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Getting from here to there – energy technology transformation pathways in the EMF27 scenarios

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Abstract Based on a large number of energy-economic and integrated assessment models, the Energy Modeling Forum (EMF) 27 study systematically explores the implications of technology cost and availability for feasibility and macroeconomic costs of energy system transformations toward climate stabilization. At the highest level, the technology strategy articulated in all the scenarios in EMF27 includes three elements: decarbonization of energy supply, increasing the use of low-carbon energy carriers in end-use, and reduction of energy use. The way that the scenarios differ is in the degree to which these different elements of strategy are implemented, the timing of those implementations, and the associated macroeconomic costs. The study also discusses the value of individual technologies for achieving climate stabilization. A robust finding is that the unavailability of carbon capture and storage and limited availability of bioenergy have the largest impact on feasibility and macroeconomic costs for stabilizing atmospheric concentrations at low levels, mostly because of their combined ability to remove carbon from the atmosphere. Constraining options in the electric sector such as nuclear power, wind and solar energy in contrast has a much smaller impact on the cost of mitigation.

1 Introduction

It is well established that technology is critical to climate mitigation. Ultimately, reducing greenhouse gas (GHG) emissions will require transformational changes to both regional and

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global energy systems, including extensive deployment of both new and existing technologies. For the purpose of this paper, two topics are of particular interest: (1) robust elements of energy system transformations associated with climate mitigation, and (2) the influence of technology availability, cost, and performance on the feasibility[1] of meeting ambitious climate goals and the costs of climate mitigation.

Both topics have been explored to various degrees in previous literature. Characterizing energy system transformations for stabilizing GHG concentrations has seen the most extensive treatment with most integrated assessment modeling papers over the last several decades providing at least some information on energy system transformations. And several recent multi-model intercomparisons have focused on this issue (Clarke et al. 2008, 2012). The influence of technology on mitigations costs and feasibility of ambitious climate targets has also been explored in a number of individual model studies (e.g., Kim et al. (2000), Riahi et al. (2012)) as well as several smaller model intercomparisons (Edenhofer et al. 2010; Luderer et al. 2012), all of which have shown the profound implications of technology availability for the transformation of the energy system under different climate targets. Although the role of technology in climate mitigation along these dimensions has been explored to various degrees in previous studies, there exists no single study that systematically explores the role of technology across a wide suite of models using a coordinated set of technology assumptions.

This paper uses the Energy Modeling Forum (EMF) 27 scenarios to fill that gap. The combination of the large number of models and the coordinated technology assumptions in EMF27 provide an unprecedented opportunity to systematically test the robustness of insights about the role of technology based on model analyses. The paper provides a characterization of the transformations in the EMF27 scenarios by analyzing adjustments throughout the conversion chain from primary to secondary to final energy. It explores the role of technologies for reducing the costs of climate mitigation through the systematic variation in technology availability and to some degree costs across all the participating models. Through this systematic approach, it provides the most comprehensive comment to date on the implications of technology for the feasibility and costs of low stabilization goals.

2 Study design and model characteristics

2.1 Study design

A core dimension of the EMF27 study is the variation of assumptions about future availability, cost and performance of technologies that might contribute to the transformation of the energy system. This technology dimension of EMF27 is then combined with different levels of climate policy, including a 550 ppm CO_2-equivalent (CO_2e) target, a 450 ppm target, and a scenario without any additional climate policies (baseline). An important difference between the two stabilization goals is that the 550 ppm target does not allow to overshoot this level of CO_2e concentrations at any time until 2100 whereas in the 450 ppm case a temporary overshoot is allowed as long as CO_2e concentrations return to 450 ppm by 2100. Table 1 summarizes the specification and motivation of the technology scenarios. Individual scenarios in the EMF27 study either rely on one of these technology variations or a combination of them. A more detailed description of the study design can be found in Kriegler et al. (2013).

[1] Feasibility here relates to the ability of models to produce specific scenarios (see Section 4.2).

Table 1 Overview of technology portfolio variations in the EMF27 study

Scenario	Specification	Motivation
FullTech	include full suite of technologies represented in models; reference final energy intensity (FE/GDP) improvements mostly compatible with historical development since 1970 of about 1.2 %/yr	
LowEI	low energy intensity: 20-30 % lower final energy demand in 2050 and 35-45 % in 2100 compared to the reference case	implementation barriers for energy efficiency lowered and behavioral change towards lower energy consumption enhanced
NoCCS	carbon capture and storage excluded from technology portfolio in all sectors	technology not fully mature, public opposition, uncertainty in storage potential, leakage rates and environmental impacts (e.g., groundwater contamination)
NucOff	phase out of nuclear energy with no new nuclear energy facilities (e.g., power plants) built beyond those under construction; existing plants operated until end of their technical lifetime	proliferation of fissile material, unresolved long-term storage, other environmental concerns and fear of nuclear accidents resulting in public opposition
LimSW	share of electricity production from intermittent solar and wind technologies (wind, solar PV and CSP) limited to 20 %	technical, economic and institutional challenges associated with the integration of intermittent electricity generation (e.g. storage, grid extension)
LimBio	global primary bio-energy supply – including purpose grown crops, residues and municipal solid waste, but excluding traditional biomass –limited to 100 EJ/yr	sustainability concerns about strong expansion of bioenergy production due to water stress, food price increases, etc.
Conv	combination of LimSW and LimBio	reliance on "conventional" supply-side options in combination with reference energy intensity improvements
EERE	combination of LowEI, NoCCS and NucOff	transformation based on energy efficiency improvements and renewable energy deployment
LimTech	combination of NoCCS, NucOff, LimSW and LimBio	limitations to all energy-related mitigation technology clusters to investigate the overall importance of technology for climate mitigation

2.2 Overview of model characteristics

The 18 models participating in EMF27 differ in many important ways, including their system boundaries, the level of detail with which they represent different processes, and the solution concepts that are applied to generate the scenarios in this study. All of these have multiple dimensions, and they cannot be discussed in detail in this paper. Here we focus on two areas of model characteristics that vary noticeably across models and that are relevant for understanding the energy system transformations in EMF27.

The first is the representation of the energy system. These structural assumptions can interact strongly with the variation of technology availability, costs and performance in the study design. Some differences in representation are readily apparent. For example, models with limited coverage of biofuels will be affected by bioenergy constraints to a lesser extent than those with extensive coverage and may have difficulties in achieving ambitious targets regardless (see Figure S4.6 in the supplementary material (SM)). However, some are far more embedded in the details of the model, such as the relative costs of technologies, constraints on their expansion, limits on deployment of renewables (RE) in electricity generation and so forth (Clarke et al. 2012; Kim et al. this issue; Kriegler et al. 2013). All these interact and influence results in important ways.

Among the most apparent elements of the system representation is simply which technologies are included in models and which are not (see Table S2.1 in SM). The coverage of technology options is quite similar in the electricity sector. Only the representation of producing electricity from concentrating solar power (CSP), geothermal energy and biomass in combination with CCS varies noticeably across models. Almost all other options listed in Table S2.1 are represented in all models. Of particular note, the coverage of bioenergy with CCS (BECCS) has increased compared to earlier reviews (Krey and Clarke 2011). As will be discussed later, this technology combination has proven particularly important. In contrast, there is far more heterogeneity in the liquids sector. The representation of coal- and gas-based synthetic fuels varies considerably (particularly in combination with CCS) whereas most models include the option of producing liquid biofuels. Hydrogen and synthetic gas production are explicitly represented in a minority of models, and, again, even less so in combination with CCS. It is important to note that not all models represent all energy carriers explicitly, but capture these implicitly in more general terms, e.g. in an aggregate non-electric sector.

Another important difference between models that influences energy system transformations is that CO_2 emissions budgets for the energy system differ noticeably across models (see Kriegler et al. (2013)). The two primary reasons are (i) differences in the total anthropogenic CO_2 emissions budget based on differences in carbon cycle treatments and the contributions of non-CO_2 substances, and (ii) differences in the allocation of CO_2 emissions between the energy system and other sectors, most notably from land-use (e.g. afforestation). These differences in energy CO_2 budgets are important because they imply that identical stabilization goals will lead to different levels of overall energy system transformation in different models, not just in the way the transformations are achieved (Blanford et al. 2013).

3 Transformation pathways under default technology assumptions

At the highest level, the technology strategy articulated in all the climate mitigation scenarios in EMF27 includes three elements relative to the development in the corresponding baseline scenario: decarbonization of energy supply, increasing the use of low-carbon energy carriers in end-use sectors, and reduction of energy use. The way that the scenarios differ is in the degree to which these different elements of strategy are implemented and their timing. Following the discussion of these high level strategies, we characterize the global energy system transformation at three levels: (i) the relative contribution of different energy sources to primary energy supply, (ii) the technologies used to produce secondary energy, and (iii) the final energy carriers supplying end-use sectors.

3.1 Carbon intensity vs. energy intensity reductions

An important question regarding mitigation is the relative balance and timing of supply- and demand-side measures. One window, although imperfect, into this interplay is the decarbonization of energy supply (measured as CO_2 emissions per unit of primary energy) and reduction of energy intensity (measured as final energy per unit of GDP). There is generally quite a large spread across models regarding the combination of these two mechanisms to reach a specific climate target (Fig. 1). In the medium to long-term overall carbon intensity reduction plays the dominant role compared to energy intensity reduction. However, the timing of these two mechanisms is significantly different with most of the energy intensity improvements relative to baseline performed in the short- to medium-term (2020/2030) when the energy supply system is still carbon

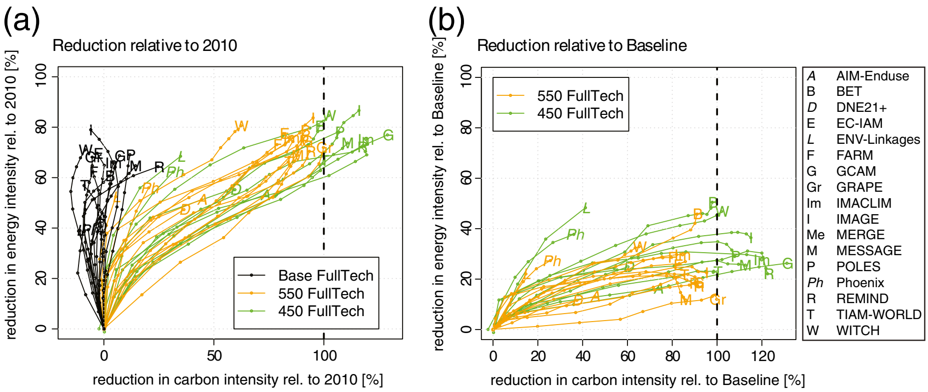

Fig. 1 Development of carbon intensity vs. final energy intensity reduction (**a**) relative to 2010 in Base, 550 and 450 FullTech scenarios and (**b**) in the mitigation scenarios relative to the Base FullTech scenario. Symbols of 2050 models are shown in italics

intensive (Sugiyama et al., Submitted for publication in this special issue) whereas the build-up of new infrastructure that is necessary for significant carbon intensity reductions takes more time, but dominates after 2030 (Fig. 1, cf. Fisher et al. (2007, Section 3.3.5.2). These high level developments on the energy supply and demand side are complemented by fuel switching to low-carbon energy carriers which is discussed throughout the remainder of this section.

3.2 Primary Energy Supply

In 2010, coal, oil and gas accounted for more than 80 % of global total primary energy supply (TPES).[2] In the baseline scenarios, primary energy use increases two- to threefold until 2100. Without policies constraining GHG emissions, fossil fuels continue to dominate energy supply (Fig. 2a, Figure S3.2a); that is, under baseline assumptions adopted by modelers, the energy system does not decarbonize without climate policy. Among fossil fuels, scenarios consistently project a decrease of the combined share of hydrocarbons and an increase in the share of coal. This renaissance in coal largely reflects differences in resource availability and extraction costs: recent increases in gas reserves notwithstanding, coal is generally perceived as far more abundant and cheaper than gas and oil (McCollum et al. 2013).

The climate mitigation scenarios place a tight limit on the use of freely emitting fossil energy, lower than in any of the reference scenarios. In the 450 FullTech scenario, cumulative TPES from 2010 to 2100 is 15 to 45 % lower than in the baseline (Figure S3.2c). Cumulative fossil fuel use decreases by at least 35 % compared to baseline levels in most 550 ppm, and by more than 50 % in most 450 ppm scenarios. The decline is most pronounced for coal because of its relatively higher carbon content.

A substantial share of the remaining coal and gas is used in combination with CCS. Some models maintain a considerable share of coal with CCS in the primary energy mix, particularly in the 550 ppm scenario, while others rely more strongly on non-fossil alternatives. Two factors that are particularly relevant for the role of CCS in stringent mitigation scenarios are the assumed capture rates and the degree to which supply chain GHG emissions (e.g., methane emissions from coal mining) are represented and can be avoided.

[2] Throughout this study, primary energy accounting is based on the direct-equivalent method.

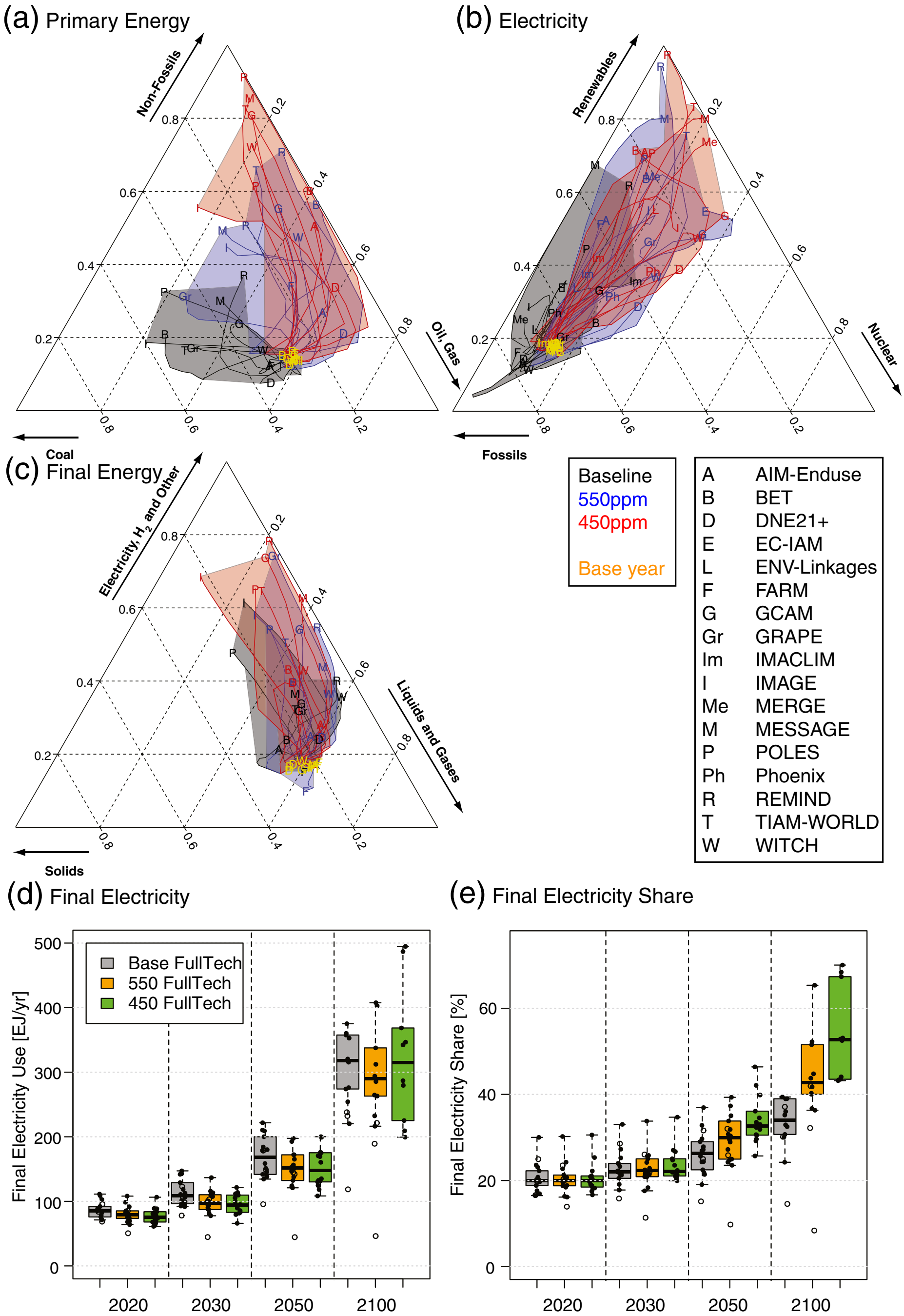

Fig. 2 Development of shares in (**a**) primary energy, (**b**) electricity generation, (**c**) final energy in the Base, 550 and 450 FullTech scenarios over time and development of (**d**) global final electricity use and (**e**) global electricity share in final energy over time in the same scenarios. In panels (**d**) and (**e**) dots refer to individual models to give a sense of the spread within the ranges. Models that did not run the 450 FullTech scenario are excluded from the boxplot, but are shown as empty circles

All models foresee a much more prominent role of non-fossil energy carriers. Although they account for less than 25 % of cumulated TPES in all baseline scenarios, their share reaches more than 50 % in many 450 ppm scenarios. Biomass assumes a unique role among the renewable energy sources (Figure S3.2c), because it can substitute fossil fuels in almost all applications (Section 3.4). Bioenergy deployment is, however, constrained by its limited resource potential, as well as limited social and political acceptance in view of competition with food production and other sustainability concerns (Chum et al. 2011; Rose et al. (this issue).

3.3 Secondary Energy Production: Electricity

About 70 % of electricity supply currently comes from fossils fuels, largely from coal and gas-fired power plants. In the baseline scenarios, electricity production remains heavily reliant on fossil fuels (Figure S4.2d). Although coal dominates power supply in most baseline scenarios (see Section 3.2), some models project an increasing share of gas. There is less agreement about the penetration of non-fossil power supply. The share of nuclear power, for example, is decreasing over time in some models (Kim et al. this issue). Renewables are scaled up in the long-term even in absence of climate policies in most models. While the increase of the RE share is rather gradual in most scenarios, some models show strong increases of RE deployment absent climate policy in the 2nd half of the century, resulting in RE shares in excess of 60 % of global electricity production by 2100 (cf. Luderer et al. (2013)). These developments are driven by a number of factors, including resource availability (Kim et al. this issue; McCollum et al. 2013), energy trade, the technological change assumptions for the power sector technologies as well as systems integration (Luderer et al. 2013) and the decision making mechanism employed by the models (Kriegler et al. 2013), all of which influence the competitiveness of power generation options.

All models in this study represent multiple technologies for decarbonizing electricity supply, including nuclear power, CCS, and renewables (Table S2.1). As a consequence, in the 450 ppm mitigation scenarios by 2050 only a small share of power supply comes from freely emitting fossil installations (Figure S3.2f). In particular, coal power generation without CCS is phased out most rapidly due to its high emission intensity. Although all models agree in showing a rapid and almost full-scale decarbonization of electricity supply, they also show that there are a variety of possible low-carbon configurations of the electricity sector (Figure S3.2) which are primarily driven by different assumptions about future technological development. In addition, models do not agree about the response in total electricity generation. About half the models that run to 2100 show higher average annual electricity generation under the 450 ppm target compared to the baseline while the other half reduces generation, in some cases significantly. In the first group of models, electricity is decarbonized pervasively at relatively moderate costs and electrification of end-use sectors (e.g., transport) is increased substantially. In the second group of models the demand reduction effect is stronger than the electrification effect in end-use, leading to a reduction in total electricity generation.

3.4 Secondary Energy Production: Non-Electric Energy

Electricity supply is often in the focus of low-carbon energy policies, largely because of the robustness of near-term electricity decarbonization in scenarios studies such as this. However, it is important to bear in mind that non-electric energy carriers currently account for more than three quarters of global final energy and more than 60 % of global energy-related CO_2 emissions at present. Further, many of the key questions about feasibility and costs of mitigation involve the options for mitigation in non-electric energy conversion and use. The starting point for these mitigation actions is a non-electric sector without climate policy dominated by fossil fuels, based on the ease with which fossil resources can be transformed to liquid, gaseous and solid fuels.

The transformation of non-electric energy under mitigation stands in sharp contrast to that of the electric sector. Whereas in the electric sector mitigation leads to an ambiguous change in production levels (see previous section), non-electric energy is unambiguously reduced relative to the baseline scenarios in all models, and the mix maintains substantial fossil energy.

Biomass is the most important low-carbon alternative for non-electric energy supply in the EMF27 scenarios, so its cost, performance, and availability have the largest influence on the transformation of non-electric energy under carbon mitigation. Biomass can substitute fossil fuels in most non-electric applications, most notably in the transport sector where few other technologies are represented in most models. Some models include hydrogen produced from carbon-free sources or from fossils in combination with CCS (Table S2.1), others include solar thermal and geothermal systems to supply heat. More broadly speaking, scenarios from models with higher technological detail generally show that these other options can make a significant contribution to emission reductions, but are insufficient to reduce the reliance on fossil fuels and biomass substantially because they are largely confined to stationary applications (solar, geothermal heat) or require building up new and costly infrastructure to substitute transport fuels (e.g., hydrogen).

3.5 Final Energy

In baselines, the current final energy structure only changes gradually over time, however, there is a general trend toward using more grid-based energy carriers, most notably electricity. In part this shift can be attributed to prices of electricity increasing more slowly than prices of other fuels. The degree to which solid fuels are phased out and the degree of electrification both vary considerably in total as well as across the end-use sectors (Fig. 2c-e, S3.1c-e).

A robust dynamic across mitigation scenarios is increased electrification (Fig. 2c-e, Figure S3.3). Due to ample availability of advanced low-carbon technologies, electricity supply can be decarbonized at relatively modest extra costs (cf. Section 4.3). As discussed, many options for replacing fossil fuels in non-electric energy supply have limited potential or are more costly. As a consequence prices for non-electric energy carriers tend to increase much more significantly than the price of electricity in mitigation scenarios. Therefore, climate policies strongly accelerate the electrification trend present in the baseline scenarios. In particular residential and commercial buildings are electrified up to 95 % under the 450 ppm target (Figure S3.1c), a trend which is less pronounced in industry where in specific applications carbonaceous fuels are costly to substitute (e.g., primary steel making). In transportation, the highest electrification rates exceed 30 % (Figure S3.1e). Where included, hydrogen can take a similar role as electricity, thereby achieving substantial shares of final energy, in particular in transport and to a lesser extent in industry.

4 Transformation pathways under varied technology portfolios

This section discusses the influence of variations in the technology portfolio for the scenarios. First, the implications for the timing of mitigation and the sectoral allocation of mitigation are presented, followed by an assessment of the implications for macroeconomic costs and feasibility of mitigation scenarios.

4.1 Timing of mitigation and sectoral emissions

The characteristics of technology options can significantly affect the cost-minimizing CO_2 emissions trajectory to meet any long-term goal. In the context of the EMF27 scenarios, this effect is largely a function of two factors: the ability to overshoot the long-term stabilization goal and the presence of options for negative emissions. For the purpose of this paper, the latter can mostly be interpreted as the use of BECCS (although there are other options like afforestation that can generate a net negative carbon flux). There is a significant impact on the timing of mitigation under the 450 ppm target if CCS is not available or if bioenergy potential is limited (Fig. 3). The potential for negative emissions is greatly reduced under these technology variations, which requires more substantial near-term emissions reductions (cf. Tavoni and Socolow (2013)). However, it is worthwhile noting that both CCS and bioenergy have a role to play in mitigation that goes beyond the potential of generating negative emissions. All other technology variations result in no significant changes in the CO_2 emissions trajectory (Figure S4.1).

Different sectors have different roles in climate mitigation which can be analyzed by looking at the development of direct emissions from sectors over time. Reductions in direct emissions are the result of decreases in energy demand or production and switching to lower carbon fuels. Across the different sectors of the energy system, decarbonization happens at different speeds and to different extend (Fig. 4a). Direct CO_2 emissions of electricity generation decline fastest and reach close to zero by 2050 in all 450 FullTech scenarios, eventually going negative for models representing the option of BECCS. The industry and buildings sectors reduce their direct emissions at similar speed and extent. In contrast, the transport sector exhibits the slowest decarbonization rate, supporting the general notion that emissions reductions in transport are most costly. The variation in the decarbonization of the transport sector can be related to some degree to fuel switching to electricity and hydrogen (Figure S4.2, Table S4.1). Also non-CO_2 emissions, mostly CH_4 and N_2O from agricultural sources, are harder to mitigate and stay at a level comparable to today even in the 450 ppm scenarios. The reason for the different timing and extent of decarbonization across sectors are primarily the availability of options and their costs (cf. Sections 3.3/3.4).

If CCS is unavailable, emissions in the electricity sector converge to zero, but cannot go negative, thereby forcing the end-use sectors to reduce their direct emissions more rapidly. This

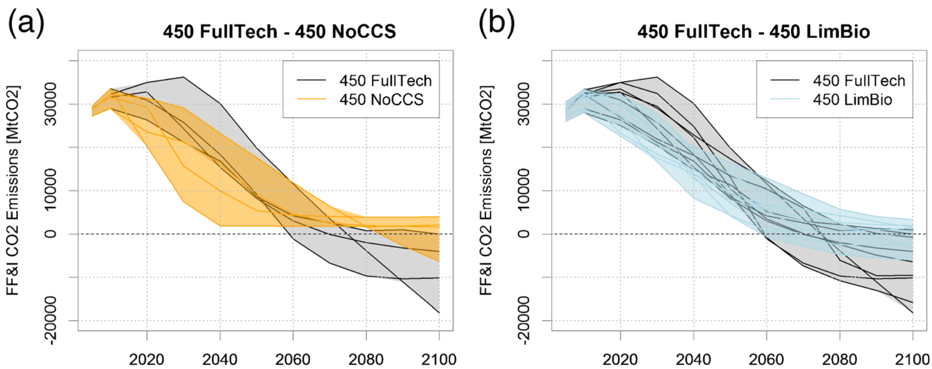

Fig. 3 CO_2 emissions from fossil fuels and industry in 450 NoCCS (**a**) and 450 LimBio scenarios (**b**) compared to the 450 FullTech scenario. Ranges shown for the FullTech scenario have been corrected for the representation bias of models by just showing the emission pathways from the set of models that the technology variation scenario is available for. The number of lines shown in each panel therefore varies

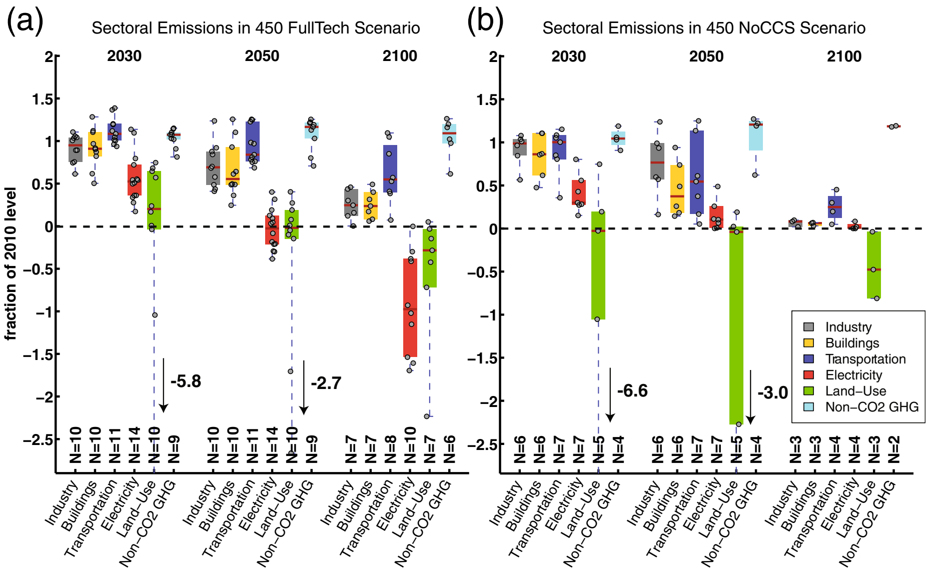

Fig. 4 Direct emissions by sector normalized to 2010 in the 450 FullTech (**a**) and 450 NoCCS scenarios (**b**). Note that values below the dashed zero line indicate negative sectoral emissions. Gray dots refer to emissions of individual models to give a sense of the spread within the ranges shown. The numbers at the bottom of the graphs refer to the number of scenarios included in the range which differs across sectors and time due to different sectoral resolution and time horizon of models

effect occurs to a lesser degree for the limitation of bioenergy supply as it effectively constrains the amount of BECCS deployment. The increased emissions reductions requirement puts a particular strain on sectors where the proportion of non-electric energy use is large. Since, as discussed above, CCS and bioenergy are the main options to decarbonize non-electric energy use, the constraints on CCS or bioenergy impose a double burden. Not only do they increase the need to abate sector emissions due to constraining negative emissions deployment, they also limit the ability to enact this abatement. As a result, end-use sectors such as transportation and industry respond with a much stronger decrease of energy use and an increased rate of electrification and/or adoption of hydrogen technologies, pushing up costs. Further, the assumptions about emissions from land-use have a marked implication on the timing and extent of decarbonization in the energy sectors with some models that include land-based carbon sinks generating some extra headroom for the energy sector emissions.

4.2 Scenario Feasibility

There are many factors that influence whether a particular climate target might be considered “feasible”. Ultimately, judgments about feasibility are based on subjective assessments of whether deployment levels could be achieved, societies would be willing to bear the associated costs, or other social, political, physical, or institutional factors might impinge on the ability to meet a particular goal. Nonetheless, among the pieces of evidence for assessing the challenge of meeting particular goals is the degree to which models are even capable of producing scenarios to meet such goals. If scenarios reaching particular climate goals cannot even be produced by models under particular assumptions about technology, it provides some evidence that meeting the goal under those circumstances would be challenging (Fig. 5a, see also SM Section 4.2).

(a) Feasibility matrix of technology variation scenarios for different climate targets

	FullTech	LowEI	NoCCS	NucOff	LimSW	LimBio	Conv	EERE	LimTech
Baseline	13/13	13/13		11/11	11/11	13/13	13/13	13/13	11/11
550 ppm	13/13	13/13	12/12	11/11	11/11	13/13	13/13	12/12	6/9
450 ppm	10/11	9/10	4/11	9/10	9/10	9/11	8/11	6/11	0/10

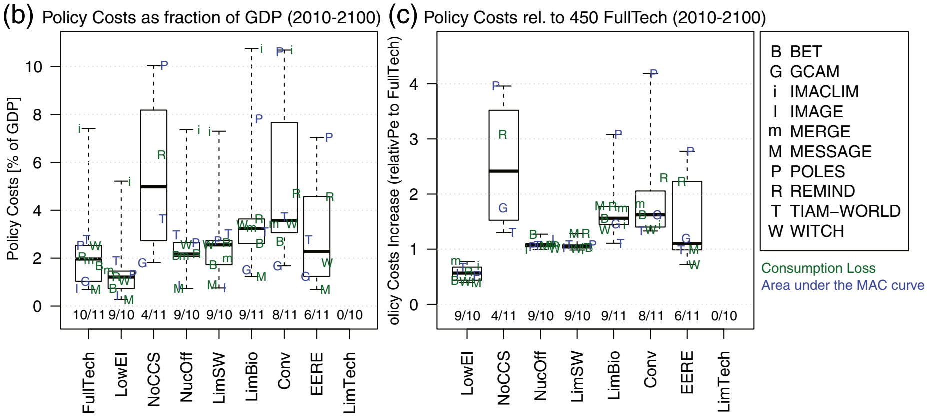

Fig. 5 Number of feasible scenarios under technology variations (**a**), climate policy costs as a fraction of GDP (**b**), and normalized to costs in the corresponding FullTech scenario (**c**) for 450 ppm scenarios with varied technology portfolios. Note that the feasibility assessment only draws on results from global full-century models only given that these can link the required transformation to specific stabilization targets. Net present value (NPV) of climate policy costs, discounted at 5 % p.a. between 2010 and 2100 and normalized to NPV of GDP over the same time horizon is shown. Due to different modeling approaches alternative cost measure have been reported (see color coding). The numbers at the bottom of panel (**b**) and (**c**) refer to feasible scenarios as reported in the feasibility matrix (**a**)

Only one model indicates difficulties in producing scenarios that meet either of the long-term mitigation goals if all technologies are available. The capability of models to produce 550 ppm CO_2e scenarios is only mildly affected by the variation of technology availability, cost and performance with very few models indicating difficulties of achieving the target under constrained technology availability. In contrast, a substantial number of models were not able to produce 450 ppm scenarios without CCS. Indeed, the vast majority of situations in which models could not produce scenarios were those in which CCS was assumed to be unavailable. In contrast, a phase-out of nuclear power or pessimistic assumptions about wind and solar power do not have a comparable effect because of numerous competing low-carbon supply options in electricity generation.

The importance of CCS can be attributed to the fact that CCS serves several different purposes, the most relevant of which is the capability of sequestering carbon from the atmosphere when applied jointly with bioenergy (Tavoni and Socolow 2013). In addition, unlike other technologies assessed in this study, it is a very versatile technology that has the potential to contribute to decarbonization via different processes, such as electricity generation and synthetic fuel production from different feedstock and in industry.

Finally, none of the long-term models found it viable to produce a scenario in which all low-carbon supply technologies are constrained. This finding shows the crucial role of technology for decarbonization and therefore reaching ambitious climate targets. It also emphasizes that energy efficiency and demand-side measures alone are insufficient for climate stabilization (cf. Section 3.1).

4.3 The Value of Technology

The implications of technology assumptions on mitigation costs are an important topic that is heavily discussed in the existing scenario literature. Mitigation costs generally vary quite significantly between models (Fig. 5b, Figure S4.3a in SM for 550 ppm), leading to significant overlaps of the ranges of cost increases in the technology sensitivity cases (Fisher et al. 2007). To reduce this model bias in mitigation costs, it is instructive to consider the change in costs relative to a benchmark case. For this purpose, we use the 450 FullTech scenario (Fig. 5c, Figure S4.3b for 550 ppm). It is important to note, however, that this approach does not fully ameliorate the variation in cost effects of different technologies portfolios. To test the robustness of the insights presented, Figures S4.4 provides cost calculations with other discount rates and for specific points in time which qualitatively support the same findings.

Another challenge in interpreting cost results arises from the fact that not all scenarios can be produced by all models. This leads to a downward bias in the cost reporting (Tavoni and Tol 2010). In general, the ranges for any of the scenarios that were not produced by all models should be considered to be higher, and perhaps much higher, than those shown in Fig. 5 and Figure S4.3 (see also feasibility indicator at the bottom of the figure panels). In addition to this representation bias, it should be noted that some models do not represent some technologies (e.g., BECCS) in the first place and therefore also do not show a strong reaction in policy costs if related options (e.g., CCS, bioenergy) are restricted (Section 2.2, Table S2.1, Figure S4.5).

In several ways, the cost sensitivity results mirror those associated with the ability of models to meet particular targets discussed in Section 4.2. A first observation is that the sensitivity of mitigation costs to technology availability significantly increases with increasing target stringency (Fig. 5 and Figure S4.3). This illustrates that broad technology portfolios become more important for reaching more ambitious climate targets, just as was indicated from the results in Section 4.2.

The second observation in this regard is that the unavailability of CCS leads to the strongest increase in mitigation costs for any single technology variation for both the 450 ppm (Fig. 5) and the 550 ppm target (Figure S4.3). This result is robust even considering the bias in scenario reporting for the scenarios without CCS. The cost increases associated with limited bioenergy are similar to those for limited CCS. CCS and bioenergy actually share two characteristics that can help motivating the similarity in the cost increase under the 450 ppm target, i.e. the generation of negative emissions and their applicability outside of the electric sector (cf. Section 3).

In contrast, constraining the three alternative electricity generation options – nuclear power, wind and solar – leads only to a modest increase of mitigation costs of below 20 % for most models in the 450 ppm scenario. This finding originates from the existence of numerous alternatives for generating electricity from low-carbon sources and that these technologies have a large degree of substitutability. More broadly, and not surprisingly, combined limits on technology generally lead to costs at the higher end of the cost ranges shown in Fig. 5.

The scenarios with reduced energy demand provide some complexities in their interpretation. On the one hand, lower energy demand reduces the costs of mitigation substantially across models as shown by the LowEI case. This benefit perhaps offsets some of the potential cost increases in the EERE scenarios. On the other hand, the benefits of the energy demand reduction do not come with a price tag in this study, essentially assuming autonomous energy intensity improvements at rates that are twice the observed ones over the past 40 years.

5 Conclusions

The EMF27 scenarios provide an unprecedented opportunity to explore the robust elements of energy system transitions toward stabilization and the influence of technology cost and availability on these transitions, the macroeconomic costs of meeting long-term mitigation goals, and the feasibility of these goals. At the highest level, the technology strategy articulated in all the scenarios in EMF27 includes three elements: decarbonize energy supply, increase the use of low-carbon energy carriers in end-use, and reduce energy use. The way that the scenarios differ is in the degree to which these different elements of strategy are implemented, the timing of those implementations, and the associated macroeconomic costs.

One robust element across scenarios is a relatively near-term decarbonization of electricity supply and a corresponding long-term increase in the use of electricity in end-use applications. There is far less agreement, however, about the appropriate mix of technologies for decarbonizing electricity, and this mix depends crucially on assumptions about supply technology characteristics and availability. What we might take away from this result is that there is more scope for choices in some elements of strategy based on other factors beyond simple economic costs (e.g., safety, waste, and proliferation concerns surrounding nuclear power or similar concerns about siting CO_2 storage reservoirs). The scenarios are also largely consistent in demonstrating greater focus on reduction in energy intensity in the near-term than in the long-term. This behavior represents a natural progression in the role of end-use sectors in climate mitigation. Energy reduction has higher value in the near-term because of the carbon intensity of key fuels, including electricity. In the long-term term, however, as electricity is decarbonized, fuel switching is relatively more valued.

The two biggest defining assumptions for clustering energy pathways in the EMF27 scenarios are the ubiquity or availability of bioenergy and the ubiquity or availability of CCS, particularly for the 450 ppm scenarios. Even absent CCS, bioenergy is an important technology because its availability helps to define the transition in the transportation sector, which presents substantial challenges for fuel switching. Similarly, even without bioenergy CCS is a valuable technology because it allows a greater reliance on fossil fuels while moving to a low-carbon economy. However, the largest value may come from the combination of bioenergy and CCS, which creates an option for negative emissions. The implications of this option are profound, easing the capability to overshoot challenging targets in the transition phase and to compensate for residual fossil fuel emissions, reducing the challenge and lowering the costs of meeting those targets. Indeed, the presence or absence of negative emissions from BECCS has the largest influence among technology variations in this paper on the shape of the overshoot pathways toward stabilization in the 450 ppm scenarios.[3] It needs to be clearly stated though that significant overshoot changes the nature of the climate target by reducing the likelihood of staying below a given temperature threshold considerably compared to a pathway that reaches the same long-term concentration target without overshoot.

At the same time, it is important not to oversimplify the relevance of these single technologies, because the stringency of a 450 ppm CO_2e goal leads to different conclusions than a 550 ppm target. The effects of technology availability were both smaller and more even in the 550 ppm than in the 450 ppm CO_2e scenarios, and only three models were not able to produce any single 550 ppm scenario. In other words, the EMF27 scenarios tell us that there are many options for meeting the level of reductions required in a 550 ppm CO_2e goal, and it is not absolutely critical to have all the

[3] Several other options to produce negative emissions such as afforestation, enhanced weathering and direct air capture are discussed in the literature, but the majority of models in the EMF27 study included bioenergy coupled with CCS as the only negative emissions option.

arrows in the quiver; but there is a step change in the magnitude of the challenge, and hence in the importance of a full technology portfolio, when moving to a 450 ppm CO_2e scenario.

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