# Climate Uncertainty and the Necessity to Transform Global Energy Supply

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## Summary

This paper analyses the policy relevance of the dominant uncertainties in our current scientific understanding of the terrestrial climate system, and provides further evidence for the need to radically transform - this century - our global infrastructure of energy supply, given the global average temperature increase as a result of anthropogenic carbon dioxide emissions. We investigate the effect on required CO2 emission reduction efforts, both in terms of *how much* and *whe*n, of our uncertain knowledge today of the climate sensitivity to a doubling in them atmospheric CO2 concentration. Also the roles of carbon-free energy and energy savings, and their evolutions over time, are researched, as well as their dependence on some of our characteristic modelling features. We use a top-down model in which there are two competing energy sources, fossil and non-fossil. Technological change is represented endogenously through learning curves, and modest but non-zero demand exists for the relatively expensive carbon-free energy resource.



**Keywords:** Global warming, $CO_2$ emissions, Climate sensitivity, Fossil to non-fossil transition, Carbon-free power, Energy savings

**JEL Classification:** 030, Q25, Q42, Q43, Q48

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## 1. Introduction

The sensitivity of the global mean temperature to increasing levels of atmospheric $CO_2$ is currently known only to about a factor of three. To be more precise, the climate sensitivity, • $T_{2X}$ – defined as the global mean climatological temperature change • T resulting from a doubling of atmospheric carbon dioxide content X – is thought, today, to lie in a range of about 1.5 to 4.5 C. These numbers have been derived primarily from computer-models, have been reported by the International Panel on Climate Change (IPCC), and have subsequently been used by both scientific and policy-making communities the world over, for almost a decade now (IPCC, 1996 and 2001). In a recent article, Caldeira *et al.* (2003) reported their finding that, in analyses in which scientists attempt to determine the levels of allowable $CO_2$ emissions, the uncertainty with which we currently know the value of the climate sensitivity, • $T_{2X}$, has a larger effect (that is, is more determinant for the calculation of these levels) than the uncertainty in our understanding today of the carbon cycle. Because of the sizeable uncertainties that dominate so many of the scientific results in the field of climatic change studies, and the relevance of these uncertainties for effective and efficient global warming policy-making, the subject of uncertainty analysis has recently been receiving increased attention (as can e.g. be seen from the number of conferences today dedicated to this topic; see, for example, MIT, 2003). This article explores the relation between climate sensitivity uncertainties and the necessity to transform world energy supply. In particular, we put our modelling results into perspective with the findings presented by Caldeira *et al.* (2003) and focus on the desired transition of the global energy system during the 21$^{st}$ century.

Today's global energy supply is highly dependent on fossil fuels, and the choice for new and/or renewable sources as the basis of our energy system will undoubtedly require a costly transition. Nonetheless, for the long run, such a transition seems inevitable, given the risks to humankind involved with climate change. Only two main options exist to reduce carbon-dioxide emissions. These are energy savings, on the one hand, and a transition to the use of non-carbon energy, on the other hand. Energy savings are essential for reaching emission reduction targets, especially in the short term, but since energy is essential for economic production (see, for example, Berry *et al.*, 1978), it needs to be complemented by a transformation of the global energy production system. In fact, since the emission intensity of energy production will finally need to fall down to close-to-zero levels (Wigley *et al.*, 1996), a radical energy system overhaul seems imperative. Most scientists and climate specialists today see both an enhanced development of energy-saving technologies and a shift towards non-greenhouse-gas-emitting energy resources as major elements of policies aiming at a stabilisation of atmospheric carbon-dioxide concentrations. Until recently, however, most top-down integrated assessment models of global warming focused on the energy saving option as the main route to reach emission reductions. Well-known examples of these are CETA, DICE, MERGE, RICE and FUND (Peck and Teisberg, 1992; Nordhaus, 1994; Manne *et al.*, 1995; Nordhaus and Yang, 1996; Tol, 1999).

To address the effect of climate sensitivity uncertainties on policies regarding the control and reduction of carbon emissions, as well as on the required timing of these reductions, we use an integrated assessment model that was specially developed to study policy questions related to global warming, energy supply and technological change. The model, DEMETER, is a general equilibrium model that incorporates a simplified climate change module. DEMETER allows analysing energy savings and energy supply transition processes simultaneously, while it does not display the technological detail of many energy systems-engineering models. Not considering it necessary to describe the model in full detail here again (see Gerlagh *et al.*, 2004, for an extensive description), we highlight four of its main elements. First, it includes two competing energy technologies, one of which has zero net $CO_2$ emissions. This allows emission reductions to be achievable through a transition towards a carbon-free technology, as an alternative to the substitution of energy by capital and labour. Second, it distinguishes old from new capital, in such a way that substitution possibilities between production factors only apply to new stocks of capital. This so-called 'vintage' approach allows for using different substitution elasticities for the short and long term, and can, in particular, describe a slow diffusion process. Third, it includes learning-by-doing, through the use of learning curves. In this way, a transition towards alternative technologies leads to lower energy production costs for these technologies, and thereby enhances their opportunities and accelerates the transition process (see also Messner, 1995). Fourth, it includes substitution elasticities, such that new technologies can spread before they become fully mature – even though their production costs are initially high.

DEMETER has been used successfully already for a few different research subjects (see van der Zwaan *et al.*, 2002; Gerlagh and van der Zwaan, 2003 and 2004; Gerlagh *et al.*, 2004). In this paper, we use DEMETER to investigate the variability of carbon emission reduction efforts, as well as that of their timing, as resulting from uncertainties in climate sensitivity, under the presence of a stringent climate change policy – that is, when constraining the global average temperature increase or applying a stringent constraint to the atmospheric carbon dioxide concentration. We also describe the sensitivity of energy savings and the evolution of the share of non-fossil technologies, to changes in a few of the most relevant model parameters. Below, section 2 concisely describes the main features of DEMETER and its calibration. Section 3 presents the results of our analysis, derives the policy implications of current uncertainties in climate sensitivity, and underlines the necessity to transform our global energy supply system. Section 4 summarises our findings and concludes.

## 2. Model Description and Calibration

DEMETER is an optimal-growth (welfare maximisation) model of the world economy. It is designed to calculate cost-effective carbon taxes that maximise the discounted value of utility obtained from the consumption of a generic consumer good. Welfare is maximised subject to a number of economic, technological and climatic constraints. The model describes three production sectors, one for the consumer good, and two for energy production. The two energy sectors use different technologies: the first 'old' technology uses fossil-fuels (*F*), while the second 'new' technology uses backstop energy sources (e.g. solar or wind energy) with assumed zero carbon-dioxide emissions (*N*). DEMETER uses a vintage approach to describe production processes, allowing a differentiation in short-term and long-term elasticities of substitution between various inputs. The production of the consumer good is described by a nested constant-elasticity-of-substitution (CES) function (see Gerlagh *et al.*, 2004). One of our specific assumptions is that production costs decrease *endogenously* as experience increases (see, for example, Chakravorty *et al.*, 1997; Goulder and Schneider, 1999; Carraro *et al.*, 2003), and that production costs converge to a strictly positive floor price. We assume a constant learning rate, $lr$>0, for technologies at the beginning of their learning curve. This means that, initially, production costs decrease by a factor (1–$lr$), for every doubling of installed vintages.

Another distinguishing feature of DEMETER is that a long-term elasticity of substitution is modelled between the two energy sources, *F* and *N*, denoted by • . The CES aggregation of *F* and *N* marks an important extension of our model compared to existing models. It describes a strictly positive demand for the new technology *N*, even if the price of the new technology largely exceeds the price of the old technology *F*. Photo-voltaic energy would be an example, since it is used in remote areas irrespective of its high costs, given the local difficulty to connect to a nearby electricity grid. We have chosen a value for the elasticity of substitution σ that is bounded and larger than one. For an extensive justification of this value we refer to Gerlagh and van der Zwaan (2004). Approximately, the parameter σ determines the share of the fossil-fuel based energy source relative to the share of the non-fossil-fuel energy source, $(F_t\ /N_t\ )$, given their relative production costs, $(p_t^F\ /\ p_t^N)$, as follows (as a function of time):

$$(F_t\ /N_t\ ) = (p_t^F\ /\ p_t^N)^{-\sigma}\ . \qquad (1)$$

Carbon emissions, $E_t$, are proportional to the use of fossil-fuel-based energy $F_t$, via the aggregate carbon emission factor $\varepsilon_t$:

$$E_t = \varepsilon_t F_t. \tag{2}$$

The factor $\varepsilon_t$ is assumed to be time-dependent (but exogenous), to account for the de-carbonisation process to which the use of fossil fuels has been subject since the early times of industrialisation, by a transition – in chronological order – from wood to coal, from coal combustion to that of oil, and most recently from coal and oil to natural gas. Carbon emissions are linked to the atmospheric carbon-dioxide concentration, which in turn determines the global average surface temperature, through a 1-box representation as in the early DICE model (Nordhaus, 1994). As in Caldeira *et al.* (2003), the stabilisation level of the atmospheric $CO_2$ concentration, $P_{stab}$, and the stabilisation value of the temperature increase, $\Delta T_{stab}$, are related through:

$$\frac{P_{stab}}{P_{280}} = 2^{\left(\frac{\Delta T_{stab}}{\Delta T_{2X}}\right)}, \tag{3}$$

in which $P_{280}$ stands for the pre-industrial atmospheric $CO_2$ concentration of 280 ppmv, and $\Delta T_{2X}$, as above, for the climate sensitivity (with central value of 3 degrees Celsius per doubling of the atmospheric $CO_2$ concentration).

The inclusion of a temperature or atmospheric carbon concentration constraint in the model results in a positive shadow price for carbon emissions. This emissions shadow price can be interpreted as the tax required on carbon emissions to meet the temperature or concentration constraint that we impose in our model. Additional to the carbon tax, the model calculates an efficient subsidy on investments in new/renewable energy production. Since investments in non-fossil-fuel energy production lower future costs of energy production, through the learning mechanism, the shadow price (or social costs) for such investments lies below the immediate costs, that is, below the consumption foregone. The gap between this investment shadow price and the immediate costs can be interpreted as the subsidy on investments that internalises the learning effect.

For this paper's purpose, we have basically analysed two kinds of scenarios. The first kind of scenario, 'business-as-usual' (BAU), assumes no control on carbon-dioxide emissions. It also assumes that there is no policy stimulating the use of the non-fossil-fuel energy source, that is, it abstracts from both taxes and subsidies. The second kind of scenario sets a ceiling on the average global temperature increase, or, roughly equivalently, a constraint on the atmospheric carbon dioxide concentration. In this study, the average temperature increase is not allowed to rise above 2 degrees Celsius, compared to its pre-industrial value. This is an ambitious scenario that involves taking drastic emission reduction steps (see Schneider and Azar, 2001). In contrast to the first type of scenario, in the temperature-constrained scenario it is assumed that both taxes on carbon emissions are applied, and subsidies are available for investments in the non-fossil-fuel energy source.

DEMETER has been calibrated in order to obtain modelling results that mimic real-world phenomena as closely as possible. The world population is assumed to grow from 5.89 billion in 1997 at a rate of 1.45 % per year, levelling off and reaching 11.4 billion by 2100 (World Bank, 1999, and Nakicenovic *et al.*, 1998). Gross World Product (GWP) in 1997 is assumed to have been 25.1 trillion US$1990 (World Bank, 1999) and its future annual per capita growth rate is assumed to be 1.5 %. The value assumed for the autonomous energy services efficiency improvement (AESEI) is 1.0 % per year. The AESEI measures the productivity increase of our CES aggregate. The combined assumptions on population growth, GWP growth and the value of AESEI result in an energy consumption growth rate of 1.9 % per year in 2000, which decreases to 0.6 % per year in 2100.

The aggregation of final energy supply over various energy sources such as electricity and heat is facilitated by conversion of all final energy data in primary energy equivalents. Specifically, for electricity, energy flows measured in ExaJoule per year (EJ/yr) are divided by 0.33, the typical conversion efficiency from heat to electricity, while electricity prices, measured in US dollars per GigaJoule ($/GJ), are multiplied by 0.33, to arrive at volumes and prices, respectively, in primary energy equivalents. Over the year 1997, commercial final energy supply (in primary energy equivalents) based on fossil-fuel energy sources is estimated to have been some 307 EJ, and related carbon emissions are assumed to have been 6.3 GtC. Carbon emissions related to land-use changes and industrial processes are around 1.3 GtC, and are assumed constant over time. By dividing the fossil-fuel carbon emissions of 6.3 GtC by the fossil-fuel commercial final energy (services) supply of 307 EJ, one obtains the carbon emission intensity of fossil-fuel commercial final energy (services) supply, $\bullet_t$, which amounts to 0.021 gC/kJ in 1997. The fossil-fuel technology is assumed to be subject to a ‘decarbonisation’ of 0.2 % per year, which continues until a floor is reached of 0.016 gC/kJ.

On the basis of the database developed for the IIASA-WEC study (Nakicenovic *et al.*, 1998), final commercial energy consumption in 1997 is estimated to be (in primary energy equivalents) 320 EJ.[1] From the same database, the share of fossil-fuel

[1] This excludes non-commercial biomass use, as well as ‘traditional’ carbon-free sources such as nuclear and hydropower. However important these may be, we do not consider these energy resources in this analysis for ease of exposition.

technologies in energy production (in 1997) is estimated to be 96 %. This corresponds to the 307 EJ mentioned above. The remaining share of 13 EJ is non-fossil-fuel energy. Thus, in equation (1), the ratio at the left-hand-side is about 24. Prices, in primary energy equivalents, for energy derived from natural gas technologies vary in a range from 2 to 3 \$(1990)/GJ (IEA/OECD, 1999, p.41). Since coal, oil and natural gas are more or less competitive, a good reference price in our calculations for the average fossil-fuel energy resource is 2.5 \$/GJ, in the model start-off year 1997 (this price in primary energy equivalents corresponds to a price of 2.5 x 3.33 = 8.3 \$/GJ in final electricity units). A large spread exists in production costs for energy from e.g. wind and solar energy (electricity) options. Prices, in primary energy equivalents, for commercial final electricity from wind turbines varied in 1995 between 2 and 7 \$(1990)/GJ, in the highest-cost and lowest-cost production cases, respectively (IEA/OECD, 2000, p.54; Gerlagh and van der Zwaan, 2004). Electricity production costs for photo-voltaic systems are still significantly higher than those for wind energy (IEA/OECD, 2000, p.21). We consider a realistic range for the ratio of production costs (non-fossil vs. fossil) to be a factor varying from 2 to 5, consistent with an elasticity of substitution ranging from about •=2 to •=4. As central value, we take •=3. Given fossil-fuel energy prices of 2.5 \$/GJ, this value for • is consistent – see equation (1) – with production costs for the non-fossil-fuel energy source of 7.2 \$/GJ, in the year 1997 (this latter price in primary energy equivalents corresponds to a price of 7.2 x 3.33 = 24 \$/GJ in final electricity units). For the basis parameter values, in 1997, energy production accounts for about 2.7 % of GWP. As lower bound for • we take •=2, and we adjust the initial production costs for the non-fossil-fuel energy source accordingly, to 12.2 \$/GJ. As upper bound we take •=4, and we adjust initial non-fossil-fuel prices to 5.5 \$/GJ.

The learning rate for non-fossil-fuel energy resources is assumed to be 20% per doubling of installed vintages, in line with the empirical evidence on this variable for e.g. solar power and wind suggesting that the learning rate ranges from 8 to 35% (McDonald and Schrattenholzer, 2000). The fossil-fuel energy technology is assumed to have used most of its learning potential already. The cumulative capacity of installed vintages up to the year 1997 is estimated to be about 1200 EJ and 32 EJ for the fossil-fuel energy option and the non-fossil-fuel energy alternative, respectively.[2] Under the baseline scenario, the cumulative capacity of installed vintages for the carbon-free energy technology is doubled by 2020. Consequently, under the central parameter choice, production costs have decreased by 20%, and for •=3 the market share will have

[2] For how we derived these figures for the cumulative installed capacity of past vintages, we refer to Gerlagh and van der Zwaan (2004).

increased by approximately 75%, corresponding to an increase of 3% in total energy supply, from 4% to 7%.

## 3. Results

We have calculated the optimal carbon emission path under three different climate sensitivities. Figure 1 shows the carbon dioxide emission evolutions both under a business-as-usual scenario (BAU, in solid squares) and under five different scenarios in which global warming is controlled through some policy intervention - in modelling terms through the imposition of an exogenous constraint on our simulations. Among the five climate-constrained scenarios, the first three cases involve a limitation of the average global temperature increase to 2 degrees Celsius, each under a different climate sensitivity assumption.

The central climate sensitivity we use is a 3 degrees Celsius temperature increase resulting from a doubling of the atmospheric concentration of carbon dioxide (C/doubling). We have varied this climate sensitivity from 3 C/doubling down to 2 C/doubling and up to 4 C/doubling. A 4 C/doubling climate sensitivity involves, naturally, a more stringent climate policy than the case in which we use a 3 C/doubling, so that more radical emission reductions are called for in the former case, compared to those needed in the latter. A 2 C/doubling climate sensitivity clearly involves less stringent policy measures, as demonstrated in Figure 1. We point out that our sensitivity analysis regarding the climate sensitivity parameter can also be interpreted as one regarding the temperature constraint used in our policy scenarios, with temperature increase targets of 1.5, 2 and 3 degrees Celsius, respectively. To put it more precisely, varying the climate sensitivity from a central value of 3 C/doubling down to a lower value of 2 C/doubling, under a 2 degrees Celsius stabilisation constraint, is equivalent to keeping the climate sensitivity at 3 C/doubling, but increasing the temperature target from 2 to 3 degrees Celsius. Inversely, varying the climate sensitivity from a central value of 3 C/doubling up to a value of 4 C/doubling, under a 2 degrees Celsius stabilisation constraint, is equivalent to keeping the climate sensitivity at 3 C/doubling, but decreasing the temperature target from 2 to 1.5 degrees Celsius.

We have generated two additional policy scenarios, as an extra check regarding the sensitivity of our results to different climate change targets. We have changed our 2 degrees Celsius constraint into an atmospheric $CO_2$ concentration constraint, of 450 ppmv and 550 ppmv ($CO_2$) respectively, the results of which are shown in Figure 1. As can be seen, for the long-term, a constraint on the atmospheric carbon dioxide concentration of 450 ppmv is slightly more flexible than a 2 degrees Celsius constraint with a 3 C/doubling climate sensitivity. But for (more than) the first half of the century, it is a more stringent constraint. The 550 ppmv carbon dioxide concentration scenario resembles the 2 degrees Celsius constraint scenario with 2 C/doubling climate sensitivity.

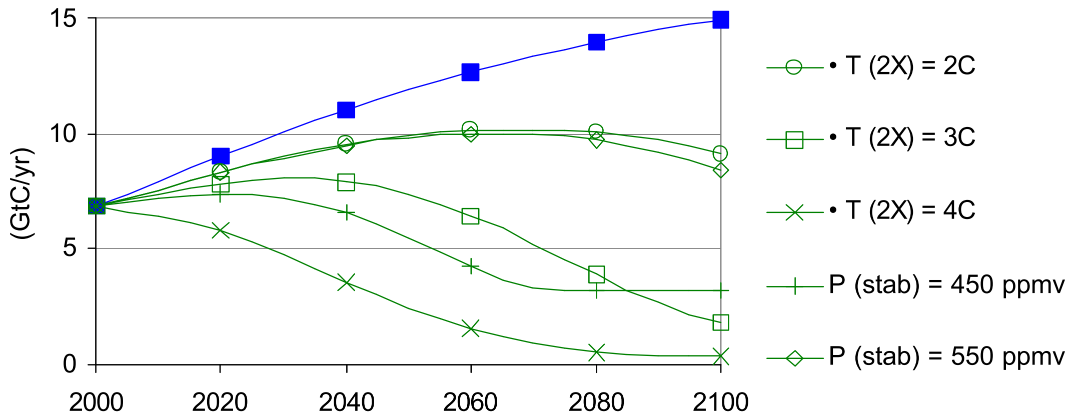


FIGURE 1. *Carbon dioxide emissions under various climate sensitivities and policy scenarios.*

Table 1 displays the variability of emissions, the share of energy savings in total emission reductions, and the share of carbon-free energy sources in total energy supply, in 2020, under three different climate sensitivities and two different concentration constraints. As can be seen, the emission reduction effort (first results-column) strongly depends on the assumed climate sensitivity, and also varies over the carbon concentration constraint employed. The extent to which energy savings are used as instrument to reach the climate objective is little dependent on the value of either the sensitivity or constraint. In formal terms, the savings vs. total emission reductions share can be expressed as:

$$\frac{(E_t^{BAU} - E_t^{2C})}{E_t^{BAU}} \Bigg/ \frac{(Em_t^{BAU} - Em_t^{2C})}{Em_t^{BAU}}, \tag{4}$$

where $E_t^{BAU}$ is the energy level in the BAU scenario, $E_t^{2C}$ the energy level in the 2 C climate-constrained scenario, $Em_t^{BAU}$ are the emissions in the BAU scenario, and $Em_t^{2C}$ the emissions in the 2 C scenario (all dependent on time *t*). By 2020, about half of the emission reductions are attained through savings.

The non-fossil share of energy supply, in 2020 - hence the extent to which a transition towards non-fossil fuels is realised by then - displays a significant dependence on the parameter values used, especially in case of the climate sensitivity parameter.

TABLE 1. E*missions, energy savings share in emission reductions, and carbon-free share in energy supply, under different climate sensitivities and climate constraints.*

| | Lower value | Basis value | Upper value | Emissions in 2020 (GtC/yr) | Energy Savings / Emission Reduction in 2020 (%) | Non-Fossil share in 2020 (%) |
|---|---|---|---|---|---|---|
| Basis (with 2 C climate constraint) | | | | 7.8 | 52 | 12 |
| Climate sensitivity (C/doubling) | ( 4, | 3, | 2) | (**5.8**, **8.3**) | (**48**, 49)* | (**9**, **27**)* |
| $CO_2$ concentration constraint (ppmv) | ( 450 | | 550) | (7.4, **8.3**) | (49, **53**)* | (**9**, 14)* |
| **Overall range** | | | | **(5.8, 8.3)** | **(48, 53)** | **(9, 27)** |

N.B. The largest extremities reached are in bold and are indicated in the last row as 'overall range'.
* Asterices denote intervals where the lower bound of the sensitivity result is associated with the upper value of the corresponding parameter.

How do these results compare with those found in the literature? Table 2 juxtaposes our findings, for two (rather extreme) climate sensitivity values, next to the ones presented in Caldeira *et al.* (2003), and indicates that, apart from a number of similarities, a few seemingly important differences exist. With a 2 C/doubling climate sensitivity, 2020 emissions in our study are found to be roughly the same as those in Caldeira *et al.* (2003); increasing this sensitivity to 4 C/doubling induces considerable decreases in emissions, of 30% and 39% in the two cases respectively. As for the carbon-free share in total energy supply, in 2020, we find that its value triples, from 9% to 27%, when changing the climate sensitivity from 2 to 4 C/doubling. In Caldeira *et al.* (2003), it is found that this value almost doubles, from 34% to 60%. For the non-fossil energy share, their results differ less from ours than it may seem from quick examination. Closer scrutiny points out that we express non-fossil shares with respect to total energy supply, while they do so in comparison to total electric power generation. This explains that the numbers displayed differ by a factor of about 4 (9 compared to 34, in the 2 C/doubling case) to 2 (27 compared to 60, in the 4 C/doubling case). The difference in results between these two factors, 4 and 2 respectively, can be explained as well. Increasing the share of power production in energy supply proves the most efficient way to increase the share of (mostly electric) non-fossil energy in total supply. With a high (4 C/doubling) climate sensitivity, reaching the 2 C climate constraint is much more ambitious than in the 2 C/doubling case, that is, much more carbon-free energy needs to be employed (in a rather short time). Hence, in the 4 C/doubling case the electricity-to-total-energy ratio is likely to be significantly higher than in the 2 C/doubling case, explaining why the numbers 27 and 60 lie closer in each other's vicinity (that is, differ by 'only' about a factor of two) than 9 and 34 (off by a factor of almost 4). Overall, the results prove thus consistent.

TABLE 2. *Emissions and carbon-free share in total energy supply, in 2020, under different climate sensitivities.*

| | | | Climate sensitivity | |
|---|---|---|---|---|
| | | | 2 | 4 |
| Emissions in 2020 (GtC/yr) | | This study | 8.3 | 5.8 |
| | | Caldeira *et al*. (2003) | 8.0 | 4.8 |
| Non-Fossil Share in 2020 (%) | (energy) | This study | 9 | 27 |
| | (electricity) | Caldeira *et al*. (2003) | 34 | 60 |

N.B. The quoted Caldeira *et al*. (2003) data are obtained through inspection of their figures 1 and 2.

We observe, with Caldeira *et al.* (2003), that even under central assumptions for the climate constraint and sensitivity, a massive transition towards non-fossil energy is called for. By the end of the century, between 75% and 100% of total power demand will need to be provided by non-$CO_2$ releasing energy sources (Caldeira *et al.* 2003), or, in between 80% and 90% of total energy supply (our analysis).

In this article we go a few steps further and exploit the advantages of using a top-down model like DEMETER: we have calculated the relative importance of energy savings versus the transition from fossil-fuel towards non-fossil-fuel energy sources for reaching the climate stabilisation objective. In Gerlagh and van der Zwaan (2004), we reported our findings regarding the share of emission reductions, relative to the BAU benchmark, reached through energy savings measures (the first policy option, as also displayed in the second results-column of Table 1). The remainder of the emission reductions, we concluded, is reached through the second policy option (a transition to non-fossil-fuel energy sources). Let's here expand on the mechanisms through which emission reductions take place. In Figure 2, we present the trade-off between energy savings and the decarbonisation of energy supply. That is, for reaching the climate stabilisation target, the model chooses between decreasing the energy intensity of total output, on the horizontal axis, versus decreasing the emissions per energy output by shifting energy supply to non-carbon energy sources, on the vertical axis. The figure presents the relative use of these two options for the period 2000-2050. The figure shows that the path is almost entirely independent of the climate change target or the climate sensitivity used, although the extent of progression along the path depends significantly on the stringency of the climate change target or the value of the climate sensitivity. The figure shows that energy savings constitute mainly an option for moderate and medium emission reductions. The first part of emission reductions is reached through both energy savings and energy decarbonisation, both in approximately equal shares, consistent with the reporting in Table 1. When energy savings exceed the level of 20%, it becomes an expensive option, in relative terms, and the development of the non-carbon energy source becomes more favourable. The curve thus bends backwards. For a substantial cut in emissions, the policy option of energy savings is then used to only a limited extent at most. The explanation is that, when the non-fossil-fuel energy source has reached a substantial share in total energy supply, it has become sufficiently competitive to take over the role of the fossil-fuel energy source as the main contributor to total energy supply.[3]

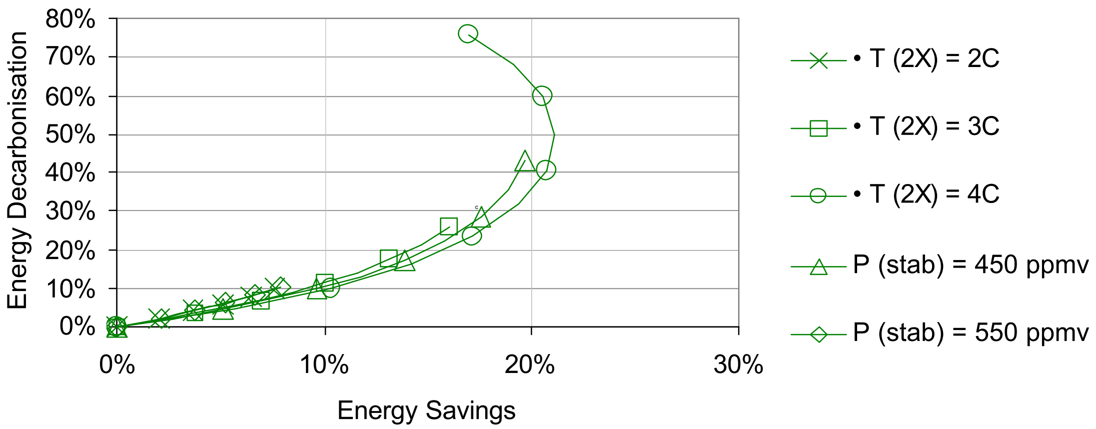


FIGURE 2. *Relative importance of energy savings and energy decarbonisation in total emissions reduction under different climate change parameters.*

Apart from showing the savings vs. decarbonisation dependence on the value adopted for the climate change sensitivity, we present a similar figure for the central climate change parameters, but now with different *economic* parameters. Figure 3 depicts four additional (2 C) scenarios in which the learning rate (LR) and energy substitutability (• ) are changed to other-than-central values, to demonstrate the impact of certain important parameter modifications. It can be seen from Figure 2 that if the non-fossil-fuel energy source has sufficient potential to replace the fossil-fuelled one, that is, if the learning rate is 30% or the substitution elasticity • has value 4, the transition to the non-fossil-fuel energy source is the main mechanism for emissions reduction, even in early periods. These cases correspond to the curves on the left-hand side of the graph. Alternatively, when the non-fossil-fuel energy source possesses no good capacity to replace fossil fuels, that is, when we assume a low learning rate,

[3] The value of the relative importance of energy savings in the total amount of emissions reduction may fall below zero: a very successful transition to non-fossil-fuel energy permits an expansion of total future energy use.

LR=10%, or a low substitution elasticity, •=2, energy savings remain the most important window for emissions reduction in both the short and medium term.

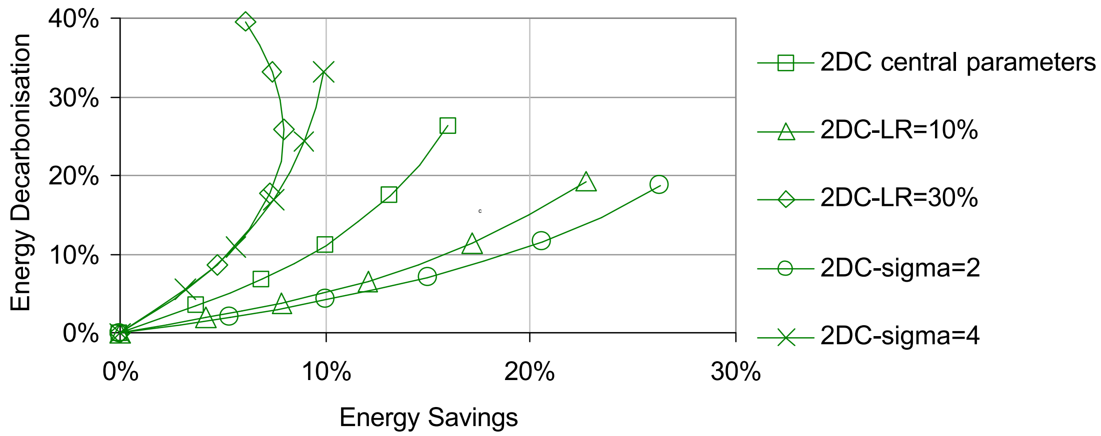


FIGURE 3. *Relative importance of energy savings and energy decarbonisation in total emissions reduction under different economic parameters.*

Nonetheless, in the long-term, the transition to the non-carbon energy source remains the dominant strategy. Figure 4 shows the share of the non-fossil-fuel energy source in total energy supply for 2 C temperature-constrained scenarios. While in the short term the transition to (and thus the share in total supply of) non-fossil energy remains sensitive to economic parameter values, in the longer run the transition becomes the predominant method to reach climate objectives, and becomes almost insensitive to choices for the values of parameters LR and •. For the central parameter choice, the non-fossil share increases by nearly 1% per year, to a share of about 95% in 2100. This finding portrays a substantial acceleration in the transition of the energy system to non-fossil-fuel energy sources in comparison to the BAU reference scenario (not plotted in the figure). In the BAU scenario, under central parameter values, the share of the non-fossil-fuel energy source increases from 4% in 2000 to 33% in 2100.

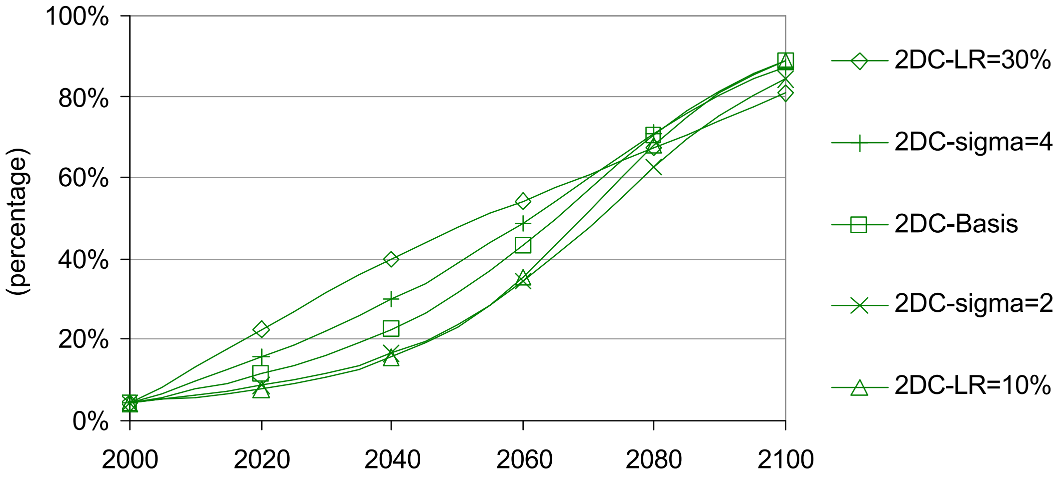


FIGURE 4. *Fraction of energy supply produced by the carbon-free technology.*

We end by turning to the main subject of this paper, the effect of assuming different climate sensitivities on long-term temperature-constrained energy supply scenarios, in particular the impact on the timing of required emission reductions. In particular, we want to confirm the acclaimed necessity of realising early carbon emission reductions. For this purpose, we need a more precise meaning of emissions abatement timing that constitutes a common measure of timing applicable to scenarios defined by different parameter values and/or climate constraints. We define the emissions reduction effort in period $t$ under a climate-constrained (e.g. 2 C) scenario as the amount of emissions reduced relative to the emissions level in the BAU scenario. The timing of abatement can be presented as the development over time of the emissions reduction effort, relative to this same effort in 2050, formally calculated by:

$$\frac{(Em_t^{BAU} - Em_t^{2C})}{Em_t^{BAU}} \Bigg/ \frac{(Em_{2050}^{BAU} - Em_{2050}^{2C})}{Em_{2050}^{BAU}}, \qquad (5)$$

where $Em_t^{BAU}$ are emissions in the BAU scenario, and $Em_t^{2C}$ are emissions in the 2 C scenario (the subscripts $t$ and 2050 indicating the particular moments in time under consideration). The results are presented in Figure 5 for scenarios with the three earlier different climate sensitivity values (with a 2 C temperature constraint) and the two carbon concentration constraint values. The figure shows that the emissions reduction effort is almost linearly increasing in time, and is almost unaffected by either changes in the climate sensitivity assumed or the $CO_2$ concentration constraint imposed. This is a remarkable finding, first of all because the calculated emission paths vary widely among different climate sensitivities and targets, as we have seen in Figure 1. Furthermore, due to the vintage structure of DEMETER, emission intensities are fixed for old vintages.

Thus, the linear path of the emissions reduction effort has to be reached through a substantial cut in the emission intensity of new vintages. We hence observe that although the overall emissions reduction effort (obviously) depends strongly on both the climate sensitivity and objective, the timing of the effort is almost independent of either this sensitivity or policy target.

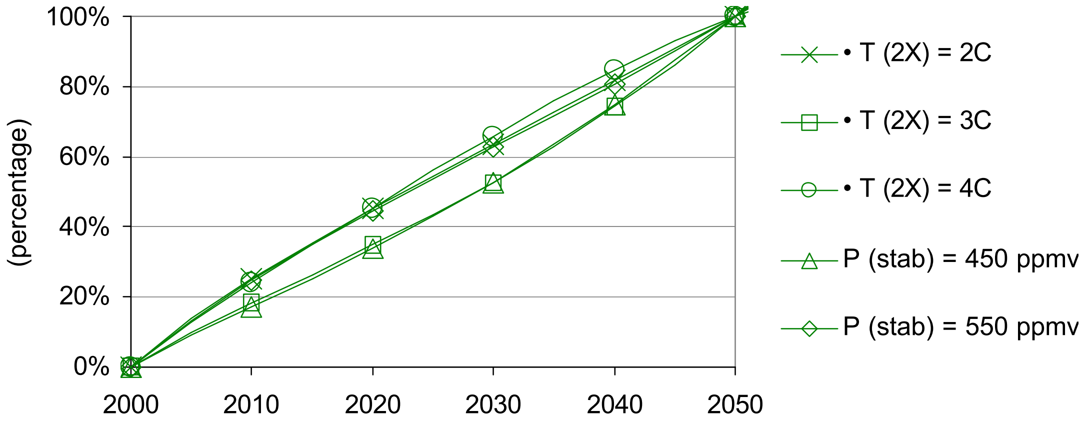


FIGURE 5. *Timing of emission reduction efforts.*

**4. Conclusions**

In this paper we have, first of all, provided further evidence of the claim brought forward in one of our recent publications (Gerlagh and van der Zwaan, 2004) that by playing around with the values of some of the parameters used in climate change models one loses significance in the findings derived from them. In particular, in the analysis presented in this paper we have done so regarding the climate sensitivity parameter. We have demonstrated that whether one assumes 2, 3 or 4 C temperature increase per doubling of the atmospheric carbon dioxide concentration matters a lot for the calculated emission path during the 21$^{st}$ century. Meanwhile, however, we have pointed out that irrespective of the climate sensitivity assumed, many results continue to hold. Regarding carbon emissions we have seen that substantial reductions are called for, under whatever climate sensitivity, and that, sooner or later, the emission path should be pushed downwards in order to reach climate change objectives. Indeed, the overall obliged energy transformation that follows from our model continues to hold, even under large variations of the value of the sensitivity parameter: by the end of the century the vast majority of energy production should be non-fossil based.

We have seen that the emission reductions that ought to be reached in 2020 are strongly dependent on the value of the climate sensitivity, as is the non-fossil share in total energy supply realised in that year. The extent to which energy savings are used to meet reasonable climate requirements, however, depends little on this sensitivity: by

2020 around half of emission reductions should be attained through savings. We have paid particular attention to compare our results with those of Caldeira *et al.* (2003). A number of numerical differences appeared to exist between their and our analysis results, but most of these were more or less explainable, or merely resulted from the difference in nature between the respective models used. Most importantly, we have confirmed one of their main conclusions. As stated by the IPCC, the temperature increase resulting from a doubling in carbon dioxide concentration is probably known only to about a factor of three. This uncertainty propagates from climate stabilisation objectives, to allowable carbon concentrations and emissions, and finally to non-fossil based energy production. Uncertainties in our understanding of climate sensitivity introduces the largest possible uncertainties in allowable $CO_2$ emission paths, as can be seen from Figure 1. It is thus not surprising that these uncertainties exceed those induced by the uncertainty with which we understand the complexity of the carbon cycle (Caldeira *et al.*, 2003). But, and this is the central thrust of our research, even if climate sensitivity is at the low end of the currently accepted range (or other modelling parameters are chosen such so as to obtain the most optimistic climate results possible), by the end of the century over three-quarters of mankind's total energy supply will need to come from sources that do not emit $CO_2$ in the terrestrial atmosphere.

The results reported here have been obtained with the integrated assessment climate model DEMETER, which includes two energy sources and learning-by-doing for both of these (fossil and non-fossil) energy sources. This top-down model allows us to study the two main options for achieving substantial reductions in carbon dioxide emissions. The first is the energy savings option, in which the substitution of capital and labour for energy is allowed for. The second is the energy transformation option, in which emission reductions can be achieved through a transition from a carbon energy technology towards a carbon-free technology. The first option turns out to be of most importance in the short run, whereas the second option is needed to reach substantial emission reductions in the long run. The finding that the transformation from carbon to non-carbon energy technologies starts to play a major role only after a few decades should not create the impression that little action is called for today. On the contrary, the emission paths determined by DEMETER clearly show that in order to stabilize climate change at an increase of the atmospheric temperature of 2 C, substantial emission reductions are also called for in the short and medium term.

This analysis has also shown that the main results regarding the required global energy transformation are robust against changes in the values of even the most sensitive economic and technological parameters. The numerical results on the role of energy savings and the carbon-free technology appear most sensitive to the learning rate of the non-fossil-fuel energy source, on the one hand, and the substitution possibilities between this energy source and the fossil-fuelled technology, on the other hand. The sensitivity of our results to the learning rate is understandable, since this rate determines the intensity of the mechanism that promotes accelerated price decreases. The learning rate contributes to determining the speed with which the transition towards a large-scale use of non-fossil-fuel energy – and thus the reduction of carbon emission – takes place. It is not surprising either that our findings are sensitive to the value of elasticity •, describing the substitution potential between the two energy sources. Increasing the value of this substitution elasticity increases the potential of a transition policy and reduces the role played by energy savings. The levels of carbon taxes and subsidies for the non-fossil-fuel energy source, required to reach the temperature change stabilisation objective, were reported on in earlier publications (see e.g. van der Zwaan *et al.* 2002): they remain relatively independent of the value of these two parameters. We also spent time analysing the important policy-relevant subject of emissions reduction timing, for which we defined a common emission abatement timing measure. We conclude that although the overall emission reduction effort depends strongly on the climate sensitivity assumed, the timing of the effort is almost independent of this sensitivity.

With our findings, we have further backed the acclaimed importance of non-carbon energy resources gradually taking over, during the 21$^{st}$ century, currently cheaply available conventional fossil fuels. Not only for the sciences occupied with solving the global warming problem, but also for those engaged in apprehending how to establish sustainable development at large (including, for example, the problem of how to preserve global biodiversity; see van der Zwaan and Petersen, 2003), providing an understanding of how to materialise such a transition is fundamental. This paper points out once again – like done by many other studies – the need for mankind to make a substantial transition, over the decades to come, from fossil to non-fossil energy use.

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(lix) This paper was presented at the ENGIME Workshop on “Mapping Diversity”, Leuven, May 16-17, 2002
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(lxii) This paper was presented at the ENGIME Workshop on “Communication across Cultures in Multicultural Cities”, The Hague, November 7-8, 2002
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(lxviii) This paper was presented at the ENGIME Workshop on “Governance and Policies in Multicultural Cities”, Rome, June 5-6, 2003
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