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SYNTHESIS

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

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## Abstract

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?

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?

**Keywords:** climate change mitigation | renewable energy | scenarios
**Mots clés :** atténuation du changement climatique | énergie renouvelable | scénarios

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## Notes

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.

Hereafter, simply referred to as large-scale, integrated models.

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.

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.

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.

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.

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.

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).

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.

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).

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.

See note 5 regarding bioenergy and CCS.

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.

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.

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.

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.

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.

See note 16.

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.

See note 17 regarding ocean energy.

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