CO$_2$ EMISSIONS OF PV IN THE PERSPECTIVE OF A RENEWABLE ENERGY ECONOMY

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ABSTRACT: The wide range of greenhouse gas emissions (30-300 g CO$_2$-eq/kWh) quoted for PV generated electricity in life cycle assessment studies so far is shown to be mainly caused by the different CO$_2$ emission of energy consumed in manufacture of PV modules. A better way of comparing the CO$_2$-eq emissions would be to calculate the *direct* CO$_2$ emissions of PV module manufacturing and quote these separately from the *indirect* CO$_2$ emissions due to energy consumption. It is shown that the indirect CO$_2$-eq emission makes up more than 90% of the total, indicating the importance of calculating and reporting these two emission sources separately.
Keywords: LCA, CO$_2$, PV emissions, global warming, energy transition

1 INTRODUCTION

Many Life Cycle Assessment (LCA) studies evaluate the environmental performance of electricity generation technologies, i.e., [1-10]. Here, usually a number of different environmental impact categories are distinguished; one category represents the impact on global warming.

The Intergovernmental Panel on Climate Change (IPCC) suggested expressing impact on global warming by a *CO$_2$-equivalent* (CO$_2$-eq) emission. Emissions to air are therefore weighted with global warming potentials of the emitted gases [11,12]. Constructing an artificial CO$_2$-eq emission allows comparisons, despite the different greenhouse gas emissions that occur in reality.

The CO$_2$-eq range of PV technology depicted in Fig. 1, however, can be very misleading. One of the main reasons for that is that most emissions are in fact indirect emissions, originating from fossil fuel based energy conversion facilities.
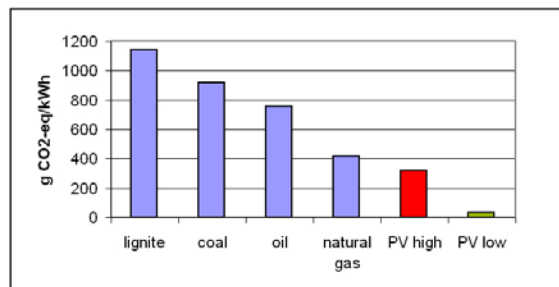

Figure 1: Greenhouse gas emission figures (CO$_2$-eq/kWh) of renewable and non-renewable electricity conversion systems, as found in literature [1-10]

If assuming coal based power plants to serve energy demands when manufacturing PV, these indirect emissions of course become very high; in contrast, if assuming e.g. hydro-, wind or PV power to serve energy demands, indirect emissions become much lower.

This paper argues that a better way of comparing the CO$_2$-eq emission of different energy production methods is to calculate the direct CO$_2$-eq emissions of that technology as such and to quote these separately from indirect CO$_2$-eq emissions related to energy use.

To this end, we perform a first-order estimation of direct emissions of crystalline silicon based PV modules.

2 METHODOLOGY

To depict the different (possibly greenhouse gas emitting) *energy* and *material* flows required to manufacture, operate and decommission fully functioning PV systems, we distinguish five main categories. In category (A), silicon feedstock related processes provide silicon wafers for category (B), in which solar modules are assembled that, together with (C), the BOS system components, allow the installation of a PV system to be operated (D). At the end of a lifetime of a PV system, we consider PV system decommissioning (category E).

We identified two categories that cause direct CO$_2$-eq emission, as indicated in Fig. 2 by arrows on the right hand side. Especially the use of plastics in solar modules
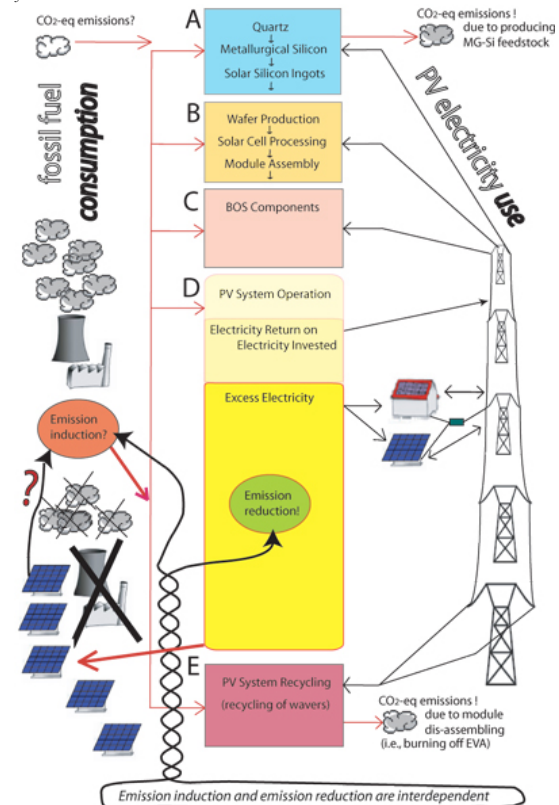

Figure 2: Five categories involved to manufacture, operate and decommission PV systems

will cause emissions in practice: we assume that plastic fractions will be incinerated in the final waste treatment process or in wafer recycling, see 'category E'. Interestingly, these emissions from decommissioning have not always been included in LCA studies so far (i.e., see studies [2-10]). Secondly, providing silicon feedstock will cause direct CO_2 emissions: quartz is reduced with carbon, which is converted to CO_2, in order to provide silicon, see 'category A'.

Thirdly, the use of process gases (such as SF_6, CF_4, C_2F_6 etc) that have high global warming potential may cause greenhouse gas emissions in practice. In process lines using CF_4 for edge isolations the unabated CF_4 emission is estimated at 0.8 g/m^2, which is equivalent to 5.6 kg CO_2-eq/m^2 [13]. Because the actual overall emission from this source is uncertain we will omit it here.

Indirect emission for producing PV (accounting for energy use during production) is depicted on the left hand side of Fig. 2. Here, many of the current studies assume an average fuel mix of a power supply system that serves the PV production plants.

Of course, fossil fuels used to produce PV will cause emissions. An example of today's high fossil fuel use is transport. Here, no transport system beside transport on rails (that can be powered with electricity) allows being powered by PV technology directly, i.e., the PV powered hydrogen age envisaged by many as *the* future energy scenario has not started yet. Many of secondary emission aspects thus have to be dealt with, in the very detailed LCA assessments of today; for this paper, however, we will leave out such considerations, and focus on the direct emissions of PV.

Direct emissions of PV we consider to correspond to the right hand side of emissions depicted in Fig. 2. We consider these are total emissions for that specific case, in which only PV electricity is used to manufacture PV systems as a whole. We will calculate direct CO_2 emissions of the shown categories in the following section 3, and present and discuss results in section 4.

3 CALCULATING DIRECT CO_2 EMISSIONS

3.1 Parameter definitions

In order to assess direct CO_2 emissions to PV electricity one needs to make a number of assumptions. One has to define current state-of-the-art technology parameters, and one has to consider electricity amounts that are generated by the PV system considered. Otherwise, it is impossible to relate a specific CO_2 emission amount to an amount of electricity, i.e., a CO_2-eq emission in g CO_2/kWh such as depicted in Fig. 1. We will use the range of parameters as listed in Table 1.

Table I: Applied parameter ranges

Wafer thickness W_{wafer}	150 – 300	μm
Silicon swarf W_{swarf}	50 - 300	μm
Plastic thickness $W_{plastic}$	2 - 7	mm
Effective efficiency η_{yield}	10 – 25	%
STC efficiency η_{STC}	10 – 25	%
Irradiation range H_E	500 – 2500	kWh/m^{2}year
Irradiance at one sun G_{STC}	1000	W/m^2
PV system lifetime t_{PV}	20-30	years

Silicon swarf (i.e. kerf loss from wafer cutting) and solar cell thicknesses have been around 300 micrometer in the past, while the *current* state of the art is around the lower range of 200 μm for wafer thickness and 160 μm for kerf loss [14]. Even lower figures may be realizable in the near future, e.g., see [15]. The considered irradiation range depicts available irradiation on earth, i.e., around 500 kWh/m^{2}yr annual irradiation in Spitzbergen and around 2500 kWh/m^{2}yr in African deserts [16]. The considered plastics consumption for module encapsulation (1 kg/m^2 EVA, 0.5 kg/m^2 PVF/PET, 0.3 kg/m^2 other) is taken from the life cycle data inventory of De Wild-Scholten and Alsema [17] Note, however, that plastics will be used in more sub-components, i.e., isolation material in wiring and inverter, which are not considered in this current study as such.

3.2 Functional unit: PV capacity

We start our analysis using the functional unit of PV capacity (denoted by P_{PV}). In our presentation of results we switch to a functional unit of energy produced expressed in kWh. It is a practical decision rather than a scientific reason (i.e., PV related figures are stated as produced or installed capacities most often). Therefore, it is convenient to also calculate a corresponding PV surface, denoted A_{PV}. A PV energy output, denoted E_{PV}, requires to be determined, if emissions are related to energy amounts. With the density of silicon ρ_{Si} (2330 kg/m^3) and plastics (890 kg/m^3) one can easily determine a specific mass of silicon or plastics incorporated into a PV system of capacity P_{PV} by

$$m = \frac{P_{PV} \cdot W_{Plastics/Wafer} \cdot \rho}{G_{STC} \cdot \eta_{STC}} \qquad (1)$$

with corresponding PV surface

$$A_{PV} = \frac{P_{PV}}{G_{STC} \cdot \eta_{STC}} \qquad (2)$$

at standard testing conditions (STC, 1000 W/m^2 irradiance, AM1.5 spectra, 25 °C). In this paper, we assume STC efficiency and *effective efficiency* of the overall PV system to be equal (see Table 1), in order to directly estimate electricity produced during overall PV system lifetime by:

$$E_{PV} = H_E \cdot \eta_{Yield} \cdot A_{PV} \cdot t_{life} \qquad (3)$$

Note that *very* low and *very* high figures result for the ranges of effective efficiency (10-25%), annual irradiation (500-2500 kWh/m^2) and lifetime (20-30 years) considered (see Table 1), i.e., 10-75 TWh as total electricity output. It is recognized that modeling PV energy yield this way is an oversimplification. However, in order to keep calculations simple and transparent, we leave out any further detailed PV system modeling for this paper.

3.3 Category A: CO_2 emissions of the silicon feedstock

As shown in Fig. 2, the first relevant process in providing silicon for c-Si solar cells is to allocate metallurgic grade silicon (MG-Si) as basic feedstock. The material required in order to produce MG-Si is

quartz. The chemical reaction to produce MG-Si from quartz can be simplified to:

$$SiO_2 + C \rightarrow Si + CO_2 \qquad (4)$$

Required processes (and chemical reactions) are of course much more complex. However, obviously CO_2 is emitted eventually. This CO_2 emission is system immanent, and one should therefore account for this emission by means of *unavoidable* CO_2-eq emission.

The (stoichiometric) amount of emitted CO_2 per kg metallurgical grade silicon (MG-Si) equals 1.57 kg, a factor we denote $f_{Si\text{-feedstock}}$.

$$m_{CO_2} = m_{Si} \cdot f_{Si-Feedstock} \qquad (5)$$

One may argue that the silicon swarf as a silicon material loss has to be considered (denoted $Y_{Siliconloss}$). However, the Si swarf from cutting is commonly reused as a commercial product for non-PV purposes; therefore we use 100% for this factor.

In order to calculate CO_2-eq emissions as a function of generated electricity amounts, one can express the total electricity generated as a function of parameters shown in Table 1. With defining a factor "c" accounting for naturally given figures (Eq. 5 and silicon density), CO_2-eq emission of providing MG-Si simply becomes

$$e_{CO_2,MG-Si} = \frac{c \cdot W_{Wafer}}{Y_{Silicon} \cdot G_E \cdot \eta_{Yield} \cdot t_{life}} \qquad (6)$$
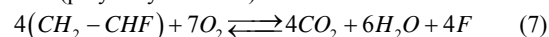
In fact, equation (6) does only depict the very logic linear relation on CO_2-eq emissions caused by MG-Si feedstock of the five parameters: wafer thickness, silicon material loss *not* recycled (we assume $Y_{Silicon} = 1$), available irradiation, effective efficiency and lifetime.

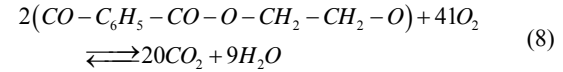3.4 Category E: CO_2 emissions of PV decommissioning

Crude oil feedstock is the current material source of today's plastics, thus CO_2 emissions result once incinerating these plastics. We therefore suggest accounting for these emissions by means of *practically not yet avoidable CO_2-eq emissions*. It is recognized, that in the future there may be a share of these plastics that are recycled. According to the current state of the art, however, plastic fractions of solar modules will probably be incinerated, because this enables recycling of silicon wafers having high economic value today [18-21]. We therefore take a rather conservative approach and calculate resulting emissions as if plastics are incinerated completely once PV system lifetime is reached.

The concerned plastics are ethylene vinyl acetate (EVA) copolymers used as lamination agents, and polyethylene terephthalate (PET) / poly vinyl fluoride (PVF) layers used as a back foil, together with the front glass cover protecting solar modules from the environment. To estimate the resulting CO_2 emission we set up a simple mass balance and assume 100% of the carbon content within the plastic fractions to cause CO_2 emission.
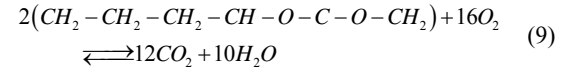
PVF (poly vinyl fluoride)

$$4(CH_2 - CHF) + 7O_2 \rightleftharpoons 4CO_2 + 6H_2O + 4F \qquad (7)$$

PET (polyethylene terephthalate)

$$2(CO - C_6H_5 - CO - O - CH_2 - CH_2 - O) + 41O_2$$
$$\rightleftharpoons 20CO_2 + 9H_2O \qquad (8)$$

EVA (ethylene vinyl acetate)

$$2(CH_2 - CH_2 - CH_2 - CH - O - C - O - CH_2) + 16O_2$$
$$\rightleftharpoons 12CO_2 + 10H_2O \qquad (9)$$

Using simplified mass balances for assuming ideal incineration of PVF (Eq. 7), PET (Eq. 8) and EVA (Eq. 9) layers (with oxygen from air) allows determination of CO_2-eq emissions factors, i.e., associated mass of CO_2-eq emission relative to a mass of incinerated plastic compounds. We find CO_2 emission factors of f_{PVF}=2.05 (the PVF layers), f_{PET}=2.28 (the PET layer) and f_{EVA}=2.34 (the EVA layers).

4   RESULTS AND DISCUSSION

We will now compare direct emissions of PV to emissions that include the indirect emissions due to energy use in production. Here, we use emission figures including indirect emissions of 30 g/kWh for present multicrystalline PV technology according to Alsema [3] and 317 g/kWh according to [4] for comparison. The correlated energy amount produced by the PV systems producing 30-317 g/kWh CO_2 in the specific studies is of course important. These electricity amounts must have been used to calculate the 30-317 g/kWh emission range. However, due to the very differing assumptions in the two studies, we assume available irradiation and effective efficiency to be the average of the ranges we consider (i.e., at 0.5 at the normalized scale in Fig. 3, indicating 1500 kWh/m²yr annual irradiation and overall effective efficiency of 17.5 %, as indicated by black marks within the figure).

The ranges of irradiation and effective efficiency we consider are so wide in order to depict resulting emissions for all kind of assumptions regarding PV system performances and installation sites. PV system lifetime we consider is set to 20, 25 and 30 years, and is used to plot the lower two curves in Fig. 3, showing the comparison of direct emissions and those emissions that include the indirect emissions.
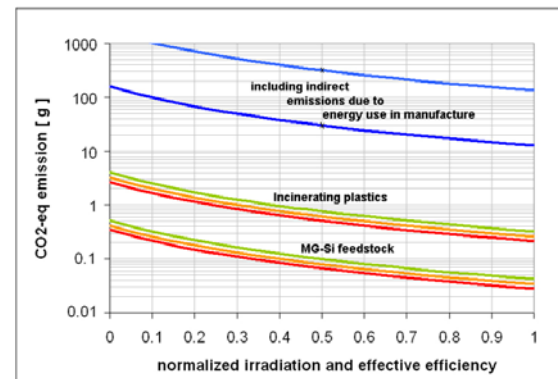

Figure 3: Comparing direct and indirect CO_2-eq emission; the normalized x-axis depicts the considered ranges of irradiation (500-2500 kWh/m²yr) and effective efficiency (10-25%).

Irrespective of which PV efficiency or annual irradiation is available for electricity generation, the fraction of greenhouse gas emission that is directly caused by PV technology is at least one order of magnitude lower than that originating from indirect sources related to energy consumption. In other words: it is shown that the indirect greenhouse gas emissions makes up more than 90% of the total, indicating the importance of calculating and reporting these two emission sources separately.

5 DISCUSSION

We have shown that many of the current figures on greenhouse gas emissions and other environmental impacts will no longer be valid (see Fig. 1 and 3), when renewable energy technologies have been implemented on a large scale, i.e., if the technology assessed will be successful in reality.

Several authors have published studies [22-26] already that, with different scopes, aims and methods, suggest adapting the "static" LCA methodology that is *currently used most often* but that leads to figures such as depicted in Fig. 1. Especially Krauter and Rüther [22] quoted the many emission sinks and sources one should consider in order to set up a sound emission *balance*. They suggested taking into account the various geographical locations with correlated emission footprints of PV production sites. In addition, they argue, one should account for emission avoidance due to PV electricity use. Therefore, however, one has to predict emissions of the future, which is always related to uncertainty.

Of course our own analysis above comprises a number of simplifications that should be addressed in a more comprehensive study. One issue is for instance the (greenhouse gas) emissions occurring in the manufacturing of materials other than silicon, like glass and silicon carbide (used in wafer cutting). Again a large part of these greenhouse gas emissions will be related to the use of fossil fuel for electricity generation or process heat, part of which in the future may be replaced by low-carbon energy sources. A second issue is the process heat that is used in silicon purification (from metallurgical to solar grade), which is presently obtained from fossil fuel fired boilers. One can debate whether this process heat may in the future also be provided by low-carbon energy sources (e.g. biomass).

Notwithstanding the complicating factors above we suggest to distinguish PV-related emissions into direct and indirect emissions. In addition, one should keep energy-related figures as specific as possible in future studies, i.e., one should *stop* summarizing both emissions related to direct fossil fuel and electricity use without indicating electricity requirements of the specific PV production processes.

By indicating the indirect emissions separately from the direct emissions, policy makers can become informed more thoroughly on PV as a sustainable technology. Here, separating emissions of PV technology *aside* from emissions resulting from fossil fuel use is a fair assessment of the long-term potential of PV as a sustainable energy technology.

Moreover, PV companies may become encouraged to use less emission intensive energy supplies (i.e. "green" energy, such as electricity provided by solar cells).

6 CONCLUSIONS

We determined direct greenhouse gas emissions of PV technology related to providing MG-Si feedstock (0.02-0.04 g/kWh and 0.3-0.55 g/kWh) and related to incinerating plastic fractions of solar modules (0.3-0.7 g/kWh and 3-6 g/kWh). The different emission ranges that result are dominated by considered low and high PV system performance (effective efficiency, irradiation and lifetime), the lower variation represents different plastic and wafer thicknesses incorporated into solar modules.

This result implies that up to 90% of the emission figures quoted in previous LCA studies may be attributed to fossil fuel combustion in either the background electricity supply system or in energy conversion systems providing process heat. These *indirect* greenhouse gas emissions may to a large extent be avoided in the future when the transition towards a low-carbon energy supply system has been realized.

Presentation of direct GHG emissions apart from indirect GHG emissions therefore allows for a better insight in the future potential of PV technology as a sustainable energy supply option.

A careful separation of process-related and energy-related emissions in future LCA study reports is essential to achieve the proposed, more balanced presentation of emissions from PV technology.

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