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Energy system developments and investments in the decisive decade for the Paris Agreement goals

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Abstract

The Paris Agreement does not only stipulate to limit the global average temperature increase to well below 2°C, it also calls for "making finance flows consistent with a pathway towards low greenhouse gas emissions". Consequently, there is an urgent need to understand the implications of climate targets for energy systems and quantify the associated investment requirements in the coming decade. A meaningful analysis must however consider the near-term mitigation requirements to avoid the overshoot of a temperature goal. It must also include the recently observed fast technological progress in key mitigation options. Here, we use a new and unique scenario ensemble that limit peak warming by construction and that stems from seven up-to-date integrated assessment models (IAMs). This allows us to study the near-term implications of different limits to peak temperature increase under a consistent and up-to-date set of assumptions. We find that ambitious immediate action allows for limiting median warming outcomes to well below 2°C in all models. By contrast, current nationally determined contributions for 2030 would add around 0.2°C of peak warming, leading to an unavoidable transgression of 1.5°C in all models, and 2°C in some. In contrast to the incremental changes as foreseen by current plans, ambitious peak warming targets require decisive emission cuts until 2030, with the most substantial contribution to decarbonization coming from the power sector. Therefore, investments into low-carbon power generation need to increase beyond current levels to meet the Paris goals, especially for solar and wind technologies and related system enhancements for electricity transmission, distribution and storage. Estimates on absolute investment levels, up-scaling of other low-carbon power generation technologies and investment shares in less ambitious scenarios vary considerably across models. In scenarios limiting peak warming to below 2°C, while coal is phased out quickly, oil and gas are still being used significantly until 2030, albeit at lower than current levels. This requires continued investments into existing oil and gas infrastructure, but investments into new fields in such scenarios might not be needed. The results show that credible and effective policy action is essential for ensuring efficient allocation of investments aligned with medium-term climate targets.

Introduction

Context

The Paris Agreement aims to hold the increase in global average temperature well below 2°C and to pursue efforts to limit it to 1.5°C. It also calls for finance flows to be consistent with these global goals. While 1.5°C and 2°C goals are to be met by 2100, the 2020s have been identified as the decisive decade for achieving them. The next decade is indeed crucial as any delay in climate action can stimulate the construction and lock-in of additional carbon-intensive energy technologies, leading to an overshoot of the 1.5°C goal while rendering the transition to a low-carbon system more difficult (Tong et al. 2019).

In this context, scenario ensembles are an important tool for understanding, in a systematic fashion, the implications of climate goals and delayed climate action for the future development of the energy system and the associated investment needs. However, a sound and policy-relevant analysis cannot only rely on a transparent forward-looking approach like integrated assessment models (IAMs) but must also consider the latest available information on techno-economic developments (e.g. current and future anticipated capital costs of mitigation technologies) and policy data (e.g. NDCs) at the global and national levels (Schaeffer et al. 2020). In addition, scenario data must reflect current real-world dynamics in the short-term. This is all the more important as scenario data are increasingly used to assess the financial risks of the low carbon transition and the level of alignment of investment portfolios with temperature targets (Weber et al. 2018; NGFS 2020).

Current knowledge

Previous research has investigated in detail the implications of current country policies and pledges (Vrontisi et al. 2018; Roelfsema et al. 2020), medium-term decarbonization requirements (Luderer et al. 2018) and energy investment needs for different long-term climate targets (McCollum et al. 2013; 2018; Kober et al. 2016). The latter revealed that overall energy investments over the next three decades need to be scaled up to reach an end-of-century target of 2°C and that investments need to shift from fossil to low-carbon energies and energy efficiency.

However, these past modeling studies have been criticized for their lack of realistic near-term projections, in particular insufficient reflection of current trends of increasing deployment of renewable technologies and declining costs (Creutzig et al. 2017), and underestimation of the growth potential of granular or small-scale technologies like solar, wind, batteries and electric cars in the near-term (Wilson et al. 2020; Sweerts, Detz, and van der Zwaan 2020). They have also been singled out for their extensive use of carbon dioxide removal (CDR) options in the long-term, like bioenergy with carbon capture and storage (BECCS) and afforestation (Anderson and Peters 2016). These technological solutions allow compensation of temporary temperature overshoots by net-negative emissions in the last decades of the 21st century, and the assumption about their long-term availability influences the required level of near-term ambition (Kriegler et al. 2018; Hilaire et al. 2019) . While these technologies could materialize in the future, alternatives might be more attractive as previous studies point to the land requirements for some of these options or the lack of current progress on key technologies (Smith et al. 2016; Fuss et al. 2018). Furthermore, the economic climate damages associated with a temporary overshoot of temperature targets and high temperature gradients (McKenna et al. 2020) have not been considered in models (Schultes et al. submitted). To address these concerns, a new scenario design with an explicit definition of net-zero CO_2 budgets (i.e. with a bound on cumulative emissions until reaching net-zero CO_2 emissions) has been proposed (Rogelj et al. 2019), structurally disentangling the near-term question of limiting peak temperature with the longer-term question whether or not to bring down temperatures strongly afterwards via CDR and thus allowing for a more comprehensive set of scenarios.

Moreover, the scientific evidence on how current and planned investments in the energy system align with the temperature goals of the Paris Agreement and how they should develop over the next few decades remains scarce. The latest IPCC assessment on 1.5°C noted that the literature on the subject is “relatively sparse” and focuses primarily on 2°C pathways.

Our contribution

Here we present a new detailed analysis of the implications of peak-warming targets (using net-zero CO_2 budgets as proxies) for the energy system up to the year 2030. We use a scenario set that spans a wide range of peak temperature targets including 1.5-2°C. This allows us to more finely assess the impact of delayed climate action and establish a clear connection between near-term energy investment requirements and peak warming consequences. Furthermore, our study is based on an updated set of policy, socio-economics and techno-economic assumptions and revised model versions. The models have been subject to a thorough vetting of current developments of key technologies, especially solar and wind. This enables us to clarify some ambiguities regarding technology priorities in earlier studies (McCollum et al. 2018). The increased technology resolution in the presentation of results furthermore allows for differentiating between more and less robust results regarding technology choice across models.

This article focuses primarily on near-term energy system developments and investments. Other articles from the same study (“ENGAGE”) and based on the same scenario dataset analyze implications for the land-use system (Hasegawa et al. (submitted)), the macro-economic mitigation costs of limiting warming to different levels (either via net-zero or end-of-century CO_2 budgets) and requirements for net-zero energy systems (Riahi et al. (submitted)), and unavoidable residual damages at different peak warming levels (Drouet et al. (submitted)).

Methods

The following paragraphs provide a short overview of the scenario design, the models, their calibration and the vetting of near-term developments, and the analysis and comparative data. More details on each of these topics can be found in the Supplementary Material.

Scenarios

This study is based on a harmonized ensemble of scenarios from seven IAMs: GEM-E3, IMAGE, MESSAGEix-GLOBIOM, POLES, REMIND-MAgPIE, TIAM-ECN, and WITCH. The scenario set includes two prospective scenarios, extrapolating the implied ambition levels of current policies (**“NPi”**, for “implemented national policies”), and those of NDC targets for 2030 (**“NDC”**) without explicit medium-or long-term targets. Additionally, two sets of scenarios explore a range of net-zero CO_2 budget scenarios, ranging from 400-3000 Gt CO_2, measured from 2018 until the year of net-zero CO_2 emissions. Non-CO_2 greenhouse gases in these scenarios are priced equivalently to the implied CO_2 prices, using 100-year global warming potentials for conversion. The first set explores **“Immediate”** policy action after 2020, while the second set of **"Delayed"** scenarios follows the trajectory of the NDC-extrapolated scenario until 2030, and only after that shifts to comprehensive policies towards the peak-budget target (without anticipation before). After reaching net-zero CO_2 emissions, total CO_2 emissions are kept net-zero, with a tolerance of +/-0.2 Gt CO_2. Unlike companion studies (Riahi et al. (submitted); Drouet et al. (submitted)), we focus here exclusively on scenarios with a net-zero budget formulation. Figure 2a includes a comparison of five additional scenarios using the end-of-century budget definition (further explored in (Riahi et al. (submitted)), with the net-zero budget scenarios and shows the equivalence of both scenario sets for the question explored here.

The scenarios are all calibrated to a middle-of-the-road SSP2 socio-economic baseline regarding GDP and population developments (Fricko et al. 2017). The COVID-19 crisis and the related drop in GDP, energy demand and CO_2 emissions are not included in the default model runs. The direct CO_2 reduction impact of the COVID-19 crisis in 2020 (Le Quéré et al. 2020) is small compared to the 400 to 3000 Gt CO_2 budgets used in this paper. The potential implications of the secondary impacts of COVID-19 on the development of the economy and investments (Cherp and Jewell 2020; Andrijevic et al. 2020) are qualitatively discussed in the discussion section, based on recent literature and additional sensitivity scenarios assuming a lower near-term GDP trajectory as a result of COVID-19 (see supplementary Figures S13 and S14).

Models and scenario vetting

This study uses seven global IAMs, all of which have previously been documented and discussed in the literature, and most of which have openly available source code. The scenarios from all models were thoroughly scrutinized with respect to recent trends up to 2019 of deployment levels of key energy technologies (BP 2020) and their cost assumptions, especially for those with rapidly falling costs such as solar photovoltaics, wind (IEA 2020b). Furthermore, near-term deployment until 2030 was reviewed for technologies with long construction and planning lead-times like nuclear and carbon capture and sequestration (CCS) to avoid unrealistic capacity expansion beyond existing plans and proposals (World Nuclear Association 2020).

Analysis and historical data

The analysis here relies primarily on explicitly represented variables in the models. An exception is global mean temperature, which has been calculated using a harmonized version of the reduced-complexity climate model emulator MAGICC, version 6.0 (Meinshausen, Wigley, and Raper 2011). Furthermore, some of the investment variables are not explicitly represented in some of the models. For models not representing investments into fossil fuel extraction or using different definitions, these have been estimated by multiplying regional extraction (calculated as the difference between primary energy usage and net trade) by a constant investment intensity estimated from IEA's global investment and primary energy data in 2019 (IEA 2020a). Investments into energy efficiency have been derived from final energy savings for all models using the approach presented by McCollum et al. (McCollum et al. 2018). Several plots in the results section compare scenario data with historical and scenario data from the IEA and BP (BP 2020; IEA 2020a). All absolute investment numbers are given in US$2010.

Most models run on 5-year time steps (except TIAM-ECN with 10-year time steps, and POLES and IMAGE with annual time steps, though only 5-year time steps are reported for these models). Most of the analysis is presented in terms of 2030 values or average values for the periods 2025 and 2030. In most models, these time steps represent the years 2023-2032, except for MESSAGE-GLOBIOM, where they represent the years 2021-2030. The choice of this temporal focus depends on the fact that including the (fixed) 2020 time step into calculation of yearly average (e.g. as would be done by calculating the 2020-2030 average from interpolated yearly data) would understate the impact of scenario-specific policy choices, which only materialize after the 2020 time step.

Results

Net-zero-budget determines peak-warming

Peak temperature correlates closely with the cumulative CO_2 budgets until CO_2 emissions reach net-zero. The relationship can be relatively well approximated by a linear relationship, starting with 1.48°C of median peak warming for a 400 Gt CO_2 net-zero budget and increasing by 0.05°C for each additional 100 Gt CO2 (Figure 1a).

Peak temperatures for a given net-zero CO_2 budget vary by less than +/- 0.13°C, which mainly comes from differences in non-CO_2 greenhouse gas emissions. To a lesser extent, differences are also due to the different temporal profiles of CO_2 emission reductions, which influence the timing of peak CO_2 forcing (see Supplementary Figure S1).

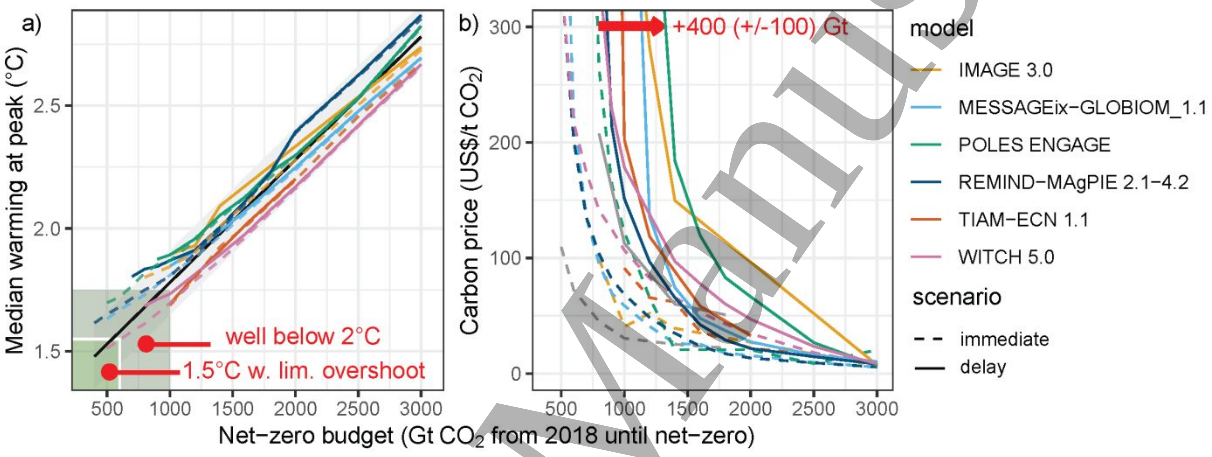

Figure 1: Relationship between peak warming and net-zero CO_2 budgets (a), and carbon prices 10 years after the introduction of comprehensive climate policies (i.e. in 2030 for immediate scenarios and 2040 for delayed scenarios) (b), for both immediate and delayed scenarios. The green shadings illustrate the areas of budgets that are in line with a possible definition of "well below 2°C" (median peak warming <1.75°C), and with a more stringent peak warming target compatible with achieving 1.5°C with only limited overshoot (median peak warming <1.55°C).

Impact of NDCs

In Delayed scenarios, in which no strengthening of ambition occurs before 2030, the feasibility frontier of net-zero CO_2 budgets (which corresponds to the very steep negative slopes in Figure 1b) shifts towards higher values (see red arrow) and, consequently, does the peak temperature. Furthermore, achieving the same CO_2 net-zero budgets after such a delay in comprehensive mitigation leads to slightly higher peak temperature outcomes, as peak CO_2 forcing is reached earlier and at a higher level (given the faster depletion of the budget). The forcing of the relatively short-lived climate forcer CH_4 is decreasing (and dominates the slowly increasing forcing of N_2O). Earlier peak CO_2 forcing results in earlier and higher overall peak forcing (Supplementary Figure S1) and temperature.

The high challenges of meeting low budget targets are reflected by the associated high carbon prices required in both immediate and delayed policy cases. Figure 1b shows the resulting trade-off curves of the carbon price required ten years after the introduction of ambitious, comprehensive policies (so in 2030 for immediate scenarios and 2040 for delayed scenarios). These are highly convex, indicating the escalating costs for very low temperature and budget targets (Luderer et al. 2013). The effect of delay is mostly a shift of these curves to the right to higher budget values. The shift for all models lies within the 300-500 Gt range, translating into roughly 0.2°C additional peak warming achievable for the same carbon price efforts in a delayed scenario. Therefore, the delay in all models makes peaking below 1.5°C impossible, and for some models, even limiting peaking to below 2°C with high likelihood becomes impossible at manageable carbon prices.

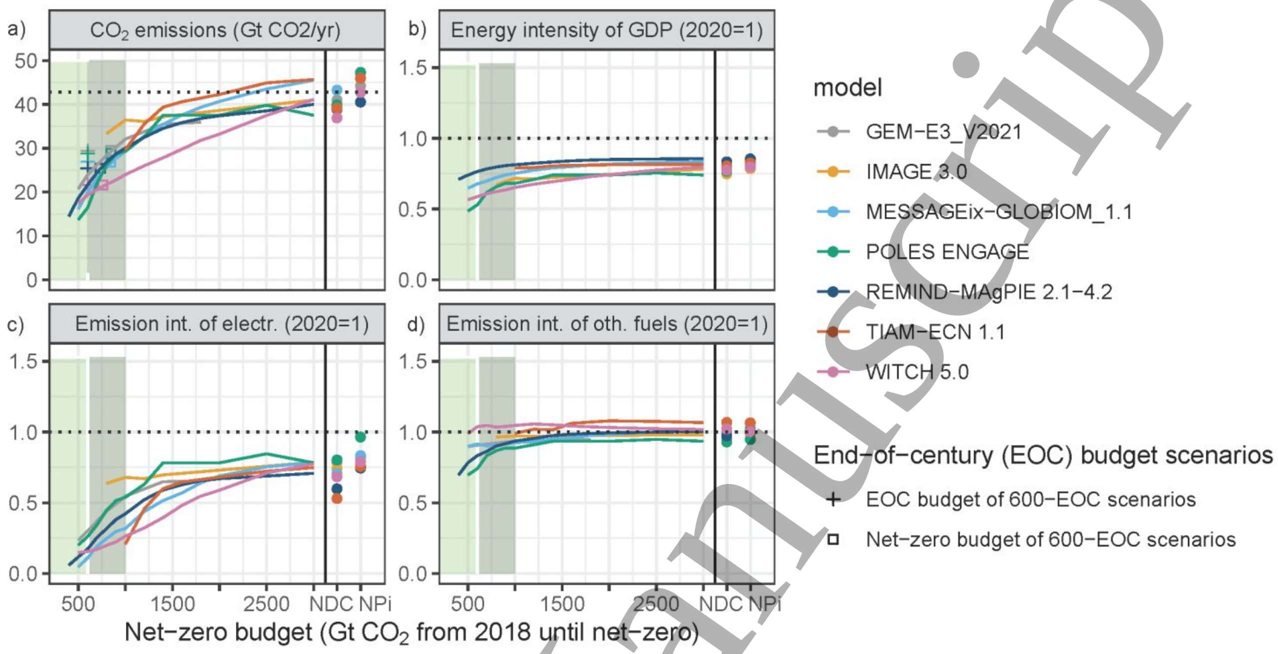

Figure 2: 2030 CO_2 emissions and changes in energy and emissions intensity indicators from 2020 to 2030 in immediate net-zero budget scenarios, as well as for the NDC and NPi scenarios. The dashed line denotes the estimated 2019 emissions (Friedlingstein et al. 2019) and the 2020 model value, respectively. Supplementary Figure S2 shows that GDP growth, the missing component of the commonly used Kaya decomposition of emission trends, differs slightly across scenarios.

2030 energy system transformation for ambitious net-zero budgets

To reach ambitious net-zero budget targets cost-efficiently, strengthening climate mitigation in 2030 is essential (Figure 2a). For the 600 Gt CO_2 net-zero budget target, our analysis projects a range of compatible 2030 CO_2 emissions of 16-25 Gt CO_2, corresponding to a reduction of 42-63% compared to 2019 levels (Friedlingstein et al. 2019). These net-zero budget scenarios feature substantially lower 2030 emission levels than 600 Gt CO_2 end-of-century budget scenarios as used in previous studies (McCollum et al. 2018), for which 2030 emissions are in a range of 21-31 Gt CO_2, or a 28-51% reduction relative to 2019. If, by contrast, net-zero budget scenarios and end-of-century budget scenarios are compared in terms of their net-zero budgets, i.e. cumulative emissions until reaching net-zero, their 2030 emissions are remarkably similar. In other words, near-term actions are not affected by what happens to emissions after they get to net-zero. Independently on whether emissions stay at net-zero (as done in the net-zero budget scenarios analysed here) or reach considerable net-negative levels to bring temperature down until 2100 (as in the end-of-century budget sensitivity scenarios), investments of the coming decade are not affected. Energy efficiency improvements and demand reduction (Figure 2b), switches to inherently cleaner fuels, CDR, and the decarbonization of different fuels all play a role in this increased mitigation action. However, the decarbonization of electricity supply (Figure 2c) stands out across all models showing the highest response to policy signals, contributing the most to overall mitigation by 2030. The carbon intensity of power supply drops to -80% compared to 2020 values in the most ambitious scenarios in all but one model (see Supplementary Section "Model differences" for explanation). In contrast, the average carbon intensity of the sum of all other fuels (solids, liquids, heat, gases, and hydrogen) only varies around +/-10 % of 2020 values in most models and scenarios. Only a few models project a reduction of up to -25% in the most ambitious budget cases. One reason for this significant drop is that the carbon intensity of power supply has already been on a declining trend for the past years (Bertram et al. 2021) and is also projected to decrease further with current policies, NDC targets or lenient net-zero budget targets, though not nearly at the rate compatible with low net-zero budget targets. The recent reductions in emission intensity of power generation have been caused by rising installations of renewables, mostly solar and wind, and a shift from coal to gas power generation in OECD countries. Fast decarbonization of power supply until 2030 is also an essential step for overall mitigation. This is a prerequisite for decarbonizing different demand sectors via electrification (Madeddu et al. 2020; Luderer et al. 2018) or the provision of low-carbon electricity-based fuels like hydrogen.

Rapid investment shifts for 1.5°C peak warming

Limiting peak warming to close to 1.5°C requires a substantial increase in overall energy system investments by 2030 compared to levels in recent years. This net increase results from reduced investments into fossil extraction and increased investments into power systems, efficiency, and low-carbon fuels (see Figure 3 and Supplementary Figure S4). While in the past five years (2015-2020) investments into fossil extraction and power generation accounted for 50% of all energy-related investments, they account for less than 20% by 2030 in scenarios with a 600 Gt CO_2 net-zero budget constraint. Conversely, investments into low-carbon power generation accounted for 15% recently but rise to more than 30% by 2030, corresponding to a quadrupling in absolute volumes. In later decades, the relative importance of low-carbon power generation decreases again, as most of the growing investment effort is directed to efficiency and low-carbon fuels supply, including hydrogen. Although it is not surprising to observe that the uncertainty of investment shares increases further into the future, it is worthwhile to note that this is also the case for more lenient climate targets (see Supplementary Figure S3).

The increase in overall investment volumes required for ambitious temperature targets leads to an increase in the share of energy investments in total GDP from 3 to up to 5% in the coming decades. In contrast, without ambitious policies, this share would continuously decrease (see Supplementary Figure S16). However, it is important to keep in mind that increased investments in climate policy scenarios are partly offset by reduced fuel expenditures – although this can vary significantly across regions and is especially problematic for major fuel exporters.

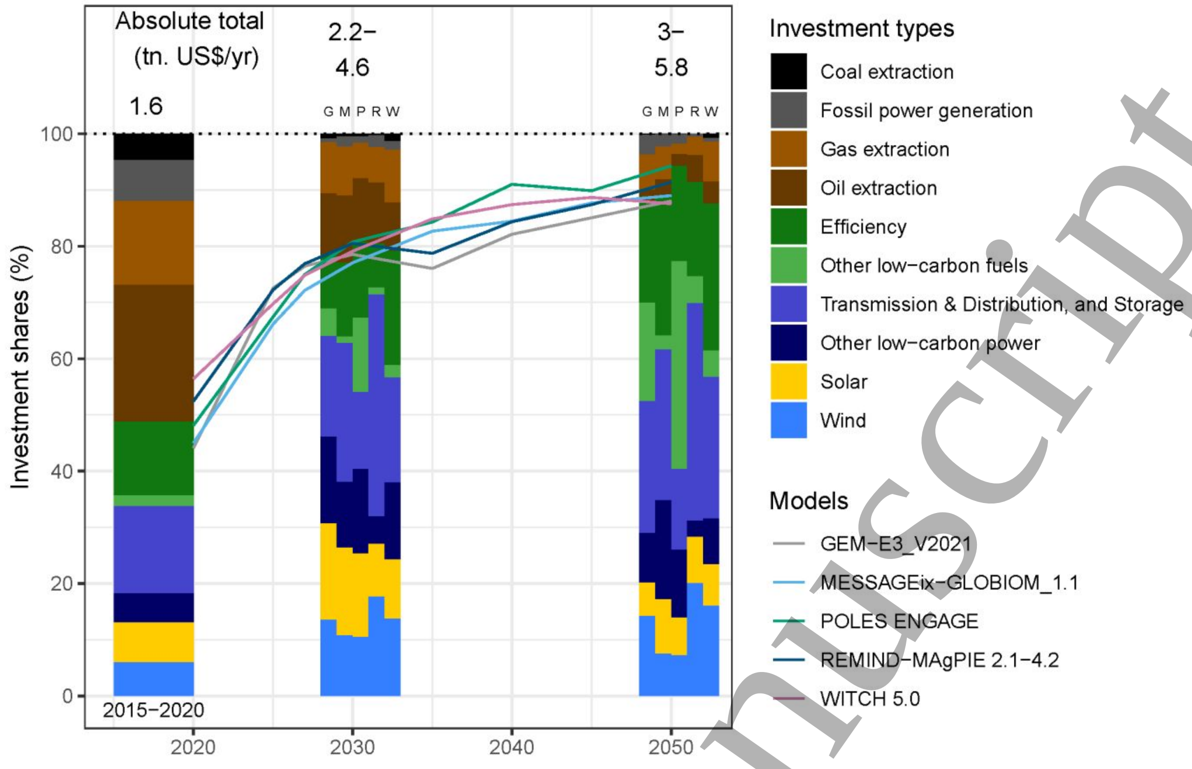

Figure 3: Investment shares (bars), and share of total investments into non-fossil technologies (lines) for all 600 Gt net-zero budget scenarios. See Supplementary Figure S3 for the figure with 1000 Gt net-zero budgets. Estimated average yearly investment numbers for 2015-2020 from IEA (IEA 2020a). Other low-carbon fuels includes hydrogen and biomass investments.

2030 investments for ambitious net-zero budgets – low-carbon power generation

Deep decarbonization of the power supply for very low carbon budgets requires a substantial increase in the sector's average annual investments in generation capacity compared to historic levels, by up to a factor of 3 for the total. Most low-carbon power generation technologies have relatively high capital costs and moderate operation and maintenance costs. Hence, upfront investment costs represent the lion's share in total electricity generation costs of these technologies. This is also why power sector investments dominate total energy investments in the first decades of very ambitious climate scenarios. These investments both decarbonize the existing power system and lay the foundation for later decarbonization of other sectors via (direct or indirect) electrification.

Three components dominate the investments into low-carbon power generation (Figure 4): Solar, wind, and the investments for enabling the integration of these technologies to the grid, primarily for the expansion of grid infrastructure and electricity storage; these three components also show the highest response to decreasing budget targets, up to four times the level in 2020 (which, given cost reductions implies an even stronger increase in capacity additions for solar and wind, see also Supplementary Figure S15). To balance intermittent supply from wind and solar with demand variation, both higher transmission and increased electricity storage are required for achieving high penetration rates of renewables. While storage and grid expansion might partly substitute each other, their combined investments always increase with higher target stringency. On the other hand, solar and wind are good complements due to their different diurnal and seasonal generation profiles, so that a balanced investment into both options is a robust strategy.

Fossil-based power generation investments decrease to very low levels for very stringent net-zero budget targets. All pathways consistent with the temperature goals of the Paris Agreement feature no investments in new coal-fired power plants without CCS. In contrast, gas power increases in most scenarios in fast-growing economies to compensate the rapid phase out of coal-power generation and to act as flexible peak capacity for variable renewables (Supplementary Table S2).

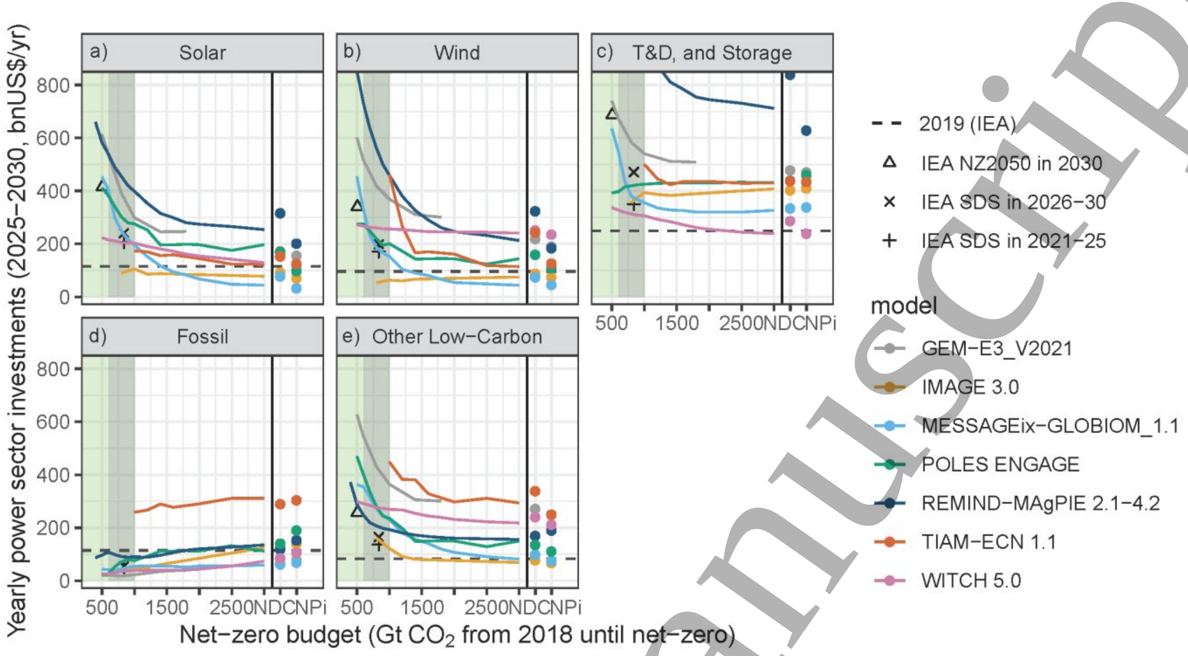

Figure 4: Average yearly power sector investments by energy technology category (2025-2030), in immediate net-zero budget scenarios, as well as the NDC and NPi scenarios. Other Low-Carbon includes nuclear, biomass, and hydro, plus geothermal and ocean energy for those models that include these options (See Supplementary Figure S5 for the corresponding plot of these individual options and Supplementary Figure S13 for a variant of this Figure with additional sensitivity scenarios including a COVID-19 shock on near-term GDP projections).

Other low-carbon options (see Supplementary Figure S5) include nuclear energy, hydropower, biomass-based electricity generation, and for those models representing it geothermal and ocean energy. Due to more complex and longer planning times (nuclear and hydro), context-specific supply chain constraints (biomass), and decreasing competitiveness with solar and wind power, the upscaling of these options for low carbon budgets is lower (Wilson et al. 2020). Given that these options offer firm capacity, they continue to attract investment despite being more expensive (Sepulveda et al. 2018). Thus, the complementarities across technologies lead to a relatively broad investment portfolio in all models and diverging results on relative shares of individual technologies. Given the high uncertainty about future costs and other characteristic of short and long-term storage technologies (Sepulveda et al. 2021), the optimal investment levels into transmission and storage vary even more strongly across models than the investments into other technologies (see also section “Model differences” in the Supplementary Material).

2030 investments for ambitious net-zero budgets – efficiency and other low-carbon solutions

Two other streams of investments are crucial for successfully achieving ambitious net-zero budget targets: Firstly, investments into efficiency in all three end-use sectors (transport, buildings and industry) are crucial for limiting the growth in energy demand and thus enabling economic prosperity for a growing global population within the boundaries of sustainable energy supply. The investment requirements are shown in Figures 3 & Supplementary Figures S3 and S4 and are estimated using a simple methodology based on reductions of final energy demand compared to a reference scenario and information on supply investments (McCollum et al. 2018).

Secondly, although investments into low-carbon fuels and CCS infrastructure are somewhat limited in volumes compared to investments in low-carbon power generation, these early investments into currently nascent technologies like hydrogen, synthetic fuels, and advanced biofuels are essential as they represent crucial options for achieving net-zero targets in hard-to-abate sectors (Detz, Reek, and Zwaan 2018) such as high-temperature industrial processes and transportation. Therefore, investments in other low-carbon fuels, including hydrogen and bioenergy with CCS, also increase considerably in later decades (see Figure 3 and Supplementary Figures S3 and S10).

2030 investments for ambitious net-zero budgets – fossil fuels extraction

The results for investments into fossil fuel extraction consistently show a decline for lower budget targets (Figure 5a). The magnitude of this decline in investments, however, is less clear than in the power sector. This can partly be explained by a much higher uncertainty about investment requirements for given energy demands, which reflect the large technological differentiation of the fossil supply sector (ranging from conventional extraction with much lower investment requirements than, e.g. offshore oil). Results are much more consistent for overall 2030 demands for different fossil fuels (Figure 5b,c,d). Coal faces a reduction of up to two-thirds of 2019 levels. Reductions in oil and gas, by contrast, are more limited even under the most ambitious budget targets. This reflects their higher specific economic value, lower emissions intensity, and more difficult near-term substitutability, which leads to lower reductions at a given carbon price. Some of the lowest scenarios project 2030 oil demands that are lower than the level of oil supply that, according to a recent detailed analysis, can be achieved without investments into any new oil fields (IEA 2020b). However, this level of supply will still require continued investments into existing fields.

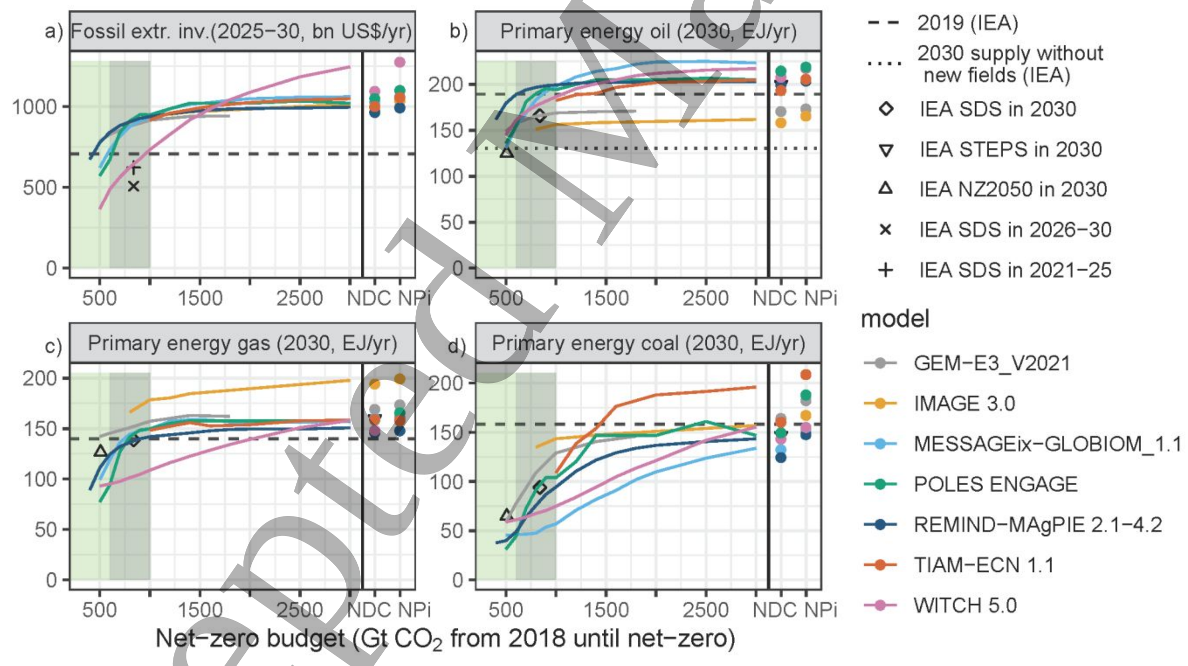

Figure 5: Average yearly investment in fossil extraction (2025-2030, a), and 2030 fossil fuel demand for oil (b), gas (c) and coal (d). Fossil fuel extraction investments are using the self-reported values for WITCH for oil, for which historic numbers are consistent with the IEA numbers used for comparison here. For other models and coal and gas, a simple estimation based on the average 2015-2019 investment intensity of primary energy use, and the observed fuel use in scenarios is used, likely overestimating investments for scenarios with declining demand. See Supplementary Material Section "Estimating investment data" for details and Supplementary Figure S14 for a variant of this Figure with additional sensitivity scenarios, including a COVID-19 shock on near-term GDP projections.

Discussion

The results of this study provide an updated and detailed perspective on the near-term energy system changes and associated investments that are consistent with the Paris Climate targets. They broadly confirm high-level results related to investment shift identified in similar earlier studies (McCollum et al. 2018; Kober et al. 2016). Given a careful vetting of scenarios for recent developments, especially regarding deployment and cost of low-carbon options, results across models are more consistent than most of these previous publications (for a discussion on model differences, see Supplementary Section “Model differences”). Thus, our study clarifies some of the previous ambiguity and addresses identified inconsistencies of previous scenarios, pointing out the crucial relevance of early decarbonization of power generation, mainly via a strong acceleration of solar and wind investments. The study also unpacks the temporal granularity of these investments, with a stronger focus on the near-term until 2030.

COVID-19

The scenarios presented in this analysis do not take the COVID-19 pandemic and the resulting global economic crisis into account. The time step ‘2020’ in the models, as all time-steps representing a 5-year period, is therefore calibrated to an energy system configuration based on the expected pre-COVID 2020 values. Numbers related to 2020 match well with recent data for 2019, while obviously data on energy use and emissions fail to reflect the reductions expected for 2020. More importantly, the 2025 and 2030 GDP assumptions are based on SSP2 trajectories and do not consider that the 2025 numbers might be lower due to COVID. Though uncertainty remains very high, five models ran additional sensitivity scenarios to test the impact of lower near-term GDP assumptions (Supplementary Figures S13 and S14). The results show that if

GDP levels in 2025 (and 2030) turn out to be lower than assumed in the default scenario, as currently projected by IMF (IMF 2020), overall energy demand will also be lower.This results in slightly lowered energy investment across all technologies in the sensitivity scenarios. . The effect on the power sector investment requirements for low net-zero budgets is limited (Supplementary Figure S13). Given that these investments also reflect the need for upscaling the related technological options with a view to longer-term net-zero energy systems, the investments in these options are increasing with increasing policy stringency, only slightly slower compared to scenarios with default GDP assumption.

If mobilizing investments would become harder due to a deepening economic crisis, this could impact investments, especially for financially distressed countries and institutions (Cherp and Jewell 2020). However, it should be noted that recovery investments are multiple times the volumes required for decarbonization globally in the next few years (Andrijevic et al. 2020). A possible impact might be more prominent for risky investments like nuclear, large hydro and CCS than for solar and wind, for which the business case will likely be more robust; investments into these technologies also remained robust in 2020 (IEA 2020b; BloombergNEF 2020). On the other hand, recovery programs might also support the further build-up of high-emitting infrastructures such as coal power plants, which would be a hurdle for ambitious mitigation.

The outlook for fossil fuels and required residual investments for low budget targets could be more strongly impacted by COVID-19, though the impact of the GDP effect in the sensitivity scenarios is also very limited (Supplementary Figure S14). Suppose behavioural changes favour less business-related air travel, and more home-based work remains partly in place after the current crises. In that case, this could lead to a decrease in oil demand beyond the pure GDP effect considered in our sensitivity cases here. This could imply that no new oil fields are required for slightly higher targets, including the well-below 2°C. In any case, the higher uncertainty regarding future demand for oil and gas has already led to a shift towards smaller, shorter-cycle investments in this sector (IEA 2020b).

Limitations

It is important to note that lower investments in low-carbon fuels than low-carbon electricity do not imply that these investments are less important. Given that some sectors will not be able to be electrified directly, it is crucial for the feasibility of net-zero energy systems that these options are scaled up. Low-carbon energy carriers such as e-fuels (Detz, Reek, and Zwaan 2018) may well be needed in those sectors for which electrification is either infeasible or too costly; early investments will assist in stimulating learning phenomena that can render these fuels cheaper in the future. Given their earlier development stage and thus higher risks, they will also require other forms of investments.

The methodology for estimating energy efficiency investments does not allow for disaggregating investment requirements into different end-use sectors. Therefore, both estimates for efficiency and fuel extraction investments are less accurate than the estimates on investment requirements for power supply. The main issue is the inherent difficulty in scoping, disentangling and measuring efficiency effects and investments compared to investments into demand-side equipment per se. Energy savings can also be achieved through behavioural changes that do not incur investments: the dominance of supply-side measures in investments thus does not imply that supply-side solutions dominate the overall mitigation effort.

The study mostly focused on investments and did not cover the issue of overall mitigation costs (Riahi et al. (submitted)) and avoided damages (Drouet et al. (submitted)) covered by companion studies. While exploring the regional details of the investment patterns is beyond the scope of this study, it is clear that the regional (economic) implications are a very strong determinant of the political feasibility of climate mitigation. Globally, increasing investment volumes related to ambitious near-term mitigation targets are partly offset by reduced fuel costs (see Supplementary Figure S 11). This is particularly beneficial for fossil fuel importers, which in many cases will be able to fund the investment requirements (see Supplementary Table S2) by the savings from lower fuel imports. Conversely, current fossil fuel exporters in mitigation scenarios face the dual challenge of reduced fuel export earnings and higher investment requirements.

Conclusions

This study shows that achieving low peak temperature targets requires a shift of energy investments in the coming decade, with decisive changes compared to current investment patterns and different from patterns implied by current policies or the NDCs submitted currently to the Paris Agreement. The scenarios show a fundamental reduction in fossil fuel investments, especially for coal. For oil and gas, some investments remain but are increasingly tightened for very low budget targets, and for oil are limited to existing fields in some 1.5°C scenarios. At the same time enhanced investments are shown for efficiency measures, low-carbon fuels, and especially low-carbon power generation. While technology choices differ across models in intermediate ambition scenarios, 1.5°C scenarios show more robust patterns, although with considerable variation of absolute levels. Solar and wind, and power grids and storage options stand out as requiring the highest share of near-term investment flows, with investments being scaled up by up to a factor of 4 compared to current levels for solar and wind.

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References

Anderson, Kevin, and Glen Peters. 2016. "The Trouble with Negative Emissions." *Science* 354 (6309): 182–83. https://doi.org/10.1126/science.aah4567.

Andrijevic, Marina, Carl-Friedrich Schleussner, Matthew J. Gidden, David L. McCollum, and Joeri Rogelj. 2020. "COVID-19 Recovery Funds Dwarf Clean Energy Investment Needs." *Science* 370 (6514): 298–300. https://doi.org/10.1126/science.abc9697.

Bertram, Christoph, Gunnar Luderer, Felix Creutzig, Nico Bauer, Falko Ueckerdt, Aman Malik, and Ottmar Edenhofer. 2021. "COVID-19-Induced Low Power Demand and Market Forces Starkly Reduce CO 2 Emissions." *Nature Climate Change* 11 (3): 193–96. https://doi.org/10.1038/s41558-021-00987-x.

BloombergNEF. 2020. "Colossal Six Months for Offshore Wind Support Renewable Energy Investment in First Half of 2020." *BloombergNEF* (blog). July 13, 2020. https://about.bnef.com/blog/colossal-six-months-for-offshore-wind-support-renewable-energy-investment-in-first-half-of-2020/.

BP. 2020. "BP Statistical Review of World Energy 2020." British Petroleum p.l.c. https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy/downloads.html.

Cherp, Aleh, and Jessica Jewell. 2020. "COVID-19 Weakens Both Sides in the Battle between Coal and Renewables." Behavioural and Social Sciences at Nature Research. April 22, 2020. http://socialsciences.nature.com/users/390808-aleh-cherp/posts/66644-by-disrupting-technology-diffusion-and-supply-chains-covid-19-may-harm-renewables-more-than-coal-but-still-weaken-coal-lock-in-in-developing-countries.

Creutzig, Felix, Peter Agoston, Jan Christoph Goldschmidt, Gunnar Luderer, Gregory Nemet, and Robert C. Pietzcker. 2017. "The Underestimated Potential of Solar Energy to Mitigate Climate Change." *Nature Energy* 2 (9): 17140. https://doi.org/10.1038/nenergy.2017.140.

Detz, R. J., J. N. H. Reek, and B. C. C. van der Zwaan. 2018. "The Future of Solar Fuels: When Could They Become Competitive?" *Energy & Environmental Science* 11 (7): 1653–69. https://doi.org/10.1039/C8EE00111A.

Drouet, L., V. Bosetti, M. Tavoni, S. Padoan, K. Riahi, C. Bertram, and D.P. Van Vuuren. (submitted). "Temperature Target and Scenario Design for Hedging Physical and Economic Climate Risks."

Fricko, Oliver, Petr Havlik, Joeri Rogelj, Zbigniew Klimont, Mykola Gusti, Nils Johnson, Peter Kolp, et al. 2017. "The Marker Quantification of the Shared Socioeconomic Pathway 2: A Middle-of-the-Road Scenario for the 21st Century." *Global Environmental Change* 42 (Supplement C): 251–67. https://doi.org/10.1016/j.gloenvcha.2016.06.004.

Friedlingstein, Pierre, Matthew W. Jones, Michael O'Sullivan, Robbie M. Andrew, Judith Hauck, Glen P. Peters, Wouter Peters, et al. 2019. "Global Carbon Budget 2019." *Earth System Science Data* 11 (4): 1783–1838. https://doi.org/10.5194/essd-11-1783-2019.

Fuss, Sabine, William F. Lamb, Max W. Callaghan, Jérôme Hilaire, Felix Creutzig, Thorben Amann, Tim Beringer, et al. 2018. "Negative Emissions—Part 2: Costs, Potentials and Side Effects." *Environmental Research Letters* 13 (6): 063002. https://doi.org/10.1088/1748-9326/aabf9f.

Hasegawa, Tomoko, S. Fujimori, B. J. van Ruijven, C. Bertram, Florian Humpenöder, and K. Riahi. (submitted). "Implications of Climate Change Mitigation without Reliance on Net-Negative Emissions on Agricultural and Land Use Systems."

Hilaire, Jérôme, Jan C. Minx, Max W. Callaghan, Jae Edmonds, Gunnar Luderer, Gregory F. Nemet, Joeri Rogelj, and Maria del Mar Zamora. 2019. "Negative Emissions and International Climate Goals—Learning from and about Mitigation Scenarios." *Climatic Change* 157 (2): 189–219. https://doi.org/10.1007/s10584-019-02516-4.

IEA. 2020a. "World Energy Investment 2020." Paris, France: IEA. https://www.iea.org/reports/world-energy-investment-2020.

———. 2020b. "World Energy Outlook 2020." https://www.iea.org/reports/world-energy-outlook-2020.

Kober, Tom, James Falzon, Bob van der Zwaan, Katherine Calvin, Amit Kanudia, Alban Kitous, and Maryse Labriet. 2016. "A Multi-Model Study of Energy Supply Investments in Latin America under Climate Control Policy." *Energy Economics* 56 (May): 543–51. https://doi.org/10.1016/j.eneco.2016.01.005.

Kriegler, Elmar, Christoph Bertram, Takeshi Kuramochi, Michael Jakob, Michaja Pehl, Miodrag Stevanović, Niklas Höhne, et al. 2018. "Short Term Policies to Keep the Door Open for Paris Climate Goals." *Environmental Research Letters* 13 (7): 074022. https://doi.org/10.1088/1748-9326/aac4f1.

Le Quéré, Corinne, Robert B. Jackson, Matthew W. Jones, Adam J. P. Smith, Sam Abernethy, Robbie M. Andrew, Anthony J. De-Gol, et al. 2020. "Temporary Reduction in Daily Global CO 2 Emissions during the COVID-19 Forced Confinement." *Nature Climate Change*, May, 1–7. https://doi.org/10.1038/s41558-020-0797-x.

Luderer, Gunnar, Robert C. Pietzcker, Christoph Bertram, Elmar Kriegler, Malte Meinshausen, and Ottmar Edenhofer. 2013. "Economic Mitigation Challenges: How Further Delay Closes the Door for Achieving Climate Targets." *Environmental Research Letters* 8 (3): 034033. https://doi.org/10.1088/1748-9326/8/3/034033.

Luderer, Gunnar, Zoi Vrontisi, Christoph Bertram, Oreane Y. Edelenbosch, Robert C. Pietzcker, Joeri Rogelj, Harmen Sytze De Boer, et al. 2018. "Residual Fossil CO 2 Emissions in 1.5–2 °C Pathways." *Nature Climate Change* 8 (7): 626–33. https://doi.org/10.1038/s41558-018-0198-6.

Madeddu, Silvia, Falko Ueckerdt, Michaja Pehl, Juergen Peterseim, Michael Lord, Karthik Ajith Kumar, Christoph Krüger, and Gunnar Luderer. 2020. "The CO2 Reduction Potential for the European Industry via Direct Electrification of Heat Supply (Power-to-Heat)." *Environmental Research Letters* 15 (12): 124004. https://doi.org/10.1088/1748-9326/abbd02.

McCollum, David L., Yu Nagai, K. Riahi, Giacomo Marangoni, Kate V. Calvin, Robert C. Pietzcker, J. Van Vliet, and Bob van der Zwaan. 2013. "Energy Investments under Climate Policy: A Comparison of Global Models." *Climate Change Economics* 04 (04): 1340010. https://doi.org/10.1142/S2010007813400101.

McCollum, David L., Wenji Zhou, Christoph Bertram, Harmen-Sytze de Boer, Valentina Bosetti, Sebastian Busch, Jacques Després, et al. 2018. "Energy Investment Needs for Fulfilling the Paris Agreement and Achieving the Sustainable Development Goals." *Nature Energy* 3 (7): 589–99. https://doi.org/10.1038/s41560-018-0179-z.

McKenna, Christine M., Amanda C. Maycock, Piers M. Forster, Christopher J. Smith, and Katarzyna B. Tokarska. 2020. "Stringent Mitigation Substantially Reduces Risk of Unprecedented Near-Term Warming Rates." *Nature Climate Change*, December, 1–6. https://doi.org/10.1038/s41558-020-00957-9.

Meinshausen, M., T. M. L. Wigley, and S. C. B. Raper. 2011. "Emulating Atmosphere-Ocean and Carbon Cycle Models with a Simpler Model, MAGICC6 – Part 2: Applications." *Atmospheric Chemistry and Physics* 11 (4): 1457–71. https://doi.org/10.5194/acp-11-1457-2011.

NGFS. 2020. "NGFS Climate Scenarios." Banque de France. 2020. https://www.ngfs.net/en/publications/ngfs-climate-scenarios.

Riahi, K., C. Bertram, B. J. van Ruijven, V. Krey, Oliver Fricko, V. Bosetti, D.P. Van Vuuren, B. C. C. Van Der Zwaan, S. Fujimori, and Matthias Weitzel. (submitted). “Long-Term Economic Benefits of Stabilizing Warming without Overshoot – the ENGAGE Model Intercomparison.”

Roelfsema, Mark, Heleen L. van Soest, Mathijs Harmsen, Detlef P. van Vuuren, Christoph Bertram, Michel den Elzen, Niklas Höhne, et al. 2020. “Taking Stock of National Climate Policies to Evaluate Implementation of the Paris Agreement.” *Nature Communications* 11 (1): 2096. https://doi.org/10.1038/s41467-020-15414-6.

Rogelj, Joeri, Daniel Huppmann, Volker Krey, Keywan Riahi, Leon Clarke, Matthew Gidden, Zebedee Nicholls, and Malte Meinshausen. 2019. “A New Scenario Logic for the Paris Agreement Long-Term Temperature Goal.” *Nature* 573 (7774): 357–63. https://doi.org/10.1038/s41586-019-1541-4.

Schaeffer, R., A. Köberle, H. L. van Soest, C. Bertram, G. Luderer, K. Riahi, V. Krey, et al. 2020. “Comparing Transformation Pathways across Major Economies.” *Climatic Change* 162 (4): 1787–1803. https://doi.org/10.1007/s10584-020-02837-9.

Schultes, Anselm, Gunnar Luderer, Joeri Rogelj, Franziska Piontek, Elmar Kriegler, and Ottmar Edenhofer. submitted. “Optimal Near-Term Climate Change Mitigation Increases When Damages below 2°C Are Taken into Account.” *Environmental Research Letters (Submitted)*.

Sepulveda, Nestor A., Jesse D. Jenkins, Aurora Edington, Dharik S. Mallapragada, and Richard K. Lester. 2021. “The Design Space for Long-Duration Energy Storage in Decarbonized Power Systems.” *Nature Energy*, March, 1–11. https://doi.org/10.1038/s41560-021-00796-8.

Sepulveda, Nestor A., Jesse D. Jenkins, Fernando J. de Sisternes, and Richard K. Lester. 2018. “The Role of Firm Low-Carbon Electricity Resources in Deep Decarbonization of Power Generation.” *Joule* 2 (11): 2403–20. https://doi.org/10.1016/j.joule.2018.08.006.

Smith, Pete, Steven J. Davis, Felix Creutzig, Sabine Fuss, Jan Minx, Benoit Gabrielle, Etsushi Kato, et al. 2016. “Biophysical and Economic Limits to Negative CO2 Emissions.” *Nature Climate Change* 6: 42–50. https://doi.org/10.1038/nclimate2870.

Sweerts, Bart, Remko J. Detz, and Bob van der Zwaan. 2020. “Evaluating the Role of Unit Size in Learning-by-Doing of Energy Technologies.” *Joule* 4 (5): 967–70. https://doi.org/10.1016/j.joule.2020.03.010.

Tong, Dan, Qiang Zhang, Yixuan Zheng, Ken Caldeira, Christine Shearer, Chaopeng Hong, Yue Qin, and Steven J. Davis. 2019. “Committed Emissions from Existing Energy Infrastructure Jeopardize 1.5 °C Climate Target.” *Nature* 572 (7769): 373–77. https://doi.org/10.1038/s41586-019-1364-3.

Vrontisi, Zoi, Gunnar Luderer, Bert Saveyn, Kimon Keramidas, Aleluia Reis Lara, Lavinia Baumstark, Christoph Bertram, et al. 2018. “Enhancing Global Climate Policy Ambition towards a 1.5 °C Stabilization: A Short-Term Multi-Model Assessment.” *Environmental Research Letters* 13 (4): 044039. https://doi.org/10.1088/1748-9326/aab53e.

Weber, Christopher, David L. McCollum, Jae Edmonds, Pedro Faria, Alban Pyanet, Joeri Rogelj, Massimo Tavoni, Jakob Thoma, and Elmar Kriegler. 2018. “Mitigation Scenarios Must Cater to New Users.” *Nature Climate Change* 8 (10): 845–48. https://doi.org/10.1038/s41558-018-0293-8.

Wilson, C., A. Grubler, N. Bento, S. Healey, S. De Stercke, and C. Zimm. 2020. “Granular Technologies to Accelerate Decarbonization.” *Science* 368 (6486): 36–39. https://doi.org/10.1126/science.aaz8060.

World Nuclear Association. 2020. “World Nuclear Power Reactors, Uranium Requirements and Future Nuclear Power.” 2020. https://www.world-nuclear.org/information-library/facts-and-figures/world-nuclear-power-reactors-and-uranium-requireme.aspx.