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Disclaimer

I would like to apologise to the reader for the crudeness of this version. References are sparse and results lack discussion. Please keep in mind this is a work in progress.

A physical baseline to model photovoltaic development and estimate its net product

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Abstract

Photovoltaic production dynamic is usually modeled using a sigmoid or S-curve function, without any physical bases. This paper aims at developing a physical model based on energy conservation and EROEI definition, that could reproduce a S-curve function and allow to investigate the net energy delivered by the photovoltaic industry. This approach gives some new insights on the discussion on energy delivered by renewable and low carbon energy, as it highlights the role of energy re-investment in EROEI calculation. It also allows to investigate energy policies that could lead to a smooth energy transition.

Keywords: PV production, EROEI, dynamic model, net energy, energy transition

1 Introduction

2 In the frame of fossil fuel depletion and climate change, development of
3 renewable, or at least low carbon energy source is a major issue for mod-
4 ern societies. In particular, photovoltaic (PV) system development is often
5 model by a logistic (sigmoid or S-curve) function (Cherp et al. (2021)), the
6 solution of the Verhulst equation. Despite the ability of the S-curve to fit PV
7 development in most countries, as in Cherp et al. (2021), there is no physical
8 bases for such model, hence the analysis of its parameters does not provide
9 insight on the PV development capability. In this article, a physical model
10 is suggested for PV system development, based on energy conservation and
11 EROEI, as previously done for fossil liquid fuel in Lamorlette (2022). This

12 model is discussed to see how it can provide a S-curve, in accordance with
 13 Cherp et al. (2021). It is also applied to global PV system development
 14 to investigate the re-investment trend of the PV industry. This allows to
 15 estimate the net energy provided by PV systems to society, which depends
 16 indirectly on EROEI, contrary to the common assumption that net energy
 17 on gross energy is equal to $(EROEI - 1)/EROEI$ (as presented in Murphy
 18 (2014) for instance). This point is discussed in details, providing insights on
 19 the controversy on PV net energy discussed in Ferroni and Hopkirk (2016)
 20 and Raugei et al. (2017). Finally, investment for energy source development
 21 in the frame of energy transition is discussed, based on recent work on fos-
 22 sil fuel depletion, to suggest adequate policies that could ensure a smooth
 23 energy transition.

24 **1. Development of the PV industry**

25 As proposed in Lamorlette (2022) for the development of the oil industry,
 26 based on energy conservation and EROEI definition, a model is here developed
 27 to describe the development of the PV industry. It is firstly derived based
 28 on yearly (discrete) production, then the model is written using a continuous
 29 formalism, what leads to an ODE.

30 *1.1. Discrete approach*

31 The growth and decay is here considered over a one year time laps ($\Delta t = 1$
 32 year). The growth is due to the industry expansion coming from energy
 33 re-investment. The decay is due to the closing of production sites, which
 34 are designed to last for a period τ , according to their EROEI calculation,
 35 with $\tau \sim 20 - 30$ years (a PV unit lifespan). PV unit efficiency decrease is
 36 indirectly taken into account in the growing term, as explained in the next
 37 section.

38 *1.1.1. Growing*

39 Let us consider a yearly production of PV energy Q , available at point
 40 of use. A fraction k of this production (dimensionless, with k in $[0; 1]$) is
 41 re-invested to develop the PV industry on a year n . Energy conservation
 42 and EROEI definition allow to write the increase in production ΔQ^+ on a
 43 year n , considering an equivalent homogeneous production over the whole
 44 lifespan τ of a PV unit (i.e. smoothing the efficiency decrease of a PV unit
 45 over its whole lifespan). With an energy investment $Q_n k$, one get an energy

46 $Q_n k E R o E I_n$ during τ years after the investment is done, based on ERoEI
 47 definition. The energy increase per unit time reads $Q_n k E R o E I_n / \tau$. It leads
 48 to:

$$\Delta Q_n^+ = Q_n k_n \frac{E R o E I_n}{\tau} \Delta t. \quad (1)$$

49 *1.1.2. Decay*

50 The decay on a year n , ΔQ^- , is equal to the increase on year $n - \tau$, as it
 51 is due to the closing of sites developed τ years before. Hence one get:

$$\Delta Q_n^- = \Delta Q_{n-\tau}^+ = Q_{n-\tau} k_{n-\tau} \frac{E R o E I_{n-\tau}}{\tau} \Delta t. \quad (2)$$

52 Using Eq.(1) and Eq.(2), the increase in production on a year n , $Q_{n+1} - Q_n$
 53 can be written:

$$Q_{n+1} - Q_n = \Delta Q_n^+ - \Delta Q_n^- = \frac{1}{\tau} (Q_n k_n E R o E I_n - Q_{n-\tau} k_{n-\tau} E R o E I_{n-\tau}) \Delta t. \quad (3)$$

54 *1.2. Continuous equivalence*

55 Eq.(3) can be written as an ODE, taking $\Delta t \rightarrow 0$. It leads to $(Q_{n+1} -$
 56 $Q_n) / \Delta t = \dot{Q}$ and therefore:

$$\dot{Q} = \frac{1}{\tau} (Q(t) k(t) E R o E I(t) - Q(t - \tau) k(t - \tau) E R o E I(t - \tau)). \quad (4)$$

57 This equation shows a convolution term which could make it complicated or
 58 even impossible to solve analytically. Nevertheless, as discussed later, the
 59 term ΔQ^- can be neglected at short or medium time scale, which would lead
 60 to analytical solutions for Eq.(4).

61 **2. Solution for a linear investment policy at medium time scale,**
 62 **recovering the S-curve**

63 Let us first discuss the relative contribution of decay in the production
 64 dynamic, that is $\Delta Q^- / \Delta Q^+$. At a time scale smaller than τ (i.e. short time
 65 scale), this contribution is strictly zero. During the development phase of a
 66 PV industry (at local scale (a country), or at global scale), according to all
 67 the measured values presented in Cherp et al. (2021), Q evolves at a time
 68 scale way smaller than τ . It means that practically, $\Delta Q^-(t) \ll \Delta Q^+(t)$ and

69 then ΔQ^- can be neglected at medium time scale, the time scale at which
 70 PV is developing. It leads to:

$$\dot{Q} = \frac{1}{\tau} Q(t) k(t) ERoEI(t). \quad (5)$$

71 Let us now consider a linearly evolving investment over a period on which a
 72 PV industry plans to develop from $Q(t_0) = Q_0$ (an initial, external energy
 73 input) to $Q(t_f) = Q_{goal}$ (a goal of production), where t_0 is the time at the
 74 beginning of the investment and t_f the time at the end of the investment.
 75 Then $k = 1$ at the beginning of the investment ($k(t_0) = 1$), $k = 0$ when the
 76 industry is fully developed (i.e. $k(t_f) = 0$) and k evolves as $1 - Q/Q_{goal}$ in
 77 between (i.e. k proportional to $-Q$). This leads to:

$$\dot{Q} = \frac{1}{\tau} Q(t) \left(1 - \frac{Q(t)}{Q_{goal}} \right) ERoEI(t). \quad (6)$$

78 Eq.(6) is strictly a Verhulst equation, with Q_{goal} the carrying capacity. With
 79 constants τ and $ERoEI$, it leads to a S-curve solution, which is in line with
 80 the work of Cherp et al. (2021).

81 This approach does not directly take into account the potential lack of
 82 material to produce PV units or the lack of space to due to geophysical
 83 constraints, but it actually takes it into account via a future decrease of PV
 84 $ERoEI$. However, this aspect is not developed in this study as it considers
 85 only constant $ERoEI$ as a baseline, in order to investigate the different
 86 analytical solution one can get from Eq.(3) or Eq.(4).

87 **3. Short time scale analysis of global PV production**

88 Contrary to many countries where the saturation (or “market size”) has
 89 been reached (as Portugal, Germany, Belgium or Greece, according to Cherp
 90 et al. (2021)), the global PV production seems to be in its development
 91 phase. Indeed, according to BP (2021), the PV product follows an expo-
 92 nential growth, with a characteristic time $t_{exp} \sim 2.82$ years (this fit provides
 93 a determination coefficient higher than 0.98 on the period 2000-2021). At
 94 short or medium time scale, Eq.(3) or Eq.(4) can be solved at constants τ
 95 and $ERoEI$, leading to an exponential solution. This solution exhibits the
 96 following characteristic time:

$$t_{exp} = 1/\ln(1 + kERoEI/\tau). \quad (7)$$

97 Identification can then leads to an estimation of the PV industry investment.

98 *3.1. Estimation of PV industry investment*

99 The previous remark suggests a way to estimate the re-investment of the
100 PV industry on itself in order to ensure a self-growing business. This as-
101 sumption seems reasonable, since PV industry can hardly expect external
102 energy for its development, as global energy consumption ensure the global
103 GNP (as suggested by the work of Tim Garrett), and our economy requires
104 GNP to keep increasing. Therefore, without external energy input, the pre-
105 vious relationships allow to estimate the investment, as long as averaged,
106 effective values can be evaluated for τ and $ERoEI$. τ is taken equal to 20
107 to 30 years, based on a PV unit lifespan. As remarked in section 1.1.1, the
108 production Q that is considered is taken at point of use, which means ERoEI
109 should be evaluated accordingly. This would refer to an ERoEI at point of
110 use. According to Raugei et al. (2017), $ERoEI \sim 9 - 10$.

111 An identification of k is then performed based on t_{exp} global value and
112 theoretical expression (Eq.(7)). The following behaviour is observed: For
113 $\tau = 20$ years, an $ERoEI$ of 7 or lower would lead to $k \geq 1$. For $\tau = 30$ years,
114 an $ERoEI$ of 11 or lower would lead to $k \geq 1$ which seems economically
115 impossible, as it would mean that PV industry is an energy sink. This
116 emphasises the result of Raugei et al. (2017) on the minimum possible value
117 of PV ERoEI. It also suggests that global PV development is close to its
118 maximum with $k(t) = 1$ from the beginning of PV development.

119 *3.2. Estimation of the net production*

120 Contrary to what the development of Eq.(4) could suggest, based on the
121 energy available at point of use, it does not strictly provides the net energy
122 from PV systems. Indeed, a fraction k is taken for re-investment, hence the
123 net product Q_N reads:

$$Q_N(t) = (1 - k(t))Q(t) . \quad (8)$$

124 According to the previous remark on the averaged, effective, value of k ,
125 it suggests that net energy from PV was and is still close to zero. This
126 could be a reason that motivated the study of Ferroni and Hopkirk (2016)
127 which claims that PV is not producing any net energy and could even be an
128 energy sink. The answer of Raugei et al. (2017) to the study of Ferroni and
129 Hopkirk (2016) seems right in term of $ERoEI$ values, however the study of
130 Ferroni and Hopkirk (2016) seems right in term of net energy delivery. This
131 whole result on net energy from PV systems is nevertheless very far from

132 the classical relationship presented in Murphy (2014) for oil (for instance),
 133 where net energy is supposed to depend directly on gross energy and EROEI
 134 through the relation:

$$Q_N = Q \frac{ERoEI - 1}{ERoEI}. \quad (9)$$

135 It seems that the confusion might come from the original derivation of this
 136 relationship, which was done for oil. Indeed, for oil, this relationship almost
 137 applies according to energy conservation, with two corrections. Firstly, as
 138 highlighted in Lamorlette (2022), it should read:

$$Q_N = Q \frac{ERoEI - 1}{ERoEI_W}, \quad (10)$$

139 where $ERoEI_W$ is the EROEI at the wellhead. The paper of Hall et al.
 140 (2009) contains everything in the text to develop Eq.(10), even a numerical
 141 application in Table 3. The paper of Lamorlette (2022) merely presents a
 142 more complete mathematical formulation of the concepts presented in Hall
 143 et al. (2009). Secondly, as discussed in Lamorlette (2022), Q_N in Eq.(10)
 144 still misses the role of energy re-investment. Hence a $(1 - k)$ (with k being
 145 the investment of the oil industry) correction was added. As k for oil is
 146 historically lower than 1% (see Lamorlette (2022)), Eq.(10) is practically
 147 applicable to oil with accurate results.

148 This whole rational however breaks down for the PV industry during its
 149 development phase, as PV industry development depends straightforwardly
 150 on $ERoEI$ but its net energy does not, mainly because re-investment is close
 151 to unity. As the same energy development modeling can be applied to wind,
 152 nuclear or other low carbon energy, net energy from these sources should be
 153 carefully evaluated during the industry development.

154 4. Toward a smooth energy transition

155 4.1. Sustaining a steady-state dynamic at long time scale

156 Solutions presented in this article in section 2 and 3 are valid at short and
 157 medium time scale, neglecting ΔQ^- . However, a steady-state at long time
 158 scale requires to take it into account, changing the required value of k
 159 to sustain this dynamic. This steady-state investment can be evaluated thanks
 160 to Eq.(4): Let us consider a constant \dot{Q} , at constant $ERoEI$. Eq.(4) leads
 161 to $k = 1/ERoEI$ and $\dot{Q} \rightarrow 0$ when $t \gg \tau$. It means that when k decreases

162 according to a given energy policy, in order to “replace” the lack of energy
 163 due to fossil fuel depletion, it should be kept above $1/ERoEI$ or equal to
 164 $1/ERoEI$ once this value is reached, to ensure the investment needed at long
 165 time scale. When this long time scale steady-state is reached, it is worthy to
 166 notice that $Q_N = (1 - k)Q = Q(ERoEI - 1)/ERoEI$. Hence this relation
 167 actually applies to any energy source that follows equations similar to Eq.(4)
 168 and Eq.(8) (i.e. PV, nuclear and wind), but only once a steady-state is
 169 reached. This result can explain the controversy about PV ERoEI: if one
 170 considers ERoEI at the most extreme boundary of the PV industry, that
 171 is $ERoEI_{EXT}$, it should take into account the whole re-investment and its
 172 value seems to be close to 1, since k seems to be close to 1, what is in line
 173 with Ferroni and Hopkirk (2016) and de Castro and Capellán-Pérez (2020).
 174 This extended ERoEI is somehow “dynamic”, as it takes into account the
 175 industry dynamic. On the other hand, an ERoEI at point of use could be
 176 considered as “static” as it does not depends on the industry dynamic. At
 177 the industry steady-state, both dynamic and static ERoEI have the same
 178 value, according to the result above, however the dynamic value does not
 179 provide any insight on the ability of a technology to develop, which suggests
 180 it is not a proper index to compare technologies.

181 It means that $ERoEI$ is not a sufficient index to evaluate the worthiness
 182 of a given technology development, it can only evaluate its sustainability
 183 once the industry is developed. The present results suggests a value of 7
 184 would be enough to sustain a production, with roughly 15% of the production
 185 dedicated to sustain the production. In our case, with PV, according to the
 186 results of section 3.1 and Eq.(8), the net production at steady-state will be
 187 approximately 90% of the global PV production. It seems that the problem
 188 of energy transition actually requires to answer the following question for
 189 a given technology: “How long will it take to reach this steady-state? Is it
 190 possible to reach it before facing fossil fuel depletion?”, what is not depending
 191 only on ERoEI, as explained in the next section for PV and nuclear.

192 4.2. Estimating the ability of an energy industry to grow

193 In order to evaluate the growing capacity of a given technology over a pe-
 194 riod t_{trans} , Eq.(3) could be used, with adaptation specific to each considered
 195 technology. For PV, it can be used straightforwardly. Considering an energy
 196 increase I_{PV} , starting with a yearly amount Q_0 , according to Eq.(3), the PV
 197 growth rate g_{PV} is $g_{PV} = 1 + ERoEI/\tau$, then, with $G_{PV} = g_{PV}$:

$$I_{PV} = Q_0 g_{PV}^{t_{trans}} = Q_0 G_{PV}^{t_{trans}}. \quad (11)$$

198 For nuclear (and wind), Eq.(3) should take into account the time t_{invest}
 199 needed to develop a production site (a nuclear power plant). This requires
 200 to apply Eq.(3) on a time laps $\Delta t = t_{invest}$, using the same rational as previ-
 201 ously. For nuclear, it leads to (subscript Nu relates to nuclear):

$$Q_{Nu_{n+t_{invest}}} - Q_{Nu_n} = \frac{t_{invest}}{\tau_{Nu}} (Q_{Nu_n} k_{Nu_n} ERoEI_{Nu_n} - Q_{Nu_{n-\tau_{Nu}}} k_{Nu_{n-\tau_{Nu}}} ERoEI_{Nu_{n-\tau_{Nu}}}). \quad (12)$$

202 Based on Eq.(12), the growth rate g_{Nu} is $g_{Nu} = 1 + t_{invest}ERoEI_{Nu}/\tau_{Nu}$.
 203 This growth rate is applied over $t_{trans}/t_{invest} \sim 2$ investment time steps. It
 204 means that the increase in energy I_{Nu} , starting with a yearly amount Q_0 can
 205 be estimated the following way, with $G_{Nu} = g_{Nu}^{1/t_{invest}}$:

$$I_{Nu} = Q_0 g_{Nu}^{t_{trans}/t_{invest}} = Q_0 G_{Nu}^{t_{trans}}. \quad (13)$$

206 The quantity I/Q_0 (or G) represents the ability of a given technology to
 207 grow in t_{trans} years (or per annum for G). For PV, $G_{PV} = 1.38$ based on the
 208 previous analysis. Taking $\tau_{Nu} = 40$ years and considering $t_{invest} = 8$ years for
 209 nuclear, according to EDF (2018), $G_{Nu} = 1.31 - 1.38$ (depending on the value
 210 used for $ERoEI_{Nu}$, 40 or 60 according to World Nuclear Association (2018)).
 211 This result suggests that nuclear is actually not a safer investment to cope
 212 with the end of fossil fuels, contrary to what the $ERoEI$ values suggest. It
 213 also highlights that the ability of a technology to replace an energy source
 214 does not depend only on its $ERoEI$ but also on t_{invest}/τ and t_{trans}/t_{invest} ,
 215 due to the general expression of I/Q_0 .

216 4.3. An energy policy based on fossil fuel depletion and growth capacity of 217 PV and nuclear

218 On the one hand, according to the study of Lamorlette (2022), it is sug-
 219 gested that the net peak oil might arrive as soon as 2028 (based on the results
 220 obtained with the most reliable ERoEI data for oil), with a 40% production
 221 decrease in 2035 and a 85% production decrease in 2050. The study of Lam-
 222 orlette (2022) can also be extrapolated to estimate the net peak gas around
 223 2036 (based on the results obtained with the ERoEI data for oil and gas), in
 224 accordance with the results of Delannoy et al. (2021a), with a decrease rate
 225 similar to oil (40% production decrease in 2043 and a 85% production de-
 226 crease in 2058). According to the study of Delannoy et al. (2021b), net peak
 227 oil might arrive as soon as 2024, with a production decrease of roughly 25%
 228 in 2030. On the other hand, according to the Paris agreement, use of fossil

229 fuel should stop in 2050. Based on these consideration, a worst case scenario
230 can be build for energy substitution, taking also into account the need for an
231 increasing energy input for our societies. This need is here evaluated using
232 a business as usual assumption for energy consumption similar to the one
233 suggested in Lamorlette (2022), that is a linear increase of the global energy
234 consumption, which fits the data of BP (2021) on the period 1950-2021 with
235 a determination coefficient higher than 0.99.

236 These data suggest energy transition should begin in 2024, at the net
237 peak oil. Considering PV (or a mix of sources with equal growth rate G)
238 as the unique substitute, since PV accounts for 1.63% of the global energy
239 mix in 2021 (BP (2021)) and considering oil account for 30.9% of the global
240 energy mix in 2021 BP (2021)), PV production needs to be multiplied by 5.1
241 by 2030 and multiplied by 8.8 by 2035. Considering gas account for 24.4%
242 of the global energy mix in 2021 (BP (2021)), PV production needs to be
243 multiplied by 18.4 by 2040. In order to follow the Paris agreement, it needs
244 to be multiplied by 66 by 2050.

245 The following transition scenario is proposed: PV growth rate is based
246 on its fitted value on the period 2000-2021, k is kept equal to 1 until 2023,
247 where it begins to decrease linearly until reaching the value $1/ERoEI$ in 20
248 years. k is then kept constant to reach the steady-state depicted in section
249 4.1. Eq.(4) and Eq.(8) are solved numerically from 2021 and the ratio R
250 of net energy at time t on gross energy in 2021 is computed to compare
251 it with the requirement presented above. Table 1 presents the comparison
252 between the two, showing a smooth transition can be achieved without any
253 additional external energy input. Nevertheless, it shows that around 2030,
254 14% of the lack of energy, hence 3.5% of the global energy mix (compared
255 to the business as usual) cannot be covered. It suggests a plateau of energy
256 might occur around 2030 before reaching the business as usual again, until
257 a steady-state is reached around 2060, after a slight overshoot between 2050
258 and 2060. Also, as mentioned in section 2, this behaviour requires a constant
259 EROEI, which should be satisfied to ensure the energy transition and the
260 steady-state after 2060.

261 Finally, it is worth noting here that this rational has been conducted at
262 global scale, but it could also be applied at local scale (i.e. a country) to
263 determine a specific, efficient investment policy, based on the resources and
264 energy mix of a given country.

Table 1: Ratio of PV net energy at time t on gross energy in 2021

time (year)	required R	computed R	relative difference
2030	5.1	4.4	-14%
2035	8.8	20	+127%
2040	18.4	56	+204%
2050	66	100	+52%

265 **Conclusion and opening**

266 In this article, a model is presented to study PV production dynamic.
 267 This model is able to reproduce the behavior of the previous S-curve function
 268 model. It also shows the following features:

- 269 • The model development, based on energy conservation and ERoEI def-
 270 inition, is applied to PV but can be applied also to wind and nuclear.
- 271 • It allows to explain why the usual relationship between gross, net energy
 272 and $ERoEI$ ($Q_N/Q = 1 - 1/ERoEI$) does not apply to any low carbon
 273 technology during its development, before a steady-state production is
 274 reached.
- 275 • It provides new insights on the PV net energy discussion, explaining
 276 how the investment dynamic can modify artificially the ERoEI mea-
 277 surement. This point highlights why ERoEI should be calculated at
 278 point of use to compare technologies.
- 279 • It shows that a technology development ability depends on $ERoEI$,
 280 but also on two dimensionless times: t_{invest}/τ and t_{trans}/t_{invest} .
- 281 • It suggests an energy policy that ensure a smooth energy transition,
 282 which leads to a steady-state production of energy around 2060.

283 Finally, it seems important to notice that, according to Barrau (2022),
 284 climate change is “the tree that hides the forest”. The collapse of ecosys-
 285 tems is a deeper and more important problem our societies are facing. The
 286 steady-state presented before is very unlikely low enough to ensure the bal-
 287 ance of earth ecosystems. Therefore, a sequel to this work could be to ask:
 288 “What steady-state (i.e. global human energy per unit time) could allow the

289 ecosystems to recover a regime made of quasi-static transformations, max-
290 imising the lifespan of the earth system as we know it, by minimising entropy
291 creation ?”.

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