The 3-machines energy transition model: exploring the energy frontiers for restoring a habitable climate

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Abstract

Along with the increasing urgency for climate action, more and more ambitious transformation pathways need to be conceived. The maximum speed of change is thereby constrained by biophysical limits. Even though it is essential for climate action to know what transformation pathways are still feasible from a biophysical perspective, there is a lack of studies and models exploring these frontiers of climate action. This paper introduces the 3-machines energy transition model, representing a first step to explore the energy frontiers for a complete phase out of fossil fuels and reducing the atmospheric CO₂ concentration below 350 ppm. Simulation experiments with this model show that even if all economic and societal obstacles could be overcome and the transition would start immediately, global peak heating may exceed 1.5 °C with a chance of at least 14 %. Simultaneously, it is still energetically possible to return to 350 ppm well before the end of this century. While these energy-constrained transformation pathways show that the climate can still be stabilized with a fair chance, they also illustrate the urgency and far-reaching change required in society.

Keywords

climate crisis | energy transition | 350ppm | negative emissions | system dynamics

1 Introduction

Effects of climate heating, such as heat waves and floods, are unfolding across the globe today [1]. Peak heating of 1.5 °C is considered the critical threshold beyond which climate tipping points may trigger events threatening ecosystems and humanity [2–6]. In addition to limiting peak heating, climate forcing resulting from excessive greenhouse gas concentrations needs to be reduced in order to stabilize the climate in the long run [5, 7]. An atmospheric CO₂ concentration of 350 ppm, already higher than during the past one million years [8–11], is considered a safe threshold [5, 7, 12, 13]. Yet, continued burning of fossil fuels [14–16] rises CO₂ concentration faster than ever [17].

There is agreement that a transition from the fossil to a renewable energy (RE) system is key and urgent [16]. Though current RE installation rate is at record heights [18, 19], it is insufficient for staying

below 1.5 °C heating [16, 20, 21], while the remaining carbon budget is rapidly depleted [22, 23]. Most proposed emission pathways allow fossil CO₂ emissions to continue, offset by carbon capture and storage (CCS) either at point sources (post combustion) as well as from air with machines (DACCS) and plants (BECCS) [22, 24–27]. Alternative pathways without carbon removal focus mostly on reducing demand [28–30]. Yet, all these proposed pathways exceed 1.5 °C peak heating with a chance of > 40 % [31] and do not or insignificantly reduce atmospheric CO₂ concentration.

Due to continued inadequate climate action, more ambitious and faster transformations become necessary to stabilize the climate [16]. To accelerate climate action, it is important to know the biophysical limits that cannot be transgressed even if all economic and societal obstacles could be overcome. In particular, building the new RE infrastructure requires to “invest” additional energy (i. e. embodied energy). The availability of energy is ultimately limiting the maximum speed of the transition [31, 32]. Besides energy, other constraints such as the availability of natural resources – e. g. materials [33–36], land or water [37, 38] – and social resources – e. g. skills and financial capital – may further slow, but cannot accelerate the transition beyond the energy limit.

Modelling can help to explore the feasible range for climate action and test the effectiveness of climate policy options. Common integrated assessment models (IAMs) explore pathways for reaching specified climate targets from an economic point of view, often based on minimizing total financial costs [39]. In IAMs, assumptions about cost developments and technological progress are necessary while highly uncertain during the modelled fundamental transformations [40] (e. g. they have been pessimistic for PV [41] and may be optimistic for CCS [30]). While current IAMs (e. g. MESSAGE [42], IMAGE [43], POLES [44], REMIND [45], TIAM [46]) consider financial investments for building RE infrastructure, only few (e. g. MEDEAS [47]) include embodied energy investments (see also Section S9). However, financial viability does not guarantee physical viability, especially when investigating rapid change. IAMs allow to simulate transformation pathways in great detail and can, in principle, be adapted to both include energy investments [47] and aim at targets different than minimizing costs. However, their complexity makes it difficult to use them for exploring a wide range of physically possible and climate optimal scenarios. Less complex models have been proposed in literature (e. g. C-ROADS¹ [48], HARMONEY [49]) to facilitate system understanding and the exploration by societal actors, however, they are not designed for exploring bio-physical and in particular energy frontiers.

This paper aims to fill this gap by exploring the energy frontiers for a twofold societal transformation: (i) the fast and complete transition from fossil to renewable energy and (ii) removing CO₂ in excess of 350 ppm permanently from the atmosphere and upper oceans. To this end, the “3-machines” energy transition model is built and presented here. This system dynamics (SD) model (Section 3) is a tool to explore transformations limited by energy for both replacing the current fossil (i. e. the “fossil engine”) with a renewable energy system (i. e. the “solar engine”) [31] and removing excess CO₂ from the atmosphere (i. e. the “carbon scrubber”). It is not intended to model transformations in great detail, but shall serve as an exploration tool for identifying promising strategies, which can be further explored in more detailed modeling frameworks, such as MEDEAS [47]. Simulation experiments (Section 4) allow identifying energy constrained pathways effective in minimizing peak cumulative CO₂ emissions, i. e. maximising the chance to stay below 1.5 °C peak heating [31], as well as minimizing the cumulative exceedance of 350 ppm, indicative for the damage on Earth systems due to excess radiative forcing. Section 5 outlines the implications of such physically constraint pathways for society.

2 Method

The scope of this analysis is to explore the energy frontiers for transitioning to a fully renewable energy system and cleaning up the atmosphere from CO₂ in excess of 350 ppm on a global scale and with a time frame from 2022 until 2100. All renewable energy converters other than direct solar are currently close to or already beyond their sustainable potential within Earth system boundaries [37]. Even though other renewables (in particular wind) may provide a significant contribution on the local scale, only solar has a large enough potential to fully replace fossil fuels globally [31, 37, 50]. Consequently, direct solar energy conversion on the already sealed surface of the built environment is considered the sole technology for new RE installations. The present renewable energy system, currently supplying 1.07 TW primarily through hydropower and biomass [51], is assumed not to change in the future and excluded.

¹<https://www.climateinteractive.org/tools/c-roads/>

Constraints other than energy and sustainable RE potentials within Earth system boundaries, such as material availability, manpower or finance, are omitted to allow finding the energy frontiers. Spatial variations, e.g. local solar resource potentials, are combined to global totals. Daily and seasonal variations are not explicitly modeled, but considered through the demand for storage [32], defined as exogenous parameters (Section S1.2). The technical and social feasibility of a chosen storage demand has to be evaluated with a spatially and temporally refined model (e.g. [52]) and is outside the scope of this research.

The effect of the energy transition and atmospheric clean-up on the climate is evaluated through net cumulative CO₂ emissions to the atmosphere and upper oceans. Peak net cumulative CO₂ emissions thereby correspond with the probability to exceed 1.5 °C peak heating [22, 31]. Furthermore, 350 ppm can be expressed as cumulative CO₂ emissions remaining in atmosphere and upper oceans. For returning to 350 ppm as much CO₂ has to be removed as had been emitted since 1988, when it had been passed the first time [53, 54]. As this research targets the fastest possible transformation of the energy system, we set other greenhouse gas emissions (e.g. CH₄, N₂O) and land use related CO₂ emissions to net zero for simplicity. Subsequent research will need to show the energetic implications and dynamics for mitigating non-energy related emissions.

Meeting the scope of this research, the “3-machines” model (Section 3) is built on energy and CO₂ balances, using the fundamental physical laws of conservation of energy and matter, and reduced to the essential system elements representing the energy system supplying humanity’s power demand linked to the carbon cycle. It is a system-dynamics (SD) model, i.e. a system of coupled ordinary differential equations (ODE). State variables represent energy stocks (box model), i.e. the system’s elements, which are linked with first derivatives (energy fluxes) representing power. The trajectories of the system are calculated by numerically solving the coupled ODE for consecutive time steps for different parameter sets defining scenarios (simulations Section 4). SD is an established method to operationalize such a model and a number of software tools are readily available. The “3-machines” energy transition model is implemented in “InsightMaker” [55], a freely-available, browser-based system dynamics (SD) application².

The energy system is represented as three point size machines, where spacial variations are reduced to global averages (Section 3.1). Electric energy is used as the universal currency for energy, i.e. all energy and power values are converted to electric energy equivalents [31, 37], which is pure exergy convertible into any other form of energy. Most renewable energy technologies, in particular solar PV, produce electricity [37]. Each of the three machines (fossil engine, solar engine and carbon scrubber) is defined through the stock of embodied energy, which can increase through new installations (i.e. embodied energy investments) and decrease when reaching end-of-life. This allows both to analyse the dynamic of the transition itself but also the subsequent replacement cycles. Technical developments in embodied energy investments – as had been observed in the past for PV [56, 57] and is expected, yet not well studied, for other key technologies [32] – are uncertain in the future, especially when considering extremely fast transitions [32]. While learning in embodied energy can be included, it is disregarded in this first version of the model. The energy system is linked to the carbon cycle through positive and negative CO₂ emissions (Section S4). The system minimises the supply gap between power demand of society and power supply by the energy system (system controller Section S3).

The model is presented in detail in Section 3 and in the supplementary materials. It was validated with structural and behavioral validation tests [58] (Section S6) and used to explore an evolution of scenarios from fossil baseline with continued growth of fossil emissions to reaching 350 ppm well before the end of this century (Section 4 and S5). The aim of the scenarios is to test the influence of key system parameters (e.g. energy demand Section S2) and find transformations that both minimize peak cumulative CO₂ emissions and cumulative exceedance of 350 ppm.

3 Model description

The three “machines” in the model are: a *fossil engine* (fC) and a *solar engine* (PV) both feeding and drawing power to and from the grid with the purpose of supplying society’s annual average power demand as well as a *carbon scrubber* (CCS) removing and sequestering CO₂. Together they constitute the energy system, which is coupled to an elementary carbon cycle and is controlled by a system controller (Fig. 1).

²The model can be accessed here: <https://insightmaker.com/insight/2swt92w2TnkTv37vM97BZX/3-machines-release1>.
Note: Insightmaker is a tool for both SD and agent based modelling (ABM). The model uses the SD functionality only.

Figure 1: Overview of the 3-machines energy transition model. Dashed arrows are information flows, solid arrows are power or CO₂ flows. The controller dynamically matches the supply with the demand by measuring their difference Δ and adjusting the various power flows in the energy system according predefined rules.

3.1 Energy system

The fossil engine (fC, Section S1.1) combines all current non-renewable energy conversion technologies (i. e. fossil, nuclear and waste) across all energy sectors (i. e. electricity, mobility and heat) into one single hypothetical thermal power plant producing electricity [31]. It converts fossil fuels into electric energy and emits CO₂ at a constant emission intensity of 5.41 Gt/TW_a, which corresponds to today's emission intensity if all fossil fuels were converted to electricity. Fossil fuel shifts are not considered for simplicity. Initially, the fossil engine operates at a capacity factor $CF_{fC,0} = 0.75$, supplying all of the non-renewable power demand.

The solar engine (PV, Section S1.2) combines all future PV installations and energy storage technologies (e. g. Li-ion batteries [59], hydro-pumped storage [60] or synthetic CH₄ [61]) in a single hypothetical machine [31, 32]. It converts insolation to electric energy with PV technologies and provides a part of the harvested power via storage. For simplicity, no other solar conversion technology (e. g. solar water heating or concentrated solar power) is considered [31]. PV installed on already sealed surface of the built environment can supply 21 TW of annual average power [37]. Only if this is exhausted, additional surface as part of the solar potential in deserts may be utilized [37], which in the model can be specified as the *desert potential fraction*. Hence, the modelled transition doesn't require solar farms on green fields, wind parks or energy forests.

Energy storage allows to be independent from PV supply for a certain period of time, the *independence time*. A larger independence time slows the growth of the solar engine as energy is necessary to build storage. Storing a larger fraction ϕ of solar supply increases storage losses [32] (Section S1.2).

The third machine is a carbon scrubber (CCS, Section S1.3), which draws power from the grid to build its infrastructure and to capture and transfer CO₂ to the lithosphere [62]. It is modelled as post-combustion capture for capturing parts of the emissions from the fossil engine exhaust with a capture efficiency of 90 % [63–65]. It is assumed that 50 % of emissions are generated at stacks where post-combustion is feasible (e. g. power plants, industrial point sources). Furthermore, CCS is modelled as direct air capture (DAC) [66–72], which removes CO₂ directly from the atmosphere. Post-combustion CCS is energetically less expensive to operate ($EI_{pcCCS} = 0.06$ TW_a/Gt [73, 74]) than DAC ($EI_{DAC} = 0.2$ TW_a/Gt Section S1.3), while the embodied energy is approximately the same ($EIT = 0.25$ a Section S1.3). Other negative emission pathways (e. g. reforestation, biochar in soils, bioenergy with carbon capture and storage [75]) are not considered as they may conflict food security and biodiversity when deployed at large scale and depend on agricultural production factors, many of which are already beyond their sustainable limit [12]. In contrast, resource requirements for DAC [72] are not critical and it can be scaled limited only by energy [76]. If powered by the fossil engine, CCS can be operated up to the full installed capacity. Powering DAC

through the solar engine, in contrast, requires either to build and operate storage or it is operated directly from local solar supply. In the latter case, the capacity factor of CCS is restricted to $CF_{\text{CCS}} \leq 0.32$ and CCS overcapacity has to be built. When optimizing for lowest total power demand, CCS is best operated directly through the solar engine (Section S1.3.1). The second best option is to operate CCS through batteries at constant load, however, material requirements for batteries are much more critical [33, 34] than for building DAC overcapacity [72]. Consequently, building DAC overcapacity is not only optimal from an energy but also material perspective. This is, however, in contrast to an economic optimisation, which favors operating DAC near base load [77].

3.2 Power demand

The power demand of society (Section S2) can be changed over time either at fixed growth rates or by following population growth and gradually adjusting per capita demand to a specified target within a specified time (*demand adjustment duration* and *demand adjustment delay time*). Per capita targets can be set, for example, to decent living energy (DLE, $\approx 300 \text{ W/person}$) [78], low energy demand (LED, $\approx 680 \text{ W/person}$) [29] or the 2000-watt-society [79]. Global population forecasts can be considered with a chosen confidence (2.5 %, 10 %, 50 %, 90 % and 97.5 %) according to UN world population prospects 2019 [80].

In 2018, global final power demand in electric energy equivalents was 7.1 TW (932 W/person , with renewable energy (RE) contributing 1.04 TW [31, 51, 81, 82]. The current renewable energy system is assumed to remain constant and not contributing to the transition. Assuming constant per capita demand from 2018 till 2022, the initial demand supplied by the current non-renewable energy system of $P_{\text{demand},0} = 6.3 \text{ TW}$.

3.3 System controller

The system controller matches supply with demand. It measures the difference between supply and demand (i.e. supply gap) and adjusts the capacity factors (CF) of the fossil and/or solar engine accordingly (Section S3). CF is defined here as the fraction of the maximum output power of installed capacity actually supplied³. CF can range between $CF \in [0, 1]$. In certain simulation runs, supply collapses irrecoverably, e.g. when there is not enough power available to maintain the required installed capacity. The system controller also governs the power invested for building and replacing installed capacity of all three machines as well as for operating CCS. Energy investments provided by the fossil engine can be controlled with the *fossil investment* factor $\beta \in [0, 1]$, describing the fraction of the maximally available idle capacity to be invested. During the transition, the solar engine can grow with its own supply or it can replace fossil output, which is adjusted with the *fossil replacement* factor $\alpha \in [0, 1]$. Power is allocated first to satisfy society's demand, second to maintain the fossil engine's installed capacity during the transition, third to build and maintain the solar engine and last to build, operate and maintain CCS.

Smaller time steps improve the quality of the control, as the controller can react faster to changes in the system. Transients shorter than $< 1 \text{ a}$ are artefacts of the simulation and have no direct translation to the real world.

3.4 Carbon cycle

The energy system is linked to a elementary carbon cycle (Section S4). The operation of the fossil engine releases CO_2 from the lithosphere to the atmosphere. Part of these emissions are absorbed by upper oceans within a short time [83, 84] and are released back in the event of falling atmospheric CO_2 concentrations [53]. The carbon transfer to the deep ocean is slow compared to the time period of interest for this study and thus omitted. This behaviour is modelled with a combined CO_2 stock for the atmosphere and upper oceans. CO_2 is removed to the lithosphere through (i) a constant natural leak (i.e. sedimentation and weathering) of 0.8 Gt/a [84–86] and (ii) CCS.

³For solar PV, capacity factors are often provided in regard to nameplate capacity (“peak” power), however, the maximum output capacity is lower and depends on the location. Nominal capacity of PV is the maximum annual energy supply, i.e. without curtailment.

4 Simulation experiments

Figure 2: Evolution of simulation experiments: a graphical overview of dependencies (inheritance indicated by “number+”). See also Fig. S16.

Using the 3-machines energy transition model, various pathways are evolved (Fig. 2), exploring narratives ranging from “continued fossil growth” to “reaching 350 ppm before the end of this century”. Pathways are evaluated against peak cumulative CO₂ emissions, which correlate with induced peak heating [22], as well as against cumulative exceedance of 350 ppm throughout the simulation period, which can be seen as a proxy for the climate-induced pressure on ecosystems. All simulation experiments cover the time period beginning of 2022 until beginning of 2100 (i.e. 78 a), to test if the climate could be stabilized before the end of this century [7, 13, 87]. The integration time step is chosen 0.1 a.

Starting with ① *fossil baseline*, energy demand grows exponentially at a growth rate of 3 % per year (Fig. 4). It increases more than five-fold and reaches over 33 TW in 2100. This demand is satisfied by the fossil engine alone, requiring it to grow together with demand. As a consequence, cumulative CO₂ emissions grow exponentially, reaching almost 10 000 Gt in 2100 and surpassing 1.5 °C with 50 % confidence within 10 a (Fig. 3).

Testing the capabilities of the fossil engine, energy demand shrinks in scenario ② *fossil degrowth*. This is to answer the question: “Is demand reduction alone effective in reaching climate targets?” Reducing

Figure 3: Cumulative CO₂ emissions since 1850 over the simulation period (2022 to 2100). Cumulative emissions correlating with 350 ppm and 450 ppm, as well as 1.5 °C heating with 50 % probability are shown as horizontal lines. The range of IPCC scenarios targeting 1.5 °C and 2 °C heating is indicated with the solid black line (mean) and the shaded light grey area (most ambitious and least ambitious pathways) [24]. For scenario descriptions (colored lines), refer to the text.

demand exponentially by $-3\%/a$, shrinks the demand to $1/5$ or 1.9 TW in 2100 (i. e. about 200 W/p, which is below minimal energy requirements per person for a decent life [78]). Still, cumulative CO₂ emissions rise to almost 3700 Gt in 2100, surpassing 1.5 °C with 50 % around 2037. Even when sacrificing a decent life, shrinking fossil demand alone is insufficient to stabilize the climate.

In scenario ③ *fossil CCS*, energy demand is held constant and a carbon scrubber is added to the fossil engine. It still leads to an almost linear growth of cumulative CO₂ emissions (Fig. 3) because building and operating the carbon scrubber requires additional power. This power has to be provided by the fossil engine, increasing CO₂ emissions and canceling negative emissions to a large extent. Scenarios ① - ③ show that the fossil engine alone is neither able to comply with the 1.5 °C nor with the 350 ppm goal, confirming that fossil fuels cannot have a future.

Switching off the fossil engine immediately, however, would collapse power supply, as today's renewable energy system is not yet capable to replace it. Consequently, the fossil engine is necessary for the construction of the new solar engine. Scenario ④ *PV* aims to find the fastest possible transition, replacing the fossil with the solar engine. Demand is kept constant and CCS as well as energy storage are excluded. Maximum fossil investment and no fossil replacement during the transition [31] results in the fastest possible transition. Transition completes within 4 a and exceeds 1.5 °C global heating [22] with 8 % probability (Tab. S5). Because all PV panels have similar and narrowly distributed lifetimes [50], they have to be replaced about the same time after the transition completed. This leads to repeating replacement cycles, which necessitate to build overcapacity of the solar engine.

An exponentially growing energy demand during and after the transition, scenario ⑤ *PV growth*, is feasible until about 2080. Thereafter supply collapses (Fig. 4) if solar PV capacity is restricted to the already built environment. The same limit is reached for a global 2000 W society (⑥ *PV 2000W*). However, extending PV installations to desert areas could prevent supply collapse when demand approaches 21 TW. Growing demand during the transition prolongs transition time, as less power is available to build solar capacity and the fossil engine needs to be grown in addition. Consequently, this increases cumulative CO₂

Figure 4: Power diagrams for each scenario. For a description of scenarios, see text. Lines show the output for a machine and shaded areas the idle capacity for each machine: fossil engine (grey), solar engine (green) with storage losses (blue) and CCS (purple). Orange line indicates the demand from society and red shaded areas show shortages in supply, i.e. when supply falls below demand.

Figure 5: Maximum cumulative CO₂ emissions from 2022 until 2100 vs. cumulative exceedance of 350 ppm from 2022 until 2100. Inlay (right bottom) shows the whole range of results and the cumulative distribution function (CDF, right axis) of the probability to violate 1.5 °C (orange) and 2 °C (red) peak heating [22]. Fossil scenarios (blue) are the highest, transition scenarios from fossil to PV with and without storage (orange) show similarly low cumulative emissions as scenarios including CCS (purple and green). The latter have significantly lower cumulative exceedance. The optimum scenario is (17) CCS with 300 W/p (lower left corner). Fig. S18 shows the same data for probability to exceed 1.5 °C global heating [22] over cumulative exceedance of 350 ppm. Numerical results are provided in Tab. S5.

emissions (Fig. 5).

In scenario ⑦ *PV 300W*, per capita demand is reduced within 14 a from today's 930 W/p to 300 W/p, which is considered the minimal average power required for a decent life [78]. The resulting transition is slightly faster, reducing cumulative emissions and the probability to exceed 1.5 °C to 5%. The effect on the climate is small, because the transition completes before most of the demand reduction is realized.

Even though global insolation is constant, the local irradiance is not. Therefore, energy storage is needed to smooth daily and seasonal solar and weather patterns [32]. Due to the considerable energetic costs of storage, demand for it is decisive for the energy transition [32, 88, 89]. In scenario ⑧ *PV storage*, storage with an independence time of 0.01 a (half a week) and providing $\phi = 0.5$ of daily demand through storage is added to scenario PV ④. Storage is provided as a mix of the three storage technologies: lithium-ion battery (electro-chemical) and pumped-hydro storage (mechanical) cover 40% each, while synthetic methane (chemical) covers the remaining 20%. This scenario exceeds 1.5 °C with 25% probability, highlighting the strong influence storage has on the transition [32].

Consequently, reducing both storage capacity and amount of stored energy has a profound effect on the transition [32]. In scenario ⑨ *PV less storage*, independence time is reduced to $\Delta t_i = 0.0016 \text{ a} = 14.5 \text{ h}$, which is minimally necessary to level out daily variations in solar supply and the fraction of daily demand stored is reduced to $\phi_d = 0.1$, aligning most of society's demand with solar supply [32]. This reduces the probability to exceed 1.5 °C to 10%, close to the fastest transition without storage (④ *PV*).

The scenarios ④ to ⑨ show that fast and complete transitions can limit global heating to below 1.5 °C with a confidence > 50% [31, 32]. This requires to increase the output of the fossil engine to grow the

solar engine. The size and type of storage is essential: less storage is better for the climate [32]. Yet, a transition to a fossil-free society alone cannot return the atmospheric CO₂ concentration to below 350 ppm within this century. This requires to build and operate the carbon scrubber (CCS).

In scenario (10) *CCS*, CCS is built and operated with idle solar PV capacity after the transition (9) is completed. Thus, it has no effect on the transition itself and therefore also no effect on peak cumulative CO₂ emissions. To avoid additional energy storage, CCS is only allowed to operate with solar power directly, thus limiting the capacity factor of the carbon scrubber to $CF_{CCS} \leq 0.32$ (Section 3 and S1.3.1). This requires more CCS capacity (see purple area in Fig. 4), however, this is energetically cheaper than additional storage (Section S1.3.1). After the transition is completed, the solar engine is kept growing until its capacity reaches the limited area of the built environment. The resulting overcapacity is used to build and operate CCS so that the clean-up can be completed before the first replacement cycle of the solar engine around 2050. After the clean-up is completed, overcapacity may be maintained (green area in Fig. 4) to increase demand and storage.

When adjusting demand to 2000 W/p ((11) *CCS 2000W*), the clean-up takes more than a decade longer, because there is less power available. Cumulative exceedance is 23 % higher than when demand remains constant (10) (Fig. 5 and Tab. S5). When adjusting demand to 300 W/p ((12) *CCS 300W*), solar capacity does not have to be built to its limit, which helps to preserve resources, as more power is available for CCS and clean-up can still be completed in 2054. Increasing the demand for storage in a 300 W/p society ((13) *CCS 300W S+*) to $\Delta t_i = 0.02$ a, i. e. one week, and $\phi_d = 0.5$, increases the probability to exceed 1.5 °C to 31 % and cumulative exceedance by 40 % relative to (10). In contrast, a 2000 W/p society with high storage and using 20 % of deserts' PV potential ((19) *CCS 2000W S+ PV+*) will exceed 1.5 °C heating with 56 % probability and increase cumulative exceedance by 70 % relative to (10). Although developing PV in deserts is challenging for many reasons [90–92], it cannot fundamentally change the dynamics of the transition. High energy demand above 1600 W per capita become possible, yet it cannot reduce the probability to exceed 1.5 °C peak heating. The clean-up may be accelerated only if energy demand is constant or shrinking. Therefore, PV in deserts is excluded in the following scenarios.

Power demand per person can still increase to 1400 W/p ((15) *moderate demand*) at moderate storage of $\Delta t_i = 0.01$ a and $\phi = 0.3$, which, however, delays the clean-up until 2073. Consequently, the probability to exceed 1.5 °C is 32 % and cumulative exceedance increases by 60 % relative to (10). Reducing storage demand to $\Delta t_i = 0.0016$ a and $\phi_d = 0.1$ in scenario (16) *sunflower*, reduces the probability to exceed 1.5 °C to 16 %, while cumulative exceedance increases only by 17 % relative to (10), even though energy demand can be increased to 1600 W/p (Fig. 5). Aligning energy demand with solar supply in order to minimize the demand for storage is an effective strategy to improve climate protection as well as increase energy demand.

Instead of performing the clean-up as a subsequent step to the transition, it is also possible to start CCS in parallel to the transition ((17) *early CCS*). For simplicity, post-combustion capture can be deployed during the transition, even though in reality, this CCS infrastructure would need to be adapted or rebuilt as DAC after the transition ended. Despite this simplification in favor of early CCS, it increases both cumulative exceedance (70 % above (10)) and cumulative emissions increasing the probability to exceed 1.5 °C to 28 % (Fig. 5). Combining sunflower (16) with early CCS ((18) *sunflower with early CCS*) also leads to lower probability to exceed 1.5 °C of 12 %, yet higher cumulative exceedance by 25 % compared to (10) than when CCS starts after the transition (16). This shows that CCS shall only be operated after the transition is completed.

Finally, we define scenario (19) *sunflower LED*, which aims at a power demand per person of 680 W/p, proposed as a low energy demand (LED) scenario by Grubler et al. [29]. Storage independence time is set to two days ($\Delta t_i = 0.005$ a, while 20 % of power is provided through storage. Part of the fossil output is replaced already during the transition, which allows for a smoother phase out of the fossil engine. This leads to a similar climate performance than sunflower (16) (Fig. 5) with lower energy demand per person but higher energy storage. Considering population prospects with 97.5 % confidence [80] ((20) *sunflower LED pop+*), the results are very similar to scenario (19). This is due to the fact that the population uncertainty is small in the near future when both the transition and the clean-up take place.

5 Conclusion

In this article, we presented the 3-machines energy transition model designed to find the energy frontiers for the energy transition and clean-up excess CO₂. As shown by the various simulation experiments,

stabilising the climate through limiting global heating to 1.5 °C with > 50 % probability and reducing atmospheric CO₂ concentration below 350 ppm remains still possible within this century, at least from an energy perspective. This, however, requires a novel strategy: first increasing fossil emissions to the maximum capacity of the fossil engine with the sole purpose of building solar capacity fastest; and second, switch off the fossil energy system as soon as the solar engine is big enough and power DAC at a massive scale to return to 350 ppm soonest. In contrast to most proposed pathways, CCS is not part of the transition, but a major activity for the subsequent clean-up phase. During both phases of the transformation, energy demand and demand for storage needs to be as low as possible, following the idea of a sunflower society, aligning demand with solar supply [32]. Though possible, this would require a fundamental rethinking of our society:

Reduce energy demand per person. The higher the global average energy demand per person, the more difficult it gets to manage the transition within the constraints of the Earth system. Lowering the energy demand below today's average helps for the clean-up but not much for the transition itself. Furthermore, it is limited by the minimum energy demand for a decent life [78, 93, 94]. Energy demand per person shall ideally reduce to somewhere around 600 W/p until the clean-up of CO₂ in the atmosphere is completed. Afterwards it may safely increase. Today, energy demand is distributed unequally across the globe. Therefore, individuals and countries with a high energy demand have the moral imperative to reduce most (e.g. by a factor of ten for the average Swiss citizen), allowing those living in energy poverty today [94] to increase energy use up to this new global average. In conclusion, *energy demand should be reduced as much as possible during the transition and clean-up, with the prospect of increasing energy supply significantly once the climate is stabilized.*

Minimize energy storage. Storage is the second critical driver in the system, as it influences both the attainable speed of the transition as well as the necessary overcapacity of PV to provide for storage losses [32]. Independence times beyond three days seem unattainable during the task of stabilizing the climate. Synthetic fuels may play only a minor role as a storage technology due to their low round-trip efficiency. Individual motorized transport, air traffic and shipping powered by combustion of synthetic fuels may at best be continued at much reduced levels. Again, after the climate is stabilized, energy storage may safely increase, adding convenience in society. However, *during the transition and carbon removal, society will need to align energy demand to renewable supply to minimize the demand for storage, i. e. implement a sunflower society* [32].

Massive negative emissions. CCS is inevitable for removing excess CO₂ from the atmosphere. From a climate perspective, however, its operation only makes sense when powered with solar energy. Otherwise, removed CO₂ is offset by the increased fossil emissions resulting from the increased power output of the fossil engine and the energy transition slowed down. *Hence, CCS needs to be powered directly with PV without energy storage when the transition is completed*, as building CCS overcapacity is energetically less expensive than building and operating storage (Section S1.3.1, purple areas in Fig. 4).

No new fossils. Even though the fossil engine needs to operate at maximum capacity during the transition, no new fossil capacity needs to be installed. The currently installed capacity of the fossil engine is more than sufficient to power fast transitions. Consequently, there is no need to build any additional fossil capacity also not for fossil fuel shifts (e.g. from coal to gas). Still, in case of a gradual shut down (as in (13), (19) and (20)), power plants with the lowest CO₂ intensity should switch off last. Furthermore, the vast majority of proven fossil reserves need to stay in the ground [95], as the amount of fossil fuels required during the transition is in the order of seven to eight annual productions only [19] (Tab. S5).

Future research will need to investigate the energy implications of transforming other climate relevant sectors, e.g. agriculture, and new infrastructures due to demand changes, e.g. public transport, and thus their effect on the energy frontier for climate action. Beyond energy and greenhouse gases, the mobilisation of materials for building the necessary infrastructure, e.g. Ag in solar PV [96], may further limit the attainable speed of the transformation. The here proposed strategies will need to be investigated in more detailed models in order to validate and derive more concrete action plans (see Section S8).

To conclude, the simulation experiments show that much more ambitious transformation pathways are energetically possible than considered by IPCC. At least energetically, atmospheric CO₂ concentration

can be reduced to below 350 ppm well before the end of this century. Yet, the probability to exceed 1.5 °C global peak heating can no longer be kept below 5 %. This would be unacceptably high for other fields e. g. aircraft design or vaccine safety [31]. It seems all the more important to follow the most ambitious pathway, safeguarding the climate for future generations as best as we can. Bringing these transformations to life requires creating new visions and narratives collaboratively across the globe, portraying a desirable and equitable life with reduced energy demand, minimal storage, massive negative emissions and a fast and complete transition.

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Supplementary materials to “The 3-machines energy transition model: exploring the energy frontiers for restoring a habitable climate”

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This section provides details of the modelling rationale, the implemented structure in InsiGhtMaker [55] as well as additional figures. The entire model implemented in InsiGhtMaker is available online under <https://insightmaker.com/insight/2swt92w2TnkTv37vM97BZX/3-machines-release1>.

S1 Energy system

Figure S1: Energy system module structure

Each of the three machines in the energy system consists of a stock of energy, i.e. embodied energy. This embodied energy is increased by power $P_{\text{build},X}$ to grow the engine and decreased by an end-of-life process. End-of-life is modelled as a two step outflow of power from the embodied energy stock: First, the embodied energy is transferred to a sub-compartment of the embodied energy ($E_{X,2}$) after a fixed time span (i.e. after the minimum lifetime $t_{L,X,\text{min}}$). From this sub-compartment, the end-of-life outflow is a third order delay function from the inflow into this sub-compartment, determined by the time difference between the average $t_{L,X,\text{avg}}$ and minimum lifetime. In this way, the engine does not die out immediately, but over an extended period of time. In other words, not every building block of the engine has the same lifetime. The construction of the machine is delayed by a first order delay by the construction delay time

($\Delta t_{\text{construction delay}}$), representing the construction time from commissioning to start of operation. This delay is smoothing also abrupt changes in the system.

Figure S2: Machine structure: relation between embodied energy and nominal (installed) capacity as well as end-of-life modelling of a machine X .

The installed capacity of each engine is proportional to the embodied energy with the *energy payback time* (EPBT):

$$P_{\text{nom},X} = \frac{E_X}{EPBT_X} \quad (1)$$

The *capacity factor* (CF) of each engine determines the fraction of nominal power that is delivered to the grid:

$$P_{\text{op},X} = LF \cdot P_{\text{nom},X} \quad (2)$$

CF can be adjusted by the system controller to ensure that the energy system meets the demand from society.

The energy grid (E_{TechS}) is modelled as a stock which collects and distributes power. The value of the stock is in the model proportional to the supply to society, however, it has no physical function or interpretation in reality. Removing this stock from the model is possible and does not change any of the results. However, representing the grid as a stock is more intuitive and, as it doesn't have an influence on the results, it remains part of the model.

S1.1 Fossil engine

Figure S3: Fossil engine phase out module structure

The *energy payback time* (EPBT) for fossil power plants is about $EPBT_{fC} = 3$ a (see⁴). With this, the embodied energy of the fossil engine is initialized to $E_{fC}(t = 0) = 25.2 \text{ TWa}$. This initial stock of the fossil engine is modelled to die out according to an exponential decay, as the age of each individual power plant is not modelled. Any newly build fossil capacity is added to a “new” stock and its end-of-life modelled according to the general model (see Fig. S2).

New fossil capacity is build for two reasons:

⁴<https://publications.parliament.uk/pa/ld200304/ldselect/ldsctech/126/12620.htm>

1. replacement of end-of-life capacity (*repair*): only happens when the repair switch fC_repair is turned on, the transition is not completed and the load factor of the fossil engine $CF_{fC} > 0$ (i.e. the fossil engine is still in operation). Repair of the fossil engine (if switched on) can only be equal to EoL.
2. growth: the fossil engine can be grown to meet a growing demand in society (*delta for growing with demand*) or explicitly (e.g. for building and operating the carbon scrubber, *delta in transition*).

No fossil fuel shifts (e.g. coal/oil $\rightarrow$ gas) are considered in the model. The simulation starts with the fossil engine delivering the required 6.3 TW of annual final power to society (Section S2). The installed capacity is $P_{nom,fC} = 8.4$ TW, considering that the capacity factor of current power plants as $CF_{el} = 0.5$ [97] and electricity constitutes around 40 % of total final energy [31, 81]. As the fossil engine comprises also mobility and heat sectors in the model, the initial CF starts with $CF_{fC} = 0.75$.

S1.2 Solar engine

Direct solar energy conversion is commonly underestimated in IAMs [41], despite having the largest potential within Earth system boundaries and considering the chemical energy demand of society [37]. Additionally, most other renewable energy resources (e.g. wind, hydro or biomass) are close to or already beyond their environmentally safe limits and can therefore not significantly contribute to replacing the fossil engine [31, 98]. In this model, the solar engine is thus entirely based on photovoltaic (PV) technology. The installed capacity is limited to $ATP_{PV,built\ environment} = 21$ TW, which is the safe limit on already sealed surfaces of the built environment, or up to $ATP_{PV} = 70$ TW when including parts of the world's deserts (confidence: 99 %) [37]. The parameter *desert potential fraction* defines the fraction of the desert potential, which may be developed.

Figure S4: PV repair module structure

A rapid initial growth of the solar engine causes very high power demand during the first and second replacement cycles, which may be difficult/impossible to provide once the fossil engine is shut down. The model allows for the following repair/replace options: First, the solar engine is repaired on demand, similar to the fossil engine, i.e. end-of-life capacity is replaced instantaneously. A second strategy is to build replacement ahead of time, i.e. after the transition is completed and before the initial installation reaches end-of-life. This *preventative maintenance* can be adjusted proportionally to the installed capacity and inversely proportional to the oversize of the solar engine relative to required demand.

$$P_{repair,PV} = \zeta_{PV,repair,inv.prop} \frac{1 \text{ (TW)}^2}{P_{nom,PV} - P_{demand,req}} + \zeta_{PV,repair,prop} \frac{E_{PV}}{T_{PV,res}} \quad (3)$$

EPBT for solar energy is set by technological parameters of PV systems and taken here as $EPBT_{PV} = 1.5$ a [31, 57, 99–102]. Technological improvements reducing embodied energy demand [56, 57] are not considered here, as in fast transitions the energy learning may not materialize [32].

S1.2.1 Storage as part of solar engine

Direct solar energy conversion is inherently variable, following cyclical daily and seasonal patterns. Additionally, weather events (e.g. extended periods of cloud coverage) make the variability less predictable. There are two basic ways to manage non-matching supply:

- *demand management*: electricity is consumed when the sun shines [32]. This strategy may appear inconvenient but is the most effective environmentally, as it does not require any additional infrastructure. For certain energy uses, this strategy is possible (e.g. washing machine); for others not (e.g. lighting). Depending on the extent society is willing to shift its demand to sunshine hours, storage options are necessary.
- *storage* (mechanical, electro-chemical, chemical or thermal [103]): requires to build infrastructure (e.g. hydro reservoirs, batteries, synfuel plants) and inflicts energy losses (limited round-trip efficiency for charging-discharging cycles).

Storage independence time ranges from zero (i.e. no storage, perfect alignment of energy demand with solar supply) to several months, fully balancing seasonal variations (i.e. constant supply at any moment throughout the year) [32].

Different storage technologies can be combined by giving relative weights to the three storage types in the model: mechanical, chemical and electro-chemical (see Section S1.2.3).

Storage has to provide the fraction ϕ of demand throughout a chosen independence time Δt_i [32]. Storage capacity $E_{\text{storage capacity}}$ therefore needs to be:

$$E_{\text{storage capacity}} = \Delta t_i \cdot \phi \frac{P_{\text{demand,stored}}}{\eta_{\text{out}}} \quad (4)$$

This required storage capacity is built during the transition alongside with the solar engine. During the transition, the storage size is proportional to solar capacity. Once it reaches the required size to fulfill ϕ for demand by society, it remains proportional to demand only.

Compensation for storage losses is the second power demand of storage. It depends on the round-trip efficiency η and the fraction of demand ϕ , which is actually stored. This fraction has two components: first, daily storage, which is a function of how well the annual average of daily demand follows solar supply [32]; second, seasonal storage, which is modelled proportional to independence time $\Delta t_i > 0.0016$ a.

S1.2.2 Energy storage relationships

Energy storage options are modelled as a combination of three exemplary storage technologies (i.e. Li-ion batteries [59], pumped hydro storage [60] and synthetic CH_4 [61]). The relevant parameters energy intensity of storage capacity EI_{storage} and round-trip efficiency η are defined and related as follows [32]. Energy intensity of storage capacity (dimensionless):

$$EI_{\text{storage}} = \frac{E_{\text{embodied}}}{E_{\text{storage capacity}}} \quad (5)$$

E_{embodied} ... embodied energy in electric energy equivalents
 $E_{\text{storage capacity}}$... nominal storage capacity in regard to stored output energy

Round-trip efficiency η (excluding embodied energy input per output, as this is already accounted for in EI_{storage}):

$$\eta = \frac{E_{\text{el,out}}}{E_{\text{el,in}}} = \frac{E_{\text{el,out}}}{E_{\text{el,stored}}} \frac{E_{\text{el,stored}}}{E_{\text{el,in}}} = \eta_{\text{out}} \cdot \eta_{\text{in}} \quad (6)$$

$E_{\text{el,out}}$... electric energy output (for an average charge cycle or over whole lifetime)
 $E_{\text{el,in}}$... electric energy input necessary to provide the output
 $E_{\text{el,stored}}$... electric energy stored in storage technology

S1.2.3 Mixing energy storage technologies

Three exemplary energy storage options are modelled explicitly: mechanical, chemical and electro-chemical. The parameters *energy intensity* EI , *round-trip efficiency* η and *output efficiency* η_{out} can be chosen to reflect specific technologies or sets of technologies in the respective categories. The three storage technologies are mixed together according to the relative weight ζ specified by the user. If the sum of these weights is zero, each technology is weighted equally, i.e. $1/3$. In all other cases, the fraction for each technology is set by the relative weight divided by the sum of all relative weights.

The combination of the three storage technologies leads to weighted parameters η and EI as follows:

$$\eta = \frac{1}{\frac{\zeta_M}{\eta_M} + \frac{\zeta_C}{\eta_C} + \frac{\zeta_E}{\eta_E}} \quad (7)$$

$$\eta_{\text{out}} = \frac{1}{\frac{\zeta_M}{\eta_{\text{out},M}} + \frac{\zeta_C}{\eta_{\text{out},C}} + \frac{\zeta_E}{\eta_{\text{out},E}}} \quad (8)$$

$$EI = \eta_{\text{out}} \left(EI_M \frac{\zeta_M}{\eta_{\text{out},M}} + EI_C \frac{\zeta_C}{\eta_{\text{out},C}} + EI_E \frac{\zeta_E}{\eta_{\text{out},E}} \right) \quad (9)$$

S1.3 Carbon scrubber

Carbon capture and storage (CCS), here understood as any technology capturing CO_2 either from stack (post-combustion) or from the atmosphere [62], is necessary to reduce atmospheric CO_2 concentration to 350 ppm within this century. However, this comes at substantial energy costs.

Figure S5: CCS module structure

CCS can either be post-combustion using fossil power plants' exhaust [63–65]; or direct air capture (DAC) [66–71] removing directly from the air. The main difference in the two methods is the energy requirement for capturing CO_2 . For post combustion capture from flue gas, CO_2 is at a much higher concentration than in the atmosphere, which reduces the energy demand. Post-combustion capture has a capture efficiency of about 90 % [63–65, 74] and we estimate that it can be implemented for a maximum of 50 % of all fossil emissions, as many point-sources are decentralized (e.g. domestic heating systems) or mobile (e.g. cars, aircrafts). As long as fossil power plants are operated, the carbon scrubber removes concentrated CO_2 from their stacks. The energy intensity of post-combustion capture is approximately $EI_{\text{CCS}} = 0.06 \text{ TWa/Gt}$ [73, 74]. Any emissions in excess of the fraction capturable at stack need to be removed from the atmosphere.

The energy intensity of DAC is generally lower for low temperature DAC (operating at $\approx 100^\circ\text{C}$) with about $EI_{\text{ltDAC}} = [0.06, 0.15] \text{ TWa/Gt}$ [70, 73, 76, 104]; than for high temperature DAC (operating at $\approx 900^\circ\text{C}$) with about $EI_{\text{htDAC}} = [0.17, 0.31] \text{ TWa/Gt}$ [69, 70, 104]. Thermal energy is thereby converted to electric energy equivalents through a heat pump with $COP_{\text{ltDAC}} = 3$ for ltDAC and direct conversion (i.e. $COP_{\text{htDAC}} = 1$) for htDAC. For our simulation experiments we use a value of $EI_{\text{DAC}} = 0.2 \text{ TWa/Gt}$.

The carbon scrubber differs from the other two machines in that it does not feed power into the grid. It draws power for both its growth (embodied energy) and its operation (i.e. removal of CO_2 from the atmosphere). It does not have an energy payback time EPBT, but an *energy investment time* (EIT) instead, which is the time the CCS machine has to be operated at full capacity until the operational energy over this time interval equals the embodied energy. We estimate EIT using the inventory of a high temperature DAC facility [69] and the operational power demand for a wide range of low and high temperature DAC systems [69, 70, 73, 76, 104]. For simplicity, we do not consider the differences in plant design of high or low temperature DAC or post-combustion CCS, assuming they would be similar in terms

of material demand. This yields $EIT = [0.05, 0.25]$ a, of which we use, in precaution and equally for DAC and post-combustion CCS, the upper limit for our simulation experiments.

Any idle capacity in the energy system can be used to grow and operate the carbon scrubber. It is designed to grow as long as there is idle capacity available. If CCS is operated through power from the fossil engine, it can be run up to its maximum capacity. When operated through the solar engine, it can only be operated to 32 % of its nominal capacity. This is because it is then operated through solar power directly, not requiring storage (Section S1.3.1).

S1.3.1 CCS vs. energy storage

In this model, CCS is operated with the solar engine without storage. Therefore, the maximum average capacity factor is limited to $CF_{CCS, \max} = 0.318$, i.e. 32 % of the nominal installed power can be operated average over the day. Alternatively, there is also the possibility to operate CCS at full capacity and provide solar power through storage. This requires to build and operate additional storage.

Removing CO_2 from the atmosphere uses $EI_{\text{DAC}} = 0.2 \text{ W}/\frac{\text{kg}}{\text{a}}$ of operational power $P_{\text{CCS, operational}}$. To build the necessary infrastructure, additional power $P_{\text{CCS, embodied}}$ is necessary:

$$P_{\text{CCS, embodied}} = \frac{P_{\text{CCS, operational}}}{CF_{\text{CCS}}} \frac{EIT_{\text{CCS}}}{t_{\text{L, CCS}}} \quad (10)$$

$$EIT_{\text{CCS}} \dots \text{Energy investment time for CCS} \quad (11)$$

$$t_{\text{L, CCS}} \dots \text{Lifetime of CCS infrastructure} \quad (12)$$

If operational power is provided through storage, storage losses and embodied energy for required storage capacity have to be provided in addition by the solar engine [32].

$$P_{\text{solar supply to CCS}} = P_{\text{CCS, operational}} \left(1 + \phi_{\text{CCS}} \left(\frac{1}{\eta} - 1 \right) \right) \quad (13)$$

$$P_{\text{storage, CCS, embodied}} = P_{\text{CCS, operational}} \frac{\phi_{\text{CCS}}}{\eta_{\text{out}}} \cdot \frac{\Delta t_i}{t_{\text{L, storage}}} \cdot EI_{\text{storage}} \quad (14)$$

$$P_{\text{CCS, total}} = P_{\text{solar supply to CCS}} + P_{\text{storage, CCS, embodied}} + P_{\text{CCS, embodied}} \quad (15)$$

In Tab. S1, a comparison between the total power required for CCS per unit of mass flow for four scenarios is provided using the formulae introduced in this section and data from the 3-machines model. The first scenario is without storage, as it is implemented in the model. The latter three scenarios include storage in such a way, that CCS can be operated at full nominal power (i.e. $CF_{\text{CCS}} = 1$). For these scenarios, the fraction of operational power for CCS needed to be stored is $\phi_{\text{CCS}} = 0.6$ and independence time $\Delta t_i = 14.5 \text{ h} = 0.0016 \text{ a}$ [32]. As can be seen in Tab. S1, the scenario without storage has the lowest power requirement per mass flow of removed CO_2 .

It is, thus, energetically more expensive to provide power through storage to operate CCS continuously than operate it intermittently when solar supply is available, avoiding storage altogether. This justifies the implementation in the 3-machines model.

S2 Demand

Humanity's demand for annual average power is the required output of the energy system. In 2018 global final power demand in electric energy equivalents was 7.1 TW (932 W/person, with renewable energy (RE) contributing 1.04 TW [31, 81, 82]). The current renewable energy system does not have to be replaced and is assumed constant thereafter. Furthermore, it consists of mainly RE other than PV, which are globally at or above their sustainable potentials [37]. Therefore, the current RE system is excluded in this model and does not contribute to the transition nor CO_2 clean-up. Leaving the demand per person constant until the start of the transition beginning of 2022, leads to a initial demand from the still non-renewable energy system⁵ of $P_{\text{demand, 0}} = 6.3 \text{ TW}$. Starting from there, power demand from society can either follow a specified trajectory or transition towards a target for power demand per person.

Different trajectories for power demand can be defined (Fig. S7). Exponential propagation is set as a default; which can model continued growth ($\text{growth rate} = 0.03$), constant demand ($\text{growth rate} = 0$) or

⁵Non-renewable energy includes all fossil energy, nuclear and waste resources.

Table S1: Comparison of removing CO₂ from the atmosphere without and with storage

Name	Variable	Unit	no storage	with electro-chemical storage	with mechanical storage	with chemical storage
DAC energy intensity	EI_{CCS}	$\text{W}/\frac{\text{kg}}{\text{a}}$	0.2	0.2	0.2	0.2
CCS energy investment time	EIT_{CCS}	a	0.25	0.25	0.25	0.25
lifetime CCS	$t_{\text{L,CCS}}$	a	20	20	20	20
maximum capacity factor CCS	CF_{CCS}	—	0.32	1	1	1
fraction of operational power for CCS stored	ϕ_{CCS}	—	0	0.6	0.6	0.6
independence time CCS operations	Δt_i	a	0	0.0016	0.0016	0.0016
storage round-trip efficiency	η	—		0.94	0.76	0.21
storage output efficiency	η_{out}	—		0.97	0.90	0.50
storage energy intensity	EI_{storage}	—		259	85	63
lifetime storage	$t_{\text{L,storage}}$	a		10	80	20
operational power for CCS	$P_{\text{CCS,operational}}$	$\text{W}/\frac{\text{kg}}{\text{a}}$	0.2	0.2	0.2	0.2
nominal power of CCS	$P_{\text{CCS,nominal}}$	$\text{W}/\frac{\text{kg}}{\text{a}}$	0.63	0.2	0.2	0.2
power to supply embodied energy of CCS	$P_{\text{CCS,embodied}}$	$\text{W}/\frac{\text{kg}}{\text{a}}$	0.0079	0.0025	0.0025	0.0025
solar supply to CCS	$P_{\text{solar supply to CCS}}$	$\text{W}/\frac{\text{kg}}{\text{a}}$	0.20	0.21	0.24	0.65
power to supply embodied energy of storage	$P_{\text{storage,CCS,embodied}}$	$\text{W}/\frac{\text{kg}}{\text{a}}$	0	0.0051	0.0002	0.0012
total power required for CCS	$P_{\text{CCS,total}}$	$\text{W}/\frac{\text{kg}}{\text{a}}$	0.21	0.22	0.24	0.66
relative total power		—	1	1.04	1.16	3.15

Figure S6: Demand module structure

Figure S7: Power demand for all scenarios.

degrowth ($growth\ rate < 0$). The second option is the adjustment from current demand per person of 932 W/p to a specified target within a defined time period.

World population is modelled according to UN population prospects 2019 [80]. The model allows to choose between five different levels of confidence for the estimate $P_{pop} = \{0.025, 0.1, 0.5, 0.9, 0.975\}$, which means that a fraction of P_{pop} of all population estimates lie below the specific projection. Population prospects influence the power demand for society.

S3 System controller

S3.1 PID controller

A proportional-integral-differential (PID) controller is used to ensure that supply meets society's demand. It adjusts power output of the fossil and solar engines by modulating their capacity factors (CF). The fossil engine's capacity factor is modulated and the CF of the solar engine is kept at one (i.e. no curtailment) during the transition. When the transition is completed, the solar engine takes over the entire supply and is adjusted to match supply and demand.

The difference in CF (ΔCF) for both PV and fC is integrated to determine the respective CF. As CF has to be in the interval between $CF = [0, 1]$, the integration is capped by an outflow compensating excess inflows.

For certain parameter settings, the parameters of the PID controller need to be tuned to stabilize the supply to society. Making the model more user friendly, a more advanced control strategy may be implemented in the future.

S3.2 Additional demand control

Idle capacity in the system can be used to power additional demand for growing and operating the three machines. Idle capacity is thereby distributed hierarchically (Fig. S9).

During the transition, the first priority for additional demand is on growing the fossil engine if necessary. This is needed to maintain the fossil engine large enough to provide society's demand at all times during the transition. The fossil engine can be grown using a fixed fraction of idle capacity ($\delta \in [0, 1]$) or in case the fossil engine's nominal capacity is smaller than oversize factor times demand, it can use a fraction proportional to the deviation ($\delta_{for\ growing\ with\ demand}$).

The second priority is on growing the solar engine. The parameter $\beta \in [0, 1]$ defines the share of the remaining free capacity (after the growth demand of the fossil engine is subtracted) invested in the growth of the solar engine. Additionally, the solar engine can grow directly proportional to its size by investing a fraction of its harvested energy ($\alpha \in [0, 1]$) into its own growth (i.e. leading to exponential growth) [31].

The last priority is given to the carbon scrubber. A fraction $\epsilon \in [0, 1]$ of the remaining idle capacity can be used to grow and operate the carbon scrubber. Power is automatically distributed to growth and operation so that the full allocated power is utilized. I.e. all power goes into operation if the available power is smaller than the usable installed capacity (i.e. limited by maximum capacity factor). Otherwise the carbon scrubber is grown with the available power in excess of operational power. The maximum capacity factor is a function of the contribution of solar energy to total supply. When CCS is operated with fossil power, it can be operated continuously (i.e. $CF_{CCS, max, effective} = 1$). When CCS is operated solely on solar power, it can only be operated during sunshine hours to avoid storage. Then the maximum average capacity factor for CCS is reduced to 0.4. The operation (and further growth) of the carbon scrubber is stopped if atmospheric CO₂ concentration is below 350 ppm.

Both parameters β and ϵ can be specified separately for the periods "in transition" and "transition completed".

S3.3 Slew rate limiter

In the model the rate of ramping up or down the growth of a machine (i.e. the available power) is limited. This reflects real world limitations, as resources e.g. natural, human and financial capital or production capacity, to build new machine capacity can only grow gradually. This behaviour is modelled with a slew rate limiter. It prevents flows from sudden changes (i.e. infinite derivatives), which may cause instabilities in dynamic systems. The used slew rate limiters are built according to (Fig. S10): First, the difference between the input variable and the limited variable is determined and divided by the simulation time step

Figure S8: PID controller module structure

Figure S9: Controller module structure

(i. e. a rate of change). This rate of change is limited by the increase and decrease limits. The limited rate is then integrated to provide the gradient limited variable. For example, a step input function is converted to a ramp-function, i. e. its slopes are limited to the slow rate.

Figure S10: Basic set up of the slew rate limiter for a variable A .

S3.4 State observers

Figure S11: State observers module structure

The state observer modules (Fig. S11) keep track on the fulfillment of the two principal aims of the model:

1. Transition from fossil to solar power supply.
2. Clean-up excess CO_2 from the atmosphere and upper ocean until the atmospheric CO_2 concentration reaches 350 ppm.

Once the installed solar capacity (P_{nomPV}) reaches its required size, the energy transition is completed and the fossil engine can be shut down. The state observer *Transition state* switches to “completed” when this condition is reached.

The CO₂ clean-up is completed when the atmospheric CO₂ concentration reaches 350 ppm, which is modelled to be the case once the cumulative emissions are ≤ 1332 Gt. In consequence, CCS can be shut down.

Additionally, the cumulative exceedance of 350 ppm is measured by integrating the cumulative emissions curve in excess of 1332 Gt (i.e. 350 ppm) over time. The value represents only the cumulative exceedance within the simulation time horizon and does not account for contributions in the past and beyond the simulation end.

S4 Carbon cycle

Figure S12: CO₂ module structure

Fossil carbon stored in the lithosphere is released as CO₂ through combustion of fossil fuels in the fossil engine (see Section S1.1). This emitted CO₂ is stored in the atmosphere and, through gas exchange, also in the upper ocean [83, 84]. Transfer to the deep ocean operates on much longer timescales than the simulation time span and is neglected for simplicity [105]. Some of the CO₂ in the ocean is permanently stored in sediments, modelled as a constant flux of CO₂ to the lithosphere (*natural leak*). This constant natural leak is set at 0.8 Gt/a [84–86], modelling the permanent natural removal through sedimentation and weathering.

Lowering CO₂ concentration in the atmosphere causes outgassing of CO₂ from the upper ocean [53]. The upper ocean acts as a temporary reservoir and in the model the time lag between the two compartments *atmosphere* and *upper ocean* is neglected (see Section S4.1).

Emissions or removal of 18.13 Gt of CO₂ to or from the atmosphere and upper ocean causes the atmospheric CO₂ concentration to change by 1 ppm [17, 31, 106]. Cumulative CO₂ emissions start from 1850 at a pre-industrial CO₂ concentration of 276 ppm [17]. Therefore, the 350 ppm threshold [7] corresponds to cumulative emissions of $m_{\text{CO}_2} = 1332$ Gt and the 450 ppm threshold [107] with $m_{\text{CO}_2} = 3132$ Gt. The initial value of cumulative CO₂ emission is set to $m_{\text{CO}_2} = 2478$ Gt, which correspond to 411 ppm in 2020 [17] plus 40 Gt for 2021.

Peak cumulative emissions correlate with induced peak heating [22, 24, 31]. For stabilizing the climate in the long run, atmospheric CO₂ concentration needs to be reduced below 350 ppm, which is considered a safe limit [7, 12, 107], as fast as possible. The climate related objectives are therefore derived as twofold: (i) minimise peak cumulative emissions alongside with (ii) minimise cumulative exceedance of 350 ppm. While the first is commonly used when designing transition models, the second addresses the cumulated

Figure S13: Annual CO₂ emissions for all simulation experiments in comparison to IPCC pathways compatible with 1.5°C global heating.

pressure on the Earth system from a unsafe climate state. This can be measured through the cumulative exceedance of 350 ppm, i. e. the integral of the cumulative emissions exceeding 1332 Gt.

The land carbon sink is usually modelled to increase with higher CO₂ concentrations due to the CO₂ fertilisation effect. However, recent a study finds, that beyond a 3-months average temperature of 25 °C the biomes become a net source rather than a sink of CO₂ [108]. The terrestrial vegetation's carbon mitigation potential may therefore be grossly overestimated. Under current climate scenarios, the tipping point for the terrestrial carbon sink is reached within the next 30 a. Therefore, the land carbon sink is excluded in this model.

Fig. S13 shows the annual CO₂ emissions for all 25 simulation experiments in comparison with IPCC pathways (grey shaded area). Note, they are fundamentally different in characteristics: initially they are increasing and drop to zero or negative within a very short time, in contrast to a gradual decline as suggested by IPCC pathways.

S4.1 Carbon cycle response to negative emissions

We tested the response of the carbon cycle to the emission dynamics (positive and negative) of different scenarios in our model. Subsequently, a simple carbon cycle model is integrated capable of approximating the results of Zickfeld et al. [53] (see Fig. S14).

Emissions to the atmosphere are translated into CO₂ concentration change with a proportionality relationship, which is linearly proportional to the CO₂ concentration in the atmosphere. I.e. the higher the atmospheric CO₂ concentration, the larger the proportionality.

$$\frac{dp_{\text{CO}_2}}{dm_{\text{CO}_2}} = \frac{dp_{\text{CO}_2,0}}{dm_{\text{CO}_2,0}} \left(1 + a_{dp/dm} \cdot \frac{p_{\text{CO}_2} - p_{\text{CO}_2,0}}{p_{\text{CO}_2,0}} \right) \quad (16)$$

$$p_{\text{CO}_2,0} = 278 \text{ ppm}$$

$$\frac{dp_{\text{CO}_2,0}}{dm_{\text{CO}_2,0}} = 0.058 \text{ ppm/Gt}$$

$$a_{dp/dm} = 0.35$$

Figure S14: Simple model of the carbon cycle in insightmaker

649 The balance flow between atmosphere and deep ocean is according to an empirically found proportionality
 650 of $prop = 0.0046 \text{ a}^{-1}$ and the time delay for the outflow from deep ocean back to the atmosphere (3rd
 651 order delay) is assumed to be $\Delta t_{\text{deep ocean}} = 300 \text{ a}$ (which is in the range provided by IPCC AR5 [105]).

Figure S15: Comparison of the atmospheric CO_2 concentration when considering exchange with deep ocean (green), when neglecting the deep ocean (blue) and when keeping the proportionality between atmospheric CO_2 concentration and cumulative emissions constant in addition (red).

652 As displayed in Fig. S15, the atmospheric CO_2 concentration follows the increase in cumulative emissions
 653 proportionally, but decreases faster. However, after negative emissions stop, the CO_2 concentration raises
 654 again, as CO_2 is emitted back from the deep ocean. When neglecting the exchange with the deep ocean
 655 (blue), predicted CO_2 concentrations are higher at peak but converge after 500 a. When additionally
 656 neglecting the linear dependency in eq. 16, the predicted concentration is very similar in peak and converges
 657 again after 500 a given that $p_{\text{CO}_2} < 600 \text{ ppm}$, which is true for all simulation runs investigated with our
 658 model.

659 The approximated linear and directly proportional correspondence between atmospheric CO_2 concentra-
 660 tion and cumulative emissions (red line) predicts the peak CO_2 concentration correctly and remains
 661 above the “true” value for the period of negative emissions until atmosphere and deep ocean are in
 662 equilibrium again. I.e. reducing the approximated CO_2 concentration below 350 ppm means that the “true”
 663 concentration will be even lower (maximum by approximately 50 ppm) until deep ocean and atmosphere
 664 are in equilibrium again.

Furthermore, as temperature response to negative emissions has the opposite tendency (slight increase when negative emissions commence and slower decrease than linear [53]), temperature will likely not fall below pre-industrial averages even if CO₂ concentration falls temporarily below pre-industrial level.

Therefore, it is justified for this simple model to approximate the climate response with the constant proportionality between cumulative emissions and atmospheric CO₂ concentration.

S5 Scenario definition

The energy limits for transition pathways are explored with numerous simulation experiments (Section 4). Parameters are varied for each simulation experiment to find the transition pathway leading to lowest maximum cumulative CO₂ emissions throughout the simulation period under the set assumptions. Simulation experiments are defined as parameter sets (see Tables S2 to S4). Each chosen set forms a simulation experiment, which can be described as a scenario narrative (Section 4). The successive simulation experiments evolve similar to a family tree (Fig. S16, Fig. 2).

The following lists some additional rationale descriptions for simulation experiments, complementing the details provided in Section 4:

- Population projections are taken for all scenarios with 50 % confidence [80], except for ②⑤ where 97.5 % confidence is selected.
- ③ **fossil CCS**: As degrowth ends with energy supply per person below the minimum for a decent life (see ②), this scenario uses a constant demand.
- ⑦ **PV 300W**: As demand reduces also after the transition is complete, there is no need for preventive maintenance of PV. PV installed capacity is always big enough to supply demand also during PV replacement cycles.
- ⑩ **PV+CCS**: CCS is deployed as direct air capture (DAC), which has a higher energy intensity than capture from stacks ($EI_{CCS} = 0.2 \text{ TWa/Gt}$ [66–70, 72]).
- ⑮ **moderate demand**: Storage consists of 56 % batteries, 27 % hydro pumped storage and 17 % synfuels.

S6 Model validation and sensitivity

Model validity is a critical aspect regarding the (empirical) robustness of simulation results. Barlas [58] distinguishes between structural and behavioral validity of system dynamics models, where *structure* refers to the model's relationships, equations, as well as parameters, and *behavior* refers to the trajectories produced by the model through the means of simulation. As the *3-machines model* aims to capture the dynamics of an unknown, future transition where little empirical data is available, the focus in model validation lies on structure-oriented tests, such as *direct structure tests* and *structure-oriented behavior tests*. Behavior-oriented tests, such as *behavior pattern tests* were used where feasible (i.e. where data from other, comparable simulation studies was available). In particular, the following tests have been performed throughout the model development process in an iterative manner:

- Structure- and parameter-confirmation tests: Equations, parameter values and data of external variables were derived from literature and are documented in the model.
- Dimensional consistency test: Each variable (*primitive* in InsightMaker) has a specified unit and InsightMaker is checking the dimensional consistency before running the model.
- Behavior extreme condition tests: Parameters have been varied in their entire feasible range and the simulation results have been checked for feasibility and logical consistency.
- Behavior sensitivity tests: Influential parameters (such as independence time, fraction of demand stored; growth rate, energy demand per person) have been identified and checked whether the simulation results reveal plausible behaviors.

Figure S16: “Family tree” of simulation experiments; simplified version of Fig. 2.

Table S2: Parameter definition for simulation experiments ① to ⑦.

Scenarios			fossil baseline	fossil degrowth	fossil CCS	PV	PV growth	PV 2000W	PV 300W
Variable	unit	①	②	③	④	⑤	⑥	⑦	
fC_repair		1	0	1	1	1	1	0	
CCS switch		0	0	1	0	0	0	0	
fC switch		1	1	1	1	1	1	1	
growth rate		0.03	−0.03	0	0	0.03			
P_demand per person aim	W/p						2000	300	
demand growth switch		1	1	1	1	1	0	0	
demand transition delay time	a						50	7	
demand transition duration	a						50	14	
population confidence selection		3	3	3	3	3	3	3	
PV repair proportional						0.2	0.2		
PV repair on demand					1	0	0	1	
PV repair inverse proportional						5	5		
beta in transition		0	0	0	1	1	1	1	
alpha		0	0	0	0	0	0	0	
oversize PV					1.1	1.1	1.1	0.75	
beta after transition		0	0	0	0.5	0.5	0.5	0.5	
gamma		0.95	0.95	0.6	0.95	0.95	0.85	0.95	
epsilon in transition				1					
epsilon after transition				1					
desert potential fraction					0				
independence time	a	0	0	0	0	0	0	0	
fraction of daily demand stored									
relative weight chemical storage									
relative weight mechanical storage									
relative weight electro-chemical storage									

Table S3: Parameter definition for simulation experiments ⑧ to ⑭.

Scenarios		PV storage	PV less storage	CCS	CCS 2000W	CCS 300W	CCS 300W S +	CCS 2000W S + PV +
Variable	unit	⑧	⑨	⑩	⑪	⑫	⑬	⑭
fC_repair		1	1	1	1	1	1	1
CCS switch		0	0	1	1	1	1	1
fC switch		1	1	1	1	1	1	1
growth rate		0	0	0	0	0	0	0
P_demand per person aim	W/p				2000	300	300	2000
demand growth switch		1	1	1	0	0	0	0
demand transition delay time	a				50	7	7	50
demand transition duration	a				50	14	14	50
population confidence selection		3	3	3	3	3	3	3
PV repair proportional		0.2	0.2	0.2	0.2	0.2	0.2	0.5
PV repair on demand		0	0	0	0	0	0	0
PV repair inverse proportional		15	15	15	15	5	15	20
beta in transition		1	1	1	1	1	1	1
alpha		0	0	0	0	0	0	0
oversize PV		1.1	1.1	1.1	1.1	1.1	1.1	1.1
beta after transition		0.5	0.5	0.5	0.5	0.5	0.5	0.5
gamma		0.95	0.95	0.95	0.95	0.95	0.95	0.95
epsilon in transition				1	1	1	1	1
epsilon after transition				1	1	1	1	1
desert potential fraction		0	0	0	0	0	0	0.5
independence time	a	0.01	0.0016	0.0016	0.0016	0.0016	0.02	0.02
fraction of daily demand stored		0.5	0.1	0.1	0.1	0.1	0.5	0.5
relative weight chemical storage		0.5	0.5	0.5	0.5	0.5	0.5	0.5
relative weight mechanical storage		1	1	1	1	1	1	1
relative weight electro-chemical storage		1	1	1	1	1	1	1

Table S4: Parameter definition for simulation experiments (15) to (20).

Scenarios			moderate demand	sunflower	early CCS	sunflower early CCS	sunflower LED	sunflower LED pop+
Variable	unit		(15)	(16)	(17)	(18)	(19)	(20)
fC_repair			1	1	1	1	0	0
CCS switch			1	1	1	1	1	1
fC switch			1	1	1	1	1	1
growth rate								
P_demand	per	W/p	1400	1600	1200	1600	680	680
person aim								
demand growth			0	0	0	0	0	0
switch								
demand transi-	a		50	40	50	40	5	5
tion delay time								
demand transi-	a		30	30	50	30	10	10
tion duration								
population confi-			3	3	3	3	3	5
dence selection								
PV repair pro-			0.5	0.5	0.5	0.5	0.5	0.5
portional								
PV repair on de-			0	0	0	0	0	0
mand								
PV repair			20	20	20	20	20	20
inverse propor-								
tional								
beta in transi-			1	1	0.77	0.77	1	1
tion								
alpha			0	0	0.2	0.2	0.8	0.8
oversize PV			1.1	1.1	1.1	1.1	1.1	1.1
beta after transi-			0.5	0.5	0.5	0.5	0.5	0.5
tion								
gamma			0.95	0.95	0.95	0.95	0.95	0.95
epsilon in transi-			1	1	1	1	0	0
tion								
epsilon after			1	1	1	1	1	1
transition								
desert potential			0	0	0	0	0	0
fraction								
independence	a		0.01	0.0016	0.01	0.0016	0.005	0.005
time								
fraction of daily			0.3	0.1	0.3	0.1	0.1	0.1
demand stored								
relative weight			0.25	0.25	0.25	0.25	0.2	0.2
chemical storage								
relative weight			0.5	0.5	0.5	0.5	1	1
mechanical stor-								
age								
relative weight			1	1	1	1	1	1
electro-chemical								
storage								

- Behavior pattern tests: As the energy transition did not happen yet, it is impossible to compare simulation results with empirical data. Instead, the simulation results were compared with simulation outputs from previous modelling exercises [31, 32] (s. next paragraph).

Scenario ④ captures the same scenario as modeled in a previous study: the fastest possible transition from fossil to solar without storage [31]. The study was made with a different mathematical model implemented in Matlab. It can now be compared to the results with the 3-machines model, however, our previous study only focused on the transition alone, therefore comparison is limited to the transition time. The behaviour and tendency is the same during the transition for both models: fastest transition is achieved with maximum fossil investment and no fossil replacement during the transition. This leads to lowest cumulative CO₂ emissions. In [31], 1.5 °C global heating is violated with 20 % at the least, while in the 3-machines model, 1.5 °C is violated with 8 %, if the cumulative distribution function (CDF) is fitted to IPCC Assessment Report 6 data [22]), or 23 %, if CDF is fitted to IPCC Special Report 1.5 °C data [24] (see Fig. S17 and Tab. S5). The latter had been used in the previous study, thus the 3-machines model predicts a slightly slower transition. This is reasonable as the 3-machines model introduces the dynamic behavior of the ramp up in PV production as well as fossil investments. In conclusion, the 3-machines model predicts the same dynamic behavior as our previous model aiming at the specific simulation experiment ④.

Figure S17: Cumulative density functions (CDF) of the remaining carbon budget for 1.5 °C (orange) and 2 °C (red) as a function of cumulative CO₂ emissions since 1850. Dashed lines show CDFs fitted to data provided by IPCC special report on 1.5 °C [24], while solid lines show CDFs fitted to data from IPCC Assessment Report 6 [22].

The value of dt can have real world implications (i.e. if small: system must be able to react fast). Simulation results are more accurate and less oscillating when using the Runge-Kutta algorithm (RK4), however, the difference to simulation runs using Euler are small, especially for integrated results such as cumulative CO₂ emissions or cumulative exceedance of 350 ppm. Control of the system becomes better with reduced dt . Simulations with Runge/Kutta (RK4) takes a bit longer to simulate.

S7 Results from simulation experiments

The results from the here presented simulation experiments are summarized in Tab. S5, which provides the key numbers for: maximum cumulative CO₂ emissions since 1850; cumulative exceedance of 350 ppm throughout the simulation period; transition time since simulation start and year when transition can be competed; clean-up time since simulation start and year when 350 ppm is reached; demand-collapse time since simulation starts and year when demand collapses; fossil fuels consumed throughout the simulation

period; probability to exceed 1.5 °C global heating based on data from Assessment Report 6 [22] as used in the main paper; probability to exceed 1.5 °C global heating based on data from Special Report on 1.5 °C [24] as used in previous papers [31, 32].

Fig. S18 shows the same data as Fig. 5 but on the x-axis the probability to exceed 1.5 °C based on data from Assessment Report 6 [22] instead of cumulative CO₂ emissions.

Figure S18: Results of simulation experiments plotted for probability to exceed 1.5 °C [22] and cumulative exceedance of 350 ppm.

Within the first ten time steps of each simulation run, the model transits to the dynamic setting of each simulation experiment. This is due to the fact, that the model is initiated in a steady state for 2021, rather than continuing past dynamics. Within the first year of simulation, the results have therefore no meaning in the real world. As the adaption to the transient state is rather short, this simplification is justified.

S8 Limitations and further research

Greenhouse gas emissions other than CO₂ and their contribution to exceed peak heating as well as for stabilizing the climate are not considered. Land use change would need to be halted completely and reversed, also to restore biodiversity. Negative emissions from reversed land use change and changed land use practises [75] may offset other GHG emissions, such as CH₄ from agriculture. Whether they could also have a significant role in the permanent CO₂ removal remains to be assessed.

The fossil engine may be operated with synfuels instead of fossil fuels. For instance, to continue operating parts of the fossil infrastructure, which are hard-to-electrify e.g. aviation. Simulations could determine, whether or not synfuels could have a positive effect on the transition. To address this question, a synfuel engine would be added to the energy system, which is supplied with CO₂ from CCS and draws power from the grid to synthesis synfuel.

Energy requirements to electrify the current mobility and heat sectors (e.g. retrofitting houses with heat pumps) is not considered in this analysis. This requires an economy-wide analysis of the induced changes in production and consumption patterns, i.e. a detailed look into the energy demand by society. It remains an open area for future research to determine the energetic costs and optimal strategy for this transition.

Table S5: Summary results of simulation experiments

Scenario	maximum cumulative emissions Gt	exceedance of 350ppm Gt a	cumulative transition time a	year a	clean-up time a	year a	clean-up year a	demand collapse time a	demand-collapse year a	fossil fuel consumption EJ	Probability to exceed 1.5 °C AR6 [22]	SRL5 [24]
① fossil baseline	9911	302615								145978	1.00	1.00
② fossil degrowth	3714	150198								27366	0.95	0.83
③ fossil+CCS	4276	159597								67246	0.99	0.90
④ PV	2619	97893	3.1	2024						2828	0.08	0.23
⑤ PV growth	2633	99024	3.3	2024						3117	0.09	0.25
⑥ PV 2000W	2636	99229	3.4	2024						3172	0.10	0.25
⑦ PV 300W	2596	96178	2.7	2024				67.3	2088	2378	0.05	0.21
⑧ PV storage mix	2738	106780	5.1	2026						5187	0.25	0.36
⑨ PV less storage	2638	99338	3.3	2024						3199	0.10	0.25
⑩ PV+CCS	2638	23996	3.3	2024	28.7	2050				3199	0.10	0.25
⑪ CCS 2000W	2687	29719	4.3	2025	41.6	2063				4182	0.17	0.31
⑫ CCS 300W	2665	27541	3.9	2025	32	2053				3739	0.14	0.28
⑬ CCS 300W S+	2776	33967	6.7	2028	34.9	2056				5958	0.31	0.39
⑭ CCS 2000W S+ PV+	2946	40938	9.2	2030	36	2057				9300	0.56	0.53
⑮ moderate demand	2784	38728	6.4	2027	50.5	2072				6096	0.32	0.40
⑯ sunflower	2696	29901	4.8	2026	43.1	2064				4722	0.18	0.32
⑰ early CCS	2759	40925	7.7	2029	52.6	2074				7289	0.28	0.38
⑱ sunflower early CCS	2683	28378	4.3	2025	36	2057				4094	0.16	0.30
⑲ sunflower LED	2667	31026	6	2027	27.8	2055				3815	0.14	0.29
⑳ sunflower LED pop+	2668	31350	6.1	2027	28.4	2056				3832	0.14	0.29

The demand for materials induced by the various scenarios of the 3-machines model may limit the growth of the 3 machines and is another area of future research. Solar PV is seen as non-critical in terms of material demand [31, 50], whereas energy storage technologies may pose serious concerns regarding material availability, most notably for Li and Co in the case of Li-Ion batteries [35, 36]. Pumped-hydro storage will be limited by suitable geographic sites. CCS technologies typically do not require special materials, except for solvents [72]. Still, due to the possible speed of the energy-constrained transition, a detailed assessment of constraints regarding material mobilisation is necessary for all materials involved. These materials can be mobilised from both primary and secondary deposits, most notably from obsolete fossil infrastructure. Material constraints can be included in the model as slow rates or absolute limits.

Regional differences in energy demand patterns, e.g. due to climate and weather conditions, are not considered in this global model. As current energy demand is distributed unequally across the globe (e.g. in Switzerland energy demand is five times higher than the global average), there is a need to redistribute energy demand from “rich” to “poor” both within and across nations ensuring a socially just transition.

S9 IAM overview

Integrated assessment models (IAM) commonly do not include embodied energy investments [47]. A text search in the documentation of prominent IAMs (MESSAGE [42], IMAGE [43], POLES [44], REMIND [45], TIAM [46]) for the terms “EROI”, “net energy”, “embodied energy”, “energy payback”, “energy invest*” confirms that the aspect of investing energy to build renewable energy infrastructure is absent in these models. The POLES model considers EROI only through operational costs (OPEX) for fossil fuels, as their extraction becomes more energy intensive with cumulative production [44]. Simulations in these models are run for time steps between 1 a and 10 a, covering 10 to 57 geographic regions. This temporal and spatial resolution is insufficient to model supply of variable renewables in detail, in particular solar and wind. In contrast, the LUT energy transition model [52], which focuses on the energy system only, matches supply and demand in hourly resolution and for 145 world regions. Still, it does not consider energy investments to build the replacing renewable energy infrastructure. The MEDEAS model [47] is, to the best of our knowledge, the only IAM that considers energy investments.

model	lead institution	time step / a	world regions	energy investments	source
MESSAGE-GLOBIOM	IIASA	10	11	no	[42]
IMAGE	Utrecht University, PBL	1 or 5	26	no	[43]
REMIND-MAGPIE	PIK	5 or 10	12	no	[45]
POLES	JRC	1	57	no	[44]
TIAM-UCL	UCL	5 or 10	16	no	[46]
WITCH	EIEE	5	17	no	[109]
MEDEAS	University of Valladolid	1	1	yes	[47]
C-ROADs	MIT	1	1 to 15	no	[48]
LUT energy transition model	LUT	0.000114	145	no	[52]

Table S6: Comparison of temporal and spatial resolution and the consideration of energy investments for selected IAMs.

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