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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. 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 partly due to the magnitudes at which these technologies are deployed, but in part also due to their deployment histories. Similarly, potential future (2009-2100) contributions are influenced by the magnitude of future capacity as well as temporal deployment profiles. 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 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 should be undertaken on the basis of avoided temperature increase rather than on the basis of annual emissions as is practice 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-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.

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 primarily a distinction between countries 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. 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 analyses to demonstrate the sensitivity of our model. Section 4 discusses the results found and concludes.

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[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   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)

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

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 rth of R fractions of gas g decaying in the atmosphere with characteristic time τ_{gr} normalised through $\sum_{r=1}^{R}f_{gr} = 1$;
- β_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 $\Delta\varrho_g(t')$;
- $\bar{\sigma}_g$ 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 sth of S fractions of radiative forcing that adjusts with characteristic time τ_{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 $\bar{\sigma}_g$ is a function of $\Delta\varrho_g(t')$). In their review of the RBP, Enting 1998 and Den Elzen *et al.* 1999 note that the calculus only 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; Hohne 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 $\varepsilon_{i,g}(t'')$, and with the two lower integral bounds of $-\infty$ set to t_0. 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 $\varepsilon_{i,g}^{\text{ref}}(t'')$. Then, the mitigation potential $M_i^{\text{ref}}(t')$ of technology i at time t' and with respect to reference scenario 'ref' is

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

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.

For each technology, we calculate one historical mitigation potential $M_{\text{hist},i}^{\text{coal}}(t')$ 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.[2]

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[3], and then contrast this with SRES storyline A2[4] as reference scenario. The baseline results of this future scenario are time-dependent mitigation potentials $M_{\text{B1},i}^{\text{A2}}(t')$ with $t_0 = 2009$ and $t' \in [2010, 2100]$.

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

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

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[2] This hypothetical scenario is in fact an upper limit for the historical mitigation potential of each technology here considered.

[3] 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.

[4] 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.

where at time t'', for technology i,

- $E_i(t'')$ 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,
- $\eta_{i,g}^{\text{ons}}(t'')$ 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.

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 ($\approx$ 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) but with a short atmospheric lifetime (10-14 years; IPCC 2007).

Amongst the input parameters P, λ, η^{ons} and η^{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 λ, η^{ons} and η^{ind} were parametrised as linear functions in time, according to

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

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

In addition to changes in technology itself, indirect emissions intensities $\eta_{i,g}^{\text{ind}}(t'')$ 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 $\eta_{i,g}^{\text{ind}}(t'')$ a scaling with the ratio of the carbon intensities χ of electricity mixes in year t''-1 and t_0:

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

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:

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

Growth rates are modelled on an annual basis, using a geometric progression $r(t'') = \gamma\, r(t''-1)$.[5] Growth evolves starting at historical values $P_i(t_0)$ and $r_i(t_0)$, and the parameter γ 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 $\{P_i(t_0), r_i(t_0), \gamma \text{ or } P_i(t'), \lambda_i(t_0), \lambda_i(t'), \eta_{i,g}^{\mathrm{ons}}(t_0), \eta_{i,g}^{\mathrm{ons}}(t'), \eta_{i,g}^{\mathrm{ind}}(t_0), \eta_{i,g}^{\mathrm{ind}}(t')\}$.

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

$$\varepsilon_g^{\mathrm{ref}}(t'') = E^{\mathrm{ref}}(t'')\,\eta_g^{\mathrm{ref}}(t'') = E^{\mathrm{ref}}(t'')\left[\eta_g^{\mathrm{ref,ons}}(t'') + \eta_g^{\mathrm{ref,ind}}(t'')\right]. \qquad (8)$$

Finally, we undertake several sensitivity analyses, by varying the fractions f_{gr} and l_s, and their corresponding characteristic times τ_{gr} and τ_{cs}, and by varying GHG emissions coefficients η.

 2.2 Data sources

Our sources of data are summarised in Lenzen and Badcock 2009. Appendix 1 gives an abbreviated overview.

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[5] 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.

3   Results
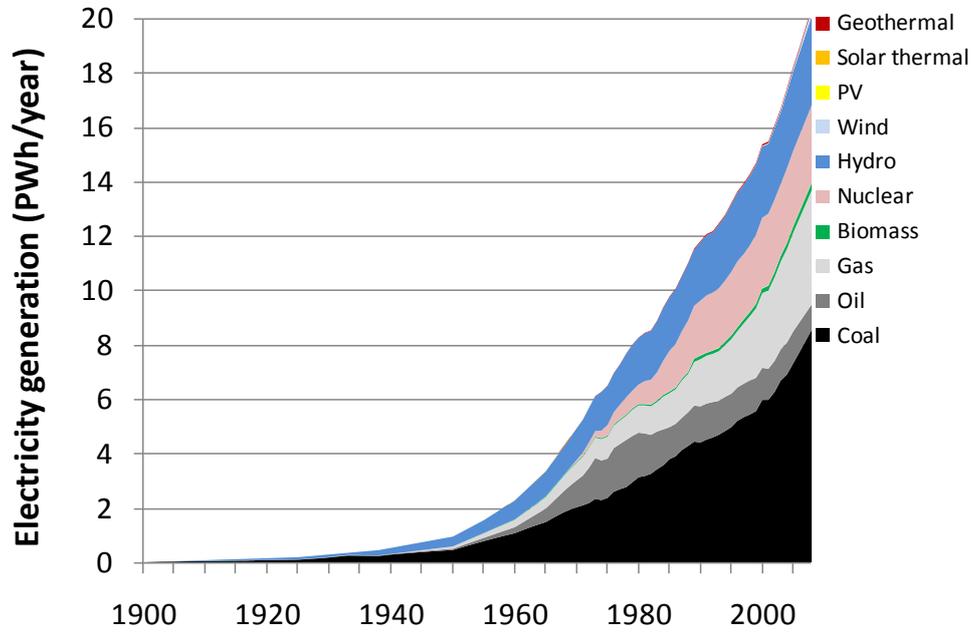
3.1 Historical mitigation potentials

Fig. 1: Historical trends in electricity generation.

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 η. Emissions in 2006 amounted to 11.4 Gt CO_2, which corresponds with data given in IEA 2008c.
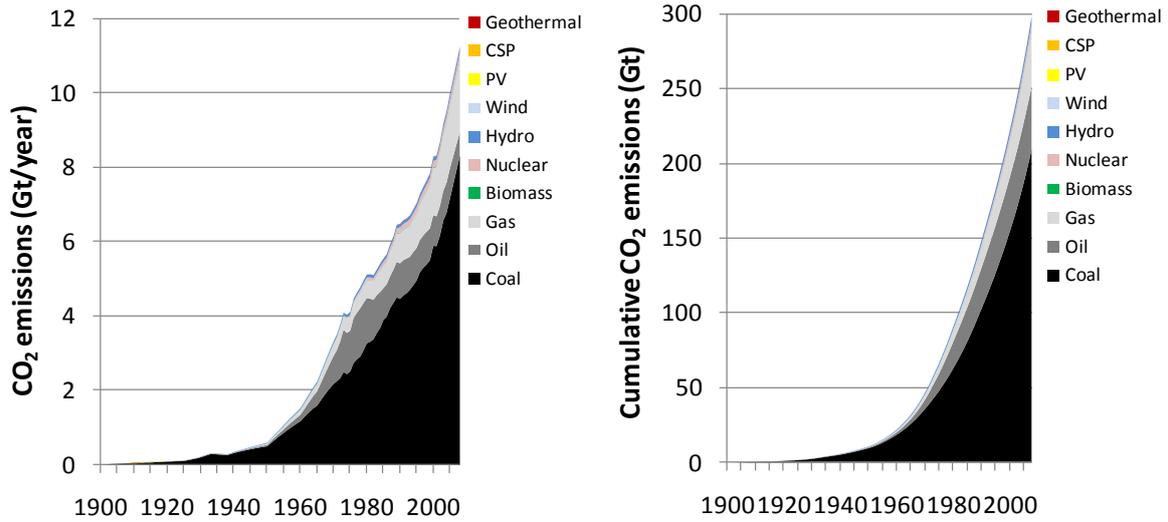
Fig. 2: Historical trends in CO_2 emissions; annual (left) and cumulative (right).

Applying Equation 3 to the historical avoided emissions "pulse" $\varepsilon_{i,g}(t'') - \varepsilon_{i,g}^{coal}(t'')$ calculated from the emissions profiles in Fig. 2 yields mitigation potentials $M_{hist,i}^{coal}(t')$ 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.

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 $\sum_i M_{hist,i}^{coal}(2006)$ 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.
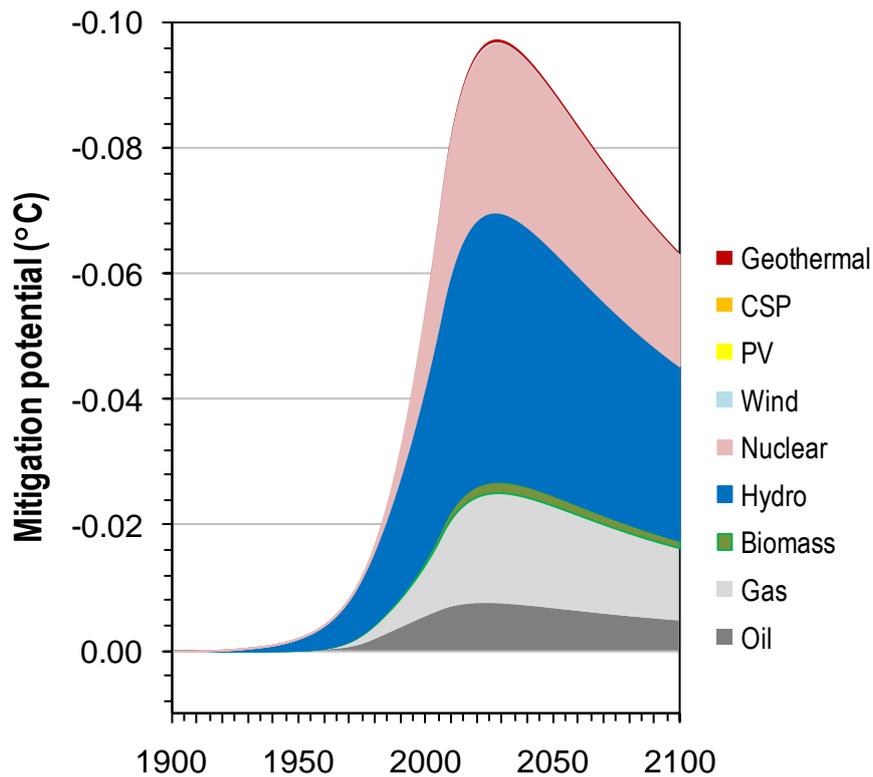
Fig. 3: Historical mitigation potential $M_{hist,i}^{coal}(t')$, carried forward to 2100.

3.2 Future mitigation potentials

Using the various constraints described in Appendix 1, and prescribing total electricity demand according to the SRES B1 scenario (Nakićenović and Swart 2000), a technology 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.
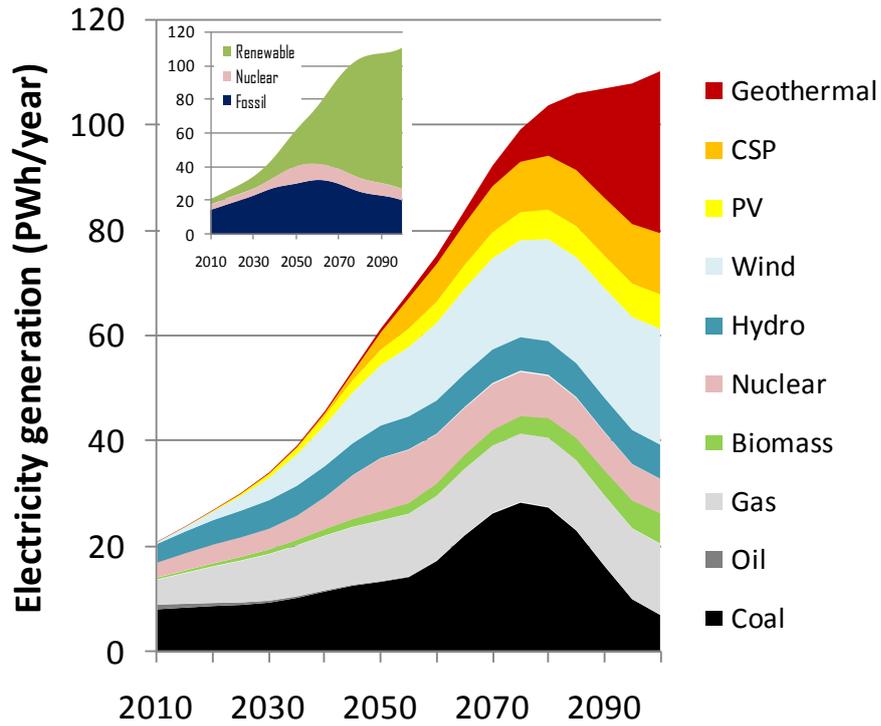
Fig. 4: Future electricity generation scenario modelled according to the constraints described in Appendix 1, and by electricity demand prescribed by the SRES B1 scenario (inset).

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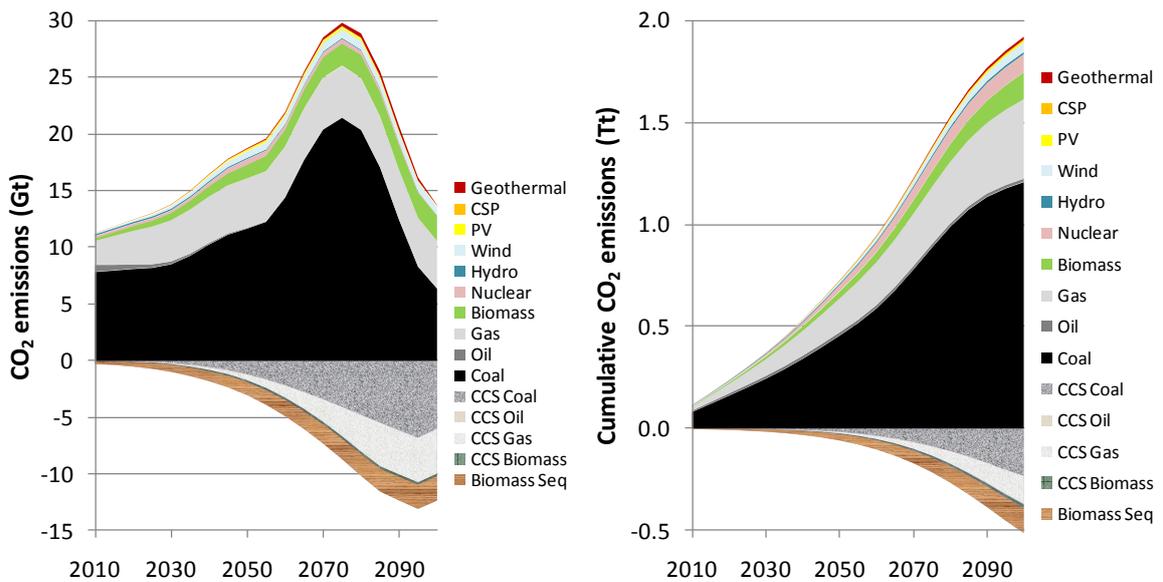
Fig. 5: Future CO_2 emissions; annual (left) and cumulative (right). Net emissions for CCS and biomass are split into positive (combustion) and negative (capture/sequestration) components.

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 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" $\varepsilon_{i,g}(t'') - \varepsilon_{i,g}^{A2}(t'')$ calculated from the emissions profiles in Fig. 5 yields mitigation potentials $M_{B1,i}^{A2}(t')$ in Fig. 6. These are now with respect to a more emissions-intensive SRES A2 scenario.
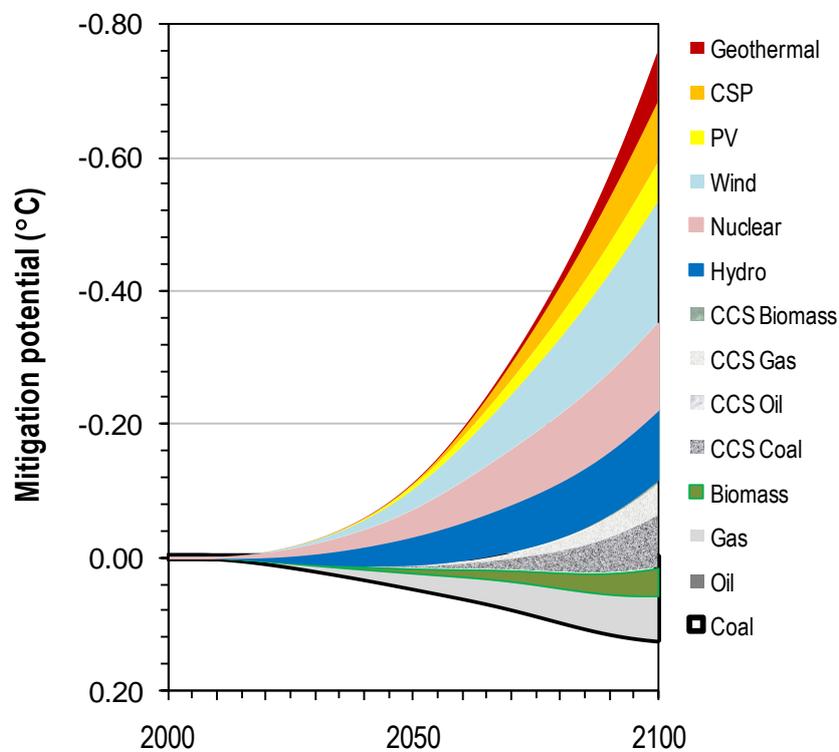
Fig. 6: Future mitigation potentials $M_{B1,i}^{A2}(t')$.

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 $\sum_i M_{B1,i}^{A2}(2100)$ of about –0.76°C.

	Coal	Oil	Gas	Nuclear	Hydro	Wind	PV	CSP	Geother mal	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

Tab. 1: Summary of annually and cumulatively avoided CO$_2$–equivalent emissions, and contributions to global temperature increase, including CH$_4$ effects for hydro reservoirs.

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 (Tabs. 1 and 2). 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.

	Coal	Oil	Gas	Nuclear	Hydro	Wind	PV	CSP	Geother mal	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%

Tab. 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).

Comparing, for the example of hydropower, the 2030 percentage contributions in terms of annual avoided emissions (39%) and cumulatively avoided emissions (55%) with those in terms of avoided the 2030 temperature increase (62%) shows 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.

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[6] for the RBP parameter set[7], 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% (Tab. 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 $\sum_i M_{B1,i}^{A2}(2100) = 0.76°C$ to $\sum_i M_{B1,i}^{A2}(2100) = 0.77°C$.

	Coal	Oil	Gas	Nuclear	Hydro	Wind	PV	CSP	Geotherm	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

Tab. 3: Comparison of mitigation potentials calculated using 'RBP' or 'Bern TAR' parameter sets.

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 with nuclear power. In their analysis of emissions from the nuclear fuel cycle, Storm van Leeuwen and

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

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

Smith 2005 arrived at significantly higher values than listed in Tab. A1.1, 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[8] reduces nuclear's mitigation potential for the century by about 10% (Tab. 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.

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

Tab. 4: Comparison of mitigation potentials of nuclear power, under variations of life-cycle emissions.

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

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 (Tab. 5).

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

Tab. 5: Comparison of mitigation potentials of hydropower, under variations of CH_4 emissions.

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[9]), as well as the reference scenario (from A2 to A1F1[10]). The 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 is higher than in B1, and c) in A1F1 reference CO_2 emissions are lower than in A2 (Fig. 7).
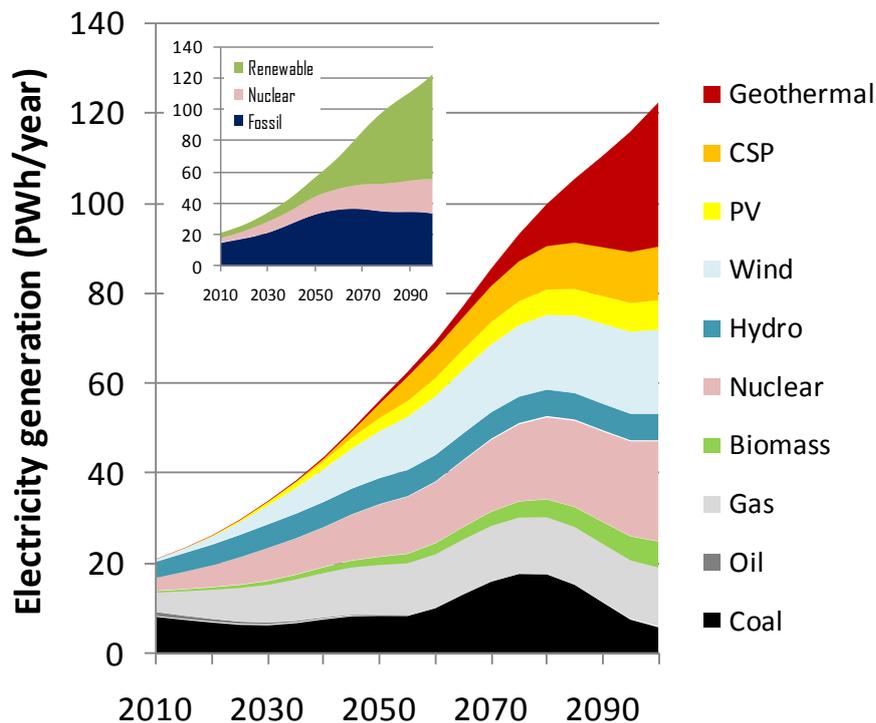
Fig. 7: Future electricity generation scenario modelled according to the constraints described in Appendix 1, and by electricity demand prescribed by the SRES B2 scenario (inset).

With the obvious exceptions of nuclear power and coal, mitigation potentials change negligibly (Tab. 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

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[9] 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.

[10] 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.

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.

	Coal	Oil	Gas	Nuclear	Hydro	Wind	PV	CSP	Geotherm	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

Tab. 6: Comparison of mitigation potentials calculated using the B1/A2 or B2/A1F1 scenario sets.

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 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 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 conclusively show that avoided temperature increase is a better proxy for comparing technologies with regard to their impact on climate change, and that comparisons based on annual or even cumulative emissions may be misleading. Thus, our results support the Brazilian Proposal to the IPCC. In addition our findings extend the policy relevance of the Brazilian Proposal in the sense that not only comparisons between countries, but also comparisons between technologies or technology portfolios should be undertaken on the basis of avoided temperature increase rather than on the basis of annual emissions as is practice today.

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Appendix 1: Data sources

A1.1   Emissions data and global warming parameters

The parameters $\bar{\sigma}_g$ and β_g in Equation 2 were parametrised using the RBP values for the fractions f and l and their corresponding lifetimes τ, as listed in Rosa *et al.* 2004 and UNFCCC 2009a; b. Values for the β and σ 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. A1.1) against historical measurements of atmospheric concentrations (CO_2 Keeling *et al.* 2008, CH_4 Steele *et al.* 2003) and ice core samples (CO_2 Neftel *et al.* 1994, CH_4 Etheridge *et al.* 2002), as well as against historical measurements of global temperature anomalies (Jones *et al.* 2009).
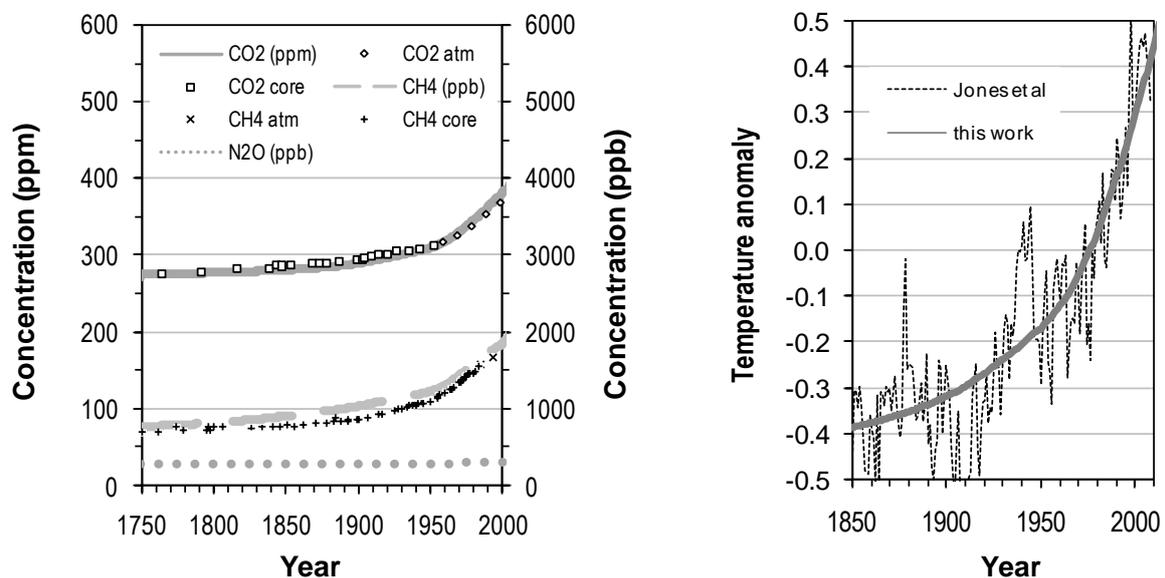
Fig. A1.1: Calibration of the RBP (grey curves) in terms of atmospheric concentrations of two greenhouse gases (left) and temperature anomaly (right) against measurements (left: markers; right: dashed curve).

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 $M_{\text{hist},i}^{\text{coal}}(t')$ 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).

A1.2 *Specific emissions coefficients η*

Specific emissions coefficients η for the various technologies were sourced from a wide range of recent assessments (Tab. A1.1). 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 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.

Technology	Life-cycle emissions (g CO_2-e / kWh_{el})		References	Comments
	2009	2100		
Pulverised coal	880 +10%	570	⎫	
Oil	640 +10%	440	⎬ IPCC05, WE07, OL08	
Natural Gas CC	385 + 20%	310	⎭	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) + CO_2(res) + CH_4(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.

Tab. A1.1: On-site and indirect GHG emissions $\eta_{i,g}^{\text{ons}}$ and $\eta_{i,g}^{\text{ind}}$.[11]

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[11] 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

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 (due to a 6-8% efficiency decrease, and to the water-gas shift reaction).[12] The life-cycle component represents CO_2 transport and injection.[13]

Emissions from construction and maintenance of hydroelectric plants amount to about 40 g CO_2/kWh, however average CO_2 and CH_4 emissions from the anaerobic decay of organic matter submerged by the reservoir have been measured to be 200 g CO_2-e/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).

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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 (Tabs. 1-3) had to be modelled based on 2006 data.

[12] 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).

[13] 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.

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 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).

Technology	Capacity factor (%) 2009	2100	References	Comments
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.

Tab. A1.2: Average capacity factors.[11]

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 2). 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 γ. CCS for biomass is not expected to be economical because of the small size of biomass-fired power plants (Damen *et al.* 2007).

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; IEA 2008c).

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 α or γ.

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 γ 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 largest 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; IEA 2008c; a). Coal-fired generation is reduced residually, by subtracting the generation of all other sources from total electricity demand prescribed by the SRES B1 scenario.

A comprehensive comparison of the scenario examined here with previous scenarios is in Appendix 2.

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.

Tab. A1.3: Present and future installed capacities and their present growth rates.[11]

Appendix 2: Comparison of our scenario with future projections in the literature

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*
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.

Tab. A2.1: Comparison of future capacities 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		WEA00	
		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
		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		WEA00	
		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.

Tab. A2.2: Comparison of future generation 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	
					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*

ETP08 = IEA 2008a, GWEC08 = GWEC 2008, IPCC05 = IPCC 2005, RI05 = Riahi *et al.* 2005.

Tab. A2.3: Comparison of future avoided emissions in our scenario (bold) with previous studies.

Technology	Cumulative avoided emissions (Gt CO_2)					Refe-rence	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**	**327.4 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.

Tab. A2.4: Comparison of future cumulative avoided emissions in our scenario (bold) with previous studies.