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Measuring the Impact of Energy Technology Investment on Long-term Sustainability

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Abstract

The global energy system currently faces a number of significant challenges which have the potential to undermine long-term sustainable development, including the need to maintain secure access to affordable energy supplies and mitigate climate change. This report explores the role of energy technology investment policies, including R&D and demonstration and deployment (D&D) programs in overcoming these challenges. The analysis considers the mechanisms by which energy technology policy initiatives may affect technology characteristics and deployment, and how technology deployment influences overall features of the energy system, and thereby energy security and climate change. The results identify potential targets for technology policy support, including the need to co-ordinate complementary technology strategies. Moreover, we discuss some critical insights related to the impact of the broader policy environment on successful technology deployment, and the potential for certain technology policies to result in undesirable technology lock-out.

This research was carried out under the SAPIENTIA project[1], sponsored by the European Commission (DG Research), which sought to develop methodologies to support decision makers concerned with the energy-environment-policy nexus in formulating technology policy. Importantly, the results presented here represent only part of the output of the integrated SAPIENTIA project, and are highly dependent on the characteristics of our modeling tools. Nonetheless, this analysis provides some instructive insights for the development of more comprehensive methodologies for the assessment of impacts of energy technology support policies.

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[1] SAPIENTIA stands for Systems Analysis for Progress and Innovation in Energy Technologies for Integrated Assessment.

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About the Author

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Mr. Turton is currently working on a PhD with the Energy Economics group at the Paul Scherrer Institute at the ETH Zurich. He also holds degrees in public policy (MPubPol) from the Australian National University and advanced science (BSc (Hons) and the University Medal) from the University of New South Wales. Before joining IIASA, Mr. Turton worked on energy and environmental policy research, analysis and development at a number of organizations in Australia, including the Australia Institute and State government energy and greenhouse policy agencies.

Measuring the Impact of Energy Technology Investment on Long-term Sustainability

Hal Turton

1 Introduction

Energy technology investment policies, including research and development (R&D) and demonstration, procurement and deployment programs, are important driving forces in the development of energy systems. Understanding the mechanisms by which technology policies generally, and R&D specifically contribute to long-term energy technology choice, and improvements in the overall energy system, are important for designing strategic policy responses aimed at achieving the goals of sustainable development (Nakićenović 1997). Ideally, an improved and quantitative understanding of the potential impact of technology investment on sustainability could provide policy and decision makers with the insights necessary to formulate the most effective energy-related R&D and complementary strategies.

Realising sustainable energy systems within the context of overall sustainable development requires overcoming a number of challenges in terms of delivering affordable, secure and clean energy for poverty alleviation and ongoing development throughout the world. Among other threats to sustainable energy development confronting policy makers, some of the most significant relate to climate change, air pollution, security of energy supply and economic development. Two of these challenges – mitigating the impacts of climate change and maintaining security of energy supply – are prominent issues on both national and international policy-making agendas. The increasing evidence of human-induced interference with the earth's climate system and mounting concern about potentially serious future adverse impacts make global climate change one of the most significant challenges to the realisation of sustainable development in the long term (IPCC, 2001a). Efforts to address climate change necessarily require a focus on the global energy system, which is the major source of anthropogenic greenhouse gas emissions. Accordingly, climate policy calls for, among others, the investigation of low-emissions alternatives for energy production, conversion and final use, including the role of technology support programs (e.g., IPCC 2001b; Hoffert *et al.* 2002; Hasselmann *et al*, 2003).

Security of energy supply is considered a more pressing short-term concern by policy makers. An excessive reliance on fossil fuels, oil and natural gas in particular, is an issue of concern because it potentially creates economic, physical and geopolitical risks (EC 2001). Specifically, the current overall dependence of OECD countries on oil supply from politically volatile regions and the definition of appropriate responses to potential supply disruptions remain challenging issues (e.g., DOC 1999; EC 2001; IEA 2001).

Climate change and security-of-supply are complex issues, and overcoming the challenges to sustainability posed by either will in all likelihood require the application of a broad portfolio of policy instruments and support (see Turton and Barreto 2005). This analysis seeks to assess the potential role of two instruments that exploit technological change, which is not only a key driving force behind the anthropogenic contribution to climate change and resource depletion, but may also be an important instrument for mitigating the impact of, and adapting to climate change and energy supply constraints (IPCC, 2001b; Nakićenović, 2003; Turton and Barreto 2005).

The specific policy instruments examined in this study include: energy-related research and development (R&D) investment and energy-related demonstration and deployment (hereon referred to as D&D) programs. Both of these policy instruments are examined using the notion of "shocks", i.e., one-off incremental investments in either research and development, or demonstration and deployment (see Turton and Barreto (2003) for a discussion). For each of these policy instruments, we examine the resulting incremental change in a number of sustainability indicators related to climate change and security of supply when the policy instrument is applied, relative to the costs of application of the instrument (measured in €1999s throughout this report). Hereafter, this ratio is referred to as the "impact" of the policy instrument.

The specific climate change indicators considered here comprise: atmospheric concentrations of CO_2 and CH_4, global temperature change and global sea-level rise. In this analysis, these indicators are generally reported for the year 2100 because the inertia in both energy and climate systems means that policy impacts take a long time to fully emerge. The indicators for security of energy supply are long-term global resources-to-production (denoted here as R:P) ratios for oil and natural gas, both of them reported for the year 2060. We discuss the selection of this year in the sections below, but generally, the first decade of the second half of the 21st century may be a time when resources of oil and gas are under significant pressure, but before which the energy system has relatively few opportunities to shift to other energy sources.

This research was carried out under the SAPIENTIA project[2], sponsored by the European Commission (DG Research), which sought to examine the effectiveness of energy-technology R&D and D&D programs in stimulating the adoption of new technologies, and the consequent impact on a number of sustainability indicators. Accordingly, this analysis builds on earlier work for the SAPIENTIA project involving development and extension of the energy-systems model ERIS (Energy Research and Investment Strategies) (Turton and Barreto 2003). This development and extension successfully sought to introduce key mechanisms of technological change in energy systems into ERIS, and compute the sustainability indicators of interest, applying the MAGICC climate model (Wigley and Raper 1997; Wigley 2003). Furthermore, relevant key energy technology candidates for R&D and D&D support were also incorporated. More detail on the model extensions is discussed in Turton and Barreto (2003).

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[2] SAPIENTIA stands for Systems Analysis for Progress and Innovation in Energy Technologies for Integrated Assessment.

The remainder of this document is organised as follows. Section 2 briefly discusses the model extensions for the SAPIENTIA project, in particular those made subsequent to the publication of the mid-term project report (see Turton and Barreto 2003). Section 3 then describes the baseline scenario, which sets the context in which the technology support policies explored in subsequent sections are applied. The main analysis begins in Section 4, which describes the effect of optimistic and pessimistic future scenarios of R&D support. Section 5 then presents an assessment of the impact of R&D and demonstration and deployment (D&D) shocks on the indicators of sustainable development. Section 5 also examines the effects of a combination of R&D and D&D shocks. Finally, we summarise and present some conclusions in Section 6.

2 Additional extensions to the ERIS model

The analysis for the SAPIENTIA project was performed using the modeling framework developed at IIASA-ECS and described in Turton and Barreto (2003). This framework comprises the energy systems model ERIS and the MAGICC climate model (Wigley and Raper 1997; Wigley 2003). ERIS[3] is a multi-regional "bottom-up" energy-systems optimization model that endogenises learning curves. The original version of the model was developed as a joint effort between ECS/IIASA and the Paul Scherrer Institute (PSI) in Switzerland during the EC-sponsored TEEM and SAPIENT projects, where it was mainly used to examine issues related to the endogenization of mechanisms of technological change (Messner, 1998; Kypreos *et al.*, 2000; Barreto and Kypreos, 2000, 2004).

At the end of 2003, the ERIS model was substantially expanded and recalibrated at ECS/IIASA in order to address the objectives of the SAPIENTIA project, in particular those related to climate change and transportation indicators. For this purpose, the model was restructured and a number of features added. The main modifications described in the mid-term report (Turton and Barreto 2003), include:

- development of cluster approach to technological learning;
- disaggregation and additional technological detail in the non-electric sector, particularly transportation;
- addition of an energy carrier production sector, specifically for hydrogen, alcohol and Fischer-Tropsch liquids production;
- incorporation of methane and nitrous oxide emissions and abatement cost curves for these gases;
- inclusion of sulfur dioxide emissions; and
- inclusion of geological and terrestrial carbon storage.

In many cases, these modifications to the ERIS model were made on the basis of output from other work packages in the SAPIENTIA project, or the anticipated output in cases where prerequisite work packages were incomplete at the time the mid-term report was prepared. Accordingly, where necessary, the model has been updated and refined subsequent to the mid-term report as prerequisite work packages were completed. For instance, Sections 2.2.3 and 3 in the mid-term report (Turton and Barreto 2003)

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[3] Energy Research and Investment Strategy

discussed preliminary approaches to the modeling of two-factor learning and clustering technological learning. Although the main elements of the approaches described in the mid-term report have been maintained, the actual formulation of learning in the ERIS model has been updated to incorporate the two-factor learning and cluster specification of Kouvaritakis and Panos (2005). The modeling of learning is discussed in Section 2.1 below.

Furthermore, the alternative technology specification has required updating of the assumed fossil fuel resources presented in Section 2.1.2 of the mid-term report. The ERIS model now includes around half the unconventional oil resources estimated by Rogner (1997) and referred to as Category VI resources in Table 1 in the mid-term report. These unconventional oil resource were not included in the interim version of ERIS described in the mid-term report, but this revision reflects a less pessimistic assessment of future availability of oil resources consistent with other features of the overall scenario used in this analysis (see Turton and Barreto 2003). Importantly, we continue to exclude highly speculative "additional occurrences" of oil and gas resources.

2.1 Learning and 2FLCs

Technology learning can be represented in energy system models such as ERIS by incorporating non-linear one or two-factor learning curves (1FLCs, 2FLCs) that represent the impact on technology characteristics of increasing experience or R&D. However, the complexity of the ERIS energy systems model renders it unsuitable for solution with non-linear programming (NLP) methods. With complex non-convex models, NLP solvers are unlikely to find the global optimum, and may experience extremely long run times. Accordingly, in the past, a mixed-integer programming (MIP) formulation of ERIS was used to approximate non-linear learning curves using a piece-wise step function (see Barreto and Kypreos 2000).

However, for the SAPIENTIA project it is necessary to apply two-factor learning curves (2FLCs) to account for the impact of different future research and development (R&D) budget allocations. A sophisticated learning formulation, that incorporates learning-by-doing, learning-by-searching, technology clusters and other features, has been proposed for the project (Kouvaritakis and Panos 2005). Many of the features of this learning formulation can be incorporated relatively easily into an MIP model formulation, including most of the non-linearities. However, the large number of learning technologies, and the errors likely to be introduced by attempting to eliminate all of the non-linearities raise some further challenges. Because it is not realistic to apply a NLP formulation of the ERIS model, and considering both the number of technology investment 'shocks' that need to be applied in the SAPIENTIA project and the uncertainty of obtaining optimal solutions, another alternative was chosen that preserved the detailed learning relationships proposed by Kouvaritakis and Panos (2005).

Accordingly, we apply an iterative linear and MIP formulation. This involves iterating between the linear programming (LP) formulation of the model and an exogenous learning sub-module which incorporates the non-linear 2FLC formulations proposed by

Kouvaritakis and Panos (2005). Cumulative installations from the LP model form the input to the learning sub-module, which calculates new specific costs that are fed back to the LP model. The LP model is rerun with these new specific costs to determine new cumulative capacities, which are then processed by the learning module. The process is repeated until there is sufficient convergence. The specific costs at convergence are then applied to an MIP model that accounts for the non-linearities associated with transmission and distribution infrastructure development (see Turton and Barreto 2003).

The main drawback of this approach is that it eliminates foresight regarding the impact of learning on future technology costs. That is, within each iteration technology cost and performance is independent of experience, although experience does affect technology characteristics in subsequent iterations. However, this loss of foresight regarding the effect of technology experience and R&D may in fact better reflect the uncertainty faced by decision makers when selecting the most suitable technologies (for deployment or R&D). Moreover, from a technical standpoint, experiments with this formulation produce results almost identical to the equivalent MIP model, but in approximately 20-35 percent of the time. Accordingly, it is assumed that any errors introduced by implementing learning in this way are smaller than those associated with the alternative of linearising and estimating complex non-linear learning equations. This approach is not only well suited for incorporating the more sophisticated learning formulation that has been proposed for SAPIENTIA, but facilitates more extensive examination of investment policy shocks.

3 Baseline scenario

One critical factor affecting long-term sustainability, including climate change mitigation and maintaining security of energy supply, and also expected to affect the impact of policies aimed at achieving sustainable development, is the likely trajectory of energy-system development without additional technology policies. The extent to which the baseline scenario of the evolution of the energy system is fossil fuel intensive, or reliant on new technologies, has a large bearing on the potential impact of additional technology policies on indicators of sustainable development. Importantly, however, it is not necessarily a simple linear relationship. For example, additional public or private support for key low-emissions technologies may have little impact when the future is dominated by either incumbent technologies, which enjoy enormous competitive advantages, or low-emissions technologies that become successful regardless. Instead, it is in those cases where technology choice is finely balanced, or where the timing of market penetration is critical to the long-term success of a technology, that technology support can be most effective in realising sustainable development. The baseline scenario can provide some indication of where potential targets for technology policy support may arise.

3.1 Policy baseline

3.1.1 Climate policy

In constructing the baseline scenario we do not make the unrealistic assumption that no efforts are made over the next 100 years to mitigate the risks of climate change. Rather, we assume that all world regions implement greenhouse gas abatement policies and measures at some point during the 21st century, although at different times and rates depending on regional circumstances. Moreover, these abatement policies are assumed to be independent of the potential technology policies explored in the SAPIENTIA project. The climate change mitigation policies and measures are represented in a stylised way in the baseline scenario in the form of taxes on greenhouse gas emissions. In reality, world regions are likely to adopt an array of abatement measures, and the use of a GHG tax in the baseline scenario merely seeks to represent the effective stringency of all of these measures. The GHG tax rates assumed in this scenario and applied to the six main gases are presented in Table 1.

Table 1: GHG tax rates (€/tonne carbon equivalent) assumed under the baseline scenario

	2000	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
Europe	0.00	14.00	21.00	33.30	50.50	70.70	98.60	98.60	98.60	98.60	98.60
Rest of OECD	0.00	7.60	12.60	22.80	37.90	56.90	83.80	83.80	83.80	83.80	83.80
Rest of World	0.00	1.40	3.60	9.20	19.40	34.30	62.20	62.20	62.20	62.20	62.20

Note: all figures are in €99.
Source: SAPIENTIA Delphi analysis.

3.1.2 R&D policy – public and private

Another critical feature of this scenario is the assumed future energy R&D investment budget and distribution across the portfolio of competing energy technologies. The R&D investment outlook, including the allocation to different technologies is described in ICCS-NTUA (2005), and this is used to develop the baseline described below. Importantly, future R&D budgets and expenditure patterns are highly uncertain, and as part of this analysis we explore this uncertainty by also examining extremely optimistic and pessimistic scenarios of future R&D. The results of this sensitivity analysis are presented in Section 4.

Firstly, however, we examine a number of salient characteristics of the baseline scenario.

3.2 Detailed description of baseline scenario results

3.2.1 Technology uptake and adoption

In the context of examining the potential for different technologies to contribute to sustainable development, it is useful to examine technology choice in the main energy sectors under this baseline scenario. Accordingly, we show in Figure 1 the uptake of different electricity generation technologies under the baseline scenario over the 21st century.

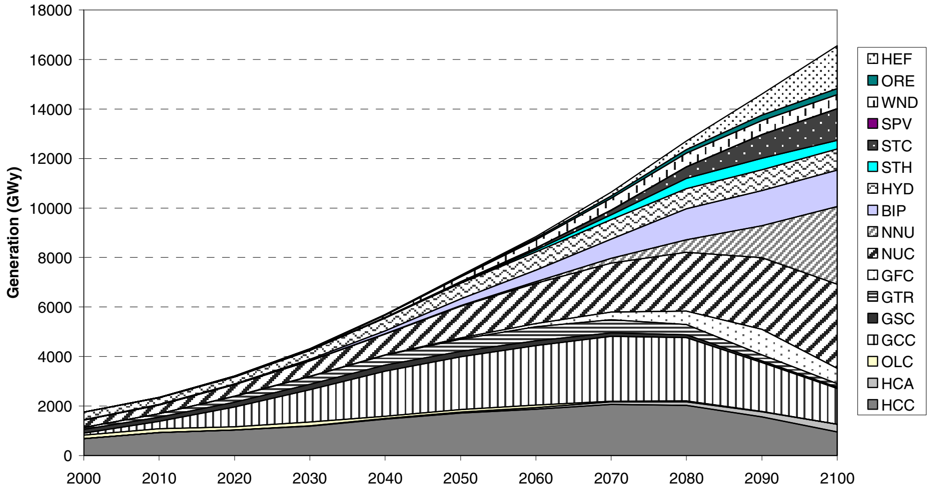

Figure 1: Global electricity generation mix, baseline scenario (with GHG abatement policy).

Note: Technology abbreviations are as follows: HCC: conventional coal, HCA: advanced coal (IGCC), OLC: oil conventional, GCC: gas combined-cycle, GSC: gas steam cycle, GTR: gas turbine, GFC: gas fuel cell, NUC: nuclear conventional, NNU: new nuclear, BIP: biomass gasification, HYD: hydro, STH: solar thermal, STC: solar thermal cogeneration, SPV: solar photovoltaics, WND: wind turbine, ORE: other renewables, HEF: hydrogen fuel cell.

The most noticeable transition across the century is the declining share of fossil fuels in electricity generation, particularly from coal, which is not surprising when one considers the imposition of GHG taxes assumed in this scenario. However, in absolute terms generation from both coal and natural gas increases until mid-way through the second half of the century, and generation from IGCC coal and gas fuel cell generators is still increasing in 2100. The decline in aggregate generation from fossil fuels coincides with an increase in generation from nuclear (both 3rd and 4th generation) and renewable sources of energy. A diverse mix of renewable generators is supported by resource constraints and niche markets, with no clearly dominant technology, although solar photovoltaics appear to be restricted to very small niche markets. Along with 4th generation nuclear power plants, hydrogen-fuelled stationary fuel cells are among the fastest growing sources of generation at the end of the century. Accordingly, if we look across the whole century, the dominant sources of global generation shift from: conventional coal, nuclear and hydroelectric generation in 2000, to; gas combined cycle, conventional coal and nuclear in 2050, and finally to; conventional and advanced nuclear, and hydrogen fuel cell generation in 2100.

The continuing dominance of fossil fuels mid-way through the 21st century, even under a baseline scenario that includes climate change mitigation policies, illustrates the inertia of energy systems, particularly the time taken for new technologies to become competitive and penetrate the market on a large scale.

Although an increasingly important part of the global energy system under this scenario, electricity generation is only one of a number of energy sub-sectors in which technological change may substantially transform production. In Figure 2 we present the development of the subsector representing other forms of secondary fuel production, which is currently dominated by oil refining. In this subsector, oil refining continues to play a dominant role throughout much of the century, and total combined output of other fuels from new energy production technologies only surpasses petroleum output after 2080 (as shown in Figure 2). These new energy production technologies comprise hydrogen synthesis technologies based on steam reforming of natural gas, pyrolysis of biomass and partial oxidation of coal. In this baseline scenario, penetration and uptake of biomass- and coal-based hydrogen synthesis technologies is relatively rapid in the second half of the century, and total hydrogen output in 2100 is roughly equivalent to refinery throughput in 2000. The fact that coal-based hydrogen production is supported may initially seem surprising when one considers the impact of a GHG tax, but occurs nonetheless because it represents a more efficient way of utilising the energy in coal where the resulting hydrogen is used in a fuel cell and, more importantly, is amenable to carbon capture. Synthesis of hydrogen via reforming of methane is not attractive, mainly because gas is already a relatively low-emissions and flexible energy carrier.

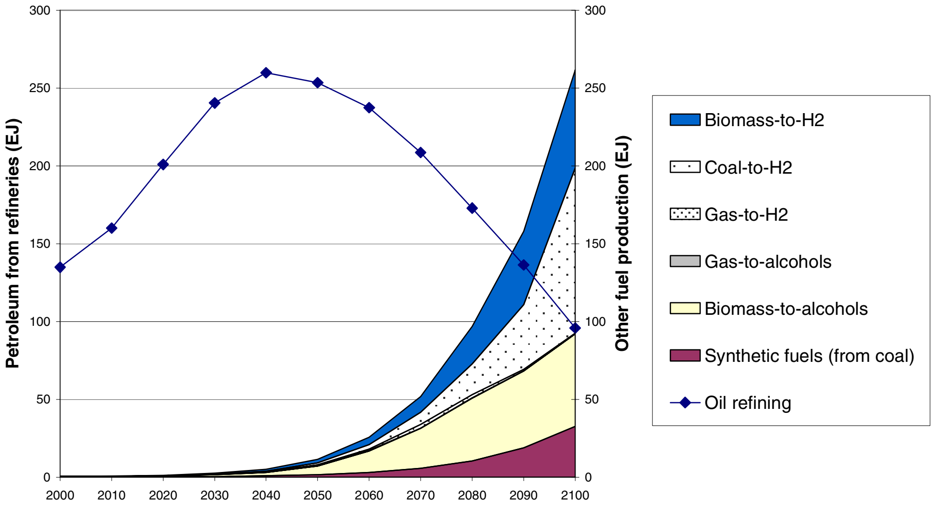

Figure 2: Global fuel conversion, baseline scenario (with GHG abatement policy)

Figure 2 shows that the other fuel production technologies that achieve significant market penetration include Fischer-Tropsch liquids synthesis and alcohol production from biomass. The attraction of Fischer-Tropsch liquids from coal is partly explained by the declining availability and depletion of oil resources, and the potential to capture some of the carbon in the coal feedstock. Biomass-to-alcohol synthesis technology, on the other hand, is attractive because of it represents a zero-emissions fuel that can be distributed and used without the need for extensive and expensive new infrastructure or adoption of new vehicle technologies.

The other main sector of interest is transportation. The choice of vehicle technologies under this baseline scenario is illustrated in Figure 3, which presents the total travel distance accounted for by different passenger car technologies over the 21st century. The assumptions applied here result in an initially gradual transition away from the conventional petroleum ICE vehicles to natural gas-fuelled vehicles – both conventional ICE and hybrid electric-ICE vehicles. However, between around 2040 and 2060, the gasoline ICE vehicle is displaced as the dominant transport technology, and replaced by the gas hybrid. Hybrids continue to play a dominant role in the transport market for the remainder of the century, although the cost premium of the technology ensures that it is unable to achieve a market share of much more than 60 percent. The increasing availability of zero-emissions alcohol fuel in the second half of the 21st century result in the gradual penetration of this fuel into both the hybrid and conventional ICE market, and the availability of relatively cheap natural gas in some world regions also ensures that the conventional ICE technology maintains a significant market share, even though gasoline plays almost no role by 2100.

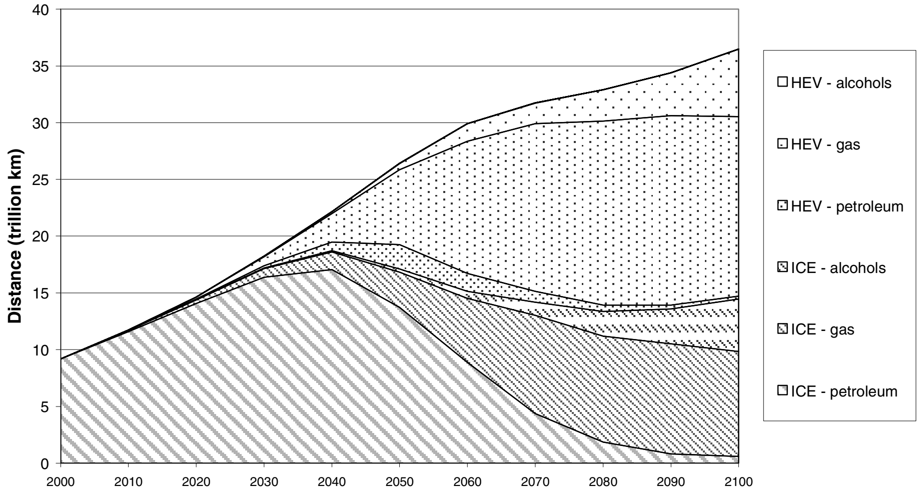

Figure 3 Global technology and fuel choice for passenger car travel, baseline scenario (with GHG abatement policy)

The only other energy-related technologies that we will mention here are those for carbon capture and storage (CCS). These technologies are attractive under this scenario, and by 2100 around 2.0 Gt of carbon are captured annually (which is close to 14 percent of energy-related CO_2 emissions – see below). Over 80 percent of this carbon is captured from IGCC plants, and in hydrogen and synthetic fuel production, with technologies that capture carbon from post-combustion flue gases remaining relatively unattractive despite the climate change mitigation policies assumed under this baseline scenario.

3.2.2 Technology costs

The technological development of the energy system described above and presented in Figures 1-3 is driven by a number of factors, including among others the GHG tax, resource availability potentials, and absolute and relative market penetration constraints.

However, two of the most important factors affecting technology choice are the cost and performance of competing technologies.

These in turn are affected by technology learning – both learning-by-searching and learning-by-doing – which are determined by the R&D budget allocation (see ICCS-NTUA 2005), and experience with the manufacture, installation and operation of technologies. Table 2 presents the development of capital costs of some key learning technologies under this baseline scenario based on costs and learning parameters from Kouvaritakis and Panos (2005). However, as mentioned above, it is important to appreciate that technology cost and performance are only two of a number of factors that affect technology adoption.

The importance of other factors is illustrated when we look at the cost of nuclear generation in Table 2. This technology remains relatively expensive compared to other forms of generation, yet plays a major role in the electricity market at the end of the century because of depletion of gas resources, and the impact of the GHG tax on the competitiveness of coal-fired generation. This is also the case with most renewables, with the share of wind turbines limited by the availability of suitable sites.

Clearly, by the end of the 21st century fuel cells are the cheapest form of electricity generation capacity. However, the challenges associated with mobilising resources for hydrogen production, and developing the necessary distribution infrastructure constrain the penetration of this technology (as seen in Figure 1). This highlights that in order to fully exploit the potential of fuel cell technologies, there may be a need to develop a long-term strategy for development and investment to co-ordinate hydrogen production, distribution and utilisation. Table 2 shows, however, that the extensive experience with and R&D investment in stationary fuel cell electricity generation technologies is unable to bring down the cost of fuel cells sufficiently to make them attractive in the private automobile market. This explains the technology mix for the transport sector presented in Figure 3, after accounting for resource constraints that promote the adoption of the more-expensive hybrid electric vehicles.

Of the other technologies presented in Table 2, the cheapest hydrogen production technology is not utilised because of competing demands for limited natural gas resources, whereas for carbon capture technologies, the investment cost per unit of energy processed is not the most important factor – instead, the cost of capture per tonne of carbon and whether the base electricity or hydrogen production technology is attractive are of more importance. This explains why the carbon capture technologies adopted are not necessarily the cheapest.

Table 2: Impact of technology learning on capital costs, baseline scenario (with GHG abatement policy)

Group	Technology	Abbreviation	2000	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
			€99/kW										
Electricity generation technologies	Conventional Coal	HCC	1,219	1,214	1,161	1,121	1,077	1,045	1,018	995	974	958	947
	Integrated Coal Gasification Combined Cycle (IGCC)	HCA	1,436	1,375	1,335	1,293	1,254	1,209	1,172	1,166	1,159	1,153	1,148
	Oil Conventional Thermal	OLC	1,108	1,070	1,056	1,055	1,054	1,054	1,053	1,053	1,053	1,053	1,053
	Gas Turbine Combined Cycle	GCC	548	535	524	517	512	510	508	507	507	507	507
	Gas Conventional Thermal	GSC	986	942	920	902	892	888	884	884	884	884	884
	Gas Turbine Open Cycle	GTR	384	374	357	345	337	331	327	326	325	324	324
	Gas Fuel Cell (generic stationary)	GFC	11,755	5,806	2,870	1,053	691	477	336	265	234	206	186
	Nuclear (2nd and 3rd gen.)	NUC	2,765	2,542	2,161	1,934	1,824	1,785	1,756	1,745	1,737	1,729	1,722
	New Nuclear (4th gen.)	NNU	8,555	7,406	6,525	5,689	4,395	3,406	2,655	2,276	1,959	1,684	1,454
	Biomass	BIP	2,477	2,081	2,006	1,954	1,907	1,868	1,836	1,836	1,836	1,836	1,836
	Large Hydro	HYD	3,227	3,144	3,064	2,931	2,747	2,524	2,381	2,311	2,286	2,270	2,250
	Solar Thermal Power Plant Cylindro-Parabolic	STH	3,111	2,889	2,674	2,465	2,280	2,130	2,006	1,999	1,991	1,985	1,983
	Building Integrated PV	SPV	6,385	4,622	3,748	3,033	2,523	2,021	1,796	1,751	1,749	1,748	1,743
	Wind Turbines	WND	1,061	957	880	813	767	737	716	713	710	709	708
	Hydrogen Fuel Cell (generic stationary)	HEF	11,755	5,806	2,870	1,053	691	477	336	265	234	206	186
			€99/m^{3}d										
Hydrogen production technologies	Hydrogen from Gas Steam Reforming (large scale)	GASH2NE	46	45	36	36	36	36	36	36	35	35	35
	Hydrogen from Coal Partial Oxidation	COALH2NE	117	109	104	98	92	87	82	81	80	78	78
	Hydrogen from Biomass Pyrolysis	BIOH2NE	122	114	104	98	93	89	86	84	82	80	79
			€99/vehicle										
Passenger car technologies	Conventional ICE Passenger Car	ICC/ICG/ICA	3,000	3,000	3,000	3,000	3,000	3,000	3,000	3,000	3,000	3,000	3,000
	Hybrid Passenger Car	ICH/IGH/IAH	7,700	5,834	5,402	5,102	5,004	4,956	4,918	4,900	4,888	4,879	4,873
	Hydrogen ICE-Hybrid Passenger Car	IHH	11,000	9,134	8,702	8,402	8,304	8,256	7,593	7,552	7,531	7,518	7,509
	Reformer-Fuel Cell Passenger Car	PFC/AFC	590,200	352,259	234,802	162,135	147,645	139,063	133,432	130,602	129,351	128,254	127,449
	Hydrogen Fuel Cell Passenger Car	HFC	472,600	234,659	117,202	44,535	30,045	21,463	15,378	12,531	11,274	10,173	9,366
			€99/toe input pa										
Carbon capture technologies	Pre-Combustion CO_2 capture (IGCC)	HCACS	31	10	10	10	10	10	10	10	10	10	10
	Post-Combustion CO_2 capture (Conventional Coal)	HCCCS	52	26	23	22	20	20	20	20	20	20	20
	Post-Combustion CO_2 capture (GCC)	GCCCS	31	24	13	13	13	13	13	13	13	13	13
			€99/m^{3}d										
	Pre-Combustion CO_2 capture (Hydrogen Production)	H2CAS	68	68	45	45	45	45	45	45	45	45	45

Now that we have a sense of technology development, and the forces affecting technology choice and the evolution of the global energy system under the baseline scenario, we can now return to the main focus of this analysis – to investigate how technology costs and rates of adoption are affected by technology support policies, including R&D and D&D, and the extent to which these policies can ultimately improve indicators of sustainability. Accordingly, below we examine the level of key indicators of climate change and security of energy supply under this baseline scenario, which establishes the benchmark against which the impact of R&D and D&D policies can be evaluated.

3.2.3 Indicators of sustainability

3.2.3.1 Climate change

Greenhouse gas emissions represent an important link in the causal chain between policy instruments and climate change impacts, because the impact of any policy initiative on climate change indicators operates via its impact on emissions. Accordingly, we present in Figure 4 below the levels of global emissions and sequestration of different greenhouse gases under the baseline scenario. In this scenario, global net greenhouse gas emissions continue rising until around 2070 where they peak at almost 22 Gt carbon equivalent per annum. Apart from a shift to less carbon-intensive energy sources (as discussed in Section 3.2.1), one of the main sources of abatement comes from sequestration – both geological and terrestrial.

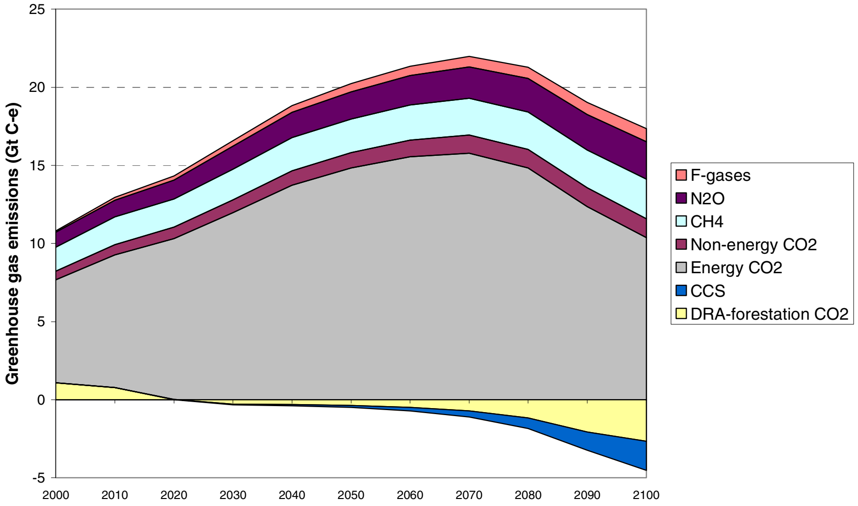

Figure 4: Global greenhouse gas emissions, baseline scenario (with GHG abatement policy).

Note: Carbon capture and storage (CCS) from energy emissions is also indicated, as are net emissions or sequestration from deforestation, reforestation and afforestration (DRA-forestation).

The impact of this emissions trajectory on atmospheric concentrations of CO_2 and CH_4 is presented in Figure 5, based on output from the MAGICC climate model (Wigley and Raper 1997). Figure 5 also shows the uncertainty range for future CO_2 concentrations described by high and low estimates for climate sensitivity. Under this scenario, atmospheric concentrations of carbon dioxide increase from around 350 ppmv in 2000 to around 700 ppmv in 2100. The impact of the change in atmospheric concentrations of CO_2, CH_4 and other gases on global temperature and sea-level is illustrated in Figure 6. Under the middle estimate of climate sensitivity (2.6 K per doubling of CO_2 concentration), average global temperature increases to around 3.2 K above 1990 levels by the end of the century, while the average rise in sea level is more than 400 mm. In Figure 6 we again present the uncertainty range for future global temperature change implied by the high and low estimates of climate sensitivity. The extent of the uncertainty associated with this indicator needs to be considered when interpreting results in the remainder of this analysis, where we seek to explore whether technology support policies, including R&D and D&D can help to mitigate some of these effects of climate change.

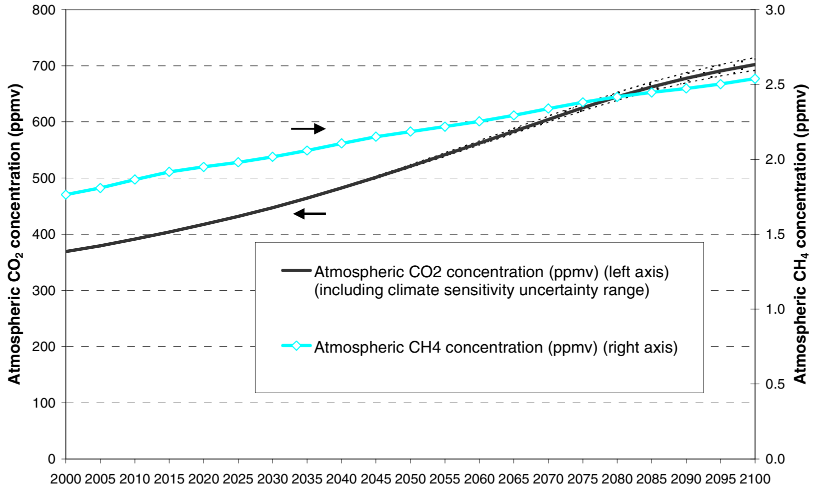

Figure 5: Atmospheric concentrations of carbon dioxide and methane, baseline scenario (with GHG abatement policy)

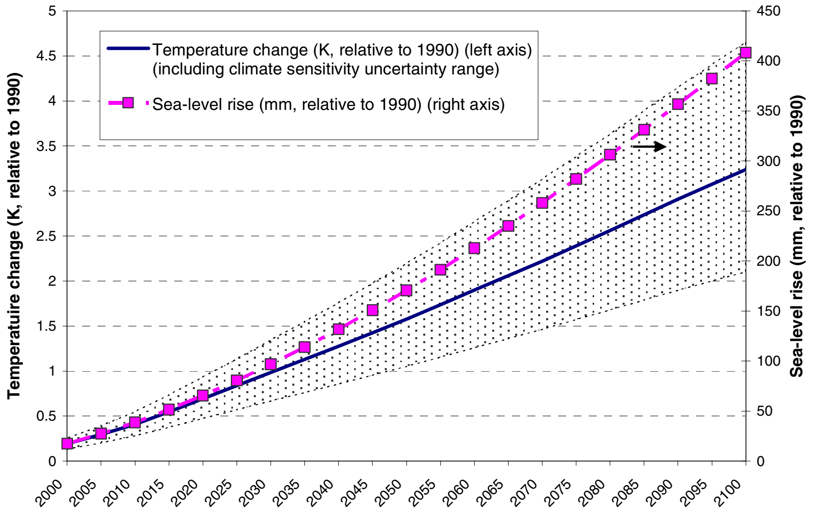

Figure 6: Temperature change and sea-level rise, baseline scenario (with GHG abatement policy)

The other major element of long-term sustainability examined in this report is the need to maintain security of energy supply, which may be particularly challenging for oil and gas resources. As an indicator of global resource security and availability, the development of the global resources-to-production ratios for oil and gas is presented in Figure 7. Importantly, this indicator differs from the reserves-to-production ratio used to measure short-term oil security, since it seeks to incorporate all resources (not only identified reserves). As discussed in Section 2, resources estimates are from Rogner (1997) and fixed for the analysis, so the R:P ratio changes only because of changes in consumption, whereas reserves will change with new discoveries (of existing resources) and improvements in extraction technologies. Since the focus of this analysis is on the long term, we are more concerned with sustainability of the resource base, rather than the efficiency with which resources can be reclassified to reserves.

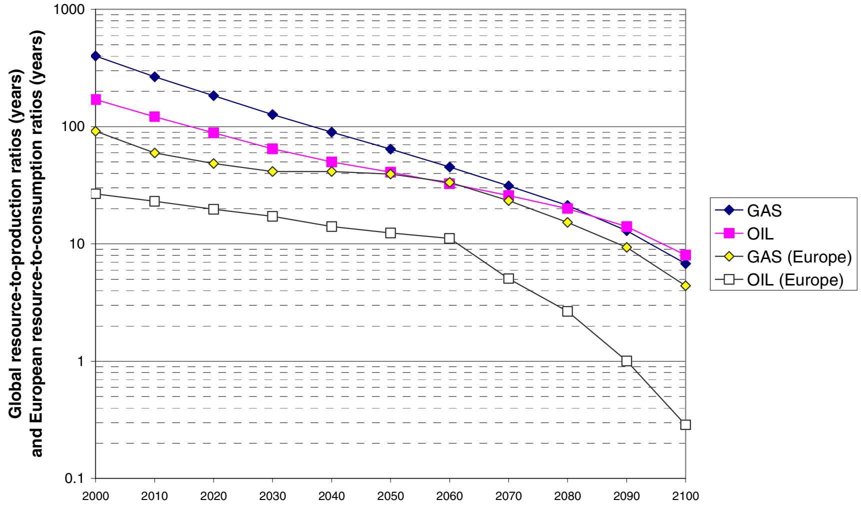

Figure 7: Global oil and gas resource-to-production ratios and European resource-to-consumption ratios, baseline scenario (with GHG abatement policy)

Figure 7 also presents the resource-to-consumption ratios for Europe (comprising all of Europe up to the borders of the former Soviet Union), to provide an indication of potential oil and gas self-sufficiency in this world region – or the potential susceptibility to a long-term disruption to international fuel trade.

Having described they key elements of the baseline scenario, and the baseline indicators of climate change and security of energy supply, we can now turn to the impact of alternative technology policies on these indicators.

4 Optimistic and pessimistic alternative technology R&D policy scenarios

The baseline scenario described in Section 3 above illustrates just one possible configuration of future technological and energy system development. Of particular interest here is the future uncertainty associated with technology policies, and the implications this has for the future uptake of new technologies, transformation of the energy system, and the impact on sustainability. To explore this aspect of uncertainty, this section examines sustainable development under two alternative scenarios of future public R&D support – one scenario where public energy R&D is double the level described in ICCS-NTUA (2005), and one where it is zero. Hereafter we refer to these as the optimistic and pessimistic R&D scenarios, respectively.

Apart from alternative R&D investment, all other factors affecting the development of the energy system under these scenarios are identical to the baseline. Accordingly, this exercise helps to illustrate the specific impact of enhanced or diminished energy R&D support. This section presents the impact of these alternative scenarios on technology choice in key energy sectors and on each of the sustainability indicators of interest, relative to the baseline.

4.1 Technology deployment

Looking first at the effect of optimistic and pessimistic future energy R&D investment on the development of the electricity sector, Figure 8 presents generation technology choice relative to the baseline scenario. Figure 8 shows the change in generation from each technology resulting from the alternative R&D scenarios as a percentage of total generation in 2050 and 2100. Even though the impacts are presented as a percentage, the inertia in the energy system means that the greatest effects are not observed until later in the century.

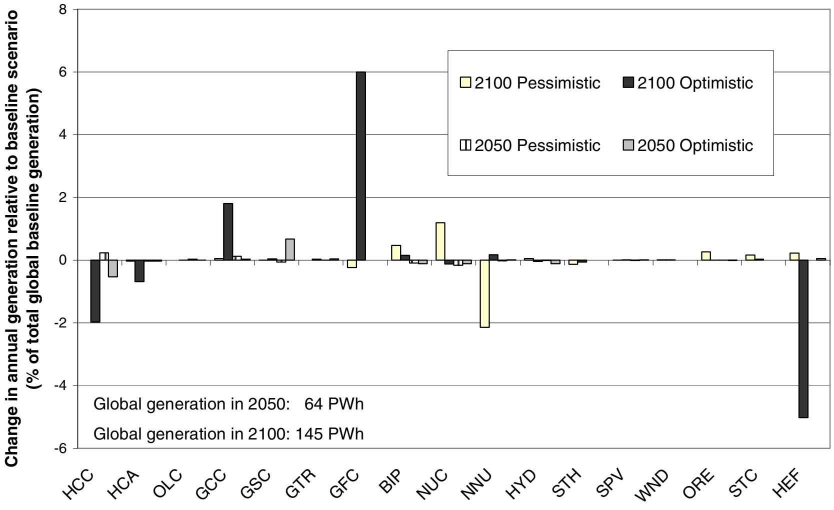

Figure 8: Change in global generation under alternative R&D scenarios, relative to baseline (2050, 2100)

Note: Technology abbreviations are as follows: HCC: conventional coal, HCA: advanced coal (IGCC), OLC: oil conventional, GCC: gas combined-cycle, GSC: gas steam cycle, GTR: gas turbine, GFC: gas fuel cell, BIP: biomass gasification, NUC: nuclear conventional, NNU: new nuclear, HYD: hydro, STH: solar thermal, STC: solar thermal cogeneration, SPV: solar photovoltaics, WND: wind turbine, ORE: other renewables, HEF: hydrogen fuel cell.

Electricity generation under the pessimistic R&D scenario is almost identical to the baseline scenario up until 2050, and even by 2100 the divergence is small. This implies that other factors, such as the climate policy and resource constraints, have a greater influence on technology choice than government energy R&D, if we assume the levels under the baseline scenario. The most significant effect of the lower energy

R&D investment in this pessimistic scenario is to delay the development of 4th generation nuclear reactors. As a consequence, one of the few ways in which the energy system can meet rising demand while responding to the climate policy assumed to apply in this scenario is to rely more heavily on 3rd generation nuclear reactors, with some additional generation from coal, biomass and some other renewables.

The optimistic R&D scenario results in a more significant, although still small transformation of the global electricity sector by 2100 by promoting gas fuel cell and combined cycle generation almost entirely at the expense of hydrogen fuel cell and coal-based generation. However, the gas and hydrogen fuel cell technologies are very similar, and affected by R&D investment in much the same way so this result cannot be attributed to any purely technological edge of gas fuel cells in electricity generation, and instead must be related to other factors, including cost and availability of gas and hydrogen. Similarly, the shift away from coal-fired generation can be attributed partly to the impact of the climate change mitigation policy, but it remains unclear how the higher levels of R&D investment are able to increase the contribution of gas-based electricity generation, remembering that in the baseline scenario gas became increasingly scarce towards the end of the century. To answer this question we clearly need to explore the development of other energy sectors, which we briefly discuss below.

One potentially important sector is transportation, where a number of new technologies, including new powertrains (such as fuel cells and hybrids) and new energy systems (such as advanced batteries, reformers and hydrogen storage) compete. However, as shown in Figure 9, a reduction in government energy R&D has little impact on the future choice of transportation technologies under the assumptions used here. The necessity to shift away from, or use more efficiently oil and gas resources is a more pressing concern than avoiding technologies that are slightly more expensive because of lower R&D support – in other words, it is still attractive to deploy technologies such as hybrid vehicles under this pessimistic scenario, even though lower R&D investment means they are less mature.

These same factors affect technology choice under the optimistic R&D investment scenario, but the additional R&D instead accelerates technology development. The impact is shown in Figure 10 where by expanding the suite of competitive vehicle technologies the optimistic R&D scenario radically transforms the development of this sector. Figure 10 shows a rapid transition from the conventional gasoline ICE through alcohol ICEs and gas hybrids to hydrogen fuel cell vehicles.

Clearly, the additional R&D investment creates a more effective and competitive way of meeting climate change mitigation goals and reducing reliance on fossil fuels. This occurs almost entirely because of the impact of the additional R&D on fuel cell competitiveness (see Appendix, Tables A1 and A2). This in turn facilitates an earlier penetration of this technology into both stationary and mobile markets, which in turn leads to additional learning-by-doing and further improvements in competitiveness.

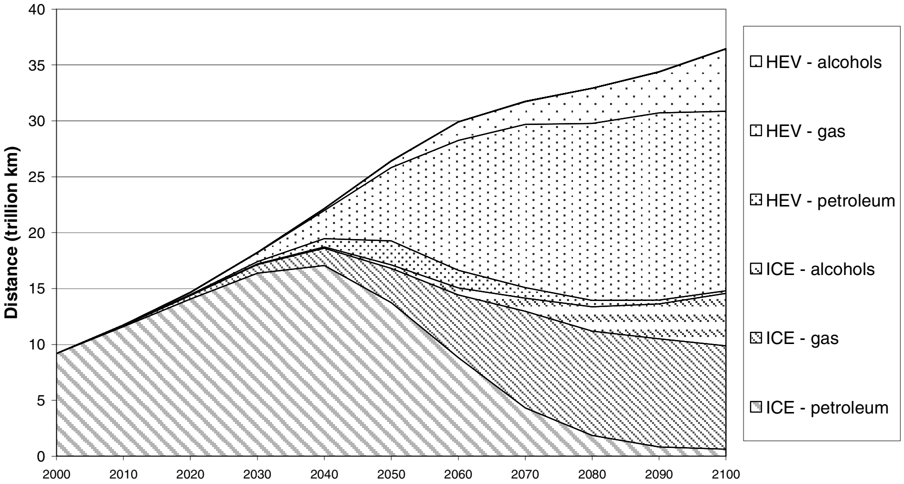

Figure 9: Global technology and fuel choice for passenger car travel, pessimistic R&D scenario (with GHG abatement policy)

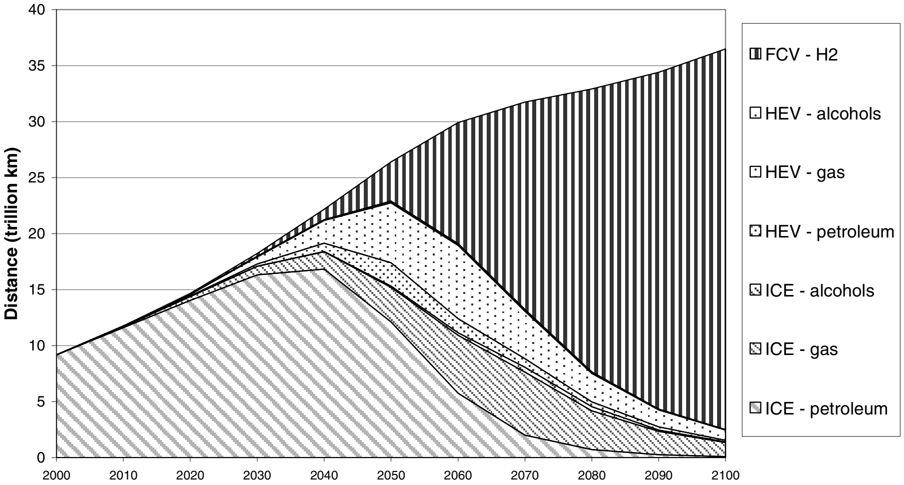

Figure 10: Global technology and fuel choice for passenger car travel, optimistic R&D scenario (with GHG abatement policy)

This overall transformation of the passenger transport sector under this optimistic scenario provides one explanation for the results observed in Figure 8 for the electricity sector. Specifically, the lower reliance on natural gas in the transport sector allows greater use of gas in electricity generation. As we saw in Table 2, even under the baseline scenario gas-fired electricity generation technologies were among the most competitive, so it is not surprising that under this optimistic scenario there is more generation from natural gas. Moreover, the quantity of hydrogen demanded by the transport sector reduces availability in other sectors, which partly explains the preference for gas over hydrogen fuel cells in electricity generation under the optimistic scenario (see Figure 8).

One would assume that such a marked shift to an alternative development path may have implications for sustainable development, particularly since there appears to be greater reliance on low- and zero-emissions fuels under the optimistic R&D scenario.

The following section examines the impact of this alternative development path on indicators of sustainable development.

4.2 Sustainability indicators

The impact on greenhouse gas emissions of the two alternative government energy R&D scenarios relative to the baseline scenario is presented in Figure 11. Not surprisingly, the impact under the pessimistic scenario is very small, which is consistent with the relatively unchanged development path of the energy system under this scenario. The optimistic scenario also has relatively little impact on emissions until late in the century, where it contributes to a substantial decline (2 Gt C-e pa) in total annual emissions. However, as shown in Figure 12, this results in only a relatively small decline in atmospheric CO_2 concentrations relative to the baseline scenario, because emissions for most of the century are only slightly below the baseline trajectory. The pessimistic scenario leads to an atmospheric CO_2 concentration almost identical to that under the baseline scenario.

Moving along the causal chain from emissions through to climate impacts, Figure 13 presents the change in average global temperature compared to the baseline scenario. These impacts on temperature are small, and somewhat counter-intuitive – for example, the lower emissions and CO_2 concentrations under the optimistic scenario result in a higher temperature because emissions of sulfur oxides (SO_x) (from coal combustion and a precursor of sulfate aerosols with negative forcing) are also reduced under this scenario. Accordingly, in Figure 13 we also show the impact on temperature assuming constant levels of atmospheric sulphate, which exhibits a path that is more consistent with emissions and concentrations. However, this is an artificial construction since SO_x emissions are declining in all scenarios and this is merely accelerated under the optimistic scenario because of a faster phase-out of coal.

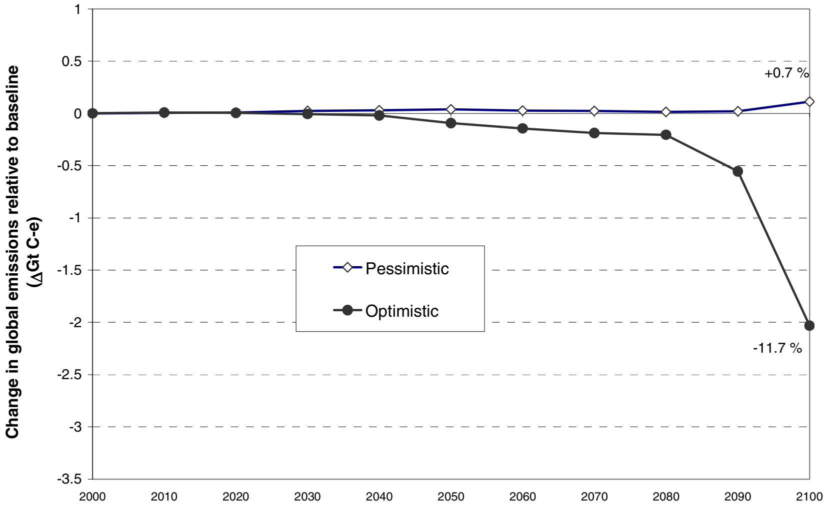

Figure 11: Change in global GHG emissions under alternative R&D policy scenarios, relative to baseline

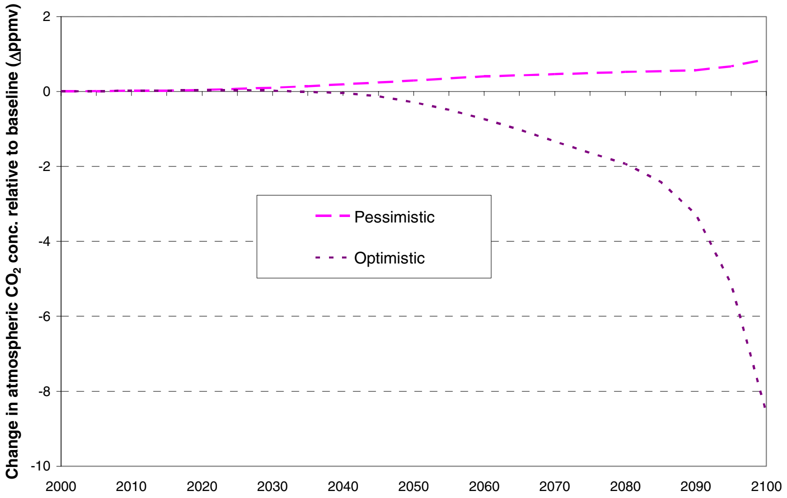

Figure 12: Change in atmospheric CO_2 concentrations under alternative R&D scenarios, relative to baseline

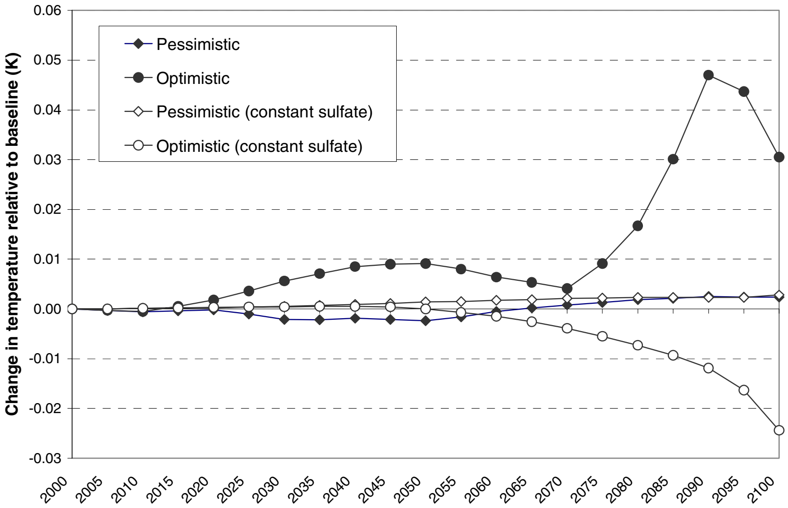

Figure 13: Change in global temperature and sea level under alternative R&D scenarios, relative to baseline

Importantly, however, for essentially all of the climate change indicators the most significant change occurs at the end of the century. Accordingly, for the remainder of this analysis of climate change indicators and impacts in this report we focus on the year 2100.

Turning now to the other set of indicators of sustainability, the effect on security of oil supply of the optimistic and pessimistic government energy R&D scenarios is presented in Figure 14. This figure shows the change in the global resources-to-production ratio (R:P), and the change in the resources-to-consumption ratio (R:C) in Europe (comprising Europe up to the borders of the Former Soviet Union). It should be remembered that this *resources*-to-production ratio differs from the commonly reported *reserves*-to-production ratio (for example, BP 2004), in that it is based on total recoverable resources, rather than current levels of identified reserves. Looking at the results for R:P and R:C, for most of the first half of the 21st century neither policy has a significant impact on the energy security ratios, but this changes by 2040-2050. Between 2050 and 2070, under the optimistic scenario the resources-to-production ratio for oil is extended by 1.1-1.9 years, equivalent to up to a 6 percent increase in the ratio, which may be sufficient to reduce vulnerability to supply disruptions. At the same time, the resource-to-consumption ratio for oil in Europe is increased by a similar relative amount. However, this coincides with a larger (although transient) reduction in the R:C ratio for gas in Europe (see Figure 15).

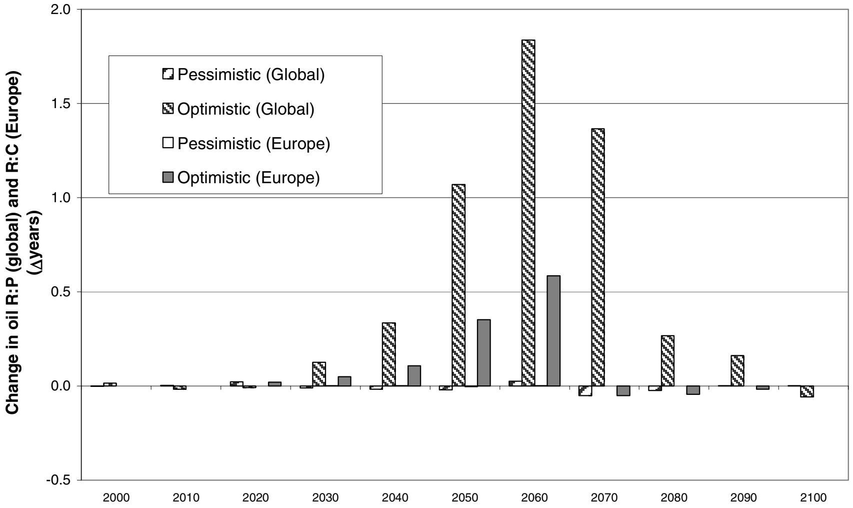

Figure 14: Change in global and European oil resource-to-production and -consumption ratios under alternative R&D scenarios, relative to baseline

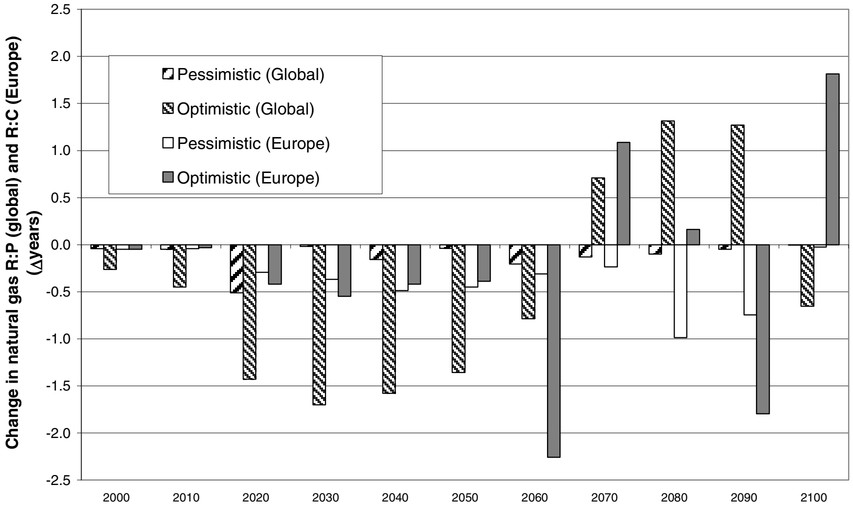

Figure 15: Change in global and European gas resource-to-production and -consumption ratios under alternative R&D scenarios, relative to baseline

This improvement in oil supply security under the optimistic R&D scenario is most likely indirectly attributable to the rapid shift to fuel cell vehicles. As discussed this alternative development path for the transportation sector alleviates some pressure from this sector on natural gas resources compared to the baseline scenario. Gas is a relatively low-emissions, clean and convenient fuel and the supplies freed up by a shift to hydrogen fuel cell vehicles can be used in other sectors, including in electricity generation, direct combustion and other forms of transport, where the greenhouse policy favours gas over oil. As a consequence, oil demand is reduced and the lifespan of resources is extended. However, this change does not persist, and increasing natural gas scarcity means that these expanded oil resources are eventually exploited (as seen in Figure 14).

This preference for natural gas means that under the optimistic R&D scenario the global resources-to-production ratio for this fuel is reduced early in the century (troughing in 2030), as seen in Figure 15, but the shift back to oil towards the end of the century eventually improves gas security of supply compared to the baseline. The pessimistic scenario, however, has a much smaller impact. Critically for long-term security of supply, the largest reduction in the global R:P ratio occurs at a time when global gas resources are still relatively abundant (2030, see Figure 7). This means this decline is less likely to have a significant impact on the likelihood or severity of supply disruptions. However, in Europe the largest decrease in the R:C ratio occurs in 2060, at a time when cheap gas resources have been largely exhausted, posing a potentially larger threat. Accordingly, for both oil and gas we focus on this period in subsequent analysis throughout this report.

4.3 Impacts

As discussed in Section 1, we are interested in measuring the impact of a change in R&D investment on the indicators of sustainability described above. This impact is defined as the change in the indicator, divided by the change in expenditure. Although this formulation is defined specifically for the standardised R&D shock exercise in the following section, it is possible to apply it to these optimistic and pessimistic scenarios.

We have already seen the change in the various indicators which represent the sustainable-development objectives of interest, so it is a relatively simple matter to divide these changes by the change in global government R&D expenditure relative to the baseline scenario. In the baseline scenario, government energy R&D investment on the technologies included in this modelling framework amounted to approximately €400 billion (undiscounted) between 2000 and 2050. Accordingly, the optimistic scenario is based on expenditure of around double this amount, while government energy R&D expenditure is assumed to be zero in the pessimistic scenario.

The impacts per billion euros of R&D expenditure under these scenarios are presented in Table 3. The units for the impact on each indicator are also indicated. So, for example, additional expenditure per year of $100 billion over the next 50 years reduces atmospheric CO_2 concentrations by approximately 2 ppm. On the other hand, reducing R&D expenditure by the same amount would increase concentrations by only 0.2 ppm. Similar differences in the impact magnitude between increases and decreases are observed for all indicators in Table 3. This is consistent with the results for the pessimistic scenario presented throughout Section 4, which do not diverge substantially from the baseline scenario results.

Table 3: Impacts on sustainability indicators of alternative R&D scenarios

Indicator	Impact Reduced investment (Pessimistic)	Additional investment (Optimistic)	Units
CO_2 conc. (2100)	-2.0E-03	-2.0E-02	ppm/€bn
CH_4 conc. (2100)	1.6E-03	-1.7E-02	ppb/€bn
Temperature (2100)	-5.6E-06	7.2E-05	K/€bn
Temperature (2100) (constant sulfate)	-6.6E-06	-5.7E-05	K/€bn
Sea-level (2100)	-4.7E-05	4.5E-04	cm/€bn
Security of oil supply (2060)	-5.7E-05	4.3E-03	years/€bn
Security of gas supply (2060)	4.8E-04	-1.8E-03	years/€bn

The fact that the pessimistic scenario does not diverge from the status quo implies that the level of government energy R&D investment assumed in the baseline scenario has a relatively insignificant impact on energy system development compared to that of other factors, such as the climate policy and resource constraints. This is not to say there is no place for government R&D in promoting new energy technologies, and the potential for such investment to transform the energy system is demonstrated by the impact of the optimistic R&D scenario. Clearly, the relationship between total R&D expenditure and the impact on indicators of sustainable development is non-linear. However, this analysis also shows that simply doubling energy R&D with little forethought in terms of overall strategy, targeting and consistency with other goals, is a very expensive way to achieve policy objectives. The next section attempts to go some way towards identifying the specific technologies that represent key targets for policy support and future R&D investment, with the aim of developing more cost-effective strategies for achieving desired sustainability outcomes.

5 Standardised R&D and D&D investment shocks

We now examine the impact of energy-related R&D and D&D investment on indicators of sustainability, focusing on climate change and security of energy supply. R&D investment is assumed to contribute to the development of new technologies and the improvement of some existing technologies. However, it should be emphasised that the process of technological change is highly uncertain, and so our analysis of the impact of R&D support programs can only provide a guide in terms of the impact of particular investment strategies. In this analysis, the impact of R&D on the development of a particular technology is assumed to manifest as a decrease in the cost deploying that technology, and possibly related technologies. This may accelerate commercialisation of a new technology, or improve the competitiveness of an existing technology, facilitating more extensive deployment.

We also examine the impact of demonstration and deployment (D&D) programs, which contribute to the accumulation of valuable experience with a particular technology in the marketplace. For instance, a successful introduction of a technology in niche markets can contribute to build up the confidence of potential users, equipment manufacturers and other social actors, such as policy makers. As a result of this experience, the technology performance and/or cost may improve, and these improvements may spillover to related technologies (see Turton and Barreto 2003 and Kouvaritakis and Panos 2005 for a discussion of the implementation of the clusters approach to learning in the SAPIENTIA project). Accordingly, strategic management of niche markets, where the technology may be attractive due to specific advantages or particular applications, may be important for stimulating the diffusion process of a given technology or cluster of related and/or complementary technologies (Kemp 1997).

As mentioned in Section 1, for the evaluation of the impacts of R&D and D&D programs we apply the notion of "shocks", i.e., one-off incremental investments in either research and development, or demonstration and deployment at the beginning of the time horizon (the year 2000). However, we treat these two shocks slightly differently to account for how R&D or D&D shocks are most likely and practicably implemented. Specifically, deployment and demonstration shocks are assumed to result in the installation of new and additional capacity of an entire technology (for example, a combined cycle gas turbine power station), which may comprise several independent components (such as a gas turbine, steam turbine and recovery boiler). The rationale behind this approach is that it is not possible to deploy a single component without also installing the rest of the system necessary for its operation. On the other hand, R&D shocks can be targeted at either an entire technology or towards individual components that cannot be deployed independently (for example, an on-board reformer for a fuel cell vehicle). Consequently, D&D shocks applied to one technology can directly stimulate the learning process for common components used by other technologies, whereas R&D shocks tend to be specific to a single technology, and spillover benefits mainly occur when the R&D shock leads indirectly to additional technology installations.

In this analysis we report the result of orthogonal R&D shocks and D&D shocks. The size of the R&D shock for each technology is set at 20 percent of cumulative R&D expenditure as at 2000 for that technology. By standardizing the size of the R&D shocks we ensure that we do not apply absurdly large investments to infant technologies (which are likely to saturate any response and reduce the impact per unit of expenditure), or unrealistically small shocks to mature technologies compared to the current levels of R&D investment. Through this approach, it is hoped that the results will better provide policy makers with a clearer indication of the potential impact on sustainability indicators of a given investment in R&D.

However, for D&D shocks we take a slightly different approach, and apply a one-off shock of 10 billion euros (€1999) to each energy technology of interest. Using a similar approach to that applied in the EC-sponsored MINIMA-SUD project (Barreto and Turton 2005), a standard D&D shock size has been chosen in order to be able to compare the effects of D&D shocks for different technologies on a common basis. Unlike R&D shocks, it is not necessary to standardise relative to previous investment because this is implicitly accounted for by the higher investment costs of less mature technologies. That is, *ceteris paribus*, €10 billion buys less capacity of an immature technology than a mature technology, so the new capacity installed as a result of the shock is already somewhat standardised.

It should be noted that the D&D shocks applied for this exercise account for the total capital cost of deploying new capacity. This is important because, in reality, a policy-maker (i.e., a government) may not need to pay this entire cost, but rather the difference in cost between the target technology and the technology that would have been deployed in the absence of policy intervention.

Like the R&D shocks, the D&D shocks shed some light into which technology would provide a larger "return-on-investment" in terms of the impact on sustainability indicators if a corresponding D&D program of the above-mentioned size were implemented. In doing so, the use of a standard size for the D&D shock greatly facilitates the comparison across technologies. As mentioned earlier, this analysis seeks to calculate "impacts" defined as the ratio Δ-Indicator/Instrument Cost, where "Δ-indicator" is computed as the change relative to the baseline scenario. The costs of either R&D or D&D programs are measured at "face value", i.e., as the respective R&D and D&D expenditures that constitute a shock.

Table 4: Description and abbreviations of technologies in the electricity generation, fuel production, passenger-car and carbon capture sectors for which R&D and D&D investment shocks were performed.

Sector	Technology Description	Abbreviation	Type of shock	
			D&D	R&D
Electricity generation technologies	Coal Conventional Thermal	HCC		x
	Integrated Coal Gasification Combined Cycle	HCA	x	x
	Oil Conventional Thermal	OLC		x
	Gas Turbine Combined Cycle	GCC	x	x
	Gas Conventional Thermal	GSC		x
	Gas Turbine Open Cycle	GTR	x	x
	Gas Fuel Cell (generic stationary)	GFC	x	a
	Nuclear (2nd and 3rd gen.)	NUC		x
	New Nuclear (4th gen.)	NNU	x	x
	Biomass	BIP	x	x
	Large Hydro	HYD		x
	Solar Thermal	STH	x	x
	Photovoltaic	SPV	x	x
	Wind Turbines Onshore	WND	x	x
	Hydrogen Fuel Cell (generic stationary)	HEF	x	a
Hydrogen production technologies	Hydrogen from Gas Steam Reforming	GASH2NE	x	x
	Hydrogen from Coal Partial Oxidation	COALH2NE	x	x
	Hydrogen from Biomass Pyrolysis	BIOH2NE	x	x
Passenger transport technologies	Gasoline-powered hybrid-ICE-electric car	ICH	x	b
	Gas-powered hybrid-ICE-electric car	IGH	x	b
	Alcohol-powered hybrid-ICE-electric car	IAH	x	b
	Hydrogen-powered hybrid-ICE-electric car	IHH	x	b
	Gasoline-powered fuel-cell car	PFC	x	a
	Alcohol-powered fuel-cell car	AFC	x	a
	Hydrogen-powered fuel-cell car	HFC	x	a
Carbon capture technologies	Pre-Combustion CO_2 capture (Integrated Gasification Combined Cycle)	HCACS	x	x
	Post-Combustion CO_2 capture (Conventional Coal)	HCCCS	x	x
	Post-Combustion CO_2 capture (Gas Turbine Combined Cycle)	GCCCS	x	x
	Pre-Combustion CO_2 capture (Hydrogen production)	H2CAS	x	x
Technology components	Generic fuel cell component	FCMS		x
	Hybrid-electric vehicle component	HYBV		x
	Pure electric vehicle component	ELVT		x
	Hybrid battery system component	HYBB		x

[a] R&D shock benefits technology through impact on "Generic fuel cell component."

[b] R&D shock benefits technology through impact "Hybrid-electric vehicle component", "Pure electric vehicle component" and 'Hybrid battery system component."

Orthogonal shocks have been performed for electricity generation, fuel production, passenger vehicle, carbon capture technologies and system components. The list of technologies, their abbreviations and the types of shocks applied are presented in Table 4. In the last section in the main analysis that follows (Section 5.4), we also examine the effects of non-orthogonal shocks combining R&D and D&D shocks.

As shown in Table 4, although R&D shocks are applied to all technologies assumed to benefit from learning-by-searching, not all technologies that may benefit from learning-by-doing are subjected to a D&D shock. This is because in many cases it is not considered realistic that additional public support would be provided to technologies considered to be mature or competitive, such as conventional coal, nuclear, large hydro and conventional oil generation.

In all cases, it is important to remember that the ultimate impact of any shock depends on many factors, limited not only to technology learning and clustering but also constraints on market penetration, resource potentials, costs and availability, and the climate change policy assumed also for these shock exercises.

5.1 An illustrative R&D policy shock

Before we present the results for all of the technologies in Table 4 that are assumed to benefit from learning-by-searching, it is helpful to present first in detail a single illustrative R&D shock.[4] The example presented here illustrates some of the possible ways in which R&D expenditure on a single technology can affect not only the competitiveness of that technology and through it the development of the energy system, but can also result in indirect spillovers that affect other unrelated technologies. By illustrating the effects elicited by a single shock, this example helps show how counter-intuitive results can arise – a fact that should be borne in mind when interpreting the results in Section 5.2 where we compare results from a large number of R&D shocks.

The example presented here is an R&D expenditure shock to the fuel cell technology. Specifically, a shock of 20 percent of cumulative R&D expenditure was applied in the base year (2000) to the generic fuel cell technology. This is estimated to be roughly equivalent to $7.5 billion in R&D expenditure (from a combination of private-sector and government), or slightly more than 1.1 percent of cumulative global energy R&D for energy conversion and transport as at 2000 (Kouvaritakis and Panos 2005).

As described in Kouvaritakis and Panos (2005), one 2FL equation is used to represent the capital cost of all fuel cell technologies, comprising both stationary and mobile technologies. As a consequence, an R&D shock on the generic fuel cell technology is expected to benefit a number of diverse applications of fuel cells. Furthermore, because many of these different fuel cell applications compete in entirely separate energy and technology markets, the impact on the development of the energy system has the potential to be wide-reaching.[5] In addition, the effect of an R&D shock is

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[4] Note, for comparison, the impact of an illustrative D&D shock is reported in Barreto and Turton (2005) – a report prepared for the EC-sponsored MINIMA-SUD project.

[5] As we saw in Section 4, the impact on fuels cells of the optimistic R&D scenario resulted in significant changes to the energy system.

likely to be reinforced by the impact of learning-by-doing, and a small competitive advantage afforded by an R&D shock may translate into the realization of a wholly different technological development path.

The impact on the future energy system of an R&D shock on the generic fuel cell technology is described below. Figure 16 compares the global electricity generation mix under this R&D shock with the baseline scenario across a number of timepoints in the 21st century.

Figure 16 appears to show that the overall impact on the electricity sector, both in scope and scale, is very similar to that presented for the optimistic R&D scenario in Figure 8. The main elements comprise a shift from hydrogen to gas fuel cells, increased generation from other gas-fired technologies, and lower generation from coal. Importantly, as in the optimistic scenario, total electricity generation from stationary fuel cells is largely unchanged from the baseline scenario – that is, under the assumptions used here fuel cells are already competitive in this sector without the R&D shock. However, in the transport sector the shock has a major effect on FC competitiveness, although again the result is similar to the optimistic R&D scenario from Section 4, as shown in Figure 17.

Accordingly, under the modelling and policy assessment framework assumptions used here, the R&D shock applied solely to fuel cells (approximately €7.5bn) results in much the same transformation of the electricity and transport sectors (and the energy system as a whole, for that matter) as the much larger-scale additional R&D investment (>€400bn) in the optimistic scenario. The effect on key indicators of sustainability is also much the same, as shown in Table 5, although the impacts are approximately 50-fold higher because the R&D expenditure is much more efficiently targeted.

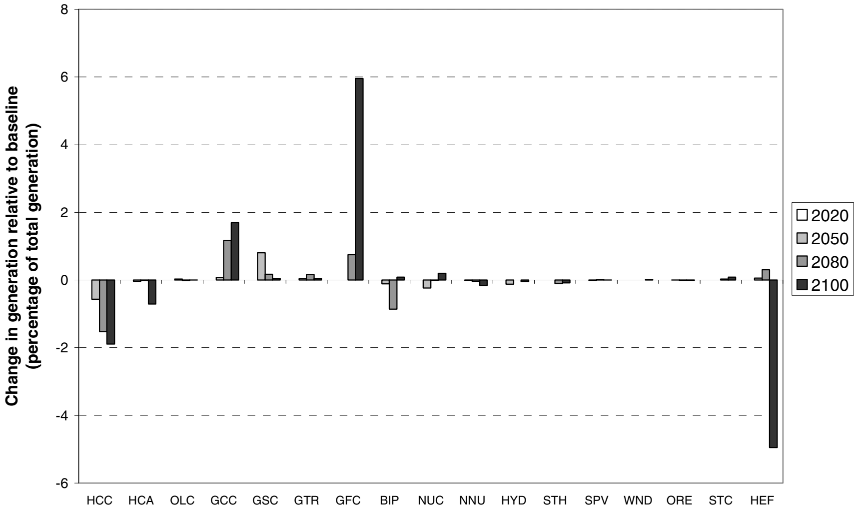

Figure 16: Change in global electricity generation under fuel cell R&D shock, relative to baseline (2020, 2050, 2080, 2100)

Note: Technology abbreviations are as follows: HCC: conventional coal, HCA: advanced coal (IGCC), OLC: oil conventional, GCC: gas combined-cycle, GSC: gas steam cycle, GTR: gas turbine, GFC: gas fuel cell, BIP: biomass gasification, NUC: nuclear conventional, NNU: new nuclear, HYD: hydro, STH: solar thermal, STC: solar thermal cogeneration, SPV: solar photovoltaics, WND: wind turbine, ORE: other renewables, HEF: hydrogen fuel cell.

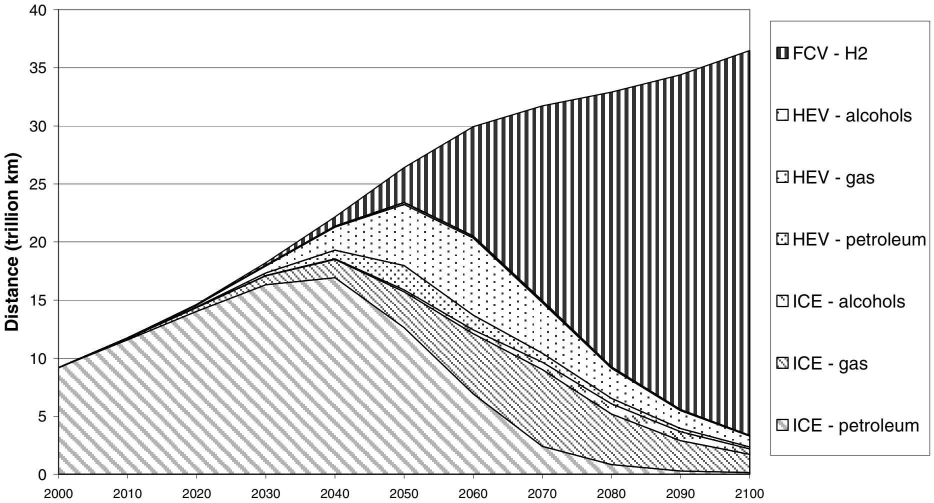

Figure 17: Global technology and fuel choice for passenger car travel with fuel cell R&D shock

Table 5: Calculation of impact on sustainability indicators of fuel cell R&D shock

Indicator	Baseline	Shock	Δ	Percentage	Impact	
						Units
CO_2 conc. (2100) (ppm)	702	695	-7.3	-1.04	-0.98	ppm/€bn
CH_4 conc. (2100) (ppm)	2539	2532	-6.9	-0.27	-0.92	ppb/€bn
Temperature change (K) (2100)	3.24	3.27	0.032	0.99	4.29E-03	K/€bn
Temperature change (K) (2100) (constant sulfate)	2.73	2.71	-0.020	-0.75	-2.72E-03	K/€bn
Sea-level rise (cm) (2100)	40.8	41.0	0.21	0.51	0.028	cm/€bn
Oil resource-to-production ratio (years) (2060)	32.6	33.7	1.2	3.62	0.16	years/€bn
Gas resource-to-production ratio (years) (2060)	45.2	44.4	-0.8	-1.80	-0.11	years/€bn

Note: rounding errors mean that reported Δs may differ from the apparent difference between the 'Baseline' and 'Shock' cases. The raw results are reported in Appendix Tables A3 and A4.

These results imply that well-targetted investments aimed at key technologies have the potential to substantially change the development of the energy system, although the impact on indicators of sustainability over this timeframe is generally small. However, when combined with complementary initiatives, additional R&D investment may have the potential to contribute to the realization of sustainability objectives. We now examine whether other R&D shocks are also able to improve sustainability indicators, with the following section summarising the results of the standardised R&D shocks for all of the technologies indicated in Table 4.

5.2 Summary of orthogonal R&D investment shocks

This section explores in brief the impact of a series of independent R&D investments in the base year (2000), on the main sustainable-development indicators discussed in Section 1. Detailed results from this orthogonal shock exercise are presented in the Appendix (Tables A3 and A4). Importantly, the results reported here comprise entirely "impacts", rather than indicator levels. That is, for each sustainable development indicator we present only the change in that indicator (relative to the baseline scenario described in Section 3) per billion euros of additional R&D investment. The detailed example in Section 5.1 for the fuel cell component illustrated how these impacts are calculated.

As we saw also in this example, although the magnitude of the changes that an R&D shock induces on the energy system may be large using this methodology, the impact on sustainability indicators can be small. This is confirmed for most shocks in Figure 18, which presents the impact on atmospheric CO_2 concentration at the end of the century under each shock. The biggest impacts appear to occur when an R&D shock is applied to either of two carbon capture technologies (GCCCS and HCCCS), and the biomass-to-hydrogen production technology (BIOH2NE).[6] However, these also happen to be three of the technologies that have historically received the least R&D support, and since the size of the shock is standardised to cumulative historical R&D investment, these technologies receive relatively small shocks (less than €50 million). This tends to exaggerate the size of any impact, even if insignificant. Accordingly, we also present the impacts from a €1 billion shock to each of these technologies (in addition, we apply the same shock also to two other carbon capture technologies (HCACS, H2CAS) and coal-to-H_2 production (COALH2NE), which have also historically received very little R&D support). The impacts under the €1 billion shock are much lower, in both relative *and in most cases absolute* terms, which indicates that these shocks do not have a particularly significant impact on atmospheric CO_2 concentrations, or any impact saturates at very low levels of additional R&D support.

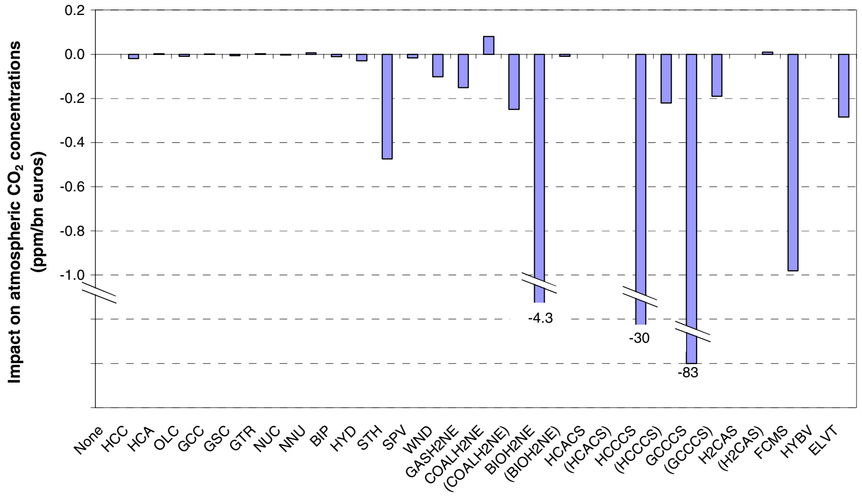

Figure 18: Impact of R&D shocks on atmospheric CO_2 concentrations in the year 2100, relative to baseline

Note: For abbreviations of the technologies see Table 4 on page 24. Impacts are reported in a way that is consistent with the change in the underlying indicator, so that a negative impact means the indicator decreased, and a positive impact means the indicator increased.

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[6] For description of abbreviations, see Table 4 on page 24.

Taking this into account, the biggest impact occurs with the R&D shock applied to the generic fuel cell technology. The impact of the R&D shock on solar thermal electricity generation may also be significant, but the absolute change in concentration was very small under this shock, however the size of the shock is just above €1 billion.

This result highlights the potential importance of fuel cells in a scenario based on the assumptions applied here. Conversely, for many other technologies it appears that these assumptions, such as the climate policy, resource endowments, and penetration and diffusion constraints for new technologies, are more significant than the impact of the R&D shock. In some ways this is a consequence of using a perfect-foresight model, which has a tendency to either install a technology to the maximum allowable extent or not to install it at all. Generally speaking then, an R&D shock will only have an impact when it results in an uncompetitive technology becoming competitive. Of course, both the model and reality are more complex this, and regional characteristics, the existence of niche markets and other factors mean that this "all-or-nothing" behavior will not necessarily occur.

However, it is important to stress the significance of the climate policy assumed in this analysis (see Section 3.1.1) when interpreting these results. Under the baseline scenario (with no R&D shocks) all GHG abatement opportunities that cost less than the rate of the GHG tax used to represent the climate policy are exploited, and this determines total emissions (and hence climate impacts). Accordingly, an R&D shock will only produce additional abatement if it reduces the cost of some of the abatement opportunities from above the GHG tax rate to below the GHG tax rate. This means that if the R&D shock makes abatement opportunities that are already competitive slightly cheaper, it will not reduce emissions (although it will reduce total system costs). On the other hand, if the R&D shock makes uncompetitive abatement slightly cheaper, but not cheaper than the GHG tax rate, it will have no significant impact on technology choice. This is illustrated in Figure 19. Accordingly, the stringency of the climate mitigation policy can have a significant bearing on the potential impact of an R&D shock. A different climate policy would be expected to change the relative impact of R&D shocks applied to different technologies, and may identify alternative technologies as possible targets for R&D support. This was seen, for example, for a combination of D&D shocks and GHG taxes in the EC-sponsored MINIMA-SUD project (Barreto and Turton 2005).

We now turn to some of the other sustainability indicators, and in Figure 20 we present the impact of the R&D shock on temperature in 2100. In this figure, we report only the larger shocks for those technologies for which the standardised shocks are very small (GCCCS, HCCCS, HCACS, H2CAS and BIOH2NE). The full results for these technologies are available in the Appendix (Tables A3 and A4), but once again, the absolute change in the indicator is effectively unchanged under the larger R&D shock indicating that these shocks do not have a significant impact or saturate at very low levels.[7]

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[7] Except for the shock applied to BIOH2NE, where the direction of the change in the indicator changes as the size is increased. Again, this implies that the impact is insignificant.

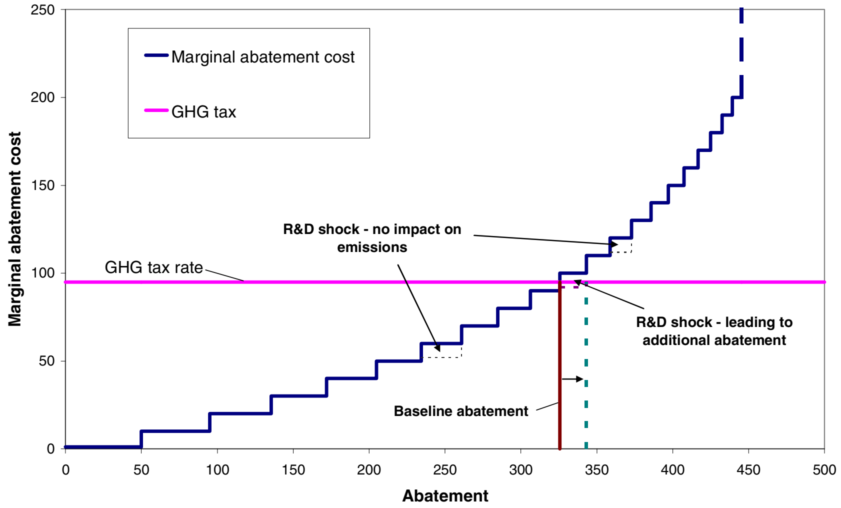

Figure 19: Illustration of impact of shock on level of GHG abatement

Figure 20 presents temperature change including and excluding the impact of sulfate aerosols. Looking first at the series with constant aerosol emissions, we see results that are entirely consistent with those for concentration in Figure 18 – with the largest impact on temperature occurring under the R&D shock to the fuel cell technology. As with concentrations, the effect with the solar thermal (STH) technology also appears to be significant, although the absolute change is very small (and this is the case for all the other technologies). When the impact on emissions of sulfate aerosols is also included, the picture is substantially different. The fuel cell shock goes from reducing temperature to increasing temperature because it displaces coal use (primarily coal-fired electricity generation as shown in Section 5.1), and presumably this also happens with the solar thermal shock.

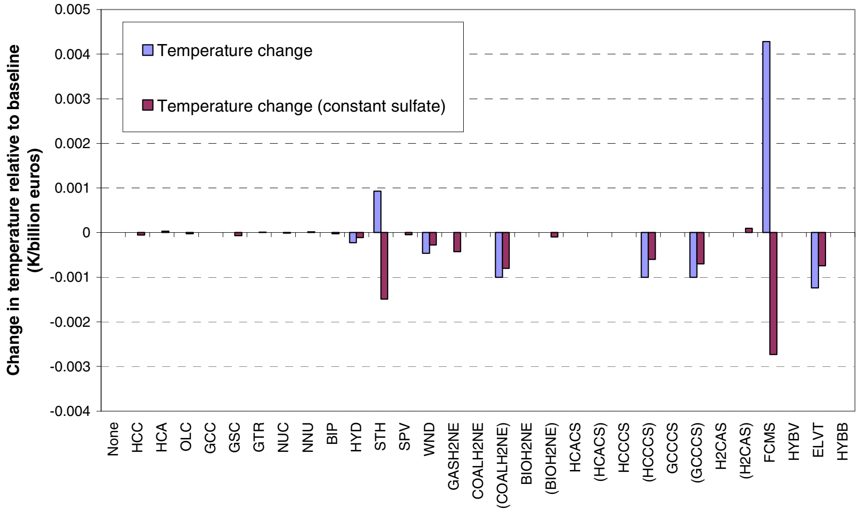

Figure 20: Impact of R&D shocks on global average temperature in the year 2100, realtive to baseline

Note: For abbreviations of the technologies see Table 4 on page 24. Impacts are reported in a way that is consistent with the change in the underlying indicator, so that a negative impact means the indicator decreased, and a positive impact means the indicator increased.

This leads to the somewhat perverse conclusion that one possible way of effectively mitigating climate change impacts is to support technologies that produce emissions of sulfur oxides (but minimal GHG emissions), whereas supporting the technology that is the most effective at reducing carbon emissions results in a higher global average temperature. However, this result occurs partly because adoption of fuel cells is still somewhat constrained, which implies that other factors limiting the deployment of fuel cell technologies also need to be addressed, in conjunction with any R&D policy support. These include the need to both mobilise new resources and technologies for hydrogen production, and finance the cost of establishing the necessary infrastructure for hydrogen distribution, possibly through public-private partnerhships. Demand-pull measures may also be need to accelerate market acceptance of new technologies, including procurement programs, tax credits and other measures.

The last sustainable-development indicator that we will present in this section is the global resources-to-production ratio for oil and gas in the year 2060. The impact on this indicator for each R&D shock is presented in Figure 21, where the largest positive impact on oil security occurs with the shock applied to the generic fuel cell technology. In addition, shocks to biomass- and coal-to-hydrogen (BIOH2NE COALH2NE), hybrid vehicle battery systems (HYBB) and carbon capture from advanced coal (HCACS) also apparently have a positive impact. This indicates that support for hydrogen technologies can potentially result in early deployment of these technologies, providing a flexible and convenient alternative to gas and oil. In addition, supporting technologies that improve the efficiency of oil consumption, such as the hybrid battery system can also extend oil availability.

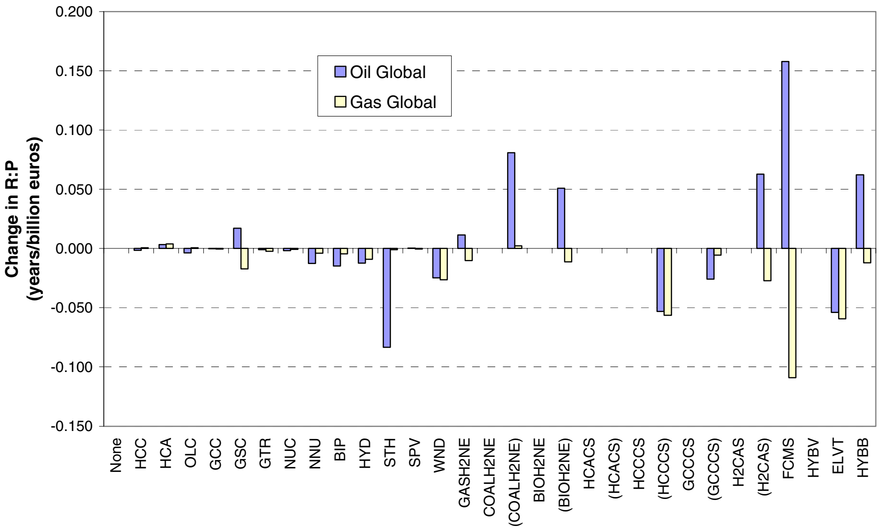

Figure 21: Impact of R&D shocks on global oil and gas resource-to-production ratios in 2060, relative to baseline

Note: For abbreviations of the technologies see Table 4 on page 24. Impacts are reported in a way that is consistent with the change in the underlying indicator, so that a negative impact means the indicator decreased, and a positive impact means the indicator increased.

Interestingly, the R&D shock to solar thermal generation worsens oil security, as do a number of other shocks targeted at technologies that may be able to contribute to a substitution of other energy sources for oil. This also occurs with gas security for many of the shocks. The explanation of why many of the shocks result in lower security for gas (and in some cases oil) is that the climate change policy appears to gear the energy system towards displacing coal. Consequently, if a shock can create additional ways of replacing coal with other fuels, including gas (and in some cases oil), then these are likely to be exploited resulting in lower R:P ratios. The fact that gas and oil are used, even though renewable and nuclear energy can theoretically displace coal, appears to be because most of the cost-effective nuclear and renewable options are already exploited under the baseline scenario; which is also why shocks to nuclear and renewable technologies have little impact. One exception appears to be solar thermal generation, but the R&D shock to this technology also appears to create additional opportunities to use oil, most likely to displace coal.

This concludes the more detailed discussion of the standardised R&D shocks. Those sustainability indicators not discussed in detail, including changes in atmospheric methane concentration, sea-level rise, and security of energy supply in Europe, are presented quantitatively in the Appendix.

Again, it is very important to re-emphasise that the impact of the R&D shocks depends significantly on the baseline scenario. Specifically, under the scenario considered here the assumed climate change mitigation policy (a GHG tax) means that a number of new low-emissions technologies are already competitive. Additional greenhouse gas abatement only occurs when an R&D shock brings the abatement cost associated with the deployment of a previously uncompetitive technology to below the level of the GHG tax. Under the climate change policy assumed for this exercise, the R&D shock applied to fuel cells was the most (and possibly only) effective shock in terms of the indicators of climate change. Furthermore, it also had the largest impact on security of energy supply, being effective at extending the oil R:P ratio. However, although this shock results in a significant transformation of the energy system (as seen in Section 5.1), the impact on the climate change indicators was only small because of the effect of other factors. Clearly, any overall strategy to achieve sustainability goals through support for energy technology R&D, should include additional policy elements that complement and fully exploit the impact of the R&D policy. One possible set of complementary measures comprise support for demonstration and deployment (D&D) programs that attempt to accelerate technology adoption by focusing on the demand side. The next section explores the possible impact of such D&D programs, by applying orthogonal D&D shocks to the technologies indicated in Table 4.

5.3 Summary of orthogonal D&D investment shocks

In this section we present the impact of a series of demonstration and deployment (D&D) shocks on the same suite of indicators discussed in the preceding section. These deployment shocks are applied in much the same way as the R&D shocks – that is, independently (orthogonally) and in the base year (2000) – and, as discussed at the start of Section 5 the magnitude of each D&D shock is €10 billion. In this section we present only "impacts" calculated based on the full cost of the D&D shock, although it is unlikely that public expenditure would need to cover all of this cost. Further, although the focus here is on "impacts", in many cases it leads naturally to a discussion of indicator levels (which are also reported in the Appendix in Table A3).

Unlike for the R&D shock exercise, we do not present a detailed example of the impact of a D&D shock. Instead, readers are referred to the IIASA/ECS report for the EC-sponsored MINIMA-SUD project (Barreto and Turton 2005), which presents in detail an illustrative example of the impact of a single D&D shock.

As we emphasised in the discussion of the R&D shocks, the reader should bear in mind that the impacts of demonstration and deployment (D&D) shocks depend on the baseline scenario. The assumed baseline technology development and climate policy may have a large bearing on the potential impact of any D&D shock.

5.3.1 Atmospheric CO_2 and CH_4 concentrations

Unlike the R&D shocks, D&D shocks affect technology learning by forcing deployment of the shocked technology. This deployment not only results in additional experience with the technology, but creates new energy-system opportunities and therefore results in different impacts to the R&D shocks, which do not necessarily lead to technology deployment.

This is illustrated for the impact on atmospheric concentrations of CO_2 and CH_4 under the D&D shocks as shown in Figure 22. Compared to the R&D shock impacts in Figure 18, the impacts in Figure 22 affect different technologies and appear to produce worse sustainability outcomes for atmospheric GHG concentrations. In some cases this is expected, such as for the impact on CO_2 concentrations of the shock applied to advanced IGCC generation, because it accelerates the deployment and improves the competitiveness of a relatively more emissions-intensive technology. However, somewhat surprisingly, a demonstration and deployment shock applied to either gas combined cycle generation (GCC), biomass generation (BIP) or solar thermal generation also results in higher atmospheric CO_2 concentrations.

Closer examination reveals that in all three cases, the shock increases the competitiveness of the shocked technology leading to installation of additional generation capacity which helps to defer the adoption of, and ultimately lock out, hydrogen fuel cell electricity generation. However, over the longer term none of the shocked technologies is able to make a sufficiently large contribution to electricity generation because of constraints on resource availability (gas and biomass), and intermittency in the case of solar thermal generation. As a consequence, heavy reliance on conventional coal-fired generation continues longer than under the baseline scenario, resulting in higher emissions and atmospheric concentrations of CO_2.

Similarly, a D&D shock applied to advanced nuclear generation also locks out the use of fuel cells, but unlike the three technologies discussed above, nuclear generation is assumed to be able to make a large-scale contribution to total generation. This means that coal-fired generation is displaced by nuclear earlier and on a larger scale than with the renewables or GCC, resulting in lower GHG emissions (although they are still higher than under the baseline because the additional nuclear generation is unable to fully offset the decline in generation from fuel cells). It should briefly be mentioned that this result for advanced nuclear generation is different to that presented in Barreto and Turton (2005) for the EC-sponsored MINIMA-SUD project mainly because of different technology assumptions regarding fuel cells.[8]

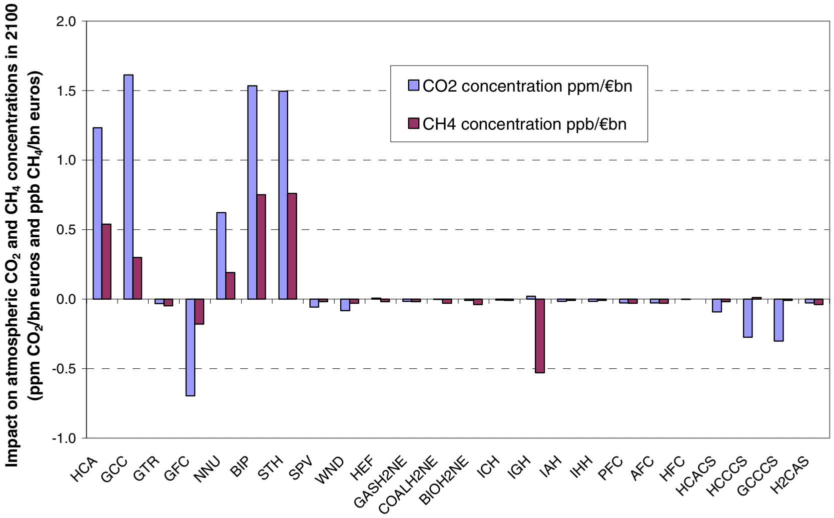

Figure 22: Impact of D&D shocks on atmospheric CO_2 and CH_4 concentrations in the year 2100, relative to baseline

Note: For abbreviations of the technologies see Table 4 on page 24. Impacts are reported in a way that is consistent with the change in the underlying indicator, so that a negative impact means the indicator decreased, and a positive impact means the indicator increased.

So far we have discussed those D&D shocks that exacerbated climate change, but there are a number, however, that result in abatement and lower atmospheric CO_2 concentrations. The largest reduction occurs with the shock applied to the gas fuel cell technology. This is not unexpected considering the importance of fuel cell generation over the century under the baseline scenario. This shock accelerates the deployment of gas fuel cells, which reduces reliance on other gas and coal-fired generation. However, the additional and early experience with fuel cells is not sufficient under the assumptions applied here to result in widespread adoption of fuel cells in transportation.

An interesting result of the shock exercise is that an identical shock applied to stationary hydrogen fuel cell generation has almost no impact on the climate change indicators of interest. This result is not surprising however, if one considers that the deployment of hydrogen fuel cell generation cannot have any significant impact on the energy system because of insufficient hydrogen production and limited distribution infrastructure – this deployment shock results in construction of a “white elephant”. This highlights the importance of adopting a co-ordinated strategy when supporting new technologies, that accounts for upstream and downstream requirements for successful deployment – in this case, the D&D policy should be complemented by support for accelerated investment in hydrogen production and distribution infrastructure, and possibly carbon capture technology.

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[8] Specifically, the technology learning parameters in MINIMA-SUD reflected lower optimism regarding the potential effect of learning-by-doing on the cost of stationary fuel cell generation capacity. Consequently, this technology was not installed in significant quantities, and hence could not be displaced by a D&D shock.

Other shocks that result in a noticeable reduction in emissions are those applied to carbon capture technologies for post-combustion capture from conventional coal and gas generation. The accelerated deployment and experience with these technologies reduces emissions earlier in the century, but because the associated electricity generation technologies play a declining role later in the century, these shocks have only a limited impact.

Deployment shocks applied to capture technologies that currently have no market – that is, carbon capture from advanced IGCC generation and from hydrogen production – have no impact because only very limited experience is gained. Similarly, shocks applied to hydrogen production technologies have essentially no impact because of limited hydrogen distribution infrastructure or hydrogen demand initially. As briefly mentioned already, this highlights the need to co-ordinate technology support policies so that they target all of the key elements in the energy chain, particularly where the deployment of each of these elements is confronted by significant barriers. Hydrogen-based technologies are perhaps the best examples of this because they are highly interdependent and all elements need to be in place before any of the potential benefits of a hydrogen-based energy system can be realised. The need for large-scale co-ordinated investment in such systems implies that there may be a role for government intervention, particularly in co-ordinating infrastructure planning and accepting some of the risk associated with interdependent capital-intensive investment.[9]

The relative impact of the D&D shocks on atmospheric concentrations of methane at the end of the 21st century closely resembles the impact on CO_2 concentrations. This is somewhat surprising because shocks were applied to very different technologies (e.g. coal, gas, renewables, nuclear, fuel cells), which are expected to have different impacts on natural gas consumption. Natural gas production is the only source of methane emissions that differs under the shocks, since the D&D shocks are assumed not to change methane emissions from other activities such as agriculture.

However, in addition to displacing hydrogen fuel cell generation, many of these shocks also displace natural gas generation through the first half of the century and hence reduce methane emissions (although in all cases the impact is very small compared to the total methane concentration). This is even the case for the shocks applied to gas combined cycle (for a short period) and fuel cell generation, which displace other less-efficient forms of gas consumption. However, it appears that under many of these shocks, most of the gas that was saved earlier in the century is exploited towards the end. The tendency of the shocks to shift gas consumption to later in the century, combined with the short atmospheric residence time of methane, means that the many shocks increase methane concentrations in 2100. However, for the shock to gas fuel cells and gas hybrids (IGH) this does not occur. The early deployment of gas fuel cells under this D&D shock continues to keep gas consumption slightly lower throughout much of the century, and even though there is an increase towards the end, it is relatively small. Conversely, the gas hybrid D&D shock works in the opposite way to the other shocks by increasing gas consumption earlier in the century, meaning that less gas is available towards 2100.

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[9] There may well also be an important government role in regulating what are likely to be monopoly hydrogen distribution assets.

5.3.2 Temperature

The impact of the standardised D&D shocks on temperature change relative to the baseline scenario is presented in Figure 23. Looking first at the results with constant sulfate aerosols, the greatest temperature increase occurs with the gas combined-cycle D&D shock, followed by the biomass and solar thermal shocks. Because of their impact on locking out one of the least emissions-intensive technologies, these three shocks produce more climate warming than the shock applied directly to IGCC generation (HCA). Accordingly, these results mirror those for atmospheric CO_2 concentrations. Similarly, the D&D shocks that reduce concentrations – comprising the shocks to gas fuel cells and two carbon capture technologies – result in equivalent mitigation of temperature change.

The impact estimates in Figure 23 that incorporate the effect of changes in aerosol emissions are somewhat more complicated. Perversely, those D&D shocks that lock out hydrogen fuel cells thereby resulting in additional generation from conventional coal, actually result in smaller temperature increases because of higher SO_x emissions from coal generators. On the other hand, the shock applied to advanced coal generation results in both higher coal use and lower SO_x emissions because IGCC generators are assumed to include desulfurisation units, contributing to a large increase in temperature. However, the D&D shock applied to the natural gas fuel cells also leads to this outcome, again because it displaces coal-fired generation and therefore reduces both CO_2 and SO_x emissions.

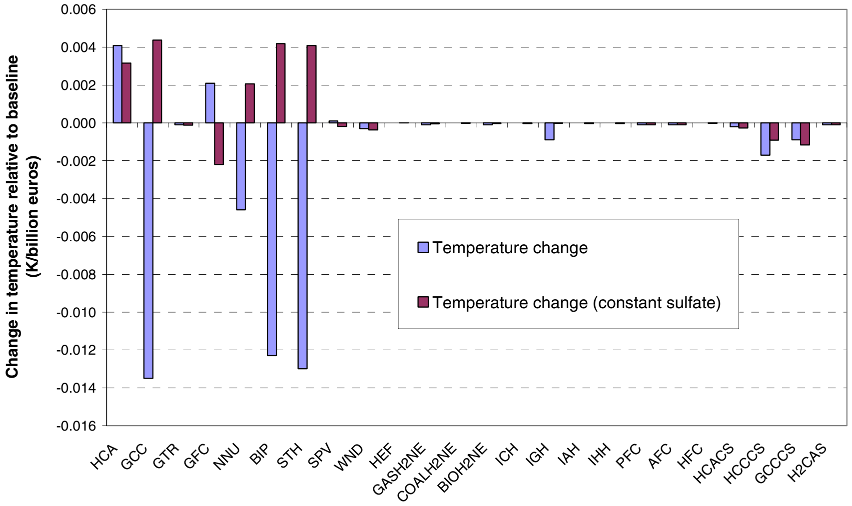

Figure 23: Impact of D&D shocks on global average temperature in the year 2100, realtive to baseline

Note: For abbreviations of the technologies see Table 4 on page 24. Impacts are reported in a way that is consistent with the change in the underlying indicator, so that a negative impact means the indicator decreased, and a positive impact means the indicator increased.

5.3.3 Security of supply

The discussion so far of the impact of the D&D shocks on other sustainability indicators has touched on some issues related to energy security of supply. We now focus on the impact on gas and oil resources-to-production ratios in more detail, to explore some of the possible impacts on security of D&D programs.

Figure 24 shows that almost all of the shocks that were observed to have a significant impact on the other indicators of sustainability, also have an impact on security of energy supply. In general, these D&D shocks tend to increase global oil availability and decrease or leave roughly unchanged, gas availability in 2060. The impact on oil can be explained by the fact that these shocks facilitate additional energy production from technologies that do not use oil, consequently leading to lower oil consumption and extending the life of oil resources. The biggest impacts on long-term oil security occur with D&D shocks applied to advanced coal IGCC, natural gas combined-cycle, advanced nuclear, biomass and solar thermal generation. Smaller positive impacts arise with demonstration and deployment of gas fuel cells and gas hydrid vehicles.

The impact of these shocks on natural gas resources-to-production ratios is consistent with the earlier discussion of these shocks, particularly in relation to methane emissions. In Section 5.3.1 above, we noted that many of these shocks displace gas consumption earlier in the century, resulting in higher gas consumption in the second half of the century. However, for shocks to gas combined cycle generation and gas hybrids, gas consumption is encouraged from earlier in the century, which results in the greatest impact on the R:P for gas (see Figure 24). The shocks to IGCC, gas fuel cells, advanced nuclear, biomass and solar thermal generation result in smaller impacts, and diverge depending on how advanced the shift back to gas is by 2060 in these scenarios. The actual pattern of gas consumption in each of these scenarios is quite complicated, and it is beyond the scope of this report to describe them in detail. However, a general note is that gas is a very attractive fuel under the assumptions applied here – it has a low carbon content and is flexible and convenient – so any D&D shock that provides a way to use more gas in place of less attractive fuels can be expected to be fully exploited over time.

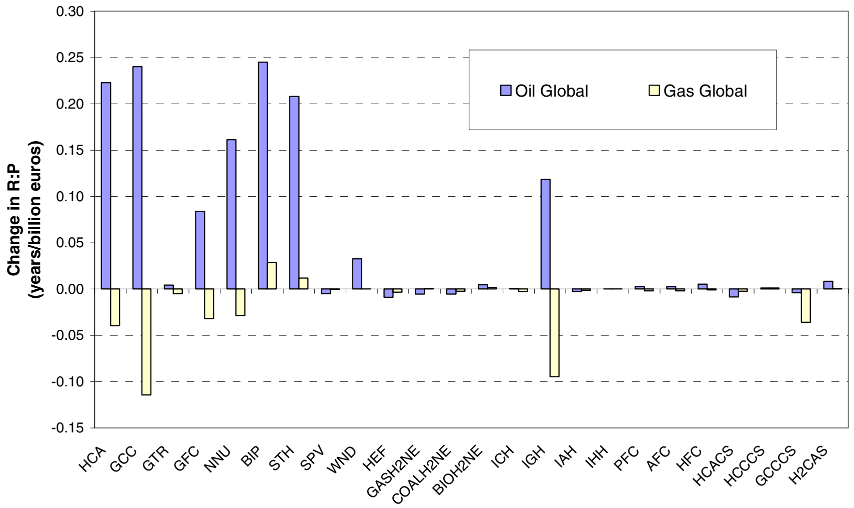

Figure 24: Impact of D&D shocks on global oil and gas resource-to-production ratios in 2060, relative to baseline

Note: For abbreviations of the technologies see Table 4 on page 24. Impacts are reported in a way that is consistent with the change in the underlying indicator, so that a negative impact means the indicator decreased, and a positive impact means the indicator increased.

It should also be noted from Figure 24 that there appears to be a trade-off between the two indicators of global security of energy supply. That is, shocks leading to a larger oil R:P ratio tend to result in a smaller gas R:P ratio, meaning that as the global energy system weans itself away from oil, it tends to increase its reliance on natural gas.

The impacts of the D&D shocks compared to those of the R&D shocks presented in Section 5.2 depend on a number of factors, including the stage of development each technology is in, and the extent to which the broader energy market is compatible for a specific technology – that is, whether the necessary complementary systems exist, particularly infrastructure, and whether there is a market for the technology output. The next section examines whether these two types of technology policies can be combined in supporting ways to create additional opportunities to realise sustainability objectives.

5.4 Combined D&D and R&D investment shocks

In our discussion of the results of orthogonal R&D and D&D shocks, we noted on a number of occasions that a shock may result in a limited or undesirable impact on sustainability because of constraints on other parts of the energy system. In some ways this is not surprising because a single shock cannot be expected to direct the development of the entire energy system onto a more sustainable path, and although it may address barriers to the adoption of one technology, it may in doing so raise barriers for other technologies.

Some of the best examples of the potential undesirable effects of a shock were observed for many of the D&D shocks which displaced hydrogen fuel cell electricity generation, effectively locking out this technology and resulting in poorer sustainability outcomes. This outcome can be partly explained by constraints on the learning and deployment rates of the fuel cell technology – that is, this technology is only locked out because its learning and deployment rates restrict its ability to recover from the delay in learning-by-doing caused by the shock. One way to circumvent some of these other constraints is to target multiple parts of the energy system with simultaneous shocks, effectively applying a more consistent technology and policy strategy. In this section we present one set of simultaneous D&D and R&D shocks to explore the potential for well-targetted technology support to transform the energy system and lead to improved sustainability outcomes. These shocks are defined and applied exactly as outlined at the start of Section 5.

In an attempt to identify shocks which may potentially have a greater impact on the sustainability indicators of interest, we selected the R&D shock with the greatest impact as the starting point for this analysis. This shock, applied to the fuel cell technology component, was observed to have the largest positive impact on a number of the sustainability indicators (see Section 5.2). In this analysis we then combine with this R&D shock each of the D&D shocks to ascertain whether the positive impact can be enhanced by targeting directly or indirectly related technologies. The effects on selected climate change and security of supply indicators are outlined below, again in the form of impacts.

5.4.1 Energy system development and atmospheric GHG concentrations

The impact on atmospheric CO_2 concentrations of the combined R&D and D&D shocks is presented in Figure 25. Again, this figure shows the impact per total shock expenditure – combining R&D expenditure of €7.47 billion and D&D expenditure of €10 billion – on this sustainability indicator. For comparison, Figure 25 also includes the impact of the R&D shock alone. The most noticeable result is that the impact of the combined shocks is generally lower than that of the independent R&D shock. However, it should also be noted that applying a similar-sized R&D shock to the fuel cell technology alone (i.e., €17.47 billion) has a lower impact per euro because of saturation of potential learning-by-searching (shown by the large dot in Figure 25). Moreover, it should be remembered that the total investment is around 130 percent greater under the combined shocks, and so the absolute change in the indicator is higher in a number of cases under the combined shock, even though the "impact" is lower. This is illustrated in Figure 25 where the dashed line shows what the impact would be if the incremental D&D shock had no effect on concentrations.[10]

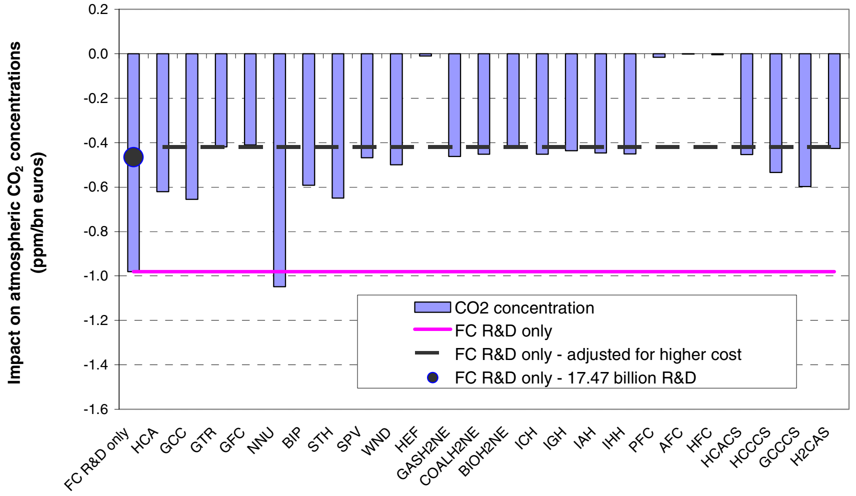

Figure 25: Impact of D&D shocks combined fuel cell R&D shock on atmospheric CO_2 and CH_4 concentrations in the year 2100, relative to baseline

Note: For abbreviations of the technologies see Table 4 on page 24. Impacts are reported in a way that is consistent with the change in the underlying indicator, so that a negative impact means the indicator decreased, and a positive impact means the indicator increased.

Figure 25 shows that the greatest impact is observed with the combined fuel cell R&D and advanced nuclear D&D shock. This is particularly interesting because this D&D shock alone resulted in an <u>in</u>crease in CO_2 concentrations of around 0.6 ppm/€bn (see Figure 22), whereas the combined shock results in a <u>de</u>crease of over 1 ppm/€bn. The increase in concentrations under the single shock was discussed in Section 5.3.1, and can be attributed to crowding out of fuel cell generation by additional advanced nuclear generation. By contrast, the combined shock provides sufficient support for

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[10] Interestingly, the dashed line is at roughly the same level as the large dot representing the impact with higher R&D expenditure. This implies that the impact of this R&D shock is already largely saturated.

fuel cells such that advanced nuclear does not displace and lock out hydrogen fuel cell generation, but instead displaces additional coal-fired generation. In addition, the combined fuel cell R&D shock results in the adoption and rapid penetration of fuel cells in transport applications, as was observed for this shock alone (Section 5.1). This example highlights the potential benefits of a co-ordinated strategy aimed at low-emissions technologies, particularly for overcoming unhelpful competition between low-emissions sources.

In Section 5.3, the advanced nuclear generation D&D shock was not the only one to displace and lock out fuel cells, leading to higher CO_2 concentrations. This result was also seen for D&D-only shocks applied to biomass, solar thermal and gas combined cycle generation (which increased CO_2 concentrations by more than 1.5 ppm/€bn, see Figure 22). However, Figure 25 shows that when combined with the fuel cell R&D shock, all of these D&D shocks now reduce concentrations because they no longer lock out hydrogen fuel cell generation. These shocks now produce an impact that is more intuitive, considering they provide support for low-emissions generation technologies. Similarly, the D&D shock applied to the advanced IGCC technology (HCA), although more emissions intensive than other sources, now improves emissions because it displaces almost entirely conventional coal generation, instead of fuel cells (which was the case when the D&D shock was applied independently, as shown in Section 5.3). Taken together, these examples highlight the importance of developing and implementing a co-ordinated and reinforcing (as opposed to competitive) technology strategy for realizing sustainability objectives.

Interestingly, combining the fuel cell R&D shock with a D&D shock targeted at directly related technologies such as gas or hydrogen fuel cell generation (GFC, HEF) has no additional impact, or results in a relative worsening (increase) in atmospheric concentrations in the case of the D&D shock to hydrogen fuel cell generation. These results can be explained by appreciating the interplay between different fuel cell technologies, and the limited availability of hydrogen.

Looking first at the gas fuel cell generation technology, a D&D shock reinforces the impact of the R&D shock on the competitiveness of fuel cell electricity generation. This results in much greater output from fuel cell generators (than under the R&D shock alone). Moreover, the D&D shock also provides a slight competitive edge to stationary fuel cells over mobile fuel cells, which is sufficient to render more attractive the use of hydrogen in stationary generation rather than transport. As an overall consequence, the impact on atmospheric CO_2 concentrations from a greater share of electricity generation from low-emissions fuel cells (compared to under the R&D shock alone) is offset by the failure of fuel cells to penetrate significantly the transport market.

In the case of the hydrogen fuel cell (HEF) D&D shock, although it provides some learning-by-doing benefits initially, its impact on the energy system is small because of the very limited availability of hydrogen production and distribution infrastructure early in the century. However, the one impact of this combined shock is to provide enough competition for the small quantities of hydrogen that are available early in the century to stifle the emergence of a fuel cell powered transportation sector. As a consequence, this D&D shock results in almost no additional fuel cell generation compared to the baseline scenario, and no deployment of fuel cells in transportation.

That is, it undermines the positive effects of the R&D shock on CO_2 concentrations, even though both shocks support very similar technologies.

A similar result is observed when the fuel cell R&D shock is combined with D&D shocks to any of the fuel cell transportation technologies (PFC, AFC and HFC). These technologies are very expensive at the time the D&D shock is applied, so deployment cannot establish the necessary critical mass to support the early emergence of a fuel cell-based transport system. However, these shocks provide some learning-by-doing experience with fuel cells, which is sufficient for the stationary technologies to gain a relative competitive advantage to mobile fuel cell applications. To put this another way, a little support is required to make mobile fuel cells competitive with other transport technologies, but too much D&D support at the "wrong" time appears to make the use of hydrogen in stationary fuel cells more attractive. Because there is more potential demand for hydrogen than there is supply, the less competitive applications (in transport) are displaced by alternative technologies – in this case, by hybrids and alcohol fuels. This result may be reinforced by the requirement for possible additional hydrogen distribution requirements for mobile fuel cell applications. In Figure 25, we see that there is almost no impact on atmospheric CO_2 concentrations relative to the baseline scenario. It is important to emphasise that this appears to be quite a complex result, with a number of reinforcing and countervailing forces operating simultaneously, so these results can only provide an initial guide as to the possible consequences of this combination of technology support policies.

The only other significant results in Figure 25 relate to the demonstration and deployment shocks applied to post-combustion carbon capture from coal and gas electricity generation (HCCCS, GCCCS). In the case of both of these technologies, the impact of the combined R&D-D&D shock appears to be roughly equal to weighted average of the separate impacts. This implies that these shocks are largely independent, even though we have seen that the fuel cell R&D shock displaces some coal-fired electricity generation.

5.4.2 Global temperature change

The impact on temperature change of the combined R&D and D&D shocks is presented in Figure 26. Once again, when the effect of the shock on emissions of oxides of sulfur (SO_x) is excluded, the impact on temperature closely mirrors the impact on atmospheric CO_2 concentrations, which is not surprising. However, a more complex picture emerges when the overall impact on temperature is examined. Figure 26 shows that the R&D shock alone has close to the worst impact on global average temperature in 2100, under the assumptions applied here. However, as discussed above, this result is largely due to the fact that total expenditure on R&D and D&D is 130 percent larger under the combined shock than for the R&D-only shock, and SO_x emissions do not change by anywhere near as much. In Figure 26 we also show what happens to the impact of the R&D shock if we simply assume a larger expenditure, illustrated by the dashed line with squares. Comparing this with the reported impacts for the combined shocks shows that in many cases the additional D&D expenditure makes only a very small change to the actual temperature. This is partly because many shocks have little additional impact, as was seen for emissions in Figure 25, but is also partly explained by the aversion to coal under the assumptions applied here, particularly the climate policy. This aversion means that any shock will tend to reduce coal consumption (especially using conventional technologies), reducing CO_2 and, in many cases, SO_x as well, which tends to balance the impact on radiative forcing and temperature change.

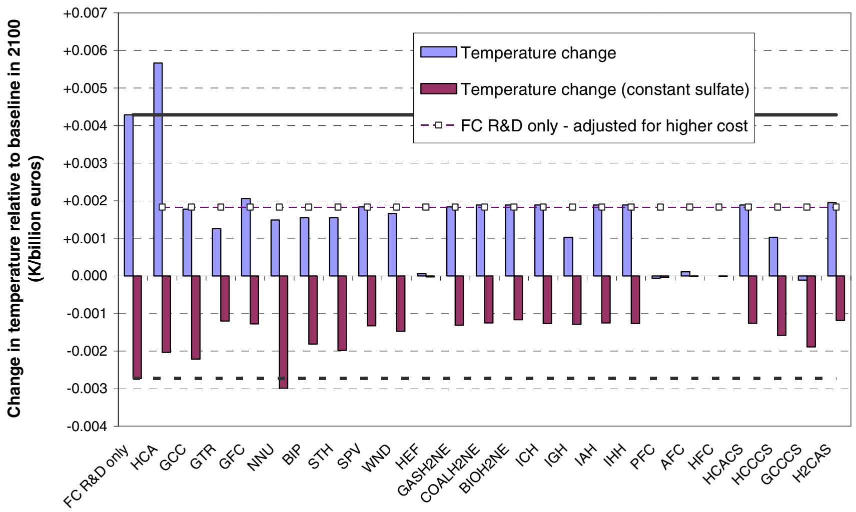

Figure 26: Impact of D&D shocks combined fuel cell R&D shock on global average temperature in the year 2100, realtive to baseline

Note: For abbreviations of the technologies see Table 4 on page 24. Impacts are reported in a way that is consistent with the change in the underlying indicator, so that a negative impact means the indicator decreased, and a positive impact means the indicator increased.

One important exception, of course, is the D&D shock to IGCC coal generation, which supports coal consumption while at the same time significantly reducing SO_2. However, the D&D shock to IGCC (HCA), in combination with the R&D shock to fuel cells, is far more effective at displacing conventional coal than either shock alone. As a consequence, CO_2 emissions and forcing are lower but SO_x emissions are much lower, and this manifests as a higher average global temperature in Figure 26.

It is interesting to contrast this result with some of the other technology shocks that result in a relative reduction in global temperature. Looking at both indicators of temperature change (with and without changes in sulfate forcing), the D&D shock applied to the gas combined cycle carbon capture technology is the only one to improve both, which also occurred when this D&D shock was applied without the gas fuel cell R&D shock. However, the impact on constant-sulfate temperature is about the same under this combination of shocks as it is for the IGCC-fuel cell combination discussed in the previous paragraph, even though the latter results in the highest temperature when SO_x emissions are considered. The choice of which is the most appropriate indicator to target has been discussed in previous sections, and the consequences of this choice is starkly illustrated by the choice between these two technology support combinations.

Importantly, however, there are other shock combinations which have an even greater impact on temperature with constant sulfate, such as the combined fuel cell R&D and advanced nuclear D&D shock. This shock also results in a *relative* improvement in the impact on global temperature when changes in SO_x emissions are also considered. Other combined shocks that improve both indicators relative to the single R&D shock are those targeted at gas combined cycle (GCC), solar thermal (STH) and biomass (BIP) generation, and carbon capture from conventional coal generation (HCCCS). Most of the other combined technology shocks behave similarly to the D&D-alone shocks, although starting from a different baseline.

5.4.3 Security of energy supply

We now turn to the impacts on indicators of security of energy supply. As mentioned earlier in this report, the resources-to-production ratio used as an indicator of energy security differs from the conventional reserves-to-production ratio (BP 2004) in that it is a long-term indicator of sustainable resources use which can only be influenced through changes in consumption, unlike the reserves-to-production ratio which can be increased by identifying and reclassifying resources.

Under the shocks examined here, impacts on the resources-to-production ratio for oil in the year 2060 are in almost all cases positive or zero, as shown in Figure 27. However, this is not surprising considering that the R&D shock alone elicits the same or a stronger response, as do many of the D&D-only shocks (Sections 5.1 and 5.3.3). In almost all cases these shocks are able to displace oil consumption largely by increasing gas consumption. As briefly mentioned earlier, under the assumptions used in these scenarios gas is a very attractive fuel. Accordingly, the additional pathways created by the shocks that allow the efficient use of gas to displace less attractive fuels such as coal are exploited. Consequently, as shown in Figure 27, this means that the incremental effect on the indicator of all but five of the D&D shocks on gas security is negative (refer to the dotted line in Figure 27 indicating the level of the R&D-only shock after adjusting for the additional cost of the D&D shocks).

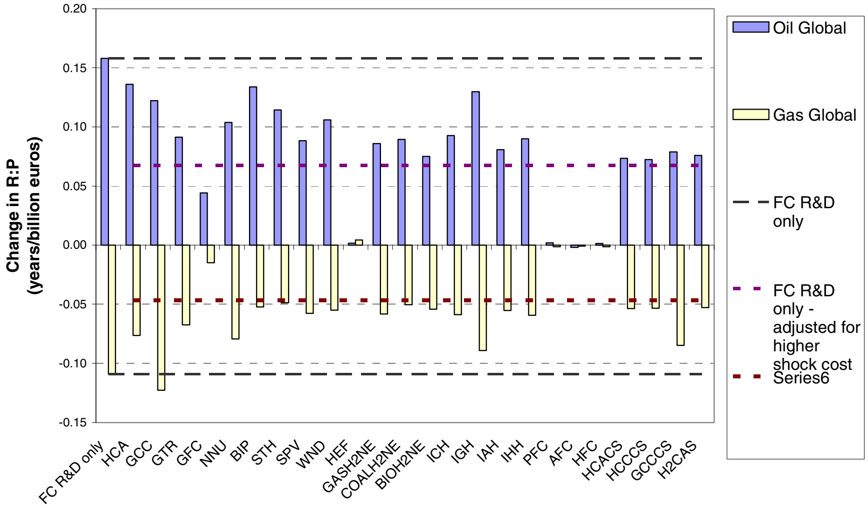

Figure 27: Impact of D&D shocks combined fuel cell R&D shock on global oil and gas resource-to-production ratios in 2060, relative to baseline

Note: For abbreviations of the technologies see Table 4 on page 24. Impacts are reported in a way that is consistent with the change in the underlying indicator, so that a negative impact means the indicator decreased, and a positive impact means the indicator increased.

The five combined D&D shocks that improve gas security (while worsening oil security) relative to the R&D-only shock have been discussed earlier in Section 5.3.3, and comprise entirely shocks targeted at the fuel-cell technologies (GFC, HEF, PFC, AFC, HFC). The impact of these shocks is small because they ultimately support stationary hydrogen fuel cell generation, but are unable to stimulate additional hydrogen production, and so these technology support scenarios do not diverge substantially from the baseline scenario (with the exception of the shock to stationary gas fuel cell generation which supports additional deployment of this technology, relative to the baseline).

Since all other combined shocks worsen gas security relative to the R&D-only shock, we can only attempt to identify those technology support combinations that have the smallest additional negative effect while maximizing oil security. Of course, the relative importance of these sustainability indicators should determine the weighting applied to maintaining the lifetime of either resource. However, it should be noted that the oil R:P ratio is generally lower than the gas R:P (see Section 3.2.3) under the assumptions applied here, so declines in the oil ratio may be more likely to lead to the emergence of more extreme vulnerabilities to supply disruption. However, the fact that gas is an increasingly important fuel for a large part of the 21st century under these scenarios, may mean that decreasing supply security of this resource will have larger and more extensive consequences.

Looking at Figure 27, the combined shocks that result in the best outcomes for oil security are those targeted at electricity generation from IGCC coal (HCA), gas combined cycle turbines (GCC), biomass, solar thermal, wind and nuclear sources, and gas hybrid vehicles (IGH). However, the shocks targeted at gas combined cycle generation and hybrids results in a significant worsening of gas security, which is not unexpected considering these are gas-based technologies, and should only be pursued if the impact on gas security of supply is considered to be managable. Of the remaining technologies, the renewable forms of generation (BIP, STH, WND) appear to perform well on both indicators, with biomass generation having the largest impact on the oil R:P.

6 Discussion, conclusions and summary

This report has examined the long-term impact on indicators of sustainable development of a number of technology support policies. The measures of sustainable development of interest include indicators of climate change – including atmospheric concentrations of greenhouse gases, temperature change and sea-level rise – and measures of security of energy supply for oil and gas. The technology support policies investigated in this analysis include investment in energy research and development (R&D) and demonstration and deployment (D&D).

The analysis was conducted using the modeling framework developed at IIASA-ECS for the SAPIENTIA project, as described in Turton and Barreto (2003), and updated to incorporate additional material from other SAPIENTIA partners (including Kouvaritakis and Panos 2005). The main elements of this framework comprise the "bottom-up" energy-systems ERIS model and the climate model MAGICC. The ERIS model incorporates technological learning and spillovers, and extensive energy and non-energy GHG abatement opportunities.

Importantly, the impact of technology support policies and measures using this framework is strongly influenced by assumptions about the baseline development of the energy system, and policy environment. A number of critical elements in the baseline scenario must be considered when interpreting the results of this analysis. These include a climate change policy, which itself encourages the adoption of a number of technologies with a positive impact on the sustainability indicators of interest. Other important features include the assumed levels of resources, limits on the deployment rates of new technologies, and assumptions about R&D expenditure and energy demand.[11] In many cases, these critical assumptions may be expected to have more influence on the development of the energy system than specific technology policies. Conversely, changing these assumptions, such as by incorporating a more stringent climate policy, will redirect the development of the energy system, and may result in other technologies becoming more important, and thus possible targets for support.

In the baseline scenario used in this analysis, the main energy system developments over the century include a transition to natural gas-based electricity generation prior to a strong shift to nuclear and renewable forms of electricity generation. In addition, fuel cells play an increasingly important role in electricity generation in this baseline scenario and are among the fastest growing technologies at the end of the century. Consequently, hydrogen becomes an important energy carrier, although other fuels remain important. In transportation, hybrid engines, natural gas and alcohol fuels all play an important role (although fuel cells do not). Greenhouse gas emissions peak in 2070, and atmospheric CO_2 concentrations rise to 700 ppm by 2100 (and are still increasing) under this scenario.

To examine the potential significance and impact of additional support for energy R&D under this baseline scenario, we analysed the impact of optimistic and pessimistic future scenarios of government R&D investment. The optimistic scenario – involving a doubling above business-as-usual of government energy R&D until 2050 – resulted in a transformation of some key elements of the energy system, illustrating the potential impact of technology support policies. Specifically, this optimistic scenario provided sufficient support to fuel cells and related technologies to lead to deployment of, and eventual domination of the transport sector by fuel cell vehicles (instead of hybrids). Furthermore, this optimistic R&D scenario also changed the electricity sector, although less significantly, by facilitating additional generation from gas combined cycle generation and a shift from hydrogen fuel cells to gas fuel cells (given that much of the available hydrogen was now consumed in the transport sector). This resulted in a displacement of coal-fired electricity generation, lower GHG emissions and improved outcomes on a number of sustainability indicators.

In contrast, the pessimistic R&D scenario (with zero government energy R&D) resulted in relatively little change in the energy system compared to the baseline scenario. This appears to raise two conflicting conclusions – firstly, that under the assumptions here government R&D support can have a significant and far-reaching impact on energy system development (optimistic scenario), while other factors influencing the development of the energy system, including the climate policy and

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[11] Assumptions about the application of other related technologies and policies, such as those aimed at reducing sulfate emissions from combustion, may also have an important bearing on the results. This particular example is discussed later in this section.

resource constraints, may have a much larger influence than public energy R&D support (pessimistic scenario). These apparently contradictory results imply that for government R&D support to be effective it needs to be compatible with the broader policy, technology and resource environment. Moreover, even taking the results of the pessimistic scenario at face value does not necessarily imply that there is no place for government energy R&D, since even though such policies may have only a small influence on the direction of energy system development, they can still have an important influence on cost.

The idea that R&D support needs to be compatible with other constraints on the energy system and policy variables was explored by targeting support to key technologies in the form of R&D investment "shocks". This exercise reinforced the conclusion that there are only limited opportunities for public R&D support to be effective in transforming the development of the global energy system, and this support needs to be compatible with other factors directing development. Specifically, almost all of the technology-specific R&D shocks had almost no effect on the development of the energy system – which is consistent with the result observed under the pessimistic R&D scenario. However, the most significant exception was R&D support for the generic fuel cell technology used in both stationary and mobile applications. This shock was sufficient to shift the development of the energy system as a whole onto a path very similar to that under the optimistic R&D scenario, but for a fraction of the cost, indicating that a single well-targetted technology support program can substantially change the development path followed by the global energy system.

In many ways it is not surprising that very few shocks were observed to have a significant impact on energy system development. This can be understood if one remembers that this scenario assumes a climate change policy, so alternative technology options can be thought of as different greenhouse gas abatement opportunities with different costs. The climate policy is modeled as a GHG tax, and all of the technology options with an abatement cost of below the tax rate are exploited under the baseline scenario. Accordingly, under the assumptions applied here an R&D shock (or support program) can only change the technology development path if it shifts the cost of an abatement opportunity from above to below the GHG tax rate. This is affected by technology characteristics, but within the mix of technologies examined here, it is not surprising that this occurred infrequently. For technology options that were already attractive, the R&D shocks only help to reduce overall energy system costs – that is, there is still a return on R&D investment, despite this investment having little or no impact on the indicators of sustainable development. On the other hand, R&D shocks targeted at technologies that are unattractive, and remain unattractive after the shock, have effectively no impact, but may represent an important part of a hedging strategy against uncertainty regarding the necessary stringency of future climate change mitigation targets.

This again highlights the importance of the baseline scenario assumptions. Were we to assume a less or more stringent climate change policy, this would change the suite of technologies that are competitive under the baseline scenario, and move the critical threshold that determines whether an R&D shock has any significant effect on the energy system. This further reinforces the notion that technology policy needs to be designed and implemented in a way that complements and enhances the existing policy environment. As mentioned, uncertainty regarding the potential policy environment warrants an effective technology policy hedging strategy, in which a suite of technologies are targeted initially, and as policy uncertainty is resolved technology support programs become increasingly focused.

One element of such a comprehensive and complementary technology policy may require combining technology-push with market-pull, to accelerate technology deployment and realise positive impacts on sustainability indicators. The role of technology demonstration and deployment (D&D) policies in achieving sustainable development objectives was also explored in this analysis. These D&D technology policies – again applied in the form of a "shock" in the base year – were examined both separately and in combination with R&D policies.

When pursued separately, some D&D investment policies were observed to have the potential to improve a number of indicators of sustainability. However, under the assumptions and baseline scenario used here, in many cases these D&D shocks "crowded out" other technologies, resulting in poorer sustainability outcomes. Specifically, most of the D&D shocks applied to electricity generation technologies resulted in one of the most successful low-emissions technologies in the baseline scenario – fuel cell electricity generation – missing a critical window of opportunity. The high level of support provided to other technologies by the D&D shock effectively lock out a nascent fuel cell generation industry, which is unable to penetrate the market later in the century because critical learning opportunities have been missed. The alternative technologies receiving the D&D support, including zero emissions technologies such as nuclear and renewable generation, make an initially positive contribution to some of the sustainability indicators, but are ultimately limited by technical and/or resource constraints, leading to a longer and larger reliance on less-sustainable technologies. This illustrates a significant danger associated with supporting certain technologies without considering the potential limitations they may face and the possible lock-out over the longer term of more promising technologies. Accordingly, support programs for technologies need to be pursued in a way that is complementary rather than competitive to the development of other technologies likely to contribute to the achievement of sustainability objectives.

Combining R&D and D&D may be one effective way of pursuing a complementary technology support strategy. This analysis demonstrated that technology lock-out of fuel cell generation could be avoided if R&D support was provided to fuel cells while D&D support provided to other technologies. This more integrated technology policy addressed multiple barriers to technology adoption in a way that was reinforcing and complementary. Consequently, the largest improvements in a number of sustainability indicators were observed under combined policies and, more importantly, high impacts (per euro) were also maintained. The most effective combined shock explored in this analysis on a number of sustainability indicators comprised R&D support for fuel cells and deployment support for advanced nuclear generation. These together accelerated the deployment of a zero-emissions and potentially large-scale generation technology (advanced nuclear), while supporting the critical early development stages for fuel cell technologies, allowing them to make a large contribution in the future energy system in both electricity generation and transport. Demonstration and deployment shocks targeted at other low-emissions technologies also resulted in incremental improvements in sustainability indicators when combined with the R&D

shock. Not surprisingly, this shows that technology policies can be most effective at realizing sustainability objectives when they combine complementary and reinforcing elements.

This is particularly relevant to the hydrogen-related technologies examined in this analysis, where D&D or R&D shocks targeted at individual hydrogen production or consumption technologies had relative little impact. Apart from the need to address barriers specific to each technology, these results illustrate the requirement for all elements of a hydrogen-based energy system to be in place before potential benefits can be fully realised. Accordingly, considering the need for co-ordination, large-scale investment and the potential risks associated with developing the infrastructure required across the hydrogen energy chain, there is potentially a very significant role for government support and deployment programs.

Importantly, however, many of the results of this analysis imply that the relative importance given to different sustainability objectives may have a bearing on the choice of targets for technology support. For instance, in many cases the R&D and D&D programs examined here supported technologies that were able to displace coal-based energy systems, thereby reducing both CO_2 and SO_x emissions. As a consequence although many of these technology policies reduced atmospheric GHG emissions, they resulted in a small increase in temperature because the negative radiative forcing from sulfate aerosols was reduced. This potentially leads to the perverse conclusion that climate change indicators can be improved by maximising SO_x emissions (probably by supporting coal-based technologies). However, taking a long-term perspective it may be reasonable to assume that SO_x-reduction policies will be implemented as part of the pursuit of other environmental goals, and so lower weighting should be attached to the effect of sulfate aerosols on temperature change in the pursuit of long-term climate change mitigation.

Another area where a potential trade-off may occur is pursuit of both climate change mitigation and maintenance of security of energy supply. Again, however, this depends on the relative importance given to different indicators. As discussed in Section 5.4.3, oil is globally less abundant than natural gas, so the fact that many of the D&D and R&D shocks that produced positive climate change impacts also improved oil security at the expense of gas security of supply may be considered a reasonable trade-off. However, because gas becomes an increasingly important fuel for a large part of the 21st century under these scenarios, it may be more important to protect the longevity of this resource, since any supply disruption may have larger and more extensive consequences. Appreciating such potential synergies (such as between climate change mitigation and oil security) and trade-offs (such as gas security) are important for designing an appropriate integrated technology policy strategy (see Turton and Barreto 2005).

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8 Appendix

Table A1. Impact of technology learning on capital costs, pessimistic R&D scenario

Group	Technology	Abbreviations	2000	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
			€99/kW										
Electricity generation technologies	Conventional Coal	HCC	1,219	1,214	1,161	1,121	1,077	1,045	1,018	995	974	958	947
	Integrated Coal Gasification Combined Cycle (IGCC)	HCA	1,436	1,404	1,380	1,353	1,324	1,286	1,253	1,244	1,236	1,228	1,222
	Oil Conventional Thermal	OLC	1,108	1,070	1,057	1,056	1,056	1,056	1,056	1,056	1,056	1,056	1,056
	Gas Turbine Combined Cycle	GCC	548	536	524	517	513	510	508	508	508	507	507
	Gas Conventional Thermal	GSC	986	943	922	904	895	892	890	890	890	890	890
	Gas Turbine Open Cycle	GTR	384	374	358	346	338	332	328	327	326	325	325
	Gas Fuel Cell (generic stationary)	GFC	11,755	6,479	3,510	1,384	589	413	294	233	205	181	164
	Nuclear (2nd and 3rd gen.)	NUC	2,765	2,671	2,334	2,073	1,906	1,840	1,790	1,771	1,759	1,746	1,737
	New Nuclear (4th gen.)	NNU	8,555	8,416	8,256	8,092	7,017	6,051	5,205	4,457	3,829	3,284	2,833
	Biomass	BIP	2,477	2,108	2,037	1,988	1,942	1,901	1,868	1,868	1,868	1,868	1,868
	Large Hydro	HYD	3,227	3,144	3,065	2,932	2,748	2,526	2,383	2,312	2,287	2,270	2,251
	Solar Thermal Power Plant Cylindro-Parabolic	STH	3,111	3,015	2,893	2,751	2,597	2,448	2,311	2,300	2,289	2,279	2,276
	Building Integrated PV	SPV	6,385	4,933	4,193	3,511	2,951	2,288	1,958	1,883	1,879	1,878	1,869
	Wind Turbines	WND	1,061	986	920	853	802	768	743	738	735	733	731
	Hydrogen Fuel Cell (generic stationary)	HEF	11,755	6,479	3,510	1,384	589	413	294	233	205	181	164
			€99/m^{3}d										
Hydrogen production technologies	Hydrogen from Gas Steam Reforming (large scale)	GASH2NE	46	45	36	36	36	36	36	36	36	36	36
	Hydrogen from Coal Partial Oxidation	COALH2NE	117	112	107	102	96	90	85	84	83	81	80
	Hydrogen from Biomass Pyrolysis	BIOH2NE	122	116	106	99	95	90	86	85	83	81	79
			€99/vehicle										
Passenger car technologies	Conventional ICE Passenger Car	ICC/ICG/ICA	3,000	3,000	3,000	3,000	3,000	3,000	3,000	3,000	3,000	3,000	3,000
	Hybrid Passenger Car	ICH/IGH/IAH	7,700	6,083	5,599	5,255	5,019	4,970	4,931	4,912	4,900	4,891	4,884
	Hydrogen ICE-Hybrid Passenger Car	IHH	11,000	9,383	8,899	8,555	8,319	8,270	7,606	7,565	7,543	7,530	7,513
	Reformer-Fuel Cell Passenger Car	PFC/AFC	590,200	379,150	260,418	175,360	143,574	136,528	131,760	129,304	128,208	127,243	126,541
	Hydrogen Fuel Cell Passenger Car	HFC	472,600	261,550	142,818	57,760	25,974	18,928	13,705	11,233	10,130	9,162	8,453
			€99/toe input per year										
Carbon capture technologies	Pre-Combustion CO$_2$ capture (IGCC)	HCACS	31	31	10	10	10	10	10	10	10	10	10
	Post-Combustion CO$_2$ capture (Conventional Coal)	HCCCS	52	52	24	22	20	20	20	20	20	20	20
	Post-Combustion CO$_2$ capture (GCC)	GCCCS	31	31	11	11	11	11	11	11	11	11	11
			€99/m^{3}d										
	Pre-Combustion CO$_2$ capture (Hydrogen Production)	H2CAS	68	68	68	68	67	66	65	64	63	62	61

Table A2. Impact of technology learning on capital costs, optimistic R&D scenario

Group	Technology	Abbreviations	2000	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
			€99/kW										
Electricity generation technologies	Conventional Coal	HCC	1,219	1,214	1,161	1,121	1,077	1,044	1,017	994	974	958	950
	Integrated Coal Gasification Combined Cycle (IGCC)	HCA	1,436	1,349	1,300	1,251	1,208	1,163	1,127	1,121	1,116	1,110	1,106
	Oil Conventional Thermal	OLC	1,108	1,069	1,056	1,054	1,053	1,052	1,051	1,051	1,051	1,051	1,051
	Gas Turbine Combined Cycle	GCC	548	535	523	516	512	509	507	507	506	506	506
	Gas Conventional Thermal	GSC	986	941	919	900	889	883	879	879	879	879	879
	Gas Turbine Open Cycle	GTR	384	373	357	344	336	330	326	325	324	323	323
	Gas Fuel Cell (generic stationary)	GFC	11,755	5,234	695	152	89	57	50	50	50	50	50
	Nuclear (2nd and 3rd gen.)	NUC	2,765	2,436	2,058	1,869	1,791	1,763	1,742	1,733	1,727	1,720	1,715
	New Nuclear (4th gen.)	NNU	8,555	6,693	5,573	4,648	3,483	2,643	2,029	1,742	1,502	1,299	1,296
	Biomass	BIP	2,477	2,056	1,979	1,926	1,880	1,843	1,814	1,814	1,814	1,814	1,814
	Large Hydro	HYD	3,227	3,143	3,063	2,929	2,747	2,524	2,382	2,312	2,285	2,269	2,250
	Solar Thermal Power Plant Cylindro-Parabolic	STH	3,111	2,784	2,523	2,298	2,119	1,983	1,877	1,871	1,865	1,860	1,858
	Building Integrated PV	SPV	6,385	4,346	3,400	2,705	2,263	1,906	1,728	1,696	1,689	1,686	1,683
	Wind Turbines	WND	1,061	932	850	786	744	719	701	698	696	695	694
	Hydrogen Fuel Cell (generic stationary)	HEF	11,755	5,234	695	152	89	57	50	50	50	50	50
			€99/m^{3}d										
Hydrogen production technologies	Hydrogen from Gas Steam Reforming (large scale)	GASH2NE	46	45	34	34	34	34	34	34	34	34	34
	Hydrogen from Coal Partial Oxidation	COALH2NE	117	107	101	95	90	84	79	78	77	76	75
	Hydrogen from Biomass Pyrolysis	BIOH2NE	122	113	103	97	93	88	85	83	81	79	78
			€99/vehicle										
Passenger car technologies	Conventional ICE Passenger Car	ICC/ICG/ICA	3,000	3,000	3,000	3,000	3,000	3,000	3,000	3,000	3,000	3,000	3,000
	Hybrid Passenger Car	ICH/IGH/IAH	7,700	5,685	5,295	5,053	4,993	4,946	4,909	4,896	4,890	4,887	4,886
	Hydrogen ICE-Hybrid Passenger Car	IHH	11,000	8,985	8,595	7,671	7,528	7,418	7,321	7,255	7,217	7,191	7,173
	Reformer-Fuel Cell Passenger Car	PFC/AFC	590,200	329,345	147,784	126,084	123,567	122,293	122,000	122,000	122,000	122,000	122,000
	Hydrogen Fuel Cell Passenger Car	HFC	472,600	211,745	30,184	7,988	5,411	4,091	3,754	3,716	3,692	3,675	3,663
			€99/toe input per year										
Carbon capture technologies	Pre-Combustion CO$_2$ capture (IGCC)	HCACS	31	10	10	10	10	10	10	10	10	10	10
	Post-Combustion CO$_2$ capture (Conventional Coal)	HCCCS	52	25	23	21	20	20	20	20	20	20	20
	Post-Combustion CO$_2$ capture (GCC)	GCCCS	31	24	13	13	13	13	13	13	13	13	13
			€99/m^{3}d										
	Pre-Combustion CO$_2$ capture (Hydrogen Production)	H2CAS	68	68	45	45	45	45	45	45	45	45	45

Table A3. Sustainability indicator levels under all technology policies

Technology policy	Policy cost	Indicators								
		Climate change indicators					Security of supply indicators			
	€bn (undiscounted)	Atmospheric CO_2 concentration (2100) (ppmv)	Atmospheric CH_4 concentration (2100) (ppbv)	Temperature change (2100) (K)	Temperature change (constant sulfate) (2100) (K)	Sea-level rise (2100) (cm)	Oil R:P (global) (2060) (years)	Oil R:C (Europe) (2060) (years)	Gas R:P (global) (2060) (years)	Gas R:C (Europe) (2060) (years)
Baseline	0	701.93	2538.5	3.239	2.726	40.8	32.56	11.15	45.17	33.35
Optimistic R&D	425,368	693.34	2531.3	3.270	2.702	41	34.39	11.74	44.38	31.09
Pessimistic R&D	-425,368	702.79	2537.8	3.242	2.729	40.8	32.58	11.15	44.96	33.04
Standardised R&D shocks										
HYD	4.48	701.8	2538.4	3.238	2.726	40.8	32.50	11.15	45.13	33.07
NUC	22.49	701.86	2538.6	3.239	2.726	40.8	32.52	11.13	45.15	33.01
NNU	6.98	701.98	2538.3	3.239	2.726	40.8	32.47	11.20	45.14	33.03
HCC	9.70	701.74	2538.5	3.239	2.726	40.8	32.54	11.13	45.17	33.17
HCCCS	0.007	701.71	2538.3	3.238	2.726	40.8	32.50	11.13	45.11	33.05
HCA	3.18	701.94	2538.5	3.239	2.726	40.8	32.57	11.15	45.18	33.36
HCACS	0.003	701.93	2538.5	3.239	2.726	40.8	32.56	11.15	45.17	33.35
OLC	9.25	701.85	2538.5	3.239	2.726	40.8	32.52	11.13	45.17	33.59
GCC	12.36	701.94	2538.4	3.239	2.726	40.8	32.56	11.15	45.16	33.35
GSC	6.05	701.89	2538.1	3.239	2.726	40.8	32.66	11.13	45.06	33.65
GTR	12.36	701.96	2538.4	3.239	2.726	40.8	32.54	11.15	45.14	33.28
GCCCS	0.003	701.71	2538.3	3.238	2.726	40.8	32.50	11.13	45.11	33.05
WND	2.15	701.71	2538.3	3.238	2.726	40.8	32.50	11.13	45.11	33.05
STH	1.07	701.42	2538.3	3.240	2.725	40.8	32.47	11.15	45.17	33.68
SPV	9.94	701.76	2538.4	3.239	2.726	40.8	32.56	11.13	45.16	33.52
BIP	4.46	701.88	2538.4	3.239	2.726	40.8	32.49	11.22	45.15	33.40
FCMS	7.47	694.61	2531.6	3.271	2.706	41	33.74	11.04	44.35	31.25
GASH2NE	0.93	701.79	2538.3	3.239	2.726	40.8	32.57	11.13	45.16	33.64
H2CAS	0.000	701.93	2538.5	3.239	2.726	40.8	32.56	11.15	45.17	33.35
COALH2NE	0.37	701.96	2538.4	3.239	2.726	40.8	32.49	11.15	45.12	33.07
BIOH2NE	0.044	701.74	2538.5	3.239	2.726	40.8	32.54	11.13	45.17	33.17
ICH	0.81	701.93	2538.5	3.239	2.726	40.8	32.56	11.15	45.17	33.35
ELVT	0.81	701.7	2538.3	3.238	2.726	40.8	32.51	11.13	45.12	33.05
HYBB	0.81	701.94	2538.6	3.239	2.726	40.8	32.61	11.13	45.16	33.64
Non-standard R&D shocks										
HCCCS	1.00	701.71	2538.3	3.238	2.726	40.8	32.50	11.13	45.11	33.05
HCACS	1.00	701.93	2538.5	3.239	2.726	40.8	32.56	11.15	45.17	33.35

Technology policy	**Policy cost**	**Indicators**								
		Climate change indicators					**Security of supply indicators**			
	€bn (undiscounted)	Atmospheric CO_2 concentration (2100) (ppmv)	Atmospheric CH_4 concentration (2100) (ppbv)	Temperature change (2100) (K)	Temperature change (constant sulfate) (2100) (K)	Sea-level rise (2100) (cm)	Oil R:P (global) (2060) (years)	Oil R:C (Europe) (2060) (years)	Gas R:P (global) (2060) (years)	Gas R:C (Europe) (2060) (years)
GCCCS	1.00	701.74	2538	3.238	2.726	40.8	32.53	11.13	45.16	33.64
H2CAS	1.00	701.94	2538.4	3.239	2.726	40.8	32.62	11.13	45.14	33.65
BIOH2NE	1.00	701.92	2538.6	3.239	2.726	40.8	32.61	11.13	45.16	33.64
COALH2NE	1.00	701.68	2538.1	3.238	2.726	40.8	32.64	11.13	45.17	33.65
FCMS	17.47	693.81	2532.2	3.272	2.704	41	34.14	11.56	44.17	31.17
Standardised D&D shocks										
HCA	10	714.25	2543.9	3.280	2.758	41.3	34.79	11.95	44.77	29.66
GCC	10	718.05	2541.5	3.104	2.770	40.4	34.96	11.95	44.02	29.73
GTR	10	701.61	2538	3.238	2.725	40.8	32.60	11.13	45.12	33.66
GFC	10	694.97	2536.7	3.260	2.704	40.9	33.40	11.12	44.85	33.68
NNU	10	708.14	2540.4	3.193	2.747	40.7	34.17	12.08	44.88	29.48
BIP	10	717.27	2546	3.116	2.768	40.4	35.01	12.04	45.45	29.81
STH	10	716.89	2546.1	3.109	2.767	40.4	34.64	11.96	45.28	29.90
SPV	10	701.35	2538.3	3.240	2.725	40.8	32.51	11.15	45.16	33.69
WND	10	701.09	2538.2	3.236	2.723	40.8	32.88	11.15	45.17	33.69
HEF	10	701.98	2538.3	3.239	2.726	40.8	32.47	11.20	45.13	32.97
GASH2NE	10	701.76	2538.3	3.238	2.726	40.8	32.50	11.13	45.17	33.70
COALH2NE	10	701.9	2538.2	3.239	2.726	40.8	32.50	11.22	45.14	33.03
BIOH2NE	10	701.83	2538.1	3.238	2.726	40.8	32.60	11.15	45.18	33.69
ICH	10	701.86	2538.4	3.239	2.726	40.8	32.56	11.13	45.14	33.60
IGH	10	702.13	2533.2	3.230	2.726	40.8	33.74	11.18	44.22	33.65
IAH	10	701.77	2538.4	3.239	2.726	40.8	32.53	11.13	45.15	33.19
IHH	10	701.77	2538.4	3.239	2.726	40.8	32.56	11.13	45.17	33.65
PFC	10	701.66	2538.2	3.238	2.725	40.8	32.58	11.13	45.15	33.65
AFC	10	701.66	2538.2	3.238	2.725	40.8	32.58	11.13	45.15	33.65
HFC	10	701.89	2538.5	3.239	2.726	40.8	32.61	11.13	45.16	33.66
HCACS	10	701.01	2538.3	3.237	2.724	40.8	32.47	11.00	45.14	33.08
HCCCS	10	699.18	2538.6	3.222	2.717	40.7	32.57	11.13	45.18	33.92
GCCCS	10	698.9	2538.4	3.230	2.715	40.7	32.52	11.45	44.81	28.72
H2CAS	10	701.65	2538.1	3.238	2.725	40.8	32.64	11.13	45.17	33.65
Combined R&D FCMS and standardised D&D shocks										
FCHCA	17.47	691.09	2526.8	3.338	2.691	41.7	34.93	11.69	43.83	30.84

Technology policy	**Policy cost**	**Indicators**								
		Climate change indicators					**Security of supply indicators**			
	€bn (undiscounted)	Atmospheric CO_2 concentration (2100) (ppmv)	Atmospheric CH_4 concentration (2100) (ppbv)	Temperature change (2100) (K)	Temperature change (constant sulfate) (2100) (K)	Sea-level rise (2100) (cm)	Oil R:P (global) (2060) (years)	Oil R:C (Europe) (2060) (years)	Gas R:P (global) (2060) (years)	Gas R:C (Europe) (2060) (years)
FCGCC	17.47	690.49	2522.9	3.270	2.688	41.2	34.69	11.66	43.02	32.09
FCGTR	17.47	694.61	2529.5	3.261	2.705	41	34.15	11.75	43.99	31.67
FCGFC	17.47	694.76	2536.5	3.275	2.704	41	33.33	11.15	44.91	33.69
FCNNU	17.47	683.62	2522	3.265	2.674	41.1	34.37	11.70	43.78	31.08
FCBIP	17.47	691.6	2530.3	3.266	2.695	41	34.89	11.27	44.25	30.82
FCSTH	17.47	690.58	2530.5	3.266	2.692	41	34.56	11.70	44.31	31.02
FCSPV	17.47	693.76	2530.6	3.271	2.703	41	34.10	11.72	44.16	31.49
FCWND	17.47	693.21	2530.9	3.268	2.701	41	34.41	11.73	44.21	30.89
FCHEF	17.47	701.76	2538.5	3.240	2.726	40.8	32.59	11.13	45.24	33.65
FCGASH2NE	17.47	693.86	2530.3	3.271	2.703	41	34.06	11.75	44.15	31.44
FCCOALH2NE	17.47	694.04	2531.2	3.272	2.704	41	34.12	11.71	44.29	31.12
FCBIOH2NE	17.47	694.55	2532.2	3.272	2.706	41	33.87	11.35	44.22	30.86
FCICH	17.47	694.04	2530.9	3.272	2.704	41	34.18	11.59	44.14	31.01
FCIGH	17.47	694.32	2527.1	3.257	2.704	41	34.83	11.72	43.61	31.36
FCIAH	17.47	694.14	2531.1	3.272	2.705	41	33.97	11.70	44.20	31.01
FCIHH	17.47	694.05	2530.6	3.272	2.704	41	34.13	11.70	44.13	31.05
FCPFC	17.47	701.65	2538.2	3.238	2.726	40.8	32.59	11.13	45.14	33.65
FCAFC	17.47	701.9	2538.5	3.241	2.726	40.8	32.52	11.15	45.15	33.40
FCHFC	17.47	701.85	2538.4	3.239	2.726	40.8	32.58	11.15	45.14	33.47
FCHCACS	17.47	694.01	2531.2	3.272	2.704	41	33.84	11.29	44.23	31.00
FCHCCCS	17.47	692.59	2531.6	3.257	2.699	40.9	33.82	11.29	44.23	31.10
FCGCCCS	17.47	691.5	2531.2	3.237	2.693	40.8	33.94	11.88	43.68	25.78
FCH2CAS	17.47	694.5	2531.1	3.273	2.706	41	33.88	11.39	44.24	31.06

Table A4. Impact on sustainability indicators of all technology policies

Technology policy	**Impacts**								
	Climate change indicators					**Security of supply indicators**			
	Atmospheric CO_2 concentration (2100) ppm/€bn	Atmospheric CH_4 concentration (2100) ppb/€bn	Temperature change (2100) K/€bn	Temperature change (constant sulfate) (2100) K/€bn	Sea-level rise (2100) cm/€bn	Oil R:P (global) (2060) years/€bn	Oil R:C (Europe) (2060) years/€bn	Gas R:P (global) (2060) years/€bn	Gas R:C (Europe) (2060) years/€bn
Baseline	NA	NA	NA	NA	NA	NA	NA	NA	NA
Optimistic R&D	-2.02E-05	-1.69E-05	7.29E-08	-5.74E-08	4.70E-07	4.32E-06	1.38E-06	-1.84E-06	-5.31E-06
Pessimistic R&D	-2.02E-06	1.65E-06	-7.05E-09	-6.58E-09	0	-5.69E-08	-2.76E-09	4.78E-07	7.26E-07
Standardised R&D shocks									
HYD	-0.029	-0.022	-2.23E-04	-1.11E-04	0	-0.012	0.000	-0.009	-0.061
NUC	-0.003	0.004	0	-8.89E-06	0	-0.002	-0.001	-0.001	-0.015
NNU	0.007	-0.029	0	1.43E-05	0	-0.013	0.007	-0.004	-0.045
HCC	-0.020	0	0	-5.15E-05	0	-0.002	-0.002	0.001	-0.018
HCCCS	-29.508	-26.825	-0.134	-0.080	0	-7.122	-2.827	-7.578	-40.712
HCA	0.003	0	0	3.15E-05	0	0.003	0.000	0.004	0.002
HCACS	0	0	0	0	0	0	0	0	0
OLC	-0.009	0	0	-2.16E-05	0	-0.004	-0.003	0.001	0.026
GCC	0.001	-0.008	0	0	0	0.000	0.000	-0.001	0.000
GSC	-0.007	-0.066	0	-6.61E-05	0	0.017	-0.004	-0.017	0.050
GTR	0.002	-0.008	0	8.09E-06	0	-0.001	0.000	-0.002	-0.006
GCCCS	-82.622	-75.111	-0.376	-0.225	0	-19.942	-7.917	-21.219	-113.995
WND	-0.102	-0.093	-4.65E-04	-2.79E-04	0	-0.025	-0.010	-0.026	-0.141
STH	-0.474	-0.186	9.30E-04	-1.49E-03	0	-0.083	0.000	-0.001	0.303
SPV	-0.017	-0.010	0	-5.03E-05	0	0.000	-0.002	0.000	0.017
BIP	-0.011	-0.022	0	-2.24E-05	0	-0.015	0.016	-0.004	0.012
FCMS	-0.980	-0.924	4.29E-03	-2.73E-03	2.68E-02	0.158	-0.014	-0.109	-0.282
GASH2NE	-0.150	-0.215	0	-0.0004297	0	0.012	-0.026	-0.010	0.310
H2CAS	NA	NA	NA	NA	NA	NA	NA	NA	NA
COALH2NE	0.081	-0.269	0	2.69E-04	0	-0.168	0.005	-0.131	-0.738
BIOH2NE	-4.338	0	0	-1.14E-02	0	-0.361	-0.481	0.162	-4.075
ICH	0	0	0	0	0	0	0	0	0
ELVT	-0.284	-0.247	-1.24E-03	-7.42E-04	0	-0.054	-0.026	-0.059	-0.375
HYBB	0.012	0.124	0	0	0	0.062	-0.031	-0.012	0.362
Non-standard R&D shocks									
HCCCS	-0.220	-0.200	-1.00E-03	-6.00E-04	0	-0.053	-0.021	-0.056	-0.304
HCACS	0	0	0	0	0	0	0	0	0

Technology policy	**Impacts**								
	Climate change indicators					**Security of supply indicators**			
	Atmospheric CO_2 concentration (2100) ppm/€bn	Atmospheric CH_4 concentration (2100) ppb/€bn	Temperature change (2100) K/€bn	Temperature change (constant sulfate) (2100) K/€bn	Sea-level rise (2100) cm/€bn	Oil R:P (global) (2060) years/€bn	Oil R:C (Europe) (2060) years/€bn	Gas R:P (global) (2060) years/€bn	Gas R:C (Europe) (2060) years/€bn
GCCCS	-0.190	-0.500	-1.00E-03	-7.00E-04	0	-0.026	-0.025	-0.006	0.292
H2CAS	0.010	-0.100	0	1E-04	0	0.063	-0.025	-0.027	0.301
BIOH2NE	-0.010	0.100	0	-0.0001	0	0.051	-0.025	-0.011	0.293
COALH2NE	-0.250	-0.400	-1.00E-03	-8.00E-04	0	0.081	-0.026	0.002	0.298
FCMS	-0.465	-0.361	1.89E-03	-1.29E-03	1.14E-02	0.091	0.024	-0.057	-0.125
Standardised D&D shocks									
HCA	1.232	0.540	4.10E-03	3.16E-03	5.00E-02	0.223	0.080	-0.040	-0.369
GCC	1.612	0.300	-1.35E-02	4.38E-03	-4.00E-02	0.240	0.079	-0.114	-0.362
GTR	-0.032	-0.050	-1.00E-04	-1.10E-04	0	0.004	-0.003	-0.005	0.031
GFC	-0.696	-0.180	2.10E-03	-2.19E-03	1.00E-02	0.084	-0.003	-0.032	0.034
NNU	0.621	0.190	-4.60E-03	2.06E-03	-1.00E-02	0.161	0.093	-0.029	-0.387
BIP	1.534	0.750	-1.23E-02	4.20E-03	-4.00E-02	0.245	0.089	0.028	-0.354
STH	1.496	0.760	-1.30E-02	4.09E-03	-4.00E-02	0.208	0.080	0.012	-0.345
SPV	-0.058	-0.020	1.00E-04	-1.80E-04	0	-0.005	0.000	-0.001	0.034
WND	-0.084	-0.030	-3.00E-04	-3.70E-04	0	0.033	0.000	0.000	0.034
HEF	0.005	-0.020	0	1E-05	0	-0.009	0.005	-0.003	-0.038
GASH2NE	-0.017	-0.020	-1.00E-04	-5.00E-05	0	-0.005	-0.002	0.000	0.035
COALH2NE	-0.003	-0.030	0	-1E-05	0	-0.005	0.006	-0.002	-0.032
BIOH2NE	-0.010	-0.040	-1.00E-04	-4.00E-05	0	0.005	0.000	0.002	0.034
ICH	-0.007	-0.010	0	-3E-05	0	0.000	-0.002	-0.003	0.025
IGH	0.020	-0.530	-9.00E-04	-2.00E-05	0	0.118	0.002	-0.095	0.030
IAH	-0.016	-0.010	0	-4E-05	0	-0.003	-0.002	-0.001	-0.016
IHH	-0.016	-0.010	0	-4E-05	0	0.000	-0.002	0.000	0.030
PFC	-0.027	-0.030	-1.00E-04	-9.00E-05	0	0.003	-0.002	-0.002	0.030
AFC	-0.027	-0.030	-1.00E-04	-9.00E-05	0	0.003	-0.002	-0.002	0.030
HFC	-0.004	0.000	0	-2E-05	0	0.005	-0.002	-0.001	0.031
HCACS	-0.092	-0.020	-2.00E-04	-2.60E-04	0	-0.009	-0.015	-0.002	-0.027
HCCCS	-0.275	0.010	-1.70E-03	-9.10E-04	-1.00E-02	0.001	-0.002	0.001	0.058
GCCCS	-0.303	-0.010	-9.00E-04	-1.16E-03	-1.00E-02	-0.004	0.029	-0.036	-0.463
H2CAS	-0.028	-0.040	-1.00E-04	-9.00E-05	0	0.008	-0.003	0.000	0.030
Combined R&D FCMS and standardised D&D shocks									
FCHCA	-0.621	-0.670	5.67E-03	-2.03E-03	5.15E-02	0.136	0.031	-0.076	-0.144

Technology policy	**Impacts**								
	Climate change indicators					**Security of supply indicators**			
	Atmospheric CO_2 concentration (2100) ppm/€bn	Atmospheric CH_4 concentration (2100) ppb/€bn	Temperature change (2100) K/€bn	Temperature change (constant sulfate) (2100) K/€bn	Sea-level rise (2100) cm/€bn	Oil R:P (global) (2060) years/€bn	Oil R:C (Europe) (2060) years/€bn	Gas R:P (global) (2060) years/€bn	Gas R:C (Europe) (2060) years/€bn
FCGCC	-0.655	-0.893	1.77E-03	-2.21E-03	2.29E-02	0.122	0.029	-0.123	-0.072
FCGTR	-0.419	-0.515	1.26E-03	-1.20E-03	1.14E-02	0.091	0.034	-0.067	-0.096
FCGFC	-0.410	-0.114	2.06E-03	-1.28E-03	1.14E-02	0.044	0.000	-0.015	0.020
FCNNU	-1.048	-0.945	1.49E-03	-2.98E-03	1.72E-02	0.104	0.031	-0.079	-0.130
FCBIP	-0.591	-0.469	1.55E-03	-1.81E-03	1.14E-02	0.134	0.007	-0.052	-0.145
FCSTH	-0.650	-0.458	1.55E-03	-1.98E-03	1.14E-02	0.114	0.031	-0.049	-0.134
FCSPV	-0.468	-0.452	1.83E-03	-1.33E-03	1.14E-02	0.088	0.032	-0.058	-0.106
FCWND	-0.499	-0.435	1.66E-03	-1.47E-03	1.14E-02	0.106	0.033	-0.055	-0.141
FCHEF	-0.010	0	5.72E-05	-2.29E-05	0	0.002	-0.001	0.004	0.017
FCGASH2NE	-0.462	-0.469	1.83E-03	-1.31E-03	1.14E-02	0.086	0.034	-0.058	-0.109
FCCOALH2NE	-0.452	-0.418	1.89E-03	-1.25E-03	1.14E-02	0.089	0.032	-0.050	-0.127
FCBIOH2NE	-0.423	-0.361	1.89E-03	-1.17E-03	1.14E-02	0.075	0.011	-0.054	-0.143
FCICH	-0.452	-0.435	1.89E-03	-1.27E-03	1.14E-02	0.093	0.025	-0.059	-0.134
FCIGH	-0.436	-0.653	1.03E-03	-1.28E-03	1.14E-02	0.130	0.032	-0.089	-0.114
FCIAH	-0.446	-0.424	1.89E-03	-1.25E-03	1.14E-02	0.081	0.031	-0.055	-0.134
FCIHH	-0.451	-0.452	1.89E-03	-1.27E-03	1.14E-02	0.090	0.031	-0.059	-0.132
FCPFC	-0.016	-0.017	-5.72E-05	-4.58E-05	0	0.002	-0.001	-0.001	0.017
FCAFC	-0.002	0	1.14E-04	-1.14E-05	0	-0.002	0.000	-0.001	0.003
FCHFC	-0.005	-0.006	0	-1.72E-05	0	0.001	0.000	-0.001	0.007
FCHCACS	-0.453	-0.418	1.89E-03	-1.26E-03	1.14E-02	0.073	0.008	-0.054	-0.134
FCHCCCS	-0.535	-0.395	1.03E-03	-1.58E-03	5.72E-03	0.072	0.008	-0.053	-0.129
FCGCCCS	-0.597	-0.418	-1.14E-04	-1.89E-03	0	0.079	0.042	-0.085	-0.433
FCH2CAS	-0.425	-0.424	1.95E-03	-1.19E-03	1.14E-02	0.076	0.014	-0.053	-0.131

Note: zeros (0) indicate no measurable impact.