Technology Options for Low Stabilization Pathways with MERGE

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This paper investigates long-term transitions of the global energy system compatible with realizing low stabilization climate targets, using an enhanced MERGE model. The results indicate that stringent mitigation targets can be met under many technology scenarios, but major technological change is needed, highlighting important roles for R&D and learning-by-doing. The analysis explores the impact of limiting the set of available technology options (to account for technical uncertainties and issues of public acceptance) and identifies important influences on energy system development and economic costs under low stabilization. Biomass availability is seen to have a major influence on the characteristics of the energy system. Carbon capture and storage technologies also prove to be potentially critical for both electricity and fuel synthesis, particularly when combined with biomass to produce net negative emissions. Additionally, the availability of fast breeders provides a competitive zero-emissions option. Energy efficiency and large-scale application of renewables are also critical to realising low stabilization scenarios.

1. INTRODUCTION

New technologies and technological change are expected to play a key role in long-term transitions of the global energy supply. This is particularly the case for the realization of climate change mitigation targets that stabilize atmospheric carbon dioxide (CO_2) concentrations at levels that avoid a greater than 2°C increase in average global temperatures above pre-industrial levels. However, questions remain as to whether existing and prospective energy technologies are sufficient to achieve such low stabilization goals (or if we are likely to require some new unexpected technology breakthroughs), and which technology options are most suited to low stabilization.

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Technology options often cited as important for substantial reductions in greenhouse gas (GHG) emissions from the energy sector include renewables, carbon capture and storage (CCS) (with advanced fossil generation), nuclear power, and biomass and biofuels. However, many of these technologies face a number of uncertainties that may limit or preclude their contribution over the long term to the global energy system. For example, competition over limited arable land may restrict the use of biofuels, whereas the public acceptability of nuclear power may limit large-scale expansion of this technology option. Similarly, unanticipated technical constraints and less optimistic assessments of suitable geological storage sites may undermine the long-term role of CCS in mitigation. On the other hand, the process of technological change could substantially change the economic and technical performance of new technologies over the long term.

One key question then is: how important are these different technology options and the process of technological change for achieving low stabilization targets? Which leads to the more specific question: if technical, political or resource constraints preclude or limit the use of a particular option, can low stabilization still be achieved and at what economic cost? This paper seeks to answer these questions and identify key technology options for low stabilization through the application of an enhanced version of the long-term energy economic and climate model, MERGE (Manne and Richels, 2004a). This enhanced version of MERGE (called MERGE-ETL) features a more detailed representation of technology dynamics and spillover effects across key technology components.

In the last decade, the role of endogenous technological improvement has been recognized as a key driver for achieving deep climate change mitigation efforts at affordable cost, and many efforts have been made to represent learning phenomena in detailed energy system models (see Barreto and Kypreos, 2004, Energy Journal Special Issue, 2006, IPCC, 2007). Endogenous technological change can either be implemented in the form of Learning-by-Doing (LbD) or Learning-by-Searching (LbS), reflecting either accumulated experience of using a technology or accounting for the effect of dedicated research and development (R&D) expenditure aimed at bringing the future costs down. These forms of learning can be represented in so-called learning curves. Single-factor learning curves representing only LbD generally overstate the importance of this form of learning (see McDonald and Schrattenholzer, 2001, Klassen et al., 2005, and Jamasb, 2007 for single-factor learning curves estimates). Two factor learning curves, first introduced in Kouvaritakis et al. (2000), account more explicitly for cost reductions achieved through the various stages of technology development both via LbD and via LbS.[1] Incorporating two-factor learning curves in energy system models as well as a more detailed representation of future technology availabilities provides a richer understanding of possible options for investment in

1. Gerlagh *et al.* (2007) consider learning-by-doing and learning-by-searching as substitutable instead of complementary activities, thus omitting the inter-temporal specificities of the various stages in technology development. This contradicts Jamasb (2007) who found that there is little evidence of substitution between these two effects, which should rather be seen as independent.

carbon-free technologies, thereby supporting policy efforts aimed at addressing climate change. Endogenous R&D dedicated to specific technologies has been little used in integrated assessment models so far. Kypreos (2007) and Bosetti et al. (2007) are exceptions.

In MERGE-ETL, technical progress in the energy sector occurs as an endogenous process, represented by two-factor learning curves describing how specific investment costs are reduced through both experience accumulation and dedicated R&D investments. In addition, this version of MERGE incorporates a clusters approach to learning, accounting for interactions between different technological options.

The model is described in more detail in Section 2. In Section 3, we explore a series of increasingly stringent stabilization scenarios consistent with an atmospheric CO_2-equivalent concentration of 550, 450 and 400 ppm[2] and their implications for energy technology deployment. These scenarios represent an increasing probability of avoiding a temperature increase of more than 2°C, from around 20% up to around 80%, respectively (Meinshausen et al., 2006). This section also analyses the importance of investment in new technology options for low stabilization. Section 4 investigates the importance of different technological options for the most stringent scenario (400ppm) through a sensitivity analysis of key assumptions regarding the availability of different technologies, resources, or rates of technical progress. Insights for mitigation policy and technology support are discussed in Section 5.

2. THE MERGE MODEL

2.1 Overview and Enhancements

The Model for Evaluating Regional and Global Effects (MERGE) is an integrated assessment model that provides a framework for assessing climate-change management proposals. We apply a modified version of MERGE5 described by Kypreos and Bahn (2003) and Manne and Richels (2004a,b). Key features of MERGE include: (1) a nine-region global disaggregation; (2) a combined ‘top-down’ Ramsey-type economic and ‘bottom-up’ engineering modeling approach; (3) a damage function and a simple climate model; and (4) international trade in oil, gas, coal, uranium, biomass, carbon permits, an energy intensive good, and a numeraire good representing aggregate trade of other products. Regional technological learning with global spillovers, climate-change impacts and the associated damages[3] further enhance the regional links and interactions.

Energy technologies have been explicitly introduced in this expanded version of MERGE-ETL. Electricity can be supplied using gas, coal, biomass and nuclear plants (both conventional and advanced designs), or renewable energy, i.e.

2. parts per million volume
3. Importantly, in this analysis we do not consider impacts of climate change.

carbon-free non-exhaustible energy, namely hydropower, wind farms and solar photovoltaic devices. Carbon capture and storage (CCS) systems are available for natural gas combined cycle (NGCC), pulverized coal (PC), and integrated gasification (coal or biomass) combined cycle (IGCC). Non-electric energy can be supplied directly from fossil fuels (e.g. mainly via heat processes in the industrial and residential sectors, or in transport) or in producing some energy carriers or secondary fuels such as synthetic fuels (Fischer-Tropsch [FT] liquids) and hydrogen. Technologies for synthetic fuel production from either coal or biomass are included. Hydrogen may be produced by coal, natural gas, biomass, nuclear power or solar thermal plants (via sulfur-iodine thermochemical water-splitting). CCS options are also available for some non-electric technologies, including FT liquids from coal and biomass and hydrogen production.

Furthermore, to better model options for electricity and hydrogen production from nuclear power in MERGE, we incorporated a simple nuclear fuel cycle global submodel. This accounts for the constraints inherent to the management of fissile material stocks, as described in Chakravorty et al. (2007). Thus, a once-through nuclear fuel cycle is considered when the model is run with a light-water reactor (LWR) technology only. Full closed nuclear fuel cycle is considered when fast-breeder reactor (FBR) technology and the recycling of all nuclear materials are allowed. Note here that since uranium ore is the only fissile commodity which is traded, nuclear expansion is constrained by the capacity of each region to manage its own build-up of stockpiled plutonium, in addition to its initial endowment of other fissile material.

2.2 Learning in Energy Technology

Previous versions of MERGE-ETL were based on a constant exogenous levelized cost of energy, except for two selected and generic learning technologies. We further break down the cost of the various energy technologies into different components: fuel costs; operation and maintenance costs; and investment costs. This disaggregation allows for the reduction of the total or some fraction of the investment cost as a result of endogenous learning (See Barreto and Kypreos, 2004 and Kypreos, 2005a,b, for an explorative study with MERGE-ETL). We apply two-factor learning curves for the investment costs of all technologies.

Technological learning describes how the specific cost of a given technology is reduced through the accumulation of knowledge. This learning process evolves either from manufacturing and operation of the technology (LbD) or research and development (LbS) expenditures allocated to that technology. A learning curve relates the specific investment cost (or part thereof) of a given technology to the two factors – experience and R&D expenditures – describing the accumulation of knowledge in that technology. This two-factor learning process can be written as:

$$INVC_{k,t} = a \cdot CP_{k,t}^{-b} \cdot \mathrm{KS}_{\mathrm{k,t}}^{\mathrm{-c}} \tag{1}$$

where $INVC_{k,t}$ denotes the specific investment cost of technology *k* at time t due to LbD and LbS, $CP_{k,t}$ denotes the cumulative production of technology *k* at time *t*, and $KS_{k,t}$ the knowledge stock specific to technology *k* at time *t*. For the sake of simplicity and due to a lack of precise estimate on the decay of knowledge accumulation for each technology, we assume that the rate of depreciation of knowledge stocks is nil. The coefficient *a* represents the investment cost at unit cumulative capacity and knowledge stock, while *b* and *c* represent the learning indices which are calculated from the learning rate (see below).

Moreover, following the paradigm of technology clusters described in Seebregts et al. (2000), we assume that development and adoption of technologies occur as a collective evolutionary process (which represents a further enhancement to previous versions of MERGE-ETL). This approach is based on the observation that a number of "key components" are often used across different technologies. Thus, experience with one technology may benefit other technologies if they share the same key component that is affected by learning processes. Table 1 depicts the relationship between key components and technologies assumed in this version of MERGE-ETL. Examples of key components here include the gasifier system, gas turbines and several carbon capture devices. For each of these learning components, a barrier or floor cost is introduced as a limit to the maximum possible reduction in investment cost.

Thus, the investment cost $INVC_{k,t}$ of technology *k* is now a function of its specific knowledge stock and of the cumulative production of the key component, rather than the technology itself.

As a first approximation, and due to a lack of empirical estimates of the two factor learning curve parameters.[4] we have chosen to classify the key components into two categories: mature (i.e. gasifier, gas turbine, nuclear fast breeder and wind) and speculative technologies (others). Both learning rates (for LbD and LbS) are set at 5% and 10% each for the mature and speculative key components respectively.[5] These learning rates are consistent with the range reported in the literature (see McDonald and Schrattenholzer, 2001), but it is important to appreciate that there are uncertainties about possible learning rates for speculative technologies. Alternative learning rates are analyzed in the sensitivity analysis section.

4 Jamasb (2007) is an exception as he provides estimates for the learning rates of a variety of technologies in a comprehensive and harmonized way. Nonetheless, Jamasb reports statistically significant estimates for mature technologies contrary to more speculative technologies, for which learning rates estimation reveals less reliable due to insufficient quality of dataset. We thus chose not to use those estimates.

5. Corresponding to a learning index (*b* or *c* in Eq. (1)) of 0.074 and 0.15.

Table 1. Relationship Between Key Components and Energy Technologies in MERGE-ETL

							Carbon capture				New nuclear			Solar	
		Gasifier	Gas turbine	Biomass balance -of-plant	Coal balance -of-plant	Advanced coal	Pre combustion	Post combustion	H2 production	Stationary fuel cell	Power production	H2 production	Wind	PV Power	Thermal H2 prod
Electric	oil-r														
	gas-r		*												
	ngcc		*												
	ngcc-ccs		*					*							
	gas-fc									*					
	coal-r														
	pc					*									
	pc-ccs					*		*							
	igcc	*			*										
	igcc-ccs	*			*		*								
	nuc														
	nuc-a										*				
	hydro														
	bio-a	*		*			*								
	wnd												*		
	spv													*	
Non Electric	oil														
	gas														
	coal														
	coal-FT	*			*										
	bio-FT	*		*											
	gas-H2														
	gas-ccs-H2								*						
	coal-H2	*													
	coal-ccs-H	*							*						
	bio-H2	*		*											
	nuc-H2											*			
	sth-H2														*

Electric	oil-r	Remaining initial oil fired
	gas-r	Remaining initial gas fired
	ngcc	Natural Gas Combined Cycle
	ngcc-ccs	Natural Gas Combined Cycle - CCS
	gas-fc	Gas fuel cell
	coal-r	Remaining initial coal fired
	pc	Pulverized coal (Supercritical)
	pc-ccs	Pulverized coal (Supercritical) - CCS
	igcc	Integrated gasification combined cycle
	igcc-ccs	Integrated Gasification Combined Cycle - CCS
	nuc	Remaining initial nuclear
	nuc-a	Generic new nuclear
	hydro	Hydroelectric
	bio-a	Biomass - CCS
	wnd	Wind
	spv	Solar photovoltaics
Non Electric	oil	Oil direct use
	gas	Gas direct use
	coal	Coal direct use
	coal-FT	Coal to synthetic fuel (Fischer-Tropsch)
	bio-FT	Biomass to synthetic fuel (Fischer-Tropsch)
	gas-H2	Gas to H2
	gas-ccs-H2	Gas to H2 - CCS
	coal-H2	Coal to H2
	coal-ccs-H2	Coal to H2 - CCS
	bio-H2	Biomass to H2
	nuc-H2	Nuclear to H2
	sth-H2	Solar thermal to H2

2.3 Scenario Assumptions and Data

The scenarios analyzed in this paper are based on revised regional gross domestic product (GDP) and population projections derived from TIMER (Van Vuuren et al., this issue) and follow roughly an IPCC B2 scenario storyline (IPCC, 2000). Input data for energy technologies mostly comes from the recent developments of GMM (Global Markal Model) at the Paul Scherrer Institute and others (see Rafaj, 2005, Yamashita and Barreto, 2004, 2005, IEA 2006, and Sims et al., 2003 for carbon emission coefficients data). Production costs for these technologies in the base year (2000) are presented in Figure 1.[6] Other information on data input and assumptions can be found in Manne and Richels (2004a).

Energy consumption for the base year has been recalibrated according to IEA statistics (2002). Oil and gas reserves and undiscovered resources include mean estimates of potential reserve growth and are split equally between ten resource cost categories, as in earlier versions of MERGE (and amount to 22 ZJ for oil and 21 ZJ for gas). Coal resources are now treated similarly, and differentiated by four grades, distinguishing the size and the cost of access for each regional deposit. Regional coal reserve and resource availabilities are based on Rogner (1997) and coal trade is based on US DOE (2004) (see Table 2).

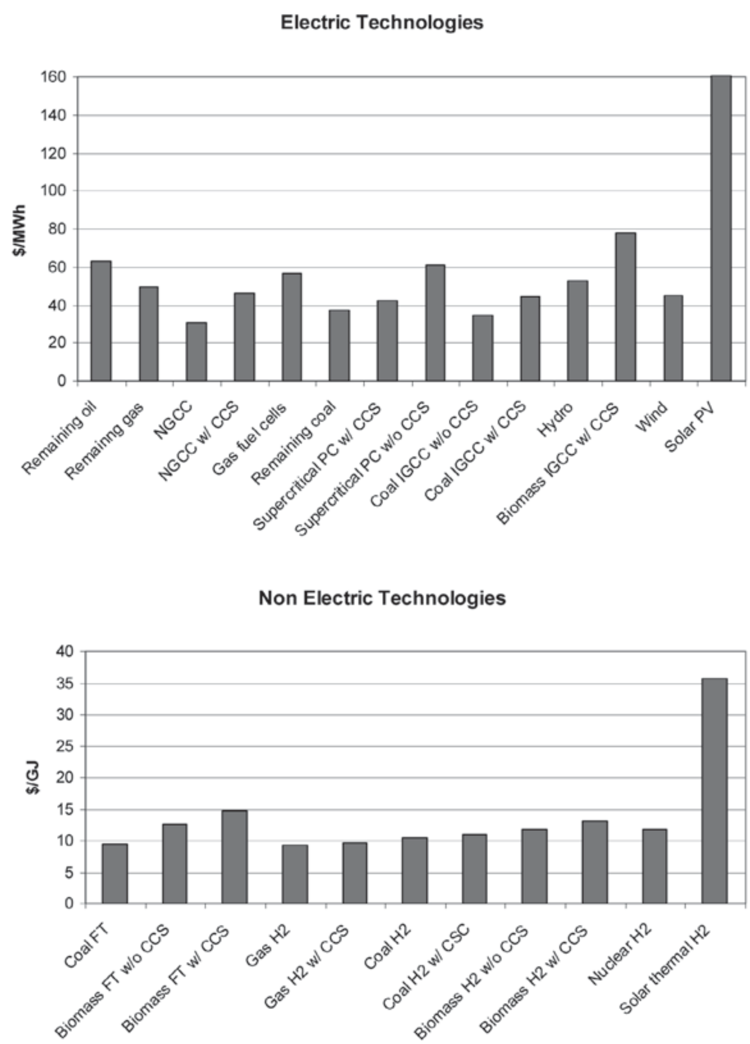
Regional estimates for uranium ore availabilities, depleted uranium stockpiles and plutonium inventories are based respectively on WEC (2004), IAEA (2001) and Albright and Kramer (2004), and are roughly consistent with more recent conventional resource estimates in IAEA (2008).

Table 2. Summary of Coal, Uranium and Biomass Availabilities (EJ) and Average Costs ($/GJ)

	Reserves	Resource categories				Total
		I	II	III	IV	
Coal						
Resource availability	18,858	12,474	23,352	41,538	166,194	262,416
Extraction cost	1.87	1.87	2.33	3.27	5.13	
Uranium						
Resource availability	1,331	333	120	143	4,113	6,040
Extraction cost	0.05	0.05	0.14	0.24	0.31	
Biomass						
Potential in 2000	-	27	8	11	2	48
Potential in 2100	-	109	30	46	10	195
Feedstock cost	0.05	2.00	4.00	7.00	10.00	

6. The existing stocks of energy conversion capacity in the base year are represented in MERGE and referred to in Figure 1 as 'Remaining …' (e.g., 'Remaining gas'), with new capacity able to installed up to a level limited by growth constraints that represent bottlenecks and inertia in the energy system.

Figure 1. Production Costs of Electricity Generation (Upper Panel) and Non-electric Energy Carriers (Lower Panel) in the Base Year (2000), Without the Impact of Technology Learning



Biomass supply curves are introduced in a similar fashion to exhaustible fossil resources. Supply curves for each biomass feedstock, namely wood residues, soybean, corn grains, sugar cane, stover and domestic wastes, are aggregated to form regional biomass supply curves, broken down into four cost categories. Biomass feedstock availabilities and production costs are compiled from Aden et al. (2002), FAO (2006), Graham et al. (2000), Hamelinck et al. (2004), Hamelinck and Faaij (2006) and IEA (2005). We assume that the available fraction of the biomass potential increases linearly over time from around 50EJ in 2000 up to the full potential of 200 EJ by 2100. The survey from Berndes et al. (2003) reports similar values, in line with Azar et al. (2006). A few other studies such as Hoogwijk et al. (2003) report much higher potential ranges, well above 1000 EJ. The impact of higher or lower availability of biomass is analyzed in Section 4.

The explicit consideration of CCS technologies requires some finer description of the geological storage capacities. We consider regional CO_2 storage potentials in a similar way to the formulation of fossil resources. Carbon storage supply curves are introduced based on Hendriks et al. (2002) data.

Abatement cost data for non-CO_2 gases is updated in the current version of MERGE. Specifically, we adopt new exogenous trends on non-CO_2 GHGs and non-energy CO_2 emissions from TIMER (see van Vuuren et al., 2006), and rescale the abatement cost curves from US EPA (see Manne and Richels, 2004a) accordingly.

3. INTERMEDIATE, LOW AND VERY LOW CLIMATE STABILIZATION SCENARIOS

In order to illustrate the effects of implementing long run climate targets as well as the incentives for R&D spending in carbon-free energy technologies, we consider four mitigation scenarios: The first is a "Baseline" scenario, defining a business-as-usual outcome. The remaining scenarios examine the implications for achieving atmospheric GHG concentrations of 550ppm CO_2 equivalent (CO_2eq), 450ppm CO_2eq and 400ppm CO_2eq (referred to as the "550ppm", "450ppm" and "400ppm" scenarios). All scenarios thus include a multi-gas strategy. Contrary to usual practice in long-term scenario analysis, and instead of imposing a binding climate target at each date, we rather impose a constraint on the radiative forcing itself, a variable in the climate sub-module of MERGE-ETL, and therefore allow for overshooting the target in the mid-term.[7] By 2120, the radiative forcing is thus constrained to reach respectively 4.5 $W.m^{-2}$, 3.3 $W.m^{-2}$ and 2.5 $W.m^{-2}$ in the three scenarios.

In the "Baseline", electricity production increases from 15,000 TWh in 2000 up to more than 75,000 TWh by 2080 before leveling-off (See Figure 2). Existing fossil fuel-based thermal plants are progressively phased out and are replaced firstly by a combination of NGCC and IGCC plants, and then almost entirely by IGCC, owing to its low fuel cost and relatively high efficiency. Nuclear power remains competitive; its capacity increases until 2050 and diminishes thereafter as it ultimately faces the exhaustion of conventional uranium resources. The cost of wind power improves substantially thanks to quick learning. Wind

7. GHGs differ in their warming influence on the global climate system due to their different radiative properties and lifetimes in the atmosphere. These warming influences may be expressed through a common metric based on the radiative forcing of CO_2 (IPCC, 2007).

power complements the power supply up to its maximum potential, assumed to be 25% of overall electricity generation by region.

The imposition of a radiative forcing target encourages the large scale adoption of carbon-free power plants, in addition to reduced demand from a combination of improvements in efficiency and some reduction in economic output (discussed further below). Under a 550ppm target, coal IGCC, nuclear power and wind farms, together with biomass IGCC plants (equipped with CCS) to a lesser extent, play an important role in the mid-term, with coal IGCC with CCS and renewable options representing long-term options. Nuclear LWRs, biomass and CCS all face resource constraints in the form of exhaustion of conventional sources of uranium,[8] competition for biomass feedstocks (for the production of synthetic fuels), and limited suitable sequestration sites. Under a 450ppm target, clean coal (IGCC) technologies become significantly less competitive due to carbon penalty, although IGCC with CCS plays an intermediate role. By contrast, natural gas is more attractive early in the century, and maintains this position later with the adoption of CCS, with NGCC supplying around 15% of total electricity in the second half of the century. The 400ppm target exhibits a similar outcome. Figure 2 also shows how the increasing stringency of the target results in a larger reduction in demand, due partly to energy efficiency. It should, however, be noted that MERGE does not represent specific efficiency technologies.

Non-electric energy needs are almost exclusively covered with gas and oil until 2060 (see Figure 3). Later in the century, synthetic fuels obtained through coal liquefaction substitute for more expensive oil, with the peak in oil extraction occurring in 2040 and gas production around 30 years later. This fossil fuel-intensive scenario leads to substantial CO_2 emissions which in turn causes a rise in atmospheric concentration above 800ppm by 2100.

The imposition of a climate target reduces consumption of non-electric energy by 10% as compared with the Baseline in 2050. This is due to a lack of cheap substitutes for direct use of oil and gas in the mid-term. In the longer term, the synthetic fuels produced from coal in the Baseline are replaced partly with biomass-based fuels (predominantly hydrogen).[9] The synthesis of fuels from biomass is combined with CCS from 2040 onward, resulting in negative emissions from this source. Solar-thermal production of hydrogen also becomes competitive under stringent mitigation policies after significant investment and learning-by-doing. Solar-based hydrogen has some features of a ‘backstop’ technology, given that it faces no meaningful resource or capacity constraints, while remaining a very expensive technology in the mid term.[10]

8. Noting that fast breeder reactors are not available in these scenarios.

9. The 400ppm scenario also includes a small amount of hydrogen synthesis from nuclear, driven mainly by the need to rapidly decarbonize the non-electric sector to meet this very stringent target.

10. Consequently, in the long run, there is also less reduction in demand in the non-electric sector under the stringent climate targets.

Figure 2. Electricity Generation in the Baseline and the Stabilization Scenarios

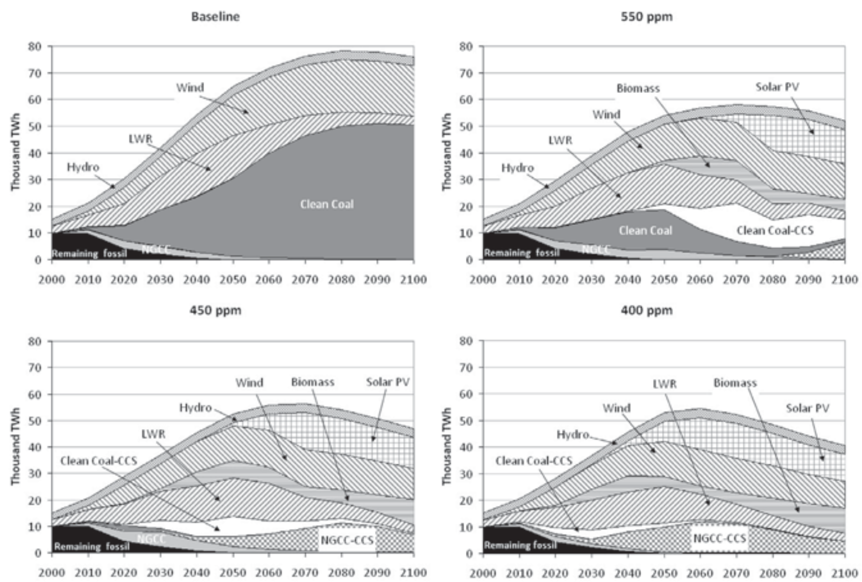


Figure 3. Non-Electric Energy Consumption in the Baseline and the Stabilization Scenarios

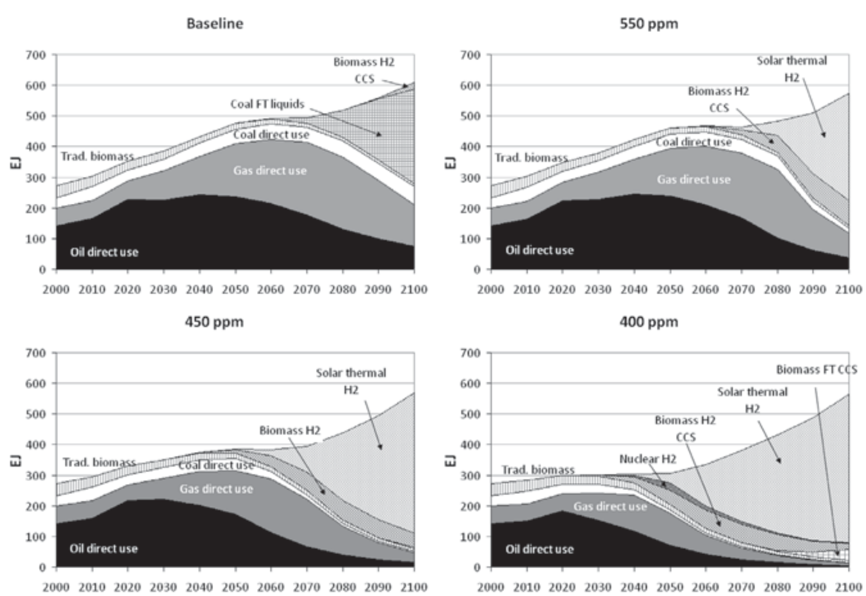
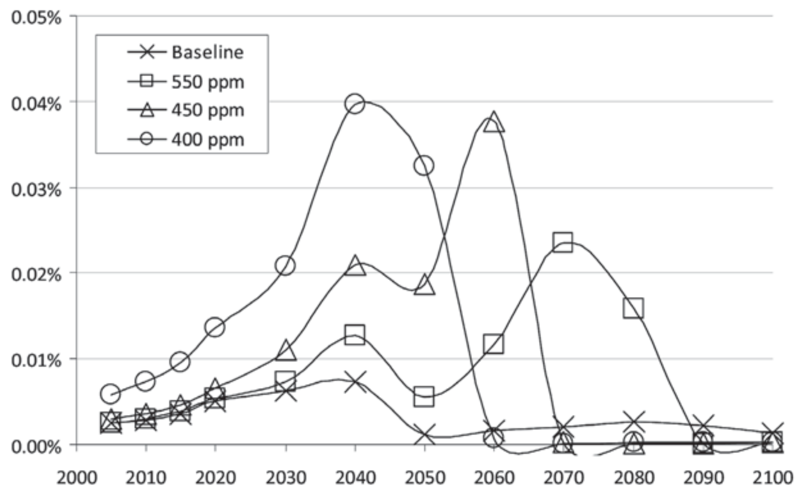


Figure 4. R&D Expenses as Fraction of GDP



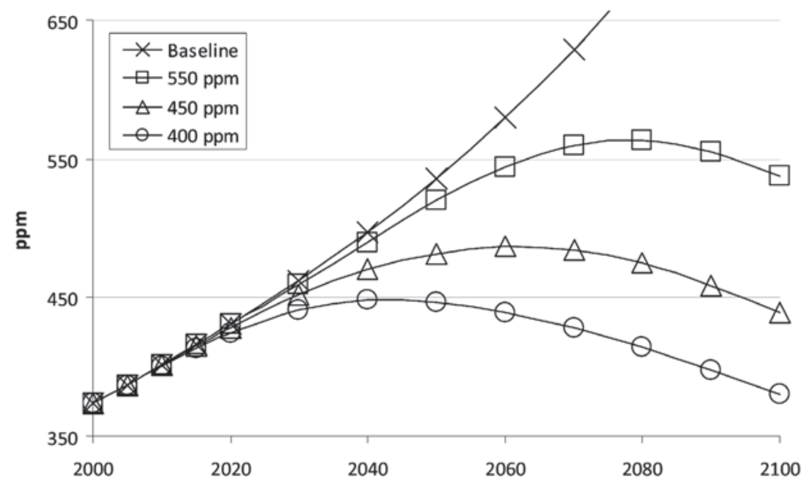
Importantly, realizing these stringent mitigation targets and ensuring this transition to new technology options involves significant technological learning and R&D efforts. Removing the option to invest in R&D in the model generates higher energy prices leading to higher costs and lower GDP and energy consumption. Figure 4 shows the allocation of financial resources to R&D investment to accelerate the development and bring down the cost of new and emerging technology options. The role of R&D remains limited in the baseline outcome given that there are fewer incentives for developing costly research efforts. In comparison, the share of GDP allocated to R&D investments varies considerably in alternative scenarios, although in the early part of the century only the 400ppm scenario deviates significantly from the baseline. In broad terms, the more stringent the mitigation target, the earlier R&D investment is needed and the greater the level, with all mitigation scenarios requiring a substantial increase in R&D above the levels in the baseline at different points over the century. The 400ppm target causes R&D funding as a share of GDP to increase by a factor of more than 4 by 2040 relative to the baseline, and also requires it to approximately double almost immediately. However, in the longer term, R&D budgets for the more stringent scenarios decline to levels below the baseline, once many of the learning options are exhausted.[11]

Next, we turn briefly to the levels of emissions. In the 550ppm case, CO_2 emissions depart notably from the baseline time-path in 2020 but keep on rising until 2050. Achieving more ambitious targets requires CO_2 emissions to peak

11. In reality, one would expect new technology options, e.g. options which are not described yet in our analysis, to emerge over the century, which would provide new targets for R&D spending.

much earlier, i.e. within a decade or so. A 450ppm target forces the emissions to fall to the year 2000 emission level in 2040, while this is needed as early as 2020 in the drastic 400ppm policy case. Moreover, with this stabilization target, emissions turn negative in 2060 thanks to the large-scale adoption of biomass-based technologies equipped with carbon capture in the power sector. In comparison, the 450ppm target results in negative emissions two decades later.

Figure 5. Atmospheric CO_2 Concentration



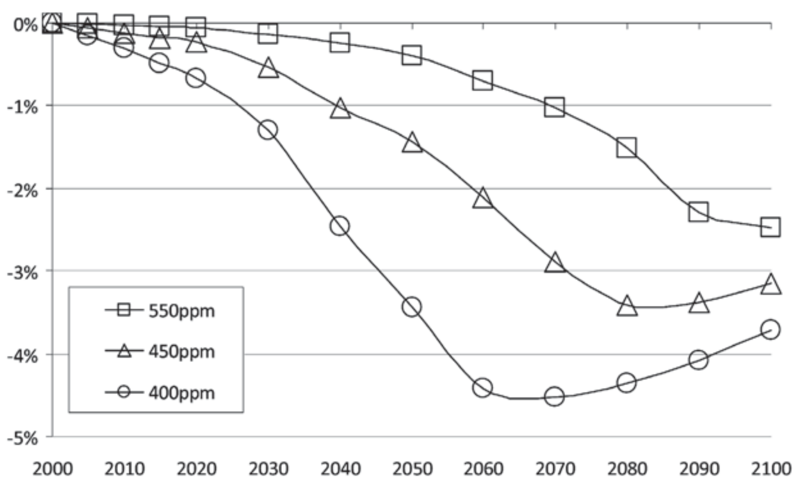
The atmospheric CO_2 concentrations corresponding to these emissions are presented in Figure 5. This illustrates the overshooting and subsequent decline in concentrations due to a large deployment of zero and negative emissions electricity generation and fuel production capacity. It should be noted that the additional options afforded through technological learning and R&D investments provide freedom to achieve the long term target even with a higher peak in concentration. We return to this in more detail in the context of the technology options analysis in Section 4, where we see that additional options provides the flexibility to delay costly abatement.

As discussed, the implementation of a stringent climate policy restricts the use of cheap but polluting energy, while simultaneously stimulating substantial R&D investment. The consequences for world GDP relative to the baseline are depicted in Figure 6. Although achieving the mitigation scenarios reduces GDP compared to the baseline scenario,[12] the induced technology development (including R&D, demonstration projects and early deployment) ultimately reduces the magnitude of these costs by making competitive technologies that

12. In all cases, it should be noted that the costs of avoided climate change and other externalities are not included in the estimated impacts on GDP.

are expensive today. A 550ppm target induces a less than one percent loss of GDP compared to the baseline by 2070. The GDP time-development in the 450ppm scenario starts diverging markedly from the 550ppm trajectory as early as 2040 and GDP losses are more than twice those in the 550ppm case by 2070. Kypreos (2007) reported lower mitigation costs related to less severe targets expressed in CO_2-only terms. The most stringent 400ppm target necessitates a very large reduction in energy consumption which translates into relatively high welfare costs. GDP is around 4% lower than the baseline by the middle of the century.

Figure 6. Change in GDP Relative to the Baseline



4. SENSITIVITY OF TECHNOLOGY OPTIONS FOR VERY LOW STABILIZATION

In this section, we present a sensitivity analysis of our results exploring alternative assumptions with respect to various characteristics concerning key technology options, including biomass, CCS, nuclear and renewable technologies. We conduct this sensitivity analysis on the 400ppm case, and therefore use the "standard" 400ppm scenario presented in Section 3 as a benchmark.

We turn first to the question biomass availability for energy production, where there is a wide range of resource estimates and uncertainty (e.g., see Hoogwijk et al. 2003; Van Vuuren et al., 2010, this issue), and concern about competition with food and fibre production and environmental protection.[13] To analyze this issue, we assume alternative biomass potentials and compare those

13. In addition, the extent to which biomass can be produced on a large scale in a sustainable manner is also a concern. For instance, N2O emissions from fertilizer application in biomass production may offset many of the sequestration benefits (see elsewhere in this Special Issue).

runs to our "central" 400ppm scenario, which features a global 200 EJ potential by 2100. Specifically, we consider cases with a 100 EJ and a 400 EJ potential by 2100, in which all regional potentials are either halved or doubled across the time horizon. We refer to those runs as "400ppm – Biomass 100EJ" and "400ppm – Biomass 400EJ".

Second, we investigate how the potential of geological reservoirs suited to underground CO_2 storage can be a limiting factor on the deployment of CCS technologies. As seen in Section 3, CCS represents an important technology for low stabilization. However, there remains significant uncertainty about the effectiveness and acceptability of this technology, including the long-term suitability of many potential storage sites. To explore this, we have constructed three additional scenarios: a case called "400ppm – low CCS" which assumes half of the potential in the central 400ppm case; a "400ppm – high CCS" case assuming twice this potential; and a "400ppm – no CCS" case which assumes CCS technology is not available.

Thirdly, we focus on nuclear power, where significant uncertainty exists about long-term public acceptability versus an optimistic attitude towards nuclear energy trying to extend the resource availability, safety and economics of Light Water Reactors with the introduction of generation IV systems. We study the implications of a global nuclear phase-out, called "400ppm – Nuclear phase-out" in which no new installations of nuclear are allowed, and a case where the availability of fast breeder reactors is assumed, called "400ppm – FBR".

The final case examines the impact of faster technological improvement in wind and solar technologies, assuming a doubling of learning rates for those technologies (case "400ppm – high LR").[14]

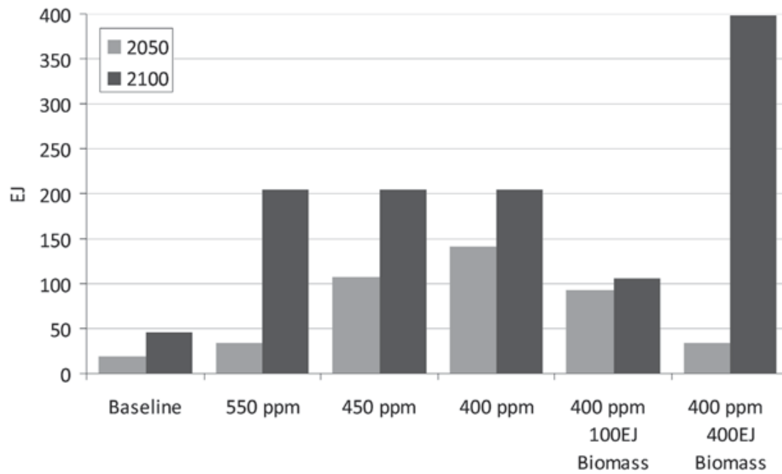
4.1 Biomass

Biomass technologies play a key role in supplying power and producing hydrogen for non-electric purposes in all of our cases, including "400ppm – Biomass 100EJ" and "400ppm – Biomass 400EJ" (see Figure 7). Importantly, however, the timing and the scale of biomass use differs across cases. Of particular note is that the prospect of limited biomass availability in the long-run increases the incentive to invest early in the development of biomass technology (via both R&D and early deployment leading to learning-by-doing). This makes biomass-based power and fuel production technologies competitive sooner than in the central 400ppm case. In fact, the full potential is already exploited by 2050. This early deployment is needed because the lower biomass potential means there are fewer options for realizing negative emissions later in the century. Consequently, earlier action is also needed with other zero-emissions technologies, and the reduced biomass availability is largely offset by other more expensive renewable sources (see Figure 8). It should be recalled that biomass use was coupled with

14. Specifically, the learning rate for wind is increased from 5% to 10%, and for solar PV and thermal technologies from 10% to 20%.

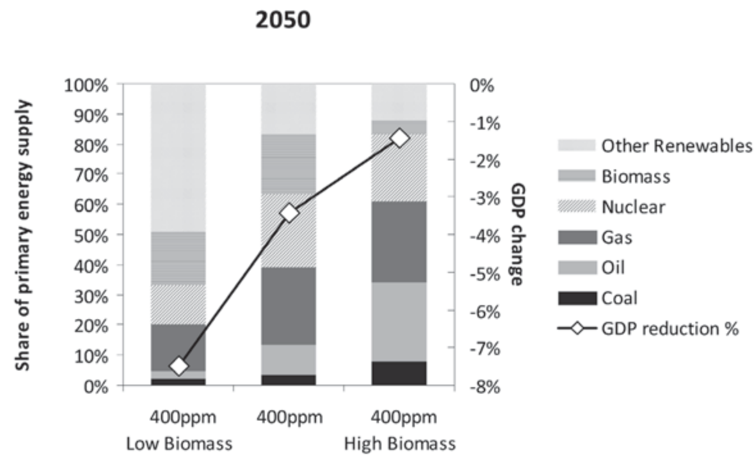
CCS in the scenarios described in Section 4, and similar options apply in this sensitivity analysis.

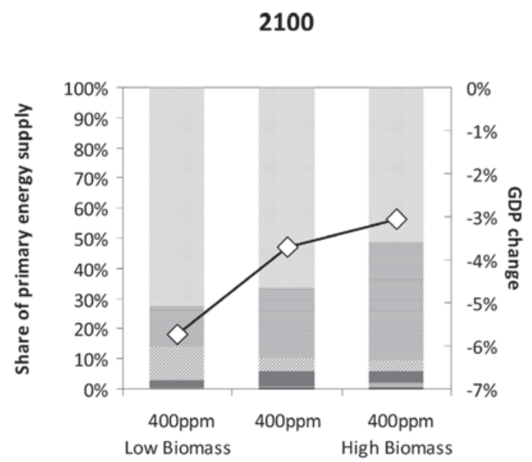
Figure 7. Biomass Consumption in Various Scenarios



In comparison, in the alternative case of abundant biomass supply ("400ppm – Biomass 400EJ"), only a small fraction of biomass potential is used by 2050. However, later in the century the full 400 EJ of potential is used, with biomass accounting for almost a third of primary energy by 2100 (Figure 7). This higher biomass potential provides the flexibility to delay abatement action and reduces the need for expensive renewables, leading also to lower GDP losses (Figure 8), which are half those under the "400ppm – Biomass 100EJ". It is worth noting that these lower GDP losses coincide with a lower demand reduction—i.e., the availability of larger biomass resources avoids the need to undertake more costly demand reductions (including efficiency).

Figure 8. Shares in Primary Energy Mix for Various Biomass Scenarios and GDP Losses Relative to Baseline

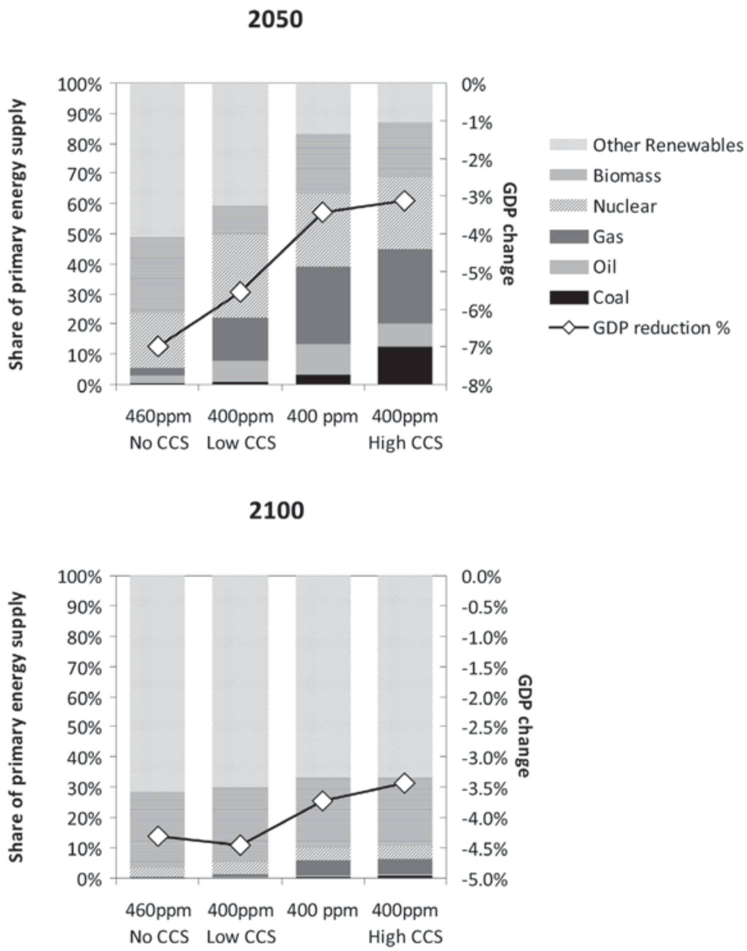




4.2 Carbon Capture and Storage

CCS was observed to be key technology for the range of mitigation scenarios in Section 3. If this option is not available (for reasons that may be technical, geological or political), as in the "400ppm - No CCS" case, achieving an atmospheric target of 400ppmv CO_2eq is not possible with the modeling assumptions used here. The most stringent forcing target that can be met is 3.2Wm-2 by 2120 (corresponding roughly to a long-term stabilization of 460ppmv CO_2eq). Even this target leads to high 7% GDP losses compared to the Baseline, as a result of the requirement to rapidly adopt wind and solar technologies (PV

Figure 9. Shares in Primary Energy Mix for Various CCS Scenarios and GDP Losses Relative to Baseline



(The "400ppm - No CCS" case only achieves a long-term stabilization of 460ppmv)

and thermal), which require massive R&D and demonstration project investments to bring their cost down.

With a low CCS potential (around 720 Gt CO_2), the introduction of fossil plants with CCS is severely restricted. More efficient gas plants (including NGCC and fuel cells) without CCS and nuclear plants supply the bulk of the increase in power generation until the middle of the century. Geological storage of CO_2 is put into operation on a large scale in the second half of the century as biomass plants take over the power sector, when the climate constraint is the most rigorous. Compared to the central CCS case, doubling the CO_2 storage potential (to almost 3000 Gt CO_2) leads to little change in the primary energy mix and alleviates GDP losses only marginally (see Figure 9). In the "400ppm-high CCS" scenario, coal-based power plants with CCS complement the power generation mix, accounting for up to 20% of electricity needs in 2040. Despite the higher availability of storage sites, such fossil-fuel plants are still phased-out because they still emit some CO_2 to the atmosphere, and are replaced with biomass generation with CCS.

In sum, a large storage potential for CO_2 is a key factor for achieving very low stabilization targets in a cost-effective climate policy. Moreover, CCS technologies applied to fossil fuel plants appear more prominent as a mid-term option, with biomass power and fuel production combined with CCS a longer-term option.

It is also interesting to note that, similar to the case with biomass, lower availability of CCS requires earlier deployment of other renewables (solar and wind). As a result, across the sensitivity scenarios, the energy mix varies more in 2050 than in 2100—by the latter period these other renewables have benefitted significantly from technology learning and appear to represent a necessary feature of a very low carbon energy system.

4.3 Nuclear Generation

Nuclear has the potential to play a role in low stabilization pathways if a number of challenges can be overcome. In the case where there is a failure to address challenges of acceptability and nuclear generation capacity is phased out rapidly (as in the "400ppm – Nuclear phase-out" case), the power sector shifts to fossil-based generation technologies equipped with CCS (see Figure 10), while demand is reduced significantly leading to higher GDP losses. In contrast, a more optimistic perspective on nuclear generation, with the introduction of FBR reactors, enables these technologies to supply more than a quarter of power requirements well beyond 2050, unlike the central 400ppm case where nuclear is limited in the second half of the century by exhaustion of uranium resources. Figure 10 also shows that providing ways to ensure that nuclear remains an acceptable option will reduce the cost of pursuing low stabilization.

Figure 10. Shares in Electricity Generation Mix for Various Nuclear Scenarios and GDP Losses Relative to Baseline

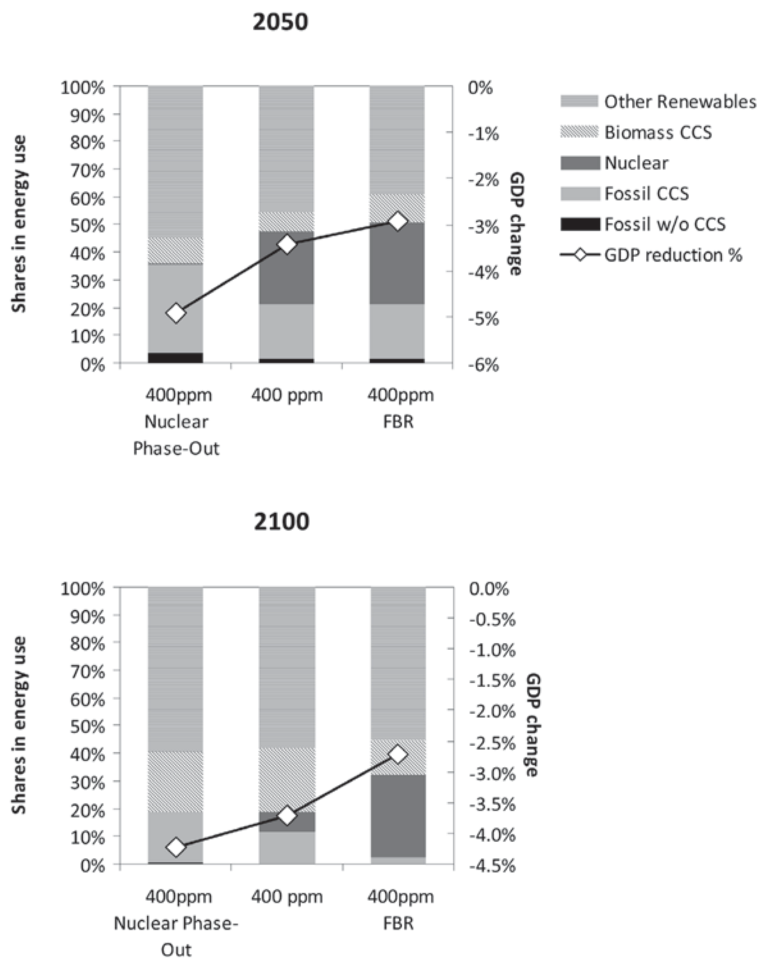
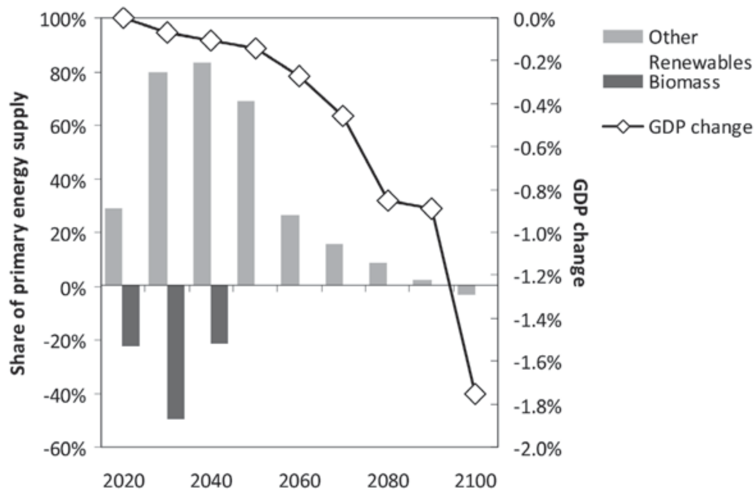


Figure 11. Changes in Renewable Energy Use and GDP in High Learning Rates Scenario Relative to 400ppm Central Scenario



4.4 Renewable Technology Progress

Finally, we examine the effect of faster technological development and innovation for renewable technologies (solar PV, wind and solar thermal-H2), by investigating a case with higher learning rates for these technologies. This is the only alternative case for renewables presented here, although it is worth noting that renewable technologies were observed to be essential for achieving the low stabilization targets. The results of the analysis with faster technological development indicate that higher learning rates accelerate the penetration of these technology options substantially (Figure 11), displacing biomass and fossil fuel use in the first half of the century. The accelerated deployment leads to higher shares of wind and solar technologies in the early to mid part of the century compared to the central 400ppm scenario, but the maximum deployment in the long run is little changed, since these technologies are necessary in the longer term to achieve the stringent climate target investigated here. The lower deployment of biomass in electricity generation in this case reduces opportunities for learning-by-doing and this technology is phased out from the power mix by the end of the century, replaced partly by IGCC and more notably with gas plants with CCS. Biomass use is then almost entirely directed to the production of H2 in the non-electric sector. Naturally, the higher the learning rates, the lower the requirements for R&D expenditure in order to reach a given level of technology performance and generation cost. Accordingly, GDP losses are almost reduced by half by the end of the time horizon.

5. DISCUSSIONS/CONCLUSIONS

The scenarios analyzed here (and elsewhere in this Special Issue) indicate that technological change represents a key element in any effort to realize long-term stabilization at low greenhouse gas concentrations compatible with limiting temperature changes from climate change to less than 2 degrees relative to pre-industrial levels. Given the importance of technology development, it is thus essential to analyze potential future options and scenarios with modeling tools able to represent features of technological change, and with a sufficiently rich coverage of technology options, such as in the MERGE-ETL model.

This analysis has identified the need for substantial R&D efforts to bring down the cost of advanced low and zero-emissions technologies—the more stringent the climate target, the earlier large investments in R&D are needed to support renewables, advanced fossil technologies (including CCS), generation IV nuclear and biomass technologies. While large, the required levels of investment are nonetheless substantially lower than the overall costs of mitigation. Learning-by-doing through demonstration programmes and early deployment represents a complement to R&D efforts, and is essential for longer-term improvements in technology.

Moreover, the analysis shows that there are significant economic and environmental risks if certain prospective low- or zero-emissions technologies are not able to be deployed (whether for technical reasons or issues of public acceptance). Limiting the available suite of technologies generally necessitates earlier action and higher economic costs; and in some cases makes achieving the 400ppmCO_2eq target impossible. This speaks in favour of pursuing multiple technologies simultaneously, rather than trying to pick winners based on current perceptions or understanding. This is reiterated in our analysis of the impact of more optimistic assumptions regarding biomass availability, FBRs, and renewables—all of which today look less attractive for various reasons, but which were seen to significantly reduce the cost and increase the flexibility of the energy system.

Importantly, we have not presented here scenarios in which combinations of technology options are unavailable—for example, simultaneous limitations on biomass, nuclear and CCS. However, the results presented are sufficient to imply strongly that further narrowing the set of technologies would further significantly exacerbate economic and environmental risks. Accordingly, for achieving very low stabilization targets, R&D, deployment and commercialization support needs to be non-discriminatory, rather than focusing on technologies that may be viewed today as more attractive, but which may be confronted by unanticipated and insurmountable challenges in the future.

Although we have quantified the cost of excluding different technology options, given the high level of uncertainty it is perhaps difficult to draw strong conclusions about which options are the most important or have the greatest potential. However, despite this uncertainty, the analysis indicates that CCS is an essential technology for achieving very low stabilization targets (given partly that today the atmospheric CO_2 concentration alone is already close to 400ppm). In addition, achieving low stabilization does not appear to be possible without large-scale deployment of renewables, particularly over the long term where we observed a tendency for the various technology scenarios to converge towards similar energy mixes based on renewable sources.

Of course, while we have investigated different climate policy and technology scenarios, this analysis has been limited to a single scenario of key scenario driving forces, such as population, economic growth and autonomous energy efficiency improvements. Alternative development pathways, including changes in lifestyle and behaviour would provide other options for achieving stringent mitigation targets. In other words, there are trade-offs between economic and energy demand growth, and technology choice. For instance, maintaining current moderate economic growth, and levels of energy consumption and mobility imply a need to pursue technology options that may be undesirable for other reasons (for example, large-scale biomass, CCS and nuclear power—although all technologies have some negative impacts – see Hirschberg and Dones, 2005). Moreover, to avoid the risk that any of the energy supply technologies examined in detail here is not available for technical reasons it is worthwhile pursuing actions addressing these other driving forces and behavioral factors.

In this context it is then also worth noting a further limitation of this analysis, which is the relatively lower level of technology detail represented on the demand side. Technology options for substantially improving energy efficiency of end-use devices will undoubtedly provide additional options for reducing energy demand. Nonetheless, current experience suggests that direct policy support is necessary to promote these options, even those that are apparently cost effective today (IEA, 2008).

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