



HAL
open science

A physical baseline to model photovoltaic and wind farm development and estimate net production

Aymeric Lamorlette

► **To cite this version:**

Aymeric Lamorlette. A physical baseline to model photovoltaic and wind farm development and estimate net production. 2022. hal-03785232v4

HAL Id: hal-03785232

<https://hal.science/hal-03785232v4>

Preprint submitted on 16 Nov 2022

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

A physical baseline to model photovoltaic and wind farm global development and estimate net production

A. Lamorlette

*Aix-Marseille Univ, CNRS, IUSTI UMR 7343
5 rue Enrico Fermi, 13 013 Marseille Cedex 13, France
Correspondence to aymeric.lamorlette@univ-amu.fr
Tel (33) 491 113 811 ; Fax (33) 491 118 502*

Abstract

Photovoltaic and wind production dynamics are usually modeled using a sigmoid or S-curve function, without 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 photovoltaic and wind industries. 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 and explains why the classic relationship between net and gross energy, that is a ratio equal to $(ERoEI - 1)/ERoEI$, does not apply to low carbon energy industries before they reach a steady-state or a quasi-static evolution. It also suggests that net photovoltaic production is still close to zero whereas wind production began to produce a net substantial energy around 2007-2010. It finally 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 such transition.

Keywords: PV production, wind 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 modern
4 societies. In particular, photovoltaic (PV) system development is often model

5 by a logistic (sigmoid or S-curve) function (Cherp et al. (2021)), the solution
6 of the Verhulst equation. Despite the ability of the S-curve to fit PV develop-
7 ment in most countries, as in Cherp et al. (2021), there is no physical bases
8 for such model, hence the analysis of its parameters does not provide insight
9 on the PV development capability. In this article, a physical model is sug-
10 gested for PV system development which applies to wind farm development,
11 based on energy conservation and EROEI, as previously done for fossil liquid
12 fuel in Lamorlette (2022). This model is discussed to see how it can provide
13 a S-curve, in accordance with Cherp et al. (2021). It is applied to global PV
14 system and wind farm development to investigate the re-investment trend of
15 these industries. This allows to estimate the net energy provided by PV and
16 wind to society, which depends indirectly on EROEI, contrary to the common
17 assumption that net energy on gross energy is equal to $(EROEI - 1)/EROEI$
18 (as presented in Murphy (2014) for instance). This point is discussed in de-
19 tails, providing insights on the controversy on PV net energy discussed in
20 Ferroni and Hopkirk (2016) and Raugei et al. (2017). Finally, investment
21 for energy source development in the frame of energy transition is discussed,
22 based on recent work on fossil fuel depletion, to suggest adequate policies
23 that could ensure a smooth 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, assuming the construction time required to
29 build a PV production unit is smaller or equal to one year. The model is
30 then written using a continuous formalism, what leads to an ODE.

31 *1.1. Discrete approach*

32 The growth and decay is here considered over a one year time laps ($\Delta t = 1$
33 year). The growth is due to the industry expansion coming from energy re-
34 investment. The decay is due to the closing of production sites, which are
35 designed to last for a period τ , according to their EROEI calculation, with
36 $\tau \sim 30$ years (a PV unit lifespan). PV unit efficiency decrease is indirectly
37 taken into account in the growing term, as explained in the next 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 $k \geq 0$) is re-
 41 invested to develop the PV industry on a year n . Energy conservation and
 42 ERoEI definition allow to write the increase in production ΔQ^+ on a year n ,
 43 considering an equivalent homogeneous production over the whole lifespan
 44 τ of a PV unit (i.e. smoothing the efficiency decrease of a PV unit over
 45 its whole lifespan). With an energy investment $Q_n k_n$, one get an energy
 46 $Q_n k_n ERoEI_n$ during τ years after the investment is done, based on ERoEI
 47 definition. The energy increase per unit time reads $Q_n k_n ERoEI_n / \tau$. 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
 84 PV $ERoEI$. This aspect is not developed in this study as it considers only
 85 constant $ERoEI$ as a baseline, in order to investigate the different analytical
 86 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 k , 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 an averaged k over the period
 98 2000-2021, the mean PV industry investment.

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 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 be
 104 evaluated accordingly. According to Raugei et al. (2017), $ERoEI \sim 9 - 10$.

105 An identification of k is performed based on t_{exp} global value and theo-
 106 retical expression (Eq.(7)). The following behaviour is observed: An $ERoEI$
 107 of 11 or lower would lead to $k \geq 1$ which would mean that PV industry
 108 is an energy sink. This emphasizes the result of Raugei et al. (2017) on the
 109 minimum possible value of PV ERoEI, as values lower than 9 would lead to
 110 an irrational energy sink. However it suggests that global PV development
 111 is close to its maximum self-growing capability, with $k(t) \sim 1$ from 2000 to
 112 2021. In other words, referring to “energy cannibalism” as in Pearce (2008),
 113 k could be seen as a cannibalism rate and its value seems to be close to 1 for
 114 PV development at global scale.

115 3.2. Estimation of net production

116 As a fraction k of the production is taken for re-investment, the net
 117 production 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 Raugé et al. (2017) to the study of Ferroni
 123 and Hopkirk (2016) is right in term of $ERoEI$ values, even a bit pessimistic,
 124 however the study of Ferroni and Hopkirk (2016) is right in term of net energy
 125 delivery.

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

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

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

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

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

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

149 4. Short time scale analysis of global wind production

150 In order to evaluate the growing capacity of wind, Eq.(3) could be used,
 151 introducing the time t_{invest} needed to develop a production site (a wind farm)

152 which cannot be neglected in the development modelling, as it is greater than
 153 a year. This requires to apply Eq.(3) on a time laps $\Delta t = t_{invest}$, using the
 154 same rational as previously. It leads to:

$$Q_{n+t_{invest}} - Q_n = \frac{t_{invest}}{\tau} (Q_n k_n ERoEI_n - Q_{n-\tau} k_{n-\tau} ERoEI_{n-\tau}) . \quad (11)$$

155 Neglecting ΔQ^- in Eq.(11) leads to:

$$Q_{n+1} = Q_n \left(1 + \frac{k_n t_{invest} ERoEI_n}{\tau} \right)^{1/t_{invest}} . \quad (12)$$

156 As done in section 3 for PV, k can be evaluated based on Q data. Never-
 157 theless, as wind production evolution is not as close to an exponential as PV
 158 production is, it is suggested that k is not as constant for wind as it is for PV.
 159 Hence the time evolution of k is studied for wind, based on Eq.(12) and con-
 160 sidering $ERoEI_W \sim 10 - 12$ according to Dupont et al. (2018), $t_{invest} \sim 3 - 4$
 161 years and $\tau_W = 20$ years (subscript W relates to wind). Eq.(12) leads to a
 162 yearly value of k which is averaged over t_{invest} years for consistency with the
 163 investment in wind energy. A plot is presented in Fig.1 for the extreme cases.
 164 It shows that wind was a major energy sink during its early development,
 165 from 1980 to 1990, where k reached values up to 681. In 1990, investments
 166 dropped and a small net production occurred between 1990 and 1997, where
 167 a re-investment greater than 1 started again until the year 2000. Therefore,
 168 wind industry has most likely become an energy source around 2000 and be-
 169 gan to provide a substantial linearly increasing net energy around 2007-2010.
 170 This last results suggests wind has been added to the global energy mix after
 171 the 2007 oil shock. These results also suggest that the self-growing ability of
 172 PV industry is way greater than wind industry, as k for wind is already close
 173 to zero whereas k for PV is close to 1. It suggests energy transition must be
 174 conducted mainly on the PV industry budget, even if part of this budget can
 175 be invested equivalently in wind or nuclear, as explained in the next section.

176 5. Toward a smooth energy transition

177 5.1. Sustaining a steady-state dynamic at long time scale

178 Solutions presented in this article in section 2 to 4 are valid at short and
 179 medium time scale, neglecting ΔQ^- . However, a steady-state at long time
 180 scale requires to take it into account, changing the required value of k to

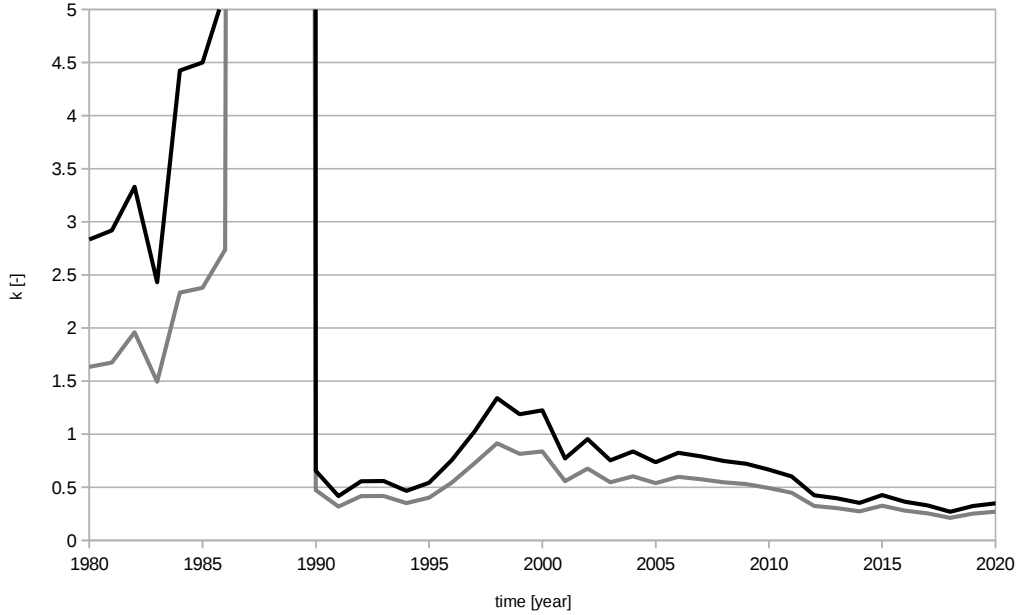


Figure 1: Re-investment of the wind industry on the period 1980-2020 for $ERoEI_W = 10$, $t_{invest} = 4$ years (black line), and $ERoEI_W = 12$, $t_{invest} = 3$ years (grey line)

181 sustain this dynamic. This steady-state investment can be evaluated thanks
 182 to Eq.(4): Let us consider a constant \dot{Q} , at constant $ERoEI$. Eq.(4) leads
 183 to $k = 1/ERoEI$ and $\dot{Q} \rightarrow 0$ when $t \gg \tau$. It means that when k decreases
 184 according to a given energy policy, in order to compensate the lack of energy
 185 due to fossil fuel depletion, it should be kept above $1/ERoEI$ or equal to
 186 $1/ERoEI$ once this value is reached, to ensure the investment needed at long
 187 time scale. When this long time scale steady-state is reached, it is worthy to
 188 notice that $Q_N = (1 - k)Q = Q(ERoEI - 1)/ERoEI$. Hence this relation
 189 actually applies to any energy source that follows equations similar to Eq.(4),
 190 Eq.(11) and Eq.(8) (i.e. PV, nuclear and wind), but only once a steady-state
 191 is reached. This result can explain the controversy about PV EROEI: if one
 192 considers EROEI at the most extreme boundary of the PV industry, that is
 193 $ERoEI_{EXT}$, it should take into account the whole re-investment and its value
 194 seems to be close to 1, since k seems to be close to 1, what is in line with
 195 Ferroni and Hopkirk (2016) and de Castro and Capellán-Pérez (2020). This
 196 extended EROEI is somehow “dynamic”, as it takes into account the industry

197 dynamic. On the other hand, an ERoEI at point of use could be considered
 198 as “static” as it does not depends on the industry dynamic. At the industry
 199 steady-state, dynamic and static ERoEI values converge, according to the
 200 result above, however the dynamic value does not provide any insight on the
 201 ability of a technology to develop, which suggests it is not a proper index to
 202 compare technologies.

203 It also means that $ERoEI$ is not a sufficient index to evaluate the worthi-
 204 ness of a given technology development, it can only evaluate its sustainability
 205 once the industry is developed. With PV, according to the results of section
 206 3.1 and Eq.(8), the net production at steady-state will be more than 90% of
 207 the global PV production. It seems that the problem of energy transition
 208 actually requires to answer the following question for a given technology:
 209 “How long will it take to reach this steady-state? Is it possible to reach it
 210 before facing fossil fuel depletion?”, what is not depending only on ERoEI,
 211 as explained in the next section for PV, nuclear and wind.

212 5.2. Estimating the ability of an energy industry to grow

213 In order to evaluate the growing capacity of a given technology over a
 214 period t_{trans} , Eq.(3) can be used for PV, and Eq.(11) can be used for wind
 215 and nuclear. For PV, considering an energy increase I_{PV} , starting with a
 216 yearly amount Q_0 , according to Eq.(3), the PV absolute maximum growth
 217 rate g_{PV} is $g_{PV} = 1 + ERoEI/\tau$, then, with G_{PV} the relative maximum
 218 growth rate ($G = g$ for PV):

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

219 For nuclear and wind, Eq.(11) is used to take into account the time t_{invest}
 220 needed to develop a production site (a nuclear power plant or a wind farm).
 221 Based on Eq.(11), the absolute maximum growth rate g for nuclear and wind
 222 is $g = 1 + t_{invest}ERoEI/\tau$. This growth rate is applied over t_{trans}/t_{invest}
 223 investment time steps. It means that the increase in energy I , starting with
 224 a yearly amount Q_0 can be estimated the following way, with $G = g^{1/t_{invest}}$:

$$I = Q_0 g^{t_{trans}/t_{invest}} = Q_0 G^{t_{trans}}. \quad (14)$$

225 The quantity I/Q_0 (or G) represents the ability of a given technology
 226 to grow in t_{trans} years (or per annum for G). For PV, $G_{PV} = 1.38$ based
 227 on the previous analysis. For wind $G_W = 1.31 - 1.4$. Taking $\tau_{Nu} = 40$
 228 years (subscript Nu relates to nuclear) and considering $t_{invest} = 8$ years for

229 nuclear, according to EDF (2021), $G_{Nu} = 1.31 - 1.38$ (depending on the value
230 used for $ERoEI_{Nu}$, 40 to 60 according to World Nuclear Association (2018)).
231 This result suggests that nuclear is actually not a safer investment to cope
232 with the end of fossil fuels, contrary to what the $ERoEI$ values suggest. It
233 also highlights that the ability of a technology to replace an energy source
234 does not depend only on its $ERoEI$ but also on t_{invest}/τ and t_{trans}/t_{invest} ,
235 according to Eq.(14) and the expression of G .

236 *5.3. An energy policy based on fossil fuel depletion and growth capacity of* 237 *PV, nuclear and wind*

238 On the one hand, according to the study of Lamorlette (2022), it is sug-
239 gested that the net peak oil might arrive as soon as 2028 (based on the
240 results obtained with the EROEI data for oil of Delannoy et al. (2021a)),
241 with a 40% production decrease in 2035 and a 85% production decrease in
242 2050. The study of Lamorlette (2022), in accordance with the results of
243 Delannoy et al. (2021b), can be extrapolated to estimate the net peak gas
244 around 2036 (based on the results obtained with the EROEI data for oil and
245 gas of Court and Fizaine (2017)) with a decrease rate similar to oil (40%
246 production decrease in 2043 and a 85% production decrease in 2058). Ac-
247 cording to the study of Delannoy et al. (2021a), net peak oil might arrive as
248 soon as 2024, with a production decrease of approximately 25% in 2030. On
249 the other hand, according to the Paris agreement, use of fossil fuel should
250 stop in 2050. Based on these considerations, suggesting a linear decrease for
251 oil after 2024, for gas after 2036 (following the trends presented above) and
252 for coal after 2044 to end the use of fossil fuels by 2050 (following the Paris
253 agreement), a worst case scenario can be build for energy substitution, taking
254 also into account the need for an increasing energy input for our societies.
255 This need is here evaluated using a business as usual (BAU) assumption for
256 energy consumption similar to the one suggested in Lamorlette (2022), that
257 is a linear increase of the global energy consumption, which fits the data of
258 BP (2021) on the period 1950-2021 with a determination coefficient higher
259 than 0.99. A second worst case scenario is also studied, where oil production
260 begin to decrease after 2028, according to Lamorlette (2022). These scenarios
261 are presented in Fig.2 and Fig.3.

262 *5.4. Contribution of PV to the energy transition*

263 Contrary to the work of Jacques et al. (2022), where a macroeconomic bio-
264 physical stock-flow consistent model is used to evaluate the economical con-

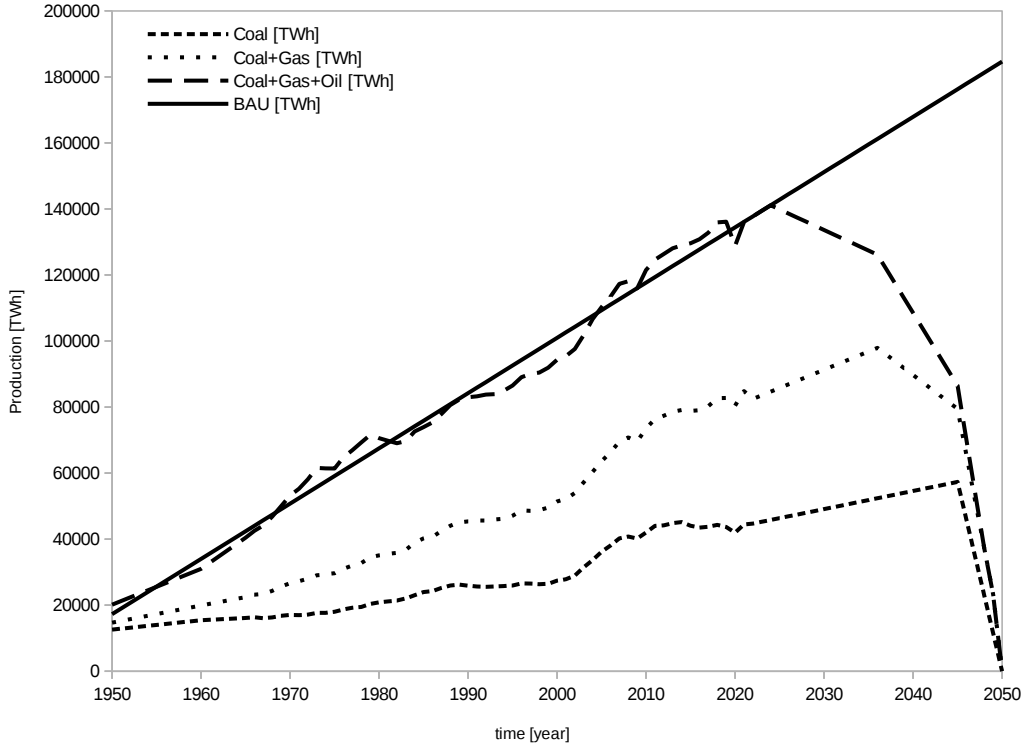


Figure 2: Worst case scenario energy resources. The gap between the solid line (the business as usual of coal, gas and oil) and the long dashed line represents the energy deficit that PV and wind needs to cover.

265 sequences of energy transition, this study only aims at studying if a smooth
 266 energy transition is physically possible. To do so, numerical simulations are
 267 performed for PV development, beginning in 2021 with a production equal
 268 to 2701 TWh (according to BP (2021)) and an investment k equal to 1, solv-
 269 ing Eq.(4) and Eq.(8). τ_{PV} is set to 30 years and $ERoEI_{PV}$ is taken in the
 270 range [8; 12]. It is noted here that the $ERoEI$ value fitted on the period
 271 2000-2021 yields $ERoEI_{PV} = 11.4 \pm 1.2$ assuming a 95% confidence inter-
 272 val can legitimately be evaluated based on PV production data. k is then
 273 optimised using an inverse method to fit the net production on the required
 274 production predicted by the scenarios described above, ensuring a long time
 275 scale linearly increasing production (equivalent to the BAU of fossil fuels pre-
 276 sented in Fig.2) by setting k to a value slightly higher than $1/ERoEI$ once

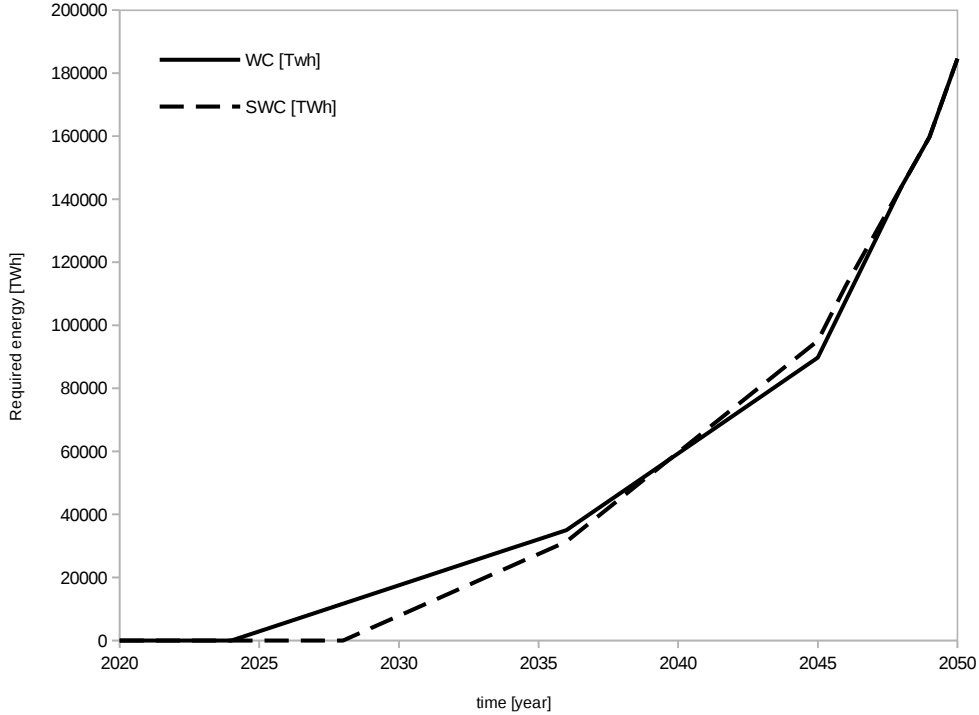


Figure 3: Worst case (WC) and Second Worst Case (SWC) scenario energy resources.

277 transition is over (an example of k time evolution for the worst case scenario
 278 and $ERoEI_{PV} = 11.4$ is presented in Fig.4).

279 These simulations shows that for the second worst case scenario, a smooth
 280 energy transition is physically achievable developing only the PV industry
 281 if $ERoEI_{PV} = 8.6$, a value lower than the practical value and lower than
 282 most references on its theoretical value, as Raugei et al. (2017) for instance.
 283 For the worst case scenario, an $ERoEI_{PV}$ of 12 is required to do so, a value
 284 that is slightly above the practical value. For $ERoEI_{PV} = 11.4$, the worst
 285 case scenario leads to a 3 year energy decline that begins in 2025, which
 286 is similar in relative energy deficit to what follows the 1979 oil shock (an
 287 averaged 1% energy deficit over 2 to 3 years). For $ERoEI_{PV} = 10$ (what
 288 could be considered as a lower bound limit of the practical value), the worst
 289 case scenario leads to a 4 year energy decline that begins in 2025, which is
 290 similar to the energy deficit observed after the 1929 crisis (an averaged 4%

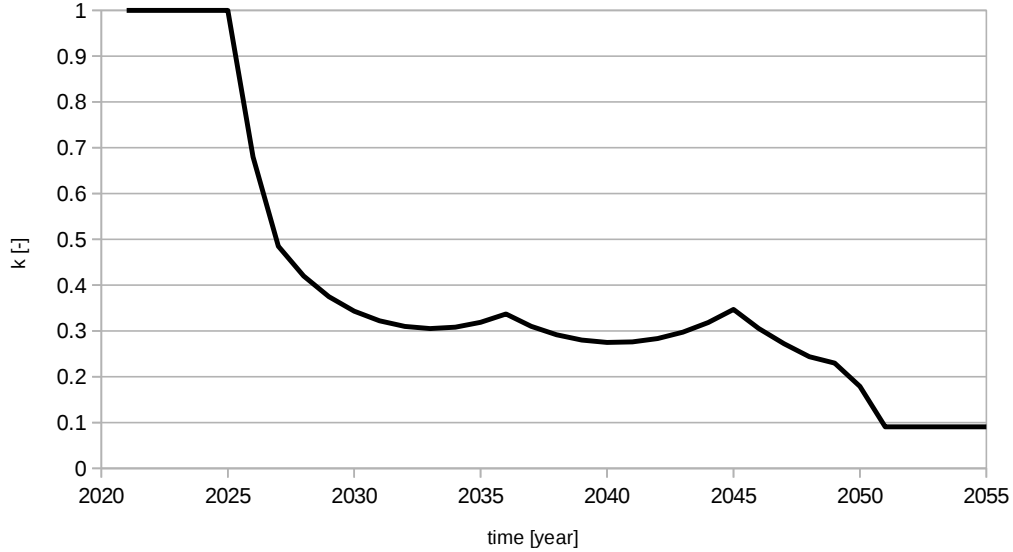


Figure 4: k time evolution for the worst case scenario and $ERoEI_{PV} = 11.4$

291 energy deficit over 3 to 4 years). These results (compiled in Table 1) suggest
 292 a smooth energy transition is physically possible using only PV if the second
 293 worst case scenario was to happen. If the worst case scenario was to happen,
 294 the $ERoEI_{PV}$ fitted value suggests that an energy crisis similar to the 1979
 295 oil shock will happen. For the lowest probable $ERoEI_{PV}$ ($ERoEI_{PV} = 10$),
 296 an energy crisis with a magnitude as important as the 1929 crisis will happen.
 297 In any case, a full disruption of energy supply is avoided.

298 Table 1 also presents the absolute maximum growth rate corresponding
 299 to the required $ERoEI_{PV}$ for the different cases. It allows to estimate the re-
 300 quired $ERoEI$ of nuclear (Nu) and wind (W) that could allow an equivalent
 301 energy transition. t_{invest} is taken equal to 3 or 4 years (the value observed in
 302 most countries).

303 These results suggest fossil fuel depletion could be handled more or less
 304 smoothly by developing only the PV industry, nevertheless, it is important
 305 to notice that in case of an energy crisis, it can only be handled if investment
 306 is kept close to its maximum during the beginning of the crisis (as observed
 307 in Fig.4), without using too much of the production to partially cover the
 308 depletion of fossil fuels, as such policy would lead to a total disruption of

309 energy supply. Finally, it is worth noting here that this rational has been
 310 conducted at global scale, but it could also be applied at local scale (i.e. a
 311 country) to determine a specific, efficient investment policy, based on the
 312 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), taking only into account PV development. For wind, case (a) corresponds to $t_{invest} = 3$ 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	11.7	14.5	1.40
Second worst	8.6	34	7.7	8.9	1.29
Worst	11.4	60	10.9	13.2	1.38
Second worst	8.2	29	7.0	8	1.27
Worst	10.0	45	9.1	10.7	1.33

313 5.5. Contribution of wind to the energy transition

314 To evaluate the extra energy wind industry can provide, Eq.(11) and
 315 Eq.(8) are solved numerically beginning in 2021 with a production equal to
 316 4872 TWh (according to BP (2021)) and an investment k equal to 0.328 (a
 317 value that ensures net wind production follows the linear growth observed
 318 from 2007-2010). The difference between this linear growth (which represents
 319 about 260 TWh per year) and the actual net wind production is considered
 320 to fill the gap that remains after the evaluation of PV production. Two
 321 extreme cases are considered as previously, that is $ERoEI_W = 10$, $t_{invest} = 4$
 322 years, and $ERoEI_W = 12$, $t_{invest} = 3$.

323 These simulations shows that in the worst case scenario, a smooth tran-
 324 sition is achievable if $ERoEI_{PV} \geq 11.4$, $ERoEI_W \geq 10$ and $t_{invest} \leq 4$
 325 years. For $ERoEI_{PV} = 10$ (the lower possible bound according to the re-
 326 sults presented in this study), the remaining energy deficit is about 1% over
 327 2 years (what is slightly smaller than the 1979 oil shock consequences), if
 328 $ERoEI_W = 12$ and $t_{invest} = 3$ years. If $ERoEI_W = 10$ and $t_{invest} = 4$ years,

329 the remaining energy deficit is about 1.8% over 3 years (what is slightly
330 higher than the 1979 oil shock consequences but way smaller than the 1929
331 crisis consequences).

332 Conclusion

333 In this article, a model is presented to study PV and wind production
334 dynamic. This model is able to reproduce the behavior of the previous S-
335 curve function model. It also shows the following features:

- 336 • It allows to explain why the usual relationship between gross, net energy
337 and $ERoEI$ ($Q_N/Q = 1 - 1/ERoEI$) does not apply to any low carbon
338 technology during its development, before a steady-state or a quasi-
339 static production is reached. This is a key consequence of the model
340 that needs to be taken into account in energy substitution modelling
341 and macroeconomic stock-flow consistent modelling to properly account
342 for renewable and low carbon energy net production.
- 343 • It provides new insights on the PV net energy discussion, explaining
344 how the investment dynamic can modify artificially the ERoEI mea-
345 surement. This point highlights why ERoEI should be calculated at
346 point of use to compare technologies.
- 347 • It shows that a technology development ability depends on $ERoEI$,
348 but also on two dimensionless times: t_{invest}/τ and t_{trans}/t_{invest} , what
349 allows to compare objectively PV, nuclear and wind.
- 350 • It suggests a proper energy policy could ensure a smooth energy tran-
351 sition, if $ERoEI_{PV}$ practical value is 11.4 or above and if $ERoEI_W$
352 practical value is 10 or above.
- 353 • It provides an index which allows to evaluate how a low carbon technol-
354 ogy could (or should) be substituted by another to optimise the energy
355 transition.
- 356 • It suggests no full disruption of energy supply will happen during en-
357 ergy transition if $ERoEI_{PV}$ practical value is 10 or above, what seems
358 realistic according to this study and $ERoEI_{PV}$ theoretical values. It
359 corresponds to $ERoEI_{Nu} > 45$ or $ERoEI_{Wd} > 10.7$ (considering wind
360 farms developed in 4 years as in most countries) if transition is handled

361 with nuclear or wind, or a mix of PV, nuclear and wind. However, it
362 suggests an energy crisis similar in magnitude to the 1979 oil shock
363 might happen around 2025.

364 Finally, it is important to remind that these results do not take into ac-
365 count the future $ERoEI$ decrease due to geophysical constraints, what make
366 these results rather optimistic. However, in the work of Jacques et al. (2022)
367 where a biophysical stock-flow consistent model is used to evaluate energy
368 transition, this aspect is taken into account based on the work of Dupont
369 et al. (2020). The study of Jacques et al. (2022) shows that energy transition
370 can be handled with about half the available resources (i.e. without facing
371 major geophysical constraints), suggesting that taking a constant $ERoEI_{PV}$
372 similar to the value obtained for regions of moderate insolation (as in Raugei
373 et al. (2017)) and a constant $ERoEI_W$ equal to 10-12 is an acceptable as-
374 sumption, and therefore suggesting these results are only slightly optimistic.

375 References

376 A. Cherp, V. Vinichenko, J. Tosun, J. A. Gordon, J. Jewell, National growth
377 dynamics of wind and solar power compared to the growth required for
378 global climate targets, *Nature Energy* 6 (2021) 742–754.

379 A. Lamorlette, A dynamic model for liquid fossil fuel production based on
380 gross product/eroei coupling, *Energy* 260 (2022) 124693.

381 D. Murphy, The implication of the declining energy return on investment
382 for oil production, *Philos. Trans. R. Soc. Lond. A: Math. Phys. Eng. Sci.*
383 (2014).

384 F. Ferroni, R. J. Hopkirk, Energy return on energy invested (eroei) for
385 photovoltaic solar systems in regions of moderate insolation, *Energy Policy*
386 94 (2016) 336–344.

387 M. Raugei, S. Sgouridis, D. Murphy, V. Fthenakis, R. Frischknecht,
388 C. Breyer, U. Bardi, C. Barnhart, A. Buckley, M. Carbajales-Dale, et al.,
389 Energy return on energy invested (eroei) for photovoltaic solar systems in
390 regions of moderate insolation: A comprehensive response, *Energy Policy*
391 102 (2017) 377–384.

392 Statistical Review of World Energy, British Petroleum (2021).

- 393 J. M. Pearce, Thermodynamic limitations to nuclear energy deployment as
394 a greenhouse gas mitigation technology, *International journal of nuclear*
395 *governance, economy and ecology* 2 (2008) 113–130.
- 396 A. Hall, S. Balogh, D. Murphy, What is the minimum EROI that a sustain-
397 able society must have?, *Energies* (2009) 25–47.
- 398 E. Dupont, R. Koppelaar, H. Jeanmart, Global available wind energy with
399 physical and energy return on investment constraints, *Applied Energy* 209
400 (2018) 322–338.
- 401 C. de Castro, I. Capellán-Pérez, Standard, point of use, and extended energy
402 return on energy invested (eroi) from comprehensive material requirements
403 of present global wind, solar, and hydro power technologies, *Energies* 13
404 (2020) 3036.
- 405 EDF, 2021. <https://www.edf.fr>.
- 406 World Nuclear Association, 2018. [https://world-nuclear.org/information-](https://world-nuclear.org/information-library/energy-and-the-environment/energy-return-on-investment.aspx)
407 [library/energy-and-the-environment/energy-return-on-investment.aspx](https://world-nuclear.org/information-library/energy-and-the-environment/energy-return-on-investment.aspx).
- 408 L. Delannoy, P.-Y. Longaretti, D. J. Murphy, E. Prados, Peak oil and the
409 low-carbon energy transition: A net-energy perspective, *Applied Energy*
410 304 (2021a) 117843.
- 411 L. Delannoy, P.-Y. Longaretti, D. J. Murphy, E. Prados, Assessing global
412 long-term eroi of gas: A net-energy perspective on the energy transition,
413 *Energies* 14 (2021b) 5112.
- 414 V. Court, F. Fizaine, Long-term estimates of the energy-return-on-
415 investment (eroi) of coal, oil, and gas global productions, *Ecological Eco-*
416 *nomics* 138 (2017) 145–159.
- 417 P. Jacques, L. Delannoy, B. Andrieu, D. Yilmaz, H. Jeanmart, A. Godin, As-
418 ssuming the economic consequences of an energy transition through a bio-
419 physical stock-flow consistent model, Available at SSRN 4174917 (2022).
- 420 E. Dupont, R. Koppelaar, H. Jeanmart, Global available solar energy under
421 physical and energy return on investment constraints, *Applied Energy* 257
422 (2020) 113968.