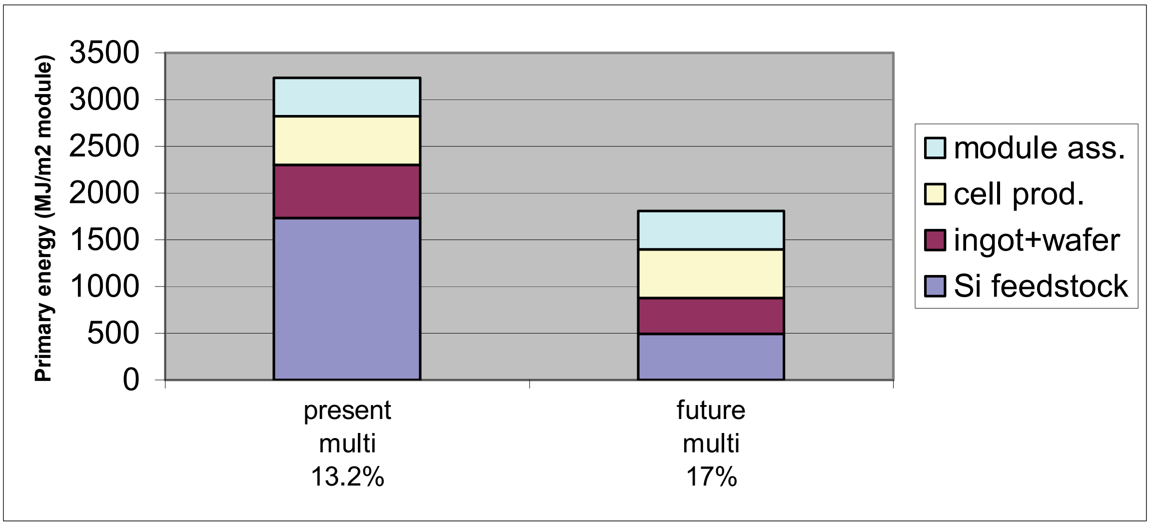


Figure 2: Comparison of primary energy input (MJ per m2 module) of present with future multicrystalline silicon module.

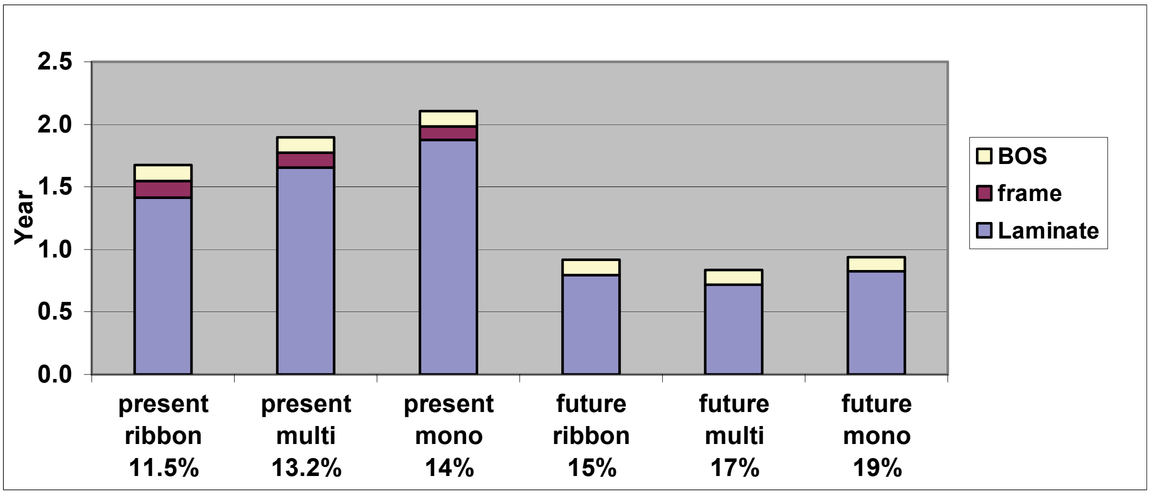


Figure 3: Energy Pay-Back Time for future silicon PV systems. System installed in South-Europe

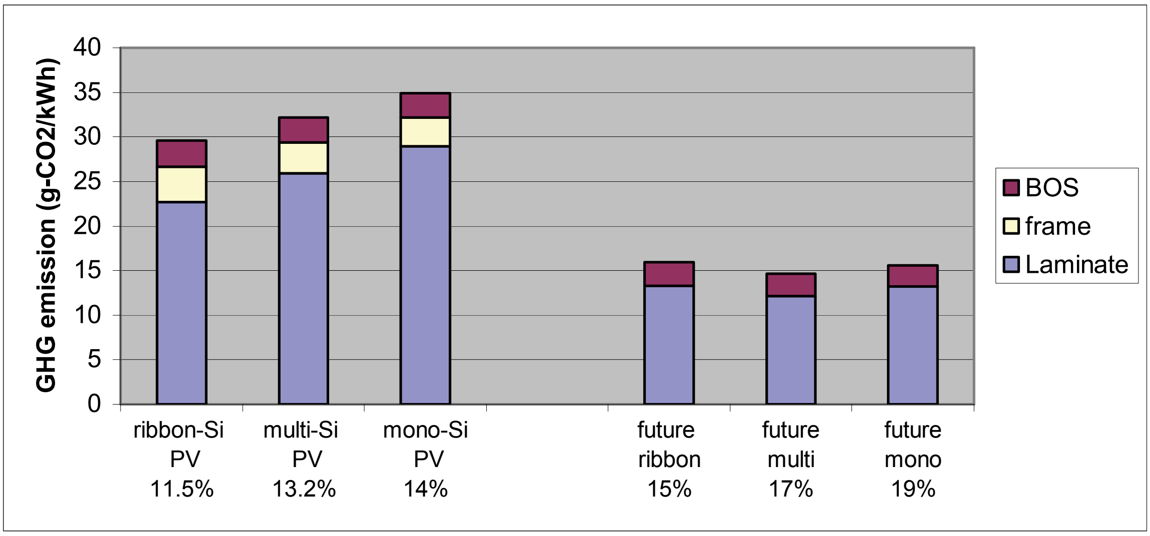
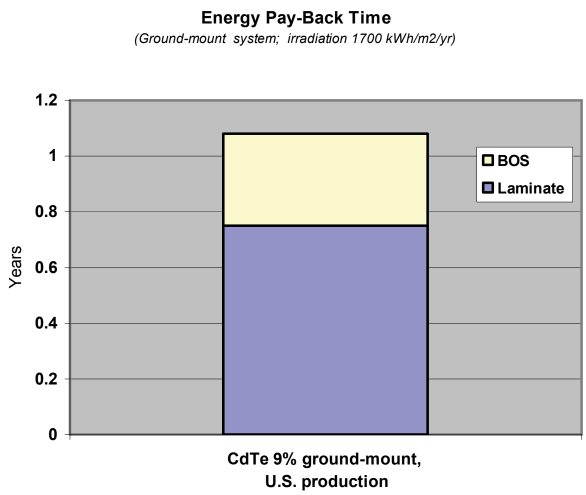
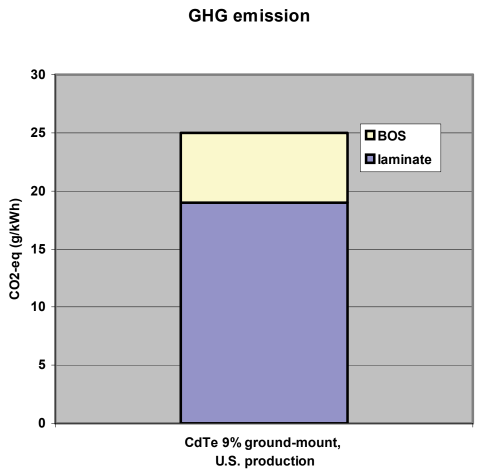


Figure 4: Life-cycle GHG emissions of present and future silicon PV systems, at a S.-European location.

Table 1: Assumptions for future multi-Si, mono-Si and ribbon technology

	Ribbon-Si	**Multi-Si**	**Mono-Si**
Si Feedstock		"Solar-grade" silicon produced with Fluidized Bed Reactor technology	
Crystallisation	Standard Technology 2004	Best Available Technology 2004	Best Available Technology 2006
Wafer thickness	300 -> 200 um	285 -> 150 um	300->150 um
Module efficiency	11.5 -> 15 %	13.2 -> 17%	14->19%
Module assembly	Frameless module	Frameless module	Frameless module





Figures 5 and 6: Environmental indicators for CdTe technology, ground-mounted system in South-Europe, PR=0.75

database). Among others the CO2 emissions of US electricity production is higher than in Europe.
We observe that for this technology an EPBT of about 1 year is already accomplished, despite the lower module efficiency in comparison with c-Si technology. Also GHG emissions are comfortably low. In an European project, named SENSE, three thin film production processes were analysed in cooperation with manufacturers. Although a final report has not been published yet, some preliminary results are shown below, with thanks to SENSE project team (figure 7). Because these results were generated with a different LCA database at the background (i.e. GaBi LCA software and database) and possibly with different LCA system boundaries, the results cannot be compared one-to-one with those of for example Fthenakis and Kim. Again we can observe that EPBT values are relatively low in comparison with crystalline silicon, and that the contribution of BOS is a bit higher, due to the somewhat lower module efficiency. Of course BOS material quantities may also differ from the c-Si case.
If we also consider future possible reductions in EPBT and GHG emission for silicon technology we can observe that the difference between thin-film and c-Si technology might well disappear into the error margin. Improvements in the energy consumption and related GHG emissions are less obvious for thin film production. Thin film module efficiency will undoubtedly increase but if we assume a module efficiency of 15% for CdTe modules the GHG emission will come down to about 15 g/kWh, i.e. in the same range as future c-Si PV.

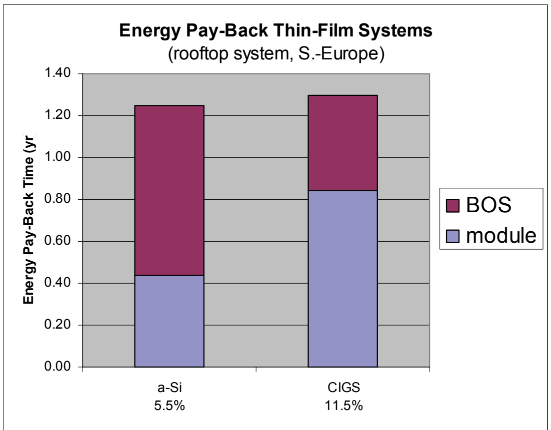


Figure 7: Energy Pay-Back Time for two thin film technologies, as reported by the SENSE project [8].
Rooftops system in S. Europe, Performance Ratio= 0.75. (Preliminary data).

One issue that has often raised concerns is the use of cadmium in CdTe modules. Cadmium in its metallic form is a toxic substance that has the tendency to accumulate in ecological food chains. However, one should be aware that the compound CdTe is more stable than most other cadmium compounds and is not soluble in water, so that risks of cadmium leaching i.e. from broken modules are small. Moreover the amount of cadmium used in PV modules is small (5-10 g/m2) and the material is completely encapsulated in the module. Risks of cadmium emission in fires have been shown to be very small, provided that double-glass encapsulation is used [11,18]. With proper emission control techniques in place the cadmium emissions from module production can be almost zero and emissions from zinc/cadmium winning have also been reduced substantially over the last decades [15]. It has even been argued that CdTe modules form an environmentally safe way of sequestering cadmium that is produced anyway (as an unavoidable by-product of zinc winning). Essential prerequisite for such a thesis is that a closed loop for cadmium can be realised, i.e. that (almost) all cadmium can be recovered from CdTe modules.
Currently a module take-back system has been set up by at least one manufacturer (First Solar) and CdTe modules are being recycled in a pilot scale process or used as a flux agent in metal smelters. First experiments with a different, more efficient recycling process have shown promising results [12].
Based on a comprehensive LCA performed by Fthenakis and Kim [17], the life-cycle cadmium emissions of CdTe-based PV systems have been compared with those of other module types and also with other energy technologies (see figure 8). According to this study the cadmium emissions of CdTe technology are among the lowest, and even lower than those of silicon PV technology. This result which at first sight may seem counter-intuitive, is caused by the cadmium emissions in electricity production plants that are fuelled by coal or oil. In other words because the *direct* cadmium emissions in the CdTe module production are very low, it is actually the electricity input for module production - and the related *indirect* cadmium emissions - which determines the total life-cycle emission for a PV system.
This again highlights the importance of reducing energy input for (c-Si) module production.

5. COMPARISON WITH OTHER ENERGY SUPPLY OPTIONS

In order to attain a sustainable energy supply system it is very important that a portfolio of low-carbon energy technologies with a reasonable cost level becomes available as quickly as possible. Most probably there will finally not be one single “best technology” but depending on the local resources (e.g. irradiation), application (e.g. stationary or moving), power demand and available infrastructure a choice among available sustainable energy options will be made.
Can PV technology be considered one of those sustainable energy options? In figure 9 we have depicted the life-cycle greenhouse gas emission of different energy supply options. Among these options we also included fossil-fuelled power plants that are combined with carbon capture and sequestration (CSS) technology. Early experiments with CSS have been promising and there appears to be a sufficiently large potential in underground reservoirs where CO2 can be stored safely for long periods [13].
Also nuclear energy is included in the figure, separately for Europe and for the US. This difference between European and US nuclear is mainly due to the different fuel processing technologies used in these two regions. In Europe the more energy-efficient ultracentrifuge process is dominant, while in the mostly uses gas diffusion at this time. It seems likely though that in the future the US will also gradually switch over to the ultracentrifuge process [16].

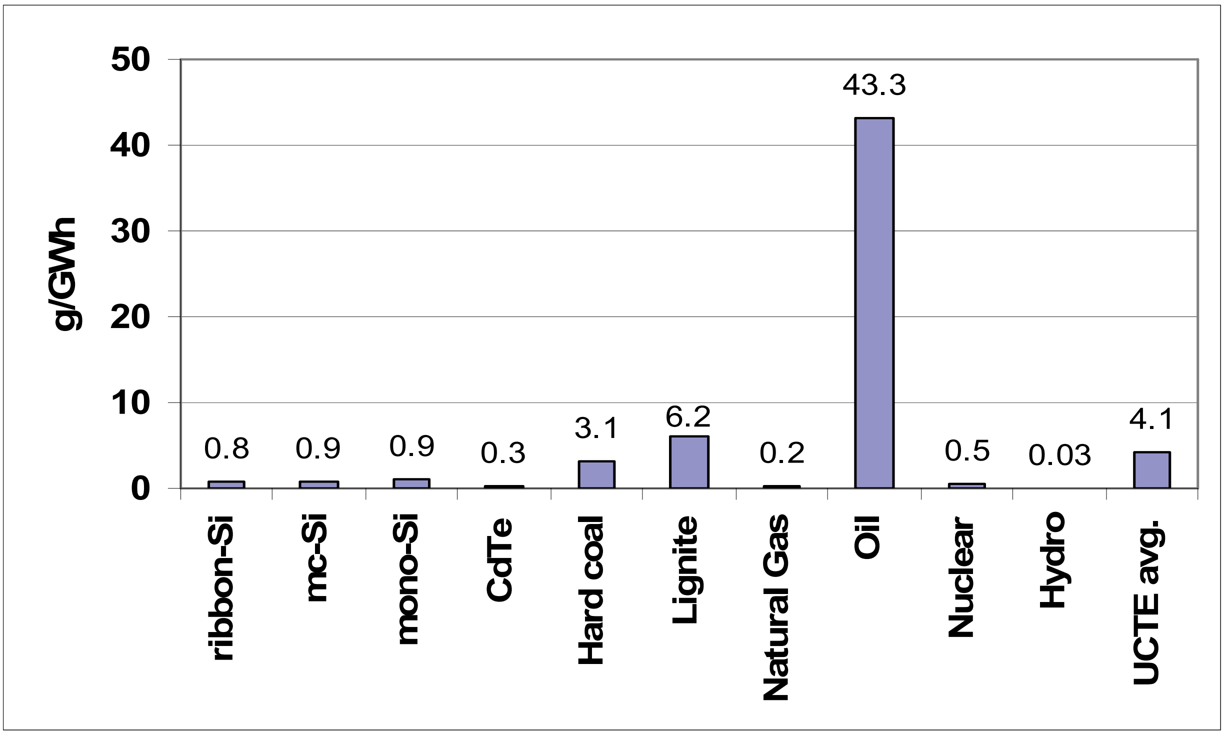


Figure 8: Life-cycle cadmium emissions (in g/kWh) from different energy technologies. PV systems located in S.-Europe, PR=0.80. Non-PV technologies based on Ecoinvent database.

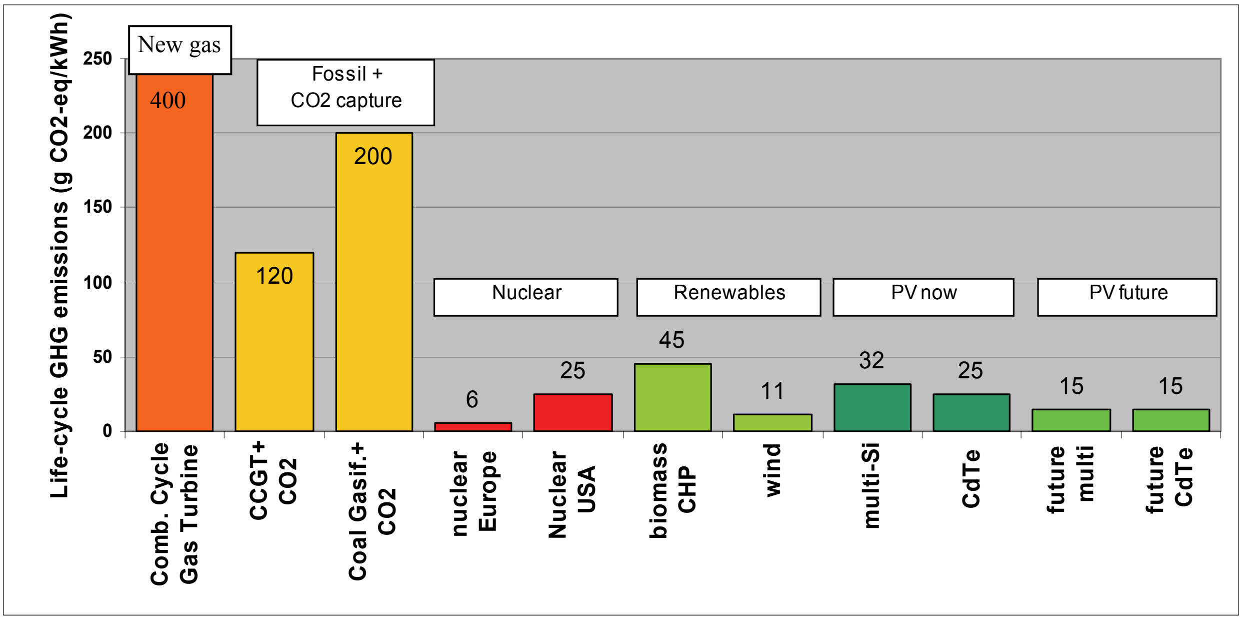


Figure 9: Comparison of GHG emissions of different energy supply options, PV systems installed in S.-Europe (Sources: [12, 13, 14])

If we compare present-day PV technology (at a South – European location) with other energy options we see that PV has considerably lower GHG emissions than all fossil options including fossil + CSS. But in comparison with nuclear and wind energy present-day PV has still relatively high GHG emissions, especially if we install PV systems at lower-irradiation regions. On the other hand we have shown that there are good prospects for further reduction of the GHG emissions, down to a comfortable low value of 15 g/kWh.

Of course sustainability comprises more than only low-carbon emissions, it also implies for example that no burdens are left for future generations, and in this respect PV technology appears to have a better profile than for example nuclear energy or fossil fuel with CSS, provided that we in PV technology are able to close the material loops by developing effective recycling processes. Also one should not forget that PV has a very large potential for application, larger than wind energy and probably also larger than nuclear and carbon storage

6. CONCLUSIONS

We have given an overview of the environmental impacts of present-day PV technology and the effects of probable future developments in (production) technology. Depending on cell technology energy pay-back times are now between 1 and 2 years for a Southern-European locations and between 1.7 and 3.5 for Middle-European locations. Thin film technology are at the lower end of this range. For silicon technology clear prospects for a reduction of energy input exist, and an energy pay-back of 1 year may be possible within a few years.

Hazardous emissions connected to PV technology are primarily related to energy consumption in the manufacturing process, as direct process emissions are almost zero. Therefore cadmium emissions from CdTe technology can be lower than those of most other energy options. Risks from the use of cadmium telluride in modules appear to be quite low, provided that the material is kept well-encapsulated (double-glass encapsulation) and that it can be recovered from waste modules.

PV systems have life-cycle greenhouse gas emissions in the range of 25-35 g/kWh (at S-European location) which is relatively low in comparison with other energy options that have a large application potential.

In conclusion we can say that PV technology is in a very good position to be included in a portfolio of low-carbon energy technologies for a future sustainable energy supply, especially if further cost reductions can also be achieved. Attention to further reduction of energy consumption should also remain a point of attention especially in the areas of silicon feedstock production and ingot growing. Further LCA studies of thin film technology should contribute to create greater transparency and more insight in improvement options for these technologies.

ACKNOWLEDGEMENTS

Part of this work was carried out in the Integrated Project CrystalClear and funded by the European Commission under contract nr. SES6-CT_2003-502583. The cadmium telluride research was conducted within the PV EH&S Research Center, BNL, under contract DE-AC02-76CH000016 with the US Department of Energy.

The authors gratefully acknowledge the help of experts from the following companies: Deutsche Cell, Deutsche Solar, Evergreen Solar, First Solar, HCT Shaping Systems, Isofoton, Photowatt, REC, Scanwafer, Schott Solar, Shell Solar (now SolarWorld) and also other unnamed experts.

REFERENCES

[1]. Fthenakis, V. and E. Alsema, *Photovoltaics Energy Payback Times, Greenhouse Gas Emissions and External Costs: 2004–early 2005 Status.* Progress In Photovoltaics: Research and Applications, 2006. **14**(3): p. 275-280.

[2] E.A.Alsema, M.J.de Wild-Scholten, Environmental impacts of crystalline silicon photovoltaic module production, *LCE2006, 13th CIRP International Conference on Life Cycle Engineering, Leuven, Belgium* (2006) http://www.ecn.nl/library/reports/2006/rx06041.html.

[2] J.E.Mason, V.M.Fthenakis, T.Hansen, H.C.Kim, Energy payback and life-cycle CO2 emissions of the BOS in an optimized 3.5 MW PV installation, *Progress in Photovoltaics* **14** (2006) 179.

[3] M.J.de Wild-Scholten, E.A.Alsema, Environmental Life Cycle Inventory of Crystalline Silicon Photovoltaic System Production - Excel file, **ECN report ECN-E--06-019** (ECN Solar Energy, 2006), http://www.ecn.nl/publications/default.aspx?nr=ECN-E--06-019.

[4] M.J.de Wild-Scholten, E.A.Alsema, E.W. ter Horst, M. Bächler, V.M. Fthenakis, A cost and environmental comparison of rooftop and ground-based PV Systems, this conference.

[5] V.M. Fthenakis, et al. Evaluation of risks in the Life Cycle of Photovoltaics in a comparative context, paper 8.CO.1.2, this conference.

[6] R. Gellings, K. Schmidtfrerick, A. Schlumberger, J. Siemer, Only united we are strong, Supply problems await areas other than silicon, Photon International, July 2006, p.80-89.

[7] B. A. Andersson, , C. Azar, J. Holmberg and S. Karlsson, Material constraints for thin-film solar cells, Energy Vol 23, Issue 5, 1998, P 407-411

[8] M. Shibasaki, personal communication, University of Stuttgart, August 2006.

[9] Müller, A., K. Wambach and E.A. Alsema, Life Cycle Analysis of Solar Module Recycling Process, Proceedings of MRS Fall 2005 Meeting, Boston, MS, Nov-Dec 2005

[10] Fthenakis V.M. and H.C. Kim, Life Cycle Energy Use and Greenhouse Gas Emissions Embedded in Electricity Generated by Thin Film CdTe Photovoltaics, Proc. MRS Fall 2005 Meeting, Boston, 2005.

[11] Fthenakis, V.M., Fuhrmann M., Heiser J. Lanzirotti A., Fitts, J. and Wang W., Emissions and Redistribution of Elements in CdTe PV Modules During Fires, Progress in Photovoltaics, Volume 13, Issue 8 , p. 713 – 723.

[12] V.M. Fthenakis and W. Wang Extraction and separation of Cd and Te from CdTe photovoltaic manufacturing scrap, Progress in Photovoltaics, 14, 363-371 (2006).

[13] B. Metz, O. Davidson, H. de Coninck, M. Loos, L. Meyer, Carbon Dioxide Capture and Storage, IPCC Special Report, Technical Summary, ISBN 92-9169-119-4, www.ipcc.ch

[14] Frischknecht et al., Ecoinvent LCA database, www.ecoinvent.ch

[15] V.M. Fthenakis and Wang W., Emission Factors in the Production of Materials Used in Photovoltaics, 20th EURPVSEC, Barcelona, Spain, June 6-10, 2005

[16] V.M. Fthenakis and Kim. H.C. l, Greenhouse-gas Emissions from Solar Electric and Nuclear Power: A Life-cycle Study, , Energy Policy, in press.

[17] V.M. Fthenakis and Kim. H.C., CdTe Photovoltaics: Life-cycle Environmental Profile, European Material Research Society Meeting (EU-MRS), Symposium O, Invited Paper, Nice, France, May 29-June 2, 2006.

[18] Fthenakis V.M., Life Cycle Impact Analysis of Cadmium in CdTe Photovoltaic Production, Renewable and Sustainable Energy Reviews, 8, 303-334, 2004.