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PERSPECTIVE

Reducing climate risks with fast and complete energy transitions: applying the precautionary principle to the Paris agreement

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1. Introduction

Who would board an aircraft, if the chances to arrive safely were only 50%? Do you think this is unacceptably unsafe? We do! And not just for air transport, but also for health care or infrastructures. Yet it seems acceptable for reaching targets to preserve a hospitable climate [1].

Despite remarkable advances in understanding the climate system, large uncertainties remain in quantifying its future response to anthropogenic greenhouse gas emissions [2, 3]. Most of these uncertainties are known and can provide a solid basis for decision support for climate action (figure S1 (available online at stacks.iop.org/ERL/16/121002/mmedia)). Yet in spite—or perhaps, because—of these large quantified uncertainties, the international community has committed itself to targets with comparatively low confidence for stabilizing the climate. The political consensus to keep global heating during this century below 2 °C, as manifested in the Paris agreement 2015 [4], is substantiated in IPCC scenarios modeling the transformation of the energy system, which limit peak heating to 2 °C with 66% or, in more ambitious scenarios, to 1.5 °C with 50% confidence, respectively [1]. This results in very high—and considering that our life support system is at stake, also unacceptable—risks to the biosphere and humanity [5–7]. Climate heating beyond 1.5 °C induces potentially existential risks to humanity with rapidly increasing chances to exceed tipping points [7].

Here we advocate the precautionary principle when designing transition pathways in presence of uncertainty, avoiding potentially dramatic and irreversible hazards with high confidence. For testing how much the probability to exceed 1.5 °C global heating can still be reduced, we explore with a minimal energy transition model the energy requirements to replace the current non-renewable with a renewable energy supply system on a global scale. For simplicity, the current non-renewable energy supply system, comprising electricity, mobility and heat, is combined in a hypothetical single *fossil engine* providing electricity, which is replaced by a hypothetical *solar engine*. Building the necessary renewable energy infrastructure first and foremost requires energy. This is the decisive physical limit for accelerating the energy transition. The novelty and purpose of our model is to find this energy limit to minimizing climate risks. Further constraints—such as the availability of materials and financial capital or institutional responsiveness—are not considered, since they may only delay but cannot accelerate the transition beyond the energy limit. The model simulations show that fast and complete transitions are energetically possible when temporarily increasing fossil emissions above current levels for the sole purpose of accelerating the growth of renewable energy capacity.

2. Historical and projected emissions

Since the onset of the industrial revolution, global greenhouse gas emissions—predominantly CO_2 [8]—are on the rise. Since world war II, CO_2 emissions—dominated by the energy sector and mostly from fossil fuels: coal, oil and gas—alarmingly increase cumulative CO_2 emissions (figure S2). CO_2 emissions rose proportionally to the power supply (figure S2), whereas contributions from land use remained almost constant at 5 Gt/a throughout the past hundred years. Industry (e.g. cement, chemicals) contributes less than 5% to global CO_2 emissions. In spite of an accelerating installation of renewable energy capacities [9], CO_2 emissions continue to rise [8]. Currently added renewable capacity is still smaller than the increase in energy demand, therefore not yet replacing fossil fuel use [10].

The IPCC special report on 1.5 °C warming [1] outlines multiple scenarios to reduce CO_2 emissions and to become negative before the end of this century. In all these scenarios, fossil carbon emissions continue (though at reduced levels) and have to be captured and removed by *negative emission technologies*.

All the IPCC scenarios violate the 1.5 °C peak heating target with a probability between 40% ('below 1.5 °C' scenario, peak emissions in 2046) and >80% ('higher 2 °C' scenario, see figure S3 and table S2). The pathways introduced in the more recent UNEP emissions gap report [11] do even further increase the probability of violating peak heating. Such high probabilities of violation would be considered unacceptable in other areas, like engineering or public health.

3. Acceptable risks

In response to often large uncertainties and potentially dangerous consequences, society has become risk averse in many areas [12]. For example, in the 1940s it used to be a very risky endeavor to board an aircraft. Eventually, it evolved to be the safest means of transportation today [13], achieved through a 'trial and error' strategy and increasingly strict regulations over the years. This strategy does not fit to manage the climate crisis as there is no planet B. Instead, we can apply the precautionary principle—which has been developed, applied and accepted for dealing with uncertainties in other areas—to explore climate compatible transition pathways.

In technical systems, such as air traffic or power generation, typically accepted probabilities for critical system failures are $<10^{-7}$ per operating hour [12], i.e. their probability of survival is >99.99999%. Similarly, the probabilities that vaccines cause severe adverse effects are generally $<10^{-5}$ [14]. Subjective risk perception may differ: for example, aviation risks might be of no concern for someone never flying or, in contrast, minuscule vaccination risks may be unacceptable for a vaccination sceptic.

Risks associated with anthropogenic climate heating beyond 1.5 °C are existential for the biosphere and humanity [1, 7]. In view of this and following the precautionary principle [12], the probability of violating critical heating thresholds must tend toward zero. Some residual probability—be it 10^{-2} or 10^{-10}—might still be acceptable for society, yet the current climate debate consents to 'residual' probabilities between 40% and >80%. Moreover, by tolerating large residual probabilities, today's society exposes future generations to unprecedented risks without their prior consent. New movements such as *Fridays for Future* or *Extinction Rebellion* demand to shift focus to future generations and other species when implementing climate actions. To illustrate the urgency for climate action: If CO_2 emissions would remain constant at 2018 levels ($\dot{m}_{CO_2} = 42$ Gt/a), the remaining carbon budget to meet the 1.5 °C with 50% confidence would be depleted before 2032 and with 90% confidence before 2023.

In the following, we explore how an acceleration of the energy transition can reduce the probability of violating 1.5 °C heating target significantly below 50%.

4. Fast and complete energy transition

Assuming that humanity is committed to an immediate and complete phasing out of fossil CO_2 emissions, i.e. a total ban of fossil fuels in the energy system across the globe and in all sectors (electric energy, mobility and heat), what would be the fastest possible transition? If the transition would start in 2022 and annual emissions remain constant on 2018 levels, additional 170 Gt of CO_2 would have been emitted since 2018 and the carbon budget reduced accordingly. Building the future renewable energy infrastructure requires energy, i.e. embodied energy, which is a decisive limiting factor for a fast transition. Considering only energy constraints, it is relatively simple to determine the minimal transition time.

Today's non-renewable supply of annual final energy, converted to electrical energy, is about $P_{el,2018} = 6$ TW [10, 15] (table S3). This annual final energy is held constant and today's non-renewable supply is replaced by renewable energy during the transition. The energy to transform the energy system has to be supplied in addition. We also assume no further land use and industry related CO_2 emissions once the transition starts as well as neglect other GHG emissions. Material, monetary or institutional constraints are not considered alongside with energy storage, distribution and geographical redistribution of demand (see section S5 for modeling details and further assumptions).

Exploring the limits to accelerating the energy transition, we built a minimal physical transition model (section S5 [16]) by merging all fossil fuel energy supply systems in a single 'fossil engine' and all renewable energy supply systems in a single 'solar engine'. Since solar photovoltaic (PV) has by far the largest potential within Earth system boundaries [15], we assume this 'solar engine' is represented by PV installations (section S5). Its embodied energy is given by its average 'energy return on energy invested', which we set to $EROI = 20$ for this analysis (section S5.1).

In this model, the growth dynamic for the installed capacity of the solar engine is set by the following three parameters (see figure 1):

(a) *Fossil replacement factor* α: the output of the solar engine can be either exclusively used to build more solar capacity ($\alpha = 0$, i.e. no fossil replacement) or to replace fossil output already during the transition (up to $\alpha = 1$, i.e. maximum fossil

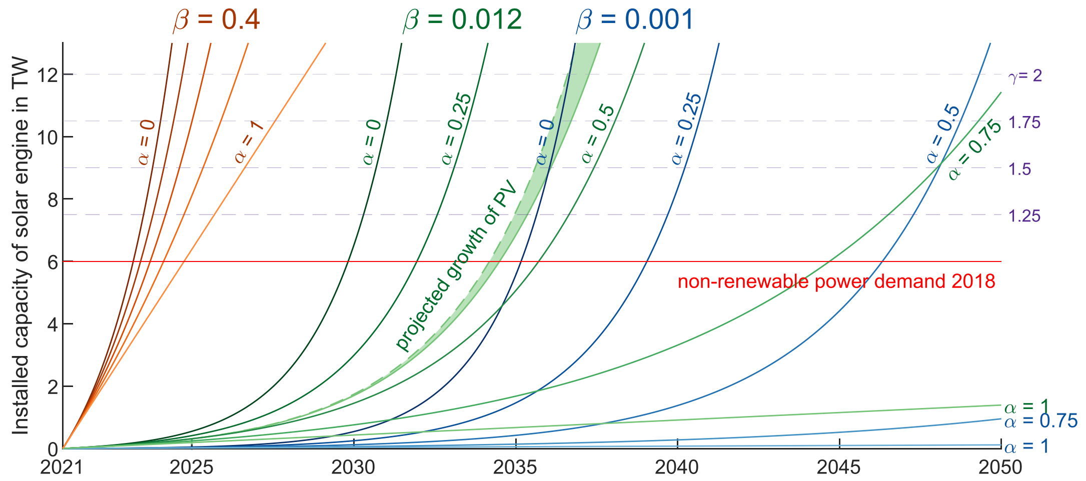

Figure 1. Growth dynamics of the solar engine displayed for three sets of parameters (for model equations, see section S5.1): fossil investment factor $\beta = 0.4$ (orange lines), $\beta = 0.012$ (green) and $\beta = 0.001$ (blue). For each β, fossil replacement factor α is varying from $\alpha = 0$ (fastest growth) through $\alpha = \{0.25, 0.5, 0.75\}$ to $\alpha = 1$ (slowest, linear growth). The transition is complete, once installed capacity of the solar engine reaches the required capacity, i.e. dashed purple lines for varying solar oversize factors $\gamma = \{1.25, 1.5, 1.75, 2\}$ (see also table S4). The projected growth of the solar engine (green shaded area), based on fitting historical PV growth data [9] with exponential (upper bound) and logistic (lower bound) functions (section S5.3), corresponds best to $\alpha = 0.44$ and $\beta = 0.012$ (figure S4) in our model. For detailed explanations of the figure, see section S5.2.

replacement and solar engine grows exclusively on additional fossil investments).

(b) *Fossil investment factor* β: The output of the fossil engine can be increased to provide additional energy, which is used to build the solar engine. This fossil investment factor, i.e. the fraction of current fossil output that is supplied in addition, ranges from $\beta = 0$, i.e. no fossil investment to build the solar engine and therefore no transition, to $\beta_{\max} = 0.4$ using the full idle capacity of today's fossil engine (section S5). The factor β indicates the increase of the fossil engine's output and thus the increase of CO_2 emissions. The fossil energy invested to grow the solar engine is assumed constant during the transition.

(c) *Solar oversize factor* γ: Considering the power demand for storage, distribution losses, curtailment as well as further growth and replacement of the solar engine, the solar engine's installed capacity needs to be larger than the required demand. The transition is completed when the solar engine's installed capacity reaches the oversized demand line (figure 1). As the non-renewable power demand needs to be met at the minimum, γ needs to be larger than one ($\gamma \geq 1$). We vary the solar oversize factor in the range of $\gamma = [1, 2]$.

Besides having the largest potential, solar PV capacity currently shows the highest growth rate among all energy resources (figure S6) [9, 17]. Extrapolating the historical growth of the global PV capacity corresponds in our model to a fossil investment factor of $\beta = 0.012$ and a fossil replacement factor of $\alpha = 0.44$ (figures 1 and figure S4). At this extrapolated historic growth rate, the solar engine would reach an output power of 12 TW ($\gamma = 2$) in 2037. This requires a nominal PV peak power of 73 TW or 5.3×10^5 km^2 of PV panels, which is about 70% the rooftop area of currently existing buildings.

The simulation results in figure 1 show that if the entire solar energy harvest replaces the fossil engine's output ($\alpha = 1$), the PV capacity grows linearly according to the constant fossil investment β. If a constant fraction of the solar harvest is used to grow the PV capacity ($\alpha < 1$), its growth becomes exponential. The solar engine grows fastest, when the fossil engine's output is not replaced by solar energy during the transition ($\alpha = 0$) but is increased to utilize all available idle capacity ($\beta = 0.4$). Consequently, fossil CO_2 emissions will temporarily increase during the transition but will be reduced to zero as soon as the solar engine can replace the fossil engine.

5. Lowest CO_2 emissions

The simulation results show that the fastest possible transition ($\alpha = 0$, $\beta = 0.4$ and $\gamma = 1$) also leads to minimal cumulative CO_2 emissions (figure 2). Between $\beta = [0.1, 0.4]$, all transitions stay below the remaining CO_2 budget for 1.5 °C global heating with 50%. If all solar engine's output is used to shrink the fossil engine ($\alpha = 1$) the cumulative emissions become infinite below $\beta < 0.1$ (vertical segment of green lines), because the solar engine does not reach the required size before the constant fossil investment is needed to replace end-of-life solar capacity. Cumulative emissions tend also to infinity when the fossil

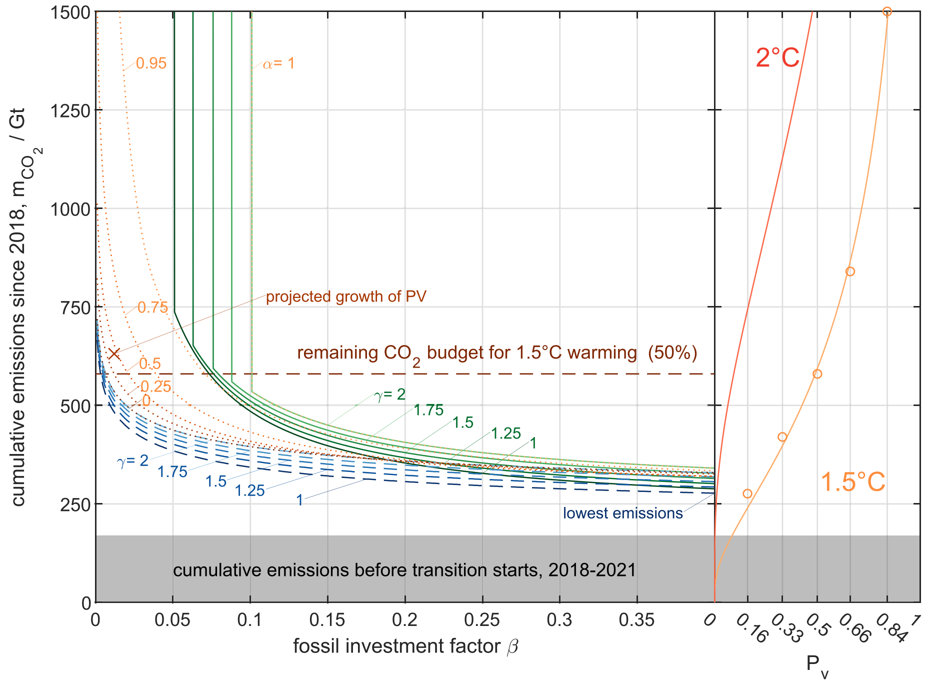

Figure 2. Cumulative emissions for fast and complete energy transitions. Left panel: cumulative CO_2 emissions since 2018 as a function of fossil investment factor β for certain fossil replacement factors α and solar oversize factors γ. The three families of curves display in orange dotted lines $\gamma = 2$ and various α; in green solid lines $\alpha = 1$ and various γ and in blue dashed lines $\alpha = 0$ and various γ (see also table S5). The horizontal dashed line is the threshold for the remaining carbon budget to stay below 1.5 °C with a confidence of 50%. Right panel: probability to violate the temperature target P_v (lower orange line for 1.5 °C and upper red for 2 °C, for fitting to data from IPCC [1] see figure S1 and section S3). Assuming the transition starts in 2022 and annual emissions remain constant on 2018 levels, additional 170 Gt of CO_2 will be emitted since 2018 until 2021 and the carbon budget reduced accordingly (grey shaded area at the bottom). For detailed explanations of the figure, see section S5.2.

investment factor tends to zero. The influence of PV oversizing (γ) is almost unaffected by β and α. For large fossil investment factors β, the cumulative CO_2 emissions are barely sensitive to the fossil replacement factor α.

Projecting historical growth of PV (closely matched by $\alpha = 0.44$ and $\beta = 0.012$ (indicated by '×' in figure 2, see also figure S4) additional 630 Gt of CO_2 would be emitted to the atmosphere from 2018 till the end of the transition and the 1.5 °C target would be violated with a probability of about 53%.

Most 'fast and complete' transition pathways (figure 2) considerably increase the confidence to limit peak global heating to 1.5 °C between 50% and 80% compared to 20% and 60% for IPCC scenarios (table S2). This can be seen by comparing the cumulative emissions for the various parameter examples (left panel in figure 2) to the corresponding probability of violating 1.5 °C heating target (P_v, orange line in right panel of figure 2).

These results suggest—perhaps counter-intuitively and against current policies—that fossil fuel use should be increased temporarily with the sole purpose to build the solar engine as fast as possible and subsequently switch off the fossil engine forever. Investing additional fossil carbon can greatly reduce the transition time and cumulative CO_2 emissions.

6. Consequences

To be in line with the precautionary principle, the design of energy transition pathways must minimize the probability of violating peak heating. As we show, the lowest probability can be achieved with the fastest possible and most ambitious transition pathway, constrained by energy only. This, however, still leads to a probability of about 20% to violate the 1.5 °C peak heating target. Although much lower than the most ambitious pathway in the IPCC scenarios, this is higher than accepted in other areas, like engineering or public health. Any further delay in climate action or additional constraints—e.g. limitations of natural-, human- and financial resources—may impair the growth of the solar engine and consequently increase climate risks.

A fast and complete transition to a solar PV powered society is conceivable: the technology is mature, produced at scale and not constrained by material scarcity [18]. Integrating PV in existing built environment suffices to replace the fossil engine, so no additional land transformation is necessary. There still are, however, many open questions such as: how does the integration of energy storage technologies affect the probability of violating the 1.5 °C target? Or, can negative emission technologies help reducing climate risks? And what implications do such technologies have on the transition?

When aiming for fast transitions, there is little excess energy available to build and operate e.g. negative emission technologies during the transition. Consequently, negative emissions can not substantially lower the probability to violate peak heating. However, combining negative emissions with ‘fast and complete’ transition pathways could significantly reduce the probability of violating 1.5 °C heating target in 2100 and draw down the atmospheric CO_2 concentration towards 350 ppm, considered to be a safe level to retain a habitable climate [5, 19, 20].

Above all, it is imperative to minimize the cumulative emissions during the transition, since this determines the amount of carbon, which has to be removed and stored safely. Additionally, risks arising from failing to scale negative emission technologies in time—which are still in their infancy—are greatly reduced by limiting cumulative emissions to the bare minimum. Any ‘fast and complete’ transition pathway limiting peak heating to 1.5 °C with more than 50% confidence in combination with 800 Gt negative emissions, which are minimally foreseen in all IPCC scenarios targeting 1.5 °C [1], may increase the confidence to stay below 1.5 °C heating in 2100 to virtual certainty.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: www.doi.org/10.5281/zenodo.5643171.

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Author contributions

H D and R W designed the study, H D developed the method and performed the analysis, H D and R W analysed and interpreted the results as well as wrote the paper.

Conflict of interest

There are no conflicts to declare.

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