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# Historical and potential future contributions of power technologies to global warming

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**Abstract** Using the mathematical formalism of the Brazilian Proposal to the IPCC, we analyse eight power technologies with regard to their past and potential future contributions to global warming. Taking into account detailed bottom-up technology characteristics we define the mitigation potential of each technology in terms of avoided temperature increase by comparing a "coal-only" reference scenario and an alternative low-carbon scenario. Future mitigation potentials are mainly determined by the magnitude of installed capacity and the temporal deployment profile. A general conclusion is that early technology deployment matters, at least within a period of 50–100 years. Our results conclusively show that avoided temperature increase is a better proxy for comparing technologies with regard to their impact on climate change, and that numerous short-term comparisons based on annual or even cumulative emissions may be misleading. Thus, our results support and extend the policy relevance of the Brazilian Proposal in the sense that not only comparisons between countries, but also comparisons between technologies could be undertaken on the basis of avoided temperature increase rather than on the basis of annual emissions as is practiced today.

## 1 Introduction

Most studies on greenhouse gas (GHG) mitigation potentials of technologies or policies approach the subject in terms of cumulative emissions, or even future annual emissions (for example Edmonds et al. 2004; Riahi et al. 2005). However, the ultimate purpose of low-

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carbon technologies is not the abatement of emissions itself, but the avoidance of damages expected from climate change. Between emissions and damages, there is a causal chain of factors such as GHG concentrations in the atmosphere, radiative forcing, global warming, and sea level rise, amongst others. Further down this causal chain,[1] quantities become successively better proxies for damages from climate change (Udo de Haes et al. 1999), however they also become more uncertain (Lenzen 2006). This is well exemplified in the European Commission's ExternE study of monetary externalities from electricity generation (Krewitt 2002).

This recognition has led the Brazilian Government to propose a methodology that measures the responsibility of countries for abating GHG emissions in terms of global warming rather than (cumulative) GHG emissions (Federative Republic of Brazil 1997). In essence, because of the long-term lags between emissions and warming effects, this methodology takes into account historical emissions, and hence penalises developed countries with a long and significant emissions history, but favours developing countries that have only recently started to increase their GHG emissions as a consequence of their development trajectory. Although the results of this methodology are associated with additional uncertainty stemming from the emissions-to-impacts conversions,[2] its benefits lie in the fact that the temperature metric is much more relevant to decision-making than the emissions metric (as explained by Rosa et al. 2004 and Muylaert de Araújo et al. 2007). This aspect forms the main focus of this article.

In order to allocate global warming contributions to countries, one has to formulate an approximation of carbon cycle and climate models, where the temperature increase $\Delta T(t)$ at a time $t$ is an additive function of distinct (historical or future) emissions "parcels" $\varepsilon(t')$:

$$\Delta T[\varepsilon_1(t') + \varepsilon_2(t'), t] = \Delta T[\varepsilon_1(t'), t] + \Delta T[\varepsilon_2(t'), t] \tag{1}$$

Whilst the Brazilian Government had a distinction between countries primarily in mind, the idea of this work is to use the above mathematical formulation of the Revised Brazilian Proposal (RBP; Meira and Miguez 2000) to distinguish energy technologies with regard to their past and potential future contributions to global warming.

Whilst we go to great length in assembling realistic data for specifying future electricity sector scenarios, and justify our assumptions about baselines and excluded emissions, we stress that the purpose of this paper lies less in the actual mitigation potentials that we report, but more in eliciting the differences in mitigation potentials and technology comparisons stemming from emissions and temperature metrics, and therefore in demonstrating how the conclusions suggested to decision-makers depend critically on the choice of metric.

The remainder of this paper proceeds as follows: The next Section will introduce the methodology of the RBP, the scenarios that we apply the RBP to, and our eight technology case studies—various electricity generation technologies, and carbon capture and storage. We define a reference scenario and a low-carbon scenario involving all eight technologies, and through these two scenarios we define our 'mitigation potentials'. We place particular emphasis on our data sources and the calibration of the RBP climate model. Section 3 contains the mitigation potentials for all eight technologies, broken down into historical (1900–2006) and potential future (2009–2100) contributions. We undertake several

[1] Life-cycle assessment (LCA) uses the terms "mid-points" and "end-points" in order to characterise the causal distance of measured and reported quantities to the question asked (Bare et al. 2000; Hertwich and Hammitt 2001; Heijungs et al. 2003).

[2] The uncertainties of impacts of climate change are noted for example in National Research Council (2011).

analyses to demonstrate the sensitivity of our model. Section 4 discusses the results found and concludes.

## 2 Methodology

We follow the RBP in decomposing global temperature increase $\Delta T(t)$ at a time $t$ into contributions by historical emissions "parcels" $\varepsilon(t')$ . The calculus proceeds in three steps: from historical emissions $\varepsilon_g(t'')$ of gases $g$ to their atmospheric concentrations $\Delta\varrho_g(t')$ above pre-industrial levels, then to mean radiative forcings $\Delta Q_g(t')$, and then to contributions $\Delta T_g(t')$ to temperature increases (see Meira and Miguez 2000)

$$\Delta T_g(t') = \frac{1}{C}\int_{-\infty}^{t}\left[\overline{\sigma}_g\left(\beta_g\int_{-\infty}^{t'}\varepsilon_g(t'')\sum_{r=1}^{R} f_{gr}e^{-\frac{t'-t''}{\tau_{gr}}}dt''\right)\right]\sum_{s=1}^{S}\frac{l_s}{\tau_{cs}}e^{-\frac{t-t'}{\tau_{cs}}}dt', \qquad (2)$$

where

- $\varepsilon_g(t'')$ are emissions of gas $g$ avoided by a certain technology in the past, or under a certain future scenario;
- $f_{gr}$ is the $r$th of $R$ fractions of gas $g$ decaying in the atmosphere with characteristic time $\tau_{gr}$ normalised through $\sum_{r=1}^{R} f_{gr} = 1$;
- $\beta_g$ is the above-pre-industrial atmospheric concentration of gas $g$ per unit annual emission of that gas;
- the term in the round brackets is the atmospheric concentration $\Delta\varrho_g(t')$;
- $\overline{\sigma}_g$ is the change in mean radiative forcing by gas $g$ per unit atmospheric concentration of that gas;
- the term in the square brackets is the mean radiative forcing $\Delta Q_g(t')$;
- $l_s$ is the $s$th of $S$ fractions of radiative forcing that adjusts with characteristic time $\tau_{cs}$ normalised through $\sum_{s=1}^{S} l_{cs} = 1$; and
- $C$ is the heat capacity of the climate system.

Meira and Miguez (2000) point out that Equation 2 ignores non-linearities in the warming response to emissions due to saturation of carbon fertilisation and ocean surface uptake (meaning $f_{gr}$ is a function of $t''$), and due to saturation of radiative forcings (meaning $\overline{\sigma}_g$ is a function of $\Delta\varrho_g(t')$). In their review of the RBP, Enting 1998) and of Den Elzen et al. 1999) note that the calculus considers oceanic but not terrestrial carbon dynamics, and that the atmospheric lifetime of GHGs are concentration-dependent. In response to these criticisms, Rosa et al. (2004) show that the omission of terrestrial processes in the RBP has only a small effect on modelled $CO_2$ concentrations, and that considering non-linear effects reduces contributions both from Annex-I as well as Annex-II countries, and that the balance of effects on absolute and relative contributions is relatively small, and, as such, does not alter the main conclusions from the RBP calculus (Den Elzen 2002; Höhne 2002).

This work focuses on the contribution of electricity-generating technologies to temperature increases. Assume that the GHG emissions resulting from the deployment of technology $i$ over time are $\varepsilon_{i,g}(t'')$. Then, the temperature increase at time $t'$ attributable to the use of this technology over the period $[t_0, t']$ is calculated using Equation 2, but with technology-specific emissions $\varepsilon_{i,g}(t'')$. We also set the two lower integral bounds from $-\infty$

to $t_0$, in order to restrict the evaluation of the mitigation potential to post-1900 periods with significant emissions. However, most current assessments characterise technology scenarios in terms of their mitigation potentials with respect to a reference scenario (for example Edmonds et al. 2004; Riahi et al. 2005). Assume that in this reference scenario, technology-specific emissions are $\varepsilon_{i,g}^{\mathrm{ref}}(t'')$. Then, the mitigation potential $M_i^{\mathrm{ref}}(t')$ of technology $i$ at time $t'$ and with respect to reference scenario 'ref' is

$$M_i^{\mathrm{ref}}(t') = \sum_g \frac{1}{C}\int_{t_0}^{t}\left[\overline{\sigma}_g\left(\beta_g\int_{t_0}^{t'}\left\{\varepsilon_{i,g}(t'') - \varepsilon_{i,g}^{\mathbf{ref}}(t'')\right\}\sum_{r=1}^{R} f_{gr}e^{-\frac{t'-t''}{\tau_{gr}}}dt''\right)\right]\sum_{s=1}^{S}\frac{l_s}{\tau_{cs}}e^{-\frac{t-t'}{\tau_{cs}}}dt' \quad (3)$$

## 2.1 Case studies

We investigate eight technologies. Seven of these are electricity-generating technologies: hydro, nuclear, wind, photovoltaic (PV), concentrating solar (CSP), geothermal and biomass power. The remaining technology is carbon capture and storage (CCS). This selection is fairly representative of technologies that are increasingly being considered important in terms of their potential capacity to contribute to a lower-carbon world economy. Currently, only nuclear and hydropower generate significant low-carbon portions of global electricity.

Equation 3 shows that mitigation potentials depend critically on the baseline, and hence the choice of baseline needs to be justified, as well the sensitivity on this choice investigated and explained.[3]

For each technology, we calculate one historical mitigation potential $M_{\mathrm{hist},i}^{\mathrm{coal}}(t')$ with $t_0$= 1900 and $t' \leq 2006$, where we contrast the historical deployment of this technology with a hypothetical scenario 'coal', in which all historically generated electricity would have been produced using coal-fired power plants. We chose this baseline because of a number of reasons: a) it represents a case study that performs worse than all technology scenarios, so that all technology-specific mitigation potentials have the same sign, and are hence easy to interpret for the reader, b) it is relatively easy to establish since it involves only one technology, and c) it is underpinned by high-quality data (as opposed to a biomass power / land-clearing baseline).

To calculate future mitigation potentials, we use two prominent IPCC SRES scenarios (Nakićenović and Swart 2000). We model future evolution of technology deployment to be consistent with SRES storyline B1,[4] and then contrast this with SRES storyline A2[5] as reference scenario. The baseline results of this future scenario are time-dependent mitigation potentials $M_{\mathrm{B1},i}^{\mathrm{A2}}(t')$ with $t_0$=2009 and $t' \in [2010, 2100]$. In addition, we carry out a sensitivity analysis in Section 3. 3. 3 where we contrast storyline B2 with reference A1. The rationale for these choices is as follows: Amongst the SRES scenarios, A2 is associated with the highest

[3] This point was made by an anonymous referee.

[4] The B1 future is characterised by a high level of environmental and social awareness and a globally coherent approach to sustainable development. Technological change and resource efficiency play an important role. Incentive systems and strong international institutions permit the rapid diffusion of cleaner technology. As a consequence, B1 is a low-carbon emission scenario.

[5] The A2 scenario represents a differentiated world, consolidated into distinct, self-reliant regions, and characterised by relatively low trade flows, slow capital stock turnover, and slow technological change. Economic, social, and cultural interactions between regions are weak, economic growth is uneven and the income gap between now-industrialised and developing parts of the world does not narrow. As a consequence, A2 is a high-carbon emission scenario.

emissions, followed by A1, then B2, and finally B1. First, the baseline should always be associated with higher emissions than the future scenario. Second, in order to be comprehensive, the sensitivity analysis should cover large variations in baseline/scenario profiles. Amongst all possible pairs, the storyline pairs A2-B1 and A1-B2 are most varied in their emission profiles, that is, A2-B1 exhibits the largest difference between baseline and scenario, and A1-B2 the smallest difference, thus providing us with the largest variations under which our temperature-based mitigation potentials can be tested for sensitivity.

We calculate emissions $\varepsilon_{i,g}(t'')$ in a bottom-up assessment of each technology as

$$\varepsilon_{i,g}(t'') = E_i(t'')\eta_{i,g}(t'') = P_i(t'')8760\text{h}\ \lambda_i(t'')\left[\eta_{i,g}^{\text{ons}}(t'') + \eta_{i,g}^{\text{ind}}(t'')\right], \tag{4}$$

where at time $t''$, for technology $i$,

- $E_{i,g}(t'')$ is the annual electricity generated,
- $\eta_{i,g}(t'')$ are the emissions of GHG $g$ per unit of electricity generated,
- $P_i(t'')$ is the nameplate capacity installed,
- $\lambda_i(t'')$ is the average capacity factor,[6]
- $\eta_{i,g}^{\text{ons}}(t'')$ are the on-site emissions of GHG $g$ per unit of electricity generated, and
- $\eta_{i,g}^{\text{ind}}(t'')$ are the indirect (off-site, embodied, life-cycle) emissions of GHG $g$ per unit of electricity generated.
- there are 8760 h in a year, which is used to convert between power in units of kW and electricity output in units of kWh

Note that we do not model the time lags between indirect emissions and direct emissions, because these time lags are in the order of magnitude of the construction phase of power plants (<10 years), which is much shorter than the atmospheric lifetime of $CO_2$ (which is in the order of centuries). Also, we do not model the temporal profile of indirect emissions; i. e. we do not distinguish between the pulses of emissions occurring during plant construction and decommissioning, and the tails of emissions occurring during operation and maintenance. This is, once again, because these fluctuations occur during the comparatively short lifetime of plants (≈30 years), but also because they are evened out through the overlap of successive plant generations. Further, some technologies, such as CCS and geothermal power, feature a significant part of their indirect emissions throughout their operation phases. We made an exception for hydropower, where we modelled emissions from dams with exponential functions of 7 years half-life (Rosa and Schaeffer 1995) parametrised on the basis of reservoir measurements (Dos Santos et al. 2006). The rationale for making this exception is the fact that these emissions are, to a large part, in the form of $CH_4$, a GHG with a relatively high Global Warming Potential (GWP≈21) but with a short atmospheric lifetime (10–14 years; IPCC 2007). The gases we include—$CO_2$ and $CH_4$ from dams—form the vast majority of emissions from electricity supply systems. We have therefore excluded emissions of other greenhouse gases, and CH4 from sources other than dams. We recognize that aerosols from coal burning in thermal power plants play a role, but because, in contrast to $CO_2$ emissions, they are highly dependent on the different burning technologies utilised, and providing such level of detail was out of the scope of our work.

[6] We define the load factor or capacity factor of an energy supply system as the equivalent percentage of time over one year during which the system supplies electricity at 100% load, that is supplies electricity at its nominal power rating. For example, a 1000 MW power plant running constantly at 800 MW power output has a capacity factor of 80%. Equally, a 1000 MW power plant running for 292 days (80%) of a year at the full 1000 MW load has a capacity factor of 80%.

Finally, we do not include wider, systemic effects of future transitions into account. Whilst effects of future technological changes in the power sector would clearly be felt in all other industry and end-use sectors of any economy, there does to date not exist a comprehensive enough methodological and data foundation to allow their quantification. For example, consequential Life-Cycle Assessment is a method aimed at covering the marginal effects of implementing a technology, and displacing and changing the operation of other technologies, as reflected by market dynamic interactions between technologies and industries.[7] However, as the IPCC Special Report on Renewable Energy Sources and Climate Change (Sathaye et al. 2011) concludes, "consequential LCAs form the minority of studies in the literature and are so context-dependent as to be incomparable to others such that even the limited results currently available are not included in the broad assessment of this section."

Amongst the input parameters $P$, $\lambda$, $\eta^{ons}$ and $\eta^{ind}$, the installed capacity $P$ undergoes by far the most significant changes over a period of a century. In this work, the effects of technological change and economies of scale on $\lambda$, $\eta^{ons}$ and $\eta^{ind}$ were parametrised as linear functions in time, according to

$$\lambda_i(t'') = \lambda_i(t_0) + [\lambda_i(t') - \lambda_i(t_0)]\frac{t'' - t_0}{t' - t_0}, \tag{5a}$$

$$\eta^{ons}_{i,g}(t'') = \eta^{ons}_{i,g}(t_0) + \left[\eta^{ons}_{i,g}(t') - \eta^{ons}_{i,g}(t_0)\right]\frac{t'' - t_0}{t' - t_0}. \tag{5b}$$

In addition to changes in technology itself, indirect emissions intensities $\eta^{ind}_{i,g}(t'')$ depend on the overall energy mix of the economies in which the components for power plants are manufactured (Lenzen and Wachsmann 2004). Therefore, as the global energy mix is decarbonised, these intensities decrease. In order to capture this effect, we included in the iterative calculation of future intensities $\eta^{ind}_{i,g}(t'')$ a scaling with the ratio of the carbon intensities $\chi$ of electricity mixes in year $t''$-1 and $t_0$:

$$\eta^{ind}_{i,g}(t'') = \left(\eta^{ind}_{i,g}(t_0) + \left[\eta^{ind}_{i,g}(t') - \eta^{ind}_{i,g}(t_0)\right]\frac{t'' - t_0}{t' - t_0}\right)\frac{\chi(t'' - 1)}{\chi(t_0)}. \tag{6}$$

For some technologies, indirect GHG emissions do not only result from plant manufacture, but in part from natural processes such as biomass decay in hydro reservoirs, or increased venting of $CO_2$ from geothermal reservoirs. In these cases, the decrease in future indirect GHG emissions shall reflect a less carbon-intensive background economy, as well as improved technological means to capture natural emissions (DiPippo 2008a; Lima et al. 2008). We model future installed capacity $P$ using time-dependent growth rates $r$:

$$P_i(t'') = P_i(t_0)[1 + r_i(t'')]. \tag{7}$$

Growth rates are modelled on an annual basis, using a geometric progression $r(t'') = \gamma r(t'' - 1)$.[8] Growth evolves starting at historical values $P_i(t_0)$ and $r_i(t_0)$, and the

[7] For an overview of consequential Life-Cycle Assessment, see Finnveden et al. 2009. See Pehnt et al. 2008 for an interesting study about the effects of variability and limited predictability of wind power on increased need for balancing reserves and efficiency penalties for the remaining conventional power plants.

[8] A geometric progression provides for a smoother transition of growth rates, but an arithmetic progression yields a smoother transition of deployment. On a cumulative basis, an arithmetic progression of growth rates leads to a slightly higher electricity production.

parameter $\gamma$ is chosen in order to realise assumed future outcomes, so that $P_i(t''=t')$ assumes a certain target capacity $P_i(t')$. In summary, a complete emissions scenario $\varepsilon_{i,g}(t'')$ for any power technology $i$ is defined by a set of parameters $\{P_i(t_0), r_i(t_0), \gamma \text{ or } P_i(t'), \lambda_i(t_0), \lambda_i(t'), \eta^{\text{ons}}_{i,g}(t_0), \eta^{\text{ons}}_{i,g}(t'), \eta^{\text{ind}}_{i,g}(t_0), \eta^{\text{ind}}_{i,g}(t')\}$.

We model the reference scenarios in the same way as in Equation 4, but characterising only total generation $E^{\text{ref}}(t'')$ and average emissions coefficients $\eta^{\text{ref}}_g$:

$$\varepsilon^{\text{ref}}_g(t'') = E^{\text{ref}}(t'')\eta^{\text{ref}}_g(t'') = E^{\text{ref}}(t'')\left[\eta^{\text{ref,ons}}_g(t'') + \eta^{\text{ref,ind}}_g(t'')\right]. \quad (8)$$

Finally, we undertake several sensitivity analyses (documented in Section 3.1), by varying the fractions $f_{gr}$ and $l_s$, and their corresponding characteristic times $\tau_{gr}$ and $\tau_{cs}$, and by varying GHG emissions coefficients $\eta$ (documented in Section 3.2).

### 2.2 Data sources

Our sources of data are summarised in Badcock and Lenzen 2010. Appendix A gives an abbreviated overview.

## 3 Results

### 3.1 Historical mitigation potentials

Historical electricity generation data (Fig. 1) can be converted into historical emissions from the power sector (Fig. 2) by applying Equation 4, supported by historical emissions coefficients $\varepsilon$. Emissions in 2006 amounted to 11.4 Gt $CO_2$, which corresponds with data given in IEA 2008).

Applying Equation 3 to the historical avoided emissions "pulse" $\varepsilon_{i,g}(t'') - \varepsilon^{\text{coal}}_{i,g}(t'')$ calculated from the emissions profiles in Fig. 2 yields mitigation potentials $M^{\text{coal}}_{\text{hist}\,i}(t')$ in Fig. 3. The vertical axis shows the negative contributions of the various conventional power technologies to global temperature increase, or in other words, *avoided temperature increase*. These contributions are with respect to a hypothetical past where all electricity would have been generated using coal. As a result, coal does not exhibit any mitigation potential.

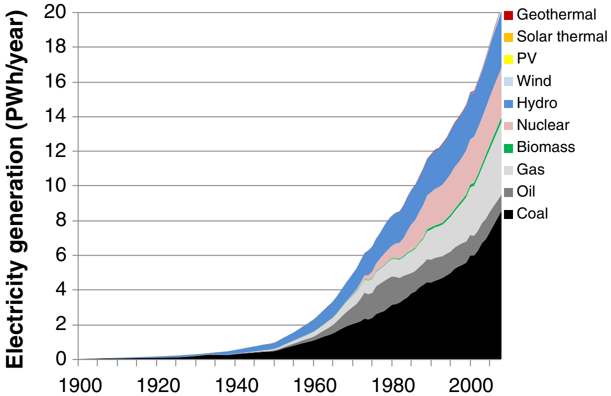



**Fig. 1** Historical trends in electricity generation

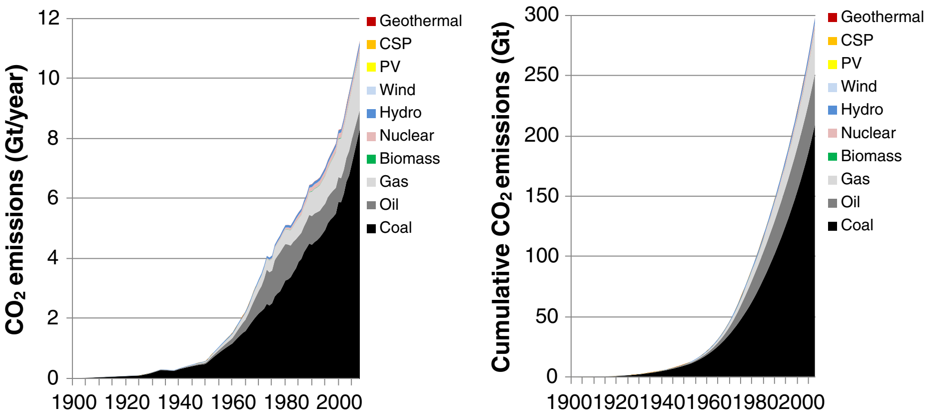


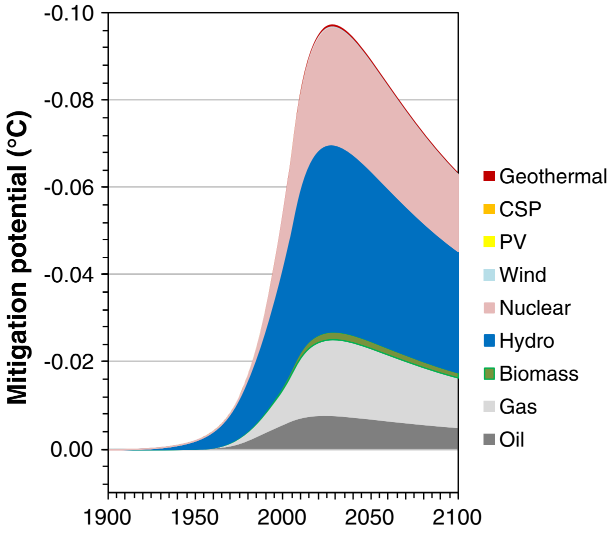

**Fig. 2** Historical trends in $CO_2$ emissions; annual (left) and cumulative (right)

The avoided emissions pulse occurs between 1900 and 2006, and drives a sharp increase of the avoided temperature increase until 2006. After this, avoided emissions cease, and avoided temperature increase declines according to the weighted response functions as in the integral calculus in Equation 3. Due to the additivity property of the RBP formulation (Equation 1), the contributions of the technologies can be added to yield a total $\sum_i M_{\mathrm{hist}i}^{\mathrm{coal}}(2006)$ of about −0.1°C. Past usage of low-carbon technologies such as nuclear and hydropower, but also fuel switching to natural gas has a clear mitigation effect far beyond the deployment period of the technologies, amounting to 0.06°C avoided temperature increase in 2100.

### 3.2 Future mitigation potentials

Using the various constraints described in Appendix A, and prescribing total electricity demand according to the SRES B1 scenario (Nakićenović and Swart 2000), a technology

**Fig. 3** Historical mitigation potential $M_{\mathrm{hist,i}}^{\mathrm{coal}}(t')$, carried forward to 2100



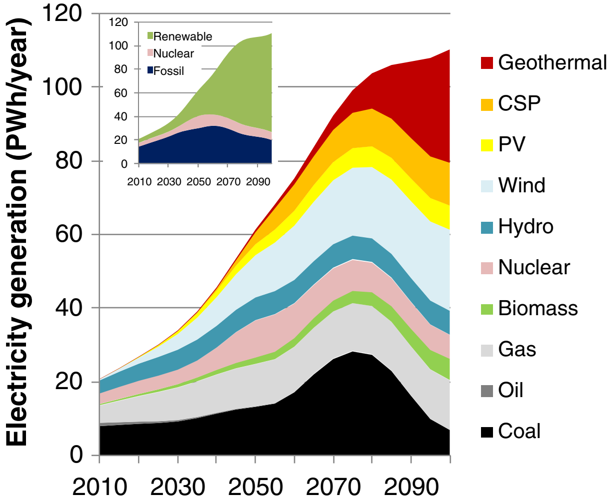



**Fig. 4** Future electricity generation scenario modelled according to the constraints described in Appendix 1, and by electricity demand prescribed by the SRES B1 scenario (inset)

scenario can be fitted "into" the SRES B1 (Fig. 4). Since this work is aimed at demonstrating the translation from emissions to temperature increase, and not at investigating the SRES scenarios, we did not attempt at exactly reproduce the B1 scenario (inset in Fig. 4), but rather incorporated recent developments such as strong renewables growth. As a result, renewables "take off" more rapidly especially between 2030 and 2050 (except geothermal at 2070), but fossil-fuel power catches up around 2070 due to strong demand growth.

The electricity generation scenario (Fig. 4) can be converted into a $CO_2$ emissions scenario from the power sector (Fig. 5) by applying Equation 4, supported by emissions coefficients $\eta$.

Even though the power mix is more and more penetrated by low-carbon sources, annual and cumulative emissions dominate due to fossil-fuel combustion. Emissions from nuclear and renewable power sources are indirect emissions only. In contrast to Fig. 3, capture and biomass sequestration of $CO_2$ are shown in Fig. 5 as negative contributions. Carbon capture

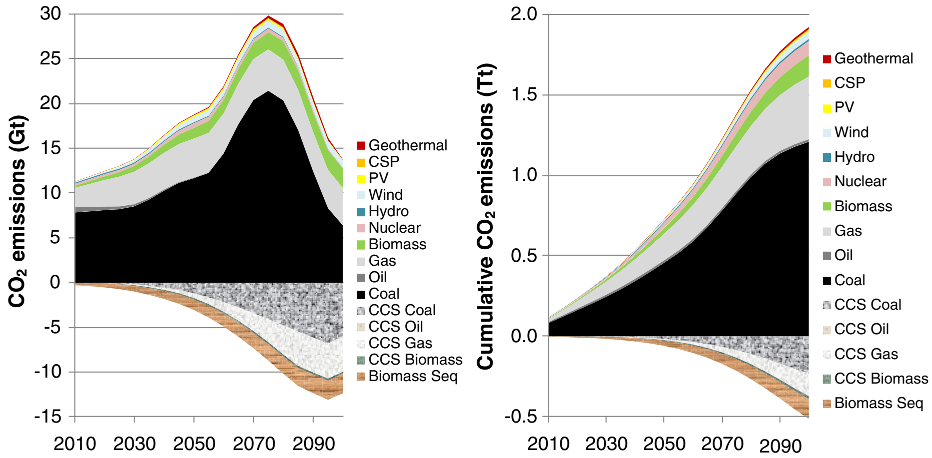



**Fig. 5** Future $CO_2$ emissions; annual (left) and cumulative (right). Net emissions for CCS and biomass are split into positive (combustion) and negative (capture/sequestration) components

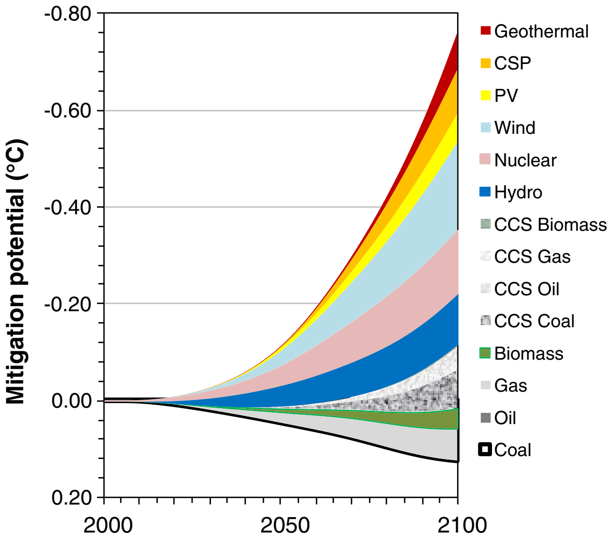



**Fig. 6** Future mitigation potentials $M^{A2}_{B1,i}$

and storage $CO_2$ is net of $CO_2$ expended for manufacture of infrastructure, and operation of all capture, transport and storage facilities.

Applying Equation 3 once again to the future avoided emissions "pulse" $\varepsilon_{i,g}(t'') - \varepsilon^{A2}_{i,g}(t'')$ calculated from the emissions profiles in Fig. 5 yields mitigation potentials $M^{A2}_{B1,i}(t')$ in Fig. 6. These are now with respect to a more emissions-intensive SRES A2 scenario.

This time, coal exhibits a positive contribution to temperature increase, because the SRES A2 scenario is less carbon-intensive than a power generation system based purely on coal. In temperature anomaly terms, it causes a warming offset of about 0.1°C by 2100, which all other technologies have to compensate. Biomass is shown inclusive of natural sequestration. As low-carbon technologies penetrate the generation system, significant avoided temperature increase start developing after 2040. Once again, due to the additivity property of the RBP formulation (Equation 1), the contributions of the technologies can be added to yield a total $\sum_i M^{A2}_{B1,i}(2100)$ of about −0.76°C.

A comparison of technologies yields interesting insights about the significance of expressing the mitigation potential of technologies in terms of annual emissions, cumulative emissions, or avoided temperature increase (Tables 1 and 2).[9] The selection of technologies comprises a group of established technologies such as gas, nuclear and hydro, and a set of "newcomers" such as non-hydro renewable and carbon capture and storage. Some of these new technologies start making a significant contribution to emissions reductions only after 2030.

Take, for example, hydropower. The 2030 percentage contributions in terms of annual avoided emissions (39%) and cumulatively avoided emissions (55%) are significantly lower than those in terms of avoided the 2030 temperature increase (62%). This discrepancy demonstrates that emissions are deficient in representing contributions to global warming. Similarly, nuclear power avoids 28% of annual emissions in 2030, 43% of cumulative emissions up to 2030, but avoids 51% of the 2030 temperature increase. In contrast, wind power avoids 29% of annual emissions in 2030, 22% of cumulative emissions up to 2030, but avoids only 19% of 2030 temperature increase.

[9] $CH_4$ emissions were converted into $CO_2$-equivalent emissions using a Global Warming Potential for a 100-year time horizon.

**Table 1** Summary of annually and cumulatively avoided $CO_2$–equivalent emissions, and contributions to global temperature increase, including $CH_4$ effects for hydro reservoirs

| | Coal | Oil | Gas | Nuclear | Hydro | Wind | PV | CSP | Geothermal | Biomass | CCS Coal | CCS Oil | CCS Gas | CCS Biomass |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Annual avoided $CO_2$-e emissions (Gt) | | | | | | | | | | | | | | |
| 2030 | −2615 | −11 | 1543 | 2154 | 2954 | 2200 | 415 | 43 | 92 | 446 | 176 | 44 | 52 | 74 |
| 2050 | −3175 | −1 | 1995 | 5218 | 3110 | 5288 | 1564 | 1781 | 357 | 921 | 1162 | 54 | 480 | 183 |
| 2100 | −1024 | 0 | 2193 | 3105 | 2791 | 8191 | 3138 | 5584 | 14730 | 2743 | 5996 | 1 | 3938 | 218 |
| Cumulative avoided $CO_2$-e emissions (Gt) | | | | | | | | | | | | | | |
| Hist to 2006 | 0 | 17 | 41 | 60 | 100 | 1 | 0 | 0 | 1 | 4 | 0 | 0 | 0 | 0 |
| Hist to 2100 | −303 | 16 | 215 | 387 | 376 | 481 | 158 | 252 | 288 | 119 | 231 | 3 | 138 | 15 |
| 2009–2030 | −72 | −1 | 31 | 52 | 68 | 27 | 4 | 0 | 1 | 8 | 2 | 0 | 0 | 1 |
| 2009–2050 | −132 | −1 | 68 | 128 | 129 | 110 | 26 | 15 | 6 | 22 | 16 | 2 | 6 | 4 |
| 2009–2100 | −303 | −1 | 174 | 327 | 276 | 480 | 158 | 252 | 287 | 115 | 231 | 3 | 138 | 15 |
| Temperature increase @ 2100 ($10^{-2}$ °C, centigrade C) | | | | | | | | | | | | | | |
| Hist to 2006 | 0.0 | −0.7 | −1.3 | −1.8 | −3.5 | 0.0 | 0.0 | 0.0 | 0.0 | −0.1 | 0.0 | 0.0 | 0.0 | 0.0 |
| Hist to 2100 | 12.2 | −0.6 | −7.9 | −14.7 | −14.0 | −18.2 | −5.9 | −9.2 | −7.7 | −4.2 | −7.9 | −0.1 | −4.7 | −0.6 |
| 2009–2030 | 1.9 | 0.0 | −0.7 | −1.3 | −1.6 | −0.5 | −0.1 | 0.0 | 0.0 | −0.2 | 0.0 | 0.0 | 0.0 | 0.0 |
| 2009–2050 | 4.5 | 0.0 | −2.2 | −3.9 | −4.3 | −3.0 | −0.6 | −0.2 | −0.2 | −0.7 | −0.3 | −0.1 | −0.1 | −0.1 |
| 2009–2100 | 12.2 | 0.0 | −6.6 | −12.9 | −10.5 | −18.2 | −5.9 | −9.2 | −7.6 | −4.1 | −7.9 | −0.1 | −4.7 | −0.6 |

**Table 2** Summary of annually and cumulatively avoided $CO_2$–equivalent emissions, and contributions to global temperature increase, including $CH_4$ effects for hydro reservoirs (in % of total effects for all technologies)

| | Coal | Oil | Gas | Nuclear | Hydro | Wind | PV | CSP | Geothermal | Biomass | CCS Coal | CCS Oil | CCS Gas | CCS Biomass |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Annual avoided $CO_2$ emissions (% of total) | | | | | | | | | | | | | | |
| 2030 | −35% | 0% | 20% | 28% | 39% | 29% | 5% | 1% | 1% | 6% | 2% | 1% | 1% | 1% |
| 2050 | −17% | 0% | 11% | 28% | 16% | 28% | 8% | 9% | 2% | 5% | 6% | 0% | 3% | 1% |
| 2100 | −2% | 0% | 4% | 6% | 5% | 16% | 6% | 11% | 29% | 5% | 12% | 0% | 8% | 0.4% |
| Cumulative avoided $CO_2$ emissions (% of total) | | | | | | | | | | | | | | |
| Hist to 2006 | 0% | 8% | 18% | 27% | 45% | 0% | 0% | 0% | 0% | 2% | 0% | 0% | 0% | 0% |
| Hist to 2100 | −13% | 1% | 9% | 16% | 16% | 20% | 7% | 11% | 12% | 5% | 10% | 0% | 6% | 1% |
| 2009–2030 | −59% | −1% | 25% | 43% | 55% | 22% | 3% | 0% | 1% | 6% | 1% | 0% | 0% | 1% |
| 2009–2050 | −33% | 0% | 17% | 32% | 32% | 28% | 7% | 4% | 2% | 6% | 4% | 0% | 1% | 1% |
| 2009–2100 | −14% | 0% | 8% | 15% | 13% | 22% | 7% | 12% | 13% | 5% | 11% | 0% | 6% | 0.7% |
| Temperature increase @ 2100 (% of total) | | | | | | | | | | | | | | |
| Hist to 2006 | 0% | 9% | 17% | 24% | 47% | 0% | 0% | 0% | 0% | 2% | 0% | 0% | 0% | 0% |
| Hist to 2100 | −15% | 1% | 9% | 18% | 17% | 22% | 7% | 11% | 9% | 5% | 9% | 0% | 6% | 1% |
| 2009–2030 | −73% | −1% | 29% | 51% | 62% | 19% | 2% | 0% | 1% | 7% | 1% | 0% | 0% | 1% |
| 2009–2050 | −41% | 0% | 20% | 35% | 38% | 27% | 6% | 2% | 1% | 6% | 3% | 1% | 1% | 1% |
| 2009–2100 | −16% | 0% | 9% | 17% | 14% | 24% | 8% | 12% | 10% | 5% | 10% | 0% | 6% | 0.8% |

These results demonstrate the benefit of early technology deployment. Hydropower is avoiding emissions at significant scales at the scenario outset (Fig. 3), and those early avoided emissions are “worth” more in terms of the response functions in the integral formulation (Equation 4). Similar observations can be made for gas and nuclear power.

In 2100, nuclear avoids less emissions than geothermal power, and until then has avoided about the same amount of cumulative emissions. However, due to the late start of geothermal, nuclear power’s avoided temperature increase is 7% higher at 17% than that of geothermal power (10%). The stark difference between nuclear and hydropower in terms of 2009–2030 avoided temperature increase is due to significant $CH_4$ emission from newly commissioned hydro reservoirs. Due to the short impact lifetime of $CH_4$, the difference between the technologies virtually disappears by 2100.

Similarly, relative to 2006, hydropower was an established technology compared to the more recent nuclear power, and hence hydro’s 2006 historical mitigation potential is higher in terms of avoided temperature increase than in terms of cumulative emissions, and vice versa for nuclear power. These effects, even though illustrative for this particular scenario only, demonstrate the conflicting conclusions derived from different measures for mitigation potential.

In percentage terms, long-term (2100) mitigation potentials converge towards long-term cumulative emissions, because the differences between technologies in start-up now fall into the tail periods of the response functions, so that the distinction between early and late technologies becomes blurred.

## 3.3 Sensitivity analyses

### *3.3.1 Using different carbon cycle and global warming models*

We investigated the sensitivity of our results with regard to the parameters used in the climate model as expressed in Eqs. 2 and 3. Due to the lack of standard deviation estimates for the various parameters, we resorted to substituting the ‘Bern TAR’ paramater set[10] for the RBP parameter set,[11] and recalculated all results. These two parameter sets are quite different in both characteristic times and fractions, thus our sensitivity analysis could be regarded as conservative.

Moving from the RBP set to the Bern TAR set, the mitigation potentials of established technologies such as gas, nuclear and hydropower decrease by about 5%, and the mitigation potentials of new technologies such as CSP, CCS and geothermal increase by between 5% and 25% (Table 3). This behaviour is due to the fact that the Bern TAR set places more emphasis on long-term responses, which is mainly facilitated by $\tau_{CO_2,1} = \infty$. Technologies with intermediate temporal profiles such as wind are unaffected. Similarly, the overall mitigation potential of all technologies increases only slightly from $\sum_i M^{A2}_{B1,i}(2100) = 0.76°C$ to $\sum_i M^{A2}_{B1,i}(2100) = 0.77°C$.

### *3.3.2 Emission coefficients*

A sensitivity analysis of emission coefficients is best carried out on those coefficients that could undergo potentially large changes. One such candidate are life-cycle $CO_2$ emissions associated

[10] UNFCCC 2009a,b. $\tau_{CO_2,1} = \infty$, $\tau_{CO_2,2} = 171y$, $\tau_{CO_2,3} = 18y$, $\tau_{CO_2,4} = 2.6y$; $f_{CO_2,1} = 15.2\%$, $f_{CO_2,2} = 25.3\%$, $f_{CO_2,3} = 27.9\%$, $f_{CO_2,3} = 31.6\%$; $\tau_{C,3} = 8.4y$, $\tau_{C,2} = 410y$; $l_{C,1} = 59.6\%$, $l_{C,2} = 40.4\%$.

[11] Rosa et al. 2004; $\tau_{CO_2,1} = 330y$, $\tau_{CO_2,2} = 80y$, $\tau_{CO_2,3} = 20y$, $\tau_{CO_2,4} = 1.6y$; $f_{CO_2,1} = 21.6\%$, $f_{CO_2,2} = 39.2\%$, $f_{CO_2,3} = 29.4\%$, $f_{CO_2,3} = 9.8\%$; $\tau_{C,3} = 20y$, $\tau_{C,2} = 990y$; $l_{C,1} = 63.4\%$, $l_{C,2} = 36.6\%$.

**Table 3** Comparison of mitigation potentials calculated using 'RBP' or 'Bern TAR' parameter sets

| | Coal | Oil | Gas | Nuclear | Hydro | Wind | PV | CSP | Geothermal | Biomass | CCS Coal | CCS Oil | CCS Gas | CCS Biomass |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Temperature increase @ 2100 (10–2°C, centigrade C) | | | | | | | | | | | | | |
| RBP | 12.2 | 0.0 | −6.6 | −12.9 | −10.5 | −18.2 | −5.9 | −9.2 | −7.6 | −4.1 | −7.9 | −0.1 | −4.7 | −0.6 |
| Bern TAR | 11.5 | 0.0 | −6.4 | −12.3 | −10.0 | −18.2 | −6.0 | −9.7 | −9.7 | −4.2 | −8.7 | −0.1 | −5.2 | −0.6 |

with nuclear power. In their analysis of emissions from the nuclear fuel cycle, Storm van Leeuwen and Smith (2005) arrived at significantly higher values than listed in Table 7, which for low ore grades of about 0.01% U are about 530 g/kWh, and hence would place nuclear power into the vicinity of advanced natural gas plants. As Lenzen et al. (2006) show, this discrepancy is mainly the result of practices assumed by Storm van Leeuwen and Smith (2005) (but not applied currently, see p. 18 in OECD NEA and IAEA (1999) for the final disposal of large volumes of low-level ore, waste rock, and mill tailings. The worst case in Lenzen et al. (2006) results in emissions of 248 g/kWh, which also agrees with the maximum value found by Sovacool (2008), but even this case is still below the estimate made by Storm van Leeuwen and Smith (2005).

Applying the RBP calculus under quadrupling of life-cycle emissions[12] reduces nuclear's mitigation potential for the century by about 10% (Table 4). This shows that considering the objective of limiting global warming, nuclear's mitigation potential is relatively insensitive to even extreme changes in life-cycle emissions.

A sensitivity analysis of $CH_4$ emission factors for hydropower is interesting because emissions from hydro reservoirs have not been measured often and well, and are also highly dependent on the biomass density at the reservoir location. Varying the values of 200 g $CO_2$-e/kWh and 7 years half life given by Dos Santos et al. (2006) and Rosa and Schaeffer (1995) yields that the mitigation potential of hydro decreases with increasing $CH_4$ emissions intensity and half-life (Table 5).[9]

Since characteristic times of anaerobic decay and $CH_4$ atmospheric lifetime (around 10 years) are short compared to the characteristic times of the climate system, mitigation potentials for temperature increase due to hydropower deployment are relatively weakly affected by assumptions about reservoir emissions. Nevertheless, the differences in sensitivity between the three quantities clearly show once again that annual or cumulative emissions are deficient yardsticks when comparing technologies with respect to their impact on global warming.

### *3.3.3 SRES scenarios*

In the last sensitivity analysis, we examine the influence of the SRES scenarios on mitigation potentials. We changed both the scenario used to envelope future electricity demand (from B1 to B2[13]), as well as the reference scenario (from A2 to A1F1[14]). The

[12] Increasing $\eta^{\text{ind}}_{\text{nucl.CO}_2}(2100)$ from 135 g $CO_2$/kWh to 530 g $CO_2$/kWh.

[13] The B2 world features concern for environmental and social sustainability, combined with a trend toward local self-reliance and stronger communities. Decision-making lies more with local and regional than with international institutions. Energy systems develop specific to locally available natural resources. Less carbon-intensive technology is advanced in some regions.

[14] The A1 storyline sees rapid and successful economic development and converging regional average per-capita incomes. Abundant energy and mineral resources coupled with rapid technical progress reduces the resource intensity of production, and increases economically recoverable reserves.

**Table 4** Comparison of mitigation potentials of nuclear power, under variations of life-cycle emissions

| Life-cycle emissions at 2100 ore grades | 135 g $CO_2$/kWh | 530 g $CO_2$/kWh |
|---|---|---|
| Annual avoided CO2 emissions (Gt) | | |
| 2030 | 2154 | 1874 |
| 2050 | 5218 | 4212 |
| 2100 | 3105 | 2952 |
| Cumulative avoided CO2 emissions (Gt) | | |
| Hist to 2006 | 60 | 60 |
| Hist to 2100 | 387 | 330 |
| 2009–2030 | 52 | 48 |
| 2009–2050 | 128 | 111 |
| 2009–2100 | 327 | 270 |
| Temperature increase @ 2100 ($10^{-2}$ °C) | | |
| Hist to 2006 | −1.8 | −1.8 |
| Hist to 2100 | −14.7 | −12.3 |
| 2009–2030 | −1.3 | −1.2 |
| 2009–2050 | −3.9 | −3.4 |
| 2009–2100 | −12.9 | −10.5 |

main differences between the changed scenario settings are that: a) in B2 nuclear power plays a more important role, and renewables play a less important role than in B1; b) in B2 electricity generation and emissions are both higher than in B1, and c) in A1F1 reference $CO_2$ emissions are lower than in A2 (Fig. 7). Note that the purpose of pairing these scenarios is not to examine the role of socio-economic-demographic drivers for mitigation

**Table 5** Comparison of mitigation potentials of hydropower, under variations of $CH_4$ emissions

| Reservoir emissions level (g $CO_2$-e/kWh) and half-life (years) | 100/7 | 200/7 | 200/15 | 400/15 |
|---|---|---|---|---|
| Annual avoided $CO_2$-e emissions (Gt) | | | | |
| 2030 | 2954 | 2954 | 2954 | 2954 |
| 2050 | 3110 | 3110 | 3110 | 3110 |
| 2100 | 2791 | 2791 | 2791 | 2791 |
| Cumulative avoided $CO_2$-e emissions (Gt) | | | | |
| Hist to 2006 | 100 | 100 | 99 | 98 |
| Hist to 2100 | 377 | 376 | 374 | 370 |
| 2009–2030 | 68 | 68 | 67 | 65 |
| 2009–2050 | 129 | 129 | 128 | 125 |
| 2009–2100 | 277 | 276 | 274 | 272 |
| Temperature increase @ 2100 ($10^{-2}$ °C) | | | | |
| Hist to 2006 | −3.5 | −3.5 | −3.4 | −3.3 |
| Hist to 2100 | −14.1 | −14.0 | −13.7 | −13.3 |
| 2009–2030 | −1.7 | −1.6 | −1.5 | −1.3 |
| 2009–2050 | −4.4 | −4.3 | −4.1 | −3.7 |
| 2009–2100 | −10.6 | −10.5 | −10.3 | −10.0 |

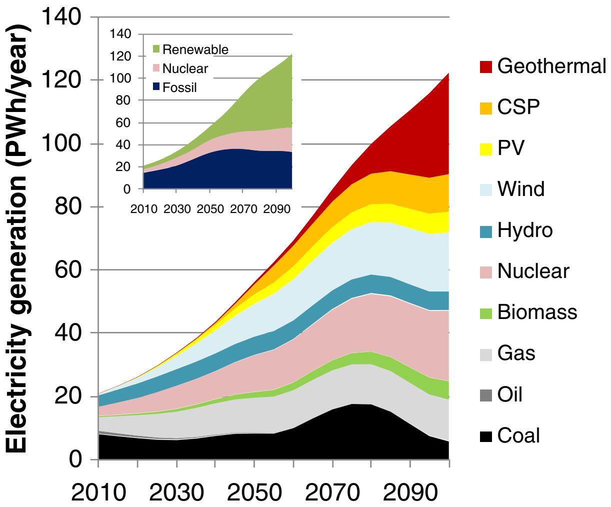



**Fig. 7** Future electricity generation scenario modelled according to the constraints described in Appendix 1, and by electricity demand prescribed by the SRES B2 scenario (inset)

potentials, but to obtain a large but realistic variation under which our temperature-based mitigation potentials can be tested for sensitivity, as explained in Section 2.1.

With the obvious exceptions of nuclear power and coal, mitigation potentials change negligibly (Table 6). As nuclear power's share is larger in B2 compared to B1, its mitigation potential almost doubles to −22.6 centigrades. With coal-based generation being calculated residually, coal's negative mitigation potential (ie warming potential) almost halves to 7.0 centigrades. For the remaining technologies, the differences between the two scenario settings are due to the reference being changed from A2 to A1F1.

## 4 Conclusions

Using the mathematical formalism of the Brazilian Proposal to the IPCC, we have analysed eight technologies—seven electricity generation technologies, and carbon capture and storage—with regard to their past and potential future contributions to global warming. We have defined the mitigation potential of each technology in terms of avoided temperature increase by comparing a "coal-only" reference scenario and an alternative low-carbon SRES scenario. We have taken into account detailed bottom-up technology characteristics such as life-cycle emissions and capacity factors.

Historically (1900–2006), hydro, nuclear, and gas-fired power have achieved the largest mitigation, at 0.03°C, 0.02°C, and 0.015°C avoided by 2100, respectively. This ranking is

**Table 6** Comparison of mitigation potentials calculated using the B1/A2 or B2/A1F1 scenario sets

| | Coal | Oil | Gas | Nuclear | Hydro | Wind | PV | CSP | Geothermal | Biomass | CCS Coal | CCS Oil | CCS Gas | CCS Biomass |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Temperature increase @ 2100 (10–2°C, centigrade C) | | | | | | | | | | | | | |
| B1 ref A2 | 12.2 | 0.0 | −6.6 | −12.9 | −10.5 | −18.2 | −5.9 | −9.2 | −7.6 | −4.1 | −7.9 | −0.1 | −4.7 | −0.6 |
| B2 ref A1F1 | 7.0 | 0.0 | −7.0 | −22.6 | −10.6 | −18.3 | −6.0 | −8.8 | −7.6 | −4.2 | −7.6 | −0.1 | −4.7 | −0.6 |

partly due to the magnitudes at which these technologies are deployed, but in part also due to their deployment histories. For example, the global capacity of gas-fired power plants is larger than that of hydropower plants, however significant hydropower capacity has been around for many more decades.

Similarly, potential future (2009–2100) contributions are influenced by the magnitude of future capacity as well as the temporal deployment profile. For example, even if geothermal power equalled hydropower capacity by 2050, the 2100 temperature increase avoided by hydropower would be larger because of its cumulative avoidance of radiative forcing over time. A general conclusion is that early technology deployment matters, at least within a period of 50–100 years. We undertake several analyses to demonstrate the robustness of these conclusions.

Our results show conclusively that avoided temperature increase is a better proxy for comparing technologies with regard to their impact on climate change. As we show in Table 2, comparisons based on cumulative emissions up to 2050 yield results that are significantly different to those obtained using the avoided temperature metric. Using annual instead of cumulative emissions may yield misleading results for mitigation potentials calculated even up to 2100. Appendix B shows that the literature contains numerous examples of mitigation potentials being calculated up to 2050, based on annual and cumulative emissions. The findings of this study indicate that such examples are less meaningful for decision-making than previously thought.

Our results support the Brazilian Proposal to the IPCC, and also extend its policy relevance in the sense that not only comparisons between countries, but also comparisons between technologies or technology portfolios could be undertaken on the basis of avoided temperature increase rather than on the basis of annual emissions as is practice today.

Whilst the aim of this paper is fulfilled by exemplifying technologies for electricity generation in order to highlight the role of metrics for establishing mitigation potentials, the same approach can be applied to comparisons of scenarios differing with regard to other criteria. This is essentially because ultimately the only input into calculating mitigation potentials are emission profiles. Hence, the avoided-temperature metric could also be applied to establishing mitigation potentials of different trajectories of population, economic development, or urban structure, amongst many other possibilities.

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## Appendix A: Data sources

### A.1 Emissions data and global warming parameters

The parameters $\overline{\sigma}_g$ and $\beta_g$ in Equation 2 were parametrised using the RBP values for the fractions $f$ and $l$ and their corresponding lifetimes $\tau$, as listed in Rosa et al. 2004 and UNFCCC 2009a,b. Values for the $\beta$ and $\sigma$ were obtained from Meira 2009. $C$ was calculated according to Equation 28 in Meira and Miguez 2000, using a climate sensitivity of 3°C. The model was calibrated and fine-tuned (Fig. 8) against historical measurements of atmospheric concentrations ($CO_2$ Keeling et al. 2008; $CH_4$ Steele et al. 2003) and ice core samples ($CO_2$

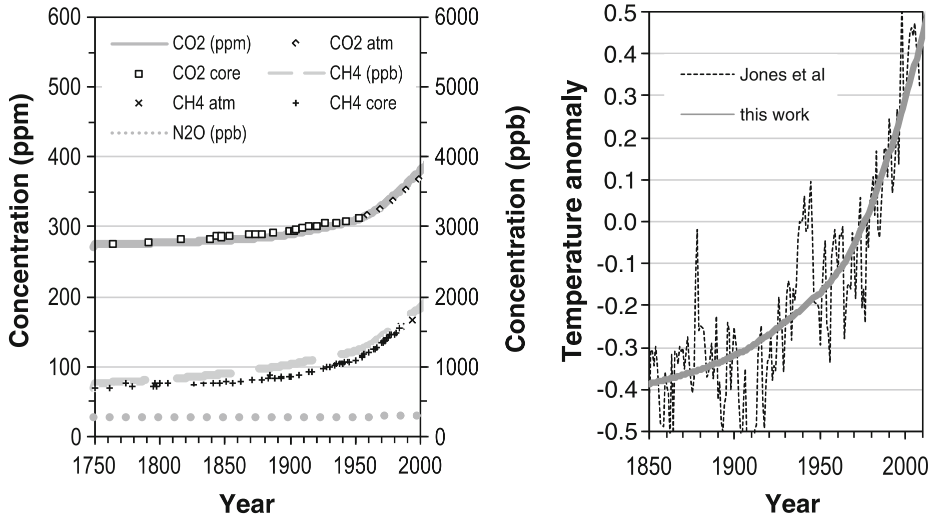


**Fig. 8** Calibration of the RBP (grey curves) in terms of atmospheric concentrations of two greenhouse gases (left) and temperature anomaly (right) against measurements (left: markers; right: dashed curve)

Neftel et al. 1994; $CH_4$ Etheridge et al. 2002), as well as against historical measurements of global temperature anomalies (Jones et al. 2009).

Present mean radiative forcing and global warming are a function of GHG emissions reaching back into the past as far as 300 years. Therefore, the calibration and fine-tuning of the RBP model requires historical emissions data starting 1750. CDIAC data on global $CO_2$ emissions from fossil fuel usage, cement production and gas flaring between 1750 and 2005 were taken from Marland et al. 2008, on $CO_2$ emissions resulting from land use change between 1850 and 2005 from Houghton 2008, on $CH_4$ emissions between 1860 and 1994 from Stern and Kaufmann 1998. $N_2O$ emissions between 1890 and 1995 were taken from the EDGAR-HYDE model, documented in Van Aardenne et al. 2001. Values prior to these periods were extrapolated using pre-1890 growth rates. These extrapolations are not expected to exert major influence on the results obtained here, since pre-1890 emissions are small compared to post-1890 emissions.

Historical mitigation potentials $M^{\text{coal}}_{\text{hist},i}(t')$ are based on historical data on electricity generation and consumption (Fig. 1 in the main text), collated mostly from IEA 2008b (post-1971) and Energy Information Administration 2008 (post-1980), but complemented by data on renewable technologies from various industry sources (Brakmann et al. 2005; DiPippo 2008b; IEA-PVPS 2008; WWEA 2008), and historical data from Darmstadter 1971 (post-1925) and Etemad et al. 1991 (post-1900), the latter two sources downloaded from the HYDE database (MNP 2008).

## A.2 Specific emissions coefficients $\eta$

Specific emissions coefficients $\eta$ for the various technologies were sourced from a wide range of recent assessments (Table 7). Note that in virtually every life-cycle study, technologies are appraised in isolation, leading to an overestimation of life-cycle emissions due to double-counting (Lenzen 2008a). For example, the manufacture of a wind turbine requires electricity from fossil, nuclear or hydropower plants, so that the life-cycle emissions from

**Table 7** On-site and indirect GHG emissions $\eta_{i,g}^{ons}$ and $\eta_{i,g}^{ind}$

| Technology | Life-cycle emissions ($g\ CO_2$-e / $kWh_{el}$) 2009 | 2100 | References | Comments |
|---|---|---|---|---|
| Pulverised coal | 880 +10% | 570 | IPCC05, WE07, OL08 | |
| Oil | 640 +10% | 440 | IPCC05, WE07, OL08 | |
| Natural Gas CC | 385 + 20% | 310 | IPCC05, WE07, OL08 | Additional venting & flaring |
| Post-combustion CCS | − 750 + 20 | − 540 + 20 | OC08, PH09, VI07 | Coal: 85% captured + life-cycle |
| Pre-combustion CCS | – 330 + 20 | – 300 + 20 | OC08, PH09, VI07 | Gas: 85% captured + life-cycle |
| Hydro | 40+60+150 | 40+60+150 | LE06, DS06 | $CO_2$(plant) + $CH_4$ (res) + $CO_2$(res) |
| Nuclear | 65 | 130 | FK07, LE08, SO08 | LWR, HWR |
| Wind | 50 | 10 | LM02, PE08, RO05 | Capacity reserves + life cycle |
| PV | 100 | 50 | FK07, LE06, PE06 | |
| CSP | 60 | 30 | LE99 | |
| Geothermal | 120 + 50 | 25 | AR05 | On-site + life cycle |
| Biomass | 30 + 50 | 100 | EC08, WE07 | Fuel cycle + infrastructure |

AR = Ármannsson et al. 2005, CC = Combined Cycle Plant, CCS = Carbon capture and storage, DS06 = Dos Santos et al. 2006, EC08 = JEC 2008, FK07 = Fthenakis and Kim 2007, HWR = Heavy Water Reactor, IPCC05 = IPCC 2005, LE06 = Lenzen et al. 2006, LE08 = Lenzen 2008b, LE99 = Lenzen 1999, LM02 = Lenzen and Munksgaard 2002, LWR = Light Water Reactor, OC08 = Odeh and Cockerill 2008, OL08 = Oliver 2008, PE06 = Pehnt 2006, PE08 = Pehnt et al. 2008, PH09 = Pehnt and Henkel 2009, res = hydro reservoir, RO05 = Roth et al. 2005, SO08 = Sovacool 2008, VI07 = Viebahn et al. 2007, WE07 = Weisser 2007.

those plants are also counted in the life-cycle inventory of the wind turbine. At present, there exist no comprehensive studies on the degree of double-counting. However, for the purpose of this work, life-cycle emissions of low-carbon power technologies are small compared to the emissions their deployment avoids, so that the error due to double-counting is unlikely to have a significant influence on our results.[15]

Indirect life-cycle emissions for natural gas are higher (≈20% of direct emissions) than for coal (≈10%) because of fugitive emissions during venting and flaring, and leakage (Lenzen 2001; Foran et al. 2005; Meier et al. 2005; Weisser 2007; Odeh and Cockerill 2008). Negative net emissions of carbon capture and storage technologies represent avoided emissions, as defined in Fig. TS. 11 in IPCC 2005. This includes the so-called energy penalty resulting from: a) the additional energy requirements for capture, and b) conversion efficiency decreases. Energy penalties (see Tab. TS. 10 in IPCC 2005; Rubin et al. 2007; Odeh and Cockerill 2008; and Davison 2007) are typically 25% in post-combustion systems (due to an 8–10% efficiency decrease, and scrubbing agent regeneration), and 15% in pre-combustion

[15] The period between the end of our historical time series (2006) and the start of our future scenario (2009) is not covered in our analysis because, on one hand, capacity and generation statistics are not yet available for many of the technologies here considered and, on the other hand, this period is past and, as such, cannot be part of a future scenario. Hence, some scenario parameters for 2009 (Tables 1, 2 and 3) had to be modelled based on 2006 data.

(due to a 6–8% efficiency decrease, and to the water-gas shift reaction).[16] The life-cycle component represents $CO_2$ transport and injection.[17]

Emissions from construction and maintenance of hydroelectric plants amount to about 40 g $CO_2$/kWh, however in addition, average $CO_2$ and $CH_4$ emissions from the anaerobic decay of organic matter submerged by the reservoir have been measured to be in the order of 3 g $CH_4$/kWh and 150 g $CO_2$/kWh (Dos Santos et al. 2006).

Emissions from the nuclear fuel cycle include mining, milling, decommissioning and waste disposal. Roth et al. 2005 and Pehnt et al. 2008 take the reduced capacity credit of wind into account in their systems LCA, and conclude that $CO_2$ emissions arising from the need of additional spinning and non-spinning reserves add between 35 and 75 g $CO_2$/kWh, thus outweighing $CO_2$ emissions from the turbine life cycle. If reserves were provided using low-carbon technologies, future life-cycle emissions for wind energy could be as low as 10 g $CO_2$/kWh (Lenzen and Munksgaard 2002).

In a case study of a hypothetical 100-MW PV plant (crystalline silicon, module efficiency 13%, system efficiency 80%) operating under Australian conditions (average capacity factor 20%, and coal-based background economy), Lenzen et al. 2006 (work undertaken by author Wood) arrive at life-cycle GHG emissions of about 100 g $CO_2$/kWh. In a dynamic LCA, Pehnt 2006 projects future life-cycle impacts of PV to decrease by about 40% until 2030. Here, we assume 50% reductions in life-cycle emissions for both PV and CSP.

Ármannsson et al. 2005 conduct a survey of $CO_2$ emissions from geothermal power plants, yielding a large range of 4–740 g $CO_2$/kWh, with a weighted average of about 120 g $CO_2$/kWh (excluding life-cycle emissions). Future emissions may be as low as 25 g $CO_2$/kWh, if only binary-cycle plants are utilised, and life-cycle emissions are halved.

Biomass is assumed to undergo a slight shift from mainly residue and waste utilisation in boilers and steam turbines, to a higher proportion of dedicated energy crops, and overall more efficient combustion in biomass integrated-gasifier combined-cycle (BIGCC) plants (IEA 2007). The more intensive energy crop production slightly outpaces efficiency gains in terms of GHG emissions (JEC 2008).

### A.3 Average capacity factors $\lambda$ (Table 8)

Reduction rates of CCS are modelled to reduce from 85% under current technology to 90% using oxyfuel combustion (Viebahn et al. 2007). Average capacity factors for hydropower are determined by the demand segment (base or peak), so that this technology occupies an intermediate position at 40%. Whilst this factor may increase in principle as hydropower plants are increasingly used for balancing variable renewable power sources, increased water shortages may be a limiting factor (Lucena et al. 2009). Therefore, the capacity factor for hydropower was assumed constant. Future capacity credits for wind power are subject to counteracting trends. Increasing geographical dispersion tends to smoothen output and decrease variability (Østergaard 2008; Oswald et al. 2008). Increasing penetration leads to more wind energy that has to be discarded (Hoogwijk et al. 2007).

Current capacity factors for PV are difficult to estimate because of the dispersed deployment of many small generators. Obviously, future capacity factors are even more

[16] The energy penalty is quantified here exclusive of life-cycle components (compare with a definition in Rubin et al. 2007, p. 4451 and footnote 3).

[17] For example, the emissions from 1 kWh generated in a pulverised-coal power plant with CCS are composed of 880 g (combustion) +88 g (10% power plant life cycle) +79 g (9% efficiency penalty) +141 g (16% remaining energy penalty)—935 g (85% capture of 880+79+141 g)+20 g (remaining CCS life cycle)=273 g.

**Table 8** Average capacity factors

| Technology | Capacity factor (%) | | References | Comments |
|---|---|---|---|---|
| | 2009 | 2100 | | |
| Pulverised coal | 75 | 85 | EIA08 | |
| Oil | 22 | 35 | EIA08 | |
| Natural Gas | 42 | 55 | EIA08 | |
| CCS | 85 | 95 | VI07, RU07, IEA06 | Reduction rates |
| Hydro | 40 | 40 | IEA08 | |
| Nuclear | 86 | 90 | BL06, LI06 | |
| Wind | 25 | 30 | GWEC08 | |
| PV | 15 | 20 | HO06, LE06 | Highly uncertain |
| CSP | 20 | 50 | SM09 | 2100 assumes storage |
| Geothermal | 71 | 90 | GG07, ST02, SB03 | |
| Biomass | 65 | 80 | IEA07, IEA08, HQ03 | |

BL06 = Blake 2006, CC = Combined Cycle Plant, CCS = Carbon capture and storage; factors given are $CO_2$ reduction rates including life-cycle emissions, EIA08 = EIA 2008a, GG07 = Gawell and Greenberg 2007, GWEC08 = GWEC 2008, HO06 = Hoffmann 2006, HQ03 = Haq 2003, IEA06 = IEA 2006, IEA07 = IEA 2007, IEA08 = IEA 2008b, LE06 = Lenzen et al. 2006, LI06 = Lim et al. 2006, LM02 = Lenzen and Munksgaard 2002, LWR = Light Water Reactor, RU07 = Rubin et al. 2007, SB03 = Sanner and Bussmann 2003, SM09 = Solar Millennium 2009, ST02 = Stefánsson 2002, VI07 = Viebahn et al. 2007.

uncertain. The average capacity factor of the US SEGS parabolic trough CSP plant is 21%. Including storage means that the plant can also produce during extended low-radiation periods, thus significantly increasing its average capacity factor. For example the Spanish Andasol trough plants have a liquid salt storage system that allows them to operate day and night at an average capacity factor of 41% (Solar Millennium 2009). Currently, geothermal power records an average capacity factor of 71% (Gawell and Greenberg 2007). However, considering that geothermal power is the only renewable energy source that is entirely independent of seasonal or climatic changes, high capacity factors in excess of 90% may be achievable in the future (Stefánsson 2002; Sanner and Bussmann 2003). Current biomass capacity factors of 65% (IEA 2007; 2008b) are expected to increase to 80% in the future (Haq 2003).[15]

A.4 Installed capacity $P$ (Table 9)

In projecting future technology deployment, we do not aim at replicating previous projections (for example UNDP 2004; Alcamo et al. 2005; IEA 2008a), and we also do not aim at providing several future pathways, as this work is not a scenario analysis. Instead, we construct one scenario that fits well within a number of future projections published in the literature (see Appendix B). We define our scenario as a set $\{P_i(t_0), r_i(t_0), \gamma \text{ or } P_i(t')\}$ of parameters for the growth of installed capacities, and justify our choice below by showing how future deployment may be constrained by a number of technical circumstances specific to the various generation technologies.

CCS is not expected to become competitive before 2030, but global storage capacity of around 200 Gt $CO_2$ appears reasonably certain. We have used twice this capacity as a constraint on cumulative $\varepsilon_i(t')$, determining $P_i(t')$ and $\gamma$. CCS for biomass is not expected to be economical because of the small size of biomass-fired power plants (Damen et al. 2007).

**Table 9** Present and future installed capacities and their present growth rates

| Technology | $P_i$(2009) (GW) | $r_i$(2009) (%) | $P_i$(2100) (GW) | References | Constrained by |
|---|---|---|---|---|---|
| Coal | 1310 | | 700 | | Calculated residually |
| Oil | 490 | −4 | 0 | EIA08 | |
| Natural gas | 1140 | 5 | 3600 | EIA08 | |
| CCS | – | – | – | IPCC05 | ≈400 Gt cumulative $CO_2$ @2100 |
| Hydro | 870 | 4 | 1700 | IEA08, PA02 | |
| Nuclear | 377 | 2 | 900 | NA00 | SRES B1 |
| Wind | 121 | 34 | 7100 | GWEC08 | $E_{wind}$=20% $E_{total}$ @2100 |
| PV | 1 | 36 | 3800 | EPIA08, PVPS08, LW08 | $P_i$(2100) based on $E_{PV}$=5% $E_{total}$ @2050 |
| CSP | 0. 5 | 19 | 2700 | DLR05, ETP08 | $r_i$ averaged 1986–2003 |
| Geothermal | 10 | 4 | 3900 | MIT06 | |
| Biomass | 51 | 6 | 800 | IEA07 | |

CCS = Carbon capture and storage, DLR05 = DLR 2005, EIA08 = EIA 2008a, EPIA09 = EPIA 2008, ETP08 = IEA 2008a, GWEC08 = GWEC 2008, IAEA08 = IAEA 2008, IEA07 = IEA 2007, IEA08 = IEA 2008b, IPCC05 = IPCC 2005, LW08 = Liu and Wang 2008, MIT06 = MIT 2006, NA00 = Nakićenović and Swart 2000, PA02 = Paish 2002, PVPS08 = IEA-PVPS 2008.

As many of the world's large rivers are already dammed, and small hydropower is still costly, global hydropower is not expected to expand to more than twice its current capacity (IHA et al. 2000; Paish 2002).

Future development of nuclear power was taken directly from the SRES B1 scenario (Nakićenović and Swart 2000). This scenario is consistent with the amount of reasonably assured and inferred resources being sufficient for 80–100 years at current generation (OECD NEA and IAEA 2008), and also with more recent assessments (UNDP 2004; EIA 2008b).

Wind is widely regarded to face grid integration problems above 20% penetration, with the main issue being excess wind energy to be discarded (Hoogwijk et al. 2007). For example in the GWEC 2008 future wind energy outlook, wind is constrained to 17% penetration even in the advanced scenario. We have hence set $P_{\text{wind}}(2100) = 17\% P_{\text{total}}(2100)$, determining $\alpha$ or $\gamma$.

Future growth of PV depends critically on the reduction of generating cost, which carries a large uncertainty (van der Zwaan and Rabl 2004). There are only few projections that attribute PV a global share of more than 5% penetration by 2050. We have therefore chosen $\gamma$ so that in combination with $P_i(t_0)$ and $r_i(t_0)$, $E_{\text{PV}}(2050) = 5\% E_{\text{total}}(2050)$. No new commercial-scale CSP plant has been commissioned until recently, so that the growth rate $r_i$(2009) was taken from the period 1986–2003. Thoughout 2040, we assume CSP to grow above 20% per year (Schott AG 2005).

The 2050 global potential of geothermal power is estimated in the ACT and BLUE scenarios of the IEA 2008a as only about 200 GW, which was taken as a reference for our projection. However, given its potential for baseload and its significant technical potential (MIT 2006; Resch et al. 2008; Blodgett and Slack 2009), geothermal power was given a "late renaissance", and allowed to expand to 30% penetration by 2100. This scenario also provides an interesting case for comparing traditional with new technologies in their effect on global warming.

Biomass is estimated to grow only moderately by some 2–3% per year (Haq 2003; Perlack et al. 2005). Finally, natural-gas-fired power is expected to grow twofold, and oil-fired power is expected to peak around 2030 (EIA 2008a). Coal-fired generation is reduced residually, by subtracting the generation of all other sources from total electricity demand prescribed by the SRES B1 scenario[15].

A comprehensive comparison of the scenario examined here with previous scenarios is in Appendix B.

## Appendix B: Comparison of our scenario with future projections in the literature

**Table 10** Comparison of future capacities in our scenario (bold) with previous studies

| Technology | Installed capacity (GW) | | | | | | Reference | Comments |
|---|---|---|---|---|---|---|---|---|
| | 2015 | 2020 | 2030 | 2040 | 2050 | 2100 | | |
| **Coal** | **1291** | **1350** | **1496** | **1900** | **2282** | **1693** | **this work** | |
| | 1662 | 1849 | 2295 | | | | EIA08 | |
| **Oil** | **368** | **297** | **186** | **110** | **61** | **1** | **this work** | |
| | 413 | 408 | 400 | | | | EIA08 | |
| **Gas** | **1561** | **1851** | **2369** | **2778** | **3078** | **3627** | **this work** | |
| | 1609 | 1923 | 2467 | | | | EIA08 | |
| **CCS Coal** | **4** | **10** | **41** | **124** | **286** | **1693** | **this work** | |
| **CCS Oil** | **4** | **10** | **49** | **110** | **61** | **1** | **this work** | |
| **CCS Gas** | **4** | **10** | **49** | **167** | **446** | **3627** | **this work** | |
| **CCS Biomass** | **4** | **8** | **21** | **40** | **59** | **105** | **this work** | |
| **All CCS** | **17** | **39** | **160** | **440** | **853** | **5427** | **this work** | |
| **Hydro** | **1145** | **1275** | **1455** | **1557** | **1612** | **1670** | **this work** | |
| **Nuclear** | **444** | **484** | **531** | **810** | **1347** | **873** | **this work** | |
| | 411 | 446 | 498 | | | | EIA08 | |
| | | 437 | 473 | | | | IAEA08 | Low estimate |
| | | 542 | 748 | | | | IAEA08 | High estimate |
| **Wind** | **398** | **744** | **1806** | **3126** | **4380** | **7111** | **this work** | |
| | 233 | 352 | 497 | 599 | 679 | | GWEC08 | Reference scenario |
| | 379 | 709 | 1420 | 1696 | 1834 | | GWEC08 | Moderate scenario |
| | 486 | 1081 | 2375 | 3163 | 3498 | | GWEC08 | Advanced scenario |
| | | 200 | | | | | IEAW01 | EWEA scenario |
| | | 1200 | | | | | IEAW01 | Wind Force 10 scenario |
| **PV** | **56** | **146** | **548** | **1221** | **1971** | **3758** | **this work** | |
| | | 55 | 200–1200 | 400–4000 | 5000–9000 | | RF09 | |
| | 11–44 | | | | | | EPIA08 | 2012 projections |
| | 12 | 34 | 130 | | 1500 | 6000 | FT09 | US only, CAES |
| **CSP** | **2** | **4** | **28** | **190** | **1034** | **2669** | **this work** | |
| | | 20 | | | | | BE05 | US DoE and World Bank |
| | 5 | 15 | 40 | | | | DLR05 | |
| | | 20–40 | | 630 | | | SCH05 | |
| | 9 | 28 | 118 | | 1500 | 4000 | FT09 | US only, hourly storage |

**Table 10** (continued)

| Technology | Installed capacity (GW) | | | | | | Reference | Comments |
|---|---|---|---|---|---|---|---|---|
| | 2015 | 2020 | 2030 | 2040 | 2050 | 2100 | | |
| **Geothermal** | **14** | **17** | **29** | **54** | **107** | **3910** | **this work** | |
| | 6 | 17 | 55 | | 200 | 200 | FT09 | US only |
| | | | | | 100 | | MIT06 | US only |
| | | | | | 200 | | ETP08 | BLUE Map |
| **Biomass** | **69** | **89** | **138** | **203** | **282** | **826** | **this work** | |
| | 13 | | | | | | SI08 | |
| | | 11 | | | | | HQ03 | US only |

BE05 = Brakmann et al. 2005; Eichhammer et al. 2005, DLR05 = DLR 2005, EIA08 = EIA 2008a, EPIA08 = EPIA 2008, ETP08 = IEA 2008a, FT09 = Fthenakis et al. 2009, GWEC08 = GWEC 2008, HQ03 = Haq 2003, IAEA08 = IAEA 2008, IAEW01 = IEA Wind 2001, MIT06 = MIT 2006, RF09 = Raugei and Frankl 2009, SCH05 = Schott AG 2005, SI08 = Sims et al. 2008.

**Table 11** Comparison of future generation in our scenario (bold) with previous studies

| Technology | Generation (PWh/y) | | | | | | Reference | Comments |
|---|---|---|---|---|---|---|---|---|
| | 2015 | 2020 | 2030 | 2040 | 2050 | 2100 | | |
| **Coal** | **8.5** | **8.9** | **9.8** | **12.5** | **15.0** | **11.1** | **this work** | |
| | 10.7 | 12.1 | 15.4 | | | | EIA08 | |
| | | 10.1 | 9.8 | | 5.9 | | WEO08, ETP08 | 550 Policy / ACT Map |
| | | | | | 5.5 | | ETP08 BLUE Map | |
| **Oil** | **0.7** | **0.6** | **0.4** | **0.2** | **0.1** | **0.0** | **this work** | |
| | 0.8 | 0.8 | 0.8 | | | | EIA08 | |
| | | 0.9 | 0.7 | | 0.9 | | WEO08, ETP08 | 550 Policy / ACT Map |
| | | | | | 0.1 | | ETP08 | BLUE Map |
| **Gas** | **5.7** | **6.8** | **8.7** | **10.2** | **11.3** | **13.3** | **this work** | |
| | 5.9 | 7.0 | 8.4 | | | | EIA08 | |
| | | 5.1 | 6.4 | | 11.5 | | WEO08, ETP08 550 Policy / ACT Map | |
| | | | | | 7.3 | | ETP08 | BLUE Map |
| **Hydro** | **4.1** | **4.6** | **5.2** | **5.5** | **5.7** | **5.9** | **this work** | |
| | | 4.2 | | | 5.6 | | EA00 | |
| | | 4.5 | 5.3 | | 5.0 | | WEO08, ETP08 | 550 Policy / ACT Map |
| | | | | | 5.3 | | ETP08 | BLUE Map |
| | | | 4.8–5.4 | | | | RE08 | |
| | | 4.2 | | | 4.2–5.6 | 4.2–5.6 | ED04 | |
| | | 3.1 | 3.3 | 3.3 | 3.3 | 4.2 | WBGU04 | |
| **Nuclear** | **3.3** | **3.6** | **4.0** | **6.1** | **10.1** | **6.6** | **this work** | |
| | 3.0 | 3.3 | 3.8 | | | | EIA08 | |
| | | 3.2 | 3.5 | | | | IAEA08 | Low estimate |

**Table 11** (continued)

| Technology | Generation (PWh/y) | | | | | | Reference | Comments |
|---|---|---|---|---|---|---|---|---|
| | 2015 | 2020 | 2030 | 2040 | 2050 | 2100 | | |
| | | 3.9 | 5.6 | | | | IAEA08 | High estimate |
| | | 4.2 | | | 11.1 | | WEA00 | |
| | | 3.8 | 4.2 | | 7.3 | | WEO08, ETP08 | 550 Policy / ACT Map |
| | | | | | 9.9 | | ETP08 | BLUE Map |
| | 3.3 | 3.6 | 4.0 | 6.1 | 10.1 | 6.6 | NA00 | SRES B2 |
| | | 4.2 | | | 4–11 | 4–16 | ED04 | |
| | | 3.3 | 1.7 | 0.8 | 0.0 | 0.0 | WBGU04 | |
| **Wind** | **0.9** | **1.6** | **4.1** | **7.2** | **10.4** | **18.7** | **this work** | |
| | 0.6 | 0.9 | 1.2 | 1.6 | 1.8 | | GWEC08 | Reference scenario |
| | 0.9 | 1.7 | 3.5 | 4.5 | 4.8 | | GWEC08 | Moderate scenario |
| | 1.2 | 2.7 | 5.4 | 8.2 | 9.1 | | GWEC08 | Advanced scenario |
| | | 1.0 | 2.0 | | 3.6 | | WEO08, ETP08 | 550 Policy / ACT Map |
| | | | 2.7 | | 5.2 | | RE08, ETP08 | BLUE Map |
| | | 1.4 | | | 4.2 | | WEA00 | |
| | | 3.6 | 19.4 | 37.5 | 37.5 | 37.5 | WBGU04 | |
| | | | 1.2–1.8 | | | | RE08 | |
| | | 2.8 | | | 6.9 | 11.1 | ED04 | |
| **PV** | **0.1** | **0.2** | **0.8** | **1.8** | **3.0** | **6.6** | **this work** | |
| | | | | | 5.6 | | WEA00 | |
| | | 0.1 | 0.4 | | 1.3 | | WEO08, ETP08 | 550 Policy / ACT Map |
| | | | | | 2.4 | | ETP08 | BLUE Map |
| | | | 0.3 | | | | HO06 | |
| | | | 0.1–0.2 | | | | RE08 | |
| **CSP** | **0.00** | **0.01** | **0.08** | **0.6** | **3.3** | **11.7** | **this work** | |
| | | | | | 2.8 | | WEA00 | |
| | | 0.1 | 0.15 | | 1.0 | | WEO08, ETP08 | 550 Policy / ACT Map |
| | | | | | 2.4 | | ETP08 | BLUE Map |
| | | | 0.02–0.1 | | | | RE08 | |
| | | | 0.14 | | | | SCH08 | |
| **Geothermal** | **0.1** | **0.1** | **0.2** | **0.4** | **0.7** | **30.8** | **this work** | |
| | | 0.1 | 0.2 | | 0.9 | | WEO08, ETP08 | 550 Policy / ACT Map |
| | | | | | 1.0 | | ETP08 | BLUE Map |
| | | 0.8 | 2.8 | 5.6 | 6.1 | 8.3 | WBGU04 | |
| | | | 0.2 | | | | RE08 | |
| **Biomass** | **0.4** | **0.5** | **0.8** | **1.2** | **1.8** | **5.8** | **this work** | |
| | | 0.8 | | | 2.8 | | EA00 | |
| | | 0.7 | 1.2 | | 1.9 | | WEO08, ETP08 | 550 Policy / ACT Map |
| | | | | | 2.5 | | ETP08 | BLUE Map |
| | | | 0.1–0.2 | | | | RE08 | |
| | | | | | | 1.4 | ED04 | |

ED04 = Edmonds et al. 2004, EIA08 = EIA 2008a, ETP08 = IEA 2008a, GWEC08 = GWEC 2008, IAEA08 = IAEA 2008, NA00 = Nakićenović and Swart 2000, RE08 = Resch et al. 2008, SCH05 = Schott AG 2005, WBGU04 = Graßl et al. 2004, WEA00 = UNDP 2000, WEO08 = IEA 2008c.

**Table 12** Comparison of future avoided emissions in our scenario (bold) with previous studies

| Technology | Avoided emissions (Gt $CO_2$/y) | | | | | | Reference | Comments |
|---|---|---|---|---|---|---|---|---|
| | 2015 | 2020 | 2030 | 2040 | 2050 | 2100 | | |
| **Coal** | **2.7** | **2.6** | **2.6** | **3.0** | **3.2** | **1.0** | **this work** | |
| | | | | | 1.4 | | ETP08 | ACT Map |
| | | | | | 1.4 | | ETP08 | BLUE Map |
| **Oil** | **0.0** | **0.0** | **0.0** | **0.0** | **0.0** | **0.0** | **this work** | |
| **Gas** | **1.0** | **1.2** | **1.5** | **1.8** | **2.0** | **2.2** | **this work** | |
| | | | | | 2.0 | 6.0 | IPCC05 | MESSAGE scenario |
| | | 1.0 | | | 4.0 | 15.0 | IPCC05 | MiniCAM scenario |
| | | | | | 4.6 | | ETP08 | ACT Map |
| | | | | | 2.2 | | ETP08 | BLUE Map |
| **CCS Coal** | **0.0** | **0.0** | **0.2** | **0.5** | **1.2** | **6.0** | **this work** | |
| | | | | | 2.0 | | ETP08 | ACT Map |
| | | | | | 3.2 | | ETP08 | BLUE Map |
| **CCS Oil** | **0.0** | **0.0** | **0.0** | **0.1** | **0.1** | **0.0** | **this work** | |
| **CCS Gas** | **0.0** | **0.0** | **0.1** | **0.2** | **0.5** | **3.9** | **this work** | |
| | | | | | 0.8 | | ETP08 | ACT Map |
| | | | | | 1.3 | | ETP08 | BLUE Map |
| **CCS Biomass** | **0.0** | **0.0** | **0.1** | **0.1** | **0.2** | **0.2** | **this work** | |
| | | | | | 0.2 | | ETP08 | ACT Map |
| | | | | | 0.3 | | ETP08 | BLUE Map |
| **All CCS** | **0.0** | **0.1** | **0.3** | **0.9** | **1.9** | **10.2** | **this work** | |
| | | | | | 0.3–0.5 | 3–10 | RI05 | |
| | | 2.6–4.9 | | | 4.7–37.5 | | IPCC05 | P.24 |
| | | | | | 2.0 | 11.0 | IPCC05 | MESSAGE scenario |
| | | | | | | | IPCC05 | MiniCAM scenario |
| | | 2.0 | | | 9.0 | 20.0 | | |
| | | | | | 2.9 | | ETP08 | ACT Map |
| | | | | | 4.7 | | ETP08 | BLUE Map |
| **Hydro** | **2.4** | **2.6** | **3.0** | **3.1** | **3.1** | **2.8** | **this work** | |
| | | | | | 0.3 | | ETP08 | ACT Map |
| | | | | | 0.4 | | ETP08 | BLUE Map |
| **Nuclear** | **1.9** | **2.0** | **2.2** | **3.2** | **5.2** | **3.1** | **this work** | |
| | | | | | 2 | 5 | IPCC05 | MiniCAM scenario |
| | | | | | 2.1 | | ETP08 | ACT Map |
| | | | | | 2.7 | | ETP08 | BLUE Map |
| **Wind** | **0.5** | **0.9** | **2.2** | **3.8** | **5.3** | **8.2** | **this work** | |
| | 0.3 | 0.5 | 0.7 | 0.9 | 1.1 | | GWEC08 | Reference scenario |
| | 0.6 | 1.0 | 2.1 | 2.7 | 2.9 | | GWEC08 | Moderate scenario |
| | 0.7 | 1.6 | 3.2 | 4.9 | 5.5 | | GWEC08 | Advanced scenario |
| | | | | | 1.3 | | ETP08 | ACT Map |
| | | | | | 2.2 | | ETP08 | BLUE Map |
| **PV** | **0.0** | **0.1** | **0.4** | **0.9** | **1.6** | **3.1** | **this work** | |

**Table 12** (continued)

| Technology | Avoided emissions (Gt $CO_2$/y) | | | | | | Reference | Comments |
|---|---|---|---|---|---|---|---|---|
| | 2015 | 2020 | 2030 | 2040 | 2050 | 2100 | | |
| | | | | | 0.7 | | ETP08 | ACT Map |
| | | | | | 1.3 | | ETP08 | BLUE Map |
| **CSP** | **0.0** | **0.0** | **0.0** | **0.3** | **1.8** | **5.6** | **this work** | |
| | | | | | 0.6 | | ETP08 | ACT Map |
| | | | | | 1.3 | | ETP08 | BLUE Map |
| **Geothermal** | **0.0** | **0.1** | **0.1** | **0.2** | **0.4** | **14.7** | **this work** | |
| | | | | | 0.1 | | ETP08 | ACT Map |
| | | | | | 0.5 | | ETP08 | BLUE Map |
| **Biomass** | **0.2** | **0.3** | **0.4** | **0.7** | **0.9** | **2.7** | **this work** | |
| | | | | | 0.1 | | ETP08 | ACT Map |
| | | | | | 1.4 | | ETP08 | BLUE Map |

**Table 13** Comparison of future cumulative avoided emissions in our scenario (bold) with previous studies

| Technology | Cumulative avoided emissions (Gt $CO_2$) | | | | | | Reference | Comments |
|---|---|---|---|---|---|---|---|---|
| | 2015 | 2020 | 2030 | 2040 | 2050 | 2100 | | |
| **Coal** | **32.4** | **45.5** | **71.6** | **100.3** | **131.8** | **302.6** | **this work** | |
| **Oil** | **0.6** | **0.7** | **0.8** | **0.9** | **0.9** | **0.9** | **this work** | |
| **Gas** | **10.4** | **16.3** | **30.9** | **48.4** | **67.9** | **173.8** | **this work** | |
| **CCS Coal** | **0.1** | **0.3** | **1.7** | **5.8** | **15.6** | **231.2** | **this work** | |
| **CCS Oil** | **0.0** | **0.1** | **0.4** | **1.3** | **1.9** | **2.5** | **this work** | |
| **CCS Gas** | **0.0** | **0.1** | **0.5** | **1.9** | **5.8** | **138.4** | **this work** | |
| **CCS Biomass** | **0.1** | **0.2** | **0.9** | **2.0** | **3.7** | **15.0** | **this work** | |
| **All CCS** | **0.3** | **0.8** | **3.4** | **11.0** | **27.1** | **387.2** | **this work** | |
| | | | | | | 100–250 | RI05 | |
| | | | | | | 220–2200 | IPCC05 | P.46 |
| **Hydro** | **26.3** | **39.6** | **68.5** | **99.1** | **130.1** | **277.4** | **this work** | |
| **Nuclear** | **20.9** | **31.0** | **52.0** | **80.4** | **128.3** | **27.4** | **this work** | |
| **Wind** | **3.8** | **8.4** | **26.8** | **60.7** | **110.0** | **480.3** | **this work** | |
| | 2.2 | 4.6 | 10.8 | 19.1 | 29.2 | | GWEC08 | Reference scenario |
| | 3.0 | 7.2 | 23.8 | 48.2 | 76.1 | | GWEC08 | Moderate scenario |
| | 3.5 | 9.5 | 31.3 | 78.8 | 130.9 | | GWEC08 | Advanced scenario |
| **PV** | **0.3** | **0.8** | **4.0** | **12.1** | **26.2** | **157.8** | **this work** | |
| **CSP** | **0.0** | **0.0** | **0.3** | **2.5** | **15.3** | **252.2** | **this work** | |
| **Geothermal** | **0.4** | **0.7** | **1.5** | **3.0** | **6.0** | **287.2** | **this work** | |
| **Biomass** | **2.2** | **3.6** | **7.7** | **13.7** | **22.2** | **114.7** | **this work** | |

GWEC08 = GWEC 2008, IPCC05 = IPCC 2005, RI05 = Riahi et al. 2005.

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