Long Term Analysis of Energy Payback Time for PV Systems

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Abstract. The energy payback performance of an energy generating technology such as PV, is usually based on a single system considering static parameters for its evaluation. However it is recognized that performances of an installed systems decrease over time, while, on the other hand, the performances of new systems is expected to slightly increase over time. Additionally the energy required for manufacturing a new system has decreased significantly in the last years and additional decrease is expected in the near future; moreover the opportunity to recycle materials from dismantled PV installations is becoming massively investigated and some technologies are already on industrial scale. These dynamic aspects inspired the present work that firstly consider the calculation of the energy payback of PV systems that should drive the most sustainable decision regarding the optimal timing for dismissing of an old PV system and replacement with a new one.

Keywords: Energy payback, energy breakeven, PV systems

1 Introduction

Photovoltaic is a fast growing market: it has boomed over the last decade, and its expansion is expected to continue worldwide in 2011 about half of the previously cumulated PV module capacity entered the market.

Energy Payback Time is defined as the period required for a (renewable) energy system to generate the same amount of energy (in terms of primary energy equivalent) that was consumed by the system itself during its life. New energy technologies are evaluated by this criteria in order to estimate their ability to contribute to our growing energy needs and to deal with carbon emissions problems [1]. However it should be noted that the Energy Payback Time of PV systems is dependent on the geographical location: PV systems in Northern Europe need around 4 years to balance the inherent energy, while PV systems in the South equal their energy input after 2 years and less.

The environmental performance of PV systems was characterized in life cycle studies [2]-[3].

The energy performance of new technologies can and often does improve as the technology evolves.
In the last 10 years, the efficiency of average commercial wafer-based silicon modules increased from about 12% to 15%; moreover usage for silicon cells has been reduced significantly during the last 5 years from around 16 g/Wp to 6 g/Wp due to increased efficiencies and thinner wafers.
Gutowski et al. [1] studied performance of growing energy systems ensembles, identifying an optimum growth rate (largest value of net energy production) and critical growth rate (rate at which the ensemble generates no new energy). A case study on PV ensembles is presented and discussed.
Another important aspect for the long-term sustainability of the PV industry is the end-of-life photovoltaic (PV) module recycling, considering the large future expected waste volumes.
As indicated by the inclusion of photovoltaic (PV) in the European Union Directive on Waste Electrical and Electronic Equipment (WEEE), end-of-life module recycling is important to the long-term sustainability of the PV industry. In addition, in order to help the management of large future expected waste volumes [4], PV recycling can contribute to resource efficiency by preserving valuable raw materials (glass, copper, aluminium, semiconductor materials, etc.) for future use in PV modules or other new products.
Recycling activity extract from PV modules three primary recyclable materials: aluminium, glass and unrefined semiconductor material. The life cycle assessment of CdTe PV module recycling has been described in [5]-[6].
Many of these effects could affect the energy performance parameters. Therefore we will show that Energy Payback Time should be properly adjusted when considering an already installed system and the decision on dismantling and replace it with a new system.

2 Model

In the following, we develop a model that is the starting point for the development of a further analysis, which is aimed to determine when a PV system should be dismantled and/or substituted by a new one.
Figure 1 presents a typical Energy Balance for a PV system, where the Energy Payback Time ($EnPBT^1$) and the Embodied Energy (E^1_E) required to manufacture all the components included into the system are considered.

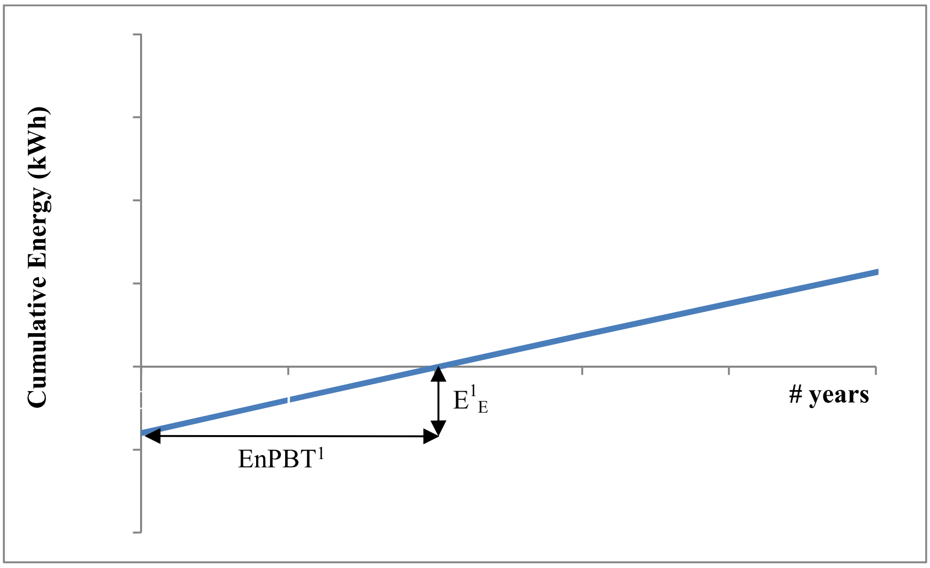

Fig. 1. Cumulative energy of a PV system installed at time t=0

At t=0 the PV system is installed, and the Embodied Energy (E^1_E) required to manufacture all the components is taken into consideration. After installation, the system produces a certain amount of energy (namely the annual produced energy, $E_{P,t}$), which is a function of the total power installed (P), the efficiency (η_t, for the t-*th* year after installation), and the annual number of equivalent hours of production, which is usually considered as a constant over time and it depends on the geographical location of the plant.
After *n* years (t = $EnPBT^1$) the PV system starts to be energetically profitable, i.e. the cumulative energy assumes positive values after *n* years. Usually a PV system is considered operative until the end of its lifetime (LT), which is usually assumed to be 25 years. However the introduction of new technologies can lead to the decision of replacing the installed modules with new modules, on the same available space.
Thus after t_1 years from its installation, plant #1 can be replaced by plant #2: the cumulative energy (CE_{t1}) decreases dramatically, as the Embodied Energy for the production of the modules included in plant #2 (E^2_E) must be summed up to the cumulative energy produced by #1 until t_1. In Figure 2 it is assumed that $E^2_E \leq CE_{t1}$, so that the total cumulative energy ($CE_{t1} - E^2_E) \geq 0$.
After t' ($t_1 \leq t' \leq t_2$) from the first installation of #1, the expected cumulative energy related to plant #1, would be $CE^1_{t'}$ while the effective cumulative energy related to plant #2 is $CE^2_{t'}$, with $CE^1_{t'} \geq CE^2_{t'}$; only after t_2 years from the first installation (plant #1) the effective cumulative energy assumes the same value of the expected one, i.e. $CE^1_{t'} = CE^2_{t'}$, and the Time To Energy Equivalence is $TTEE^{1\text{-}2}$.

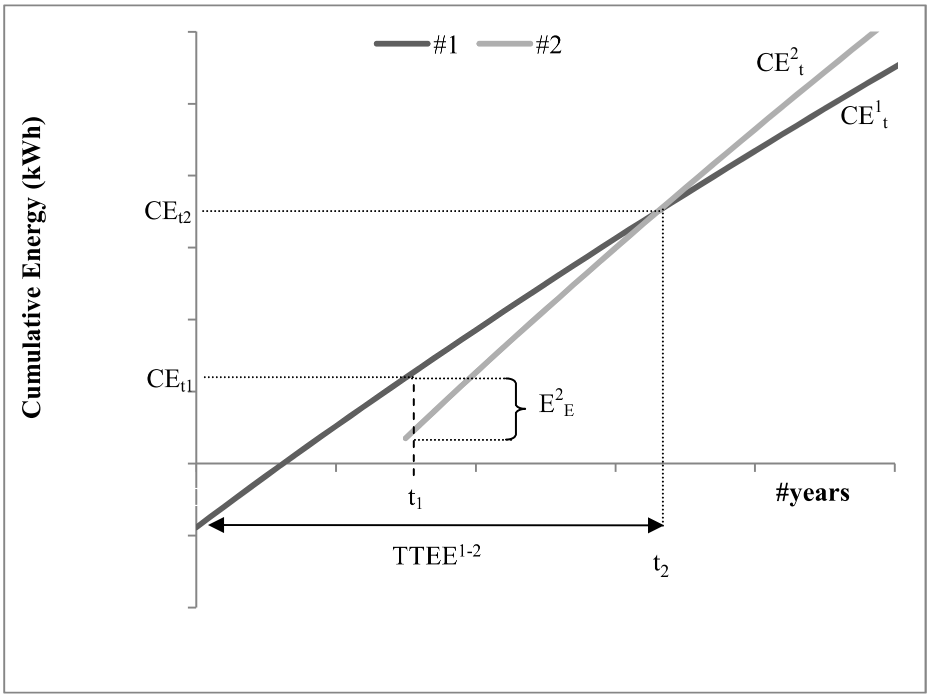

Fig. 2. Cumulative energy of two PV systems (#1 installed at t=0 and #2 installed ad $t=t_1$)

Starting from the considerations introduced in the first paragraphs, the Embodied Energy E^2_E required to manufacture the system #2 is lower than the energy required to produce system #1. The reason is that with the introduction of new technologies, the required production energy is lower, i.e. developing new processes that requires less semiconductor material. Thus the relationship of embodied energy of modules related to plant #1 and #2, is $E^2_E \leq E^1_E$.

Moreover Figure 2 shows that the curve representing the cumulative energy related to plant #2 has a greater slope the one related to plant #1: this is a consequence of the increased performances of system #2, that allow to install a greater power on the same area of plant #1.

Therefore the respective relationship on Energy Payback Time for the new systems ($EnPBT^2$), with respect to the old one ($EnPBT^1$) becomes $EnPBT^2 \leq EnPBT^1$. It should be noted that those two Energy Payback Time are calculated with respect to the base case scenario of no previous system installed.

In order to answer the first question "should the system installed at time t=0 be replaced by a new system after some years from its installation, from an energy point of view?"

For $0 \leq t \leq TTEE^{1-2}$ (where TTEE indicates the time to equivalent energy of system #1 and system #2) the cumulative energy produced by system #1 (effectively for $t < t'$, theoretically for $t' \leq t < TTEE^{1-2}$), represented by the black continuous line in Figure 3, is higher than the cumulative energy produced when substitution $t = t'$ is implemented (grey dashed line in Figure 3), while for t ≥ $TTEE^{1-2}$ the opposite situation arises.

In Figure 3 it is also highlighted the value of $Re\mathrm{EnPBT}^{t',(1-2)}$, which represents the *Replacement* Energy Payback Time of the plant #1 with plant #2, at time t': the next paragraph focuses the discussion on such a value, in order to determine whether or not it is convenient (from the energy point of view) to replace an existing system, or to install another one next to it.

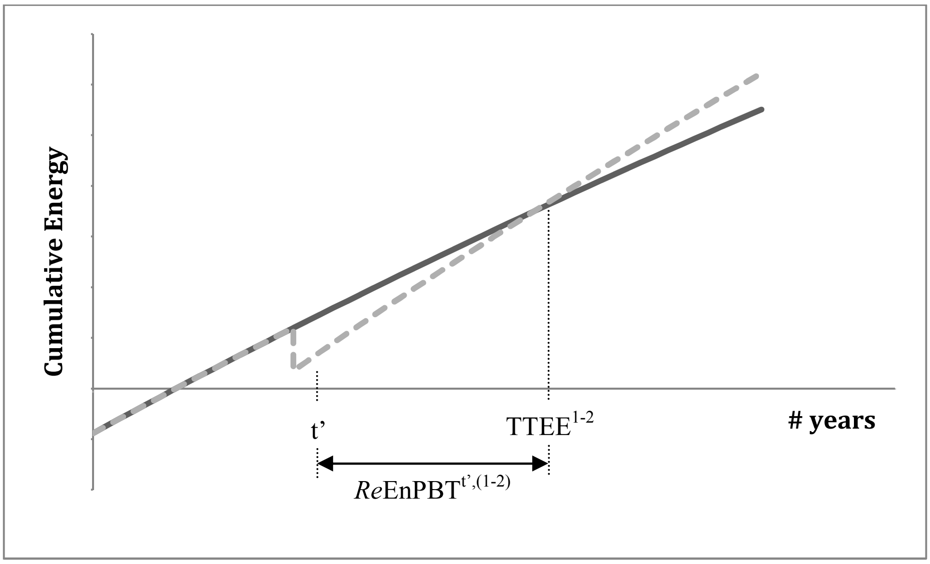

Fig. 3.*Replacement* Energy Payback Time of PV system #2

Recalling the main considerations presented in the previous paragraph, such as the reduction in energy required for manufacturing a module, lead to a decrease in Energy Payback Time for the single plant. Thus, as reported in Figure 4, the *Replacement* Energy Payback Time is a decreasing function of the substitution time t'. Typically for three different substitution times, t'_A, t'_B and t'_B, with $t'_A \leq t'_B \leq t'_B$:

$$Re\mathrm{EnPBT}^{t'A} \geq Re\mathrm{EnPBT}^{t'B} \geq Re\mathrm{EnPBT}^{t'B}$$

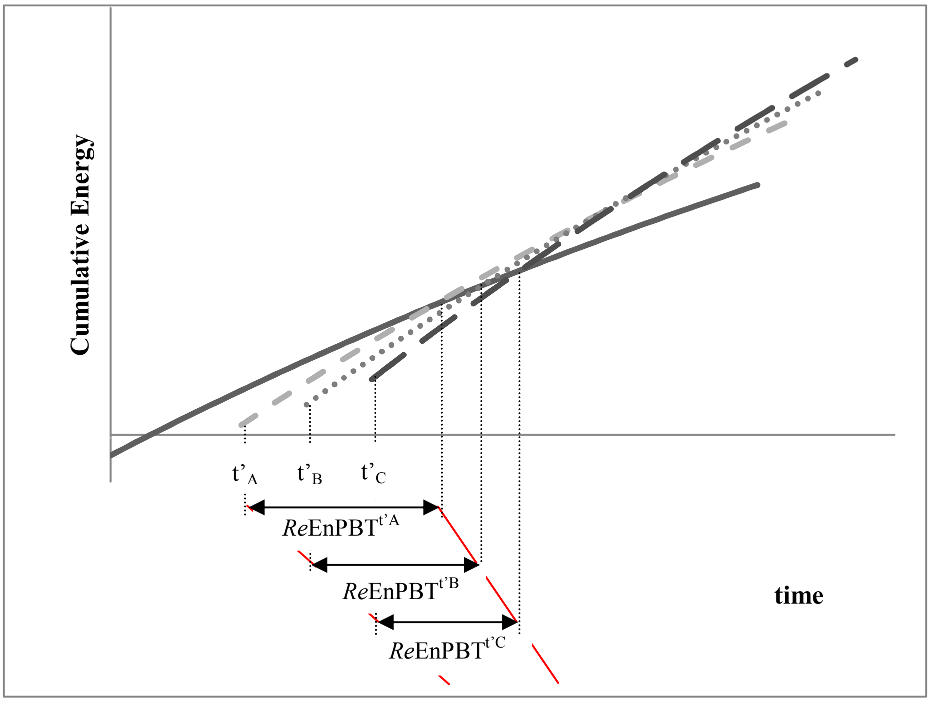

Fig. 4. *Replacement* Energy Payback Time of PV systems replaced at different times

Such evidence suggests the existence of a replacement time value, t^*, that represents the value under which the substitution of the plant modules is not profitable from an energy production point of view: the associated *Replacement* Energy Payback Time is greater than the Energy Payback Time of a new system. The model shows that for replacement time greater than t^* the replacement of the PV system becomes profitable: the associated *Replacement* Energy Payback Time is lower than the Energy Payback Time of a new system.

3 Numerical Analysis

To study the behaviour of the model presented in the previous section, a numerical analysis is performed to investigate how the model parameters influence the energy model. In table 1 main parameters considered as reference for the numerical analysis are reported.

Table 1. PV System parameters considered

Available area	400 m^2
First installation year	2012
PV modules technology	Si poly-crystalline

Efficiency degradation See [Jordan et al., 2011] for reference	Year 1 (after installation): 3% Years 2 to 10: 0.7% Years 11 to 25: 0.45%
Plant power (kWp)	50
PV modules efficiency at time 0	12.5%
Embodied energy	8890 kWh/kWp (5% decrease every 15 years, due to technology progress)
Plant location	South Italy (yearly equivalent operating hours: 1500 h)

In case of replacement at the 15-th year (t = 15), the *Replacement* Energy Payback Time is 18.02 years. For the other two examined cases (replacement after 20 years, t=20, and 25 years, t=25), the *Replacement* Energy Payback Time is equal to 14.37 years and 12.02 years, respectively. Therefore for this case even after 25 years from the installation of the system #1 the *Replacement* Energy Payback Time *Re*$EnPBT^{t',(1-2)}$ is larger than the new system Energy Payback Time ($EnPBT^{2}$) and thus it is not convenient to replace the old system with a new one but it is preferable to add a new system and keep operating the old one. Further analysis could be devoted to the determination of the replacement rime $t^{'}$.

4 Conclusion

The analysis presented here has never been considered by energy analysts, because, usually the attention is focused on a single system measures on a mid-term time basis and main energy basis considered parameters, such as, mainly, the energy payback time of a new installation. Due to the described growth in the number of PV installations in recent years we are convinced that also a long term analysis should be valuable, considering the option of replacing an old system after several years of production in favour of a new and most performing system. This work is the first attempt to depict the problem of the replacement decision on an energy basis considering most of the parameters that influence the problem. Next step of the work is the development of an analytical model so as to perform an analytical sensitivity analysis of the break even time from which it is convenient to replace the old installation. Moreover an economic analysis of the problem presented could be valuable, even if from this point of view the analysis is strongly affected by the country and year of the considered PV installation (due to differences in the incentive scheme and changes of that over time). Finally it should be noted that the analysis included here, if properly adjusted, could be applied to any kind of energy system from wind power to biomass or biogas systems.

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