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# ENERGY PAY-BACK TIME: METHODOLOGICAL CAVEATS AND FUTURE SCENARIOS

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## ABSTRACT

Energy Pay-Back Time has almost universally been adopted as the indicator of choice to express the energy performance of PV. In this paper, an in-depth review of the methodology and all underlying assumptions and conventions is presented. A prospective analysis of the potential evolution of the EPBT of PV over the next four decades is then performed, assuming optimistic grid penetration figures and taking into account expected technological improvements. Results show that combining the two opposing effects of a reduction in cumulative energy demand for PV manufacturing and an increase in grid efficiency will likely result in severely limited reductions, or even possible increases, in the EPBT of PV. This is entirely due to how EPBT is operationally defined, and it has nothing to do with the actual energy performance of PV in the future.

**KEYWORDS:** EPBT, efficiency, scenarios, electric grid, primary energy

## 1. INTRODUCTION

The adoption of Energy Pay-Back Time (EPBT) as the de facto standard metric for the energy performance of photovoltaic (PV) systems ensues from a time when the first commercial modules were very energy-intensive to produce, and obviously this had serious consequences on their associated environmental impact, and impaired the credibility of PV as a truly viable 'green' alternative [1; 2]. As a result, the most common preoccupation at that time was that of testing whether, and how quickly, the complete PV systems would be able to 'pay back' the same amount of energy that was required to manufacture and operate them. Since then, modern PV systems have come a long way towards much improved energy performance, as amply documented by a large body of scientific literature [3; 4; 5; 6; 7; 8]. Yet, the EPBT metric has stuck as the indicator of choice, in spite of the availability of alternative metrics, such as for instance EROI [9; 10], which are more commonly adopted when dealing with other (non-PV) energy technologies.

In this paper, I present a thorough review of the underlying assumptions, and perform a prospective analysis with the intent of evaluating whether EPBT may still be an appropriate indicator to describe the energy performance of PV, once we move away from a conventional grid that is heavily reliant on fossil electricity, and of which PV constitutes but a negligible fraction.

## 2. METHODS AND ASSUMPTIONS

Operationally, EPBT is measured in years, and it is calculated as [8]:

*Eqn. 1)* $\mathrm{EPBT} = E_{PP} / E_{OUT\text{-}eq,yr}$

where:

$E_{PP}$ = primary energy for the construction and end-of-life (EoL) of the PV system (power plant) [$\mathrm{MJ_p}$]

$E_{OUT\text{-}eq,yr}$ = net yearly energy output (i.e. subtracting direct energy use in the operation phase), *expressed in terms of primary energy equivalent* [$\mathrm{MJ_p/yr}$]

$E_{OUT\text{-}eq,yr}$ is calculated by taking the ratio of the net electricity produced by the PV system in one year to the life-cycle energy efficiency of the current electric grid: $E_{OUT\text{-}eq,yr} = (E_{OUT,yr} / \eta_{grid})$.

Thus, a wordier but arguably less ambiguous definition of EPBT could be “how many years it will take for a PV system to produce as much electricity as could be produced by the current grid mix, using the same amount of primary energy ($E_{PP}$)”. This latter phrase makes it clearer that EPBT is *intrinsically* a comparative indicator, which is *only* rigorously defined within the framework of a specific reference grid efficiency ($\eta_{grid}$). In order to correctly interpret the information provided by EPBT, it is therefore essential to be unambiguous about how $\eta_{grid}$ is defined and calculated, and clearly state all the associated assumptions and conventions.

In its latest World Energy Outlook [11], the International Energy Agency states that: “The choice of methodology to calculate the total primary energy demand (TPED) that corresponds to a given amount of final energy (such as electricity and heat) is important [...] but not straightforward. [...] For coal, oil, gas, biomass and waste, TPED is based on the calorific value of the fuels. For other sources, the IEA *assumes* an efficiency of 33% for nuclear and 100% for hydro, wind and solar photovoltaics (PV). [...] As a result, for the same amount of electricity produced, the TEPD calculated for biomass will be several times higher than the TPED for hydro, wind or solar PV.”

In the widely-employed and well-respected life cycle assessment (LCA) database Ecoinvent [12], a similar but slightly more refined approach is adopted. Specifically, in the case of PV, "the use of solar energy is calculated with the amount of electricity delivered by the cell to the inverter" [13], and the ratio of the primary energy in the captured solar radiation to the output electricity is taken to be 3.85 $MJ_p/kWh_{el}$. This corresponds to assuming a 93.5% primary energy-to-electricity conversion efficiency for the PV system ($\eta_{conv}$), due to the average inverter losses. The other energy losses, e.g. due to system degradation and atmospheric depositions, which typically add up and result in an overall life-cycle performance ratio of ≈ 0.8, are not taken into account here, as they affect the PV system's ability to capture the solar energy ($\eta_{cap}$) and not its subsequent conversion into electricity ($\eta_{conv}$).

To sum up, for conventional thermal electricity generation, we have that, in the operation phase:

$$\mathrm{E_P} \xrightarrow{\eta_{th}} \mathrm{E_{OUT}} \;\Rightarrow\; \mathrm{E_{OUT}} = \eta_{th} \cdot \mathrm{E_P}$$

where:

$E_P$ = primary energy in the feedstock fuel [$MJ_p$]

$E_{OUT}$ = delivered electricity [$MJ_{el}$]

$\eta_{th}$ = primary energy-to-electricity conversion efficiency (heat rate) of the thermal power plant

On the full life-cycle scale, we have:

*Eqn. 2)*
$$\eta_{th,LC} = \frac{\mathrm{E_{OUT}}}{\mathrm{E_{PP}} + \mathrm{E_P}} = \left[ \frac{\mathrm{E_{OUT}}}{\mathrm{E_{PP}} + \mathrm{E_{OUT}} / \eta_{th}} \right]$$

where:

$E_{PP}$ = additional (non-feedstock) primary energy required over the system's life cycle [$MJ_p$]

$\eta_{th,LC}$ = life-cycle primary energy-to-electricity conversion efficiency of the thermal electricity production system

*Eqn. 2* applies to all thermal electricity generation systems, i.e. oil-, gas-, coal-, and biomass-fired, as well as nuclear systems (for the latter, $\eta_{th} = 0.33$ is assumed).

Instead, for PV electricity, we have:

$$\mathrm{E_{IN}} \xrightarrow{\eta_{cap}} \mathrm{E_P} \xrightarrow{\eta_{conv}} \mathrm{E_{OUT}} \;\Rightarrow\; \mathrm{E_{OUT}} = \eta_{conv} \cdot \mathrm{E_P}$$

where:

$E_{IN}$ = primary energy in the total incident solar radiation [$MJ_p$]

$\eta_{cap}$ = effective solar energy capture efficiency of the PV modules, including all losses due to degradation, soiling, etc.

$E_P$ = primary energy in the captured solar radiation [$MJ_p$]

$E_{OUT}$ = delivered electricity [$MJ_{el}$]

$\eta_{conv}$ = primary energy-to-electricity conversion efficiency of the PV system (i.e. inverter efficiency, typically = 93.5% according to Ecoinvent)

Thus, on the full life-cycle scale, we have:

*Eqn. 3)*

$$\eta_{PV,LC} = \frac{E_{OUT}}{E_{PP} + E_P} = \left[ \frac{E_{OUT}}{E_{PP} + {E_{OUT}}/{\eta_{conv}}} \right]$$

where:

$E_{PP}$ = additional (non-solar) primary energy required over life cycle [$MJ_p$]

$\eta_{PV,LC}$ = life-cycle primary energy-to-electricity conversion efficiency of the PV system

This corresponds to taking the captured (*not the total incident*) solar radiation ($E_P$) as the conceptual homologue of the primary energy in the fuel that is fed to a conventional thermal power plant.

*Eqn. 3* also applies to other renewable electricity generation systems (wind and hydro), in which case $E_P$ stands for the respective captured primary energy ('kinetic energy in wind' and 'potential energy in hydropower reserve').

In the end, the life-cycle energy efficiency of the electric grid is calculated as:

*Eqn. 4)*

$$\eta_{grid} = \sum_i \omega_i \cdot \eta_{i,LC}$$

where *i = (oil, gas, coal, biomass, nuclear, hydro, wind, or PV).*

It is noteworthy that in virtually all LCAs and energy analyses, the reported life-cycle cumulative energy demand (CED) of a PV system does *not* include the converted renewable primary energy ($E_P$), i.e. CED is taken to coincide with $E_{PP}$. This is a potential source of confusion and internal inconsistency, since $E_P$ *is* instead included in the calculation of $\eta_{PV,LC}$ and hence $\eta_{grid}$, which in turn plays a role in the calculation of $E_{PP}$, given that a part of the energy input to manufacture a PV system is in fact electricity sourced from the grid. Such potential issue remains of course negligible as long as PV represents a tiny contributor to the electric grid (i.e. $\omega_{PV} \approx 0$ in *Eqn. 4*), but it may no longer remain 'hidden' if and when PV expands and starts to play a major role in the electricity generation mix.

## 3. SCENARIOS AND DISCUSSION

In order to draft my scenarios for the future evolution of $\eta_{grid}$ and EPBT, I took cadmium telluride (CdTe) as the reference PV technology, which, according to the latest life cycle analyses performed independently by myself and colleagues [6; 7; 8], is the best-performing PV technology to date, from the points of view of its life-cycle cumulative energy demand and EPBT. It should be noted, however, that the trends shown and discussed here essentially depend on the intrinsic definitions of EPBT and $\eta_{grid}$, and not on the specific type of PV modules employed. Therefore, from a qualitative point of view, all results are transferable to all other PV technologies as well, including those still under development.

The latest published LCA studies converge in indicating that modern CdTe PV has a cumulative energy demand (CED = $E_{PP}$) of roughly 1,400 $MJ_p/m^2$ [6; 7; 8]. Assuming a typical performance ratio of 0.8 [14] and in the average southern EU insolation conditions of 1,700 $kWh/(m^2 \cdot yr)$, one square metre of CdTe PV (11% module efficiency) thus produces approximately 4,500 kWh ≈ 16,000 MJ of electricity over its expected 30-year life span. Adopting Ecoinvent's 93.5% primary energy-to electricity factor ($\eta_{conv}$), as explained in Section 2, we may thus calculate $\eta_{PV,LC}$ for CdTe PV, according to *Eqn. 3*, as:

$$\eta_{PV,LC} = \left\lfloor \frac{16{,}000}{1{,}400 + {}^{16{,}000}\!/_{0.935}} \right\rfloor \approx 0.86$$

Since such $\eta_{PV,LC}$ is considerably higher than the current average grid mix efficiency ($\eta_{grid}$), if we gradually increased PV grid penetration ($\omega_{PV}$ in *Eqn. 4*) to, say, $x$, in first approximation the resulting new $\eta'_{grid}$ would be improved by a factor of $(\eta'_{grid}/\eta_{grid}) = 1 + x \cdot [(\eta'_{grid}/\eta_{grid}) - 1]$.

However, such a simple *ceteris paribus* calculation is in fact incorrect, since the improved grid efficiency would in turn affect the $E_{PP}$ of PV (reducing it), given that part of the energy that is required for PV is itself sourced from the electric grid. In order to estimate the evolution of the life-cycle energy efficiency of the electric grid ($\eta_{grid}$) as PV penetration increases, an iterative calculation is therefore required. The results of two such iterative calculations are presented in Figure 1, where PV grid penetration is made to increase linearly from today's negligible 0.2% to an optimistic 21% in 2050, corresponding to EPIA's 'paradigm shift' scenario [15]. The initial value of $\eta_{grid}$ is taken as today's average for the EU-25 (0.31), and, for the sake of simplicity, none of the non-PV technologies composing the grid are allowed to change their respective life-cycle efficiencies ($\eta_{i,LC}$). The two scenarios differ in assuming, respectively:

- constant electricity demand for the manufacturing and EoL of CdTe PV, and constant module efficiency (11%) for the 'stagnant PV technology' scenario;
- progressive technological improvement leading to a –1% per year reduction in the electricity demand for the manufacturing of CdTe PV, and a +1% per year relative improvement in module efficiency (leading to 16.5% efficient modules in 2050) for the 'improving PV technology' scenario[1].

**Figure 1** Scenarios for the evolution of grid efficiency, under two sets of conditions.

The efficiency of the grid mix rises considerably ( ~ +35% in relative terms, and ~ +11% in absolute terms by 2050) in both scenarios, due to the increase in $\omega_{PV}$; the differences between the two scenarios are instead subtle, because the improvements in PV technology are relatively small, compared to the large gap between $\eta_{PV,LC}$ and the initial value of $\eta_{grid}$.

Figure 2 then shows how EPBT evolves in the same two scenarios. A third line is also added in Figure 2, indicating the evolution that EPBT would have due to the same technological improvements, but if it were calculated by artificially keeping $\eta_{grid}$ constant at its 2010 value. This latter set of data is of course no longer consistent with how EPBT is defined, and it is only reported in order to put in full evidence the opposite effects on EPBT of (i) improvements in PV technology, and (ii) an increase in PV grid penetration.

**Figure 2** Scenarios for the evolution of the EPBT of CdTe PV, under three sets of conditions.

Figure 2 sheds light on the consequences of sticking to using EPBT as the standard energy indicator for PV when the grid penetration of the latter rises beyond today's essentially negligible proportions. Unless it were agreed to choose to change the way EPBT is defined at some arbitrary point in the future, the two opposing effects of a reduction in $E_{PP}$ and increase in $\eta_{grid}$ will likely result in severely limited reductions, or even possible increases, in the EPBT of PV.

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[1] Such incremental improvements are consistent with past trends, and are deemed to be attainable (First Solar Inc., 2009. Personal communication). The generally agreed-upon full efficiency potential for CdTe modules is 18%.

It is important to stress that this is an unavoidable consequence of how EPBT is operationally defined, and it has nothing to do with how good the actual energy performance of PV will intrinsically be in the future. In fact, going back to the proposed alternative wording of the EPBT definition given in Section 2 ("how many years it will take for a PV system to produce as much electricity as could be produced by the current grid mix, using the same amount of primary energy"), this seemingly paradoxical result actually makes perfect sense. If the PV system under study is set up against a (much) improved grid mix, it is quite obvious that it will have a harder time ‘paying back’ its energy investment, in terms of the primary energy equivalent to its yearly electricity production (the latter being calculated as the ratio $E_{OUT,yr} / \eta_{grid}$).

Switching to a simpler and absolute energy performance indicator such as the Energy Return On Investment (EROI), instead of sticking to an *intrinsically comparative* indicator like EPBT, might provide a way out of this conundrum, and avoid potential misunderstandings and foreseeable difficulties in communicating the results of future environmental assessments of PV. EROI, in its simple definition, is the ratio of the energy delivered by a process ($E_{OUT}$) to the investment of primary energy to make it happen ($E_{PP}$) [9; 10]. However, as discussed elsewhere [16], inconsistencies have occurred in the existing EROI literature, where ambiguities have resided in the strict definition of ‘investment’.

## 4. CONCLUSIONS

The Energy Pay-Back Time indicator has been almost ubiquitously employed in the published PV literature, and remains a valuable indicator of the life-cycle energy performance of PV systems, *as compared to the existing electric grid*. In the future, as more and more PV power is installed, and the grid itself comes to be powered by PV in a non-negligible proportion, EPBT may no longer provide the best indication of performance improvements in PV systems, though. In anticipation of this, it may be advisable to start complementing, or possibly even replacing, EPBT with a different performance indicator having an absolute, rather than comparative, meaning. Above all, clear and unambiguous definitions of underlying assumptions and system boundaries are and will always remain essential corner stones of any meaningful analysis, regardless of the chosen indicators.

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