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Life cycle assessment and energy pay-back time of advanced photovoltaic modules: CdTe and CIS compared to poly-Si

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Abstract

The paper is concerned with the results of a thorough energy and life cycle assessment (LIA) of CdTe and CIS photovoltaic modules. The analysis is based on actual production data, making it one of the very first of its kind to be presented to the scientific community, and therefore especially worthy of attention as a preliminary indication of the future environmental impact that the up-scaling of thin film module production may entail. The analysis is consistent with the recommendations provided by ISO norms 14040 and updates, and makes use of an in-house developed multi-method impact assessment method named SUMMA, which includes resource demand indicators, energy efficiency indicators, and "downstream" environmental impact indicators. A comparative framework is also provided, wherein electricity produced by thin film systems such as the ones under study is set up against electricity from poly-Si systems and the average European electricity mix. Results clearly show an overall very promising picture for thin film technologies, which are found to be characterised by favourable environmental impact indicators (with special reference to CdTe systems), in spite of their still comparatively lower efficiencies.

Keywords: LCA; Photovoltaics; CdTe; CIS; Thin film

1. Introduction

Photovoltaic (PV) energy generation devices have experienced a sharp, almost 10-fold increase in production over the last decade in all major industrialised countries. Since the late 1990s, two new PV technologies have begun to be employed commercially alongside the more traditional Si-based systems: cadmium telluride (CdTe) and copper indium diselenide (CIS). These thin film PV modules still constitute a tiny fraction of the total PV market, but things may change quickly as new manufacturers hit the market each year.

Many comprehensive studies on Si-based PV are available in the scientific literature (of which we will only cite a few among the most representative: [1–3] but only few papers so far have covered CdTe and/or CIS in any depth [3–7]. Moreover, most of the available papers on thin film PV have been based on predicted data extrapolated from laboratory-scale production. On the contrary, the present analysis of thin film PV modules is entirely based on hard production data (prototype batch production for CIS and standard production for CdTe, respectively), and as such is especially worthy of attention as a preliminary indication of the future environmental impact that the up-scaling of their production may entail.

2. Analysed systems and major assumptions

The main topic of the present analysis is the production and use of thin film (CdTe and CIS) photovoltaic modules. For comparative purposes, the authors also performed a parallel analysis of more traditional poly-crystalline silicon (poly-Si) modules, making use of manufacturer-provided module assembly data and of available life cycle inventory data regarding Si wafer production (ETH-ESU [8]).

The analysis was initiated within the framework of a European research study on the acceptability of advanced PV systems (PVACCEPT/IPS-2000-0090), and its main scope is to evaluate how these newer technologies compare

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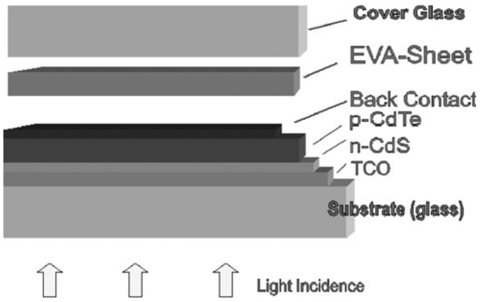

Fig. 1. Structure of a typical CdTe PV module.

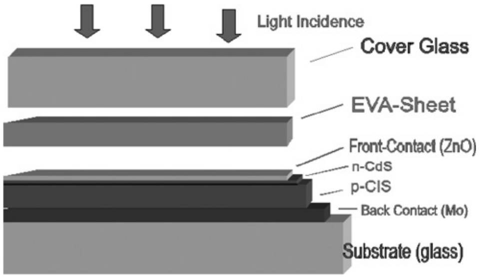

Fig. 2. Structure of a typical CIS PV module.

to the more mature silicon-based ones from the points of view of environmental and thermodynamic performance in real-life installations.

In thin film technologies the photoactive P/N junction is made up of two semiconductor compounds, CdTe or $CuInSe_2$ and CdS, which are directly deposited in extremely thin layers (~10 and ~0.1 μm, respectively) on a treated transparent glass pane by means of a vacuum vaporisation process. Series connection of adjacent P/N junctions is achieved by means of a series of automated laser and mechanical scribing processes, and then a second protective glass pane is added on top to form the finished module. The structures of typical CdTe and CIS modules are illustrated in Figs. 1 and 2, respectively.

For the purposes of the present analysis, the system boundaries were drawn around the module production facility, and thorough inventories of the necessary inputs for the production process of 1 m^2 of frameless CdTe and CIS modules were made, which are presented in Tables 1 and 2 (sensitive data, including photoactive material quantities, are presented in aggregated form for confidentiality reasons, but were individually available to the authors). In order to enlarge the scale of analysis to the complete cradle-to-gate life cycle of the product, the indirect energy and material requirements for the upstream production stages relative to the inputs listed in Tables 1 and 2 were estimated based on the available databases (ETH-ESU [8], BUWAL 250 [9]). The employed electricity mix is assumed to be that of the European Union for the co-ordination of production and transmission of Electricity (UCPTE), Medium Voltage, throughout.

Table 1
Inventory of main input flows to the CdTe module manufacturing process

Glass	24,960 g/m^2
Water	1250 g/m^2
EVA	630 g/m^2
$\{CdTe+CdS+CdCl_2+Sn+Ni/V+ITO+Sb_2Te_3\}$	230 g/m^2
Electricity	236 kWh/m^2

Table 2
Inventory of main input flows to the CIS module manufacturing process

Glass	24,960 g/m^2
Water	1250 g/m^2
EVA	880 g/m^2
$\{Mo+Cu+In+Ga+Se+CdS+ZnO+CuSn\}$	70 g/m^2
Electricity	24.3 kWh/m^2

The nominal conversion efficiency of the modules are equal to 9% for CdTe and 11% for CIS, while that of poly-Si modules was assumed to be 14%, which is a typical value for the current state of the art in actual production systems.

As a side note on the topic of efficiency, it should be considered that, while Si-based modules operate at lower.than.nominal efficiency in low irradiation conditions (overcast weather), the opposite is true for thin-film types, the efficiency of which actually increases in such conditions. In this work, however, nominal efficiency values were employed, in order to facilitate the comparability to other literature studies.

For crystalline Si-based modules, one important set of assumptions must be made regarding the preliminary step of Si wafer production. In fact, since in these systems this invariably turns out to be the most energy demanding step by far, these assumptions are of crucial importance, and also lie at the basis of the large variability that is to be found in the available scientific literature on this topic. In synthesis, there are two major possible sources for the Si wafers employed in PV: off-grade silicon coming from the semiconductor industry or direct solar grade silicon (SoG-Si) production.

In the first case, one further decision has to be made regarding the possible allocation of the calculated energy and environmental impacts of electronic grade silicon (EG-Si) production to the electronic industry according to economic criteria. Such allocation would result in lower impact indicators for the EG-Si employed in PV, since the electronic industry currently represents approximately a 70% share of the total EG-Si market.

In the present study, the choice was made to employ widely accepted "standard" literature data on Si wafer production (ETH-ESU [8], 310 μm-thick wafers), which essentially reflect the exclusive use of off grade Si from the semiconductor industry. When allocated entirely to PV according to a purely material allocation, this option can be regarded as a "worst case" reference scenario for modern poly-Si PV (referred to herein after as "poly-Si A"). A second scenario is also provided, in which only 30% of the material and energy requirements of EG-Si production and of its associated emissions are allocated to PV (referred to herein after as "poly-Si B"). Lastly, for those indicators for which data were available (namely: GER, EPBT and GWP), the comparison was also extended to include the results published in a recent authoritative literature study by Alsema et al. [1] (referred to herein after as "poly-Si C"), which may be considered representative of the current (2005) state of the art of poly-Si PV. This latter study makes use of many updated data, and assumes a wafer thickness of 285 μm and the use of a different electricity mix for the production of the polycrystalline Si feedstock (50% natural gas/50% hydropower).

For all analyses, the average Southern European yearly irradiation, 1700 kWh/(m^{2}a), was chosen as a common basis, and for all systems, a 25% efficiency loss was assumed with respect to the nominal values (i.e. performance ratio = 75%), in order to cumulatively account for the losses caused by the cables and the inverter, as well as by atmospheric dust deposition. This is standard procedure adopted in most studies on photovoltaic electricity, and reflects the fact that real-life efficiencies are always lower than those attainable with single cells in laboratory conditions.

In order to compute the energy pay-back time of all types of modules, the average UCPTE electricity generation efficiency of 32% was assumed.

Lastly, since all those indicators which are expressed per kWh of electricity produced are directly dependent on the assumed lifetime of the system, the latter was assumed to be equal to 20 years for all PV systems (the literature study for system "poly-Si C" originally assumed 30 years, but data were adapted). A lifetime of 20 years is in accordance to the warranty given by the manufacturers of CIS and CdTe thin film modules has already been proven to be easily attainable for poly-Si modules.

The analyses were first performed for the frameless modules (laminates), and then all three were similarly extended to include the so-called balance of system (BOS) for a typical grid-connected rooftop installation. The same BOS assumptions were applied to all systems, including "poly-Si C". An inventory of the BOS components per square mere of PV module is presented in Table 3.

Module decommissioning at the end of their life cycle was not included in the analysis, because of lack of reliable data for the new technologies employed. All waste materials generated in the production phase are assumed to be recycled and/or safely disposed of (including the acidic and basic solutions used for module washing).

3. Evaluation method

The analysis consists of a thorough LCA, carried out in accordance to the relevant recommendations by the International Standardisation Office (EN ISO 14040 and updates), and is performed in four stages: (1) scoping, (2) inventory analysis, (3) impact assessment, and (4) interpretation.

Table 3
Inventory of main input flows to the BOS per square metre of PV module

Al (frame)	1900 g/m^2
Steel (support structure)	25,000 g/m^2
Cu (cables and contact boxes)	40 g/m^2
Plastics (cables and contact boxes)	40 g/m^2
Fuel oil (for installation)	10.8 MJ/m^2

The choice of the impact assessment method to be applied is generally left to the analyst. This, of course, strongly affects the interpretation stage and whatever conclusions can be drawn from the results of the LCA.

It is the authors' firm belief that no single method is by itself capable of providing an all-encompassing picture of the environmental performance of a technological system, each and every one only being appropriate within a limited field of applicability. The choice was then made to perform a multi-method analysis, in which the results of several different methods are compared and integrated.

Using their original "sustainability multi-method multi-scale assessment" (SUMMA) approach [10], the authors employed a selection of methods, which offer complementary points of view on the complex issue of environmental impact assessment, namely: material flow accounting [11–13], embodied energy analysis [14,15], emergy synthesis [16–18] and CML 2 baseline 2000 [19]. A brief introduction to the employed methods is provided here; for further details on each individual method, the reader is asked to refer to the cited literature.

- Material flow accounting is a method that looks at overall material resource depletion on the life cycle scale. The chosen indicators are the abiotic and water material input per unit of service (MIPS) indicators, which are proxies respectively for the total amount of abiotic matter (i.e. minerals, fuels, etc.) and water that were directly *and indirectly* required to provide the necessary inputs to the manufacturing process, expressed per unit of delivered service (kWh of electricity).
- Embodied energy analysis is a popular method whereby the total commercial energy requirement of the analysed system is assessed on its life cycle scale. Two useful indicators are produced: the gross energy requirement (GER) itself, measured in MJ of primary energy per kW-peak of installed electric power, and the energy payback time (EPBT), computed as the ratio of the GER to the avoided primary energy requirement for the production of the same amount of electricity delivered by the system (assuming the average conversion efficiency of the chosen electric mix).
- Emergy synthesis (spelt with an 'm') attempts to evaluate the environmental support required by the

analysed system on the global scale, also taking into account all the free environmental inputs such as sunlight, wind, rain, tidal energy and geothermal heat which are not usually accounted for in embodied energy analyses, and, most importantly, extending the accounting back in time to include the environmental work needed for resource formation. A system is thus evaluated in terms of its solar 'emergy', defined as the total amount of solar available energy (exergy) that was directly *and indirectly* required in order to produce or support the system itself (including, for instance, the solar energy previously required for the formation of the employed fossil fuels). When expressed per unit of output, this quantity is termed specific emergy or transformity , and can be considered a "quality" factor which functions as a measure of the intensity of the overall support provided by the biosphere to the system under study. In this paper it was chosen to present the emergy synthesis indicator in relative, dimensionless terms, where the transformity of the European UCPTE electricity mix is taken as the reference value (= 100%). This was done in order to better focus on the comparison among the different technologies rather than on absolute numbers.

- CML 2 baseline 2000 is the updated version of a popular impact assessment method which is included in many commercial LCA software packages. In particular, in this study we selected three indicators from this method, namely: global warming potential (GWP), acidification potential (AP), and freshwater aquatic ecotoxicity potential (EP). Each of these three indicators aims to assess the potential environmental harm caused by the system's emissions with reference to its respective impact category, and makes use of specific equivalency ('characterisation') factors to a chosen reference compound (CO_2, SO_2 and 1,4-dichlorobenzene, respectively). AP and EP are here presented in dimensionless terms, where the AP and EP of the European UCPTE electricity mix are respectively taken as the reference values (= 100%). This was done in order to better focus on the comparison among the different technologies rather than on absolute numbers.

In SUMMA, the inventory analysis (LCA stage 2) forms the common basis for all the subsequent impact assessments (LCA stage 3), which are carried out in parallel, thus ensuring the maximum consistency of the input data and inherent assumptions.

The resulting indicators are then interpreted (LCA stage 4) within a comparative framework, in which they are set up against each other and contribute to providing a comprehensive picture on which conclusions can be drawn.

4. Results and interpretation

The calculated impact indicators for the analysed PV systems are presented in Figs. 3–10. For GER, EPBT and GWP (Figs. 5, 6 and 8), an extra column is added for the results of the study by Alsema et al. [1] ("poly-Si C"). Additionally, in all figures it was chosen to include one more column showing the value of the same indicator for electricity produced using the UCPTE electric mix (based on literature data); this was done in order to provide an external reference point for PV.

The results presented here can be considered representative of the current state of the art of thin film modules in Europe in early 2005, since Antec Solar and Wuerth Solar were respectively the only producers of CdTe and CIS modules on the market at the time. As already mentioned in Section 1, however, the data made available to the

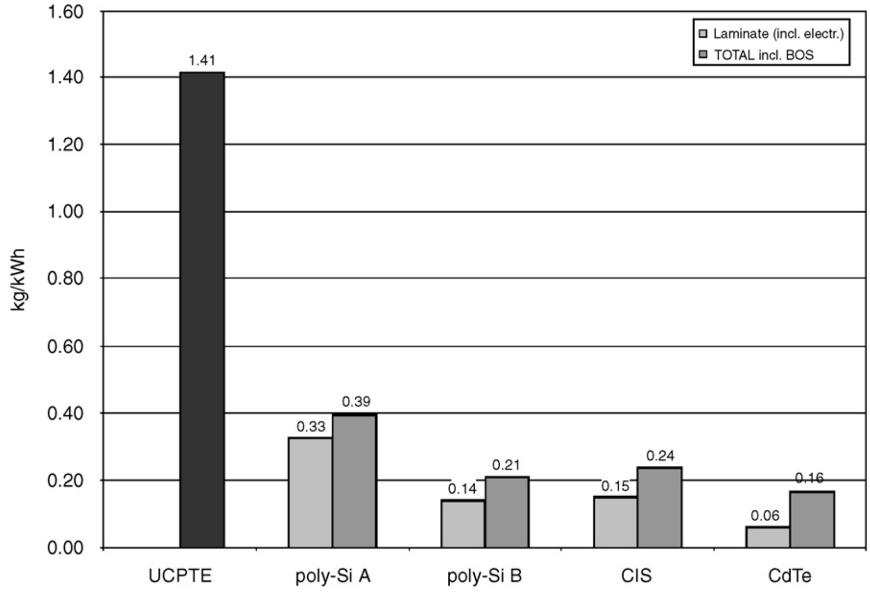

Fig. 3. Abiotic material input per unit of service of PV systems and of the UCPTE electricity mix.

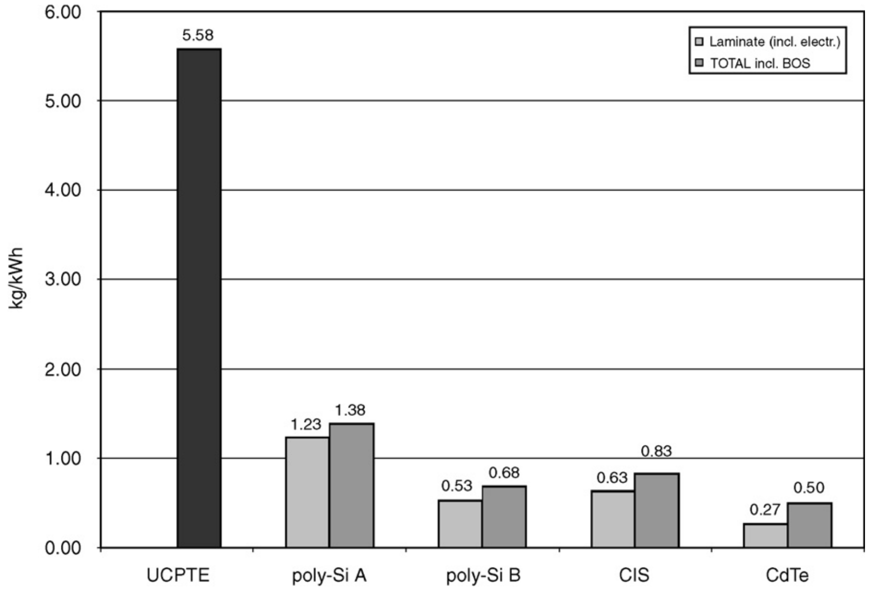

Fig. 4. Water material input per unit of service of PV systems and of the UCPTE electricity mix.

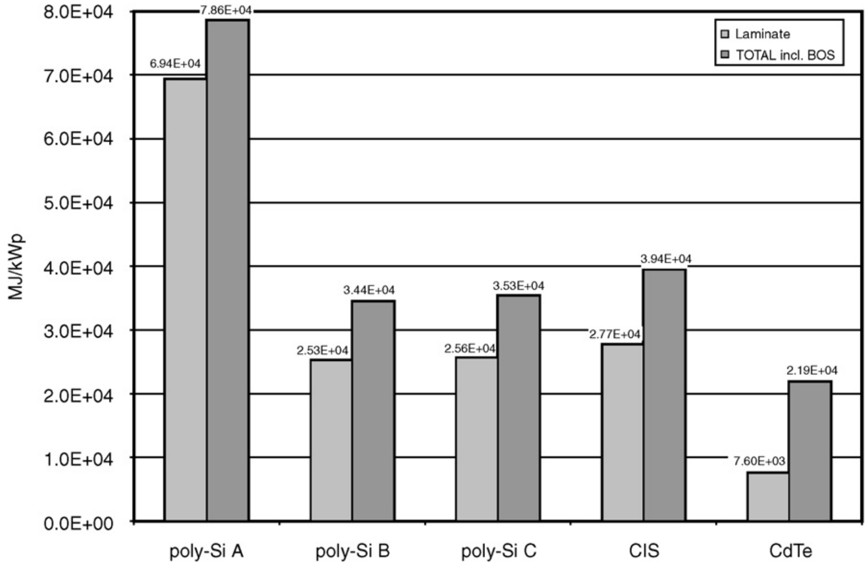

Fig. 5. Gross energy requirement of PV systems.

authors on CIS were relative to prototype batch production units, and therefore are probably subject to comparatively larger improvements in the near future, as standard production begins. In this regard, it will be interesting to compare the findings of this study to those of later analyses based on mass-production CIS modules, when they are available.

In particular, the following considerations apply:

- The performance of both thin film systems (CdTe and CIS) can be considered quite satisfactory, especially considering their early developmental stage, since they compare favourably to the well-established poly-Si systems. It could be argued that the contribution of the technology-specific chemicals employed in thin film modules (i.e. In_2O_3, CdS, CdTe and Sb_2Te_3 for CdTe; Mo, In, Ga, Se, CdS and ZnO for CIS) to the calculated overall environmental impact indicators is still hard to quantify precisely. However, the pivotal reason for the comparatively low impact lies in the very small quantities of chemical compounds that are needed in these systems, an inherent advantage of thin film technologies. This can easily be confirmed by means of a sensitivity analysis, which shows that in no case do such technology-specific chemicals cumulatively contribute to more than 20% of the overall impact indicator.
- As far as frameless modules are concerned, the best environmental and thermodynamic performance is

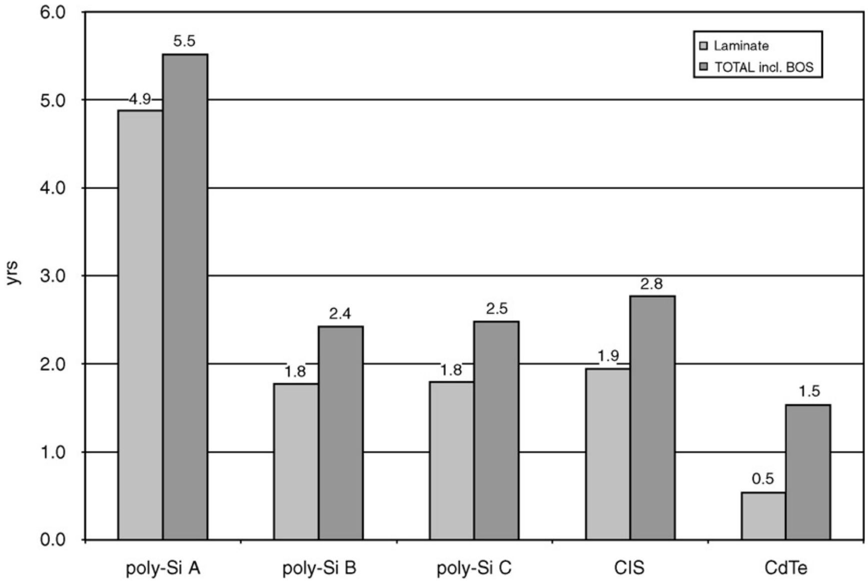

Fig. 6. Energy pay-back time of PV systems.

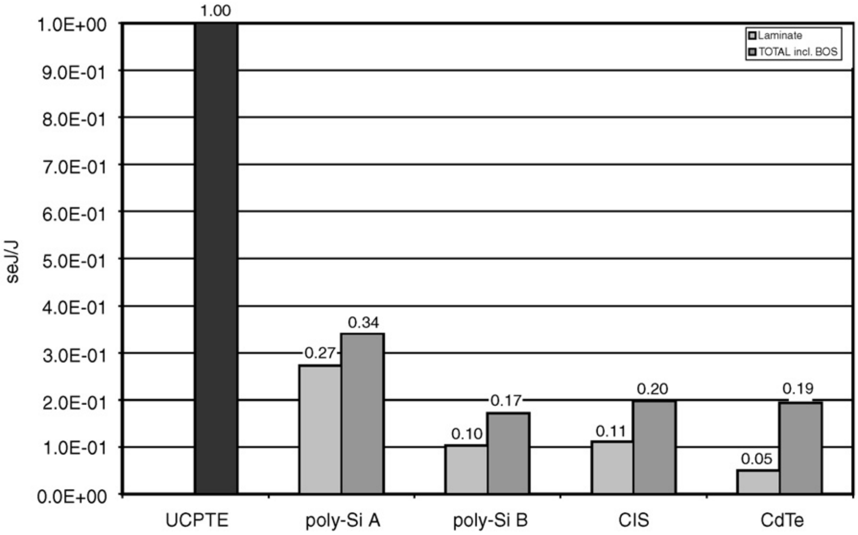

Fig. 7. Transformity of PV systems and of the UCPTE electricity mix (comparison in relative terms).

invariably that of CdTe thin film modules, in spite of their lower efficiency. It is interesting to note that this is also true for the calculated freshwater ecotoxicity potential (EP) indicator. In fact, even though this technology is partially based on the toxic element cadmium, it must be realised that the thin CdTe layer is encapsulated within sealed glass panes, and that CdTe itself is a very stable compound with a virtually zero vapour pressure at normal operating temperatures, and a very high 1700 °C melting point [20]. Calculated life cycle Cd emissions from CdTe PV systems were estimated to be at worst 0.06 μg(Cd)/kWh [4], a figure which is to be compared to the typical *routine, unavoidable* emission from coal-powered thermal power plants, which range from an optimistic 2 μg(Cd)/kWh [21] to a more typical 14 μg(Cd)/kWh [8]. One further interesting figure which helps put things into perspective is the average 3265 mg/kWh Cd content in rechargeable Ni–Cd batteries (calculated assuming 1000 recharge cycles) [22].

- Moving on to the complete PV systems, which include the BOS components, it can be seen that the influence of the latter is comparatively larger for those modules that have a lower intrinsic environmental impact in the first place (CdTe and CIS). The lower specific efficiencies of CIS and especially CdTe modules also cause a higher requirement for support structure per kWp, thus partly reducing their competitive advantage. It should however be noted that thin film module efficiencies are expected to rise in the near future as a consequence of technical

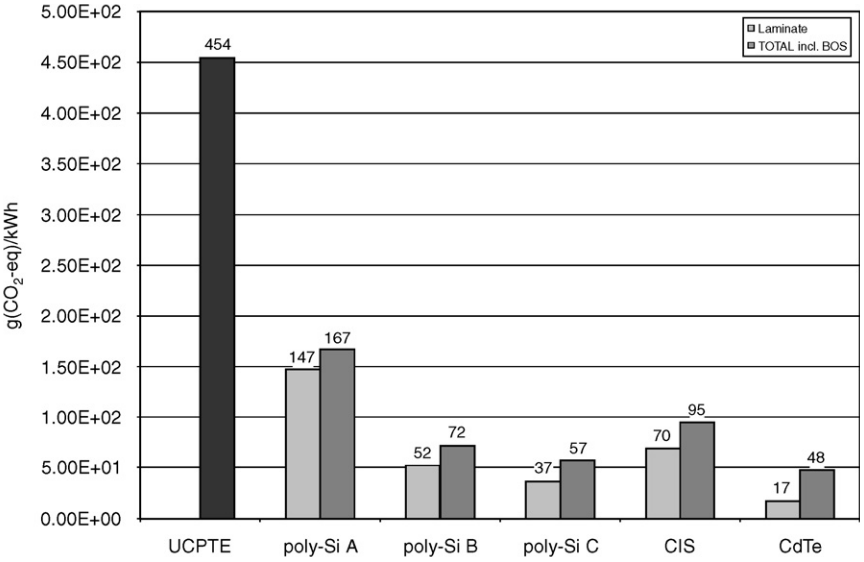

Fig. 8. Global warming potential of PV systems and of the UCPTE electricity mix.

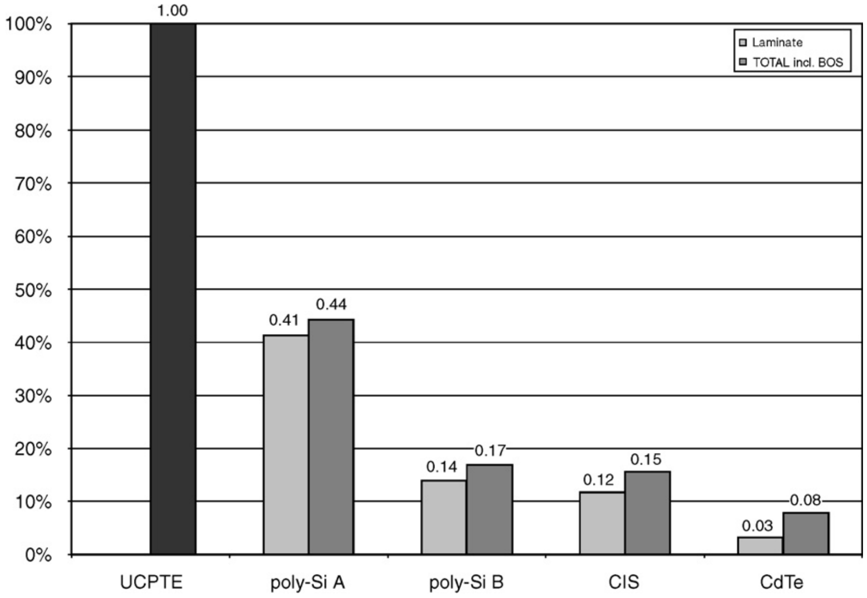

Fig. 9. Acidification Potential of PV systems and of the UCPTE electricity mix (comparison in relative terms).

advancement, and at the same time newer, lighter and/or building-integrated support structures can dramatically reduce the impact associated to the BOS.

- In the case of thin film modules, larger production runs are likely to improve their environmental and thermodynamic performance even further. In particular, it is not unreasonable to expect a fairly significant improvement in CIS modules, given the semi-prototype nature of the system analysed here. What could be regarded as a purely economic matter is instead closely related to the environmental impact too, since process optimisation can reduce wastes and hence the requirement for environmental support.
- For Si-based systems, on the other hand, the one most important chance of improvement lies in the more widespread use of the more energy-effective direct method of solar grade Si production, since the production of the Si feedstock is still overwhelmingly the most energy intensive and environmentally burdensome step of the whole chain. Furthermore, according to recent literature studies [1], the more widespread production of ribbon-type Si modules is also likely to give a positive contribution towards the reduction of the energy and environmental requirements of Si-based PV, by doing away with the inefficient wafer cutting step.

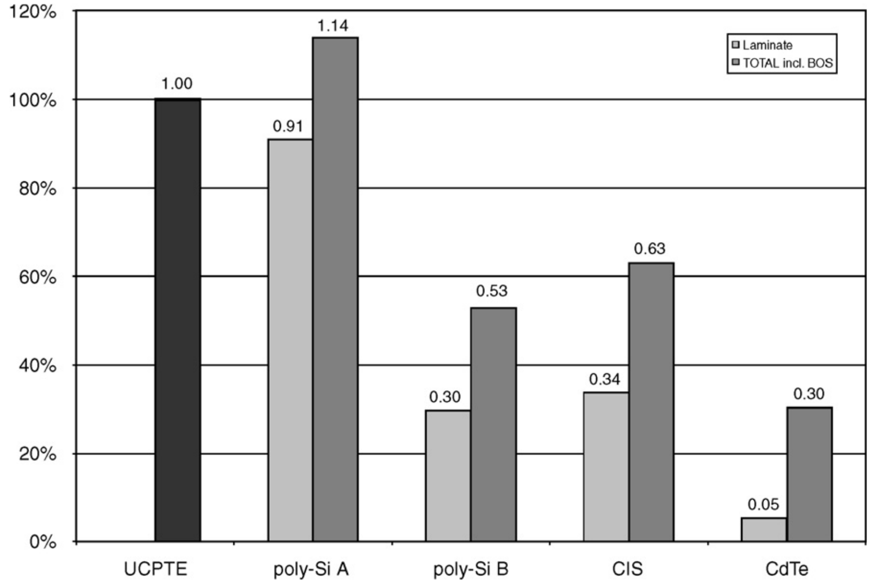

Fig. 10. Freshwater ecotoxicity potential of PV systems and of the UCPTE electricity mix (comparison in relative terms).

5. Conclusions

The environmental and thermodynamic performance of modern CdTe and CIS thin film PV modules has been shown to be already favourably competitive with that of the more established technology of poly-Si, in spite of their early developmental stage. This is an important indication that such systems may well acquire a larger role in the future scenarios of renewable electricity generation. Since the BOS components may have a significant effect on the complete installation relative to the modules themselves, special attention in this regard, such as a reduction of the employed amounts of steel and aluminium, is required. Last but not least, the need for the development of specific recycling strategies for the decommissioning of CdTe and CIS PV modules is recognised. Of course, this point is economically linked to the foreseen up-scaling of production, but it should not be underestimated if these systems are bound to turn into anything more than a niche product.

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