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# ENERGY PAYBACK TIME OF PHOTOVOLTAIC ELECTRICITY GENERATED BY PASSIVATED EMITTER AND REAR CELL (PERC) SOLAR MODULES: A NOVEL METHODOLOGY PROPOSAL

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ABSTRACT: Renewable energy (RE) capacity is projected to surge to an 85% share of global electricity generation by 2050, the photovoltaic (PV) share specifically is expected to increase from 1% to 22%. Increasing shares of RE in the grid mix will influence energy performance indicators, such as energy payback time (EPBT). To accurately calculate and interpret energy performance indicators, these influences must be captured. In this paper, the IEA PVPS Task 12 methodology to calculate EPBT and non-renewable EPBT (NR-EPBT) is applied. The method is evaluated quantitatively, based on the implications introduced by the grid efficiency parameter. A modified methodology for calculating EPBT (M-EPBT is proposed and applied within a range of three global average grid efficiency scenarios. M-EPBTs are found to be significantly lower for all scenarios. In the mid scenario (ηaGlobal = 33%), M-EPBT values are compared to the respective EPBTs for three installation locations, which are lowered by following magnitudes: -29% for Rio De Janeiro (Brazil), -21% for Ottawa (Canada), and -23% for Catania (Italy). Future EPBT projections until 2050 show that the M-EPBT can represent the expected energy intensity improvements of the PV system and balance of system (BOS) technologies without an altering effect of local grid efficiency at the PV system installation location more effectively.
Keywords: Energy payback time; PERC; grid efficiency; energy performance

## 1 INTRODUCTION

Today, more than 90% of the photovoltaic (PV) market share is dominated by crystalline-silicon wafers, with aluminum back surface field (Al-BSF) identified as the most common industrial process. However, passivated emitter and rear cell (PERC) technology is gaining more attention and is predicted to hit a market share of almost 60% by 2027 [1].

To compare the energy performance of different PV module technologies and system setups, but also to compare different energy generation technologies, the energy payback time (EPBT) is a widely applied indicator to illustrate energy performance. EPBT of mono-crystalline PV systems has decreased by 12% over the last 24 years as the cumulative production doubled, indicating a powerful learning rate for PV systems, and providing a positive energy performance assessment in comparison to other energy sources [2]. EPBT of PV systems is expected to keep on decreasing as the technology itself enhances.

Mainly, three parameters affect the EPBT values: cumulative energy demand (CED), the installation location's grid efficiency, and the PV system's specific yield. In this paper, the currently followed methodology of the International Energy Agency (IEA) PVPS Task 12 for calculating PV system's EPBT and non-renewable-EPBT (NR-EPBT) is evaluated quantitatively, based on the implications introduced by the considered grid efficiency [3], and thereafter, a new methodology for calculating the EPBT is proposed. It should be noted that the proposed methodology is not limited to PERC solar modules specifically, but can be utilized for all PV module technologies, through altering the related parameters accordingly.

## 2 METHODOLOGY

### 2.1 EPBT and NR-EPBT methodology

The IEA PVPS Task 12 defines EPBT as the period, captured in years, required for a renewable energy system (PV system in our case) to generate the same amount of energy (primary energy equivalent) to what was used to produce the system itself [3]. Equation (1) illustrates the integral elements of the EBPT computation methodology [3].

$$\mathrm{EPBT}=\frac{(\mathrm{CED_{mat}}+\mathrm{CED_{manuf}}+\mathrm{CED_{trans}}+\mathrm{CED_{inst}}+\mathrm{CED_{EOL}})}{\left(\left(\dfrac{\mathrm{E_{agen}}}{\boldsymbol{\eta}_\mathbf{G}}\right)-\mathrm{CED_{O\&M}}\right)} \quad (1)$$

$\mathrm{CED_{mat}}$: CED (in MJ) to produce materials comprising PV system
$\mathrm{CED_{manuf}}$: CED (in MJ) to manufacture PV system
$\mathrm{CED_{trans}}$: CED (in MJ) to transport materials during lifecycle
$\mathrm{CED_{inst}}$: CED (in MJ) to install the system
$\mathrm{CED_{EOL}}$: CED (in MJ) for end-of-life management
$\mathrm{E_{agen}}$: Mean annual electricity generation (in $\mathrm{kWh_{electric}}$)
$\mathrm{CED_{O\&M}}$: CED (in MJ) for operation and maintenance
$\eta_G$: Grid efficiency, primary energy to electricity conversion at the demand side ( $\frac{\mathrm{kWh_{electric}}}{\mathrm{MJ}}$ )

As can be drawn from equation (1), the EPBT accounts in the numerator for the energy that is embedded in the PV system, including the CED for material, manufacturing, transport, installation as well as for end-of-life energy expenses. In the denominator, the mean annual energy generation is converted by the installation location local grid efficiency to primary energy equivalents (PE-eq.) with the energy demands for operation and maintenance ($\mathrm{CED_{O\&M}}$) being subtracted.

Besides the EPBT, the IEA PVPS Task 12 proposed the NR-EPBT as an indicator to capture a PV system's energy performance. The NR-EPBT is calculated analogously to the EPBT methodology, except replacing primary energy (PE) with non-renewable primary energy (NR PE) for both the manufacturing and generation side. NR-EPBT quantifies the time needed to compensate for the employed NR PE in a PV system's life cycle. The calculation of EPBT and NR-EPBT do not differ greatly in the case of country or region dominated by non-renewable energy sources. However, in the case of high renewable energy (RE) share in the grid mix, these values differ significantly, and it seems impossible to distinguish in different EPBT analyses between technological progress in efficient PV production technology and share of RE (or NR) in the production and installation locations' grid mix. In this context, due to this methodological implication, the NR-EPBT is not seen as a relevant indicator for energy performance within this work and subsequently not further applied in the following analyses.

2.2 Grid efficiency

The electrical yield of a PV system is dependent on its installation location with respect to local irradiation and climate patterns [3]. Apart from that, EBPT is additionally biased by the average grid efficiency at each individual installation site. The grid efficiency serves as a conversion rate to translate generated PV electricity to PE-eq. The grid efficiency is calculated with the following equation as taken from [4]:

$$\eta_{G,I} = \frac{E_{grid,I}}{CED_{E,I}} \quad (2)$$

$CED_{E,I}$: PE-eq. (in MJ) for average electricity mix of the grid at installation location I to generate $E_{grid,I}$
$E_{grid,I}$: Electric energy supplied by the grid at installation location I

In that context, $CED_{E,I}$ is the PE-eq. for the average electricity mix at the installation location. It is calculated as the sum of the CEDs of all energy sources in the grid mix, as given by the Ecoinvent CED method's subcategories. This approach of summing the CEDs is indeed problematic, since Ecoinvent states that: 'We refrain from giving an aggregated total of the CED-indicators' [5]. Due to the different approaches followed at each subcategory, summing the CEDs can lead to energetic inconsistencies. An increased share of RE in the grid mix can lead to higher grid efficiencies, because of an intrinsic considered 100% conversion efficiency for RE. Conventional electricity generation technologies are accounted with fundamental different conversion efficiencies. In the case of coal power, the upper heating value of the feed stock is accounted as PE-eq, for nuclear power the PE-eq. in the isotopes. This inconsistent approach results in much lower conversion efficiencies compared to the assumed 100% efficiency for RE generation in the Ecoinvent database. Hence, when PV systems are manufactured at one location and installed in different locations, electricity grids with high RE deployment lengthen EPBT values [2,4].

At the manufacturing location, grid efficiency influences embedded CED of the PV products. As PV and balance of system (BOS) manufacturing lines are fed with electrical and thermal energy, power plants convert PE upstream the production line to secondary energy carriers, such as electricity and heat. Subsequently, assuming a steady manufacturing process at a particular production location and increasing average grid efficiency, lowers the CED of PV and BOS manufacturing and therewith shortens PV systems' EPBT [6].

Consequently, EPBT implies two contrary effects with respect to increasing RE penetration in future power grids. First, increasing the grid efficiency reduces module and BOS' CED in PV manufacturing. Second, increasing grid efficiency alters the translation of output electric energy to PE-eq on the generation side, resulting in longer EPBT. Considering the stated opposing trends, EPBT might not be able to illustrate improving energy performance caused by future module efficiency and manufacturing CED improvements adequately [2,7].

2.3 EPBT dataset

All data used for this work was taken from an attributional life cycle assessment (LCA) study of Friedrich et. al [4], including the life cycle inventory (LCI) of a 15 kWp Czochralski Passivated Emitter Rear Cell (Cz PERC) system and respective CEDs for production and operation, as well as location specific irradiance and grid efficiency parameters necessary for yield assessment.

In order to compare the EPBT values, China as a PV system production location is considered. China has the highest manufacturing share of PV modules and BOS components [2].

## 3 RESULTS

3.1 Novel approach for EPBT methodology

As stressed by Friedrich et al. [4] and Raugei [7], grid efficiency tends to have a significant influence on the amount of generated PE-eq. on the generation side of PV systems. To contradict the distorting effect of increasing RE share on the EPBT indicator, the M-EPBT is proposed. In this light, it is the novel approach's goal to maintain the energy saving implication of high grid efficiency in manufacturing, in other words lowering the CEDs in the production of PV systems, and to exclude its payback time lengthening effect on the generation side. To fulfill the latter outlined requirements, the location dependent grid efficiency ($\eta_G$) in the denominator (equation (1)) is substituted by the average global grid efficiency ($\eta_{gGlobal}$) in equation (3). The concept of average global grid efficiency is further explained later in this section.

$$\text{M-EPBT} = \frac{(CED_{mat}+CED_{manuf}+CED_{trans}+CED_{inst}+CED_{EOL})}{\left(\left(\frac{E_{agen}}{\eta_{aGlobal}}\right) - CED_{O\&M}\right)} \quad (3)$$

$CED_{mat}$: CED (in MJ) to produce materials comprising PV system
$CED_{manuf}$: CED (in MJ) to manufacture PV system
$CED_{trans}$: CED (in MJ) to transport materials during lifecycle
$CED_{inst}$: CED (in MJ) to install the system
$CED_{EOL}$: CED (in MJ) for end-of-life management
$E_{agen}$: Mean annual electricity generation (in $kWh_{electric}$)
$CED_{O\&M}$: CED (in MJ) for operation and maintenance
$\eta_{aGlobal}$: Average global conventional grid efficiency ($\frac{kWh_{electric}}{MJ}$)

The proposed methodology alteration shall implement following principles in the M-EBPT indicator:

a. M-EPBT magnitudes shall be significantly less influenced by the electricity grid mix at the installation location, especially by the EPBT lengthening impact of RE sources.
b. Energy savings in the CED for manufacturing will be considered. Improvements in grid efficiency at the production location, due to increasing RE penetration, will lower CED for manufacturing processes.

c. In contrast to NR-EPBT, the proposed method considers RE that is consumed in the production phase.
d. Module efficiency improvements will be depicted in the indicator. Alteration of generated PE-eq by increasing grid efficiency no longer compensates module and energy efficiency improvements in manufacturing.
e. To develop an indicator which allows facile intercountry comparison, $\eta_{aGlobal}$ is assumed constant for all installation locations.

In other words, the proposed indicator illustrates how many years it will take for a PV system to produce as much electricity as could be produced by the average global electricity generation sources, using the same amount of PE.

With respect to the fact that global grid mixes will develop toward 100% RE in the future, it may seem contradicting that the generated energy is converted partly to NR energy-eq in the proposed method. However, given that from a theoretical perspective, RE (e.g., PV systems) still replaces formerly installed NR energy in future highly RE grids, as similar to the argumentation for NR-EPBT in the IEA Task 12 methodology guidelines [3]. Hence, the M-EPBT represents a viable method to explicitly illustrate the strict substitution of NR electricity generation by RE sources.

To incorporate the above explained concept numerically, $\eta_{aGlobal}$ is defined within the following sensitivity range:

i) low scenario $\eta_{aGlobal} = 26\%$
ii) mid scenario $\eta_{aGlobal} = 33\%$
iii) high scenario $\eta_{aGlobal} = 40\%$

$\eta_{aGlobal}$ is implemented within a sensitivity span to account for the fact that a reliable value of the average conventional global grid efficiency of conventional generation was not found in literature. As mentioned in [4], the global average may be approximated with the average efficiency of thermal (conventional) power plants lowered by transmission losses. Having this in mind, we defined the mid scenario with $\eta_{aGlobal} = 33\%$ and the respective low and high scenarios with a deviation of +/-7%, which is aligned to the conventional grid efficiency deviation span stated by Ritchie et al. [8].

Following the Ecoinvent LCA data and CED methodology, it is known that certain locations, due to low efficient conventional power generation, are characterized by significantly lower grid efficiencies, such as Jaipur, India (Indian grid) with 17.5% and Cape Town, South Africa with 21.9 % [4]. Nevertheless, these locations represent a minority and are expected to increase efficiency in the future due to technological improvement. Moreover, there exists locations with high grid efficiencies, such as Kinshasa, Republic of Congo, where the grid efficiency is 73.5%. EPBT values of such high grid efficiency locations are set to be lowered with the new methodology. Within this approach, the resulting M-EPBT allocates comparable energy performance values for PV systems installed at various locations, with varying PV electric yield (due to solar irradiation), and varying local grid efficiencies. An overview of the input data for the EPBT and M-EPBT is presented in table I.

**Table I:** Parameters to assess energy payback indicators (EPBT and M-EPBT) for the installation locations Ottawa (Canada), Rio de Janeiro (Brazil), and Catania (Italy)

| | | Dependency: Installation location | | |
|---|---|---|---|---|
| **Installation Location of the PV System** | **Energy Performance Indicators** | **Grid efficiency** *(kWh/ kWh)* | **aGlobal-grid efficiency** *(kWh/ kWh)* | **PV yield** *((kWh/kW)/a)* |
| Ottawa, Canada (Canadian grid) | EPBT | 42.8% | | |
| | M-EPBT upper | | 40% | |
| | M-EPBT mid | | 33% | **1,260** |
| | M-EPBT lower | | 26% | |
| Rio de Janeiro, Brazil (Brazilian grid) | EPBT | 46.6% | | |
| | M-EPBT upper | | 40% | |
| | M-EPBT mid | | 33% | **1,438** |
| | M-EPBT lower | | 26% | |
| Catania, Italy | EPBT | 40.4% | | |
| | M-EPBT upper | | 40% | |
| | M-EPBT mid | | 33% | **1,586** |
| | M-EPBT lower | | 26% | |

3.2 M-EPBT results

As can be extracted from figure 1, the M-EPBT magnitudes range from 0.67 years to 1.02 years in Catania, Italy, 0.72 years to 1.12 years in Rio de Janeiro, Brazil and between 0.83 years to 1.29 years in Ottawa, Canada. Besides the M-EPBT high scenario for Catania, Italy, where $\eta_{aGlobal} = \eta_G$, the M-EPBTs display distinctly lower values compared to the respective EPBTs that are plotted on the left side of the x-axis in figure 1 for the respective three installation locations.

The broadest difference between EPBT and M-EPBT with respect to the mid grid efficiency scenario ($\eta_{aGlobal} = 33\%$) is found in Rio De Janeiro with a M-EPBT decrease of 29%, whereas Catania and Ottawa range from -21% to -23% compared to EPBT. Energy performance influencing factors, such as location specific yield and total CED for system manufacturing are considered equally for EPBT and M-EPBT within one location. Thus, the divergence between EPBT and M-EPBT is to be explained with the modified grid efficiency at each installation site. As outlined from a theoretical perspective in section 2.2, it may be observed that the share of RE sources in a particular installation location’s grid mix is directly correlated to the extension of EPBT. As the proposed M-EPBT method implies an equal $\eta_{aGlobal}$ for the three installation locations, the proportional share between M-EPBT and EPBT illustrates the lengthening effect of high RE penetration in installation location’s grid mixes. Hence, the higher the RE share in the respective installation grid mix, the larger the difference between EPBT and M-EPBT. Since Rio de Janeiro displays concurrently the highest share of RE in the grid (grid efficiency = 46.6%) and the largest difference between EPBT and M-EPBT, the presented results support this hypothesis. Subsequently, the proposed M-EPBT methodology serves as an explicit indication for i) the specific conditions at each installation location, in particular for the magnitude of solar radiation, the minor impacts of operation and maintenance energy expenses, and CED for transport from manufacturing to installation location, and ii) for grid efficiency and energy efficiency improvements at the manufacturing location.

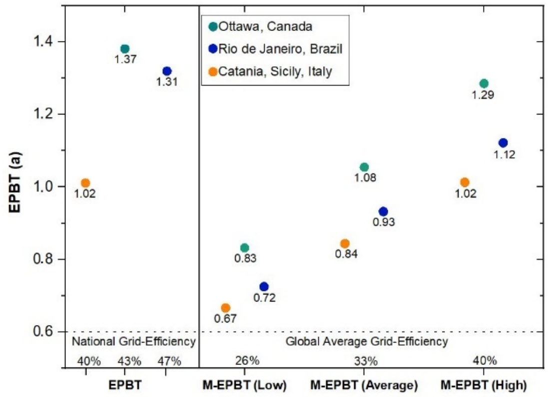


**Figure 1:** EPBT and M-EPBT of a 15 kWp slanted rooftop Cz PERC PV system produced in China for the installation locations Ottawa (Canada), Rio de Janeiro (Brazil), and Catania (Italy). Depicted from LCA and EPBT dataset of Friedrich et al. [4]

3.3 Application of EPBT and M-EPBT in future scenario

PV systems are expected to be more efficient and less energy demanding in the future, due to technological developments [7]. According to the technology roadmap published in 2018 by the International Renewable Energy Agency (IRENA) [9], by 2050, RE sources are expected to reach an 85% share in the worldwide electricity generation mix, with solar PV's share increasing from 1% to 22% [9]. The EU has already pledged for zero carbon emissions by 2050 [9].

Moreover, in the last decade, the average silicon module efficiency has increased from 12% to 17% today, with the number being even higher for PERC modules (21%) [12]. This trend is expected to continue in the future, driven by solar cell efficiency increase. An efficiency of 24% is projected by 2050 for one junction crystalline-Si (c-Si) modules [10], limited mainly by the maximum theoretical efficiency of 29.4% of c-Si cells [11]. In addition, the production chain of c-Si modules and BOS components have improved in the last years, leading to less energy intensive production methods. In 2006, the first LCA reports showed a lifecycle energy demand for mono-crystalline modules produced in Europe of 36 MJ-eq/Wp [12], while today the CED of PERC solar modules produced in Europe is 8.6 MJ-eq/Wp [9]. Although these values cannot be directly compared due to differences in electricity supply, they clearly show a trend of future reduced CED for module production.

In order to demonstrate the above-mentioned trends and their effect on the future EPBT and grid efficiency we follow the method proposed by Raugei [7] and apply the mid scenario value for $\eta_{aGlobal}$ = 33%. The main target of the following methodology is to demonstrate future trends and effects that will arise with the current EPBT framework, rather than predicting exactly the EPBT in the future.

According to [7], the grid efficiency is the result of the weighted sum of the life cycle efficiencies of each energy source in the grid:

$$\eta_G = \sum_i w_i * \eta_{i,LC} \quad (4)$$

i: Energy source
$w_i$: Share of the energy source *i* in the grid (in %)
$\eta_{i,LC}$: Lifecycle primary energy-to-electricity conversion efficiency of the corresponding energy source (in %)

The lifecycle efficiency is calculated differently for thermal power plants and RE sources, because of the different approaches discussed above in the CED calculations by the Ecoinvent database [5]. For thermal power plants (fossil, nuclear, biomass), the grid efficiency equation is as follows, according to [7]:

$$\eta_{th,LC} = \frac{E_{out}}{CED_{pp} + CED_p} = \frac{E_{out}}{CED_{pp} + \frac{E_{out}}{\eta_{th}}} \quad (5)$$

$E_{out}$: Total produced electricity (in MJ)
$CED_p$: PE in the feedstock (in MJ)
$CED_{pp}$: Additional (non-feedstock) PE required over the system's lifetime (in MJ)
$\eta_{th}$: Lifecycle primary energy to electricity conversion efficiency of the thermal electricity production system (in %)

As for PV solar energy, the grid efficiency equation is as follows, according to [7]. The same formulation as the PV energy can also be applied for hydro and wind, but with different conversion efficiencies [5,7]:

$$\eta_{PV,LC} = \frac{E_{out}}{CED_{pp} + CED_p} = \frac{E_{out}}{CED_{pp} + \frac{E_{out}}{\eta_{inv}}} \quad (5)$$

$E_{out}$: Total produced AC electricity over the whole PV lifetime (in MJ)
$CED_p$: PE in the captured solar radiation (in MJ). This represents the DC electricity that the solar module produces
$CED_{pp}$: Additional (non-solar) PE required over the system's lifetime (in MJ)
$\eta_{inv}$: Primary energy-to-electricity conversion efficiency of the PV system (taken as the average inverter efficiency = 93.5% according to [5] (in %)

Two different scenarios are considered:

- *Improved technology scenario:* Improved PV system technology, where the PV specific yield is expected to increase due to an increase in module and BOS efficiencies until 2050 [10]. The CED of PERC systems is decreasing linearly by 1% per year until 2050 [7]
- *Stagnant technology scenario:* CED, module efficiencies, and PV yield are kept constant as in the reference year 2020

In both scenarios, the share of solar energy increases from 1% in 2020 to 22% in 2050 [9]. Moreover, the installation location is chosen to be the average European grid and solar irradiation, with PERC modules produced in China [4].

Based on equation (6), the lifecycle efficiency of PV solar is found to be 83.8% in 2020 and 2050 in the stagnant technology scenario, and 87.5% in 2050 in the improved technology scenario. By assuming that the lifecycle efficiency of all the other technologies remain stable, the projected grid efficiency is calculated for both scenarios based on equation (4).

The grid efficiency increases steeply, reaching 43.8% in the stagnant scenario and 44.6% in the improved scenario. The difference between the two scenarios is rather small, indicating that the increase is mainly driven by the increased share of PV, rather than the technological development. Table II summarizes the given input parameters, and the grid efficiency results.

**Table II:** Main input parameters for current and future projections of M-EPBT in 2050, for two different scenarios, as well as the projected grid efficiency changes [1-4]

| PV system parameters | 2020 | 2050 | |
|---|---|---|---|
| | | Stagnant Technology | Improved Technology |
| Production Location | China | | |
| Installation Location, Capacity | Average EU, 15 kWp rooftop | | |
| Average Solar Irradiation *[(MWh/m²)/a]* | 1.33 | | |
| PV Yield *(GJ/a)* | 58.9 | | 70.2 |
| CED PV System *(GJ)* | 219 | | 153 |
| Solar Share in Grid Mix *(%)* | 1 | 22 | |
| Calculated Grid Efficiency *(%)* | 33 | 43.8 | 44.6 |

Figure 2 shows that the EPBT in the technology improvement scenario is decreased steeper for the modified methodology (-41%) compared to the standard methodology (-21%).

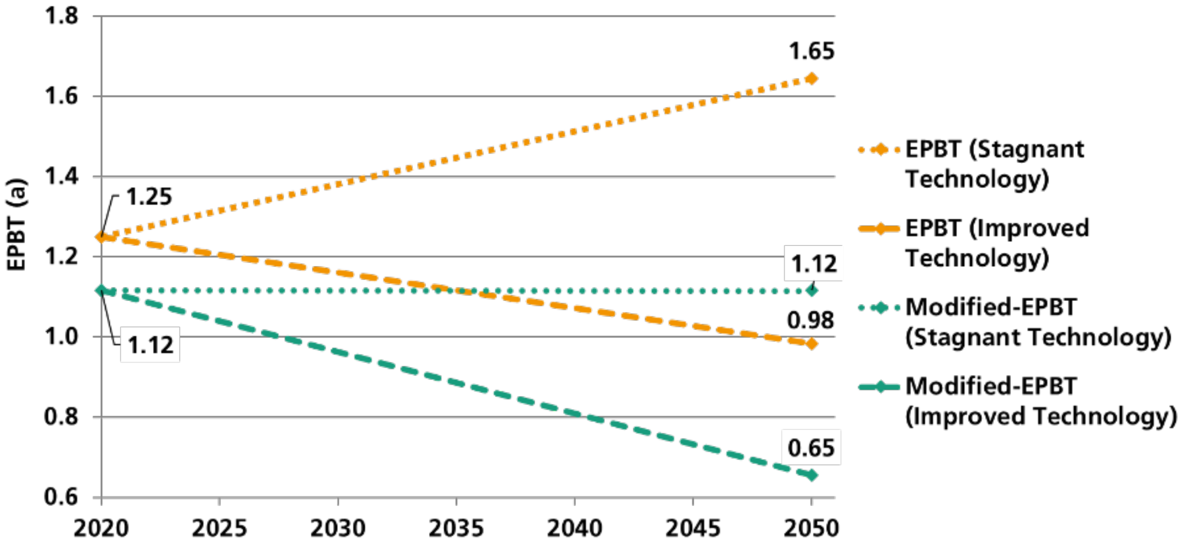


**Figure 2:** EPBT evolution until 2050, as calculated by the current IEA methodology (EPBT) and the proposed M-EPBT, for two different scenarios

In the standard EPBT case, the counteracting effects of increased grid efficiency and reduced $CED_{pp}$ lead to a limited EPBT reduction. Moreover, in the stagnant technology scenario, the EPBT calculated with the standard methodology, has increased more than 30%, reaching 1.65 years in 2050, dictated mainly by the installation location's grid efficiency rise. M-EPBT remains stable in the stagnant technology scenario throughout the years.

For both scenarios, it is demonstrated that the standard EPBT methodology cannot fully express future technological improvements of the PV system technology, due to the imminent EPBT value rise. The newly proposed methodology provides a solution to translate the technology development into reduced EPBT. In this way, the improvements in the system yield and production technology can be depicted in the M-EPBT, despite the increase of the share of RE sources.

## 4. CONCLUSION

This work focused on the EPBT analysis of PERC modules and the proposal of a new methodology (M-EPBT) for the calculation of the EPBT, in order to overcome some identified weaknesses of the current IEA Task 12 approach.

The conducted analysis demonstrates selected shortcomings of the EPBT. Due to its methodological dependency on grid efficiency, particularly at the PV system's installation location, the EPBT is not seen as a valid energy performance indicator for grid mixes characterized by high RE generation. As emphasized, increasing grid efficiency influences the conversion of output PV electric energy to PE-eq on the generation side, resulting in longer EPBTs. Hence, technological improvement in module technology and energy saving in production will be (partly) compensated by this effect. Regarding future grids being dominated by RE, the EPBT could no longer deliver sound indication for PV system's energy performance.

Also, the second IEA methodology approach NR-EPBT, is seen as insufficient to illustrate energy performance. In detail, the NR-EPBT lacks by only considering NR PE-eq in manufacturing. Especially considering worldwide increasing RE penetration, it is seen as inadequate from a methodological perspective to exclude highly efficient RE manufacturing in the PV system's CED. Second, as the IEA NR approach assumes, the same amount of electric output ($E_{agen}$) is solely produced by the PV system, it is divided by the NR grid efficiency, which itself may reach higher values than the total grid efficiency by method. Again, under consideration of rising RE deployment, this efficiency increasing effect can dramatically amplified the ($E_{agen}/\eta_G$) term in the NR approach, resulting in delusively longer

NR-EPBT values for locations with high RE power generation.

To address the stated distorting effects, the M-EPBT was introduced. The novel approach maintains the primary energy saving implication of high grid efficiency in manufacturing (by including the non-renewable and renewable PV system CEDs) and excludes its payback time lengthening effect on the generation side. To fulfill the latter outlined requirement, the installation location grid efficiency ($\eta_G$) was substituted by the average global conventional lifecycle grid efficiency ($\eta_{aGlobal}$).

The EPBT and M-EPBT were projected for a 2050 scenario, including module efficiency and manufacturing CED improvements. As expected, the M-EPBT appears to decrease more steeply (-41%) from 1.12 years to 0.65 years, in comparison to the standard EPBT approach (-21% from 1.25 years to 0.98 years), simply because the previously mentioned counteracting effects are eliminated. Thus, the proposed methodology provides a solution to illustrate the technological development undistorted in the M-EPBT energy performance indicator.

All in all, many qualitative and quantitative parameters shall be considered in the evaluation and assessment of EPBT as an indicator. Above all, clear and unambiguous definitions of underlying assumptions and system boundaries, from the researchers, are cornerstones of LCA in general, and EPBT in particular.

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