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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 and to compare the ability of different low carbon technologies to ensure 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 $Q_n k ERoEI_n$ during τ years after the investment is done, based on ERoEI
 47 definition. The energy increase per unit time reads $Q_n k ERoEI_n / \tau$. It leads
 48 to:

$$\Delta Q_n^+ = Q_n k_n \frac{ERoEI_n}{\tau} \Delta t. \quad (1)$$

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:

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

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

$$Q_{n+1} - Q_n = \Delta Q_n^+ - \Delta Q_n^- = \frac{1}{\tau} (Q_n k_n ERoEI_n - Q_{n-\tau} k_{n-\tau} ERoEI_{n-\tau}) \Delta t. \quad (3)$$

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:

$$\dot{Q} = \frac{1}{\tau} (Q(t)k(t)ERoEI(t) - Q(t - \tau)k(t - \tau)ERoEI(t - \tau)). \quad (4)$$

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 the data of BP (2021), the PV product follows
 92 an exponential growth, with a characteristic time $t_{exp} \sim 2.82$ years (this fit
 93 provides a determination coefficient higher than 0.98 on the period 2000-
 94 2021). At short or medium time scale, Eq.(3) or Eq.(4) can be solved at
 95 constants τ and $ERoEI$, leading to an exponential solution. This solution
 96 exhibits the following characteristic time:

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

97 Identification can then leads to an estimation of k , the PV industry invest-
98 ment.

99 3.1. Estimation of PV industry investment

100 Eq.(7) allows to estimate the investment, as long as averaged, effective
101 values can be evaluated for τ and $ERoEI$. τ is taken equal to 20 to 30 years,
102 based on a PV unit lifespan. As remarked in section 1.1.1, the production
103 Q that is considered is taken at point of use, which means ERoEI should
104 be evaluated accordingly. This would refer to an ERoEI at point of use.
105 According to Raugei et al. (2017), $ERoEI \sim 9 - 10$.

106 An identification of k is performed based on t_{exp} global value and theo-
107 retical expression (Eq.(7)). The following behaviour is observed: For $\tau = 20$
108 years, an $ERoEI$ of 7 or lower would lead to $k \geq 1$. For $\tau = 30$ years,
109 an $ERoEI$ of 11 or lower would lead to $k \geq 1$ which would mean that PV
110 industry is an energy sink. This emphasizes the result of Raugei et al. (2017)
111 on the minimum possible value of PV ERoEI, as values lower than 9 (for
112 $\tau = 30$ years, the most realistic value) would lead to an irrational energy
113 sink. However it suggests that global PV development is close to its maxi-
114 mum self-growing capability, with $k(t) = 1$ from 2000 to 2021.

115 3.2. Estimation of the net production

116 As a fraction k of the production is taken for re-investment, the net
117 product Q_N reads:

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

118 According to the previous remark on the averaged, effective, value of k , it
119 suggests that net energy from PV was and is still close to zero. This is in
120 line with the study of Ferroni and Hopkirk (2016) which claims that PV is
121 not producing any net energy and could even be an energy sink. Therefore,
122 considering $k = 1$, the answer of Raugei et al. (2017) to the study of Ferroni
123 and Hopkirk (2016) is right in term of $ERoEI$ values, however the study of
124 Ferroni and Hopkirk (2016) is right in term of net energy delivery.

125 This whole result on net energy from PV systems is nevertheless very
126 far from the classical relationship presented in Murphy (2014) for oil (for
127 instance), where net energy is supposed to depend directly on gross energy
128 and ERoEI through the relation:

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

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

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

133 where $ERoEI_w$ is the EROEI at the wellhead. The paper of Hall et al.
 134 (2009) contains everything in the text to develop Eq.(10), even a numerical
 135 application in Table 3. The paper of Lamorlette (2022) merely presents a
 136 more complete mathematical formulation of the concepts presented in Hall
 137 et al. (2009). Secondly, as discussed in Lamorlette (2022), Q_N in Eq.(10)
 138 still misses the role of energy re-investment. Hence a $(1 - k)$ (with k being
 139 the investment of the oil industry) correction was added. As k for oil is
 140 historically lower than 1% (see Lamorlette (2022)), Eq.(10) is practically
 141 applicable to oil with accurate results.

142 This whole rationale however breaks down for the PV industry during its
 143 development phase, as PV industry development depends straightforwardly
 144 on $ERoEI$ but its net energy does not, mainly because re-investment is close
 145 to unity. As the same energy development modeling can be applied to wind,
 146 nuclear or other low carbon energy, net energy from these sources should be
 147 carefully evaluated during the industry development.

148 4. Toward a smooth energy transition

149 4.1. Sustaining a steady-state dynamic at long time scale

150 Solutions presented in this article in section 2 and 3 are valid at short and
 151 medium time scale, neglecting ΔQ^- . However, a steady-state at long time
 152 scale requires to take it into account, changing the required value of k to
 153 sustain this dynamic. This steady-state investment can be evaluated thanks
 154 to Eq.(4): Let us consider a constant \dot{Q} , at constant $ERoEI$. Eq.(4) leads
 155 to $k = 1/ERoEI$ and $\dot{Q} \rightarrow 0$ when $t \gg \tau$. It means that when k decreases
 156 according to a given energy policy, in order to compensate the lack of energy
 157 due to fossil fuel depletion, it should be kept above $1/ERoEI$ or equal to
 158 $1/ERoEI$ once this value is reached, to ensure the investment needed at long
 159 time scale. When this long time scale steady-state is reached, it is worthy to
 160 notice that $Q_N = (1 - k)Q = Q(ERoEI - 1)/ERoEI$. Hence this relation
 161 actually applies to any energy source that follows equations similar to Eq.(4)

162 and Eq.(8) (i.e. PV, nuclear and wind), but only once a steady-state is
 163 reached. This result can explain the controversy about PV EROEI: if one
 164 considers EROEI at the most extreme boundary of the PV industry, that is
 165 $ERoEI_{EXT}$, it should take into account the whole re-investment and its value
 166 seems to be close to 1, since k seems to be close to 1, what is in line with
 167 Ferroni and Hopkirk (2016) and de Castro and Capellán-Pérez (2020). This
 168 extended EROEI is somehow “dynamic”, as it takes into account the industry
 169 dynamic. On the other hand, an EROEI at point of use could be considered
 170 as “static” as it does not depends on the industry dynamic. At the industry
 171 steady-state, dynamic and static EROEI values converge, according to the
 172 result above, however the dynamic value does not provide any insight on the
 173 ability of a technology to develop, which suggests it is not a proper index to
 174 compare technologies.

175 It also means that $ERoEI$ is not a sufficient index to evaluate the worthi-
 176 ness of a given technology development, it can only evaluate its sustainabil-
 177 ity once the industry is developed. The present results suggests a value of 7
 178 would be enough to sustain a production, with roughly 15% of the produc-
 179 tion dedicated to sustain the production. In our case, with PV, according to
 180 the results of section 3.1 and Eq.(8), the net production at steady-state will
 181 be more than 90% of the global PV production. It seems that the problem
 182 of energy transition actually requires to answer the following question for a
 183 given technology: “How long will it take to reach this steady-state? Is it pos-
 184 sible to reach it before facing fossil fuel depletion?”, what is not depending
 185 only on EROEI, as explained in the next section for PV, nuclear and wind.

186 4.2. Estimating the ability of an energy industry to grow

187 In order to evaluate the growing capacity of a given technology over a pe-
 188 riod t_{trans} , Eq.(3) could be used, with adaptation specific to each considered
 189 technology. For PV, it can be used straightforwardly. Considering an energy
 190 increase I_{PV} , starting with a yearly amount Q_0 , according to Eq.(3), the PV
 191 absolute maximum growth rate g_{PV} is $g_{PV} = 1 + ERoEI/\tau$, then, with G_{PV}
 192 the relative maximum growth rate ($G = g$ for PV):

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

193 For nuclear and wind, Eq.(3) should take into account the time t_{invest} needed
 194 to develop a production site (a nuclear power plant or a wind farm). This
 195 requires to apply Eq.(3) on a time laps $\Delta t = t_{invest}$, using the same rational

196 as previously. It leads to:

$$Q_{n+t_{invest}} - Q_n = \frac{t_{invest}}{\tau} (Q_n k_n EROEI_n - Q_{n-\tau} k_{n-\tau} EROEI_{n-\tau}) . \quad (12)$$

197 Based on Eq.(12), the absolute maximum growth rate g for nuclear and wind
 198 is $g = 1 + t_{invest} EROEI/\tau$. This growth rate is applied over $t_{trans}/t_{invest} \sim 2$
 199 investment time steps. It means that the increase in energy I , starting with
 200 a yearly amount Q_0 can be estimated the following way, with $G = g^{1/t_{invest}}$:

$$I = Q_0 g^{t_{trans}/t_{invest}} = Q_0 G^{t_{trans}} . \quad (13)$$

201 The quantity I/Q_0 (or G) represents the ability of a given technology to
 202 grow in t_{trans} years (or per annum for G). For PV, $G_{PV} = 1.38$ based on the
 203 previous analysis. Taking $\tau_{Nu} = 40$ years and considering $t_{invest} = 8$ years
 204 for nuclear, according to EDF (2021), $G_{Nu} = 1.31 - 1.38$ (depending on the
 205 value used for $EROEI_{Nu}$, 40 to 60 according to World Nuclear Association
 206 (2018), subscript Nu relates to nuclear). This result suggests that nuclear is
 207 actually not a safer investment to cope with the end of fossil fuels, contrary
 208 to what the $EROEI$ values suggest. It also highlights that the ability of a
 209 technology to replace an energy source does not depend only on its $EROEI$
 210 but also on t_{invest}/τ and t_{trans}/t_{invest} , due to the general expression of I/Q_0 .

211 4.3. An energy policy based on fossil fuel depletion and growth capacity of 212 PV and nuclear

213 On the one hand, according to the study of Lamorlette (2022), it is sug-
 214 gested that the net peak oil might arrive as soon as 2028 (based on the
 215 results obtained with the EROEI data for oil of Delannoy et al. (2021a)),
 216 with a 40% production decrease in 2035 and a 85% production decrease in
 217 2050. The study of Lamorlette (2022), in accordance with the results of
 218 Delannoy et al. (2021b), can also be extrapolated to estimate the net peak
 219 gas around 2036 (based on the results obtained with the EROEI data for
 220 oil and gas of Court and Fizaine (2017)) with a decrease rate similar to oil
 221 (40% production decrease in 2043 and a 85% production decrease in 2058).
 222 According to the study of Delannoy et al. (2021a), net peak oil might arrive
 223 as soon as 2024, with a production decrease of approximately 25% in 2030.
 224 On the other hand, according to the Paris agreement, use of fossil fuel should
 225 stop in 2050. Based on these considerations, suggesting a linear decrease for
 226 oil after 2024, for gas after 2036 (following the trends presented above) and

227 for coal after 2044 to end the use of fossil fuels by 2050 (following the Paris
 228 agreement), a worst case scenario can be build for energy substitution, taking
 229 also into account the need for an increasing energy input for our societies.
 230 This need is here evaluated using a business as usual (BAU) assumption for
 231 energy consumption similar to the one suggested in Lamorlette (2022), that
 232 is a linear increase of the global energy consumption, which fits the data of
 233 BP (2021) on the period 1950-2021 with a determination coefficient higher
 234 than 0.99. A second worst case scenario is also studied, where oil production
 235 begin to decrease after 2028, according to Lamorlette (2022). These scenarios
 236 are presented on Fig.1 and Fig.2.

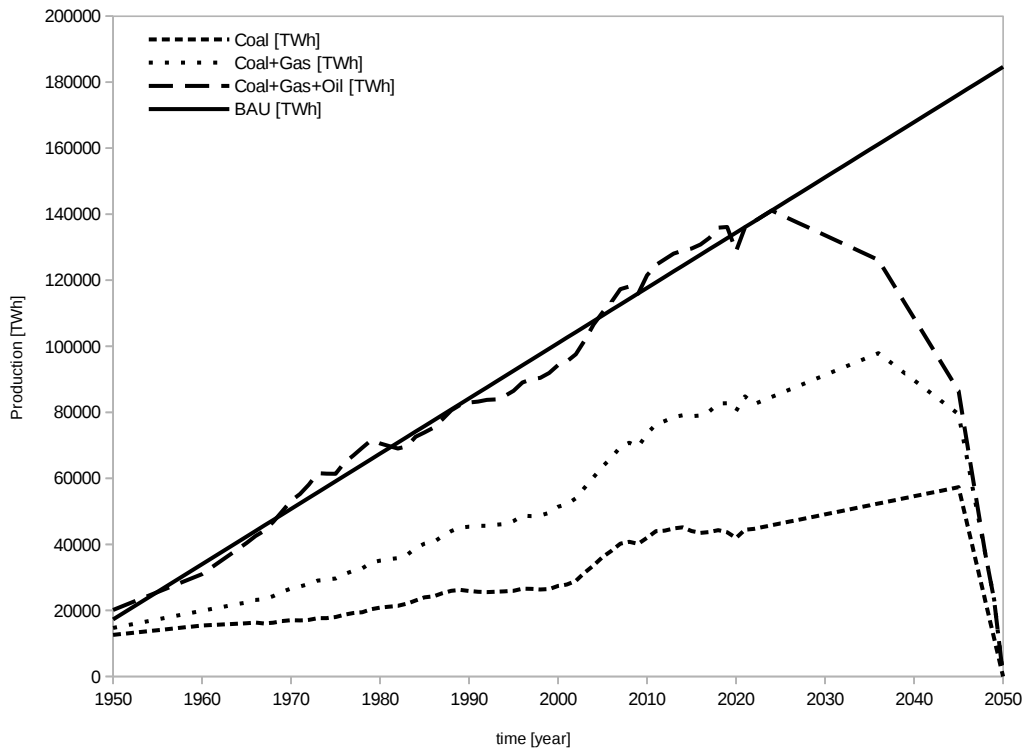


Figure 1: Worst case scenario energy resources. The gap between the solid line (the business as usual of coal, gas and oil) and the long dashed line represents the energy deficit that PV needs to cover.

237 In order to study if a smooth energy transition is physically possible,
 238 numerical simulations are performed for PV development, beginning in 2021

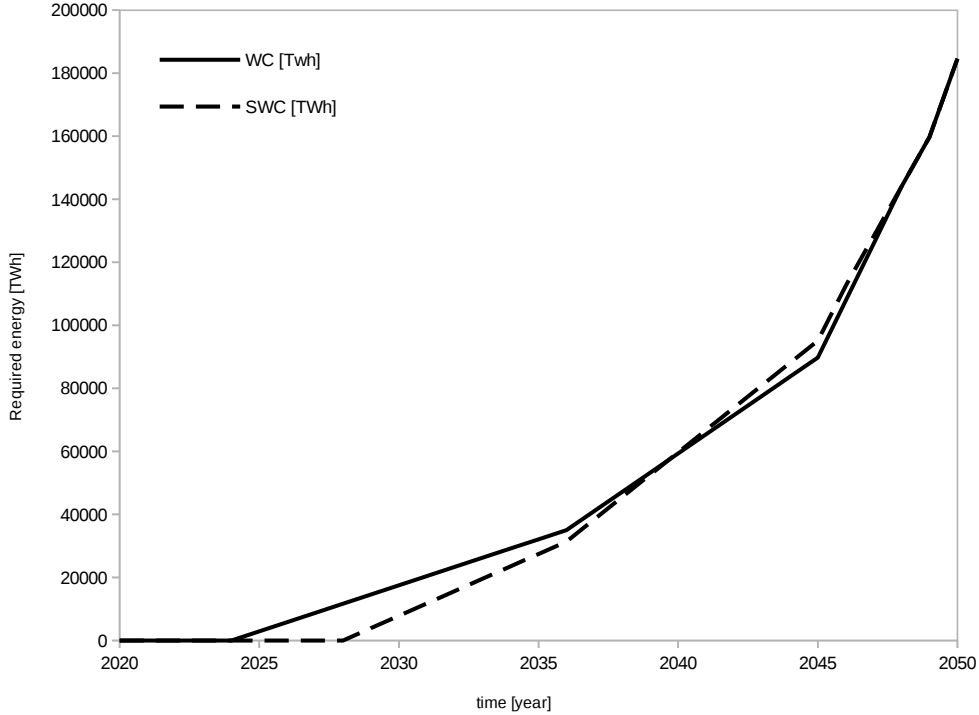


Figure 2: Worst case (WC) and Second Worst Case (SWC) scenario energy resources.

239 with a production equal to 2701 TWh (according to BP (2021)) and an
 240 investment k equal to 1, solving Eq.(4) and Eq.(8). τ_{PV} is set to 30 years and
 241 $ERoEI_{PV}$ is taken in the range [8; 12]. It is noted here that the $ERoEI$ value
 242 fitted on the period 2000-2021 yields $ERoEI_{PV} = 11.4 \pm 1.2$ assuming a 95%
 243 confidence interval can legitimately be evaluated based on PV production
 244 data. k is then optimised using an inverse method to fit the net production on
 245 the required production predicted by the scenarios described above, ensuring
 246 a long time scale linearly increasing production by setting k to a value slightly
 247 higher than $1/ERoEI$ once transition is over (an example of k time evolution
 248 for the worst case scenario and $ERoEI_{PV} = 11.4$ is presented on Fig.3).

249 These simulations shows that for the second worst case scenario, a smooth
 250 energy transition is physically achievable if $ERoEI_{PV} = 8.6$, a value lower
 251 than the practical value and lower than most references on its theoretical
 252 value, as Raugé et al. (2017) for instance. For the worst case scenario, an

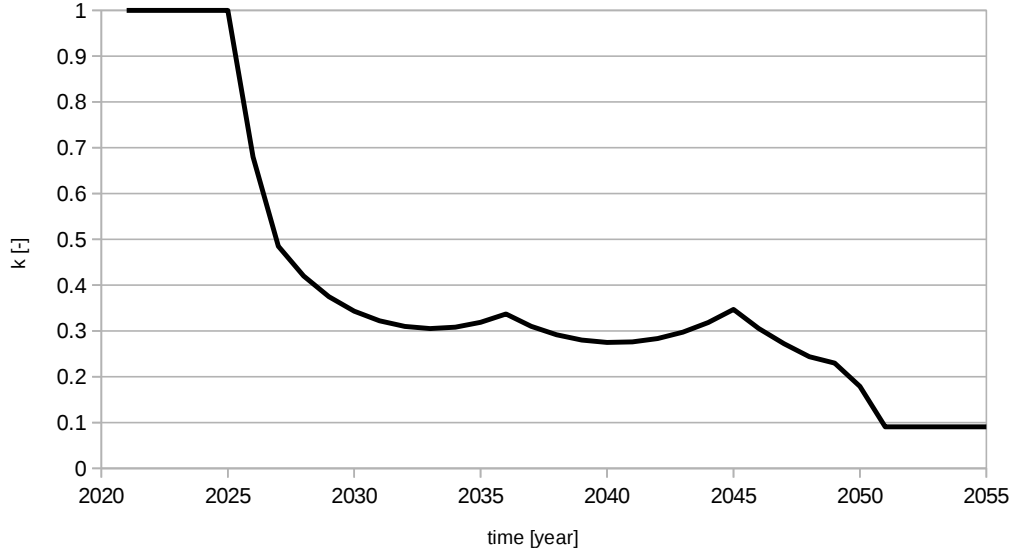


Figure 3: k time evolution for the worst case scenario and $ERoEI_{PV} = 11.4$

253 $ERoEI_{PV}$ of 12 is required to do so, a value that might be slightly above the
 254 practical value. For $ERoEI_{PV} = 11.4$, the worst case scenario leads to a 3-4
 255 year energy decline that begins in 2025, which is similar in relative energy
 256 deficit to what follows the 1979 oil shock. For $ERoEI_{PV} = 10$ (what could
 257 be considered as a lower bound limit of the practical value), the worst case
 258 scenario leads to a 4 year energy decline that begins in 2025, which is similar
 259 to the energy deficit observed after the 1929 crisis. These results (compiled
 260 in Table 1) suggest a smooth energy transition is physically possible if the
 261 second worst case scenario was to happen. If the worst case scenario was
 262 to happen, the $ERoEI_{PV}$ fitted value suggests that an energy crisis similar
 263 to the 1979 oil shock will happen. For the lowest probable $ERoEI_{PV}$
 264 ($ERoEI_{PV} = 10$), an energy crisis with a magnitude as important as the
 265 1929 crisis will happen. In any case, a full disruption of energy supply seems
 266 avoided.

267 Table 1 also presents the absolute maximum growth rate corresponding
 268 to the required $ERoEI_{PV}$ for the different cases. It allows to estimate the
 269 required $ERoEI$ of nuclear (Nu) and wind (Wd) that could allow an equiv-
 270 alent energy transition. τ_{Wd} is here taken equal to 25 years and t_{invest} is

271 taken equal to 4 years (the value observed in Germany) or 8 years (the value
 272 observed in France).

273 These results suggest fossil fuel depletion can be handled more or less
 274 smoothly, nevertheless, it is important to notice that in case of an energy
 275 crisis, it can only be handled if investment is kept close to its maximum
 276 during the whole crisis (as observed on Fig.3), without using the production
 277 to partially cover the depletion of fossil fuels, as such policy would lead to a
 278 total disruption of energy supply. Finally, it is worth noting here that this
 279 rational has been conducted at global scale, but it could also be applied at
 280 local scale (i.e. a country) to determine a specific, efficient investment policy,
 281 based on the resources and energy mix of a given country.

Table 1: Required $ERoEI$ and relative maximum growth rate for the different scenarios, considering a smooth transition (first two lines), a crisis similar to the 1979 oils shock (lines 3 and 4) and an energy decrease similar to the consequences of the 1929 crisis (last line). For wind, case (a) corresponds to $t_{invest} = 8$ years and case (b) corresponds to $t_{invest} = 4$ years. Bold values are lower or equal to theoretical or practical values, meaning the considered technology can physically handle a given scenario, for a given energy crisis level.

Scenario	$ERoEI_{PV}$	$ERoEI_{Nu}$	$ERoEI_{Wd(a)}$	$ERoEI_{Wd(b)}$	G
Worst	12.0	69	43	18	1.40
Second worst	8.6	34	21	11	1.29
Worst	11.4	60	38	16.5	1.38
Second worst	8.2	29	18	10	1.27
Worst	10.0	45	28	14.0	1.33

282 Conclusion and opening

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

- 286 • The model development, based on energy conservation and $ERoEI$ def-
 287 inition, is applied to PV but can be applied also to wind and nuclear.
- 288 • It allows to explain why the usual relationship between gross, net energy
 289 and $ERoEI$ ($Q_N/Q = 1 - 1/ERoEI$) does not apply to any low carbon

290 technology during its development, before a steady-state production is
291 reached.

292 • It provides new insights on the PV net energy discussion, explaining
293 how the investment dynamic can modify artificially the EROEI mea-
294 surement. This point highlights why EROEI should be calculated at
295 point of use to compare technologies.

296 • It shows that a technology development ability depends on $ERoEI$,
297 but also on two dimensionless times: t_{invest}/τ and t_{trans}/t_{invest} , what
298 allows to compare objectively PV, nuclear and wind.

299 • It suggests a proper energy policy could ensure a smooth energy tran-
300 sition, if $ERoEI_{PV}$ practical value is greater than 12.

301 • It suggests no full disruption of energy supply will happen during energy
302 transition if $ERoEI_{PV}$ practical value is greater than 10, what seems
303 realistic according to this study and $ERoEI_{PV}$ theoretical value. How-
304 ever, it suggests an energy crisis similar to the 1979 oil shock might
305 happen around 2025.

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