Climate change mitigation easier than suggested by models

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Scenarios play a central role in helping policymakers envisage pathways to limit global warming to well below 2°C. We demonstrate that the most recently assessed set of climate stabilization scenarios still favors fossil fuels, and in particular coal, and bioenergy. In contrast to insights from empirical innovation studies, scenarios are optimistic on deployment of lumpy, energy-systems technologies, such as carbon capture and storage, while insufficiently reflecting innovation dynamics in granular technologies. Our analysis shows that two pathways for rapid decarbonization remain systematically undersampled in models that underpin IPCC scenarios: A) strong growth in intermittent renewables, in particular solar PV, together with electrification of sectors; and B) widespread adoption of efficient end use technologies, digitalization, and new service provisioning systems enabling low energy demand. A combination of continued PV growth and sector coupling with low to medium energy demand (a corridor of 250 to 500 EJ of primary energy) would make fossil fuels obsolete by 2050, thus enabling near-term cost effective climate change mitigation and reducing the need for carbon dioxide removal in the 2^nd^ half of the century. These pathways are realistic, target inclusive well-being, but remain underrepresented in the modelling literature. We see three modeling innovations that would improve resolution of near and mid-term dynamics: 1) updating of renewable energy cost assumptions and fuller representation of technological learning curves, 2) more explicit modelling of sector coupling and specifically power-to-X technologies, and 3) including insights from hourly resolution modelling of energy systems.

As policymakers work to limit global warming well below 2°C as enshrined in the Paris Agreement, they rely on insights from model-based scenarios to identify efficient pathways to decarbonization. However, comparing these pathways with empirical evidence on technology adoption raises concerns that these scenarios have a systematic technology bias both towards fossil fuels and towards lumpy technologies. For example, 3 out of the 4 illustrative pathways selected in the IPCC's recent special report (SR1.5), and 93% within the full scenario ensemble, rely on high deployment of carbon capture and storage (>5GtCO_2 sequestered in 2050), a lumpy technology with large unit size and high investments costs that does not meet the targets set by the industry. The same scenarios inadequately reproduces the technologicallearning and upscaling in renewables observed over the past 10 years.

We systematically analyze the SR1.5 database of 416 mitigation and baseline scenarios and observe four sources of bias: i) baseline scenarios depend much more on fossil fuels – particularly coal - than historical trends indicate; b) bioenergy with carbon capture and storage (BECCS), as well as other carbon dioxide removal technologies, are upscaled quickly and draw very high amounts of CO_2 out of the atmosphere; c) renewable upscaling and adoption rates are very conservative; and d) energy efficiency and demand reduction is only scarcely reflected. Climate protection scenarios have provided a precious source of evidence for understanding net-zero transition dynamics. To remain policy-relevant in the future, a new generation of models need to improve the representation of technology learning and diffusion, more directly reflect real world dynamics, and draw on stylized facts from the innovation economics literature.

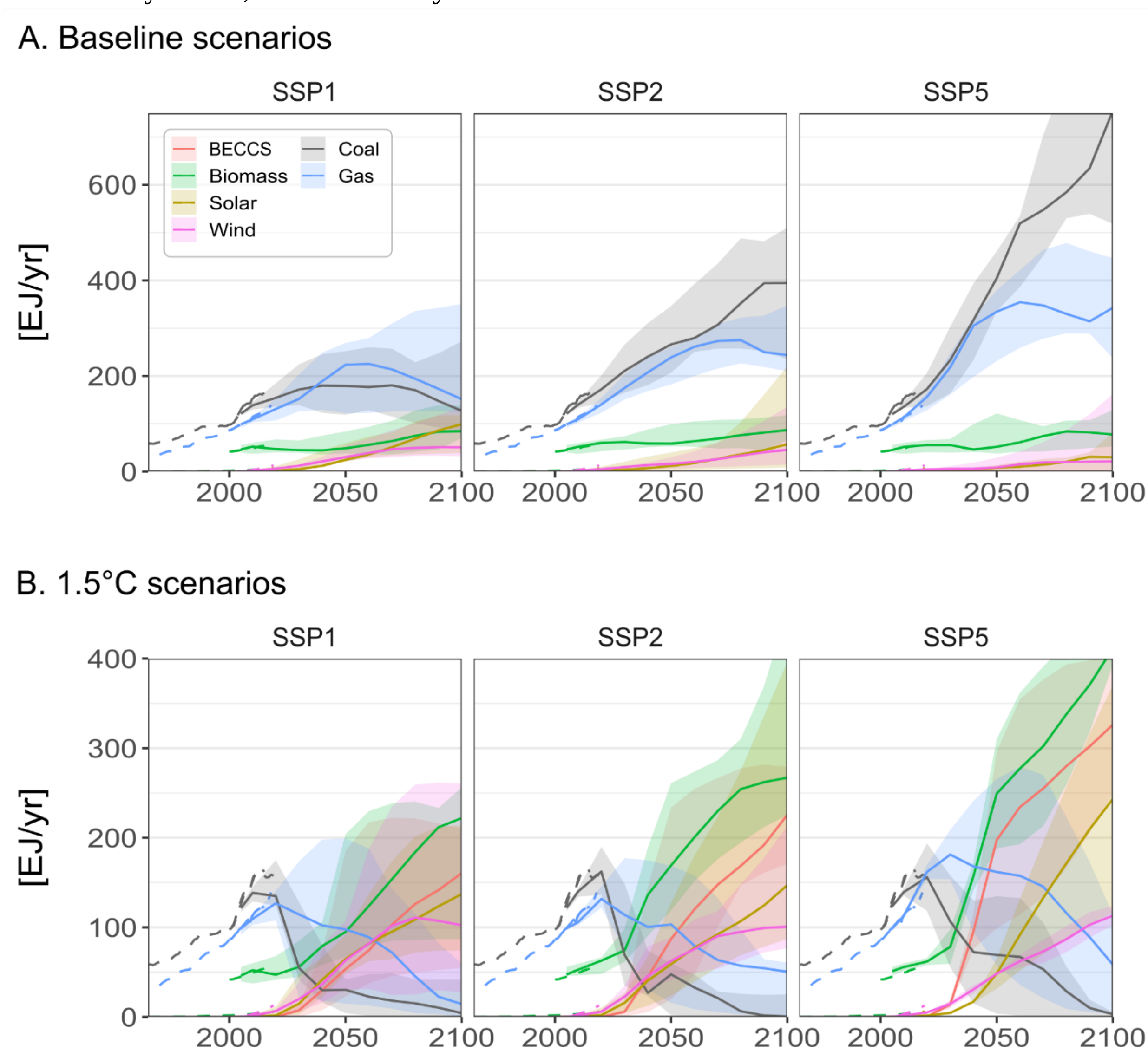

Figure 1. ***Climate stabilization scenarios display high dependence on carbon-based energy carriers, coal in baseline, and coal and biomass combined with CCS in mitigation scenarios, insufficiently reflecting the high potential of solar PV.*** *A) Shared socio-economic pathway (SSP) scenarios show high growth in coal consumption for primary energy. B) Mitigation scenarios building on SSPs show high deployment of bioenergy and BECCS*

Preference for coal

Coal features predominantly in baseline scenarios. The shared socio-economic pathways (SSPs) indicate five distinct trajectories of demographic and socioeconomic changes through 2100, serving as a robust backdrop with which to evaluate climate policies (1). While the baseline SSPs are designed to explore a wide range of global changes, ranging from “sustainability” to “inequality”, they have one feature in common: they all rely heavily on coal. Per capita coal consumption has stayed constant globally since 1950, with the exception of 2002-12, when it temporarily rose due to expanding Chinese coal capacity. Baseline SSPs are strongly skewed toward high coal trajectories, with per capita coal consumption increasing in all SSPs but SSP1. In SSP2 (“Middle of the Road”) coal grows 3 to 6 times faster than its historically observed average annual growth and in SSP5 coal grows 8-13 times faster (Fig. S1). Only in the most optimistic SSP1 (“sustainability”) keeps per capita coal consumption constant, thus roughly replicating historical experience. Overall, benchmarking scenarios for investigating climate stabilization are systematically biased towards higher coal dependence than what appears plausible from historical evidence (Fig. 1A). In 2050, only 2% of SR1.5 baselines are more conservative than history (lower value than the minimum per-capital coal consumption over 1965-2019). In contrast, close to 25% of baselines have twice as much coal than the mean historical values over 1965-2019. Despite the diversity of extant and emerging energy supply technologies, in these scenarios only natural gas and biomass contribute substantially to primary energy, aside from coal (Fig. 1A; nuclear not shown here for clarity) (2).

SSP reference scenarios do not contain *additional policies* (3), but the models are calibrated on data that include current and past policies, which are expected to continue into the future. Therefore, the *no additional policy* assumption does not explain the strong deviation from long-term historical patterns of coal use and the failure to phase-in renewables as empirically observed.

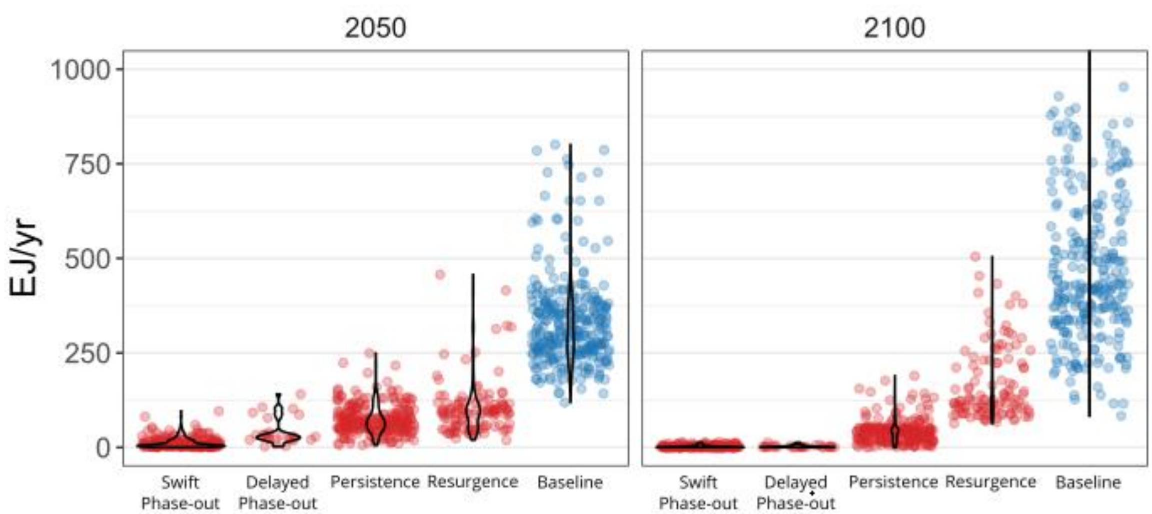

Figure 2. Coal in mitigation models. *In mitigation scenarios, four different types of coal deployment occur, with coal persistence and coal resurgence scenarios showing continued dependence of coal, coupled with CCS. Scenarios here comprise those used for the IPCC AR5 and the IPCC SR1.5 (10, 11).*

Coal as mitigation technology?

Coal remains a dominant energy source in many mitigation scenarios, not just in the SSP baseline scenarios discussed above (Figure 2). For example, in the scenarios underlying the SR1.5, 34% of all scenarios display rapid coal phase out, 3% delayed phase out, 41% coal persistence, and 22% coal resurgence ((4) and Fig. S1). Coal intensive pathways in climate policy scenarios occur because coal is affordable, can be combined with CCS, and is assumed to not face substantial competition from alternative low carbon technologies. However, we can currently observe many markets where coal is being out-competed by other technologies even with only modest climate policy (5). This is evidenced by the 653 GW of coal-fired power plant projects that have been abandoned in several countries, including China and India, since 2016 (6). An additional motivation for regional and national administration is also clear: The health benefits of coal phase out by better air quality or sufficiently substantial to motivate local action and thus negating global free-rider dynamics (7). Further, hopes of rapid diffusion and adoption of CCS technology at the beginning of the century did not materialize (8) . Despite nearly two decades of effort, only two full scale CCS power plants exist, one of which recently shut down (9). Effectively, modeled scale-up of CCS is in many scenarios much faster than for any other technology (Figure 3). In mitigation scenarios from SR1.5, this leads on average to coal consumption in combination with CCS of 28 EJ/year in 2050. With an average coal consumption of 40 EJ/year in these scenarios, this corresponds to an average of 61% of the coal burnt in combination with CCS technology. The observed modest CCS deployment in industrial applications to date casts doubt whether such results are realistic. Low deployment and cancellations are the result of high capital costs, uncertain revenue streams, and technological readiness (8).

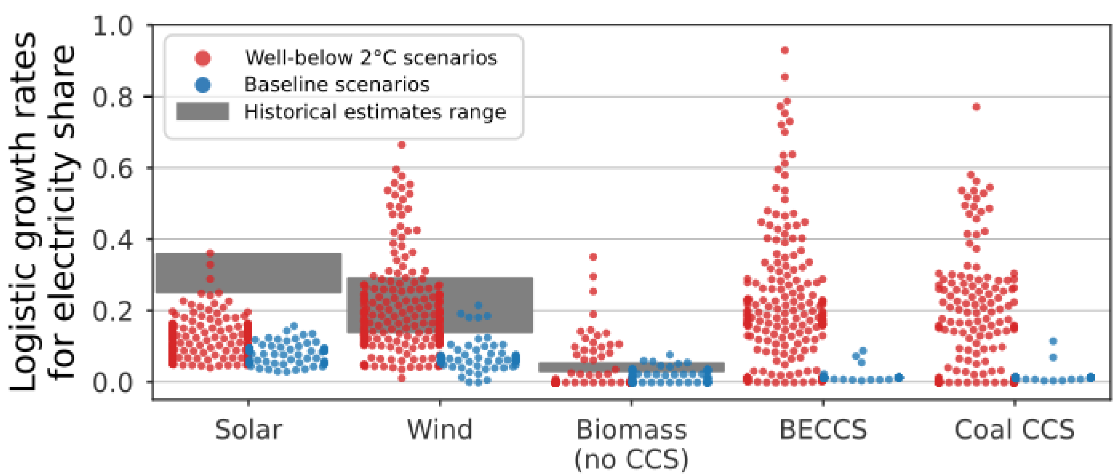

Figure 3. Historical and modelled logistic growth rates of mitigation technologies. *Models show bioenergy and CCS growth rates far above historical observations, and PV (and to lesser degree wind) growth below historical observations. Each point indicates the estimate of the growth rate parameter of a logistic fit to the share of a technology in the electricity mix for scenarios in the SR1.5 database.*

Bioenergy replacing coal

In well-below 2°C scenarios, models often replace baseline coal with bioenergy, while wind and solar provide low to intermediate levels of useful energy. Bioenergy - with or without CCS - is in many cases the major source of energy providing 7-54% of total primary energy in 2050 – tripling to quintupling from today's levels to 120-200 EJ. Mitigation scenarios model 100-400 EJ biomass in 2100 (Fig. 1B). In 2050, 65% and 79% of scenarios have more than 100 EJ of bioenergy with and without CCS, respectively. n contrast, solar and wind are modelled at about 50 EJ each in 2050 and 100 EJ for wind and 150 EJ for solar photovoltaic (PV) in 2100. Underlying reasons for this thirst for bioenergy in models include its versatile use and many different deployment pathways, while the environmental and social impacts of bioenergy, as well the challenges of polycentric governance of land use remain underrepresented (12, 13). This shows that carbon-based primary energy remains at the center stage of integrated assessment models, even in scenarios consistent with the goals of the Paris agreement.

Many scenarios – particularly those that limit global warming below 1.5°C – heavily rely on BECCS. However, the models' hunger for bioenergy is persistent and sometimes even larger when BECCS is not permitted, as options for decarbonizing the economy get more limited – particularly in transportation. The growth rates of BECCS –a large-scale energy technology with huge investment requirements - are also much higher in models than what has been observed in recent decades (Fig. 3); realisation would require a fundamental shift in CCS diffusion and adoption that is hardly perceived today. Globally at present, only one fully scaled plant combines the two components and counts as BECCS (producing ethanol) (17).

The high demand for bioenergy and BECCS has huge implications for land-use and thus non-climate planetary stability (14–16). Most scenarios are inconsistent with a precautionary threshold of 0.5 Mkm^2 land for bioenergy, corresponding to today's usage, and aiming to protect half earth for biodiversity (18). Of the scenarios in the SR1.5 database that present land use, 97% (126 out of 132) are above this precautionary threshold (19). The sustainability threshold for BECCS specifically has been estimated at between 0.5 and 5 Gt CO_2/yr in a systematic review (20). Here, 91% of all scenarios are above the lower threshold in 2050, and 33% are above the higher threshold (19). Out of the 4 illustrative pathways in the IPCC Special Report "Global Warming of 1.5°C" (SR1.5), 3 rely on BECCS at cumulative carbon dioxide removal (CDR), corresponding roughly to average sequestration of 3 Gt CO_2/yr, 8 Gt CO_2/yr, and 20 Gt CO_2/yr between 2050 and 2100 (10). This huge demand of bioenergy makes these scenarios hardly compatible with other sustainable development goals, such as "zero hunger" and protecting "life on land".

The high demand for BECCS in models strongly depends on demand for CDR (Figure S2), which in turn is an artefact of a particular modeling assumption (21). An updated scenario design logic suggests to consider peak warming and the intertemporal requirement for negative emissions explicitly (22), thus highlight the reliance on 2020 until 2050 mitigation efforts to avoid the dependence on risky mitigation strategies. Out of 53 'as likely as not' 1.5°C scenarios, the majority (34 scenarios) model a low overshoot to 1.6°C and end-of-century stabilization at about 1.3°C. This high reduction below 1.5°C in 2100 is intended to increase the likelihood that 1.5°C is not crossed to >66%. A reduction by 0.3°C roughly requires additional CDR of about 700 Gt CO_2. However, in 2050 we are much more likely to understand the transient climate response to emissions (TCRE), and would only need to apply that high amount of CDR if the TCRE is higher than expected, or if planetary climate thresholds are crossed that initiate positive feedback loops in global warming (23). This case would require high amounts of CDR only to maintain temperatures at 1.5°C or 1.6°C, if possible at all. If TCRE is below or at current estimated values, the demand for CDR will be much lower, with cumulative negative emissions below 200 Gt CO_2 until 2100. Together, this reveals that high CDR and BECCS deployment in models depend on very specific assumptions at the end of the century.

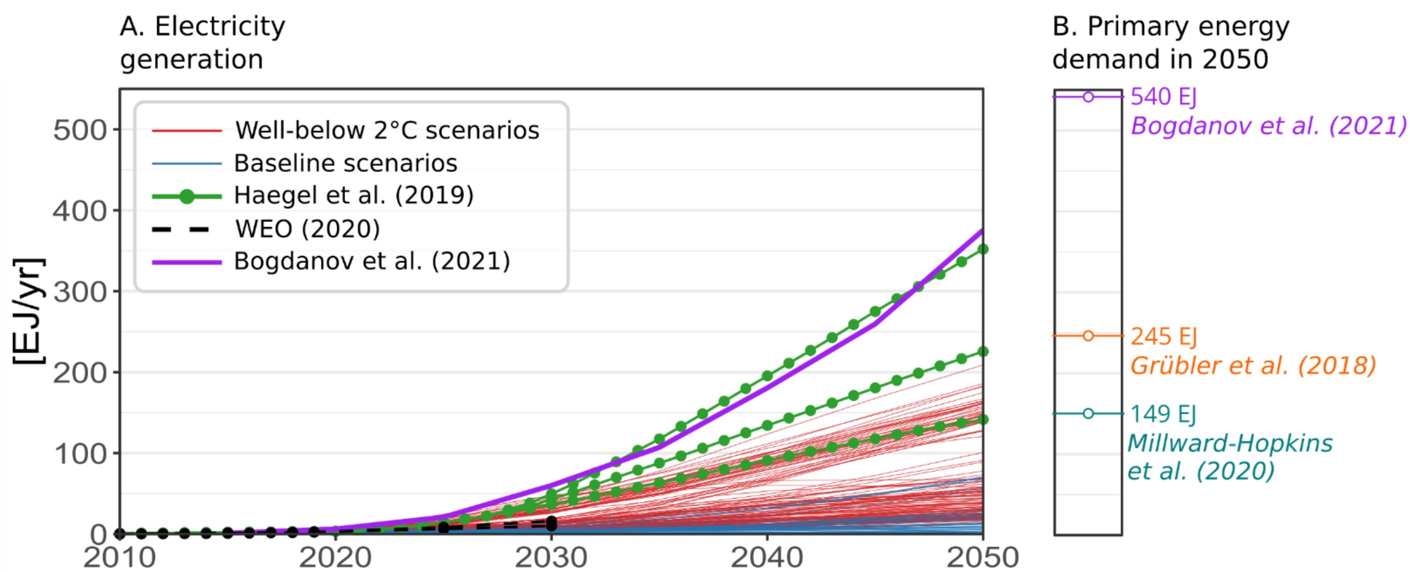

Figure 4. Electricity from solar PV in mitigation scenarios (A) and primary energy demand (B)*. Projections from solar experts (24) show double or triple rates of electricity from PV compared to integrated assessment models. Electricity generation by solar and wind, coupled with wide-ranging electrification of transport, heating, and industry can satisfy total primary energy demand in low to medium energy demand scenarios in 2050.*

Underestimated solar PV

Energy models lag real-word developments especially for renewables (25). Climate stabilization scenarios assume that PV will grow, but much slower than it has over the past two decades, such that it contributes only modestly to meeting global electricity demand, reaching levels of 20-50 EJ in 2050 (26). The same models also realize PV levels of 30 EJ (POLES) to 100EJ (REMIND) in 2050 if CCS technologies and nuclear are banned (26). Other model runs provide 100-150 EJ from PV of electricity from PV in 2050 (Fig. 4). 80% of well-below 2°C scenarios have less than 50 EJ of solar PV in 2050. Meanwhile, new scenarios, published after the IPCC 5^{th} Assessment Report, many of which originate from outside the integrated assessment community, find much higher shares of intermittent wind and solar in decarbonization and energy system pathways (Fig. S3, (27)). A statistical analysis demonstrates that models used in IPCC scenarios systematically project lower PV adoption pathways compared to models that are not used in the IPCC, in part because IPCC scenarios assume higher capital costs (28). PV technology experts suggest that PV could deliver 125-350 [central estimate: 225] EJ/yr by 2050, which is twice as much as coal provides in 2020 (24) (Fig. 4) (Similar magnitudes were also modelled in (29–31)). For comparison, a low energy demand scenario projects 245 EJ of total primary energy in 2050 (32). The historical experience of solar PV—growing at 30% annually over the past twenty years and continuing to fall in costs—suggests that PV modelers' scenarios are more realistic than the climate stabilization scenarios of IAMs (Fig. 3). Growth rate in wind are modelled more realistically. While the majority of scenarios envisage growth rates below historically observed data for wind, other scenarios project growth rates more than double what has been observed (Fig. 3).

Possible reasons for this bias include reliance on theoretical assumptions (theory of learning by extraction)(2), insufficient gauging of growth rates of renewables (33), and limitations of intermittent renewables by mandating baseload supply (33). Related explanations identified in meta-studies of PV in IPCC scenarios include lack of electrification beyond the power sector and high PV capital costs, including many scenarios in which 2050 costs are above current costs (27). A notable finding is that future PV growth rates in non-IPCC scenarios are not only higher than those on IPCC scenarios but have been increasing over time (28). IAMs also include technical constraints that may slow variable renewables' growth, such as higher integration costs at high shares of variable renewables and additional costs due to electrification of sectors that depend heavily on solid, gasified or liquid fuels. A specific concern is that IAMs lack hourly resolution of electricity supply and demand, rendering modeling of the integration of intermittent renewables difficult. In turn, models assume integration costs of 23 $/MWh for solar and 37$/MWh for wind in low-penetration scenarios (<20% of demand) (34), costs that increase to above 100$/MWh for higher penetration (35). At least one integrated assessment model, REMIND, has been updating its assumptions on integration costs, leading to substantial increase in intermittent renewable shares of electricity supply (36). Several models have also included hourly resolution (37), but results have not yet been published. As a result of these assumptions on PV and the broader energy system, biomass remains a preferred option in IAMs valued for its flexibility as energy carrier in different sectors, for example in transport, and in some models for its contribution in providing baseload electricity. In turn, intermittent renewables are limited, as demand flexibility and storage technologies are assumed to be costly or not represented in models. Demand-side solutions, e.g., load smoothing via price signals, are only now considered in some new scenario runs.

Missing innovation dynamics in demand as well as in renewables and storage

IAMs are missing much of the innovation dynamics that are rapidly changing energy systems across the world. The dynamics in solar discussed above represents a broader phenomenon increasingly observed: granular technologies—those with small unit size that are amenable to scale through aggregation—show much faster innovation dynamics than large scale technologies (Figure 5) (38). Granular technologies learn faster and become adopted faster, because they involve lower risk, involve many more iterations and thus opportunities for improvement, and are suitable in a much broader variety of adoption contexts. Most demand-side technologies are granular (38, 39) since they are almost always small scale. Examples include heat pumps, lighting, appliances, windows, and batteries (Figure 5). The enhanced dynamics observed in granular technologies point to a much larger potential for reducing energy demand as those technologies also improve and become adopted more quickly. In addition, general purpose technologies such as digitalization facilitate novel service provisioning systems, which enable the satisfaction of needs and wants while reducing associated primary energy demand and GHG emissions (40). Examples include compact cities that increase accessibility while reducing travel distance demand (41), flexitarian or vegan diets that are healthy and tasty while reducing meat production (42), and the integration of electronics into a single gadget (32).

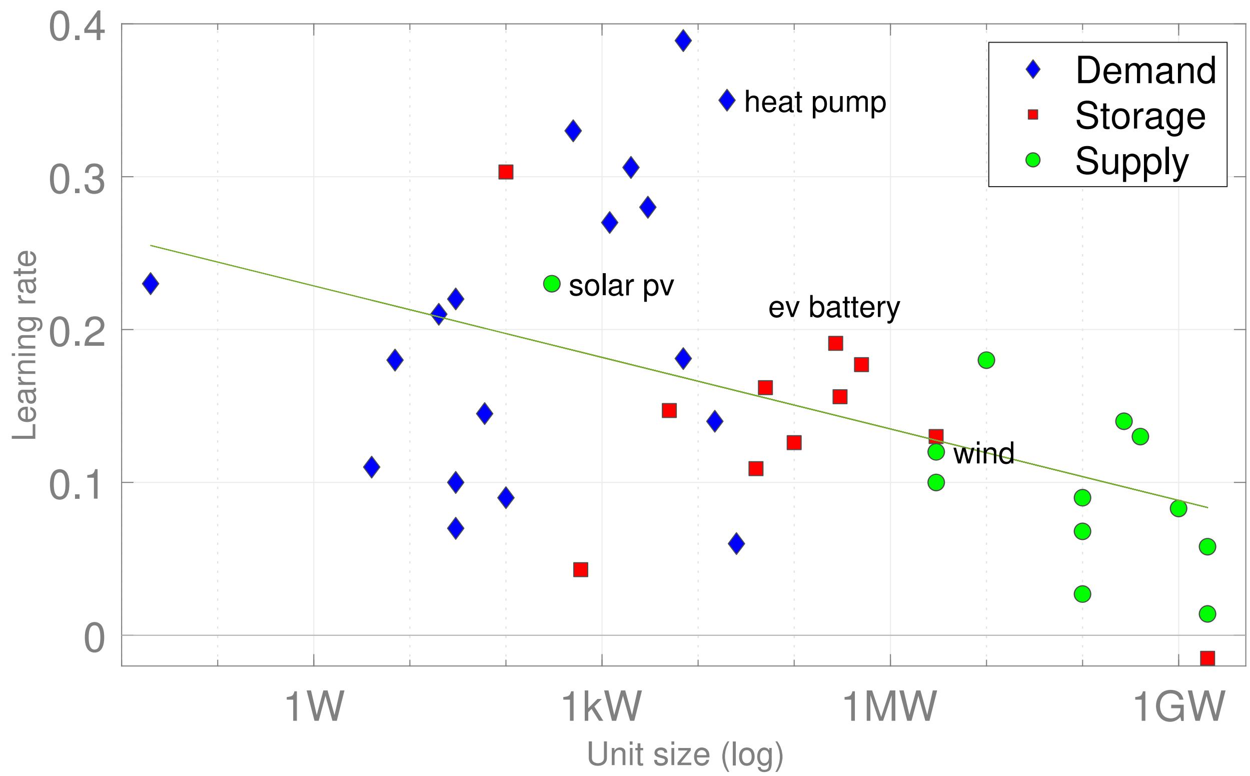

Figure 5. Demand technologies show high learning rates. *Learning from small-scale granular technologies outperforms learning in larger supply side technologies. Line is linear fit of log unit size to learning rate for all 41 technologies plotted. Source: (39)*

Resulting energy demand scenarios contrast with high energy demand in many IAMs. In all SSPs, energy demand rises from 580 EJ in 2019 to above 700 EJ in 2050 and in SSP5 to more than 1200 EJ in 2100. This is more than twice the current level (in non-mitigation scenario this demand is mostly satisfied with coal, Fig 1A). In contrast, recent models that take a service provisioning perspective suggest that a global reduction of more than 40% in primary energy use between 2020 and 2050, driven by demand-side granular technologies and service system configurations, is possible and consistent with conditions required for a good life (32, 43). Importantly, the 245 EJ modelled in a low energy demand scenario for 2050 (32), and the 149 EJ minimal energy required for a decent living for all in 2050 (43), are within scope of what PV can provide, even in some integrated assessment scenarios (Fig 4).

We note also that even on the supply side, rapid innovation extends beyond solar (Figure 5). Onshore wind, offshore wind, as well as mobile and stationary batteries have shown similar learning for many of the same reasons: modularity, massively iterative manufacturing, and simplification that comes from shifting much of the most cutting edge technology to production rather than in devices (44). As a result, in just the past 10 years, the cost of electricity from solar has fallen by 87%, wind by 38%, and battery storage by 85%. Wind and solar have grown from 1.4% of global electricity supply in 2009 to 8% in 2019, and they continue to grow, as a variety of new countries adopt them. While not pervasive yet, one can observe profit maximizing firms shutting down existing coal plants and replacing them with new hybrid solar-battery systems, even in markets ws1ith no carbon price or other climate policy (45); in an increasing number of places building new solar is cheaper than just the operating costs of coal plants.

Mitigation pathways are cheaper than expected

These dynamics and the observed bias in climate stabilization models have major implications for climate change mitigation and associated policies. Solar and wind are now cost competitive with fossil fuels in most world regions (46), resulting in constantly reduced cost estimates of investments required to curb global warming (47). The reductions in costs described above have led to levelized cost of energy (LCOE) for unsubsidized solar PV and wind of about 30-40 $/MWh and thus outcompeting the marginal cost of electricity from coal (48). In the first half of 2020, 90% of private investment in new energy capacity was in renewables (IEA). As intermittent renewables obtain higher market shares, the capacity factor of fossil-fuel based coal and gas plants declines rapidly, which in turn increases their LCOE. This reduces construction of new plants, and to the extent that some operational costs are fixed, hastens the retirement of existing plants (49). In fact, low-cost renewables foster mitigation even when only weak climate policies are present (while alone falling short of ambitious climate mitigation goals) (50).

A key mechanism for rapid decarbonization with intermittent renewables is sector coupling, i.e. direct and indirect electrification of transport, heating, and industry via power-to-X processes. A multi-sectoral, multi-regional cost optimal pathway for 145 regional energy systems reveals that stabilization at 1.5°C can be achieved by 100% renewable energy and sector coupling, while realizing substantial energy savings and providing lower cost energy compared with today (31). Crucially, rapid electrification increases overall energy efficiency, thus enabling a decline of total primary energy demand from 450 EJ in 2015 to 280 EJ in 2035, while simultaneously increasing energy services provided (totally primary energy demand increases again to 540 EJ in 2050, roughly consistent with SSP1 specifications) (31). This intermittent renewable based 1.5°C pathway requires a more than 5-fold increase in electricity supply from 2015 to 2050, dominated by wind energy until 2030, and thereafter by solar PV. Heat pumps and electric heating will provide a share of more than 40% of all heating by 2050. The associated capacity growth, especially in solar PV, is not constrained by materials, and could be ramped up to capacity levels beyond what is needed in 2050 (51). This renewable focused energy transition would keep LCOE stable. While capital investments would triple, the concurrent reduction in marginal fossil fuel costs would counteract increased financing needs, keeping levelized costs at around 50–57 €/MWh between 2020 and 2050 (31). Another energy system model finds that European levelized costs of electricity will fall from the current 69 €/MWh to 51 €/MWh, if 100% of electricity is provided by renewables, mostly solar, and if grid interconnections are expanded (52). These scenarios demonstrate that high renewable pathways matching a low to medium energy demand corridor of 250 to 500 EJ can achieve net-zero carbon until 2050.

While investment needs remain substantial, and access to finance in low and middle income countries is crucial, these results demonstrate that high PV scenarios are not only cost competitive in comparison to other future technology mixes, but that economies will even save money in the medium term. Not only is a different set of technologies expected to deliver rapid climate change mitigation – intermittent renewables instead of biomass with CCS – but also that the costs of climate change mitigation appear lower than previously expected and lower than those portrayed in IAM scenarios. Further, the history of innovation suggests that public supported for innovation dynamics can generate booms for economies, rather than burdens (53).

Another main implication concerns the use of scenarios within the IPCC. Scenario models may need to refocus on using up-to-date data on adoption, costs, and learning to ensure that models remain useful for policy decisions. (54) From our perspective, we see three modeling innovations that deserve immediate attention: 1) updating of renewable energy cost assumptions and fuller representation of technological learning curves, 2) more explicit modelling of sector coupling and specifically power-to-X technologies, and 3) including insights from hourly resolution modelling of energy systems (27, 33, 55). Meanwhile, a consideration of energy system models that lack integrating climate considerations but maintain high spatial and temporal resolution in energy systems and up-to-date technology representation at decade long time scales, such as the LUT Energy System Transition model (31, 56), would complement the century long modelling of IAMs in IPCC reports.

It can take ten years or more to proceed from model update to publication, to reflection in assessment reports like the IPCC, to publication of IPCC reports, to mainstreaming of messages in the public, means that rapid technological. The length of these timelines in a context of rapidly developing technology can make policy messages outdated. With dynamic technologies like solar, wind, and lithium ion batteries, even using data 5 years old can be misleading to decision makers. To improve this situation, all steps of climate stabilization scenario generation and publication should be accelerated. Specifically, this may include higher reliance on modular and more agile model structures, annually updated scenario databases and associated publications, and a strong emphasis on models gauged with most recent empirical data in assessment reports (54). A higher diversity of models and scenario methods included in IPCC assessments would better represent multiple perspectives on intermittent renewables, sector coupling and energy end use (28, 57). At the same time, the desirability of full integration of all relevant dimensions should not sideline up-to-date consideration of technological learning and adoption.

Solution pathways with intermittent renewable energies and granular technologies, including end use, are among the most cost effective and are in line with recent real world energy system dynamics. Phasing out coal will require regulation, minimizing end use efficiency rebound will require policy, and ramping up solar and end-use technologies will need additional investments. Yet, our observations indicate that there are good reasons to expect that global efforts to reduce GHG emissions can be done more cost effectively than widely assumed, which makes reaching the goals of the Paris agreement more likely.

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Data and materials availability: See Materials and Methods for references to the databases accessed.

Supplementary Materials:

Materials and Methods

To estimate logistic growth rates from historical data, we fit both logistic and exponential curves to the shares of electricity from different sources like solar, wind and biomass as computed from world energy data (58). Because the estimates depend on the fitting method, we fit the curves using non-linear least squares on the values themselves as well as on their natural logarithm with the scipy package (59). Finally, we vary the onset of historical data points from 1985 to 2000 (with fixed end year 2019). We pool all estimates for the logistic growth rate from these variant strategies and use the full range of the resulting values as a comparison to logistic growth rates from IAMs in Fig. 3.

The SSP scenarios displayed in Figure 1 are taken from the SR1.5 Scenario Explorer (60). The light-coloured ribbons indicate the multi-model range while dark-coloured solid lines represent medians across models.

The scenarios depicted in Figure 2 have been compiled from the IPCC Fifth Assessment Report (61), the AMPERE (62, 63), LIMITS (64, 65) and RoSE databases (66, 67) and SR1.5 database (60). The classification of coal dynamics (i.e. swift phase-out, delayed phase-out, persistence and resurgence) are taken from source (4).

The scenarios shown in Figure 3 are from (4), SR 1.5 database (60) and the World Energy Outlook (68). Well-below 2°C scenarios correspond to the categories Below 1.5C, 1.5C low overshoot, 1.5C high overshoot and Lower 2C of the SR1.5 database.

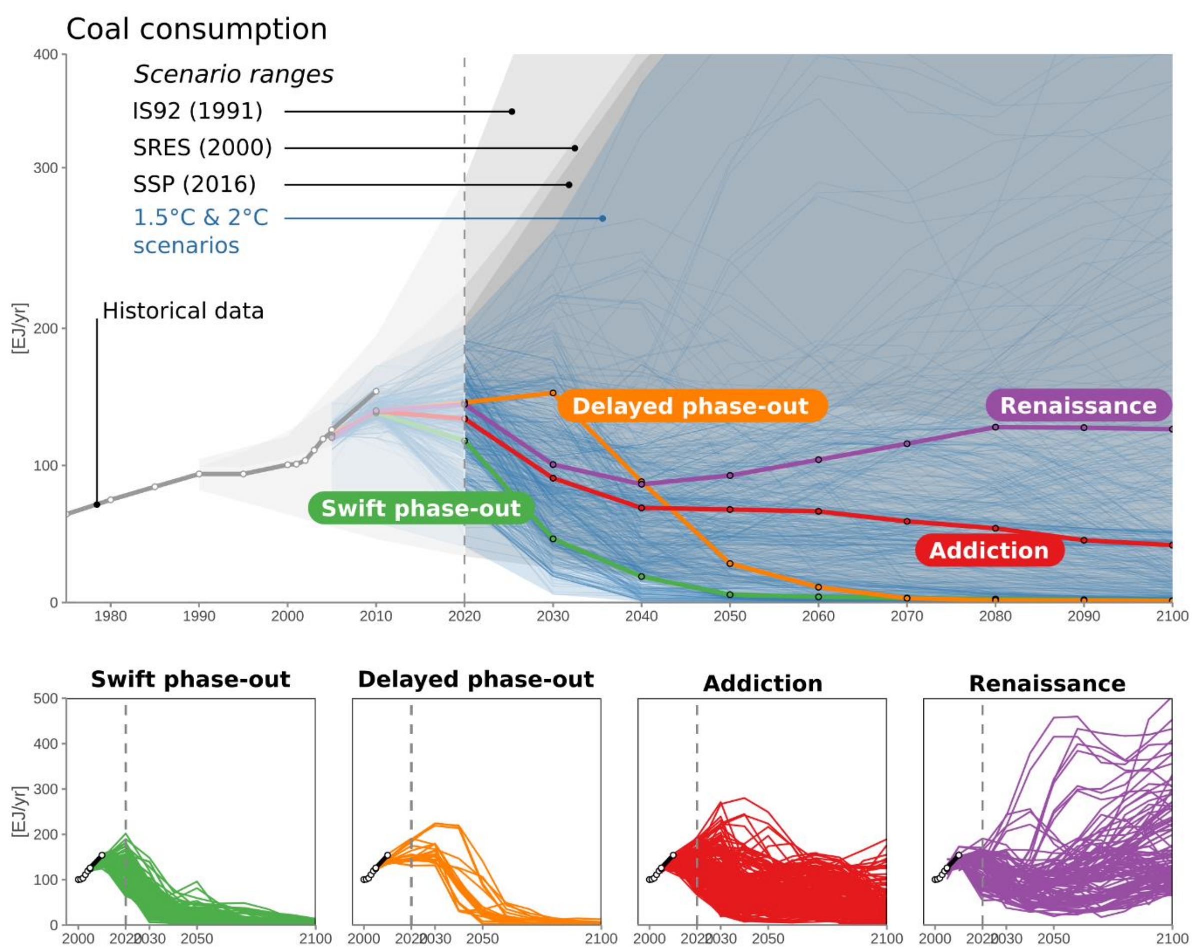

Figure S1. Coal transition archetypes in Paris-consistent mitigation scenarios. The upper panels show 592 coal transition pathways in 1.5°C and 2°C scenarios. The grey shaded areas shows the extended range of coal consumption in baseline scenarios of key scenario ensembles: IPCC IS92 emission scenarios (69), IPCC SRES scenarios (70) as well as the Shared Socio-Economic Pathways (SSPs) (71)(Riahi et al 2017). The colored pathways show median scenarios of four archetypical scenario clusters in the lower panels. The lower panels show all member scenarios of the respective coal transition pathway clusters. Source: (4)

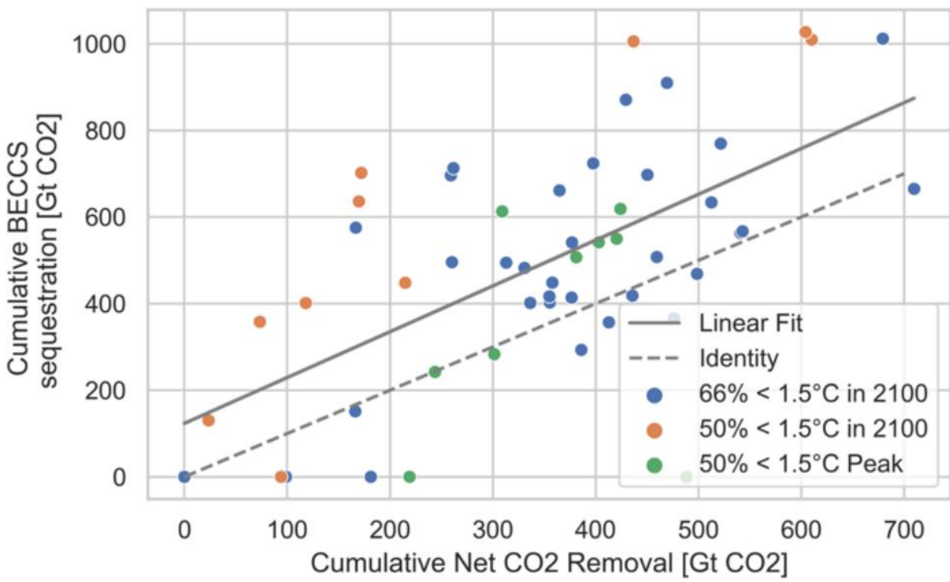

Figure S2. In models, BECCS depends on CDR demand. In scenarios underpinning the IPCC Special Report "Global Warming of 1.5°C" (SR1.5) consistent with 1.5°C warming, BECCS demand increases with cumulative net CO_2 removal. Source: *(21)*.

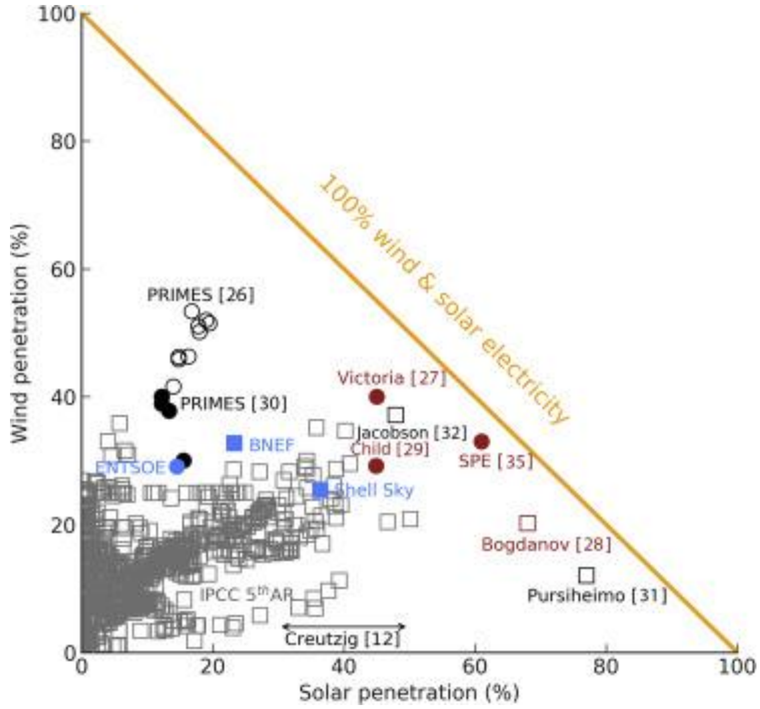

Figure S3. Recent models suggest that share of solar and wind can have much higher share of global electricity supply in 2050 than what is suggested from scenarios underpinning the 5th Assessment Report of the IPCC. Source: (27)