Supplementary Materials: Systematic Assessment of Carbon Emissions from Renewable Energy Access to Improve Rural Livelihoods

Judith A. Cherni, Raúl Olalde Font, Lucía Serrano, Felipe Henao and Antonio Urbina

1. Summary of State of the Art Parameters for PV Technologies and Expected Evolution According to European Photovoltaic Technology Platform

Table S1. Life-cycle analysis forecast factors for three types of photovoltaic technology (2011–2025).

Time horizon	PV Technology Type		Power Conversion Efficiency (%)	Cost of 200 MWp (€/Wp)	EPBT (Years)	E_{emb} (GJ/kWp)
	Silicon		>19% mono >17% multi	2–3	2.0	45–56
	Thin film—CdTe		14%	1.2–3	1.25	7.6
	Organic		10.6%	<0.5 (est)	1.35	7.6
State of the art: 2015	Silicon	Poly	>17%	5	2	45 to 56
		Mono	>19%			
	Thin-film/silicon	Glass substrate	>11%	<0.7	1.13	17
		Flexible substrate	>10%	<0.6		
	Thin-film CIGS		15%	<0.7	2.2	27.7–39.4
	Thin-film—CdTe		14%	<0.6	1.25	7.6, 10.2–17.5, 21.9
	Organic		5% [3]	1	1.35	7.6
2016–2025	Silicon	Poly	>19%	2.5–2.2	1–1.5	n/a
		Mono	>21%			
	Thin-film silicon	Glass substrate	>14%	<0.5 (for 500MWp)	1.25	
		Flexible substrate	>13%	<0.4 (for 500 MWp)		
	Thin-film CIGS		16%–17%	<0.5	1.25	
	Thin-film—CdTe		16%	<0.4	1.25	
	Organic		10% [1,2]	0.5–0.6	<0.5	

[1] Some sources refer to W_{el} for electricity power (not energy) and others to MWh for thermal energy (used for all primary energy, comprising electricity and other sources Therefore, the units used here are not uniform; [2] This figure has already been surpassed by polymeric- and perovskite- based organic solar cells, as indicated in the discussion in the main article.

2. Description of Energy Related Parameters Used for Life Cycle Assessment

Although all parameters described below are standard in literature regarding photovoltaic systems, a detailed description and the required equations for its numerical evaluation are provided in the following lines. These parameters have been used for the LCA analysis of the different photovoltaic technologies as described in the manuscript.

The energy pay-back time (*EPBT*) of solar systems (the smaller the amount, the better), is calculated as follows:

$$EPBT = E_{EMBEDDED}/E_{GEN\_YEARLY} \quad \text{(S1)}$$

where $E_{EMBEDDED}$ stands for in-built energy and is obtained by multiplying the total surface of installed solar modules (the size of each PV system corresponds with the amount of energy required) by the embedded energy of the PV system (given in kWh/m^2 and obtained by LCA methodology—see below), and divided by the amount of energy generated yearly by the system:

$$E_{GEN\_YEARLY} = G \times PR \times P_p/I_{STC} \quad \text{(S2)}$$

where E_{GEN_YEARLY} is the total energy that the solar panels produce per year; G stands for solar irradiation (kWh/m^2); PR represents the Performance Ratio (see below); P_p is the nominal peak power of the PV system (kWp) (also called "installed capacity"); and $ISTC$ represents irradiance at standard conditions (1 kW/m^2). Since the equation is normalized by $ISTC$, its value is equivalent to the number of hours of irradiance under standard conditions during a year.

The Performance Ratio (PR) measures losses that can impact the performance of the PV system compared to the nominal design values; it often ranges between 0.70 and 0.85 and depends on the particular design of the system under study. For example, shortfalls can be due to minor electricity losses in cables, tiny voltage drops due to dirt on the modules, poor efficiency of regulator and inverter, deviations of optimum angle and inclination of installed PV panels; and temperature losses and seasonal variations. Thus, the larger the performance ratio, the more efficient the panel is.

Equation (S3) calculates the Energy Return Factor (ERF), that is, the amount of energy that a solar installation would generate throughout its lifetime per unit of energy invested in its manufacture. Hence, the greater this value, the more advisable a particular type of SHS. This information parameter relates energy-pay-back time ($EPBT$) to the real lifetime of the solar home system. If the real lifetime differs from that stated on the manufacturer's guarantee, the ERF should be recalculated, and will deliver a smaller (or greater) value:

$$ERF = LT/EPBT \tag{S3}$$

where LT stands for the lifetime of the technology, as shown on the manufacturer's guarantee; and $EPBT$ is the energy pay-back time (see Equation (S1)).

The energy that the solar system is able to generate during its lifetime (E_{GEN}) is calculated as follows:

$$E_{GEN} = E_{GEN\_YEARLY} \times LT \tag{S4}$$

Finally, the CO_{2eq} avoided emissions (Equation (S5)) is obtained by multiplying EGEN (Equation (S2)) by the amount of CO_2 emissions per kWh that has been or will be released by the current electricity generation technologies in the country where the new solar energy devices are to be installed. Note, however, that manufacturing, transporting and use of solar home systems also release CO_2. Therefore, the amount of CO_2 emissions of a country's current electricity mix is reduced by deducting the corresponding amount of CO_2 emitted by the solar panels process. CO_2 accountability at each stage is calculated as follows:

$$CO_{2\,Manufacture} = S \times E_m\,[CO_2/kWh_{PE}]_{man} \tag{S5}$$

$$CO_{2\,Use} = E_{GEN}\,[CO_2/kWh]_{use} \tag{S6}$$

$$CO_{2\,Transport} = CO_{2\,lorry} + CO_{2\,ship} \tag{S7}$$

$$CO_{2\,Avoided} = CO_{2\,Use} - CO_{2\,Manufacture} - CO_{2\,Transport} \tag{S8}$$

where $[CO_2/kWh_{PE}]_{man}$ represents the total CO_2 emissions per kWh of total primary energy supply in the country where the PV system has been manufactured. S is the surface size of PV panels of the installed system; and E_m stands for the energy employed to manufacture the PV modules (energy embedded per unit of module surface).

$[CO_2/kWh]_{use}$ is the CO_2 emissions per kWh from electricity generation at the country where the PV system will be operating. E_{GEN} is the energy delivered by the PV system during its lifetime. CO_2 Transport, CO_2 lorry and CO_2 ship are the emissions released by the transportation of the PV system from manufacturing to installation sites (including transport by land and sea).

3. Sensitivity Analysis of the Proposed Energy Solutions

A sensitivity analysis with respect to the impact of weight selection on the final score obtained for the different energy solutions has been performed using the methodology described in reference [74] in the manuscript. In particular, the following set of weights are used for the sensitivity analysis: Equal weights, Average of the next three sets, Interdependency weight, Entropy weight and Unsuitable solutions weight (Table S2).

Table S2. Different sets of weights of the five assets proposed in order to perform the sensitivity analysis.

	Natural	Physical	Human	Social	Financial
Equal weights	0.20	0.20	0.20	0.20	0.20
Average of the next three sets	0.41	0.15	0.17	0.17	0.11
Interdependency weight	0.07	0.22	0.22	0.22	0.26
Entropy weight	0.55	0.07	0.17	0.17	0.03
Unsuitable solutions weight	0.60	0.15	0.10	0.10	0.05

Using this different sets of weight, the calculation described in the manuscript has been repeated. The result is shown in Figure S1, where the final score for the different energy solutions is presented for three photovoltaic alternatives, the existing baseline and a Diesel generator. The variation of the three photovoltaic solutions is minimal, showing the low dependency of the methodology on the selection of weights, even if these sets of weights are very different. This fact points out that the optimum solutions score depends only on the parameters obtained by the field work (technical, geographical and stakeholders opinions and expectations obtained by the questionnaire).

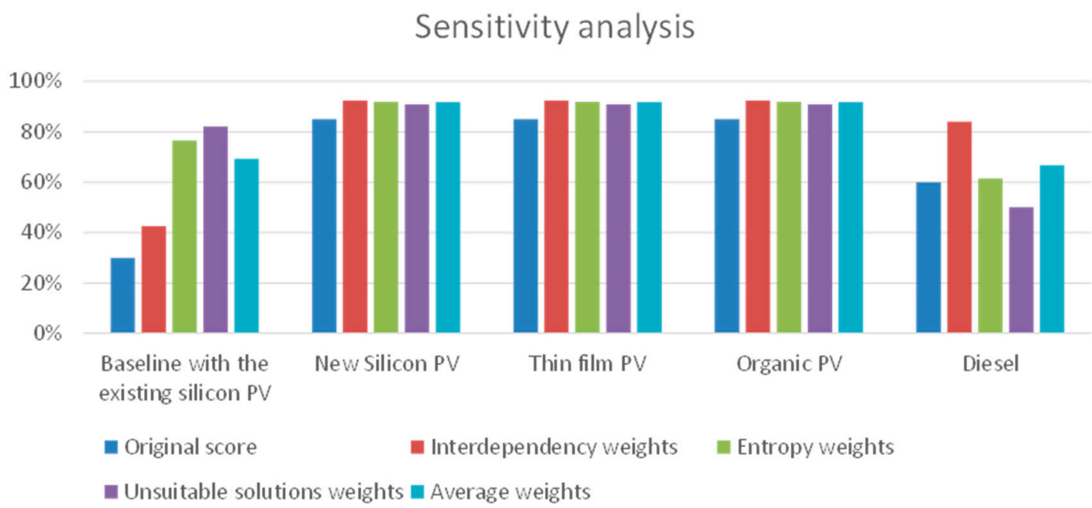

Figure S1. Sensitivity analysis showing the impact of the selection of different sets of weight on the final score for the energy solutions.