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## Attractiveness of Using Photovoltaic Panels in a Building Connected to a Mainly Renewable Electricity Grid

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# Attractiveness of Using Photovoltaic Panels in a Building Connected to a Mainly Renewable Electricity Grid

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**Abstract.** Photovoltaic (PV) panels contribute to overall building's loads, but generally have their impacts offset at the operational stage. For increasingly renewable electricity grids, PV's contribution to lowering non-renewable energy becomes less significant. This paper aims at investigating the non-renewable cumulative energy demand (CED<sub>nren</sub>) and global warming potential (GWP) payback times associated to onsite PV generation in the highly renewable Brazilian grid, considering a 50-year building service life. Operational energy consumption was simulated in Energy Plus. CED<sub>nren</sub> and GWP were calculated through the CED method and CML-IA, respectively. SimaPro 7.3 and Ecoinvent 2.2 supported performed LCAs. Different PV settings were analyzed to rank the most effective technological options. Amorphous and single-Si panels performed worst (around 17 years of non-renewable CED payback time, whilst for GWP the payback time was much shorter for all technologies). PV's production and replacement loads played a significant role, therefore technological investments to increase panels' durability and improve manufacturing efficiency could ensure its attractiveness.

## 1. Introduction

The 'Net Zero' concept emerged as an exciting – though challenging – reference to establish goals and describe success towards aggressive energy use reduction centred on an overall sustainability approach instead of on targeted proportional reductions. Goals for the implementation of ZEBs have been discussed and proposed internationally, e.g. within the US Energy Independence and Security Act of 2007 [1] and the recast of the European Directive on Energy Performance of Buildings (EPBD) adopted in May 2010 [2]. South America, on the other hand, falls wide behind, with little or no government initiatives for the implementation of nearly/net zero energy constructions. In fact, the only energy efficiency labelling program for buildings in Brazil has the ultimate goal of achieving maximum efficiency, but does not value nor does it mention net zero energy buildings [3]. This lack of policies resonates in available national literature: a quick search performed on Scopus using "LCA AND photovoltaic AND Brazil" as investigated keywords in peer reviewed journals comes back with one single entry.

With high embodied impacts, photovoltaic panels contribute greatly to a building's life cycle loads [4], but generally have their impact offset at the operational stage of the built environment. A current discussion, however, sheds light to the fact that as electricity grids become more renewable-based, PV's contribution to lowering the non-renewable energy demand becomes less significant [4].



Considering the clear dominance of renewable sources in the Brazilian electricity mix (>80%), this paper aims at investigating the non-renewable cumulative energy demand (CED<sub>nren</sub>) and global warming potential (GWP) payback times associated to onsite PV generation, considering a building reference service life (RSL) of 50 years. To do so, we adapted the typically adopted energy payback time (EPT) concept [5], following the propositions of [6], through Equation 1.

$$EPT = \frac{(E_{mat} + E_{manuf} + E_{trans} + E_{inst} + E_{EOL})}{((E_{gen}/nG) - EO\&M)} \quad (1)$$

Where:  $E_{mat}$  is the primary energy demand (PE) to produce the materials composing the PV system;  $E_{manuf}$  is the PE to manufacture the PV array;  $E_{trans}$  is the PE for transportation;  $E_{inst}$  is the PE to install the system;  $E_{EOL}$  the PE for end-of-life management;  $E_{gen}$  the annual electricity generation;  $EO\&M$  the annual PE for operation and maintenance and, finally,  $nG$  refers to grid efficiency, i.e. the average PE to electricity conversion efficiency at the demand side.

To assure a fair comparison between the renewable electricity grid and the PV panels, we adopted the ‘non-renewable energy payback time’ (CED<sub>nren</sub> payback time, from here on out called non-renewable CEDPT) equation, an adjusted conceptual approach also proposed by [6] in which the term ‘primary energy’ is replaced by ‘non-renewable primary energy’ (CED<sub>nren</sub>).

We performed analogous calculation to obtain the GWP payback time (GWPPT). The concept of considering the avoided GWP loads associated to PV electricity generation has also been explored by [7][8][9] and, in the latter case, also for endpoint results provided by the ReCiPe impact assessment method. All these authors, however, used the traditional EPT equation.

## 2. Methodological approach

This research was developed in four main parts: (i) operational energy consumption simulation in Energy Plus; (ii) modelling of four different PV systems’ technologies, using Homer Energy software; (iii) Life Cycle Assessment (LCA) of installed PV systems and of the Brazilian electricity grid, using SimaPro platform; and (iv) calculation of each PV system’s non-renewable CED and GWP payback times. Additionally, a sensitivity analysis was performed to assess possible ranking shifts when using the traditional energy payback time (EPT) calculation.

Our case study is the ‘minimum life cycle embodied energy and emissions’ (minLC<sub>ee</sub>) building, a 1,005.21 m<sup>2</sup> of gross floor area (GFA) living lab experimentally designed for the University of Campinas, in Brazil, and developed as a sustainable construction demonstration project.

Life Cycle Assessments were performed here to compare PV technologies and the Brazilian electricity grid’s carbon and energy-related impacts. These results then fed the calculation of the non-renewable cumulative energy and global warming potential payback times, more thoroughly explained in the following subsections.

### 2.1. Operational energy simulation

We used Energy Plus software v. 6.0.0.023 to model the building’s energy demand. The Energy Plus weather file (EPW) for Campinas – São Paulo was developed as part of the Living Lab research project and later integrated to the Brazilian EPW database. Process energy included office and general miscellaneous equipment, computers, elevator, kitchen cooking and refrigeration, lighting exempt from the lighting power allowance. Regulated (non-process) energy included lighting (for the interior, rooftop, façade, building grounds etc); heating, ventilation, and air conditioning (HVAC) for space heating and cooling (fans, pumps, toilet exhaust etc), and the small domestic hot water system.

### 2.2. Modelling of the PV system

For the minLC<sub>ee</sub> Living Lab PV simulation, HOMER Energy software was used to synthesize hourly load data based on user-specified average daily load profiles for weekdays and weekends, consistent with the operational schedules simulated in EnergyPlus.

PV system sizing procedure discounted generation losses (1) as the orientation and exposure angle of the envelope surfaces varied for facade- and rooftop-mounted applications; (2) when the panel is subjected to outdoor temperatures above the standard test conditions; and (3) over time. To account for the latter, a degradation factor of 0.5% per year was applied, assuming a total 25-year service life [10] to ensure that the desired panel performance is maintained over the whole period of study.

### 2.3. LCA's goal and scope definition, inventory and impact assessment

The LCAs herein presented aimed at calculating the impact of different PV technologies and of the Brazilian electricity grid throughout the life cycle of the minLCee building. The functional unit was the whole building, considering a 50-year reference service life. PV panels were assumed to have a 20% replacement after 25 years of service life, following local PV installers' estimates.

The scope of the performed PV LCA is from cradle-to-grave, specifically covering life cycle phases A1-A3, A4, B4 and C1 [11]. Following the geography of available PV data on Ecoinvent 2.2, panels were considered as either manufactured in Germany (single and multi-Si and CIGS) or in the United States (a-Si). We followed this import assumption to model transportation impacts (module A4).

Inventory data on the Brazilian low-voltage electricity mix and on crystalline silicon (single-Si, multi-Si) and thin film (amorphous-Si and CIS) photovoltaic technology generations were taken from Ecoinvent 2.2. Data for PV's balance of system (BOS) were not found in that database, and CED<sub>nren</sub> values were taken from [12] and GWP values from [13]. CED<sub>nren</sub> and GWP were calculated through the Cumulative Energy Demand (CED) method and CML Impact Assessment method (CML-IA, version 2001), respectively, in SimaPro 7.3.

### 2.4. Energy and GWP payback time calculations

Non-renewable energy payback time (CEDPT) is calculated through Equation 1 [6], replacing the primary energy demand values described in section 1 with the non-renewable CED components calculated for each life cycle stage, divided by the annual non renewable CED balance during use. GWP payback time (GWPPT) was calculated analogously.

## 3. Results presentation and discussion

### 3.1. Photovoltaic system modelling

Simulation in Homer Energy software yielded different effective generation areas depending on the PV technology adopted (Table 1). Actual installed areas took into consideration each available surface's potential for effective generation, assuming ideal conditions. PV panels were assumed to be installed in the 'PV roof plan', tilted to create an ideal condition for solar energy generation. If additional panel area was needed to achieve the calculated system power, then the remaining horizontal roof plan and, finally, the façades could be used (Table 2).

**Table 1.** System power and effective area requirements for the four PV technologies tested

PV technology	System power (kWp)	Effective generation area (m <sup>2</sup> )	Installed PV area (m <sup>2</sup> )
single-Si	22.74	<b>133.72</b>	133,72
multi-Si	22.68	161.92	162,85
a-Si	<b>22.14</b>	316.41	326,26
CIS	22.51	187.48	189,89

Even though a-Si is the most efficient technology in terms of system power demanded and, therefore, a good alternative for projects with more surfaces available, single-Si PV technology is the most efficient alternative in terms of area needed to deliver each kWp (Table 1).

**Table 2.** Effective energy production simulated for façade and horizontal rooftop mounted PV applications in Campinas, Brazil (22.90°S, 47.06°W)

Effective generation	
North facade	60%
East facade	56%
West facade	55%
Horizontal plan	95%
Reference condition (23° tilted North)	100%

### 3.2. Photovoltaic system's LCA and CED and GWP payback times

The PV systems' CEDnren and GWP values are comparatively shown in Table 3 and in Figure 1.

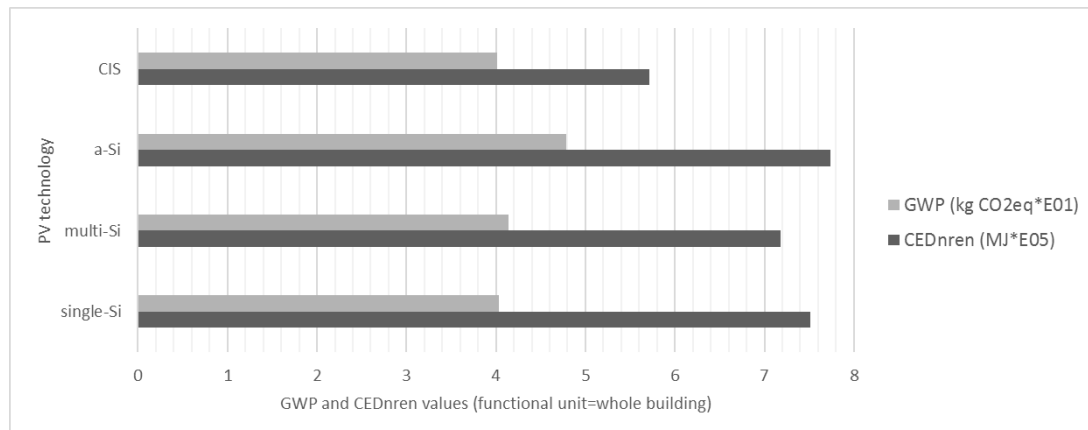
**Table 3.** CEDnren and GWP values for each PV technology per m<sup>2</sup> of panel surface

PV technology	CEDnren (MJ/m <sup>2</sup> )	GWP (kg CO <sub>2eq</sub> /m <sup>2</sup> )
single-Si	3,404	198
multi-Si	2,611	159
<b>a-Si</b>	<b>1,112</b>	<b>73</b>
CIS	1,943	123

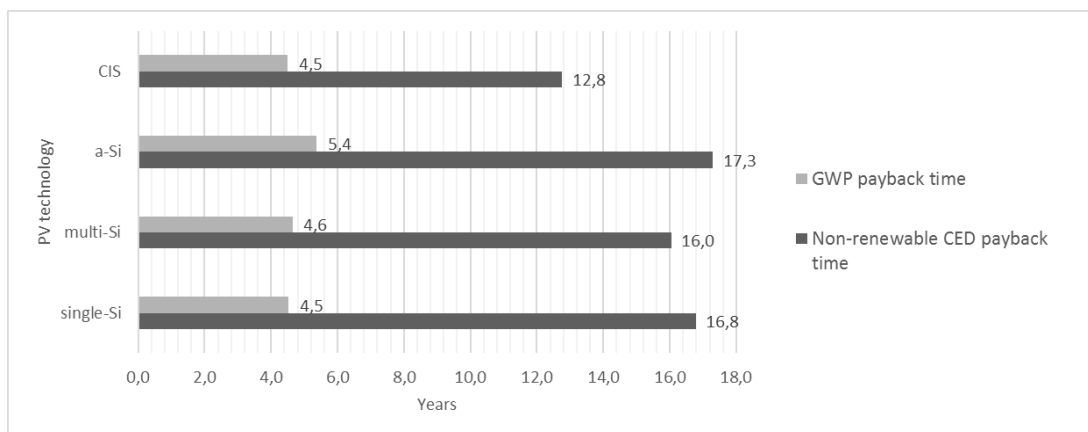
While a-Si technology is the best available option in terms of unit surface area (Table 3), when the PV array scale is considered (Figure 2) this perception is shifted, and it offers the worst performance among all assessed technologies. As previously discussed, the ineffectiveness of a-Si technology in terms of installation area needed played an important role here, deeply affecting its attractiveness for our case study building. In terms of absolute values, CIS panels stand out as the best option for this case study (Figure 1).

Payback time calculations need inputs on the annual operational energy and the impacts embodied in the electricity mix. Energy Plus simulation showed that the minLC<sub>ee</sub> building would consume less than 31 kWh/m<sup>2</sup> GFA per year of RSL. The LCA of the Brazilian low voltage electricity mix then yielded a yearly embodied GWP of 9 t CO<sub>2eq</sub>, and a CEDnren of 62 GJ. These values fed the non-renewable CEDPT and GWPPT calculations (Figure 2), which ranked similarly to the absolute values shown in Figure 2. Amorphous and single-Si panels performed worst and would take around 17 years to even out their non-renewable embodied energy. For GWPPT, the panels presented a much shorter payback time, between 4,5 and 5,4 years.

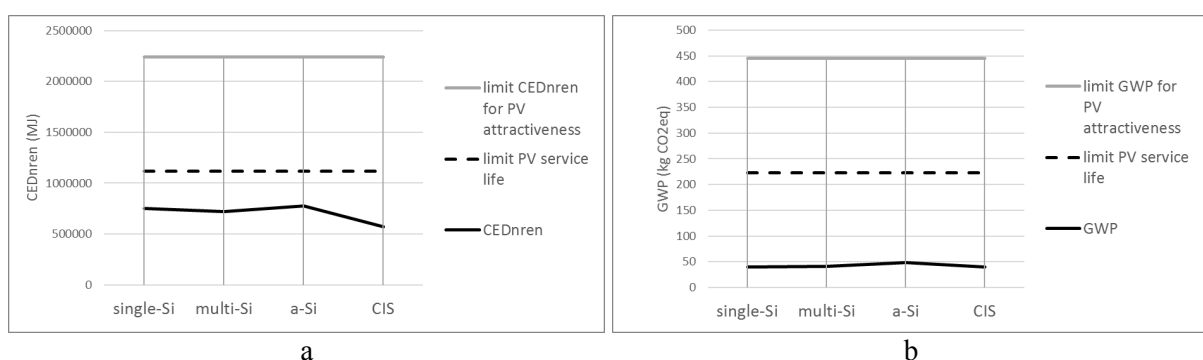
Figures 3a and 3b respectively show the maximum CEDnren and GWP that would assure PV's environmental attractiveness for a case study with 50-year RSL. For reference, the figures also show the limit values for a payback time of 25 years, equivalent to the panels' service life. For non-renewable CED, the PVs are close to their service life limit, but still far below the maximum value that would make the connection to the power grid preferable. CIS is clearly preferable in terms of non-renewable CED, whilst for GWP, all PV systems show similar results and are well below both PV and building's service life limit.



**Figure 1.** GWP and CEDnren values for the PV technologies assessed



**Figure 2.** Non-renewable CED and GWP payback times



**Figure 3.** PV technologies (a) CEDnren and (b) GWP and respective attractiveness thresholds for our case study, considering 25 (PV array service life, dashed line) and 50 years (building service life, solid gray line) payback times

The panels' lower GWPPT relatively to non-renewable CEDPT is related to the high GWP associated to the Brazilian power grid, mainly based on large hydropower plants. The hydropower generation dataset in Ecoinvent 2.2 shows a considerable amount of CO<sub>2</sub> and CH<sub>4</sub> emissions. These greenhouse gas emissions

(GHG) are assumed to originate from flooded biomass and discharged sewage. GHG data for Brazilian hydro power plants were extrapolated from Swiss dams and, therefore, bear high intrinsic uncertainty.

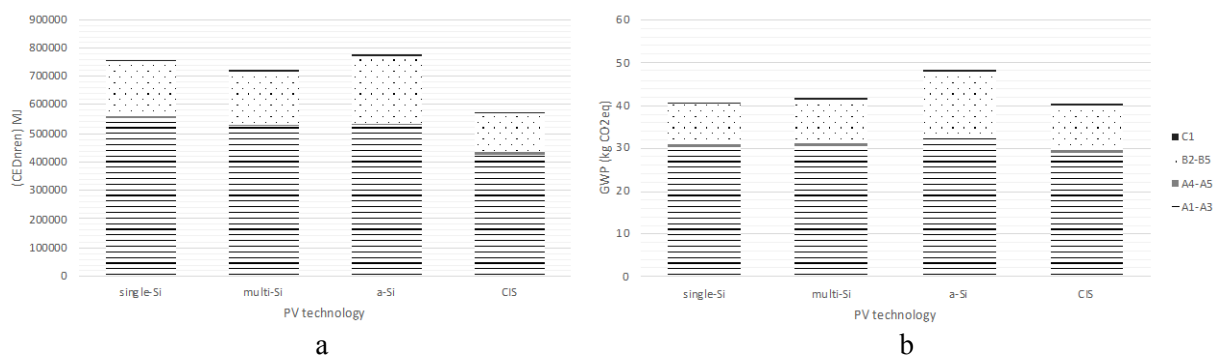
Positioning our non-renewable CEDPT values in relation to published data was challenged by a lack of results of the same nature, since most papers focus exclusively in the traditional calculation of EPT. Results for GWPPT obtained by [8][9] relate to a different PV technology, namely building integrated centralized photovoltaics (BICPV), while results found by [7] show values for a concentrating photovoltaic thermal system (CPVT), so there is no technical equivalence to guarantee a fair comparison.

### 3.3. Contribution analysis of the photovoltaic panels' LCA

Manufacturing (A1-A3) and replacement (B) loads clearly dominate the PV panels' embodied loads, as shown for CED<sub>nren</sub> and GWP in Figure 4. The panels transport from Germany and USA (A4) did not play a significant role, which points to the fact that – assuming similar production efficiency – local manufacturing would not significantly alter their environmental profile.

Demolition loads are also discrete. The consideration of life cycle phases C2, C3 and C4 could alter the end of life phase's contribution to PV's total embodied impact, but due to their data's uncertainty authors chose to disregard them. The replacement loads significance indicates that technological investments to increase panels' durability could increase its attractiveness in contexts with a high renewable share in electricity grids.

Differences between CED<sub>nren</sub> and GWP rankings are slim, limited to single-Si panels' slightly best profile when evaluating exclusively GWP loads. PV technologies' embodied loads in manufacturing (A1-A3) clearly rule their environmental profile, which points to the need of focusing on improving production technology to achieve truly environmentally attractive panels. As we move towards decarbonization worldwide, PV panels attractiveness in terms of non-renewable energy will depend, on one side, on the loads embodied within grid infrastructure and transmission losses and, on the other, on its own manufacturing loads and service life.

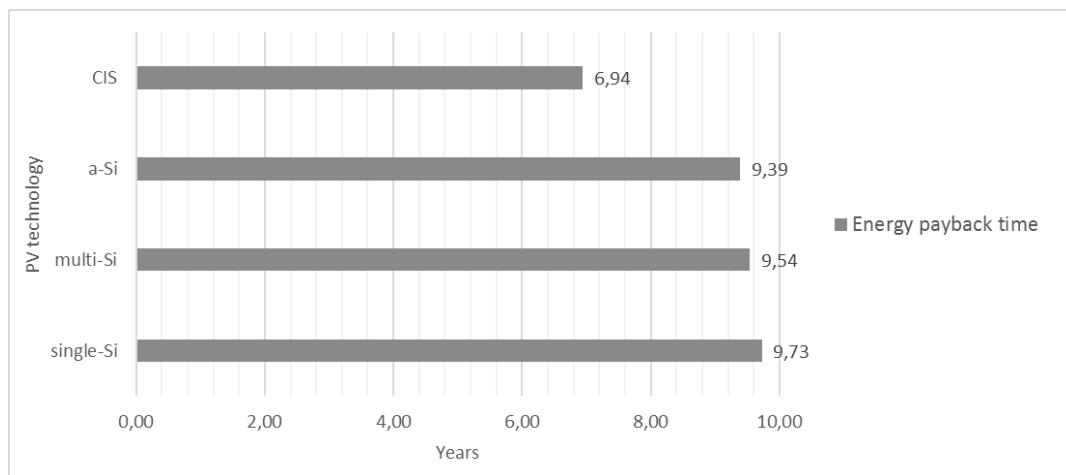


**Figure 4.** PV array contribution to non renewable (a) CED and (b) GWP over minLCee life cycl

### 3.4. Sensitivity analysis: traditional EPT X CEDPT

Energy payback time is a concept that has been widely explored in PV LCA studies [5][14][15][16]. Our adjusted calculation aimed at considering the avoided grid-related non-renewable loads, to assure a fair comparison between the possible energy sources while taking into consideration the renewable dominance of the Brazilian grid – therefore considering how decarbonization might influence PV's attractiveness. Figure 5 shows the traditionally calculated EPT values for the minLCee building, considering the four assessed PV technologies. When comparing the above values with the ones presented in Figure 3, one can see that a-Si, multi-Si and single-Si are still less attractive for our building case study, however, a-Si panels are now a better option than multi and single-Si – as opposed to its position as least environmentally attractive option as shown in Figure 3. Absolute non-renewable CEDPT values are almost twice the traditional EPT values. This confirms the hypothesis presented in

[6], in which the authors point to the possible variation between numerical values of EPT and non-renewable CEDPT due to increased share of renewable energies in power grid mixes. EPT figures are of great value for a designer's decision-making process and, in this case, both EPT and non-renewable CEDPT positioned the same option as preferable. However, when faced with a choice between technologies with similar EPTs, CEDPT would be a sound, scientific tiebreaker, valuable especially in contexts with highly renewable-based grids.



**Figure 5.** Traditional EPT values for the studied PV technologies

#### 4. Conclusions and final remarks

This research's main contribution lies in the creation of seldom published information in two different fronts: non-renewable CEDPT values for photovoltaic panels, and the attractiveness of solar energy generation in a renewable-dominated electricity grid scenario. For our specific case study, the renewable character of the Brazilian electricity grid was not sufficient to nullify PV's environmental attractiveness from carbon and energy perspectives. Further assessments should be performed to confirm if energy and GWP are enough to provide a meaningful assessment of on-site generation's appeal, or if other categories should be also investigated. Moreover, we acknowledge that calculating both GWP and CED indicators might be redundant, due to their widely documented high correlation, but we argue that upon the decarbonization trend of electricity grids this correlation might be decreased, so both metrics are worthy of investigation.

As in most LCAs, our main limitation here was the unavailability of inventory data on all evaluated products and systems. Our background data source did not contain information on PV's BOS, for which GWP and CED<sub>nren</sub> were taken from published literature. Additionally, Ecoinvent's data on the four assessed technologies were restricted to Germany and the United States. However, nowadays, single and multi-Si PV panels used in Brazil are manufactured in China. We chose to keep the transportation distance in accordance with the geography set by the dataset, to assure modelling consistency throughout the building's life cycle phases A1-A3 and A4. The minLC<sub>ee</sub> w/LCA was carried out before Ecoinvent version 3 was launched. Recalculation of our LCA within version 3.3 is in course, but is not yet available for publication here. Still, in the newest version of the database (v.3.3), the renewable share of the Brazilian electricity production mix was very similar (84%) to the 87% registered in v.2.2, and the PV panels' datasets were not updated in version 3.3. Main conclusions would therefore be maintained.

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