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Research article

Can the 1.5 ℃ warming target be met in a global transition to 100% renewable energy?

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Abstract: First, we recognize the valuable previous studies which model renewable energy growth with complete termination of fossil fuels along with assumptions of the remaining carbon budgets to reach IPCC warming targets. However, these studies use very complex combined economic/physical modeling and commonly lack transparency regarding the sensitivity to assumed inputs. Moreover, it is not clear that energy poverty with its big present impact in the global South has been eliminated in their scenarios. Further, their CO_2-equivalent natural gas emission factors are underestimated, which will have significant impact on the computed greenhouse gas emissions. Therefore, we address this question in a transparent modeling study: can the 1.5 ℃ warming target still be met with an aggressive phaseout of fossil fuels coupled with a 100% replacement by renewable energy? We compute the continuous generation of global wind/solar energy power along with the cumulative carbon dioxide equivalent emissions in a complete phaseout of fossil fuels over a 20 year period. We compare these computed emissions with the state-of-the-science estimates for the remaining carbon budget of carbon dioxide emissions consistent with the 1.5 ℃ warming target, concluding that it is still possible to meet this warming target if the creation of a global 100% renewable energy transition of sufficient capacity begins very soon which will likely be needed to power aggressive negative carbon emission technology. The latter is focused on direct air capture for crustal storage. More efficient renewable technologies in the near future will make this transition easier and promote the implementation of a global circular economy. Taking into account technological improvements in 2nd law (exergy) efficiencies reducing the necessary global energy demand, the renewable supply should likely be no more than 1.5 times the present level, with the capacity to eliminate global energy poverty, for climate mitigation and adaptation.

Keywords: bioenergy; climate change; carbon budget; geothermal energy; hydropower; renewable energy; solar energy; wind energy; fossil fuels; EROI; carbon budget 1.5 ℃; Direct Air Capture (DAC); circular economy

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Abbreviations: CCS: carbon capture and sequestration; CSP: concentrated solar power; DAC: direct air capture; DACCS: Direct Air Capture with Carbon Storage; EROI: energy return on energy invested; EROEI: equivalent to EROI; GHG: greenhouse gas; IEA: International Energy Agency; IPCC: Intergovernmental Panel on Climate Change; LULUCF: land use, land-use change and forestry; NET: negative emission technology; NG: natural gas; PV: photovoltaics; R&D: Research and Development; RE: renewable energy; WMO: World Meteorological Organization

Units: GJ: gigajoule (10^9 joule); kJ: kilojoule (10^3 joule); GT, Gt: gigatonne (10^9 tonne); mtoe: million tonne oil equivalent; GW: gigawatt (10^9 watt); m: meter; MW: megawatt (10^6 watt); TW: terawatt (10^{12} watt)

1. Introduction

In a historic report, the Intergovernmental Panel on Climate Change/World Meteorological Organization(IPCC/WMO) strongly back the goal of keeping warming at no more than 1.5 ℃, recognizing that meeting this target is still possible, requiring deep and early carbon emissions reductions and obviously far-reaching and unprecedented changes in all aspects of society [1]. Further, this report recognizes that implementation of negative emission technology (NET) is imperative, coupled with radical and early reductions in carbon emissions. It is increasingly evident that warming above the 1.5 ℃ limit will significantly increase the potential for onset of tipping points leading to catastrophic climate change [2,3]. Since this 2018 IPCC report, the latest assessments point to an even greater challenge to keep warming at the 1.5 ℃ target arguing that a rapid large-scale deployment of NET is imperative to have any chance of achieving the 1.5 ℃ target [2,4–7]. The latest IPCC Report emphasizes that curbing methane emissions will have significant benefits in slowing down global warming [8].

First, we acknowledge the valuable previous studies which model renewable energy (RE) growth with complete termination of fossil fuels along with assumptions of the remaining carbon budgets to reach IPCC warming targets [9–14]. Two of these studies [10,14] provided simulations showing the sensitivity to assumed energy return on energy invested (EROI) ratios (reference 10 calls them EROEI ratios which are equivalent, i.e., energy return over energy invested) of composite RE supplies (wind, photovoltaics (PV), concentrated solar power (CSP)), including for an assumed emissions cap corresponding to 510 Gt CO_2 by 2100 (see Supplementary Information, accessible from the doi of their paper). It should be emphasized that reference 10 excludes carbon capture and storage (CCS) from fossil fuel consumption, indeed, more critically, any NET from their analysis. In their simulations reference 10 assumes EROI values of composite renewables at 2014 which remain constant until the end at 2100, ranging from 6.67 to 60 with 18–22 corresponding to what is "needed for the least challenging transition trajectories" delivering 1.5 to 2.5 kW/person at 2100 (see p.28, Figure S15, Supplementary Information, reference 10). As expected, their simulation for early transition to renewables results in full fossil fuel phase out at 2050 (emission cap at 510 CO_2 Gt) has the lowest "feasibility index", i.e., judged the hardest to achieve). This conclusion is apparently the outcome of their combined economic and physical model, with embedded assumptions about near future political economic conditions. A more plausible scenario would to be to assume that the composite EROI would progressively grow from the assumed current best value at the starting time as renewable technologies have shown significant efficiency improvements over the past few decades.

With the exception of reference 10 and 14 the sensitivity to assumed physical inputs is not readily apparent. All these studies are based on very complex combined economic market-based and physical modeling and lack transparency. For example, regarding the most recent study, we point the reader to the PROMETHEUS model [12]:

> The PROMETHEUS model provides detailed projections of energy demand, supply, power generation mix, energy-related carbon emissions, energy prices and investment to the future covering the global energy system. PROMETHEUS includes relations and/or exogenous variables for all the main quantities, which are of interest in the context of general energy systems analysis. These include demographic and economic activity indicators, primary and final energy consumption by main fuel, fuel resources and prices, energy-related investment, CO_2 emissions, and technology dynamics. (Supplement, ANNEX A: Detailed description of the PROMETHEUS model).

It is not clear whether energy poverty now with a big impact in the global South has been eliminated in their scenarios, either early on or even as an end result. Further, from what we can infer from details provided, these studies do not use the new research which points to the CO_2-equivalent natural gas (NG) emission factor being greater than coal, which will have significant impact on the greenhouse gas (GHG) emissions (see Table 1) and hence lower the assumed CO_2-only carbon budgets assumed for the IPCC warming targets. None of these studies considers the energy requirements for NET [9–14].

Table 1. Energy components and their emission factors.

	2018 World Energy Consumption [mtoe]	CO_2-equivalent emission factor (CO_2 only) [tonnes/TJ]
Oil (conventional)	4586 [25]	76 (68) [22]
Coal	3838 [25]	106 (90) [22]
NG	3262 [25]	110 (50) [22]
Nuclear	707 [25]	3 [38]
Hydropower	362 [25]	37 [29]
Biomass	1327 [25]	60 [39]
Geothermal	7 [26]	34 [38]
Wind + Solar	282 [25]	3 or 0* [38]

* Note: 3 when generated using fossil fuels, 0 when generated using existing renewable energy. In Reference 25 "Other" in source includes wind, solar and geothermal, so geothermal, found from source [37] was subtracted from "Other".

Regarding the impact of their market-based inputs to their results, we find very problematic the neglect of potential future politically-driven obstacles, such as conflicts including wars. For example, reference 11 says:

> Modelling results show that a carbon neutral electricity system can be built in all regions of the world in an economically feasible manner. This radical transformation will require steady but evolutionary changes for the next 35 years, and will lead to sustainable and affordable power supply globally (Abstract).

A model based on the present physical characteristics of RE technologies can at least demonstrate potentially what can be achieved if political economic obstacles can be overcome. Hence, we present this study with greater transparency using a much simpler physical model, leaving out market-based inputs to encourage a reexamination of the previous, more complicated studies, while at the same time confronting directly the energy requirement of direct air capture negative carbon emissions which was not included in the previous research cited. The energy demand of fossil fuels, their composition and contribution to generating RE capacity are readily apparent in our model results. Therefore, in contrast to previous studies mentioned, in our modeling the following important parameters are transparently represented, namely, the fraction of RE (wind, PV, CSP) invested to make more of itself, where CSP is applied mainly in deserts (f), the fraction of the non-RE supply equal to *present* primary energy consumption level invested to make RE technology (F_{ff}) and the Energy Return/Energy Invested Ratio (EROI) for the RE Technology (M). These and other model parameters are defined and discussed in both the Materials and Methods as well as in the Results and Discussion sections.

Consistent with the recognition of IPCC/WMO [1] that meeting the 1.5 ℃ warming target will require far-reaching and unprecedented changes in all aspects of society, we emphasize this RE transition will need a robust path of demilitarization of global society, thereby freeing up vast material resources, especially metals, with the phaseout of the fossil fuel and military infrastructures. In addition, the RE infrastructure should have the capacity to eliminate energy poverty especially in the global South as well as be able to confront the new challenges of the 21st Century, in particular climate mitigation and adaptation especially in the global South.

Therefore, we examine how the 1.5 ℃ target could still be met, building on previous simulations [15]. Our new modeling examines the creation of a global 100% RE supply with a calculation of the cumulative carbon dioxide emitted in a complete phaseout of fossil fuels in a 20 year transition with an assumed starting point at the beginning of 2018. Our objective is to see if estimates of the remaining carbon budget for 1.5 ℃ warming are exceeded in our simulations. In addition, we consider whether our computed cumulative carbon dioxide emissions can be reduced at or below this carbon budget using RE-powered NET, supplemented by potential natural carbon sinks such as restoration of coastal wetlands [16] and a global shift to plant-based diets [17].

The carbon budget for the 1.5 ℃ warming target

Here is a useful definition of a carbon budget for purposes of this discussion:

> A carbon budget is a single number that encapsulates the finite limits of our planet's physical system and highlights the need to reach net zero—if we continue to release emissions on a net basis, the budget is breached and the temperature keeps rising [4].
>
> The world's remaining emissions budget for a 50:50 chance of staying within 1.5 ℃ of warming is only about 500 gigatonnes (Gt) of CO_2. Permafrost emissions could take an estimated 20% (100 Gt CO_2) off this budget [18], and that's without including methane from deep permafrost or undersea hydrates. If forests are close to tipping points, Amazon dieback could release another 90 Gt CO_2 and boreal forests a further 110 Gt CO_2 [19]. With global total CO_2 emissions still at more

> than 40 Gt per year, the remaining budget could be all but erased already (p. 594 in reference 2).

On the issue of non-energy contributors to the carbon budget, we note this explanation [4]:

> A central difference between International Energy Agency (IEA) and IPCC carbon figures is that whereas the IPCC budgets relate to total emissions of CO_2, the IEA scenarios focuses primarily on the energy sector, which is the largest single source of anthropogenic CO_2 emissions through the burning of coal, oil and gas. The remainder is accounted for by emissions from industries, land use, land-use change and forestry (LULUCF) LULUCF alone accounted for 13% of global CO_2 emissions in 2018 [iv], so tweaking these assumptions can have considerable implications for the final 'budget' figure. [iv: https://www.globalcarbonproject.org/carbonbudget/index.htm].

Figure 3 in Reference 4 shows the IPCC carbon budget for 1.5 ℃ as 580 CO_2 GT (50% chance), with a start at the beginning of 2018, with a 15% emissions reduction produced in 2018–19 resulting in 493 CO_2 GT remaining. In 2020, we witnessed a significant decline in CO_2 emissions as a result of the global COVID-19 crisis [20]. However, in the first half of 2021 global carbon dioxide emissions from the electric power sector rose to above pre-pandemic levels [21]. For the start at the beginning of 2018 subtracting 13% for the LULUCF emissions [5] yields an energy-only CO_2 budget of 505 GT.

The issue of non-CO_2 greenhouse contributors should be noted:

> Other greenhouse gases (such as methane, fluorinated gases or nitrous oxide) and aerosols and their precursors (including soot or sulphur dioxide) affect global temperatures. Estimating the remaining carbon budget thus also implies making assumptions about these non-CO_2 contributions. This further complicates the relationship between future CO_2 emissions and global warming (p. 335 in reference 18).

Thus, we conclude that burning NG to produce CO_2 is included in the CO_2 carbon budget, and that the CO_2-equivalent warming from methane as a greenhouse gas has been taken into account in the estimate of this budget. The assumed emission factor for CO_2-equivalent warming from methane is a source of uncertainty for the CO_2 carbon budget but we use published source [22] as a likely estimate of impacts. In this study we compute both the CO_2-only and CO_2-equivalent emissions. In addition, emissions from permafrost, undersea hydrates, Amazon dieback and boreal forests will likely reduce the carbon budget left for 1.5 ℃ warming [2,23].

A recent assessment of uncertainties in the remaining carbon budget for 1.5 ℃ warming target [24] provides further clarification:

> Considering only geophysical uncertainties, our median estimate of the 1.5 ℃ remaining carbon budget is 440 $GtCO_2$ from 2020 onwards, with a range of 230–670 $GtCO_2$, (for a 67–33% chance of not exceeding the target). Additional socioeconomic uncertainty related to human decisions regarding future non-CO_2 emissions scenarios can further shift the median 1.5 ℃ remaining carbon budget by ±170 $GtCO_2$ (Abstract).

We will proceed to use these estimates of the remaining carbon budget left for keeping below the 1.5 ℃ target in the assessment of the results of our modeling.

2. Materials and methods

Modeling computations were done numerically based on the equations shown in Table 2, supplementing the approach of reference 15).

Table 2. Equations and definitions of model parameters.

Equations:

1a. $d(P_{RE})/dt = [(M/L)(f)(P_{RE})] + [(M/L)(F_{ff})(P_{2018})]$

Solution: $P_{RE} = (f)^{-1}(F_{ff})(P_{2018})[e^{[(f)(M/L)(t)]} - 1]$

(Modified from Eqs 1 and 2 of reference 15)

1b. $R^{*} = P_{FF} + P_{RE}$

2. Σ CO_2-equivalent emissions $= \Sigma E_x \bullet F_x$

Definitions:

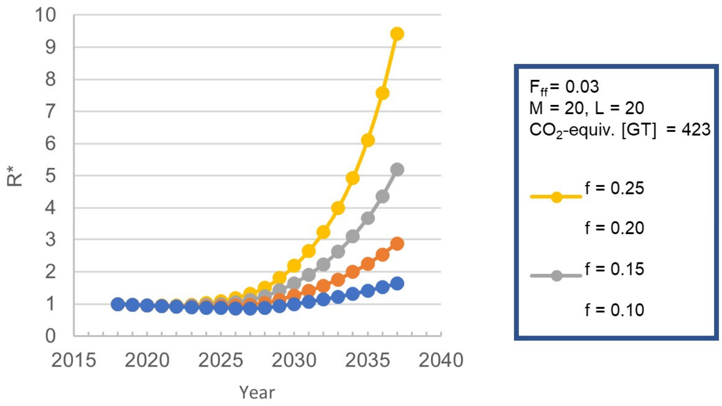
R* is global primary energy consumption relative to the consumption in 2018 corresponding to 18.95 TW in power units (p. 47, reference 25); the renewable component grows to 100% in 20 years as the fossil fuel contributions decline, finally to zero in our simulations.
P_{FF} is the global primary energy consumption of non-RE at time t
P_{RE} is the global primary energy consumption of RE at time t
P_{2018} is the 2018 global primary energy consumption
f is the fraction of RE (wind, PV, CSP) invested to make more of itself, where CSP is applied mainly in deserts.
F_{ff} is the fraction of the non-RE supply equal to *present* primary energy consumption level (P_{2018}) invested to make RE Technology (constant amount invested over the 20 year transition to 100% renewable supply)
M is the Energy Return/Energy Invested Ratio (EROI) for the RE Technology
L is the Lifetime of the RE Technology
E_x is the energy consumed annually by each energy source
F_x is the emission factor for each energy source

In these simulations, the RE supply (P_{RE}) grows because it is being created from modest contributions of the non-RE component (F_{ff} x P_{2018}) along with contributions from the continuously growing renewable supply itself (f x P_{RE}); P_{RE} grows exponentially with time. We emphasize that P_{RE}'s significant exponential growth in the late stages of the transition are simply results of the model equation and should not be taken as necessarily physically plausible given the material constraints. Once the necessary level of renewable energy supply is achieved, new capacity can be programmed to simply replace the old infrastructure. The CO_2 emissions are computed by summing up the emission factor (F_x) multiplied by each energy source as a function of time (E_x) (see Eq 2). The assumed EROI ratios equal to 20–30 for the RE technology are consistent with estimates for currently available wind and PV [15,26–33]. As reference 30 emphasizes, these renewable technologies now can provide final stage EROI ratios of 20 to 30 for energy (electricity) entering the economy, even higher than comparable ratios for fossil fuels. We take note of the analysis of comparative EROI ratios, with its argument for the plausibility of a RE transition [34]. The advantages of this transition, coupled with boosts in energy conservation and efficiency, also point to the increased availability of supplementary energy needed for energy storage and grid modernization. It is very likely that the EROI ratio of RE will increase in the near future with ongoing research and development (R&D), in particular with high efficiency thin-film PV [35] and floating offshore multi-megawatt wind turbines coming online, making possible a faster RE transition. We disagree with pessimistic assessments of wind/solar EROI ratios [e.g., 36] based on the previously provided critiques. Modest contributions to the future global energy supply will likely come from geothermal sources used for heating buildings and powering negative carbon emission technology in locales with high heat flow, along with hydropower.

The baseline energy consumption of each contributor and assumed emission factors are shown in Table 1. Note that in contrast to previous studies of RE transition which have underestimated the CO_2-equivalent emission factor for NG we input a value slightly higher than coal, a result of leakage to the atmosphere from the wellhead to consumption [22], which we submit makes our results more reliable than these previous studies.

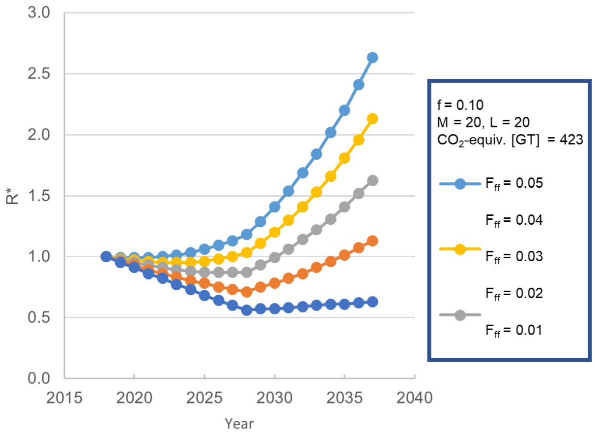
3. Results and discussion

Simulations shown in Figures 1, 2, 3, 4a all assume a linear phaseout to zero in 10 years of coal, NG, with a linear phaseout in 20 years of the other energy sources (nuclear, biomass, hydropower and geothermal). A linear phaseout is most reasonable from a practical perspective given it guarantees a steady, equal-sized reduction per year. The phaseout of oil for all simulations was modeled to be more gradual, going to zero consumption at the end of the transition to 100% RE supply. As shown in Figure 5 oil usage was progressively ramped down numerically, initially slowly and then faster later on so as to maintain global energy consumption in early stages of the transition to renewables near current levels to avoid energy poverty hardship worldwide, as well as remain to the end as a fossil fuel supply creating new RE capacity (the F_{ff} input). Since they all entailed the same scenario of fossil fuel phaseout, all these simulations not surprisingly resulted in the same computed cumulative CO_2-equivalent emissions, which turned out to be equal to 423 GT, well below the current carbon budget corresponding to the 1.5 ℃ target. We emphasize this is the model output, not previously anticipated.



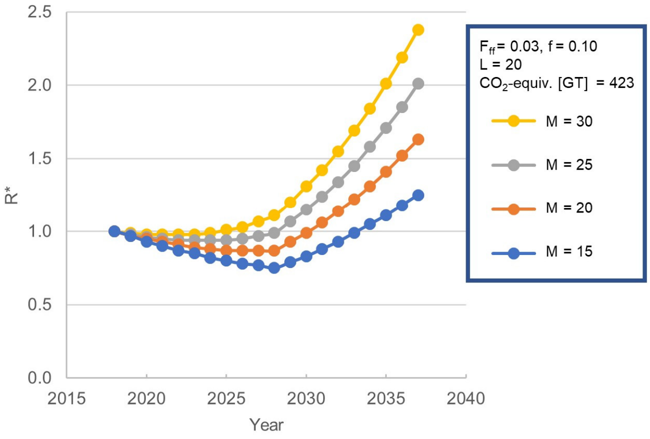
L is the Lifetime of the RE Technology

Figure 1. Future energy consumption (r*) as a function of time with varying renewable energy (re) reinvestments (f).



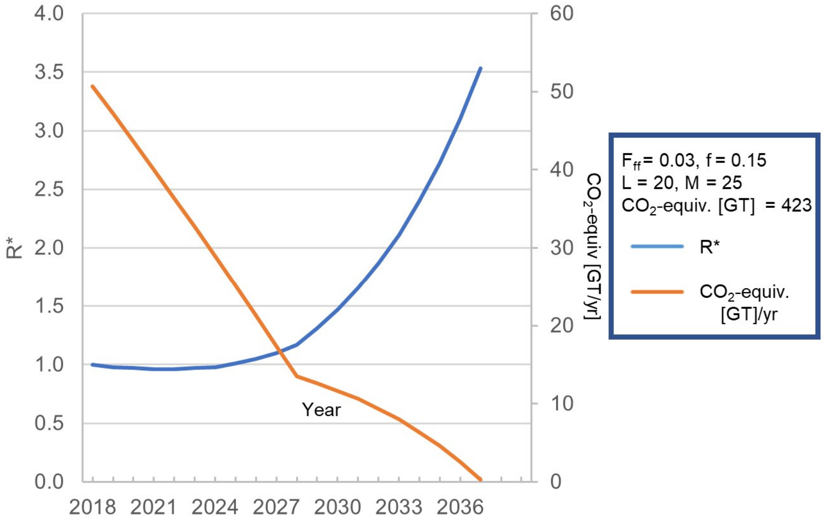
L is the Lifetime of the RE Technology

Figure 2. Future Energy Consumption (R*) as a function of time with varying Fossil Fuel Reinvestments (F_{ff}).

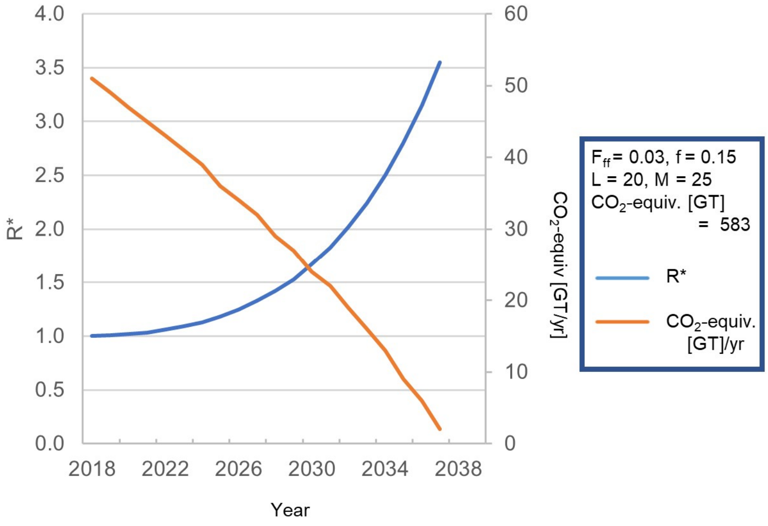


L is the Lifetime of the RE Technology

Figure 3. Future Energy Consumption (R*) as a function of time with varying Energy Return/Energy Invested Ratios (EROI) for the RE Technology (M).



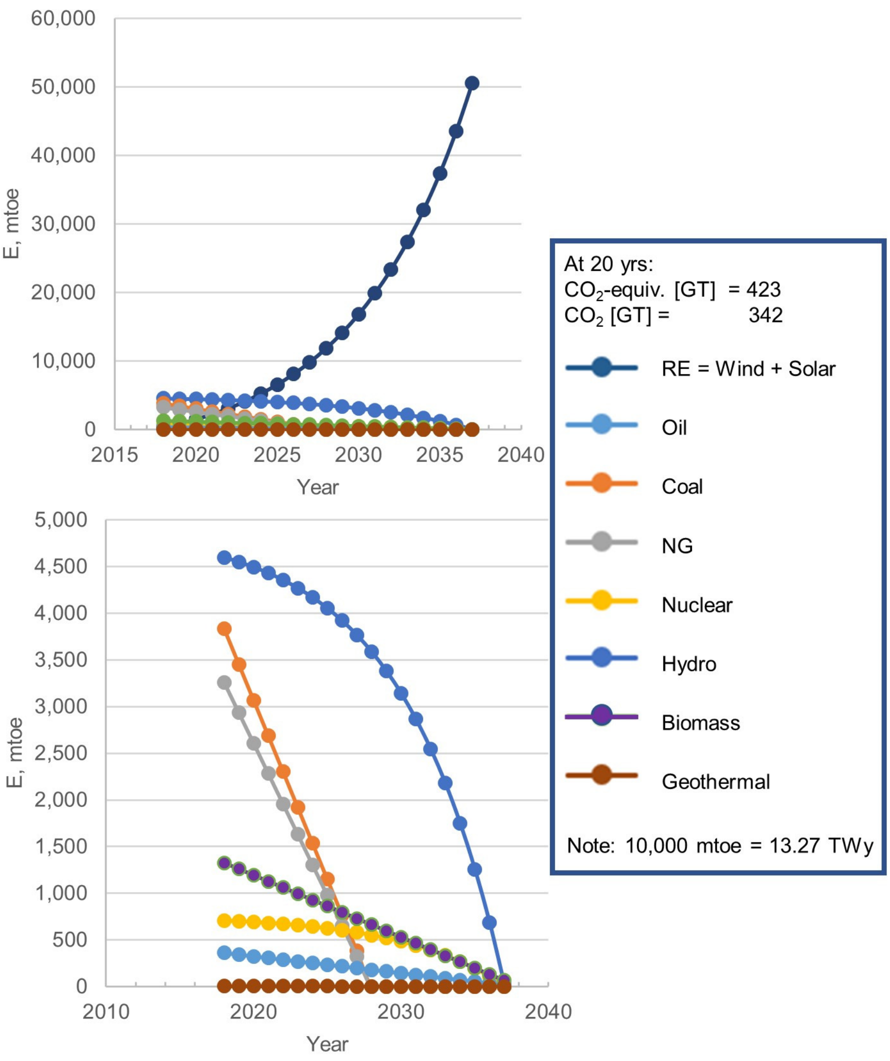
(a)



(b)

L is the Lifetime of the RE Technology

Figures 4. (a) Future Energy Consumption (R*) and CO$_2$-equivalent emissions/year as a function of time. Scenario I: Coal and Natural Gas (NG) terminate in 10 years; (b) Future Energy Consumption (R*) and CO$_2$-equivalent emissions/year as a function of time. Scenario II: Coal and Natural Gas (NG) terminate in 20 years.



E is the energy consumed annually by each energy source (mtoe)

Figure 5. Future Energy Consumption (R*) by energy source as a function of time for Scenario I, with cumulative CO_2-equivalent and CO_2 emissions at 20 years.

Several simulations test the sensitivity of the assumed constants to the rate of RE generation which in addition to the remaining non-renewables equals R*, with the same computed cumulative CO_2-equivalent emissions of 423 GT (Figures 1, 2, 3, 4a). Figure 1 shows the sensitivity of the R* growth to the assumed f inputs ranging from 0.10 to 0.25, with higher values generating faster growth of RE supplies. Again, we emphasize these high levels of RE capacity (also shown in Figure 4a,b) are only model results driven by the mathematics of Eq 1a. We are not making the case that these high levels (roughly over 1.5 times the current primary energy consumption level) are feasible scenarios for the assumed timescale of energy transition, given the material requirements (see Supplement for further discussion). We empathize that higher levels of energy production are certainly possible but would likely require more time to be built out. Similarly Figure 2 shows the sensitivity of R* growth to assumed F_{ff} inputs ranging from 0.01 to 0.05. Note that this variation of the fossil fuel reinvestment in making RE does not change the growth of CO_2-equivalent emissions since the same amount of each fossil fuel is consumed in the 20 year transition time. Figure 3 shows the sensitivity of R* growth to the assumed M values ranging from 15 to 30, with progressively higher inputs generating faster growth of RE supplies. Figure 4a shows the CO_2-equivalent emission flux as a function of time along with the growth of R*. Unlike Figures 1 through 4a, Figure 4b shows the effect of the linear phaseout of coal and NG in 20 years, with as expected a greater cumulative CO_2-equivalent emissions equal to 583 GT, exceeding the median estimate for 1.5 ºC carbon budget [24]. For this scenario, unless sufficient NET is implemented before the completion of this assumed transition the 1.5 ℃ target will be breached.

With the same phaseout termination of non-RE supplies assumed in Figures 1 through 4a, Figure 5 show the assumed phaseouts as a function of time of the fossil fuels (oil, coal, NG) as well as the other energy sources (nuclear, biomass, hydropower and geothermal), along with the growth of RE supplies (Figure 5a). In addition, as noted in the legend for Figure 5, the CO_2-only cumulative emissions correspond to 342 GT, well below the median estimate for 1.5 ℃ carbon budget [24]. Table 3a,b show the computed CO_2-equivalent and CO_2-only contributions for each fossil fuel for the two "Scenarios" shown in Figure 4a,b, respectively. Note that the CO_2-equivalent and CO_2-only emissions are both within the uncertainties for the remaining carbon budget [24] for the complete phaseout of coal and NG in 10 and 20 years (Figures 4b, 5). Scenario II with complete phaseout of coal and NG delayed to 20 years corresponds to CO_2-only emissions of 448 GT just above the median estimate given in [24]. Obviously further delay in phaseout of these two fossil fuels with the highest emission factors will increase the emissions level. Even Scenario I results in CO_2-only cumulative emissions of 342 GT, above the 230 GT corresponding to a 67% chance of not exceeding the 1.5 ℃ warming target [24]. Given the uncertainties in the remaining carbon budget that take into account additional potential subtractions from this budget [2,24], it will be imperative to begin this RE transition very soon, applying the precautionary principle recognizing that aggressive negative carbon emissions should start as soon as the RE supply is sufficient for mitigation. We note that in our simulations the RE consumption level at the end of the assumed 20 year transition time reaches roughly 1.5 times the 2018 primary energy consumption level for conservative inputs of f (0.10), F_{ff} (0.03) and M (20), namely corresponding to about 29 TW.

Table 3a. Total emissions after 20 years [GT]: scenario I, No coal & NG after 10 years.

	Oil	NG	Coal	Total from FF	Total all Sources
CO_2-equiv.	200	83	93	375	423
CO_2-only	179	38	79	295	342

Table 3b. Total emissions after 20 years [GT]: scenario II, no coal & NG after 20 years.

	Oil	NG	Coal	Total from FF	Total all Sources
CO_2-equiv.	200	158	179	536	583
CO_2-only	179	72	152	402	448

The amount of oil consumed in our scenarios for the complete transition in 20 years (Figure 5) is 62,800 mtoe, or 3.6% of the proven global oil reserves of 1,740,000 mtoe [41]. For Scenario II, with full phaseout in 20 years, the total NG consumption is equivalent to 35,600 mtoe or 2.0% of proven NG reserves and for coal, the total is equivalent to 38,900 mtoe or 5.2% of proven reserves [41].

Further, while there would be huge health benefits in the elimination of anthropogenic aerosol emissions driven by fossil fuel combustion in a 100% wind/solar transition, cancelling out their significant cooling effect for the 1.5 ℃ target [42,43]. While this effect is included in the IPCC carbon budget, there remains uncertainty in its impact [42].

Critics of ambitious plans for creating RE infrastructure point to onerous material requirements of metals [44]. In particular, the requirement of rare earth elements has been identified as posing a significant challenge, even with efficient recycling [45,46]. Recycling rates of the rare earth metals, such as neodymium used in RE technologies, are currently very low [47,48]. Alternative technologies reducing and even eliminating the use of rare elements are being developed and implemented in wind turbines [48–50] and energy storage technologies (e.g., Na-S batteries, instead of the less abundant lithium, liquid air energy storage technology, and Fe-air battery technology [51]). There is now a robust R&D program for dematerialization of efficient PV technology with reference 35 having nearly 500 citations on Google Scholar. Plans for creating global PV capacity at terawatt scale are now being considered by leaders in the industry [52,53], as well as being technologically possible [54]. Recycling and industrial ecologies powered by wind/solar power have the potential of significantly reducing the need for mining. Hence, a transition to a post-extractivist future is possible, promoted by a wind/solar transition, which should be coupled with a strong global regulatory regime necessary for environmental, worker and community protection.

Further, the scenario outlined here would very likely require progressive demilitarization of global society [55], i.e., the phasing out of the fossil fuel and the military infrastructures, which would liberate vast quantities of materials, especially metals, for the creation of a global wind and solar power infrastructure. Likewise, it would free up materials in the conversion of the automobile-roadways complex to electrified rail and public transit powered by wind-solar energy sources. This potential phaseout of the global fossil fuel and military infrastructures could contribute an enormous input to a circular economy, recognizing that the full potential of this economy can only be realized with progress towards a global RE supply. The U.S. National Renewable Energy Laboratory and green corporate sector are now recognizing this fact and of course the investment opportunities it represents [56–58]. We recognize that the circular economy approach has the goal to make better use of resources/materials through reuse, recycling and recovery, while minimizing the energy and environmental impact of resource extraction and processing, with bio-based industry and bioenergy playing a central role. Therefore, we note the recent research on food and solid waste [59,60] and bioenergy [61–63] in the context of implementing the circular economy. These innovations should complement the transition to a RE-based economy.

Georgescu-Roegen made historic contributions as the founder of ecological economics. However, his fallacious so-called 4th law of thermodynamics [64] which conflates open and closed systems with respect to energy and mass transfers was rejected over thirty years ago even by leading ecological economics scholars who recognized that incoming solar radiation could be the energy supply of global civilization [e.g., 65]. The Earth's surface is not closed but rather open to energy going in and out, hence utilizing the low entropy solar flux to the Earth's surface to do the work of civilization pays its entropic debt to space as waste heat, since the surface's low albedo will generate virtually the same heat flux whether or not the incident solar flux is used to do work [66,67]. Hence, there is a critical difference between the high efficiency capture of the solar flux generating wind/solar power and the fossil fuel energy supply which of course has driven climate warming.

> Looking ahead, a prospective sustainability revolution will require scaling up new renewable and decarbonized energy technologies and the development of much

> more efficient material recycling systems–thus creating a more autotrophic social metabolism. (Abstract, reference 67)

Indeed, this translates into what is called a "solar-powered recycling revolution" [p.362, in reference 67].

And last but not least, global progress towards demilitarization will promote a badly needed international regime of cooperation so critical to a rapid solar transition and elimination of the global consumption of fossil fuels [68]. For example, we cite the geopolitical barriers now blocking supergrid implementation in Asia [69]. We take note of the potential synergy between demilitarization, termination of fossil fuel consumption and the improvement of the quality of life, especially in the global South, as a result of the freeing up of vast material and financial resources; the direct and indirect costs of the global subsidization of fossil fuels amount to \$5 trillion a year [70] while the global annual military expenditures are on the order of \$2 trillion [71].

The role of NET to meet the 1.5 ℃ target

The most energy-efficient approaches to mitigation of carbon dioxide emissions are switching to RE combined with energy efficiency measures in industry, transportation and buildings [72]. This mitigation needs to be coupled with negative carbon emissions, which is getting a lot of attention by the scientific community following the IPCC/WMO report [1], with increasing focus on Direct Air Capture with Carbon Storage (DACCS) technologies [72–75]. A promising approach is Climeworks-CarbFix injection into subsurface basalt at Hellisheidi, Iceland [73,76,77].

In their review of mineral carbonation as a process for carbon sequestration from the atmosphere, reference 76 cites a range of the energy requirement of 3.4 to 10.7 GJ/ton of CO_2 captured from air, with the upper limit corresponding to 471 kJ/mole CO_2. Assuming a rough requirement of 500 kJ/mole CO_2 for direct air capture (DAC) leading to permanent storage via subsurface mineral carbonation, reducing the carbon dioxide emissions by 150 GT in 10 years would require the use of the equivalent of 5.38 TW of RE production. Reducing the energy requirement to the lower limit of 3.4 GJ/ton of CO_2 [76] would correspond to 1.61 TW of RE production or for a drawdown of 300 GT in 10 years, 3.22 TW. This RE power would of course be applied for the time periods indicated. These energy estimates are well within the computed total renewable production created by 2028 in simulations with $f \geq 0.15$, recognizing that the level of global renewable power supplies can level off by design once sufficient power is generated for the required drawdown flux. In addition, some of the necessary energy could apparently come from other sources linked to the mineral carbonation process:

> The efficiency of the DAC process is inevitably directly linked with the CO_2 emissions generated by its energy source; for maximum efficiency, the energy demand of the DAC process should be supplied by available low-grade industrial-waste heat or low- CO_2-emitting geothermal heat (p. 98, reference 76).

These rates of carbon storage, from 15 to 30 GT CO_2/year, are consistent with the higher estimates for potential sequestration in the crust for air capture in onland peridotite (Figure 4, reference 78). The subsurface capacity for mineral carbonation is virtually unlimited given the volume of available rock and leak-free with respect to potential release of carbon dioxide to the atmosphere. Other sequestration technologies driven by RE supplies may potentially play an important role, such as electrochemical processes using ocean water [79,80].

Of course, in these simulations we are not arguing for the need to create a RE infrastructure with a primary energy consumption of 2 to over 3 times the present consumption level in 20 years. Rather, taking into account technological improvements in 2nd law (exergy) efficiencies reducing the necessary global energy demand, the goal should likely be below 1.5 times the present level. This goal would have the capacity to eliminate global energy poverty, for climate mitigation and adaptation as well as other challenges posed in the next few decades, thereby optimizing the quality of life of all of humanity along with the preservation of biodiversity. Reference 81 projects a 23% improvement in efficiency from 100% RE-driven electrification by 2050.

References 82 and 83 emphasize that energy poverty corresponds to lower life expectancies across the world than the highest level achievable (e.g., Japan). This dependency is illustrated by graphing by nation female life expectancy at birth versus per capita energy use (Figure 35.13, p. 723, reference 83). The rough minimum to achieve highest life expectancy now corresponds to 3.5 kW/person applied continuously, with most of humanity living in the global South below this minimum with depressed life expectancies (for an updated graph see p.88, Figure 4.1, reference 68). It is important to recognize that numerous factors depress the life expectancy in countries even with higher energy consumption levels than this minimum, e.g., income inequality and of course the level of air pollution from burning fossil fuel [68,84].

Several well-researched studies have concluded that the necessary energy demand in a RE transition could be significantly lower than the present without the need for DAC technologies, rather relying on restoration of natural ecosystems [81,85,86]. Recognizing the importance of this research, we conclude that their level of projected energy demand is insufficient to eliminate energy poverty in several high population countries of the global South such as India, as well as to effectively meet the challenges of climate mitigation and adaptation [68].

We acknowledge as one reviewer pointed out, economies built around consumerism as a facet of an industrialized society are challenged to be able to achieve just distributions of energy and resource use around the world and in maintaining these within feasible levels as suggested by our simulations. Therefore, we again recognize, that far-reaching and unprecedented changes in all aspects of global society are imperative to achieve global justice, as previously mentioned in the context of the 2018 IPCC Report [1]. Further, the same reviewer recognized as we do that the current economic system is predicated on economic growth, which has been thoroughly critiqued by scholars with a degrowth analysis [e.g., 87–90]. Taking into account this critique, we argue that the qualitative aspects of economic growth should be unpacked, distinguishing sustainable growth addressing essential needs of humans and nature versus unsustainable, leaving the majority of humanity in poverty or worse while degrading global ecosystems and reducing biodiversity [68]. In this paper, we confront the threat of catastrophic climate change with a scenario for sustainable economic growth and degrowth of the unsustainable.

A rough calculation can provide some idea of future energy needs in 20 to 30 years from now. Assuming a minimum of 3 kW/person minimum applied continuously for achieving the highest world standard life expectancy, 9 billion people and an efficiency gain of 30% for a 100% RE transition, $3 \times 9 \times 0.70 = 19$ TW (in power units) which is equal to the present global primary energy consumption. Adding incremental needs, climate mitigation and adaptation, biosphere cleanup and ecosystem restoration will of course increase this estimate. There is significant uncertainty in just how much more energy in the future will be needed globally to confront climate change, highly contingent on future warming scenarios [91]. Just considering the energy demands of climate mitigation in our scenarios, at least the increment of 3 to 11 TW would be needed. Not including the drawdown from restoration of natural ecosystems which could significantly reduce this requirement, we take this increment as a minimum since other incremental needs are not included.

We recognize the debate between the pessimists [92,93] and optimists [94,95] regarding the possibility of making such a rapid energy transition. Reference 95 argue:

> The roadmaps call for countries to move all energy to 100% clean, renewable wind-water- solar (WWS) energy, efficiency, and storage no later than 2050 with at least 80% by 2030 (Summary).

Reference 93 concludes:

> Replacing the current global energy system relying overwhelmingly on fossil fuels by biofuels and by electricity generated intermittently from renewable sources will be necessarily a prolonged, multidecadal process (Abstract).

We note that the roadmap of reference 95 does not invoke the need for biofuels while making the case for a reliable baseload energy supply by renewable sources. Reference 94 concludes:

> We find that the principal barriers to 100RElec are neither technological nor economic, but instead are primarily political, institutional and cultural (Abstract). (100RElec is an abbreviation for large-scale electricity systems that are 100% renewable.)

We agree, with the biggest barrier being the existing political economies on our planet.

This scenario of rapid transition to wind/solar energy should be coupled with aggressive energy conservation in energy-wasteful countries in the global North such as the U.S. thereby making possible a rapid buildup of RE production in the global South to terminate energy poverty. Reference 96 argues that self-sustained temperature rise from runaway melting of permafrost could potentially be avoided by atmospheric removal of 33 GT CO_2-equivalent per year. Recognizing that the modeling and conclusions of this study have been vigorously challenged by climate scientists [97], the RE requirement for this flux is consistent with the potential generation in our modeling for $f \geq 0.15$ for the first ten years of the transition to a global 100% RE supply.

Of course, NET can be significantly supplemented by the restoration of natural ecosystems, thereby providing a carbon sink from the atmosphere into biomass and soil. For example, an estimate of 299 GT of CO_2 could be sequestered with this approach [16]. Further, a global shift away from animal-sourced food production to plant-based diets by 2050 could apparently provide a very significant sequestration of carbon estimated to be 332–547 GT CO_2 [17]. However, we question whether this level of sequestration may be over-estimated because of near future warming even up to the 1.5 ℃ target as a result of increased respiration of soil carbon [98–100]. On the other hand, as this paper points out gains from non-CO_2 GHG reductions should be included in this shift to a plant-based diet. In addition, as a reviewer pointed out, the GHG savings for a plant based diet are also limited by energy used to produce needed fertilizers as well as taking into account food wastes used for small animal production.

However, industrial scale carbon sequestration from the atmosphere into the crust will be necessary for both short term and long term time scales since the carbon sink of natural ecosystems will saturate and diminish their capacity even with an additional 0.5 ℃ of warming, as the oceans will continue to reequilibrate with the atmosphere, resulting in a carbon dioxide flux to the atmosphere as this gas is sequestered into the crust. Indeed, reference 74 points out:

> From our scenarios, DACCS is foreseen to remove between 16 and 30 $GtCO_2$/year over the period 2070–2100. This implies that a significant fraction (from 10 to 19%) of the carbon removed would be released back to the atmosphere from the oceans, requiring an additional removal of 1.7 to 9.5 GtCO2/year to meet the same carbon budget. (p. 8 in reference 74).

Water and material requirements for infrastructure must be addressed in a robust program of NET [75,77]. The use of sea water in subsurface mineral carbonation [78,101] is likely the best option, along with solar-powered synthesis of chemicals used in DAC, such as monoethanolamine, from air-derived nitrogen and carbon [102,103], although more efficient technologies can be anticipated in the future.

CCS from fossil fuel power plants [104] increasingly powered by the RE infrastructure should arguably be a component of a plan to optimize the rapid reduction of carbon emissions while providing the necessary global energy supply, but taking note of an important critique [105] we emphasize that this mode of CCS should not be implemented to prolong the unnecessary consumption of fossil fuels.

Finally, as argued in recent Nature Editorial [106] we emphasize that nuclear power is indeed the best option for the global energy supply, but this nuclear power is the fusion reactor in the core of the Sun, supplying the solar flux to Earth, rather than nuclear fission reactors.

4. Conclusions

We present these model results to provide approximate limits to the pace of both necessary fossil fuel termination and RE creation to meet the 1.5 ℃ warming goal. We conclude it is technically possible to keep warming at or below this goal even utilizing the present state-of-the-science RE technologies in a 20 year transition to 100% global RE supply with a rapid termination of fossil fuels with the highest emission factor, i.e., coal and natural gas, which are completely phased out in the first 10 years. In this 20 year transition, conventional oil consumption progressively decreases, initially slowly and then faster later on so as to maintain global energy consumption in early stages near current levels to avoid energy poverty hardship worldwide, as well as remain to the end as a fossil fuel supply creating new RE capacity. We recognize, as did the IPCC, that far-reaching and unprecedented changes in all aspects of global society are imperative to achieve these goals, not simply creating and siting RE and NET technologies. As many have already recognized, the challenge is overcoming the political economic obstacles to meet this goal, in order to begin this transition in the near future. Guided by the precautionary principle, terminating fossil fuel consumption coupled with building extra RE capacity as early as possible for DAC of carbon dioxide is imperative, given the physics of greenhouse gas forcing [107] as well as the uncertainties in the presently estimated carbon budget left for 1.5 ℃ warming including additional potential subtractions [2,24]. While timely restoration of natural ecosystems and regenerative agriculture [108] can potentially reduce the need for DAC technology, delay in fossil fuel termination will very likely lead to warming beyond the 1.5 ℃ target.

Conflicts of interest

The authors have no potential conflicts of interest and no sources of financial support. Both authors are responsible for all aspects of this research. All relevant data are cited in references provided and indicated in Tables and Figures.

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