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synthesis article

Role of renewable energy in climate mitigation: a synthesis of recent scenarios

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The role of renewable energy in climate change mitigation is explored through a review of 162 recent medium- to long-term scenarios from 15 large-scale, energy-economic and integrated assessment models. The current state of knowledge from this community is assessed and its implications drawn for the strategic context in which policymakers and other decision-makers might consider renewable energy. The scenario set is distinguished from previous ones in that it contains more detailed information on renewable deployment levels. All the scenarios in this study were published during or after 2006. Within the context of a large-scale assessment, the analysis is guided primarily by four questions. What sorts of future levels of renewable energy deployment are consistent with different CO_2 concentration goals? Which classes of renewable energy will be the most prominent energy producers and how quickly might they expand production? Where might an expansion in renewable energy occur? What is the linkage between the costs of mitigation and an expansion of renewable energy?

Keywords: climate change mitigation; renewable energy; scenarios

Le rôle des énergies renouvelables dans l'atténuation du changement climatique est examiné par la revue de 162 scenarios récents à moyen et long terme provenant de 15 modèles d'évaluation intégrée énergie-économique de large échelle. L'état des connaissances actuelles de cette communauté est évalué et ses implications tirées du contexte stratégique au sein duquel les décideurs politiques et autres décideurs pourraient envisager l'énergie renouvelable. Le scénario établi se distingue des précédents dans la mesure où il contient une information plus détaillée sur le degré de déploiement des énergies renouvelables. Tous les scénarios de cette étude furent publiés durant ou après 2006. Dans le cadre d'une évaluation à grande échelle, l'analyse est guidée principalement par quatre questions. Quels futurs degrés de déploiement d'énergie renouvelable sont compatibles avec les différentes cibles de concentration de CO_2? Quelles catégories d'énergie renouvelable seraient les principaux producteurs d'énergie et à quelle vitesse leur production pourrait-elle s'accroitre? Quel est le lien entre les coûts de l'atténuation et l'expansion de l'énergie renouvelable?

Mots clés : atténuation du changement climatique; énergie renouvelable; scénarios

1. Introduction

Concern over potential changes to the global climate has increased in recent years as advances in scientific understanding have clarified the links between human activities, greenhouse gas concentrations and change in the Earth's climate (IPCC, 2007a, c). Options to address climate change are an increasingly prominent topic for policymakers in both national and international forums. Energy technology is at the heart of solutions to climate change. The deployment of technologies that will use less energy or that can produce energy with lower CO_2 emissions will ultimately be a primary means for reducing anthropogenic emissions.

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This article addresses the role of renewable energy[1] in climate mitigation. Renewable energy encompasses a wide range of energy sources and technologies, including solar power and heat, wind power, geothermal energy, bioenergy, hydroelectric power and ocean-based energy. The distinguishing characteristic of renewable energy sources is that they are derived from natural processes that are continually renewed.

To explore the role of renewable energy in climate mitigation, this article provides a synthesis of the results from 162 recent medium- to long-term scenarios constructed using 15 large-scale, energy-economic and integrated assessment models.[2] These scenarios are among the most sophisticated and recent explorations of how the future might evolve to address climate change. As such, they provide a window onto the current understanding of the role of renewable energy technologies in climate mitigation. Most of the scenarios are CO_2 stabilization scenarios, but the set also includes scenarios without meaningful efforts to address climate change. The scenario set is distinguished from previous scenario data sets on this topic in that the authors worked directly with the modelling teams to extract more detailed information on renewable deployment levels than in previous assessments (Morita et al., 2001; Hanaoka et al., 2006; Nakicenovic et al., 2006). The scenario set also includes a large number of 'second-best' scenarios that suggest less optimistic views on international mitigation efforts or consider the consequences of constraints on the deployment of low-carbon energy technologies. It is also distinguished by how recent the scenarios are – all scenarios in this study were published during or after 2006.

The goal is to identify what these scenarios, taken in total, say about the strategic context surrounding renewable energy and climate mitigation. As a synthesis, the focus is on assessing and confirming the current state of knowledge from a community of large-scale, integrated modellers. In other words, the question that this article addresses is as follows – taking the results of the 162 scenarios in this study as representative of the current state of knowledge in this community, what are the most important and robust lessons that emerge and that might provide a strategic context for policymakers and other decision-makers?

The discussion is motivated and guided by four strategic questions. First, what sorts of future levels of renewable energy deployment are consistent with different CO_2 concentration goals? Or, put another way, what is the linkage between CO_2 concentration goals and the deployment of renewable energy? Second, which classes of renewable energy will be the most prominent energy producers and how quickly might they expand production? Third, where would an expansion in renewable energy occur? Finally, what is the linkage between the costs of mitigation and an expansion of renewable energy? The answers to all of these will have important implications for the social, institutional and physical infrastructures necessitated by climate change mitigation.

Among the more important themes that emerge from the scenarios are the following. There is little precision in the linkage across the scenarios between renewable energy deployments and the stabilization goal. In other words, the precise role that renewable energy might play in climate mitigation is highly uncertain. At the same time, a substantial, and in some cases extraordinary, expansion of renewable energy is common across most of the scenarios, irrespective of the climate goal. Further, much of this expansion takes place in the developing world. The scenarios provide no indication of a single, consensus silver-bullet renewable energy technology. Yet there is evidence that some renewable energy sources – wind energy, solar energy, bioenergy – are more likely to play an important role than others. Finally, the scenarios reinforce current uncertainty regarding whether a future heavily reliant on renewable energy to reduce CO_2 emissions will be extraordinarily costly or whether the costs will only be modest.

The remainder of this article proceeds as follows. Section 2 introduces the scenarios explored in this article. Section 3 discusses the general characteristics of the relationship between renewable energy deployment levels and climate goals. Sections 4 and 5 discuss the primary drivers of renewable energy deployment levels: energy demand and competition with other energy technology solutions. Section 6 explores renewable energy deployments by technology, with a focus on timing and regional deployment. Section 7 discusses the linkage between renewable energy deployments and the costs of mitigation. Finally, Section 8 provides concluding thoughts.

2. The scenarios

Scenarios are a tool for understanding, but not predicting, the future. Scenarios provide a plausible description of how the future may develop based on a coherent and internally consistent set of assumptions about key driving forces (e.g. rate of technological change, prices) and relationships (IPCC, 2007b). In the context of this article, they are therefore a means to explore the potential contribution of renewables to future energy supplies and to identify the drivers of their deployment. They are not predictions; however, with the possible exception of some sensitivities, they are generally constructed to represent futures with underlying drivers that are considered plausible, given all the present uncertainty about how the coming century might unfold.

The scenarios in this article are based on quantitative modelling approaches, as opposed to qualitative narratives (see Morita et al. (2001) and Fisher et al. (2007) for reviews of the qualitative narrative approach to scenarios development). In the past (e.g. Herzog et al., 2005; Barker et al., 2007), quantitative scenario modelling approaches, such as those explored in this article, have been broadly separated into two distinct groups: top-down models that are rooted in macroeconomic modelling traditions and bottom-up models that are rooted in energy-engineering modelling traditions. Recent developments have made this distinction less meaningful. Most models still trace their lineage to one tradition more than the other, but many models now combine important aspects from both approaches and thus belong to the class of so-called hybrid models (Hourcade et al., 2006; van Vuuren et al., 2009). It should be noted that the blurring of the distinction between top-down and bottom-up approaches does not imply that models are becoming uniform. A wide range of important methodological differences persist between models. For example, and particularly relevant for this synthesis, the degree of detailed technology information included in the integrated models varies across the models (see Table 3 and the discussion below).

The terms top-down and bottom-up can also be misleading because they are strongly context-dependent: they are used differently in different scientific communities. For example, in past Intergovernmental Panel on Climate Change (IPCC) assessments (IPCC, 2001, 2007b), all large-scale integrated modelling approaches were classified as top-down models, regardless of whether they included significant technology information (van Vuuren et al., 2009). The interpretation of both terms also depends on the aggregation level that is typically addressed by the respective scientific community. In the energy-economic modelling community, macroeconomic approaches are traditionally classified as top-down models and energy-engineering models as bottom-up. However, in engineering sciences, even the more detailed energy-engineering models that represent individual technologies such as power plants, but essentially treat them as ‘black boxes’, are characterized as top-down models. For both reasons, the scenarios in this article are not classified here as either top-down or bottom-up; they are referred to simply as large-scale, integrated models.

The important methodological characteristics of the models producing the scenarios in this article are as follows. (i) They capture, in a single integrated platform, many of the key interactions that serve as the environment in which renewable energy technologies will be deployed, including interactions with other technologies, other parts of the energy system, other relevant human systems (e.g.

agriculture, the economy as a whole) and important physical processes associated with climate change (e.g. the carbon cycle). (ii) They have a basis in economics in the sense that decision-making is largely based on economic criteria. (iii) They are long term and global in scale, but with some regional detail. (iv) They include the policy levers necessary to meet emissions outcomes. (v) They have sufficient technology detail to create scenarios of renewable energy deployment at both regional and global scales.

This article reviews 162 scenarios from the recent literature, from 15 models (see Table 1). All the scenarios in this study were published during or after 2006. The scenarios therefore reflect the most recent understanding of key underlying parameters and the most up-to-date representations of the dynamics of the underlying human and Earth systems.

Although this set of scenarios is by no means exhaustive of recent work on mitigation scenarios, it is large enough and extensive enough to provide robust insights into the current understanding of the role of renewable energy in climate change mitigation. The bulk of the scenarios in this article come from three coordinated, multimodel studies – the Energy Modeling Forum (EMF) 22 international scenarios study (Clarke et al., 2009), the ADAM project (Knopf et al., 2009; Edenhofer et al., 2010) and the RECIPE comparison (Luderer et al., 2009; Edenhofer et al., 2010) – which harmonize some scenario dimensions, such as baseline assumptions or climate policies across the participating models. The remaining scenarios come from individual publications.

The full set of scenarios covers a large range of CO_2 concentrations (350–1,050 ppm atmospheric CO_2 concentration by 2100[3]), some of which represent scenarios of aggressive action to address climate change and others represent no-policy, or baseline, scenarios.[4] The mitigation scenarios include scenarios in which the 2100 concentration is not exceeded in this century, as well as those in which CO_2 concentrations temporarily exceed their 2100 value before declining to that value (overshoot scenarios). The full set of scenarios covers time horizons 2050 to 2100, and all the scenarios are global in scope.

The scenarios also include a relatively large number of 'second-best' scenarios that cover less optimistic views on international action to deal with climate change (delayed participation) or address consequences of constraints on the deployment of low-carbon energy technologies (Table 2). Although scenarios assuming idealized climate policy approaches and full technology availability ('first-best scenarios') have historically dominated the mitigation scenario literature, second-best scenarios have received growing attention in recent years (Clarke et al., 2009; Edenhofer et al., 2009). The assumptions regarding delayed participation in this study vary considerably, but are mostly taken from the EMF 22 study (Clarke et al., 2009) and the RECIPE project (Edenhofer et al., 2009; Luderer et al., 2009). Similarly, constraints on technology availability are not defined homogeneously across all scenarios in the analysed set, but the constrained technology studies that are highlighted here are those with constraints on the deployment of carbon capture and storage (CCS) and nuclear energy. Both these technologies are direct competitors of renewable energy technologies in producing low-carbon energy.[5]

A final distinguishing characteristic of the scenarios in this study is that information on renewable energy deployment levels was collected at a level of detail beyond that found in existing scenario databases, such as those compiled for IPCC reports (Morita et al., 2001; Hanaoka et al., 2006; Nakicenovic et al., 2006). For example, many scenario databases represent renewable energy technologies as either bioenergy or non-biomass renewables (e.g. Clarke et al., 2009). In contrast, this study involved a major effort to collect renewable energy deployment information for wind energy, solar energy, bioenergy, geothermal energy, hydroelectric power and ocean energy. Table 3 lists the renewable energy technologies that are covered by the integrated models that contributed scenarios to this analysis, as well as the availability of fossil energy with CCS and nuclear energy.[6]

TABLE 1 Energy-economic and integrated assessment models considered in this article

Model	No. of scenarios	Baseline scenarios	Policy scenarios				Comparison project	Citation
			First best	Second-best technology[a]	Second-best policy	Second-best technology and policy		
AIM/CGE	3	1	1	0	1	0	–	Masui et al. (2010)
DNE21	7	1	3	3	0	0	–	Akimoto et al. (2008)
GRAPE	2	1	1	0	0	0	–	Kurosawa (2006)
GTEM	7	1	4	0	2	0	EMF 22	Gurney et al. (2009)
IEA-ETP	3	1	2	0	0	0	–	IEA (2008)
IMACLIM	8	1	2	4	1	0	RECIPE	Luderer et al. (2009)
IMAGE	17	3	5	6	0	3	EMF 22/ ADAM	van Vuuren et al. (2007, 2010), van Vliet et al. (2009)
MERGE-ETL	19	4	3	12	0	0	ADAM	Magne et al. (2010)
MESAP/ PlaNet	1	0	0	1	0	0	–	Krewitt et al. (2009)
MESSAGE	15	2	4	7	2	0	EMF 22	Krey and Riahi (2009), Riahi et al. (2007)
MiniCAM	15	1	5	4	3	2	EMF 22	Calvin et al. (2009)
POLES	15	4	3	8	0	0	ADAM	Kitous et al. (2010)
REMIND	28	4	6	14	4	0	ADAM/ RECIPE	Leimbach et al. (2010), Luderer et al. (2009)
TIAM	10	1	5	0	4	0	EMF 22	Loulou et al. (2009)
WITCH	12	1	4	4	3	0	EMF 22/ RECIPE	Bosetti et al. (2009), Luderer et al. (2009)
TOTAL	162	26	48	63	20	5	–	

[a]Although in the vast majority of second-best technology scenarios the deployment of individual technologies or technology clusters has been constrained, in a few cases included under this category the potential for bioenergy has actually been expanded compared to the model's default assumption.
Note that the total number of scenarios per model varies significantly.

TABLE 2 Number of long-term scenarios categorized by CO_2 concentration levels in 2100 and by inclusion of delayed participation in mitigation (second-best policy) and limitations on renewable energy, nuclear energy and CCS deployment

	CO_2 concentration by 2100 (ppm)	No. of scenarios	Policy scenarios			
			First best	Second-best technology	Second-best policy	Second-best technology and policy
Baselines	>600	26	–	–	–	–
Category IV	485–600	32	11	13	6	2
Category III	440–485	63	20	29	11	3
Category II	400–440	14	7	6	1	0
Category I	<400	27	10	15	2	0

The CO_2 concentration categories are defined in the IPCC AR4, WGIII (Fisher et al., 2007). Note that Categories V and higher have been omitted in this analysis and Category IV has been slightly extended to 600 ppm from its original upper bound of 570 ppm in the AR4, because no policy scenarios in the analysed set reach higher CO_2 concentrations than 600 ppm by 2100. In turn, the lowest baseline scenarios start at CO_2 concentration levels slightly above 600 ppm by 2100.

Several caveats must be kept in mind when interpreting the scenarios in this article. First, the scenarios do not represent a random sample that should be used for formal uncertainty analysis. No formal uncertainty methods were used to pick or generate the scenarios. Furthermore, many of the scenarios come from three major model comparison exercises, and therefore include some assumptions that are consistent across large subsets of the scenarios, limited primarily to future technology availability and the timing of international action in a global climate mitigation regime. Many of the scenarios represent sensitivities based on other scenarios in the set, primarily along these same two dimensions. This includes not just runs from the three major model comparison exercises, but also analyses from individual publications (e.g. Akimoto et al., 2008; IEA, 2008). Although the scenarios should not be interpreted as representing a truly random sample, this does not mean that they do not contain information about uncertainty. In scenario ensemble analyses such as this, there is a constant tension between the fact that they are not truly a random sample and the fact that the variations among the scenarios result largely from a lack of knowledge about key forces that might shape the future. In this way they do provide real and often clear insights into uncertainty.

Second, it is important to acknowledge the limitations of the models themselves. Maintaining a global, long-term, integrated view involves trade-offs. Models often do not incorporate potentially important interactions at a finer scale, or do so in a highly stylized fashion. These are not power system models or engineering models. For example, the limitations on intermittent electricity generation on the grid, which can have an important influence on the deployment of wind and solar power, are often represented in a highly stylized fashion. Furthermore, although all the models are based on economic decision-making criteria and are designed to explore policy options, they cannot accurately represent all details that govern decision-making, particularly in the short term, or represent all existing regulations and policies in place at regional, national or international scales. For these reasons, the scenarios generated from these models are most useful for the medium- to long-term outlook. For shorter time horizons, other tools such as market outlooks or shorter-term national analysis, which explicitly address all existing policies and regulations, would be more suitable sources of information.

TABLE 3 Renewable energy technologies covered by the integrated models that contributed scenarios to the present analysis

Model	Renewable energy technologies																					Competitors	
	Bioenergy to electricity	Bioenergy to electricity (w/CCS)	Biomass to liquids	Biomass to liquids (w/CCS)	Biomass to gas	Biomass to gas (w/CCS)	Biomass to hydrogen	Biomass to hydrogen (w/CCS)	Hydro power	Wind (generic)	Wind onshore	Wind offshore	Solar power (generic)	Solar PV	Concentrating solar power	Solar thermal heat	Geothermal power	Geothermal heat	Ocean power (generic)	Ocean tidal	Ocean wave	Fossil CCS	Nuclear energy
AIM/CGE	+	+	+	−	+	−	−	−	+	+			+			−	+	−	−			+	+
DNE21	+	+	+	−	−	−	−	−	+		+	−	+			−	+	−	−			+	+
GRAPE	+	−	+	−	−	−	+	−	+		+	+		+	−	−	−	−	−			+	+
GTEM	+	−	−	−	−	−	−	−	+	+			+			−	−	−	−			−	+
IEA-ETP	+	+	+	+	+	−	+	+	+		+	+		+	+	+	+	+		+	+	+	+
IMACLIM	−	−	+	+	−	−	−	−	+		+	+	+			−	−	−	−			+	+
IMAGE	+	+	+	−	−	−	+	+	+		+	−		+	−	−	−	−	−			+	+
MERGE-ETL	+	+	+	+	−	−	+	+	+	+				+	+	−	−	−	−			+	+
MESAP/PlaNet	+	−	+	−	+	−	+	−	+		+	+		+	+	+	+	+	+			−	−
MESSAGE	+	+	+	−	+	−	+	+	+	+				+	+	+	+	+	−			+	+
MiniCAM	+	+	+	−	+	−	+	+	+	+				+	+	−	+	−	−			+	+
POLES	+	+	+	−	−	−	+	+	+		+	+		+	+	+	−	−	−			+	+
REMIND	+	−	+	+	+	−	+	+	+	+				+	−	+	+	+	−			+	+
TIAM	+	+	+	−	+	−	−	−	+		+	+		+	+	+	+	+	−			+	+
WITCH	+	−	+	−	−	−	−	−	+	+			+				−	−	−			+	+

Note that a '+' means that the technology is represented in the respective model and was used at least in one of the scenarios that were evaluated in this study. A '−' means that the technology was explicitly not included in the study. A blank means that it is unspecified whether the technology is included, because a more aggregate representation is used. For example, many models represent wind power using a generic wind technology rather than explicitly representing onshore wind and offshore wind. Note also that these are characteristics of the models at the time that the scenarios listed in Table 1 were produced. Many of the models have in the interim made changes to include more technologies or more explicit representations. Note also that even if a model generally included a technology, it may have been removed for particular sensitivity analyses that are included in the data set (e.g. fossil energy with CCS).

3. Renewable energy deployment and climate goals

This section provides a brief overview of the relationship between renewable energy deployment levels and long-term CO_2 concentrations. It is useful to note that, not surprisingly, there is a strong correlation between fossil and industrial CO_2 emissions and long-term CO_2 concentration goals across the scenarios (Figure 1). This is consistent with past scenario literature (Fisher et al., 2007). Because perceived uncertainty in the nature of key physical processes underlying the global carbon cycle is sufficiently small in relation to other factors, cumulative emissions are maintained within relatively tight bounds for scenarios with similar CO_2 concentration goals. Any variation in emissions pathways among scenarios with similar concentration goals derives largely from the remaining uncertainties in the carbon cycle, assumptions about or representations of CO_2 emissions from land use and land-use change, and assumptions about the factors that influence the timing of mitigation. Factors that influence the timing of mitigation include, among other things, the rate of technological improvements, underlying drivers of emissions in general such as economic growth, and methodological approaches for allocating emissions over time.[7]

The scenarios provide far less guidance about the relationship between renewable energy deployment and CO_2 concentration goals (Figure 2). On the one hand, there is a generally rising trend in renewable deployments as the stringency of the constraint is increased. Hence, all other things being equal, one should expect large renewable energy deployments to be associated with more stringent CO_2 concentration goals. At the same time, there is enormous variation among deployment levels for any specific CO_2 concentration goal. In other words, to the extent that these scenarios provide a window into the collective knowledge of this community, they confirm substantial uncertainty about the role that renewable energy might play in climate mitigation.[8]

The scenarios tell a more consistent story about the general direction of renewable energy deployment in the future. The future levels of renewables deployment are dramatically higher than those of today in the vast majority of scenarios. In 2007, global renewable primary energy supply using

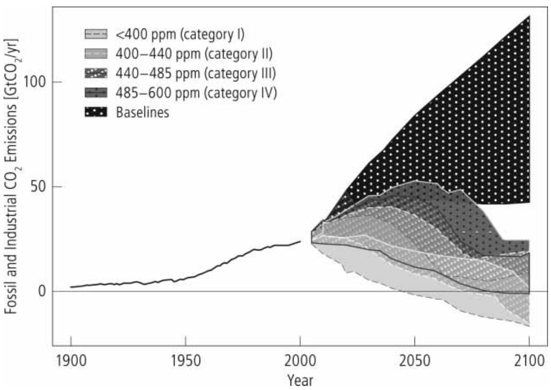

FIGURE 1 Historic and projected global fossil and industrial CO_2 emissions across all scenarios between 1900 and 2100. Shadings are based on categories of atmospheric CO_2 concentration level in 2100. Historic emission data from Nakicenovic et al. (2006)

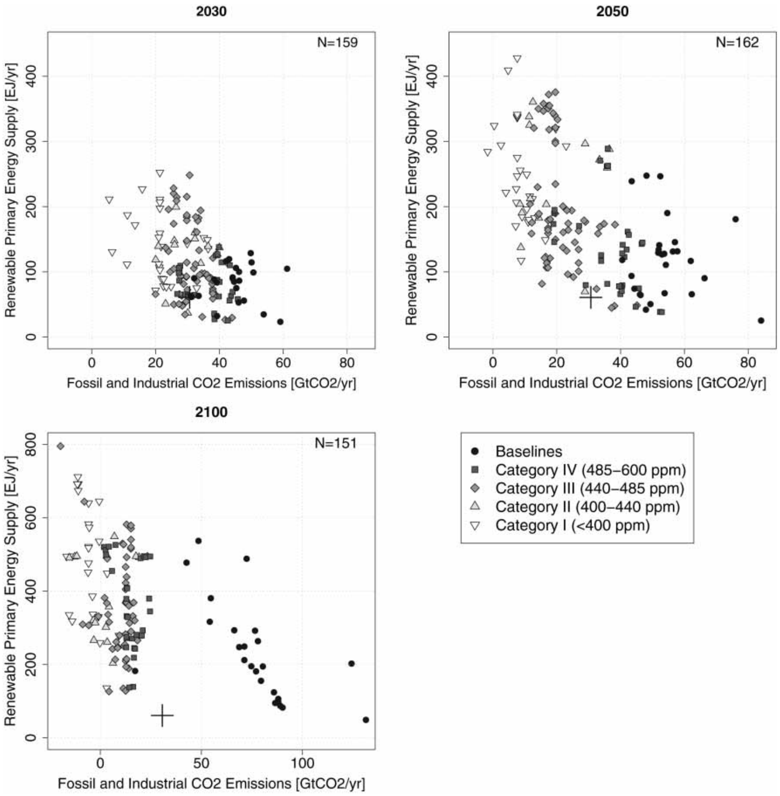

FIGURE 2 Global renewable primary energy supply (direct equivalent) across all scenarios as a function of fossil and industrial CO_2 emissions in 2030, 2050 and 2100. Shadings and symbols are based on categories of atmospheric CO_2 concentration level in 2100. The black crossed lines show the relationship in 2007. Pearson's correlation coefficients for the three data sets are −0.39 (2030), −0.55 (2050) and −0.51 (2100). The numbers in the right upper corner of the individual graphs correspond to the actual number of scenarios underlying the graphs. Not all scenarios provided data for all periods

the direct equivalent method stood at 61 EJ/year (IEA, 2009).[9] In contrast, by 2030, many scenarios indicate a doubling of renewable energy deployment or more, relative to today. By 2050, deployments in many of the scenarios reach 200 EJ/year or up to 400 EJ/year. This is an extraordinary expansion. The deployment levels in 2100 are even larger, reflecting continued growth throughout the century. Indeed, even deployments of renewable technologies in the baseline scenarios are quite large in many instances.

Taking these results together, the scenarios confirm two of the most important elements of strategic context surrounding renewable energy and climate change. First, strategic planning for renewables should take place in the context of high uncertainty. Second, despite this uncertainty, decision-makers should be considering futures that go well beyond incremental increases in renewable deployment. They should be planning for futures with substantially more, and for some technologies orders of magnitude more, renewable energy than the present.

4. Setting the scale for deployment

The deployment of renewable energy in climate mitigation does not take place in a vacuum; it takes place in the context of growing demands for energy and competition with other low-carbon energy sources. This section and the next explore the uncertainty in renewable energy deployment levels by isolating the effects of energy demand from the competition with other low-carbon supply sources.

Although CO_2 mitigation does put downward pressure on total global energy consumption, the effect is small enough in general that only a limited relationship can be discerned between total primary energy consumption and long-term climate goals (Figure 3). The effect of mitigation on primary energy consumption is overwhelmed by a variation in assumptions about the fundamental drivers of energy demand. The variation is simply a reflection of the fact that these forces cannot be predicted with any degree of certainty today.

It is interesting to note that the variation in primary energy consumption increases with the stringency of the concentration goal. Although this article does not explore the basis for this behaviour, it is useful to comment on it as a means to highlight the potential role of end-use options. The behaviour is consistent with the following logic. The emission-constrained scenarios are more varied because these scenarios may assume, at one extreme, abundant inexpensive low-carbon options (leading to high primary energy demands) or, at the other extreme, approaches to mitigation based on reducing the demand for energy (leading to low primary energy demands). The baseline scenarios are less varied because they do not include the variation in downward pressure on primary energy demands that results from CO_2 emissions constraints.

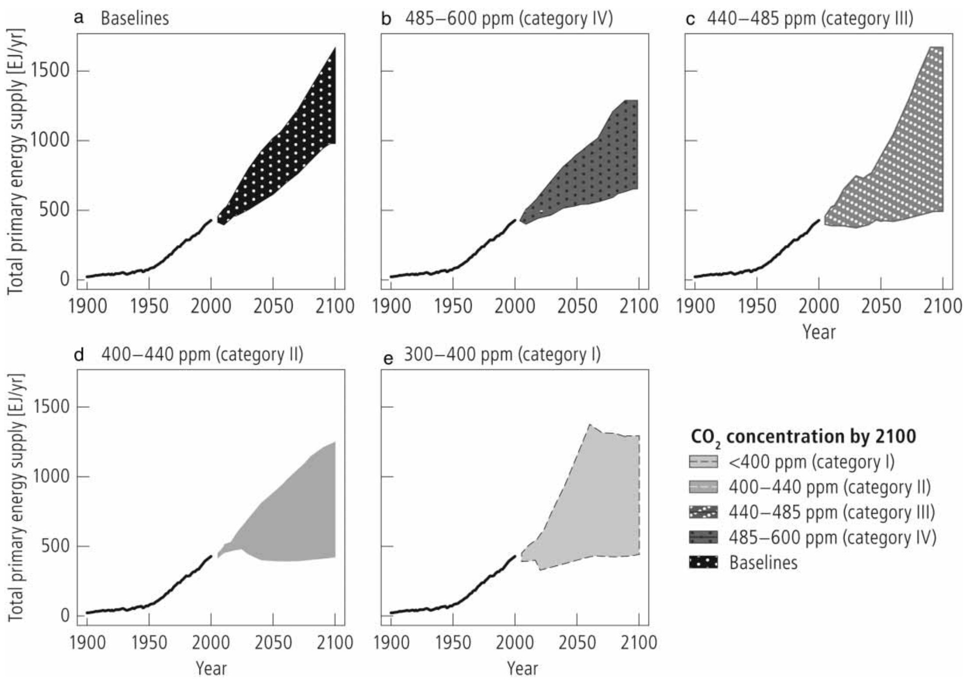

FIGURE 3 Historic and projected global primary energy supply (direct equivalent) across scenarios. Shadings are based on categories of atmospheric CO_2 concentration level in 2100. Historic data from Grubler (2008)

In contrast to the variation in total primary energy, the production of freely emitting fossil energy is tightly constrained by the long-term CO_2 concentration goal (Figure 4). Earth systems, most notably the global carbon cycle, put bounds on the levels of CO_2 emissions that are associated with meeting long-term CO_2 concentration goals. Limits on CO_2 emissions, in turn, bound the amount of energy that can be produced from freely emitting fossil energy sources. There is still some degree of flexibility in the limits on freely emitting fossil energy, as reflected by the ranges shown in Figure 4. Factors that lead to this flexibility include the ability to switch between fossil sources with different carbon contents (e.g. natural gas has a lower carbon content per unit of energy than coal), the potential to achieve negative emissions by utilizing bioenergy with CCS or forest sink enhancements (which will allow for greater emissions of freely emitting fossil energy), and differences in the time path of emissions reductions over time as a result of differing underlying model structures, assumptions about technology and emissions drivers, and representations of physical systems such as the carbon cycle.

Simple arithmetic dictates that the production of low-carbon energy – renewable energy, nuclear energy and fossil energy with CCS – is the difference between total primary energy demand and the production of freely emitting fossil energy that meets the long-term climate goal (Figure 5). As the stringency of the policy is tightened, freely emitting fossil energy will decrease, and low-carbon energy production will need to increase to fill the gap (Clarke et al., 2009; O'Neill et al., 2010). Although energy consumption (relative to a no-policy scenario) should also decrease in response to mitigation because of higher fuel prices,[10] the demand response from mitigation is swamped by variability in demand more generally across the scenario set, as discussed above. The result is that, although there is a strong correlation between the CO_2 concentration goal and low-carbon energy, there is still substantial variability in low-carbon energy for any given CO_2 concentration goal.

The uncertain competition between renewable energy, nuclear energy and fossil energy with CCS adds another layer of variability in the relationship between renewable energy deployment and the CO_2 concentration goal. In total, then, given the variability in pathways to a long-term goal, the

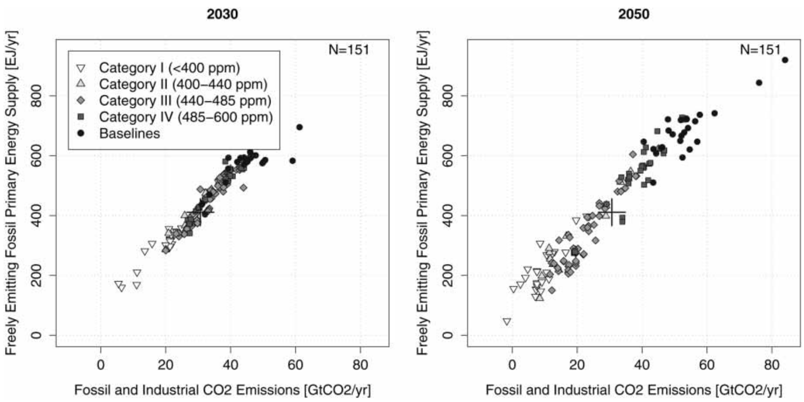

FIGURE 4 Global freely emitting fossil primary energy supply across the scenarios by 2030 and 2050 as a function of fossil and industrial CO_2 emissions. Shadings and symbols are based on categories of atmospheric CO_2 concentration level in 2100. The black crossed lines show the relationship in 2007. Pearson's correlation coefficients for the two data sets are 0.96 (2030) and 0.97 (2050). The numbers in the right upper corner of the individual graphs correspond to the actual number of scenarios underlying the graphs

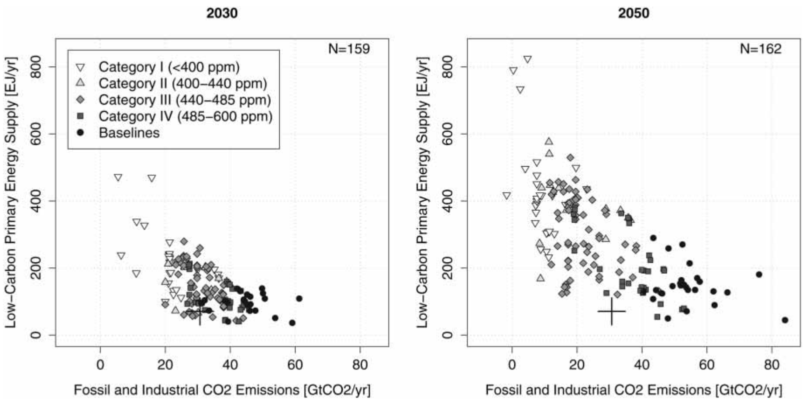

FIGURE 5 Global low-carbon primary energy supply across the scenarios by 2030 and 2050 as a function of fossil and industrial CO_2 emissions. Shadings and symbols are based on categories of atmospheric CO_2 concentration level in 2100. The black crossed lines show the relationship in 2007. Pearson's correlation coefficients for the two data sets are −0.60 (2030) and −0.68 (2050). The numbers in the right upper corner of the individual graphs correspond to the actual number of scenarios underlying the graphs

variability in energy system size associated with any long-term goal, and the competition between three low-carbon supply options, it is not surprising that there is a great deal of variability in the relationship between CO_2 concentration goals and renewable energy deployment levels presented in the previous section (Figure 2).

5. Competing low-carbon supply options

This section explores how the competition between renewable energy and competing low-carbon sources influences the deployment of renewable energy. If policymakers expect that technological, environmental, social, national security or other barriers may inhibit the deployment of CCS and/or nuclear energy, then they should naturally expect that that renewable energy will be called upon to play a more prominent role in climate mitigation.

How much larger a role is an open question. On the one hand, it could be argued that constraints on only CCS or nuclear energy will have a limited influence on the deployment of renewable energy, because the majority of the energy it would have provided will be provided instead by the other rather than by renewable energy sources. One line of reasoning behind this argument is that renewables are simply too expensive to be meaningful substitutes for nuclear energy and CCS. A second is that renewable energy cannot meaningfully substitute for CCS and nuclear energy, because two of the more important renewable electric technologies, wind and solar, provide electricity intermittently, whereas nuclear energy and CCS are associated with baseload electricity.[11] But arguments can be made the other way as well. Technological improvements could reduce the costs and improve the performance of renewable technologies so that they become substantially more competitive with nuclear energy and fossil energy with CCS. Furthermore, it could be argued that intermittency may not prove a substantial constraint on renewable generation. There are renewable sources that can provide baseload power – for example, hydroelectricity, geothermal energy and concentrating solar power (CSP) with thermal storage – and advances in storage technologies, grid management and demand-side management technologies could simultaneously open the door for substantially larger shares of intermittent generation on the electricity grid. Although the scenarios in this study cannot resolve this issue, it is instructive to observe how the scenarios reflect on it.

One way to gain first-order insights into this issue is to compare scenarios with explicit limitations on the deployment of CCS and nuclear power with scenarios that do not have such explicit limitations.[12] A number of these scenarios are included in the scenario set explored in this article (Table 1).[13] The approach to constraining CCS deployment is consistent across the scenarios: the option to install CCS is simply excluded either on new or on existing power plants and other energy conversion facilities with fossil or bioenergy energy as an input (e.g. synthetic fuel production). However, there are several approaches to constraining nuclear energy in the scenarios. Two of these approaches maintain nuclear deployments at low levels, allowing current stocks to retire over time and not allowing any new installations, or maintaining the total deployment of nuclear energy at current levels, which might reflect either lifetime extensions or just enough new installations to counteract retirements. A third option is to maintain nuclear deployment in mitigation scenarios at baseline levels, that is, the level of nuclear energy that occurs in the scenarios without any emissions mitigation. This latter category of scenarios is difficult to interpret because nuclear energy could expand substantially in baseline scenarios, depending on the underlying assumptions (see the caption of Figure 6 for details).

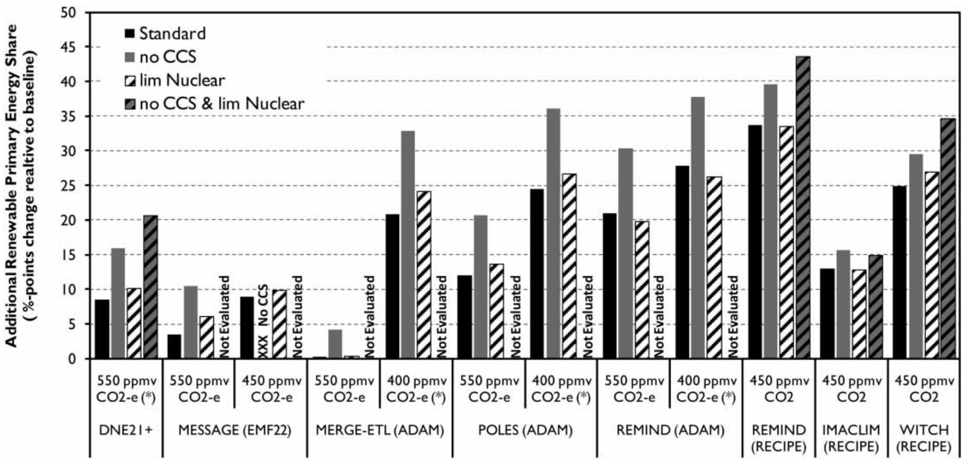

FIGURE 6 Increase in renewable primary energy share by 2050 in representative constrained technology mitigation scenarios in percentage points compared with the respective baseline scenarios. The 'XXX' indicates that the concentration target for the scenario was not achieved. Note that the definition of 'lim Nuclear' cases varies across scenarios. The DNE21+, MERGE-ETL and POLES scenarios represent nuclear phase-outs at different speeds; the MESSAGE scenarios limit the deployment to 2010 levels; and the REMIND, IMACLIM and WITCH scenarios limit nuclear energy to the contribution in the respective baseline scenarios, which still implies a significant expansion compared with current deployment levels. Note also that the REMIND (ADAM) 400 ppmv no-CCS scenario refers to a scenario in which cumulative CO_2 storage is constrained to 120 Gt CO_2 (no CCS at all was found to be infeasible). For the same reason, in the MERGE-ETL 400 ppmv no-CCS case a cumulative CO_2 storage of about 720 Gt CO_2 was allowed, which resulted in deployment of bioenergy with CCS only. Also the POLES 400 ppmv CO_2e no-CCS scenario was infeasible, and therefore the concentration target of the scenario shown here was relaxed by approximately 50 ppm CO_2. All other no-CCS scenarios do not allow the option to install CCS. The DNE21+ scenario is approximated at 550 ppmv CO_2e based on the emissions pathway through 2050

Not surprisingly, all other things being equal, when nuclear energy and CCS are constrained, renewable energy constitutes a higher proportion of total primary energy (Figure 6). Two countervailing effects simultaneously influence the change in renewable energy share. First, with fewer competing options, renewable energy will constitute a larger share of low-carbon energy – how much being dependent on assumptions about substitution possibilities as discussed above. Second, higher mitigation costs resulting from the lack of options should put downward pressure on total primary energy consumption, because options for reducing energy consumption become increasingly attractive. The relative influence of these two forces varies across models. In the DNE21 and to some extent the POLES scenarios shown in Figure 6, the absolute increase in renewable energy share dominates. In IMACLIM, MESSAGE and REMIND, the demand decrease tends to have a stronger effect on the increase in renewable energy share.

Beyond sensitivities in single models, the pattern is less clear. Figure 7 shows the relationship between renewable energy production and non-renewable low-carbon energy production across the full scenario set. This representation of the scenarios removes much of the variability caused by the concentration goal and energy consumption, largely isolating the competition between the three low-carbon sources. In general, renewable energy production is lower in those scenarios without constraints on nuclear and/or CCS deployment. On the other hand, renewable energy provides almost all of the low-carbon energy in a number of scenarios, with limits on only one of these competitors, or even without explicit limitations. If deployment of both nuclear energy and CCS is constrained, renewable energy must, of course, produce the vast majority of low-carbon energy.[14]

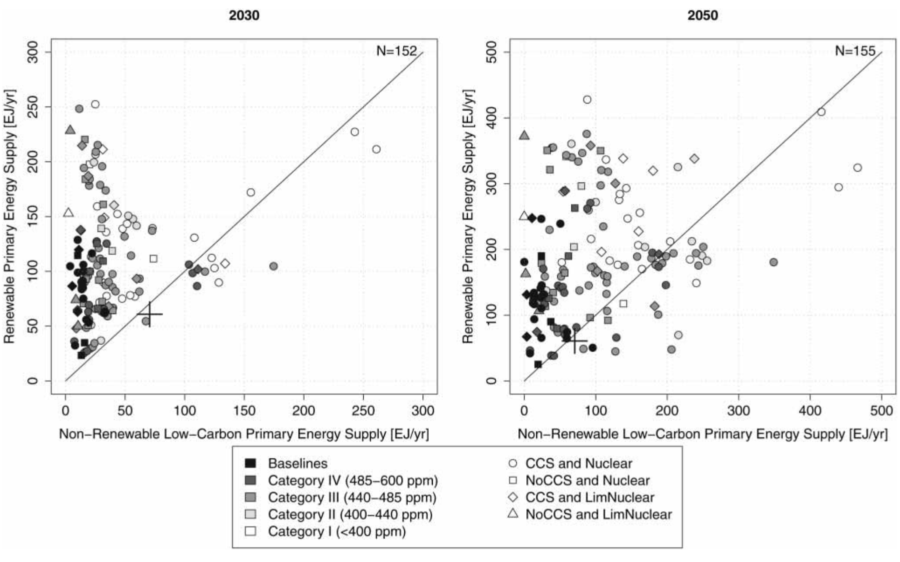

FIGURE 7 Global renewable primary energy supply (direct equivalent) plotted against non-renewable low-carbon primary energy supply (direct equivalent) across the scenarios by 2030 and 2050, depending on the availability of the competing low-carbon energy supply options CCS and/or nuclear energy. Shadings are based on categories of atmospheric CO_2 concentration level in 2100 and the symbols correspond to different technology portfolios. The black crossed lines show the relationship in 2007. The numbers in the right upper corner of the individual graphs correspond to the actual number of scenarios underlying the graphs

Another salient issue is the relative influence of constraints on the deployment of CCS and constraints on the deployment of nuclear energy. Although there may be reasons to argue that constraints on CCS should have a larger effect than constraints on nuclear energy,[15] and perhaps vice versa, the scenarios do not provide sufficient information to draw such a conclusion. In the small set of individual model sensitivities in Figure 6, the effect goes in both directions, although more of the scenarios indicate a larger influence from the absence of CCS than from nuclear energy. The larger scenario set in Figure 7 presents no obvious pattern.

6. Deployments by technology, over time and by region

Renewable energy is not a single technology. It represents a range of technologies, including wind power, solar energy, bioenergy, hydropower, geothermal energy and ocean-based sources. One distinguishing characteristic of this study is that deployment data were collected at a level of regional and technological disaggregation not available in previous scenario overview studies.

A first observation from these results is that there is no technology for which the deployment is not characterized by enormous uncertainty (Figures 8, 9 and 12). Although this is not surprising, it is an important reminder that there is no consensus silver bullet in climate mitigation.

Beyond this uncertainty, several salient patterns emerge. One observation is that bioenergy,[16] solar energy and wind power consistently provide more energy at a global level and in the long run than geothermal energy or hydroelectric power.[17] A second observation is that some technologies expand more rapidly than others (Figure 10). Growth rates are first-order indicators of the pressure on the social, institutional and technological infrastructures that will be required to support those technologies. Indeed, scenarios that include high growth implicitly assume that social, institutional or technological barriers to large-scale deployment are largely overcome. Global production of bioliquids and solar energy grow dramatically relative to today in many scenarios. In particular, solar energy is still a small contributor to the global energy system today, but both play a large role in the future energy system in many scenarios. Although wind power is also a large producer in many scenarios, its growth is slower because wind energy production is already much larger today than solar power production. Being a mature technology, there is generally little growth in hydroelectric power production. Direct biomass use in end-use sectors is largely stable or even slightly declining across the scenarios.[18]

A third observation is that the deployment of some renewables (e.g. solar, geothermal, modern biomass) is influenced more strongly by climate policy than others (e.g. wind, hydro, direct use of solid biomass). To a large degree, this pattern mimics the patterns of growth more generally, indicating that the more broadly a technology is used today, the less it is subject to the presence or absence of climate policy. This is consistent with the intuition that technologies used widely today have proven to be competitive with other energy sources and are therefore perhaps not as dependent on climate policy to spur their deployment as emerging technologies. At the same time, this is not to suggest that the only reason for growth in production from emerging technologies such as solar photovoltaics (PV) and liquid biofuels technologies is climate policy. Production from both of these increases dramatically in many scenarios, even without climate policy, suggesting that other forces (for example technological improvements or increasing prices for conventional liquid fuels) are at play.

An important aspect of deploying renewable energy sources on a large scale is their integration into existing supply structures. Systems integration is most challenging for intermittent electricity generation technologies such as wind power, solar PV and wave energy. A first-order proxy for the challenges related to systems integration is therefore the share of different intermittent renewable energy sources, mostly wind power and solar PV, at the global level (Figure 11).[19] Again, those scenarios with high

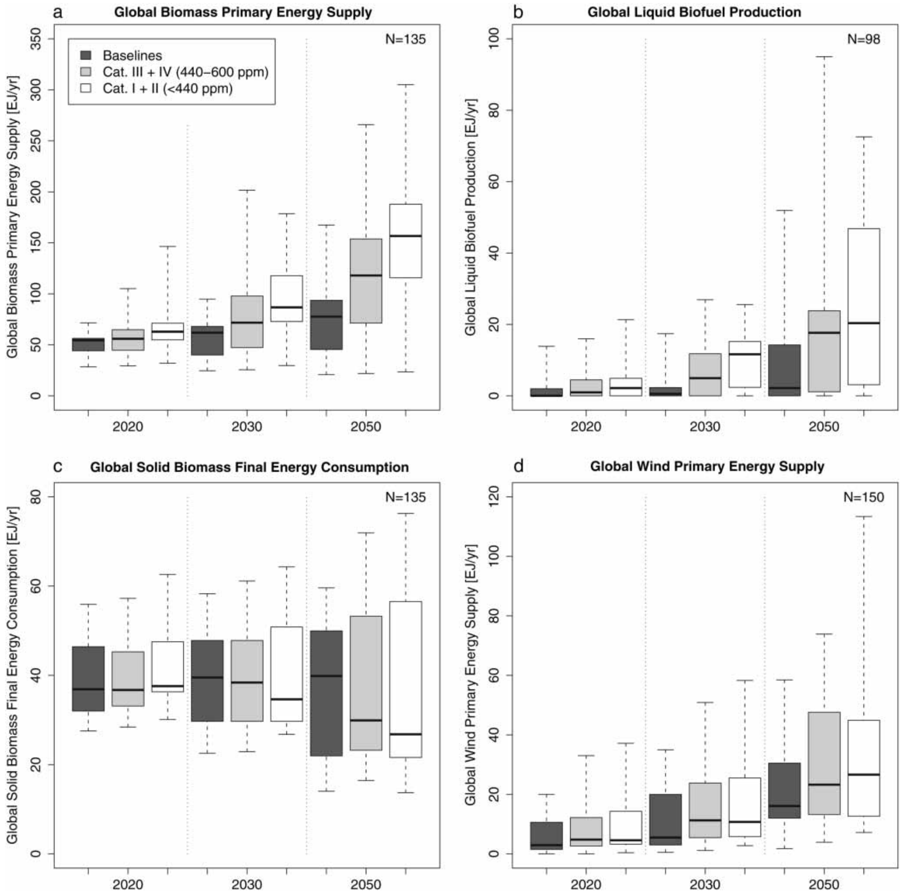

FIGURE 8 Global primary energy supply of biomass (a), global liquid biofuel production (b), global solid biomass final energy consumption (c) and global wind energy production (d) across the scenarios by 2020, 2030 and 2050, grouped by different categories of atmospheric CO_2 concentration level in 2100. The thick black line corresponds to the median, the coloured box corresponds to the interquartile range (25th–75th percentile) and the whiskers correspond to the total range across all reviewed scenarios. The numbers in the right upper corner of the individual graphs correspond to the actual number of scenarios underlying the graphs. Not all models provided data at the level required to generate technology- or fuel-specific figures

proportions of wind and solar PV on the grid implicitly assume that any barriers to grid management in this context are largely overcome, for example, through electricity storage technologies, demand-side management options and advances in grid management more generally.

A final observation is that, by 2050, renewable energy production in the non-Annex I countries is generally larger than that in the Annex I countries (Figures 12 and 13). This results directly from the assumption that these regions will continue to represent an increasingly large share of total global energy consumption and CO_2 emissions (see, for example, Clarke et al., 2009). All other things being equal, higher energy consumption will require greater mitigation and greater deployment of low-carbon energy sources to achieve a given climate target. This result is an important reminder of the challenges facing planners and policymakers if renewable energy is to play a substantial role in

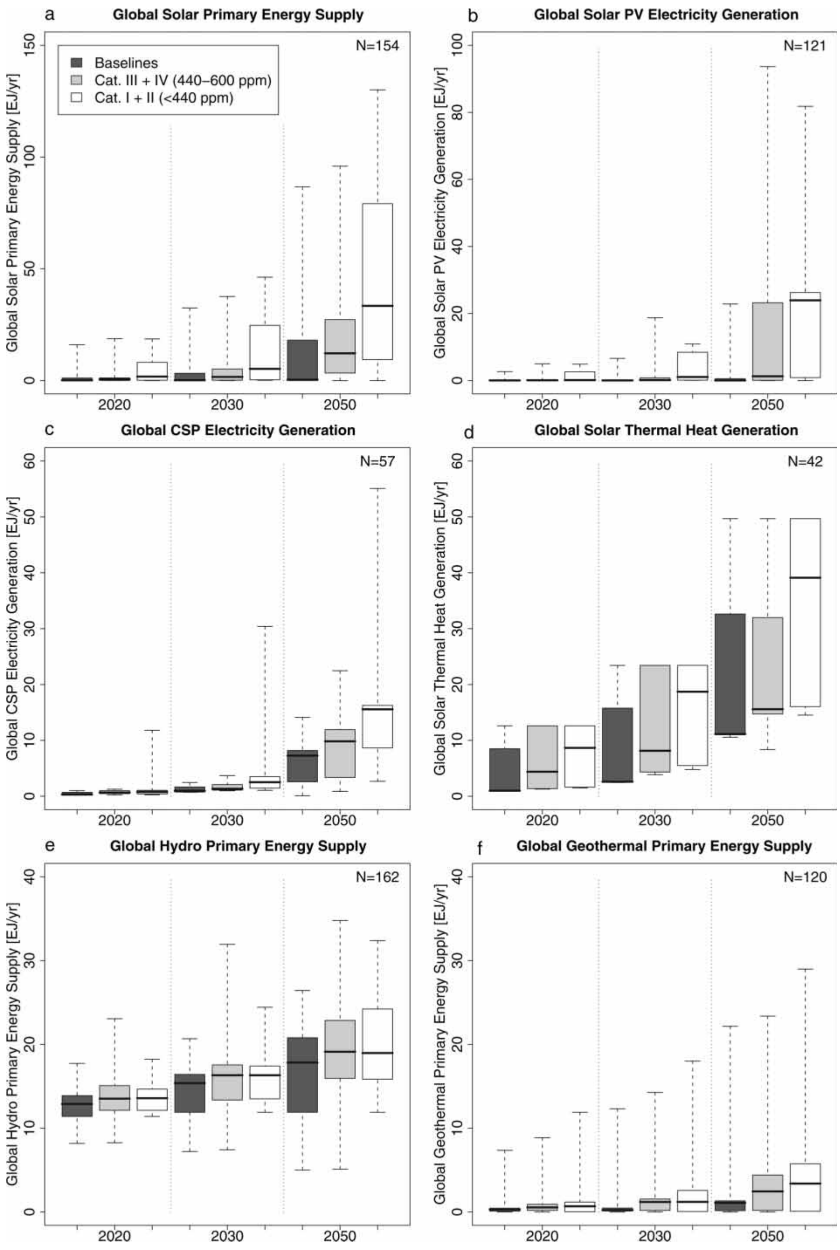

FIGURE 9 Global solar primary energy supply (a), global solar PV electricity generation (b), global CSP electricity generation (c), global solar thermal heat generation (d), global hydro primary energy supply (e) and global geothermal primary energy supply (f) across the scenarios by 2020, 2030 and 2050, grouped by different categories of atmospheric CO_2 concentration level in 2100. The thick black line corresponds to the median, the coloured box corresponds to the interquartile range (25th–75th percentile) and the whiskers correspond to the total range across all reviewed scenarios. The numbers in the right upper corner of the individual graphs correspond to the actual number of scenarios underlying the graphs. Not all models provided data at the level required to generate technology- or fuel-specific figures

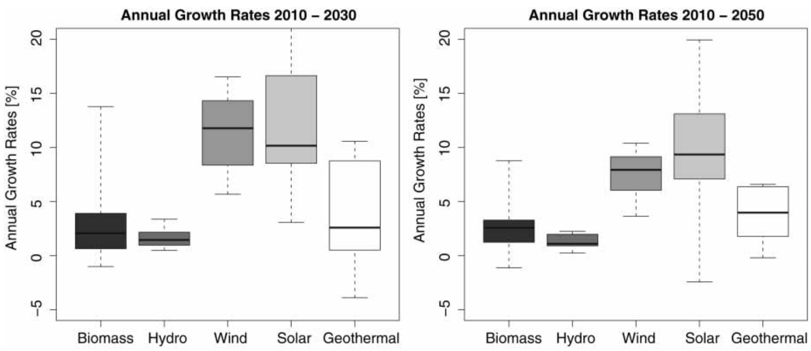

FIGURE 10 Annual growth rates of different renewable energy sources across the scenarios for the periods 2010–2030 and 2010–2050. The thick black line corresponds to the median and the coloured box corresponds to the interquartile range (25th–75th percentile). Note that in contrast to the previous boxplots, the whiskers correspond to the 5th and 95th percentiles across all reviewed scenarios. This change of definition was necessary, because growth rates strongly depend on base year (2010) values, which are particularly uncertain for emerging technologies. Note that the number of observations for each bar may be less than the full set of 162 scenarios based on limitations in the reported data

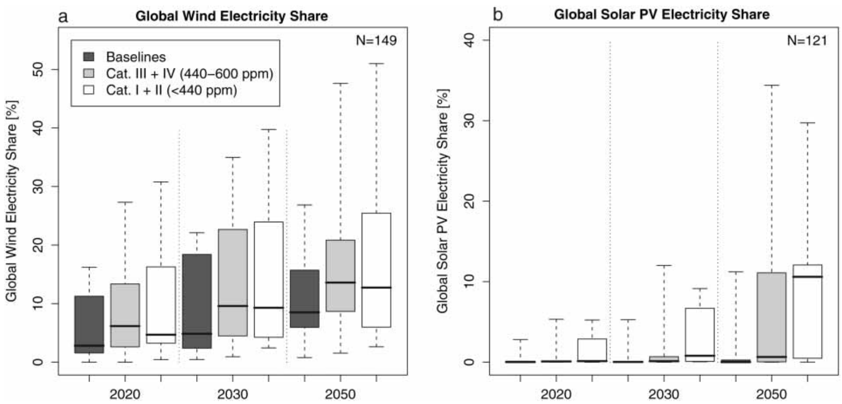

FIGURE 11 Share of wind (a) and solar PV (b) in global electricity generation across the scenarios by 2020, 2030 and 2050, grouped by different categories of atmospheric CO_2 concentration level in 2100. The thick black line corresponds to the median, the coloured box corresponds to the interquartile range (25–75th percentile) and the whiskers correspond to the total range across all reviewed scenarios. The numbers in the right upper corner of the individual graphs correspond to the actual number of scenarios underlying the graphs

climate mitigation. It will require deployment not only in those countries with the most advanced institutional and technological infrastructures, but also in emerging economies and developing countries. It will require very different investment flows from those in existence today, an associated stability in policy environments (e.g. carbon tax, feed-in tariffs) necessary to achieve these flows, and enhancements to infrastructure (for example, in the electric grid infrastructure) to incorporate increased intermittent renewable energy production.

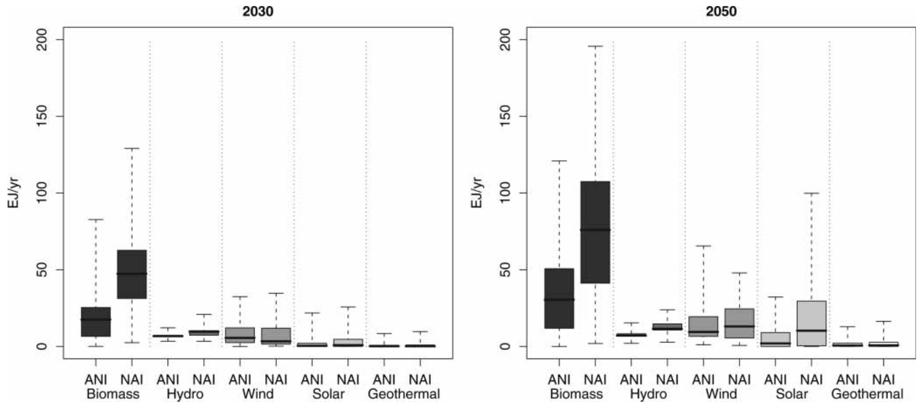

FIGURE 12 Renewable primary energy supply (direct equivalent) by source in Annex I (ANI) and non-Annex I (NAI) countries across the scenarios by 2030 and 2050. The thick black line corresponds to the median, the shaded box corresponds to the interquartile range (25th–75th percentile) and the whiskers correspond to the total range across all reviewed scenarios. Note that the number of observations for each bar may be less than the full set of 162 scenarios based on limitations in the reported data (Note also that this figure is constructed based on the direct equivalent accounting method. In particular, this means that bioenergy is accounted for prior to conversion to fuels such as ethanol or electricity. In contrast, the other technologies generally produce electricity, and they are accounted for based on the electricity produced in these cases. If they were to be converted to primary equivalents using the substitution method, then their energy production might be roughly three times larger, based on average fossil electricity efficiencies.)

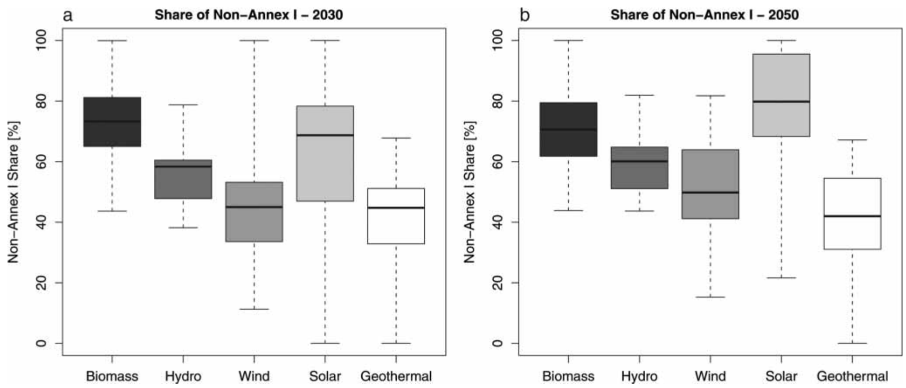

FIGURE 13 Share of non-Annex I countries in the global deployment of different renewable sources in the long-term scenarios by 2030 and 2050. The thick black line corresponds to the median, the coloured box corresponds to the interquartile range (25th–75th percentile) and the whiskers correspond to the total range across all reviewed scenarios. Note that the number of observations for each bar may be less than the full set of 162 scenarios based on limitations in the reported data

At the same time, it is important to note that the distribution of renewable energy production across countries over the next several decades is highly dependent on the nature of the international policy structure. In scenarios that assume the near-term implementation of a globally efficient regime in which emissions reductions are undertaken where and when they will be most cost-effective, renewable energy growth in non-Annex I countries can be rapid, depending, of course, on the degree of mitigation. A more realistic assumption is that mitigation efforts may differ substantially across regions in the near- to mid-term, with some regions taking on larger commitments than others. In this real-world context, the distribution of renewable energy deployments in the near term would be skewed towards those countries taking the most aggressive action. As an example, Figure 14 shows the change in renewables deployment in China in 2020 and 2050 from the EMF 22 study (Clarke et al., 2009). This study explored the implications of delayed participation by non-Annex I regions on meeting long-term climate goals. In the delayed accession scenarios, China takes no action on climate prior to 2030. After 2030, China begins mitigation. When China delays mitigation, the relative deployments of renewables are lower. The impact is generally more severe for tighter emission constraints, because the degree of mitigation is higher in these cases. Delay clearly decreases deployment during the period when China is taking on no mitigation (2020) (the right panel in Figure 14). The effect is ambiguous in the period after China has begun mitigation (the right panel in Figure 14). In some cases, deployments are larger in 2050 and in some cases they are lower. This ambiguity occurs in part because China may need to quickly ramp up mitigation efforts by 2050 if action has been delayed but the same long-term climate target is to be met as for the case with immediate action. It is also important to note that there is some degree of renewables deployment in every region, even in the absence of mitigation. This is the reason why there is little effect on renewables deployment in some scenarios in 2020.

7. Renewable energy and the costs of mitigation

One way in which researchers characterize the challenge of mitigation is by quantifying its economic consequences. Within this context, several questions about renewable energy arise. One common question is how much CO_2 abatement, at what cost, can be provided by individual renewable energy technologies? It was not considered feasible to provide mitigation cost results of this sort

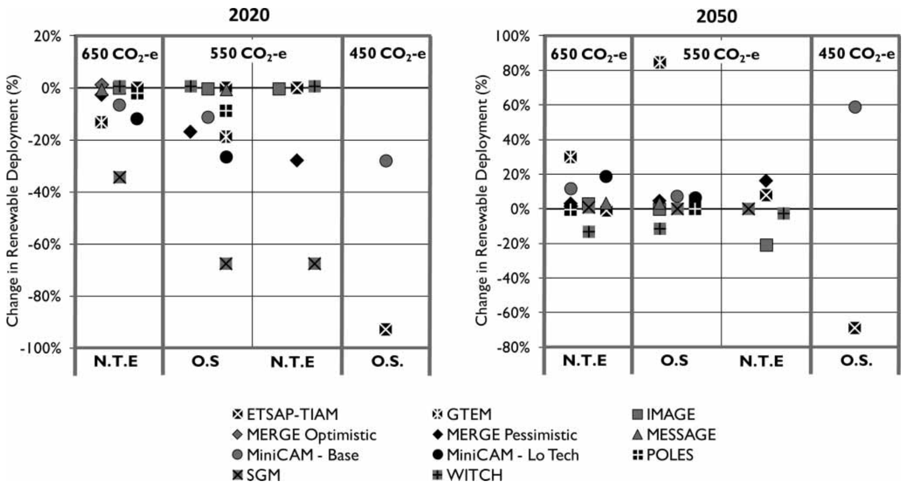

FIGURE 14 Change in renewables deployment in China across EMF 22 scenarios as a result of delayed accession in 2020 (left panel) and 2050 (right panel) relative to a scenario with full global participation beginning in 2012. In these scenarios, delayed accession means that China takes no action on climate in 2020 and begins action after 2030. Adapted from Clarke et al. (2009)

using the scenarios in this article, primarily because assignments of mitigation to particular technologies are not an output of integrated models. Assignments are the result of post-processing, offline, accounting calculations that rely on analyst judgement about key assumptions. Applying these assumptions to the scenarios would blur the signal from the scenarios themselves.

A second question is what sorts of renewable energy deployment levels will be associated with what sorts of carbon prices? The answer would inform both the carbon prices that might be needed to spur renewable energy deployment and the economic consequences that deploying renewables might imply. This is, in fact, a question that was posed and explored in the most recent IPCC assessment report (IPCC, 2007b), which asserted that renewable energy could provide 30–35% of global electricity generation at carbon prices below \$50/t CO_2. The scenarios in this study demonstrate no meaningful correlation between carbon prices and renewable energy production (Figure 15). In 2050, scenarios with carbon prices above \$600/t CO_2 include renewable energy production of less than 150 EJ; scenarios with carbon prices below \$200/t CO_2 include renewable energy production above 300 EJ. The long-term uncertainty represented by this scenario set – about economic growth, energy demands, technological improvements, energy infrastructure and so forth – is simply too substantial to create a meaningful relationship. This sort of variation in carbon prices is an inherent part of the modelling landscape (e.g. Clarke et al., 2007, 2009).

One limitation of CO_2 prices as cost metrics is that they only provide the marginal costs of abatement and not the total cost. Cost measures such as changes in GDP or consumption, or total mitigation costs can provide a broader sense of the cost implications of renewable energy deployment. Several of the analyses that provided scenarios for this study explored the relationship between GDP impacts and the presence or absence of renewable energy and competing low-carbon technologies. Consistent with

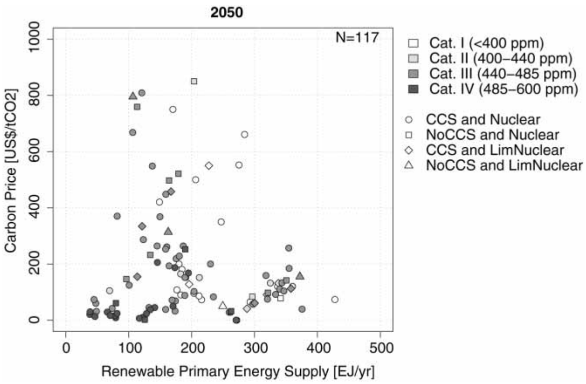

FIGURE 15 Carbon prices and renewable energy deployment levels in 2050 in the long-term scenarios. The colour coding is based on categories of atmospheric CO_2 concentration level in 2100. Different symbols in the graph denote the availability of CCS and/or nuclear energy in the scenarios. Shadings are based on categories of atmospheric CO_2 concentration level in 2100 and the symbols correspond to different technology portfolios. The number in the right upper corner of the graph corresponds to the actual number of scenarios underlying it. Note that this figure does not include baseline scenarios

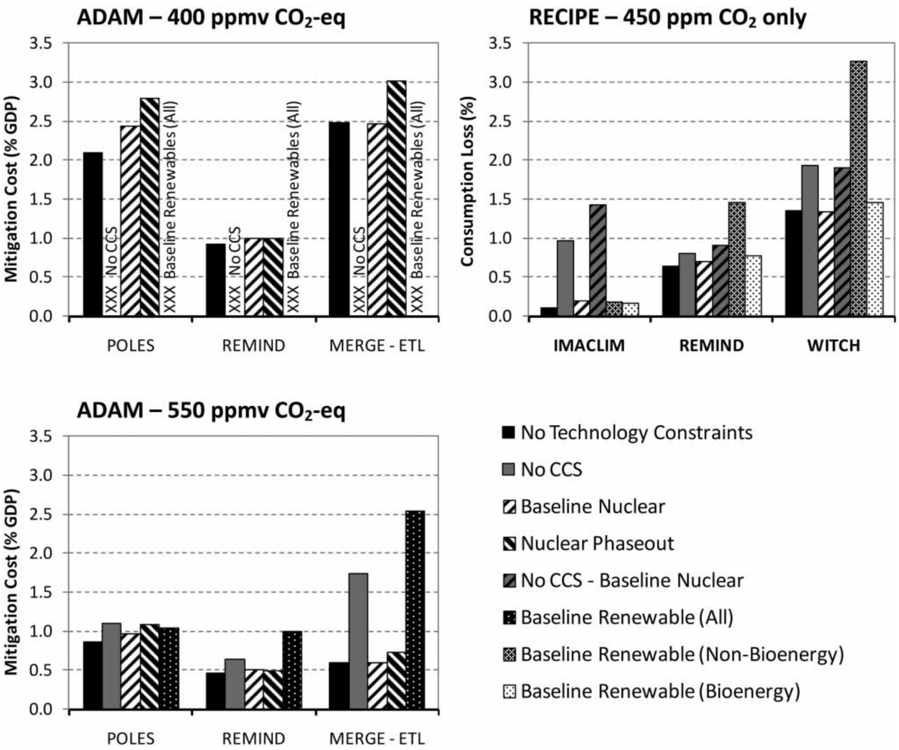

FIGURE 16 Mitigation costs from two model comparison exercises, the RECIPE project and the ADAM project, under varying assumptions regarding constraints on technology deployment. Note that costs are expressed differently between studies and models. The RECIPE project measured costs as the decrease in cumulative consumption through 2100 relative to baseline no-policy scenario consumption. Mitigation costs in the ADAM project are presented in terms of aggregated GDP losses (MERGE and REMIND) or increase of abatement costs (POLES) through 2100 relative to the respective no-policy scenarios under identical technology assumptions. All scenarios described as 'baseline' restrict technology deployment to its baseline levels. The nuclear phase-out scenarios assume no new investments in nuclear power. The 'XXX' indicates that the CO_2 concentration target for the scenario was not achieved. Data for RECIPE were taken from Luderer et al. (2009) and data for ADAM from Edenhofer et al. (2010). Note that climate targets in ADAM are defined in terms of CO_2e concentration of all greenhouse gases while in RECIPE the climate target is defined for CO_2 concentrations only

intuition, these studies demonstrate that the presence of renewable energy technologies reduces the costs of mitigation. This is not very surprising; increasing the number of available options should not increase costs. Perhaps more instructive is the relative magnitude of the costs in these studies when renewable energy growth is constrained relative to cases in which fossil energy with CCS and nuclear energy are constrained. For example, in both the ADAM (Edenhofer et al., 2010) and RECIPE projects (Luderer et al., 2009), each involving three models, the cost increase that results from the absence of the option to expand on renewable energy deployment is not clearly of a distinctly different order of magnitude than the cost increase from the absence of the option to implement fossil energy with CCS or expand production of nuclear energy beyond today's levels or beyond baseline levels (see Figure 16).

8. Conclusions

Four important and strategic lessons emerge from the presented synthesis. Although these lessons are not new, they are important reminders for policymakers and other decision-makers. The fact that these lessons emerge from the combined research of an important community exploring mitigation in a long-term context adds to the weight of the supporting evidence.

The precise role that renewable energy might play in climate mitigation is uncertain, but a substantial and potentially dramatic expansion is likely. There is little precision in the linkage between renewable global energy deployments and the stabilization goal among the scenarios. This is not surprising given the uncertainty about the evolution of renewable energy technologies, the competitiveness of other options for reducing CO_2 emissions and the underlying drivers of energy demand. Nonetheless, it is an important confirmation that strategic planning for renewable energy in the context of climate change should be conducted within a framework of considerable uncertainty. At the same time, the scenarios consistently point to a substantial, and in some cases extraordinary, expansion of renewable energy at a global scale, irrespective of the climate goal. Indeed, renewable energy deployments increase significantly even in the majority of scenarios that do not include mitigation efforts. The implication is that decision-makers should be considering futures that go well beyond incremental increases in renewable deployment. They should be planning for futures with substantially more, in some cases orders of magnitude more, renewable energy than we have today.

Much of the expansion in renewable energy production will take place in the developing world. A common assumption in recent scenarios is that developing regions will represent an increasingly large share of total global energy consumption and CO_2 emissions (e.g. Clarke et al., 2007, 2009; Keppo and Rao, 2007). All other things being equal, higher energy consumption will require greater mitigation and greater deployment of low-carbon energy sources. As a reflection of this, renewable energy deployment levels in the scenarios are generally as high or higher in the longer term in developing countries than in developed countries. The timing of this expansion depends on the nature of international climate architectures. If near-term architectures push back mitigation in the developing regions as a means to start action, then the expansion of renewable energy could be delayed. At the same time, emissions in both developed and developing countries will eventually have to be reduced dramatically to achieve CO_2 concentration goals; hence, an expansion in developing countries is an inevitable outcome of global mitigation. This result is an important reminder of the global nature of the challenges that will arise if renewable energy is to be a foundation of climate mitigation. It will require deployment not only in those countries with the most advanced institutional and technological infrastructures, but also in emerging economies and developing countries. This, in turn, will require very different investment flows from today, the associated stability in policy environments necessary to achieve these flows, and enhancements to infrastructure (e.g. the electric grid infrastructure) to incorporate increased intermittent renewable energy production.

There is no consensus 'silver-bullet' renewable energy technology, yet there is evidence that some renewable energy sources are more likely to play an important role than others. There is no renewable technology for which deployment across the scenarios is not characterized by enormous uncertainty; that is, there is no obvious winner. Despite these uncertainties, several instructive patterns do emerge from the scenarios. In general, bioenergy, solar energy and wind provide more energy at the global scale and in the long run than geothermal energy or hydroelectric power.[20] Hence, although there is no obvious silver bullet, there is an indication that some renewable energy sources are more likely to play an important role than others. The pathway to larger deployments also varies. Both biomass liquids and solar energy production grow dramatically relative to today in many scenarios. In particular, solar energy is still a relatively small contributor to the global energy system today, so large-scale deployment would require substantial growth. Although wind power also grows substantially, its growth is slower because wind energy production is already much larger today than solar power production. Growth rates are first-order indicators of the pressure on the social, institutional and technological infrastructures that will be required to support those technologies. Indeed, scenarios that include high growth implicitly assume that any social, institutional or technological barriers to large-scale deployment are overcome.

One cannot say with certainty today whether a future heavily reliant on renewable energy will be extraordinarily costly or whether the costs will only be modest. The scenarios in this study demonstrate no meaningful correlation between carbon prices and renewable energy production. Indeed, this sort of variability in indicators of mitigation cost is common in multimodel scenario analyses. Several of the analyses that provided scenarios for this study included sensitivity studies to explore implications of constraints on renewable energy deployment, as well as nuclear power and CCS, on mitigation costs. Although these studies make it clear that costs will be higher than they would otherwise be if any of these three options are for some reason unavailable, a more general relationship could not be obtained when looking across the full set of scenarios in this study. The long-term uncertainty about economic growth, energy demands, technological improvements, energy infrastructure and so forth is simply too substantial to create a meaningful relationship.

Although these strategic lessons are important and strategic reminders, the fact that they are characterized by so much uncertainty is unsatisfactory. To some degree this uncertainty is unavoidable, for obvious reasons, and policymakers and other decision-makers should undoubtedly avoid planning based on implied omniscience about how the world might evolve decades or more into the future. Nonetheless, scenario research could provide more information to unpack this uncertainty. Researchers comparing scenarios across studies and models, such as those producing this article, need to more aggressively pursue methods for comparing assumptions, both explicit in model parameters and implicit in model structure. This article took a first step by identifying which technologies were even represented in the models, but more can be done. This is a very challenging task. Beyond the obvious burden of collecting additional information from disparate modelling groups, it is challenging because models may take very different approaches to representing the inherent complexity of the energy system and other important human and natural systems that interact with the energy system. However, it is clearly an important area for future research, and we believe that it constitutes a natural next step.

Acknowledgements

We thank the following modelling teams for providing data for this scenario review: AIM/CGE, DNE21+, GRAPE, GTEM, IEA-ETP, IMACLIM, IMAGE, MERGE-ETL, MESAP/PlaNet, MESSAGE, MiniCAM, POLES, REMIND, TIAM and WITCH. Without their cooperation, this analysis would not have been possible. We are also grateful for support from the IPCC Working Group III TSU as well as for valuable comments from three anonymous *Climate Policy* reviewers, which helped improve the article significantly.

Notes

1. Renewable energy is one of three classes of low-carbon primary energy. The others are nuclear energy and fossil energy combined with carbon capture and storage (CCS) technology. 'Low-carbon' energy is used here to describe renewable energy, fossil energy with CCS, and nuclear energy. This is not completely precise. For

example, bioenergy coupled with CCS can result in negative carbon emissions. Conversely, land-use change emissions directly or indirectly associated with bioenergy crop production have been shown to be significant in particular instances. Further, all the sources may have some degree of life-cycle emissions, and fossil energy with CCS will generally not result in full capture of all carbon emissions. Nonetheless, the phrase ‘low-carbon’ energy is sufficiently descriptive for the purposes of this article.

2. Hereafter, simply referred to as large-scale, integrated models.
3. For a number of scenarios, mostly baselines, no atmospheric CO_2 concentrations were provided. In these cases, we approximated the concentrations in 2100 that were relevant for grouping the scenarios into the categories as defined in Fisher et al. (2007). To estimate CO_2 concentrations in 2100, we followed the procedure below: (i) if possible we used name tag concentrations supplied with the scenarios; (ii) if those were not available we approximated CO_2 concentration levels in 2100 based on the similarity of CO_2 emission trajectories with scenarios with known CO_2 concentrations.
4. Many of the models that produced the scenarios also include representations of non-CO_2 greenhouse gas emissions (e.g. CH_4, N_2O and F gases). Several include representations of short-lived species (e.g. aerosols). Most include representations of the Earth system sufficient to calculate the total change in radiative forcing or global mean surface temperature. For simplicity, however, this study focuses exclusively on CO_2 emissions and concentrations.
5. Note that the absence of CCS influences not only the availability of fossil energy with CCS, but also the availability of bioenergy with CCS. The opposite is not true in all models. That is, many scenarios that include CCS for fossil energy do not include CCS for bioenergy.
6. Note that combinations of CCS with various fossil conversion technologies, such as power plants, liquid fuel and hydrogen production, vary significantly across models that in general include fossil CCS as an option.
7. Despite the fact that most scenarios allocate emissions over time and across regions according to the objective of minimizing costs, some differences remain. For example, some models are intertemporally optimizing, which means that the resulting emissions pathways are a true optimization result; in contrast, other models do not perform intertemporal optimization and must therefore approximate the optimal solution, for example by employing a carbon tax that rises at a fixed rate over time. More complicated are second-best scenarios with incomplete cooperation. These scenarios are non-optimal by definition. Modellers have some flexibility to define approaches to emissions pricing and allocations in scenarios such as these, and approaches can vary among models and modellers.
8. The direct equivalent method is used throughout this article for accounting primary energy. This treats all non-combustible energy sources in an identical way by adopting the secondary energy perspective; that is, each unit of electricity, heat or hydrogen produced from non-combustible sources is accounted as one unit of primary energy. This choice understates energy from many renewable sources relative to the primary-equivalent approach in which secondary energy is converted back to the equivalent fossil inputs. This choice also implies that all renewable energy sources apart from bioenergy are treated identically. When comparing the contribution of bioenergy with that of the other renewable sources, it has to be kept in mind that a conversion efficiency in the range of 30–90% (strongly dependent on the type of secondary fuel) has to be applied to arrive at the production of a comparable secondary output. For a more detailed discussion on different primary energy accounting conventions, see, for example, Lightfoot (2007) and Macknick (2009).
9. Note that there is a small difference between this value, 60.8 EJ without rounding, and the value of 62.5 EJ for 2007 published in IEA (2009) due to the different primary energy accounting methods used. In contrast to the direct equivalent method that is used throughout this paper, the physical content method adopted by the IEA includes a thermal conversion efficiency of 33% for nuclear power, 10% for geothermal electricity, 50% for geothermal heat and around 38% for concentrating solar power for estimating primary energy based on secondary energy production from these non-combustible sources.
10. This is not always true. There have been scenarios in which primary energy increases because of large-scale electrification in response to climate policy (Loulou et al., 2009).
11. CCS and nuclear power are not explicitly linked to baseload electricity generation. CCS can be applied to dispatchable electricity units. Both might be used in conjunction with hydrogen production in scenarios that envision widespread use of hydrogen. CCS might be used for liquid fuels production from fossil sources or bioenergy.
12. See note 5 regarding bioenergy and CCS.

13. A more systematic study of the competition between renewables and other supply options across the scenarios in this article would require detailed information from each of the scenarios far beyond what was collected for this study. It would require parameter assumptions (e.g. detailed cost and performance information by technology by region) together with information on methodologies for representing renewable energy. Many important assumptions are implicitly buried in these methodological assumptions. Collecting, comparing and evaluating parameter or methodological assumptions is conceptually challenging, because of the complexity of the energy system in which different supply options compete and because of fundamental differences in which this system is modelled. For example, the competitiveness of wind power depends on a range of factors beyond turbine costs, including the distribution of wind sites and their quality (i.e. wind class), transmission distances and costs to bring wind energy to the grid, and the technologies (e.g. electricity storage technologies) and management techniques available for managing large levels of intermittent electricity supply technologies on the grid. Models may have very different ways of representing and parameterizing each of these factors. Indeed, the need to represent this sort of complexity is a large part of the rationale for integrated models in the first place.
14. Note that renewable energy may not provide all the low-carbon energy even with deployment constraints on both nuclear energy and CCS because, as mentioned earlier, constraints on nuclear energy do not necessarily remove all nuclear power from the energy system. Some studies include a nuclear phase-out, others constrain nuclear power to today's levels, and still others constrain nuclear power to its baseline levels.
15. One hypothesis is that the presence or absence of CCS could influence renewable energy more strongly than the presence or absence of nuclear energy because CCS can be coupled with bioenergy to create energy with negative CO_2 emissions. There is no such possibility for nuclear energy. At the same time, there are many other factors that influence the deployment of these technologies.
16. Several important points bear mentioning in comparing bioenergy production with production from the other renewable sources. First, total primary energy from biomass and solid biomass final energy consumption include traditional biomass, which contributes close to 40 EJ in the base year with a modest decline over time in most scenarios. Second, reporting in direct equivalents rather than using the substitution method can tend to overemphasize the production of total bioenergy consumption relative to production of other renewable energy sources, which are generally associated with electricity and heat production. At the same time, biofuels production is expressed in terms of production rather than consumption. Because we are using direct equivalent accounting, a conversion factor would need to be applied to primary energy consumption of primary biomass feedstock for biofuel production.
17. Ocean energy has not been included in this analysis as it is only represented in four scenarios from two integrated models. By 2050, the highest contribution from ocean energy across these four scenarios is less than 2.5 EJ globally. This lack of representation in integrated models illustrates that ocean energy technologies are still in an early development stage and that there is little resource data with global coverage available, which is an important ingredient for an adequate representation of this renewable energy source.
18. See note 16.
19. Note that CSP is not included in the figure. The degree to which CSP might be intermittent is somewhat ambiguous, because CSP can be equipped with thermal storage so that it can behave in a manner more similar to a baseload technology.
20. See note 17 regarding ocean energy.

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