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Impact assessment of energy-related policy instruments on climate change and security of energy supply

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Environmentally Compatible Energy Strategies (ECS) Program

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Contents

Abstract

This report assesses the impact of several representative policy instruments on sustainability indicators in the areas of climate change and security of energy supply, two important dimensions of sustainable development addressed in the MINIMA-SUD project sponsored by the European Commission (DG Research). Specifically, we pay attention to the effectiveness of these policy instruments in stimulating technological change that could lead to a more secure and climate-benign global energy system in the long-term future. For such purpose, we examine the incremental change in a number of sustainability indicators when the policy instrument is applied relative to the costs of application of the instrument. This measure is referred to as the "impact" of the policy instrument. We concentrate our attention on the following policy instruments: Energy-related demonstration and deployment (D&D) programs and a carbon-equivalent (C-eq) tax.

Impact assessment of policy instruments is an important element of the policy development process of the European Commission, among others. It represents a systematic and careful attempt to shed light on the possible effects of policy proposals. As such, it serves as an aid to the decision-making process. Specifically, impact assessment of policy instruments plays an important role in the implementation of the sustainable-development strategy of the European Commission. Although the numerical results presented here are specific to our particular analysis and highly dependent on the characteristics and limitations of our modeling tools, we want to offer this analysis as a contribution towards the development of more comprehensive methodologies for the assessment of impacts of policy instruments in the context of the quest towards a sustainable global energy system.

Acknowledgments

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Impact assessment of energy-related policy instruments on climate change and security of energy supply

Leonardo Barreto and Hal Turton

1. Introduction

Defining and measuring sustainable development indicators and identifying instruments that could promote sustainability in different domains has become an important task for a number of social actors at the regional, national and international levels (e.g., Parris and Kates, 2003). Energy is one important element of sustainability. Driving the global energy system into a sustainable path is progressively becoming a major concern and objective for policy makers (IEA, 2001; Schrattenholzer *et al*., 2004). The emergence of a sustainable global energy system, however, is a gradual long-term process that will require a profound transformation of its current structure.

Climate change and security of energy supply have high priority in national and international policy-making agendas. The increasing evidence of human-induced interference with the earth's climate system and mounting concerns about potentially serious future adverse impacts make global climate change one of the most important challenges of sustainable development in the long term (IPCC, 2001a). In this regard, the global energy system plays a major role, since energy-related fossil-fuel combustion contributes a substantial share of anthropogenic greenhouse gas (GHG) emissions. Thus, climate policy calls for, among others, the investigation of alternatives for energy production, conversion and final use with a low release of greenhouse gases to the atmosphere (e.g., IPCC, 2001b; Hoffert *et al.*, 2002; Hasselmann *et al.*, 2003).

On the other hand, security of energy supply has become a more pressing concern for policy makers in view of a number of structural weaknesses in this area. An excessive reliance on fossil fuels, oil and natural gas in particular, is an issue of concern because of the economic, physical and geopolitical risks associated with it (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 difficult issues (e.g., DOC, 1999; EC, 2001; IEA, 2001).

Technological change has been recognized as both a key driving force of the anthropogenic contribution to climate change and an important instrument for mitigation and adaptation to climate change (IPCC, 2001b; Nakićenović, 2003). In a GHG mitigation strategy, no single technology can play the role of a "magic bullet". Thus, a broad portfolio of technologies is needed if long-term goals are to be met (Edmonds, 2001; Hoffert *et al.*, 2002). Technological change plays also an important role in security of energy supply. In the long-term, the technological trajectory of the global energy system will have a significant influence on the resulting dependence from particular primary-energy resources and/or world regions supplying them. A sound concept of security of energy supply calls for, among others, a diversification of technologies and energy sources (EC, 2001).

Impact assessment is an important element of the policy development process of the European Commission (EC, 2002). It represents a systematic and careful attempt to shed light on the possible effects of policy proposals. As such, it serves as an aid to the decision-making process. Specifically, impact assessment plays an important role in the implementation of the sustainable-development strategy of the European Commission. This report examines the impact of several representative policy instruments on sustainability indicators in the areas of climate change and security of energy supply, two important dimensions of sustainable development addressed in the EC-sponsored MINIMA-SUD project.[1] In particular, we pay attention to the effectiveness of these policy instruments in stimulating technological change that could lead to a more secure and climate-benign global energy system in the long-term future. For such purpose, we examine the incremental change in a number of sustainability indicators when the policy instrument is applied relative to the costs of application of the instrument. In what follows, this measure is referred to as the "impact" of the policy instrument.

We concentrate our attention on the following policy instruments: Energy-related demonstration and deployment (D&D) programs and a carbon-equivalent (hereon referred to as C-eq) tax. The effects of D&D programs are examined using the notion of "shocks", i.e., small one-off incremental variations in the cumulative capacity of a given technology (see Turton and Barreto (2004) for a discussion). As for the C-eq tax, the response to a wide range of values is analyzed. The use of a C-eq tax allows non-CO_2 abatement opportunities to compete with energy system abatement, forest sinks and carbon capture and storage (CCS).

The climate change indicators considered here are as follows: atmospheric concentrations of CO_2 and CH_4, global temperature change and global sea-level rise. These indicators are reported for the year 2100. The indicators for security of energy supply are long-term global resources-to-production (denoted here as Ru/P) ratios for oil and natural gas, both of them reported for the year 2050.

Climate change and security-of-supply are complex challenges encompassing many aspects and achieving sustainability goals in these areas will require a portfolio of policy instruments. Therefore, it is also of interest to assess the combined effects of different policy instruments. Here, we examine how a combination of different C-eq tax levels and D&D programs would affect sustainability indicators in these two areas.

The analysis is performed with the the "bottom-up" energy-system ERIS model, which has been linked to the climate model MAGICC (Wigley and Raper, 1997; Wigley, 2003; see also Hulme *et al.*, 2000). A detailed description of the energy-system ERIS model can be found in Turton and Barreto (2004).

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[1] The acronym MINIMA-SUD stands for Methodologies for Integrated Impact Assessment in the field of Sustainable Development.

The remainder of this document is organized as follows. Section 2 and section 3 briefly introduce the indicators of climate change and security of energy supply considered in this exercise and discuss the corresponding "instrument-to-indicator" causal chains. Section 4 presents a brief discussion of the baseline case, which provides the context for the discussion of results in subsequent sections. Section 5 presents an analysis of the impact of a carbon (equivalent) tax on the above-mentioned sustainability indicators. Section 6 assesses the impact of demonstration and deployment (D&D) shocks on the same indicators. Section 7 examines the effects of a combination of carbon taxes and D&D shocks and the derivation of the corresponding "impact surfaces". Finally, section 8 outlines some conclusions.

2. Indicators of Climate Change

Among other sustainability indicators, the MINIMA-SUD project addresses climate change. There is increasing evidence of anthropogenic interference with the Earth's climate system and mounting concerns about possible serious adverse impacts of future global climate change (IPCC, 2001a,b). Thus, mitigation and adaptation to climate change constitute important aspects of a transition to sustainability in the long term.

Figure 1 presents a simplified representation of the economic-climate cause and effect chain considered in this study. That is, from socio-economic driving forces (in particular technological change in energy systems) to climate variables, assuming that all concentration changes act on climate change via radiative forcing. No subsequent steps in the causal chain, such as climate change impacts or damages are considered here. Also, except for the impact of temperature on the terrestrial carbon cycle, a once-through chain has been assumed, with no feedbacks from climate variables to driving forces.

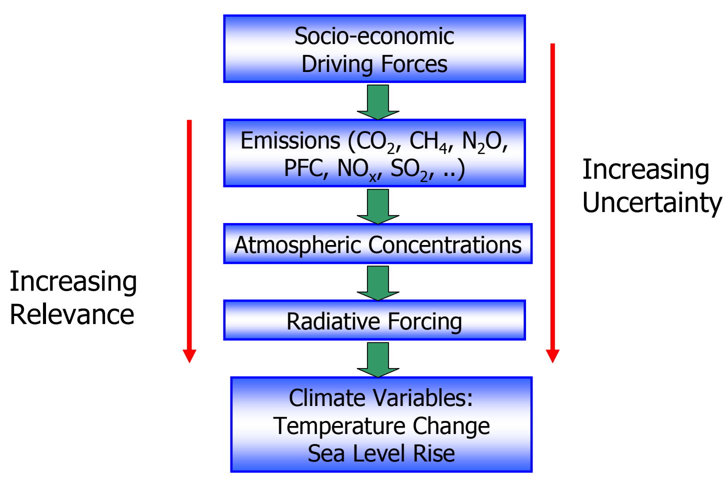

Figure 1: The cause-effect chain from driving forces to climate change considered here (adapted from IPCC, 2001b and Fuglestvedt et al., 2003). It is assumed that all atmospheric concentration changes act on climate change via radiative forcing. Other than temperature feedbacks on terrestrial carbon cycle, a once-through causal chain has been assumed.

According to their relevance, current use in the climate change debate and measurability, the following climate change indicators have been chosen: Global emissions of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), concentrations of CO_2, CH_4 and N_2O in the atmosphere, radiative forcing, annual-mean global temperature change and global-mean sea level rise. These indicators allow an aggregate but meaningful characterization of climate change at the global level and have been widely recognized and used, in particular by the IPCC (1996, 2001b). Despite their aggregate character, these indicators have a straightforward interpretation and allow an adequate examination of the effects of alternative policies on climate change at the global scale.

CO_2 is the largest historical contributor to climate change and will most likely continue to have a very important relative role in the future. CH_4 and N_2O are the two main non-CO_2 GHGs. The atmospheric concentrations and radiative forcing of these three GHGs have been increasing as a result of human activities (IPCC, 2001b). Our modeling framework endogenizes these three main GHGs, although we concentrate mainly on the contribution of the global energy system. Exogenous assumptions are made for other GHGs.

Along the cause-effect chain in Figure 1 above, uncertainties increase as one moves from GHG emissions towards climate variables. Three key uncertainties have been identified. The first of these is the magnitude of the CO_2 fertilization effect, determined with reference to the average deforestation rate during the 1980s, which plays a key role in determining the future atmospheric concentrations of CO_2. Second is the climate sensitivity, i.e., the long-term (equilibrium) change in global mean surface temperature following a doubling of atmospheric equivalent CO_2 concentration (IPCC, 1996), which is a key parameter in translating a given amount of radiative forcing into a corresponding temperature change. The third key source of uncertainty is the impact of aerosols on radiative forcing.

Figure 2 presents the instrument to indicator chain for the climate change objective. Essentially, demonstration and deployment (D&D) programs can stimulate the technology learning of low-emissions energy technologies, bringing cost reductions and other performance improvements. This makes those technologies more cost-effective and attractive in the marketplace, leading to their diffusion, initially in niche markets and later in broader markets. The imposition of a carbon-equivalent tax, on the other hand, provides an incentive for the adoption of technologies with lower associated GHG emissions. As a result of the diffusion of low-emissions energy technologies, the global energy system emits a smaller amount of GHG to the atmosphere, thereby leading to lower atmospheric GHG concentrations. All other things being equal, lower GHG concentrations result in a lower radiative forcing and a smaller increase in temperature and sea level.

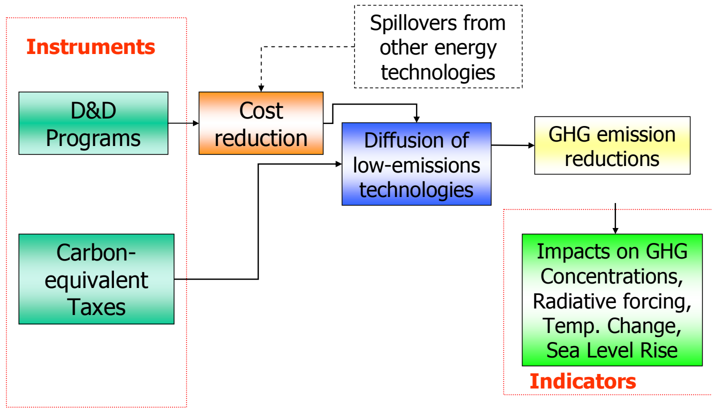

Figure 2: Instrument-to-indicator chain for the climate change objective.

3. Indicators of Security of Energy Supply

Security of energy supply has revived as a major concern for policy makers, in particular in OECD countries. Specifically, considerable debate has taken place in the European Union (EU) on how to address the geopolitical shortcomings of its energy supply (EU, 2001) which is still mainly based on fossil fuels, a large fraction of which are imported.

Although it appears that the global fossil fuel resource base is abundant when conventional and unconventional reserves and resources are taken into account (e.g., Rogner, 1997, 2000), the distribution of those resources, oil in particular, is geographically unequal. A large fraction of the currently known oil reserves and resources is concentrated in politically unstable regions. But, in the long-term, alternative development paths of the global energy system could lead to very different patterns of dependence on energy imports across regions. Specifically, development and deployment of technology clusters able to use primary energy resources indigenous to a given region may lead to a reduced dependence on imported energy carriers.

It has been argued that the current patterns of use of fossil resources are not sustainable. Global long-term resource-to-production (Ru/P) ratios have been proposed as a proxy indicator of the sustainability of a given development path of the global energy system, based on the rationale that if those resources stay in the ground the environmental and social effects associated with their extraction are avoided (see Schrattenholzer *et al.*, 2004 for a discussion).

Here, following Schrattenholzer *et al.* (2004) we use long-term global resource-to-production (Ru/P) ratios both as an aggregate indicator of the availability of fossil resources and, therefore, of the security-of-supply of these fuels at the world level and as a proxy indicator for one important aspect of sustainability of the global energy system, namely the use of non-renewable resources. It must be noted, however, that this indicator depends on assumptions on the available fossil resource base. The long-term global Ru/P ratio is only applied to oil and gas. In the case of coal, although the Ru/P ratio would provide an indicator of sustainability, relatively abundant reserves and resources mean there are few issues of security of energy supply. It must be noted, however, that this is an indicator of physical, and not economic, dependence. Also, it must be emphasized, that this is an indicator of dependence, rather than vulnerability (for a discussion, see e.g., Kendell, 1998).

Clearly, assumptions on the resource base and its geographical distribution constitute one of the main uncertainties in the computation of these indicators. The availability of fossil resources is a function of both geological uncertainty and economic attractiveness. However, in the long term, technological change may substantially alter the picture by improving the ability to identify, quantify and access resources, which together will also increase the economic attractiveness of those resources (Rogner, 1997, 2000). The pace and direction of technological change are, however, highly uncertain.

Figure 3 presents the instrument-to-indicator chain for the security-of-energy-supply objective. In broad terms, the policy instruments may stimulate the diffusion of more efficient fossil-based or non-fossil-based technologies, both of which have the potential to reduce total fuel consumption and facilitate a substitution away from imported fuels towards indigenous regional resources (including renewables, uranium and coal). As a result, technology diffusion can lead to reduced global consumption of highly traded fossil fuels (oil, gas), thus leading to an increase in global long-term Ru/P ratios and/or a reduction in the regional (physical) import dependence. It must be noted, however, that some technological paths may bring synergies between the climate change and the security-of-energy-supply objectives as measured in this study while others could be beneficial for one of them and detrimental to the other.

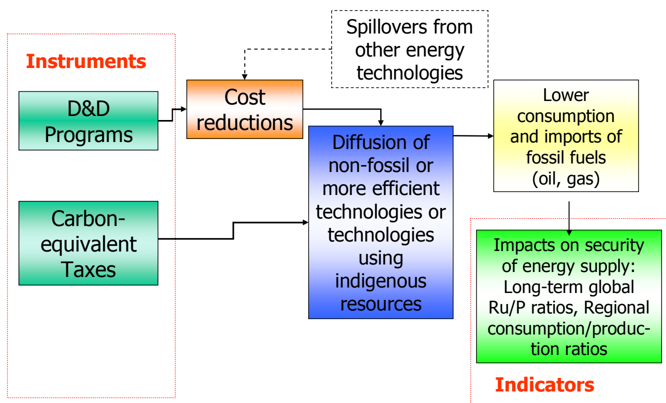

Figure 3: Instrument-to-indicator chain for the security of energy supply objective.

4. The Baseline Scenario

In order to give an adequate context to our analysis, in this section we describe the main characteristics of our baseline scenario, as quantified with the ERIS-MAGICC modeling framework. Basic economic, population, energy demands and technology assumptions of this scenario are described in Turton and Barreto (2004).

In the baseline scenario, the world production of primary-energy resources experiences a substantial increase, reaching approximately 60 TWyr by the end of the 21st century (Figure 4).[2] Both oil and coal experience a sizeable growth in this scenario. Natural gas plays the role of a transition source and its production increases substantially during the 21st century but declines towards the end of it, as the (assumed) resource base is exhausted. Although fossil fuels remain dominant, renewables, biomass in particular, and nuclear energy experience a substantial growth in the second half of the 21st century.

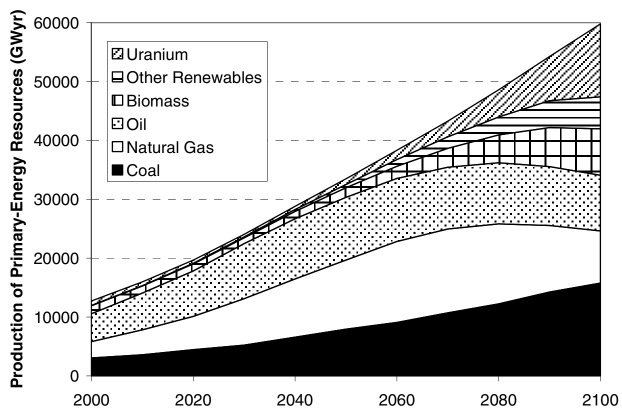

Figure 4: Global production of primary energy resources in the baseline scenario.

By the end of the 21st century, global electricity generation reaches over nine times its level in the year 2000 (Figure 5). The rapidly-increasing electricity demand is covered by a diversified set of generation technologies. Non-fossil technologies substantially augment their contribution to electricity supply in the long term. On the one hand, both standard and advanced nuclear designs gain sizeable shares of electricity production in the long run. On the other hand, although individual renewable-based technologies do not attain a large share of the generation mix, the renewable-based technology cluster as a whole captures a significant fraction of the global electricity production. Among others, biomass gasification plants, wind turbines and solar thermal plants are deployed.

Nonetheless, fossil-fired generation still supplies a sizeable share of the global electricity mix. Installations of conventional coal-fired power plants vigorously grow during the 21st century. Advanced coal-based gasification technologies make some inroads towards the end of the century. Combined-cycle gas turbines experience a significant growth in the medium term but are displaced by other technologies such as gas fuel cells, renewable-based technologies and nuclear power plants in the long run.

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[2] One TWyr is equivalent to 31.54 EJ.

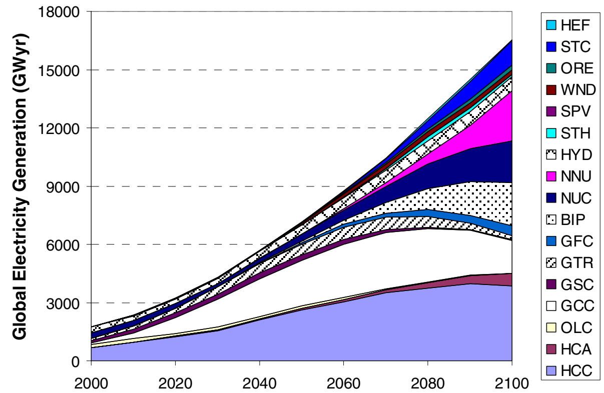

Figure 5: Global electricity generation mix in the baseline scenario. The technology abbreviations are as follows: HCC: conventional coal, HCA: advanced coal (IGCC), OLC: oil conventional, GCC: gas combined-cycle, GSC: gas steam cycle, GTR: gas turbine, GFC: gas fuel cell, BIP: biomass gasification, NUC: nuclear conventional, NNU: new nuclear, HYD: hydro, STH: solar thermal, SPV: solar photovoltaics, WND: wind turbine, ORE: other renewables, HEF: hydrogen fuel cell.

Fuel production in this scenario remains dominated by oil products (Figure 6). Nonetheless, synthetic fuels are able to capture some market share in the second half of the 21st century. Specifically, the production of coal-based Fischer-Tropsch liquids increases, especially in regions with abundant indigenous coal resources (e.g., China). In addition, hydrogen from coal and, to a lower extent, biomass penetrates in the long term alongside with alcohol from biomass. Notice that, in this scenario, natural gas is mainly converted to electricity or directly used in stationary sectors or in gas-powered vehicles. Therefore, only a very small fraction of natural gas is used for the production of synthetic fuels.

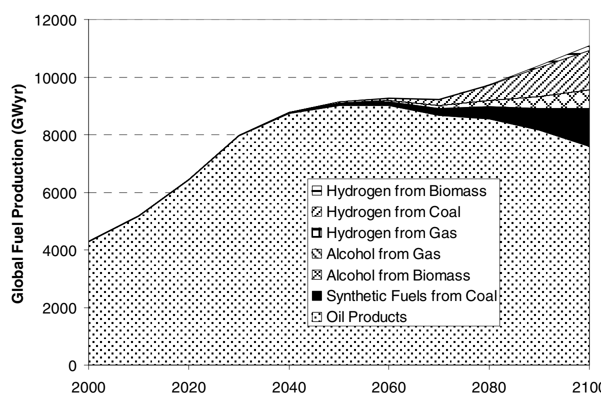

Figure 6: Global production of fuels in the baseline scenario.

As described in Turton and Barreto (2004), the ERIS model introduces technology clusters, for example, groups of technologies that share key learning components. As a reference for our discussion below, Figure 7 presents the cumulative installations of the key components relative to their cumulative capacity in the year 2000 in our baseline scenario. As can be seen, already in the baseline scenario several of the learning components experience substantial progress along their learning curves. For the list of key components and how they relate to technologies in the ERIS model see the appendix.

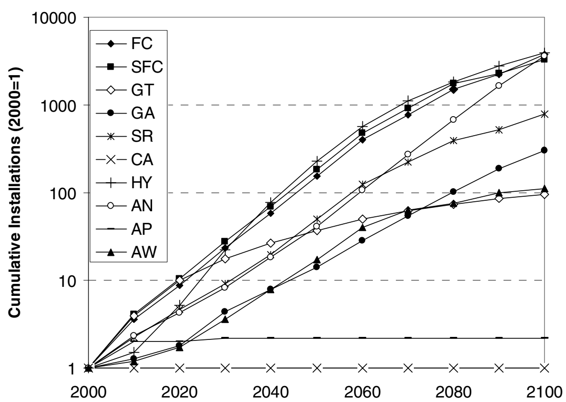

Figure 7: World cumulative installations of key components under the baseline scenario. Cumulative capacity is relative to that in the year 2000 (set to 1 as reference). The abbreviations of the key components are as follows: FC: Fuel cell, SFC: Stationary fuel cell, GT: gas turbine, GA: gasifier, SR: Steam or auto-thermal reformer, AN: Advanced nuclear, AP: Solar photovoltaics, AW: Wind turbines, HY: Hybrid battery system, CA: CO_2 adsorption and stripping, Note: the Y-axis scale in this graph is logarithmic. For the relation between learning components and technologies see the appendix.

We now briefly discuss the technological transition in the passenger car sector under our baseline scenario. There are three main kinds of competing technologies, namely internal-combustion-engine vehicles (ICEVs), today's dominant technology, hybrid-electric vehicles (HEVs), an advanced technology that may be at least partially compatible with today's technological regime, and fuel-cell vehicles (FCVs), an advanced revolutionary technology that requires the emergence of a new technological regime. Our scenario portrays a gradual, measured technological transition in the passenger car sector (Figure 8). The petroleum-fired internal combustion engine is gradually displaced by more advanced technologies along the 21st century. Specifically, there is a shift to hybrid-electric vehicles (HEVs), which achieve 50% market share around 2070-80. In terms of fuels, a more diversified passenger car sector emerges as well. Specifically, although at the end of the 21st century petroleum-based HEVs dominate and conventional petroleum-based internal combustion engines still hold a residual share of about 20%, gas- and alcohol-powered HEVs make sizeable inroads in the passenger car market. Fuel-cell vehicles achieve only a very small penetration of the market in this slow-transition scenario (0.5%, mainly hydrogen fuel-cell vehicles).

Figure 9 shows the carbon-equivalent of CO_2, CH_4 and N_2O emissions in the baseline scenario. The total emissions of these three GHGs increase substantially along the time horizon, peaking at about 29 GtC-eq[3] around the year 2090 and leveling afterwards. The

[3] Here, the unit ton refers to metric tons.

largest contribution is that of CO_2 emissions, which reach approximately 24 GtC-eq at their peak in the year 2090.[4]

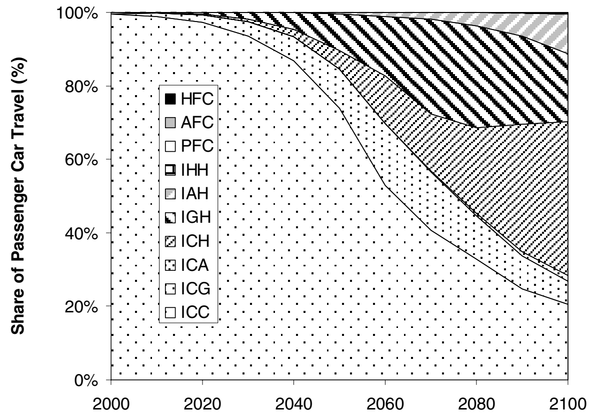

Figure 8**:** Share of global car travel by drive-train technology and fuel in the baseline scenario. Abbreviations of technologies are as follows: ICC: internal combustion conventional (gasoline), ICG: internal combustion gas, ICG: internal combustion alcohol, ICH: internal combustion (gasoline) hybrid, IGH: internal combustion gas hybrid, IAH: internal combustion alcohol hybrid, IHH: internal combustion hydrogen hybrid, PFC: petroleum fuel cell, AFC: alcohol fuel cell, HFC: hydrogen fuel cell. Note: dotted shading indicates ICEVs, diagonal shading indicates HEVs, and each FCV technology is indicated with either no (petroleum), medium (hydrogen) or dark (alcohol) shading.

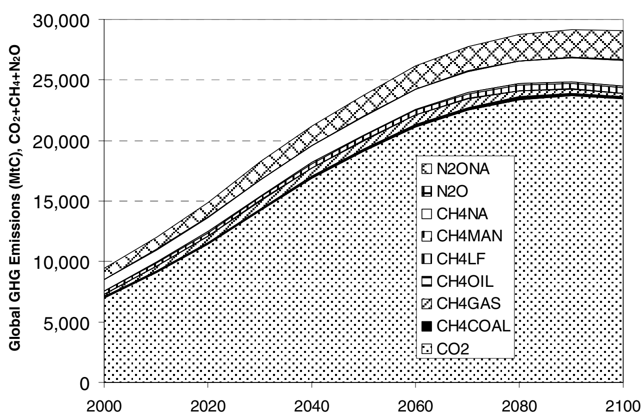

Figure 9: Global emissions of CO_2, CH_4 and N_2O (C-eq) in the baseline scenario. Abbreviations for the emission sources are as follows: CO2: CO_2 from energy-related activities and cement production, CH4COAL: CH_4 from coal production, CH4GAS: CH_4 from gas production, CH4OIL: CH_4 from oil production, CH4LF: CH_4 from land fills, CH4MAN: CH_4 from manure, CH4NA: Non-abated CH_4, N2O: N_2O from adipic and nitric acid production, N2ONA: Non-abated N_2O.

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[4] As discussed in Turton and Barreto (2004), marginal abatement curves (MACs) for CH_4 and N_2O emissions from a number of sources are specified in the ERIS model, following the study by EPA (2003). However, abatement cost curves were not available for several significant sources – notably enteric fermentation and agricultural soils (N_2O) and some sources of CH4– and it is conservatively assumed that there are no abatement opportunities associated with these activities. In this report, these categories are referred to as non-abated (NA).

Using the emission profiles for the three main GHGs, CO_2, CH_4, N_2O, and sulfur dioxide (SO_2) computed by ERIS, together with assumptions about the emission pathways of other GHGs[5], the atmospheric concentrations of CO_2, CH_4 and N_2O as well as global temperature change and global sea-level rise are computed with the climate MAGICC model (version 4.1, Wigley, 2003). The MAGICC runs have been carried out assuming a CO_2 fertilization effect of 1.1 GtC/year, a climate sensitivity of 2.6 ^oC and aerosol radiative forcings of -0.4 W/m^2 (direct),-0.8 W/m^2 (indirect) and -0.2 W/m^2 (biospheric) respectively.

Figure 10 presents the corresponding concentrations of these three GHGs in the atmosphere. Concentrations of CO_2 and CH_4 increase rapidly in this scenario, reaching approximately 850 ppmv and 3200 ppbv respectively by the year 2100. N_2O concentrations grow much slower and reach approximately 470 ppbv by the end of the 21st century. Notice that the MAGICC model computes changes from a reference historical level in the year 1990.

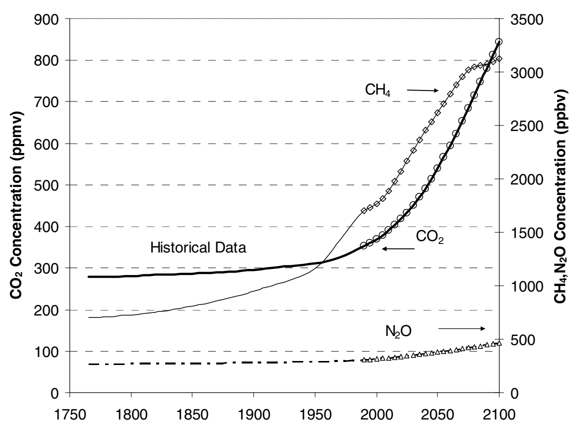

Figure 10: Concentrations of CO_2 (ppmv), CH_4 (ppbv) and N_2O (ppbv) for the baseline scenario, computed with the MAGICC climate model. Historical values are shown as reference. Source: CDIAC, 2003.

Under this scenario, annual global temperature change and annual global sea level steadily rise along the 21st century (Figure 13). By the end of the 21st century, global temperature change reaches 3.4 ^oC and sea-level rise amounts to approximately 43 cm, both relative to year-1990 levels. Due to the large inertia and long time scales inherent to the response of the oceans to a climate forcing, which are much larger than those of the atmospheric system (IPCC, 2001a), the global sea level rises at a somewhat slower pace than global temperature.

[5] The MAGICC climate model requires emission pathways for other GHGs, which are not computed by the ERIS model. In this case, they have been taken from the IPCC/SRES B2 scenario as quantified with the MESSAGE and AIM models (SRES, 2000).

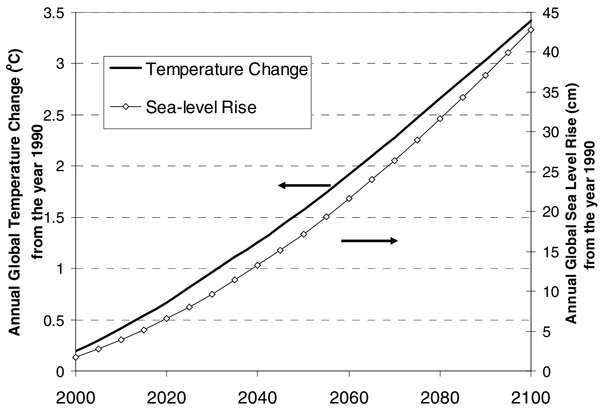

Figure 11: Annual global temperature change and annual global sea-level rise for the baseline scenario, as obtained with the MAGICC climate model. Note: changes are relative to the year 1990.

We now turn to the indicators of security of energy supply, for example, the global resources-to-production ratios (hereon referred to as Ru/P ratio) of oil and natural gas. In this analysis, we compute the ratio between the fossil resource base, specified in the model following the categorization of Rogner (1997, 2000)[6], and the global production of primary fossil fuels in a given time period (the year 2050 in our case).

It should be noticed that the indicator used here does not correspond to the conventional notion of reserves-to-production ratio, which considers only the proven reserves today. The reason why we have chosen to compute a resources-to-production ratio (Ru/P) instead of the more commonly used reserves-to-production ratio is the deterministic treatment of fossil reserves and resources in the ERIS model. That is, the categories included in the model are assumed to be available for the whole optimization period, only at a higher extraction cost. If they become cost-effective they will be used. Therefore, from a modeling point of view, these categories are certain. In reality, several of the categories used in this analysis have an inherent uncertainty and, therefore, they are not included in the calculation of reserves-to-production ratios commonly reported in the literature (e.g., BP, 2003).

Figure 12 presents the global resources-to-production ratios (Ru/P) for oil and natural gas in the baseline scenario. As can be seen, under our moderate assumptions about their resource base and the rapidly-increasing consumption patterns implied by the assumed energy demands and technology dynamics in this scenario, Ru/P ratios for both of these fossil primary-energy resources significantly decline along the 21st century. By the year 2050, Ru/P ratios for oil and gas have gone down to approximately 59 and 56 years respectively and by the year 2100, the figures for both of them reach about 9 years.

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[6] See Turton and Barreto (2004) for details on the assumptions about the fossil resource base in the ERIS model in our scenario. The categories labeled as unconventional resources and additional occurrences in Rogner (1997, 2000) were not considered.

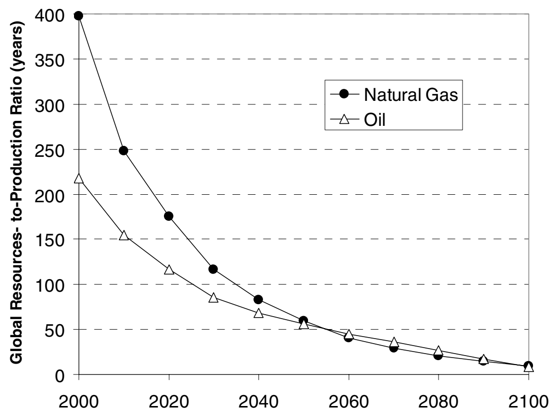

Figure 12: Global resources-to-production (Ru/P) ratios for oil and natural gas in the baseline scenario.

5. The Impact of a Carbon-equivalent Tax

A carbon (equivalent) tax is a generic climate policy instrument that provides an incentive to shift toward low-emissions technologies without imposing a cap on GHG emissions. Here, we consider the imposition of a tax on the carbon-equivalent emissions of the three main GHGs (CO_2, CH_4 and N_2O) at the global level. In this section, we discuss the impacts of applying C-eq taxes ranging from $0-1000/ton C-eq. The discussion will be concentrated on the impact of the C-eq tax on the sustainability indicators of interest in this study.

The impact measure is defined here as the Delta Indicator/Instrument Cost ratio. "Delta Indicator" is the incremental change in a given indicator relative to the baseline case, i.e., the case without the application of the policy instrument. By convention, positive values of impacts imply an improvement in the respective sustainability indicator and vice versa. That is, for the climate-change indicators, such as CO_2 concentration and global temperature change, an improvement represents a decrease in the indicator. For other indicators, such as the resources-to-production (Ru/P) ratios used here to measure security of energy supply, an improvement is represented by an increase in the indicator.

"Instrument Cost" is the estimated cost of applying a given policy instrument. For the carbon-equivalent tax we use the difference in total discounted system costs between a baseline case with zero C-eq tax and the case where a non-zero C-eq tax is imposed on the global energy system, subtracting the tax revenues. In our partial-equilibrium modeling framework this is equivalent to the loss of consumer surplus.

5.1 Impact of a carbon-equivalent tax on climate change

In this section we discuss the impact of the carbon-equivalent tax on the climate-change indicators. Before proceeding with the discussion, we illustrate with an example how the impact measure used in this report is derived. Figure 13 presents one selected climate-change indicator, CO_2 concentration in the atmosphere for the year 2100 in this case, as a function of the C-eq tax. The total discounted system costs resulting in each case after the imposition of a non-zero C-eq tax are also shown, after subtracting the C-eq tax revenue. As expected, an increasing C-eq tax results in a reduction of the CO_2 concentration in the atmosphere, as compared with the baseline scenario. The decline in CO_2 concentration is steeper for low C-eq tax values but it becomes less pronounced at higher C-eq tax levels.

The imposition of the C-eq tax induces technological change towards energy sources and technologies with low GHG emissions, which result in a higher total discounted energy-system cost than in the baseline case. At low C-eq tax levels, low-cost abatement measures, such as the mitigation opportunities of non-CO_2 GHGs and forest sinks, are exhausted. At higher tax levels, more expensive mitigation options, such as CO_2 capture and storage (CCS) and deployment of fuel-cell hydrogen vehicles in the transportation sector, are tapped.

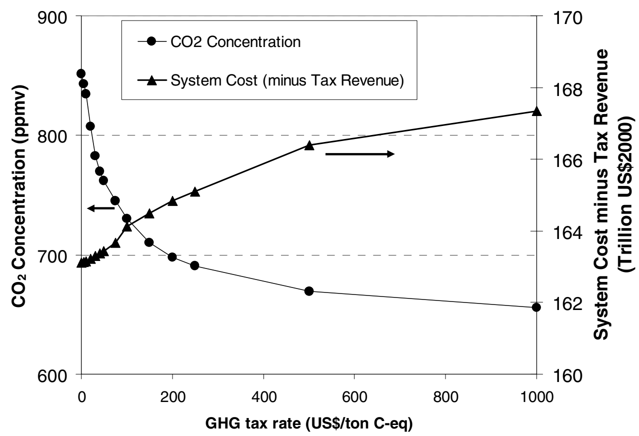

Figure 13: CO_2 concentration in the atmosphere for the year 2100 and total discounted system costs (subtracting the C-eq tax revenue) as a function of the C-eq tax.

Using these values, the differences in CO_2 concentration and total discounted system costs (subtracting the C-eq tax revenue), relative to the baseline scenario can be computed. The corresponding change in CO_2 concentration ("delta indicator") and the change in total discounted system costs ("instrument cost") are shown in Figure 14. Notice that, by convention, we are assuming that positive values of the impact measure mean an improvement in the sustainability indicator. In the case of the climate indicators used here, an improvement is represented by an actual reduction in the magnitude of the indicator, e.g., a reduction in the atmospheric concentration of CO_2. For those indicators, we use a minus sign in front of the change in concentrations when computing the "delta indicator" variable.

Using these two variables, namely the delta in CO_2 concentration in the year 2100 and the instrument cost, the impact of the C-eq tax on CO_2 concentration can be estimated as the above-described ratio. Figure 15 presents the impact on CO_2 concentration for the range of C-eq taxes examined.

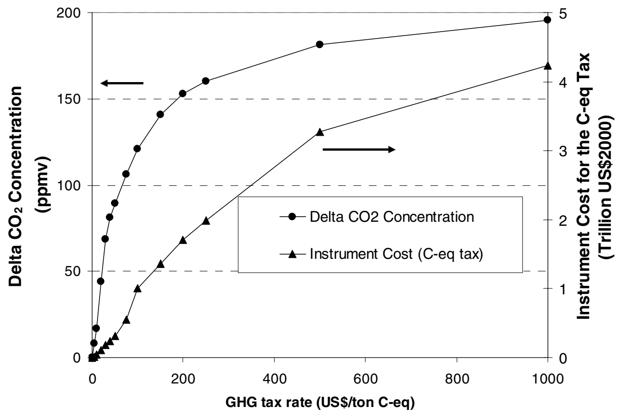

Figure 14: "Delta indicator" for the CO_2 concentration in the atmosphere (year 2100) and the corresponding "instrument cost", computed as the difference between the total discounted system costs in the C-eq-tax case (subtracting the C-eq tax revenue) and those of the baseline scenario. By convention, a positive impact means an improvement in the indicator (in this example a reduction on the CO_2 concentration in the atmosphere). Therefore, the delta indicator is computed with a minus sign in front in this case.

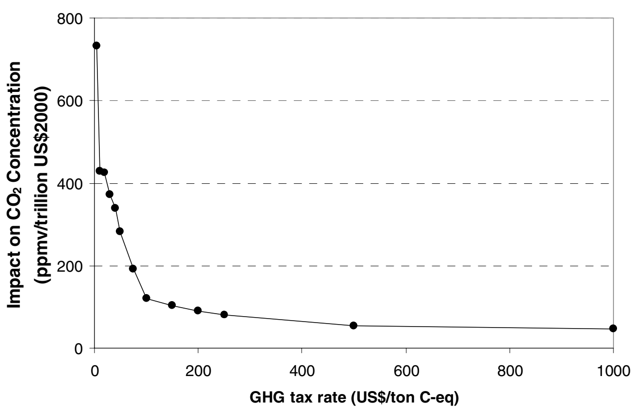

Figure 15: Impact of the carbon-equivalent tax on the CO_2 concentration in the atmosphere for the year 2100 as a function of the carbon-equivalent tax. The impact measure is computed as the ratio between the difference in CO_2 concentration in the baseline scenario and the C-eq tax case and the corresponding instrument cost (difference in total discounted energy-system costs subtracting the C-eq tax revenue). By convention, a positive impact means an improvement in the indicator (in this case a reduction on the CO_2 concentration in the atmosphere).

As can be seen in Figure 15, at low C-eq tax levels, the impact on the CO_2 concentration indicator is high. That is, with a relatively small C-eq tax rate cheap mitigation options can be tapped and a relatively large change in CO_2 concentration is achieved. However, the impact decreases as the C-eq tax rate is raised. This is so because the incremental reduction of CO_2 concentration achieved with a given level of carbon-equivalent tax becomes increasingly smaller, as mitigation options are exhausted, while the corresponding costs of application of the policy instrument become higher, as more expensive mitigation options have to be introduced at higher C-eq tax levels.

We now discuss the impacts of the C-eq tax on the other climate-change sustainability indicators examined here. Figure 16 presents atmospheric concentrations of CH_4 and N_2O for the year 2100 as a function of the C-eq tax rate. These two GHGs offer potential for cheap abatement options, which is exhausted at low C-eq tax rates. CH_4 concentrations decrease substantially as the C-eq tax rate becomes higher. However, the decrease is steeper at lower C-eq tax levels, where most of the CH_4 abatement options are introduced. Notice that in the case of a C-eq tax rate of 1000 US$/ton, most of the mitigation occurs in CO_2 emissions and the CH_4 concentration is slightly higher for this case than it is for a C-eq tax of 500 US$/ton.

As for N_2O, abatement options are available from 20 US$/ton C-eq. Therefore, C-eq tax rates below this value do not lead to any abatement of this greenhouse gas. Once the C-eq tax surpasses this threshold, abatement of N_2O takes place. However, as mentioned above, due to data constraints of the US EPA (2003) study, we have assumed a significant portion of N_2O emissions to be non-abated (i.e., no marginal abatement curve is specified, see the category N2ONA in Figure 5 above). Thus, after an initial steep decline, N_2O concentrations remain unaffected by the increase in the C-eq tax rate. Because of this reason, we have chosen not to report impacts on this particular indicator in this study.

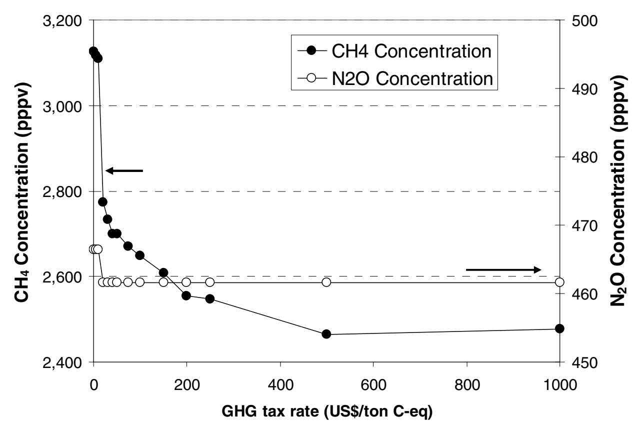

Figure 16: CH_4 and N_2O concentrations in the atmosphere for the year 2100 as a function of the C-eq tax.

Figure 17 presents the impact of the carbon-equivalent tax on the CH_4 concentration in the atmosphere for the year 2100 as a function of the carbon-equivalent tax. As in the case of CO_2 concentration above, the impact is higher at low C-eq tax rates, where the cheaper options for CH_4 mitigation are available and decline at higher C-eq tax rates.

Figure 18 presents the global temperature change and sea-level rise indicators for the year 2100 as a function of the C-eq tax rate. As expected, the C-eq tax results in smaller GHG emissions and, therefore, in smaller GHG concentrations in the atmosphere, which in their turn lead to a lower climate forcing. As a result, both global temperature change and sea-level rise are reduced as the C-eq tax rate increases. However, since there is considerable inertia in the climate system (IPCC, 2001a) due, among others, to the slow transport of heat into the oceans and slow response of ice sheets, the response of surface air temperature and sea level to the C-eq tax is much slower and is less pronounced than that of GHG concentrations.

Also, notice that a C-eq tax rate of 1000 US$/ton C-eq produces slightly higher global temperature change and sea-level rise than a 500 US$/ton C-eq tax. The reason for this lies in the difference between SO_2 emissions in these two cases. SO_2 emissions in the ERIS model are mainly linked to coal production and use. A C-eq tax of 1000 US$/ton C-eq produces a strong reduction in coal consumption and, therefore, in the associated SO_2 emissions (see Figure 19 below). Since SO_2 has a negative climate forcing, a reduction in SO_2 emissions leads to an increase in the total climate forcing and, therefore, slightly higher temperature change and sea-level rise in the case of a US$ 1000/ton C-eq tax than it is for a tax of 500 US$/ton.

Figure 20 presents the impact of the C-eq tax on global temperature change and global sea-level rise in the year 2100 as a function of the C-eq tax rate. As before, impacts are generally higher at lower C-eq tax rates and decline at higher levels.

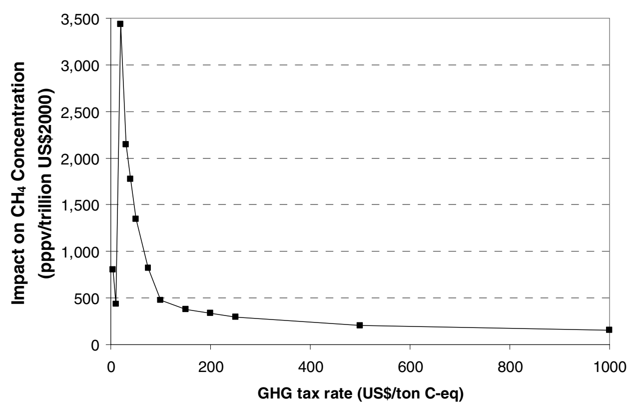

Figure 17: Impact of the carbon-equivalent tax on the CH_4 concentration in the atmosphere for the year 2100 as a function of the carbon-equivalent tax.

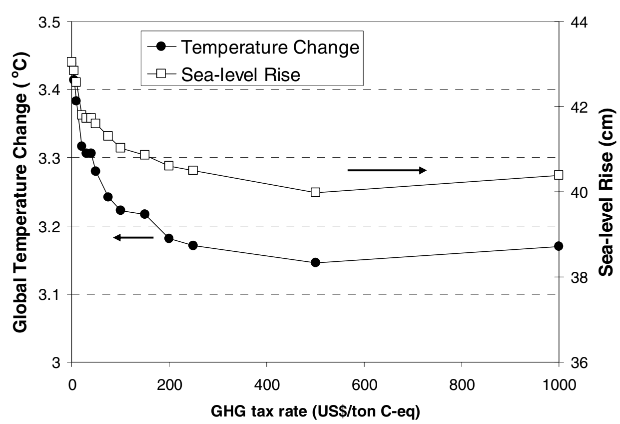

Figure 18: Global temperature change and annual sea-level rise in the year 2100 as a function of the C-eq tax.

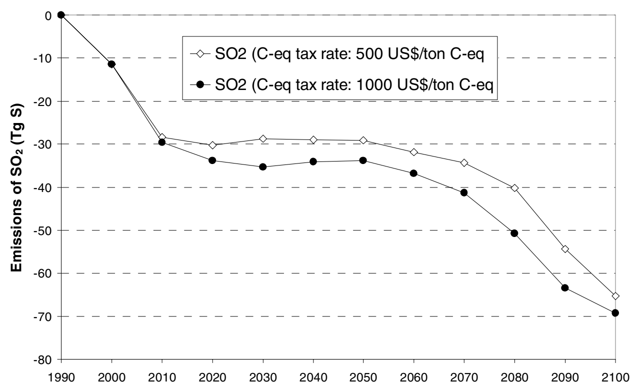

Figure 19: Comparison of SO_2 emissions for the cases with C-eq tax rates of 500 US$/ton C-eq and 1000 US$/ton C-eq. According to the specifications of the MAGICC model, SO_2 emissions are measured relative to the values in the year 1990.

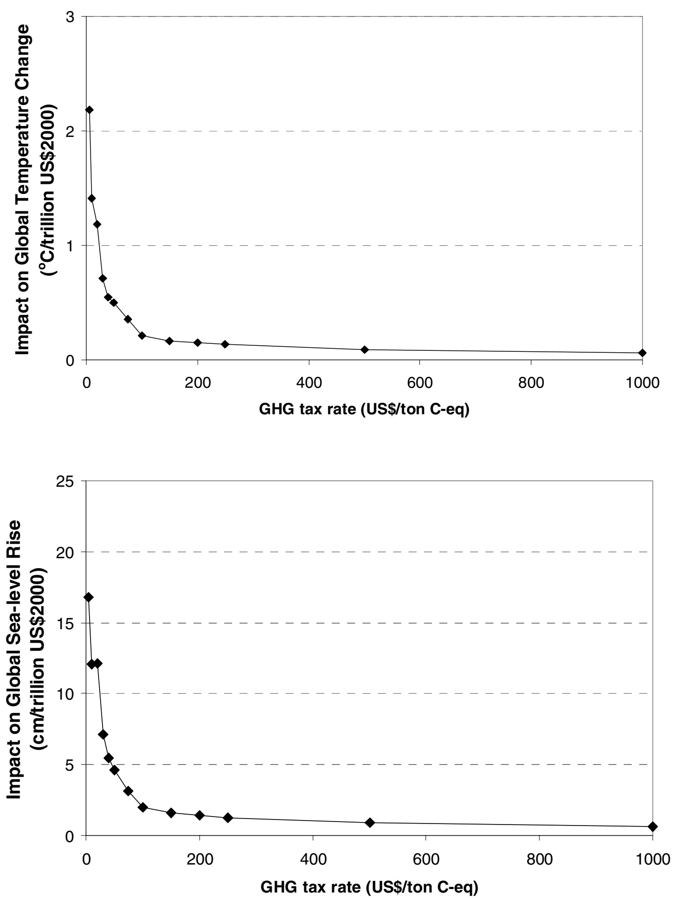

Figure 20: Impact of the carbon-equivalent tax on global annual temperature change and global annual sea-level rise in the year 2100 as a function of the carbon-equivalent tax. The impact measure is computed as the ratio between the difference in the respective indicator in the baseline scenario and the C-eq tax case and the corresponding instrument cost (difference in total discounted energy-system costs, subtracting the C-eq tax revenue). By convention, a positive impact means an improvement in the indicator (a reduction in the global temperature change or sea-level rise).

5.2 *Impact of a carbon-equivalent tax on the security of energy supply*

We now turn to discuss the impacts of the carbon-equivalent tax on the global indicators of the security of energy supply, i.e., the long-term resources-to-production (Ru/P) ratios for oil and natural gas in the year 2050.[7] Notice that for these two sustainability indicators an increase relative to the baseline means an improvement and vice versa. Figure 21 presents these two indicators as a function of the C-eq tax rate. The effect of the C-eq tax on the global oil Ru/P is fairly consistent. Increasing the carbon-equivalent tax leads to an increase in the oil Ru/P ratio (an improvement). That is, with a higher tax imposed on GHG emissions, the global energy system weans away from oil, a CO_2-intensive fossil energy source, towards less carbon-intensive fossil fuels like natural gas and non-fossil resources (renewables and nuclear energy).

The effect of the C-eq tax on the global Ru/P ratio for gas is less consistent, as the fluctuations in the indicator show. However, some trends are recognizable. Specifically, relatively low levels of the C-eq tax lead to a decrease in the Ru/P ratio of natural gas. That is, a larger consumption of natural gas takes place as the system moves away from the more carbon-intensive coal and oil fossil resources. At larger C-eq tax rates, more expensive non-fossil resources and technologies are introduced and the gas Ru/P increases again. Above approximately 100 US$/ton C-eq, the Ru/P ratio of natural gas remains more or less unaffected by further increases in the C-eq tax rate.

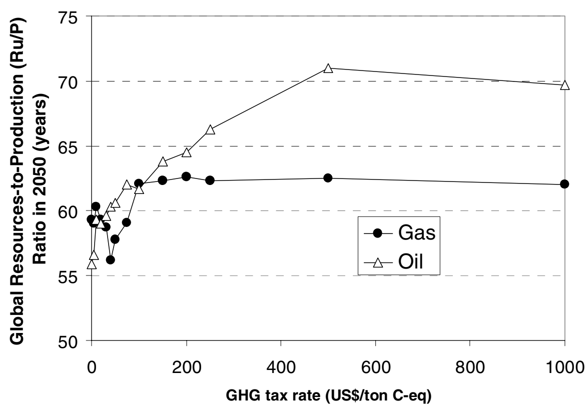

Figure 21: Long-term global resources-to-production (Ru/P) ratio (in years) of natural gas and oil for the year 2050 as a function of the C-eq tax rate.

Accordingly, the impact of the C-eq tax on the natural gas Ru/P ratio (Figure 22) shows significant fluctuations between positive and negative values before finally becoming positive and declining at large C-eq tax levels. The impact on the oil Ru/P ratio (Figure 23) is, as with other indicators discussed above, higher a low C-eq tax rates and declines at larger C-eq tax levels.

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[7] Notice that the resources-to-production (Ru/P) ratios for oil and natural gas are reported here for a given year (2050). As such, the indicators represent a "snapshot", rather than a dynamic picture, of the changes in consumption of oil and natural gas in a given case.

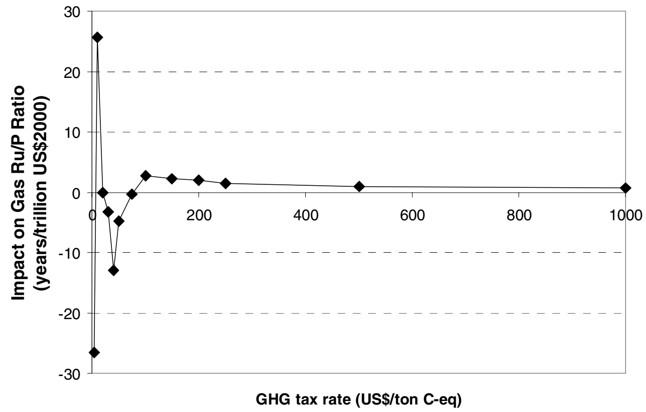

Figure 22: Impact of the C-eq tax on the long-term resources-to-production (Ru/P) ratio of natural gas for the year 2050 as a function of the C-eq tax rate.

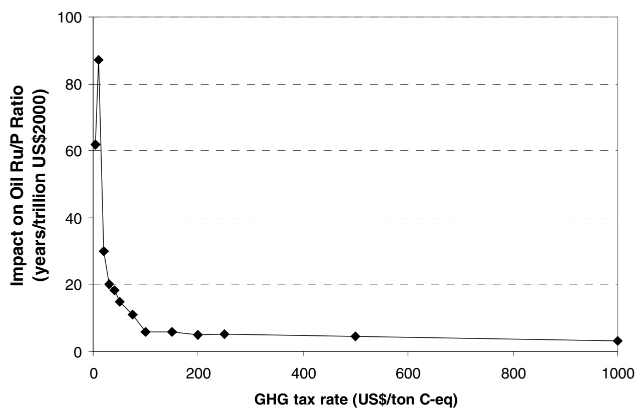

Figure 23: Impact of the C-eq tax on the long-term resources-to-production ratio of oil for the year 2050 as a function of the C-eq tax rate.

As a final comment, it should be noticed that one cannot separate these results from the baseline scenario they are associated with and described above. The developments of the baseline scenario provide the context in which the emission reductions of the GHG mitigation scenario take place (Roehrl and Riahi, 2000; IPCC, 2001b). The baseline dynamics, in combination with the level of the carbon-equivalent tax imposed on the global energy system, determine how difficult it is to achieve the corresponding reduction in emissions and which technologies, and to what extent, intervene in the GHG mitigation strategy. Therefore, they have an effect on the quantification of the impact of a given policy instrument, the C-eq tax in this case, on sustainability indicators.

6. Impact of Demonstration and Deployment (D&D) Programs

We now examine the impact of energy-related D&D programs on the sustainability indicators of interest in this study. Demonstration and deployment (D&D) programs enable the accumulation of valuable experience in the marketplace. From this experience, performance and/or cost improvements may result, which could improve the competitiveness and facilitate a broader deployment of a given technology or cluster of technologies. Specifically, a strategic management of niche markets, where the technology may be attractive due to specific advantages or particular applications, may stimulate the diffusion process of a given technology or cluster of related and/or complementary technologies (Kemp, 1997). A successful introduction of the technology in niche markets can contribute to build up the confidence of potential users, equipment manufacturers and other social actors, such as policy makers.

For the evaluation of the impacts of demonstration and deployment programs we apply the notion of "shocks", i.e., small one-off incremental variations in the cumulative capacity of a given technology at the beginning of the time horizon (the year 2000). In order to provide a realistic treatment of technology demonstration and deployment programs the D&D, or capacity, "shocks" affect an entire *technology* comprising a number of learning and non-learning components, rather than an isolated key component. 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.

In this section, we report the result of orthogonal D&D shocks (i.e., one technology at the time) of 10 billion dollars (US$2000) size applied to a large number of energy technologies. 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. This gives a policy maker a clearer notion of what the impacts on sustainability indicators would be if a given sum of money is invested on a D&D program for a particular technology. Also, the D&D shocks shed some light into which technology would provide a larger "return-to-investment" on sustainability indicators if a corresponding D&D program of the above-mentioned size would be undertaken. In doing so, the use of a standard size for the D&D shock greatly facilitates the comparison across technologies.

Our analysis follows the notion of "impact" explained above, i.e., the impact of D&D programs is computed as the ratio Delta Indicator/Instrument Cost. In such context, the "delta indicator" numerator is computed as above relative to the baseline scenario. The costs of D&D programs are measured at "face value", i.e., as the respective D&D expenditures that constitute a "shock".

Orthogonal shocks have been performed for electricity generation, fuel production and passenger-car technologies. The list of technologies and their abbreviations can be found in Table 1 (see also Appendix). In section 5 below, we examine the effects of combining these orthogonal D&D shocks with a wide range of C-eq taxes.

Table 1: Description and abbreviations of technologies in the electricity generation, fuel production and passenger-car sectors for which D&D shocks were performed.

Sector	Abbreviation	Description
Electricity generation	HCA	Advanced coal power plant (Integrated Gasification Combined Cycle, IGCC)
	GCC	Gas-fired combined-cycle gas turbine
	GTR	Gas-fired single-cycle gas turbine
	GFC	Gas-fired high temperature fuel cell
	NNU	Advanced nuclear power plant
	SPV	Solar photo-voltaics
	WND	Wind turbine
	HEF	Hydrogen fuel cell
Fuel production	SYNFNE	Synthetic fuels from coal (Fischer-Tropsch liquids)
	BIOALNE	Alcohol from biomass (methanol)
	GASALNE	Alcohol from natural gas (methanol)
	GASH2NE	Hydrogen from natural gas
	COALH2NE	Hydrogen from coal
	BIOH2NE	Hydrogen from biomass
Passenger cars	ICH	Gasoline-powered hybrid-ICE-electric car
	IGH	Gas-powered hybrid-ICE-electric car
	IAH	Alcohol-powered hybrid-ICE-electric car
	IHH	Hydrogen-powered hybrid-ICE-electric car
	PFC	Gasoline-powered fuel-cell car
	AFC	Alcohol-powered fuel-cell car
	HFC	Hydrogen-powered fuel-cell car

It is important to notice that, among other factors, the clusters approach to technology learning may have a significant impact on the results, because of the interactions it creates between technologies. When a given technology receives a D&D shock, this implies a stimulus for the installations of its learning and non-learning components. Through the action of clusters, the D&D "shock" represents a stimulus to deploy other technologies sharing the key learning components as well.

Under the action of the underlying technology learning mechanism, our perfect foresight model has a tendency to either install a technology to the maximum allowable extent or not to install it at all. This is typically referred to as "all-or-nothing" behavior. Under these conditions, the clusters approach may lead to the installation of technologies sharing key components with the technology that receives the D&D shock. This is due to the fact that additional cumulative capacity in one of the members of the cluster will lead to a reduction in the investment costs of the key technology, thus bringing a cost reduction to all the members of the cluster. This may result in some apparently counterintuitive results, but it actually represents a better representation of how technological change would be stimulated in the real world, i.e., the fact that the presence of technology spillovers lead to the co-evolution of related and/or complementary technologies (Nakićenović, 1997).

The final outcome will also depend on other factors. Among others, absolute and/or market penetration constraints, learning rates and floor costs, resource potentials, costs and availability, cluster membership, etc., play an important role in the competition between technologies in our perfect foresight optimization modeling framework. In order to illustrate the role of these and other factors, below we describe one example of a demonstration and deployment (D&D) shock in detail.

6.1 An illustrative demonstration and deployment (D&D) shock

Before presenting the results for the whole set of technologies, we illustrate the effects of a demonstration and deployment (D&D) shock with an example. This example illustrates some of the impacts and interactions that a comprehensive energy-system model like ERIS is able to examine. It also provides some indication of the possible difficulties that may arise when comparing a large number of scenarios.

A shock of US$10 billion gross[8] was applied in the base year (2000) to advanced coal-based electricity generation, modeled in ERIS as integrated gasification combined cycle (IGCC) generation. This shock is equivalent to 6,000 MW of generation capacity, or around 3 large power stations.[9]

As described in Turton and Barreto (2004), the IGCC (denoted HCA, for hard coal advanced) technology comprises learning and non-learning components shared by other technologies. Of the learning technologies, the gasifier is also used in fuel production (Fischer-Tropsch liquids, H_2 from coal and biomass and alcohols from biomass) and the gas turbine is used in other electricity generation technologies (including the gas turbine and gas combined-cycle generation). A D&D shock on the advanced coal generation technology could be expected to have an impact on these technologies that use a common component. Furthermore, the shock may also have an impact on other technologies (with which the IGCC shares no common components), particularly on other competing electricity generation technologies.

The impact on the future energy system of a D&D shock on advanced coal generation projected by the ERIS model is significant and fairly extensive. Figure 24 presents the global electricity generation mix under a D&D shock (HCA) scenario for the period 2000-2100. Figure 25 presents a comparison of the global electricity generation mix under baseline (no-shock) and D&D shock (HCA) scenarios for the year 2100.

Overall electricity generation is roughly equal under each scenario and increases over 9-fold over the century. In the D&D shock scenario, the share of electricity supplied from advanced coal generation technologies (denoted, HCA) is significantly larger than under the baseline scenario (12.4% *versus* 3.8% in 2100). This is mostly at the expense of conventional coal (HCC) and gas combined cycle (GCC) generation. Some of the other technologies also account for a slightly smaller proportion of generation, although this reduction is relatively insignificant. Accordingly, although the HCA and GCC technologies share the gas turbine component, the HCA technology benefits more from the D&D shock. This is due to the relative impact of the shock on the gas turbine (GT) component compared to the gasifier (GA) component. It should be noted that GCC generation is extremely competitive in the baseline scenario, and accounts for a large share of generation, particularly in the middle of the century.

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[8] That is, the shock covers the entire cost of the technology. In reality, the actual expenditure required from government might only be the difference between the cost of the 'shocked' technology and that of a commercially viable competitor.

[9] A large D&D-shock size has been chosen in order to ensure a perturbation large enough for the model to show noticeable changes. However, impacts are normalized, i.e. presented per unit of currency.

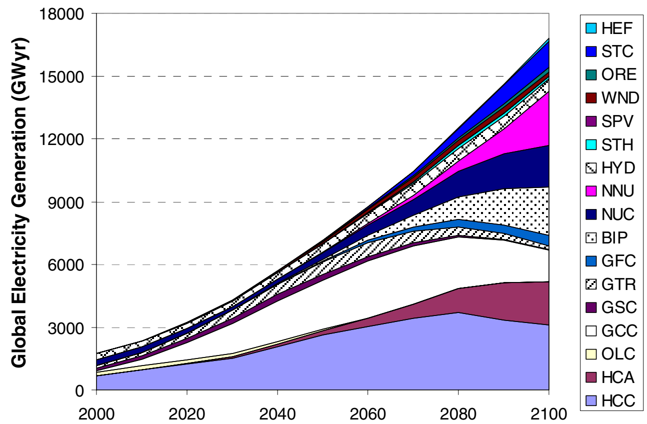

Figure 24: Global electricity generation mix under a D&D shock on the HCA electricity generation technology. The technology abbreviations are as follows: HCC: conventional coal, HCA: advanced coal (IGCC), OLC: oil conventional, GCC: gas combined-cycle, GSC: gas steam cycle, GTR: gas turbine, GFC: gas fuel cell, BIP: biomass gasification, NUC: nuclear conventional, NNU: new nuclear, HYD: hydro, STH: solar thermal, SPV: solar photovoltaics, WND: wind turbine, ORE: other renewables, HEF: hydrogen fuel cell.

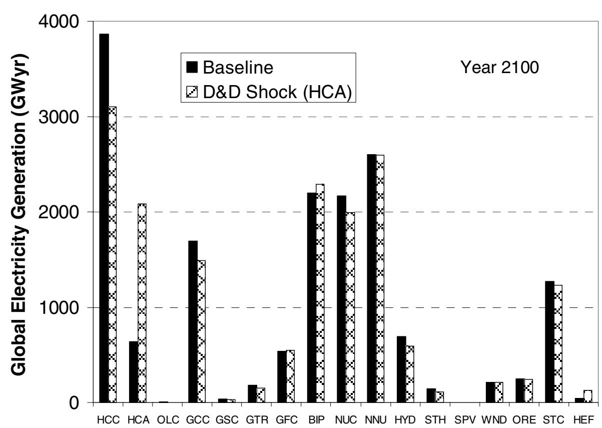

Figure 25: Comparison between the global electricity generation mix under the baseline scenario and under a D&D shock on the HCA electricity generation technology for the year 2100. For technology abbreviations, see Figure 24 above.

Figure 26 compares the impact on all learning components of the baseline and D&D shock directed at the advanced coal generation. These figures present an index of cumulative installed capacity of each component (2000 = 1). For example, under the baseline scenario by 2100 the cumulative installed capacity of gas turbines is 100 times the cumulative installed capacity in 2000. Interestingly, however, the cumulative installed capacity of this component is roughly the same in the D&D shock scenario. This is consistent with the result shown in Figure 24 and Figure 25, where some of the additional installation of HCA displaced GCC generation. In contrast, Figure 26 shows that under the D&D shock scenario by the end of the century the total installation of gasifiers is 50% higher than in the baseline. Moreover, the rate of installation is accelerated by approximately one decade in the shock scenario.

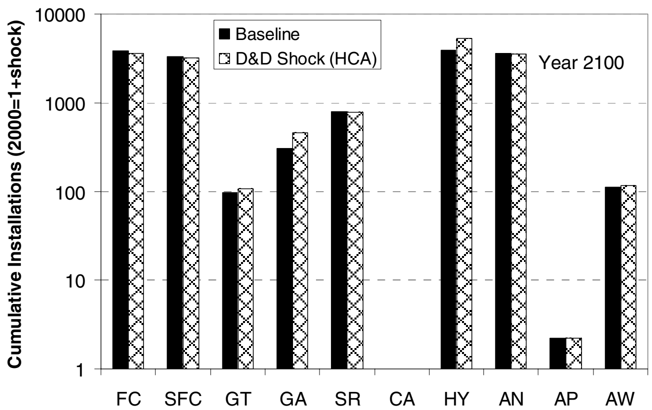

Figure 26: Comparison between the cumulative installations of key components under the baseline scenario and the D&D shock on the HCA electricity generation technology. Cumulative capacity is relative to that in the year 2000 (set to 1 as reference). The abbreviations of the key components are as follows: FC: fuel cell, SFC: stationary fuel cell, GT: gas turbine, GA: gasifier, SR: steam or auto-thermal reformer, AN: advanced nuclear, AP: solar photovoltaics, AW: wind turbines, HY: hybrid battery system, CA: CO_2 adsorption and stripping, AG: gas non-electric. Note: the Y-axis scale in this graph is logarithmic. For the relation between learning components and technologies see Appendix.

There are a number of other interesting results presented in Figure 26. In particular, the uptake of the hybrid electric vehicle (HEV) battery system (also used in fuel-cell cars) is substantially higher under the shock scenario (for example, in 2050 cumulative installed capacity is 2.7-times the level in the baseline scenario). This component is technologically unrelated to the components used in the HCA, and is far removed also from the electricity generation sector. For this reason this result is the subject of more detailed analysis below. Of the other components, there is slightly slower uptake of the FC and SFC under the shock scenario (in 2050 cumulative capacity is around 25% lower in shock scenario). This can be attributed mostly to displacement of the fuel cell from electricity generation. There also appears to be a slightly accelerated uptake of advanced wind generation technology (AW key component) in the first half of the century (the difference between the scenarios peaks in 2030). In absolute terms this is a very small change in capacity, which can most likely be attributed to competition between other electricity generation technologies.

We now return to the impact of the HCA D&D shock on the uptake of the HEV battery system. Figure 27 shows the share of passenger motor vehicle (PMV) travel according to different technologies under the shock scenario. Under the baseline there is a gradual shift to HEVs, which achieve 50% of the market share around 2070-80 (see Figure 8 above). Under the shock scenario this is accelerated, with 50% share achieved by 2050-

60.[10] In addition, gas-powered HEVs capture a much larger market share at their peak (37% *versus* 28%). Hydrogen fuel-cell vehicles (FCVs) remain "locked out" of the market (with approximately 0.4% market share in 2100).

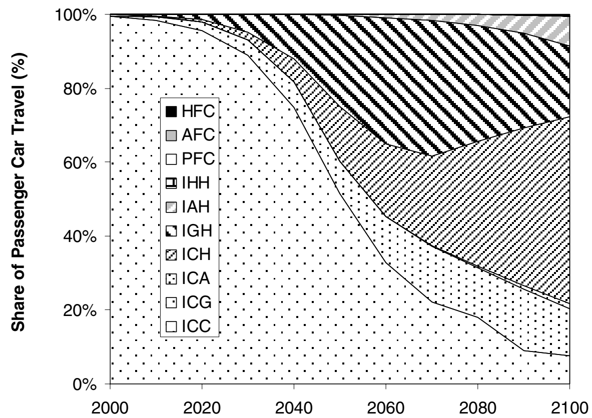

Figure 27**:** Share of global car travel by drive-train technology and fuel under the D&D-shock on advanced coal generation (HCA). Abbreviations of passenger-car technologies are as follows: ICC: Internal combustion conventional (gasoline), ICG: internal combustion gas, ICG: internal combustion alcohol, ICH: internal combustion (gasoline) hybrid, IGH: internal combustion gas hybrid, IAH: internal combustion alcohol hybrid, IHH: internal combustion hydrogen hybrid, PFC: petroleum fuel cell, AFC: alcohol fuel cell, HFC: hydrogen fuel cell. Note: dotted shading indicates ICEVs, diagonal shading indicates HEVs, and each FCV technology is indicated with either no (petroleum), medium (hydrogen) or dark (alcohol) shading;

The question is: how does a shock on the HCA electricity technology manifest as uptake of HEVs? This is answered partly by examining projections of total fuel consumption under the two scenarios. Not surprisingly, consumption of coal over the century is higher (~3%) under the D&D shock scenario, where the coal-based electricity generation technologies capture a larger market share (even though there is a shift from less efficient to more efficient coal generation). And, as discussed, this displaces electricity generation from natural gas (mainly GCC), with the total gas demand slightly lower (~1.5%) under the D&D scenario. It appears that the reduced demand for gas in electricity generation enables its greater use in the PMV sector. That is, under the baseline scenario the higher demand for gas makes it necessary to use more expensive gas resources earlier, and this expensive gas is not competitive in passenger transportation. The increased availability of cheaper gas under the shock scenario enables a shift to low-cost gas HEVs (as observed in Figure 27). This shift, in turn, results in learning-by-doing in the HEV battery system components which improves the competitiveness and accelerates the uptake of other hybrid technologies, notably the gasoline HEV.

[10] This refers to all hybrid-electric cars considered in this exercise, i.e., gasoline (ICH), gas (IGH), alcohol (IAH) and hydrogen (IHH) hybrid-electric car technologies.

In most other energy demand sectors, such as stationary non-electric and district heating, the D&D shock had almost no discernible impact. However, one impact on the choice between H_2 and electricity is significant. In the stationary non-electric sector, the ERIS model allows surplus electricity to satisfy demand (that is, the more convenient and flexible energy carrier can readily be used in place of other energy carriers). Under the shock scenario a much larger amount of electricity is used in this sector, and it displaces mainly hydrogen. Simultaneously, in the shock scenario there is much less production of H_2 from coal (even though this production technology shares the gasifier component used in advanced coal generation). Another way to think of this is that under either scenario coal is indirectly used to supply non-electric stationary energy demands, via conversion to either H_2 or electricity. Both coal-to-electricity and coal-to-H_2 technologies benefit from the D&D shock, however the lower efficiency of electricity generation actually means that this technology benefits more from the shock and subsequent learning-by-doing.[11] As a consequence, global hydrogen production in 2100 drops approximately 33% below the baseline levels.

Overall, the impact of the D&D shock on total discounted energy system costs and greenhouse gas emissions was small. Total discounted energy system cost was around 0.1% lower in the D&D shock scenario, although this result should not be viewed as significant owing to the use of an MIP modeling approach. The higher use of coal observed under the shock scenario results in greater CO_2 emissions and hence, slightly higher atmospheric concentrations of this gas by the end of the century (+0.5%), compared to the baseline scenario.

As a summary, Figure 28 presents the changes in the sustainability indicators under the D&D shock on the HCA technology relative to the baseline scenario (expressed as percentage of the baseline figures). As expected, with support for this coal-intensive technology, CO_2 and CH_4 concentrations in the atmosphere as well as global temperature change and global sea-level rise increase. N_2O concentrations are not affected. The global resources-to-production (Ru/P) ratio of oil increases while the global Ru/P ratio of natural gas decreases. Please notice that although percentage changes relative to the baseline are used in the figure to give the reader an idea of the order of magnitude of the changes, percentages are not used in the calculation of the impacts below.

[11] That is, production of 1 MWh of electricity requires a greater installed capacity of gasifier component than is needed to produce 1 MWh of H_2.

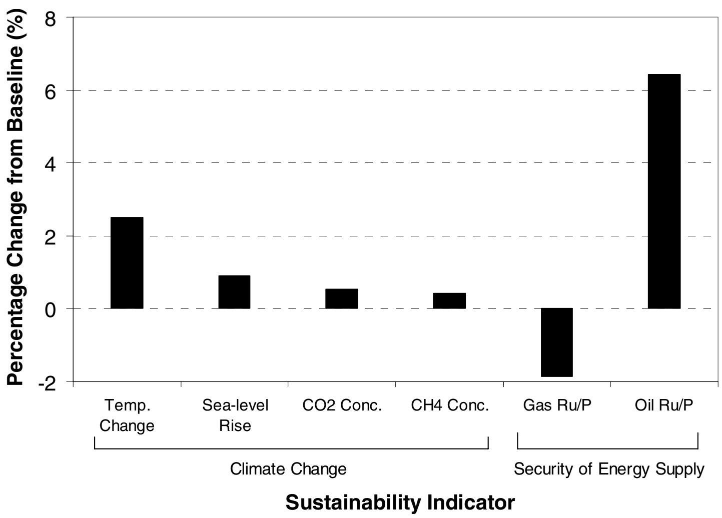

Figure 28: Percentage changes on the sustainability indicators relative to the baseline scenario as a result of a D&D shock on the advanced coal-fired generation technology (an IGCC power plant, here denoted as HCA for Hard Coal Advanced). Please notice that although percentage change relative to the baseline is used in the figure to give the reader an idea of the order of magnitude of the changes, percentages are not used in the calculation of the impacts below.

These illustrative results for a D&D shock highlight some of the advantages for policy analysis of using a comprehensive bottom-up energy system model with resource constraints and competing fuel demands. This modeling approach helps identify to policy-makers the potentially unexpected spillovers from technology-specific D&D policies. The case described here may be an example of a positive spillover, where there is a more rapid shift to efficient transportation technologies, but it is possible that such spillovers may produce undesirable results as well.

This example also highlights some of the difficulties that may be encountered when comparing the impact of many different shock scenarios. For instance, it is likely that other surprising and possibly counter-intuitive results will emerge, and to fully explain each may require extensive and detailed analysis. This is not possible in every case since a large number of shocks are examined. However, this is not to suggest that these results would be unreliable, rather that it might not be possible to go into detail to explain every observed result, and only broader trends can be analyzed thoroughly.

6.2 A summary of impacts of D&D shocks

We now present a summary of the impacts of the technology demonstration and deployment (D&D) shocks performed in our exercise on the sustainability indicators considered here. Since, as explained above, complex interactions take place in the model when a D&D "shock" is applied, we do not attempt to single out and explain all of them for the large number of cases examined here. Instead, some general trends can be identified and are described below.

Although the discussion here will concentrate on the impacts and not on the indicators, we first illustrate with an example how the impacts are derived. Figure 29 presents the concentrations of CO_2 and CH_4 in the atmosphere for D&D shocks on a number of technologies in the electricity generation, fuel production and passenger-car sectors.

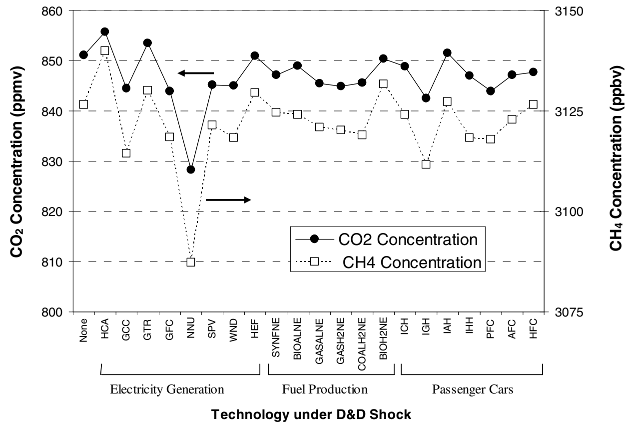

Figure 29: CO_2 and CH_4 concentrations in the atmosphere in the year 2100 for the set of technology demonstration and deployment (D&D) shocks conducted in this study. For the abbreviations of the technologies see Table 1 above or the appendix. The label "None" refers here to the baseline scenario, i.e., the case without D&D shocks.

It is important to understand that, using this methodology, the magnitude of the changes that a D&D shock induces on the energy system and on sustainability indicators is small, and this may affect the calculation of the impacts. Figure 30 illustrates this by showing percentage changes in CO_2 and CH_4 concentrations relative to the baseline for the set of D&D shocks on energy-related technologies. For CO_2 concentrations, changes relative to the baseline range from +0.5% (HCA) to -2.7% (NNU). As for CH_4 concentrations, the range is +0.43% (HCA) to -1.25% (NNU).

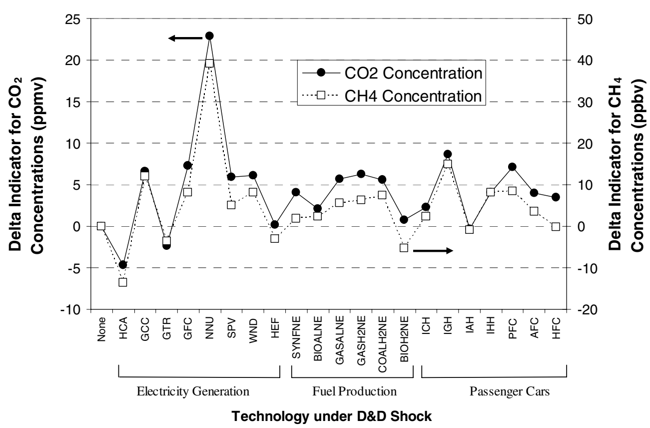

Figure 30: "Delta Indicator" for CO_2 and CH_4 concentrations relative to the baseline scenario under D&D shocks on a set of electricity generation, fuel production and passenger-car technologies. For the abbreviations of the technologies see Table 1 or the appendix. The label "None" refers here to the baseline scenario, i.e., the case without D&D shocks.

Figure 31 presents the corresponding impacts of this set of D&D shocks on atmospheric concentrations of CO_2 and CH_4. As mentioned before, impacts are measured relative to the baseline scenario (i.e., the case without shocks) and the costs of D&D programs remain constant across technologies, in order to ensure comparability.[12] Also, the reader should bear in mind that, by convention, positive impacts imply an improvement on sustainability indicators and vice versa. In the case of climate-change indicators (e.g., CO_2 concentrations), a positive impact means a reduction in comparison to the levels in the baseline case. Notice that since N_2O concentrations are not affected by this set of D&D shocks, the corresponding impact (i.e., zero) is not reported here.

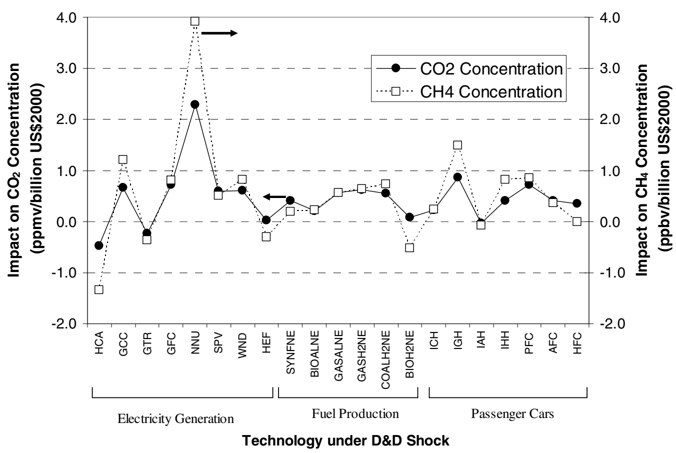

Figure 31: Impact of D&D shocks on CO_2 and CH_4 concentrations in the atmosphere in the year 2100. For abbreviations of the technologies see Table 1 or the appendix. By convention, positive impacts imply an improvement in the indicator, in this case a reduction in the CO_2 and CH_4 concentrations.

As expected, positive impacts on CO_2 concentrations appear to be higher for low-carbon technologies. Specifically, under our assumptions, new nuclear power plants (denoted as NNU) achieve the highest positive impact on CO_2 concentrations. Other technologies having a noticeable positive impact are the gas combined-cycle turbine (GCC), the gas fuel cell (GFC), solar photovoltaics (SPV) and wind turbines (WND). Conversely, the highest negative impact is that of the advanced coal power plant (denoted as HCA), followed by the gas turbine (GTR).

This result points out the important role nuclear energy may have in achieving climate change policy goals. Clearly, such a role, which has been recognized within the debate on security of supply at the European level (EC, 2001a), has strong conditioning factors such as the unsolved question of processing and transporting radioactive waste, other safety considerations and public acceptance, among others.

In the case of fuel production technologies, the most significant positive impacts are observed for alcohol production from natural gas and hydrogen production from natural gas and coal.

[12] As mentioned above, in our case a size of 10 billion (US$2000) has been chosen for all the D&D shocks.

In some cases, such as that of hydrogen production from biomass (BIOH2NE) or hydrogen fuel cells for electricity generation (HEF), the D&D shock is not enough to make the technologies competitive and, therefore, the resulting impact is zero. However, due to the tolerance of the Branch and Bound (B&B) algorithm used to solve the Mixed Integer Program (MIP) underlying the ERIS model, small changes in the optimal solution may occur. Those small changes may lead to slightly positive or slightly negative impacts. Since they are within the error limits of the solution algorithm, these values should be considered negligible for practical purposes, i.e., the corresponding impact should be understood as zero.

Among the passenger-car technologies, the largest impact is achieved by the gas-based hybrid-electric car (IGH) followed by the petroleum-based fuel-cell car (PFC). In this GHG-unconstrained scenario, the impact of alcohol-based and hydrogen-based fuel cell vehicles (AFC and HFC respectively) is smaller. Actually, the petroleum-based fuel-cell car (PFC) is not introduced under the D&D-shock case. Its impact is due to the learning spillovers brought about by the clusters approach implemented in ERIS. That is, the shock on the PFC produces a reduction in the costs of its key learning components (hybrid battery (HY), fuel cell (FC) and on-board reformer (SR)). Other technologies, the hydrogen fuel-cell car (HFC) among others, benefit from these spillovers. The final outcome is a positive impact on CO_2 and CH_4 concentrations.

Figure 32 presents the impacts of the set of D&D shocks on global temperature change and global sea-level rise. As can be seen, although the patterns tend to be similar to those of CO_2 and CH_4 concentrations, in general, impacts on global temperature change and sea-level rise are less significant, among others due to the above-mentioned inertia of the earth's climate system, which precludes rapid changes in these indicators.

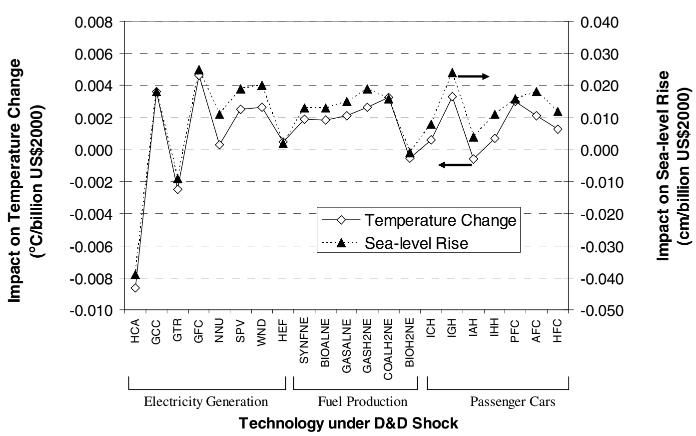

Figure 32: Impact of D&D shocks on global temperature change and global sea-level rise in the year 2100 (and measured from the year 1990). For abbreviations of the technologies see Table 1 or the appendix. By convention, positive impacts imply an improvement in the indicator, in this case a reduction in the global temperature change or sea-level rise.

Also, notice that some D&D shocks having a sizeable positive impact on CO_2 and CH_4 concentrations do not have a large impact on temperature (e.g., the advanced nuclear power plant (NNU)). The reason for this is the fact that, in several cases, these technologies displace coal-based electricity generation or coal-based synthetic fuel production (Fischer-Tropsch liquids, hydrogen). As a result, CO_2 emissions and, therefore, CO_2 concentrations in the atmosphere, diminish. However, SO_2 emissions from coal production are also reduced and, consequently, the negative forcing associated with SO_2 decreases. The final outcome is the result of these two counteracting effects. In the case of advanced nuclear generation (NNU), the impact of the D&D shock on global temperature change is still positive but less significant than it was on CO_2 and CH_4 concentrations (see Figure 31).

We now turn to the impacts on indicators of security of energy supply. Impacts on the resources-to-production (Ru/P) for oil in the year 2050 are in most cases positive or zero. In general, in our D&D shocks there is a tendency to displace oil consumption. Among others, significant positive impacts on oil Ru/P can be observed for advanced coal power plants, natural gas combined-cycle turbines and fuel cells, advanced nuclear plants, production of alcohol and hydrogen from gas and Fischer-Tropsch liquids from coal. Biomass-based production of final-energy carriers, however, is relatively unattractive under this GHG-unconstrained scenario. Nonetheless, the shock on biomass-to-H_2 produces a small positive impact on oil Ru/P ratio.

D&D shocks on several hybrid-electric and fuel-cell vehicles produce positive impacts on the oil Ru/P ratio. This includes the petroleum-based fuel-cell passenger car, although its impact is much more reduced than that of other advanced car technologies. Notice that, with the exception of the petroleum-based fuel-cell passenger car, no other oil-based technologies were considered in this set of D&D shocks.

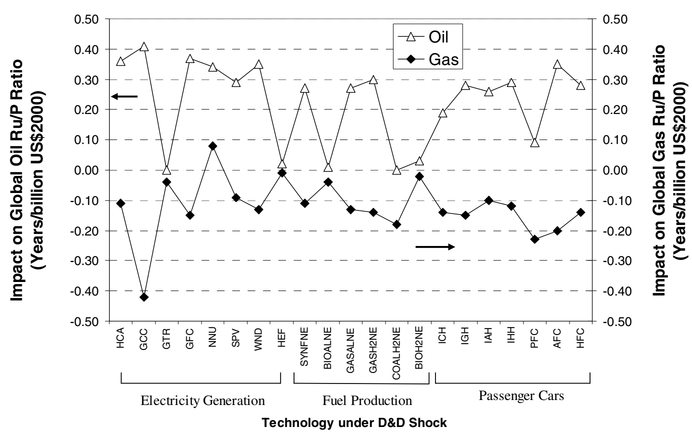

Figure 33: Impact of D&D shocks on global resources-to-production ratios for oil and natural gas (both in the year 2050). For abbreviations of the technologies see Table 1 or the appendix.

As for the impacts on the resources-to-production (Ru/P) ratio of natural gas, for the most part of the set of D&D shocks conducted here the resulting impacts were negative. This is not surprising for the gas-based technologies. As for other technologies, as a rule, the effects of the D&D shocks tend to displace consumption of gas in one sector, thus making it available for other sectors. The final effect is an increase in the total consumption of gas (in 2050) under the D&D shocks as compared to the baseline scenario. The only exception is advanced nuclear power plants (NNU), which have a relatively significant positive impact.

Notice that, in our scenario, natural gas constitutes a valuable and attractive primary energy resource. Also, our assumptions on its resource base do not include uncertain unconventional and additional occurrences. Thus, natural gas consumption rises and declines along the 21st century as its resource base is exhausted.

It appears to be a trade-off between the two global indicators of security of energy supply, namely oil and gas Ru/P ratios. That is, shocks leading to a larger oil Ru/P ratio tend to result in a smaller gas Ru/P ratio, meaning that as the global energy system weans away from oil, it tends to increase its reliance on natural gas.

Again, and as it was the case with the C-eq tax analysis presented above, the reader should bear in mind that the impacts of demonstration and deployment (D&D) shocks depend on the baseline scenario. Specifically, and under the scenario considered here, where no value for GHG emissions is imposed, the D&D shocks applied here are more likely to effectively stimulate the penetration of technologies that are either already competitive in the baseline or close to become competitive.

7. Combining instruments: Carbon taxes and D&D Shocks

We have also investigated the impact of D&D shocks in combination C-eq taxes for the range of shocks and taxes examined above. The rationale behind this exercise is the fact that policy makers may have to combine several policy instruments in order to achieve one or more policy goals. This is so both for both climate change and security of energy supply.

For instance, an effective climate policy regime may need to rely on a wide portfolio of instruments. While imposing a price on GHGs, such as the C-eq tax examined here, would send a signal to economic actors to shift towards less GHG-intensive technologies, it may also be necessary to stimulate the technology learning of these technologies in order to make them competitive in the marketplace and provide the economic actors with a sufficiently broad set of options such that the most cost-effective, environmentally-benign, safe and publicly-acceptable technologies can be chosen. Demonstration and deployment (D&D) programs, where valuable experience with a technology or cluster of technologies can be gathered and from which performance/cost improvements may result, could be an important instrument with which to complement a GHG tax.

Selected results of D&D shocks under the C-eq tax are presented below. It should be noted that the results presented in this section can only summarise what is an extensive analysis of over 200 combinations of D&D shock and C-e tax. The purpose is to identify consistent trends and robust responses in the indicators of interest. In other words, and as was discussed earlier in relation to D&D shocks, it is not practicable to go into detail for each combination of D&D shock and C-e tax and analyse specific energy system features.

The example D&D shock presented in Section 6.1 should be borne in mind when considering the results presented here. This example illustrates the potential for complex and sometimes counter-intuitive results to arise across the whole energy sector in response to a single shock, and such results are expected to be observed with the combined shock and tax. However, the example in Section 6.1 was also designed to show that such results are logical and readily explained with further analysis. Unlike with the example, it is not practicable to analyse each run at the level of detail necessary to fully explain the results observed. As mentioned earlier, this is not to suggest that these results are unrealiable, but that it is only possible to analyse the broader trends in detail here.

As a rule, one might expect that the effect of D&D shocks becomes smaller as the carbon-equivalent tax becomes larger, due to the fact that increasing the C-eq tax results in a more restricted technology choice, since low-emissions technologies are favored more and more. However, this will depend on the technology, particularly where some of the more expensive technologies only become competitive in a carbon-constrained world. For example, when the C-eq tax is high enough, carbon capture and storage (CCS) becomes cost-effective. Under these circumstances, performing D&D shocks on carbon-intensive technologies, such as coal-based IGCC power plants (HCA) or hydrogen production (COALH2NE), may result in a stronger positive impact on climate change indicators than observed at lower levels of taxation.

In addition, D&D shocks applied directly to CCS technologies may have a similar impact, and for this reason these are included in the analysis here. That is, to the list of technologies to which a D&D shock was applied in Section 6 (see Table 1), are added the CCS technologies listed below (Table 2). These technologies were not included in the analysis of simple D&D shocks because, in the absence of a carbon cost or constraint, these technologies are not used.[13]

Table 2: Description and abbreviations of carbon capture technologies for combined D&D and carbon (equivalent) tax shocks.

Sector	Abbreviation	Description
Carbon capture and storage	HCACS	Carbon capture from advanced coal (IGCC) power plant and synthetic fuel (F-T liquids) production (i.e., pre-combustion)
	HCCCS	Carbon capture from conventional coal power plant (i.e., post-combustion)
	GCCCS	Carbon capture from gas-fired combined-cycle gas turbine (i.e., post-combustion)
	H2CAS	Carbon capture from H_2 production

Some illustrative and summarised results for the combined D&D shock and GHG tax are presented below. Firstly, we present selected impacts of adding D&D shocks to some representative GHG taxes. This is followed by a presentation of the impacts of applying GHG taxes to a single D&D shock. Taking this approach helps identify the marginal impact of the additional instrument, and whether the presence of the D&D

[13] These technologies are assumed not to share components with any of the non-CCS technologies (see Turton and Barreto 2004), and hence exclusion of these technologies from the analysis in Section 4 has not resulted in important spillovers to other groups of technologies being overlooked.

shock or GHG tax affects the impact of a subsequent addition of the second instrument. Finally, we present some overall results of the combined shock and tax. Although we still continue to measure the impact relative to the baseline case (i.e., without C-eq tax or D&D shocks), where appropriate we compare the case that combines the two policy instruments with the case where only one of them is applied.

7.1 Impact of D&D shocks under different GHG taxes

Figure 34 presents the marginal impacts on atmospheric CO_2 concentration of combining D&D technology shocks with three different levels of GHG tax. The results are not vastly different from those presented in Figure 31 in the absence of a GHG tax (see Section 6.2). Again, the results highlight the potentially important role nuclear energy may play in achieving climate change policy goals.

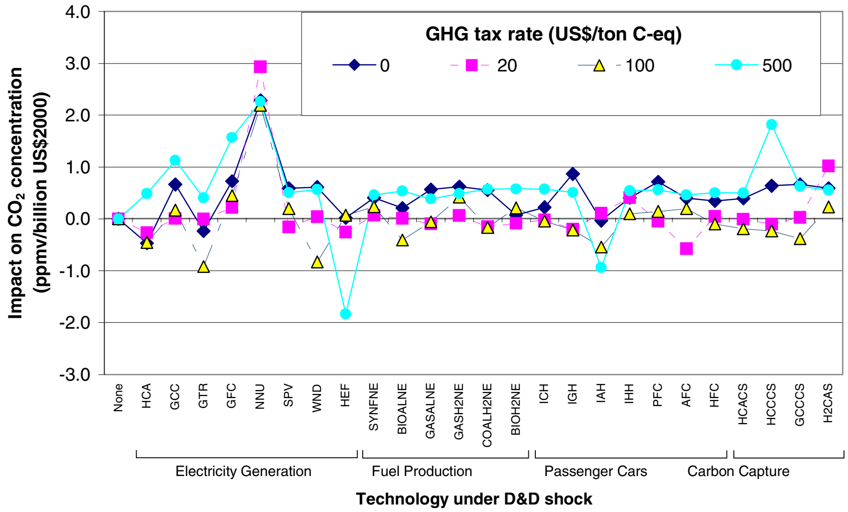

Figure 34: Impact of D&D shocks on atmospheric CO_2 concentrations in the year 2100, under GHG taxes of $20, 100 and 500/ton C-eq. For the abbreviations of the technologies see Table 1 and Table 2 or the appendix. The label "None" refers here to the baseline scenario, i.e., the case without D&D shocks (but including the GHG tax). By convention, positive impacts imply an improvement in the indicator, in this case a reduction in the CO_2 concentrations. Note also, this figure presents impact on concentration per direct policy cost, and does not include the impact of the D&D shock on total energy system costs.

However, there are some notable differences from the no GHG tax baseline. In particular, and somewhat surprising, is that for a number of technologies the impact of the D&D shock increases at higher tax levels. One might expect the opposite; that at higher tax levels the energy system is more restricted in the set of technologies. However, technologies such as HCCCS (carbon capture from conventional coal generation) and GFC (gas fuel cells) apparently require high GHG taxes to be competitive, and without such taxes the respective D&D shocks do not results in any significant change in the energy system. Conversely, a D&D shock on HEF (hydrogen fuel cell electricity generation) under higher GHG taxes appears to have a negative impact on CO_2 concentration (i.e., concentration increases). Again, it appears this technology may require a high GHG tax rate, but its uptake, while lowering energy system costs, requires greater fossil fuel use – that is, the additional generation from

HEF in all likelihood displaces other zero-emissions sources, and additional primary energy is needed for either H_2 production, or to substitute for H_2 in other sectors.

These results highlight that there are GHG tax thresholds at which various less carbon-intensive technologies become competitive in their own right. Well below this threshold the D&D shock has little impact, and well above it can only accelerate the uptake of an already attractive technology, but not transform the evolution of the energy system substantially. However, at a GHG tax just below the threshold level, a D&D shock may be sufficient to make a technology competitive, thereby resulting in a potentially significantly different energy system. This is illustrated once more in Figure 35 for the impact of D&D shocks on temperature change under three GHG tax rates. Again, as was shown in Figure 32 in Section 6.2, the pattern of impacts is similar to that seen for CO_2 concentration except, again, for those D&D shocks that displace conventional coal electricity generation. These shocks result in lower emissions of not only CO_2, but also SO_2 which has a negative forcing. The results for sea-level rise are similar.

The impact of the D&D shocks under different GHG tax levels on resources-to-production ratio (Ru:P) for oil is presented in Figure 36.[14] Most D&D shocks, irrespective of the GHG tax rate, increase Ru:P for oil, because most of the technologies utilise fuels other than oil, or improve the efficiency of oil utilisation. However, the size of the impact of a D&D shock is reduced at higher tax levels. This is partly because, as shown in Figure 23 in Section 5.2, higher tax rates alone increase the ratio, implying that there is reduced scope for further increases from D&D shocks applied to high tax rates.

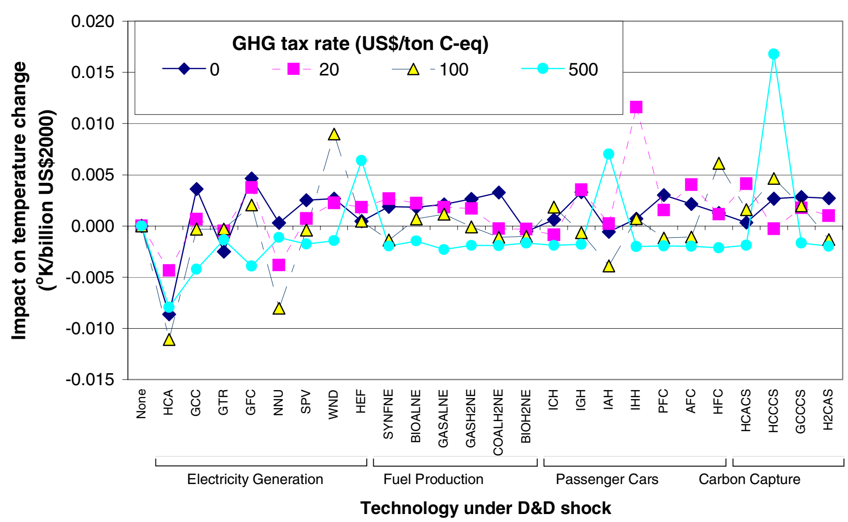

Figure 35: Impact of D&D shocks on temperature change by the year 2100, under GHG taxes of $20, 100 and 500/ton C-eq. For the abbreviations of the technologies see Table 1 and Table 2 or the appendix. The label "None" refers here to the baseline scenario, i.e., the case without D&D shocks (but including the GHG tax). By convention, positive impacts imply an improvement in the indicator, in this case a reduction in temperature. Note also, this figure presents impact on temperature per direct policy cost, and does not include the impact of the D&D shock on total energy system costs.

[14] See appendix for Ru:P for gas.

The direction of the impact of the D&D shocks across the range of C-eq tax rates presented in Figure 36 is fairly consistent. That is, those shocks observed to increase Ru:P in the absence of a tax also increase the ratio under higher tax rates. However, some technologies that are uncompetitive in the absence of a GHG tax appear to respond more to a D&D shock at higher GHG tax rates, particularly some of those technologies associated with H_2 production (COALH2NE, BIOH2NE) and use (HEF). This once again illustrates the potential for a D&D shock to complement a GHG tax that is not sufficient alone to make a new technology competitive. Moreover, it implies that the addition of a well-targeted shock can shift the development of the energy system to a more sustainable path.

Importantly, the choice of most effective D&D shock depends on the likely level of GHG taxation applied.

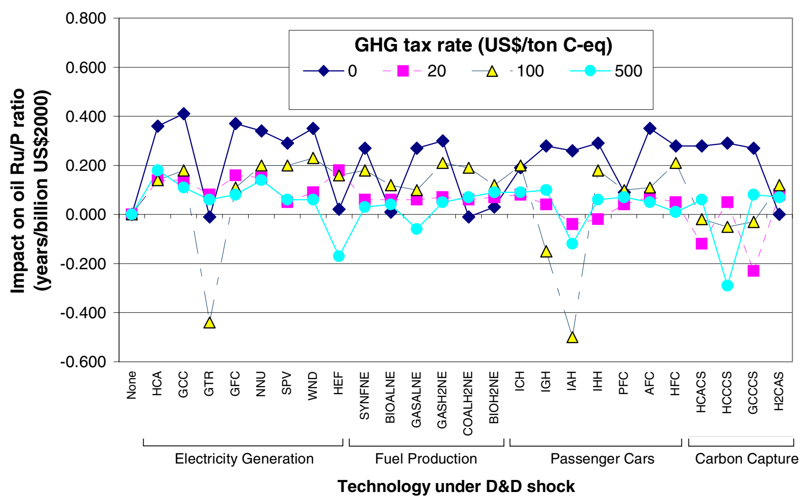

Figure 36: Impact of D&D shocks on global resources-to-production ratios for oil (in the year 2050), under GHG taxes of $0, 20, 100 and 500/ton C-eq. For the abbreviations of the technologies see Table 1 and Table 2 or the appendix. The label "None" refers here to the baseline scenario, i.e., the case without D&D shocks (but including the GHG tax). Note, this figure presents impact on temperature per direct policy cost, and does not include the impact of the D&D shock on total energy system costs.

7.2 Impact of GHG taxes on a single D&D shock

So far in this section we have examined the impact of applying D&D shocks to the energy system at a number of different GHG tax levels. To complement this analysis, we now present the impact of applying the full range of GHG taxes in combination with a single D&D shock. This will serve as an illustrative example.

It is important to emphasise that this approach seeks to illustrate the marginal impact of combining a GHG tax with a D&D shock. Accordingly, impacts are presented relative to a baseline that already includes the impact of the shock alone. In the figures below, the impacts are compared with those occurring in the absence of any D&D shock (as presented in Section 5). We present the impact of GHG taxes on a scenario where a D&D shock is applied to the coal-to-H_2 production technology (COALH2NE).

Figure 37 presents the impact on atmospheric concentrations of CO_2 and CH_4 in 2100 per unit of cost of the GHG tax for the no shock and D&D shock cases, as a function of GHG tax rate. Not surprisingly, the general pattern is similar with and without the tax – that is, the overall impact of a GHG tax is not affected by the shock. However, there are some notable differences, including the larger response at lower tax rates (up to $30/ton C-eq), and a shift in the point of inflexion from $30-40/ton C-eq to $40-50/ton C-eq. These points of inflexion occur where the ratio of cost to impact either does not change or increases as we move to a higher tax rate.[15] This appears to be unusual because each unit of GHG abatement becomes more expensive as taxes are increased. However, the reader should remember that Figure 37 presents concentrations rather than emissions, and there is no obvious reason why two very similar estimates of total discounted system necessarily imply similar temporal emissions or, therefore, similar concentrations.

Further information on the nature of these points of inflexion are revealed by comparison of results for global temperature and sea-level, which are presented in Figure 38. For the D&D shock, the point of inflexion persists irrespective of the impact being measured, where it occurs only for CO_2 concentration in the no-shock case. Otherwise, the with and without shock scenarios are extremely similar, although the initial impact appears to be higher with the D&D shock.

The point of inflexion between $40 and $50/ton C-eq when a D&D shock is applied to the COALH2NE (coal-to-H_2) technology occurs primarily because there is only a very small change in total discounted system costs, and this is accompanied by small changes in indicators. If there is almost no additional cost from moving from one GHG tax to a higher GHG tax (net of GHG tax revenue) it implies that there are few abatement opportunities at prices between the two tax rates. Because this occurs only in the presence of the D&D shock, it implies that the shock changes the cost of those abatement opportunities that, in the absence of a shock cost between $40 and 50/ton C-eq. This seems to indicate that many of the abatement opportunities associated with the coal-to-H_2 technology (and of related technologies that share the gasifier component) cost between $40 and 50/ton C-eq in the absence of a shock. The D&D shock increases experience with the gasifier, accelerating learning and reducing costs, thereby increasing the competitiveness of technologies that use the gasifier[16] meaning they are used more widely at lower tax rates than in the absence of the shock.

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[15] So, in the case of CO_2 concentration with the D&D shock, the increase in ratio does not mean that the atmospheric CO_2 concentration is higher at a higher GHG tax, but rather that the additional discounted system cost of moving from $40 to 50/ton C-eq is proportionally less than the decline in CO_2 concentration in 2100 associated with this tax increase.

[16] Including coal-to-H_2, biomass-to- H_2, advanced coal (IGCC) generation, synthetic fuel (F-T) production from coal. Moreover, a shock that benefits these technologies will in turn benefit other technologies that share other components – for example, additional installation of advanced coal generation will also benefit technologies that use turbines – or closely related technologies – for example, additional coal-to-H_2 production will benefit H_2-using technologies and displace other technologies. The potential implications for the evolution of the energy system are highly complex.

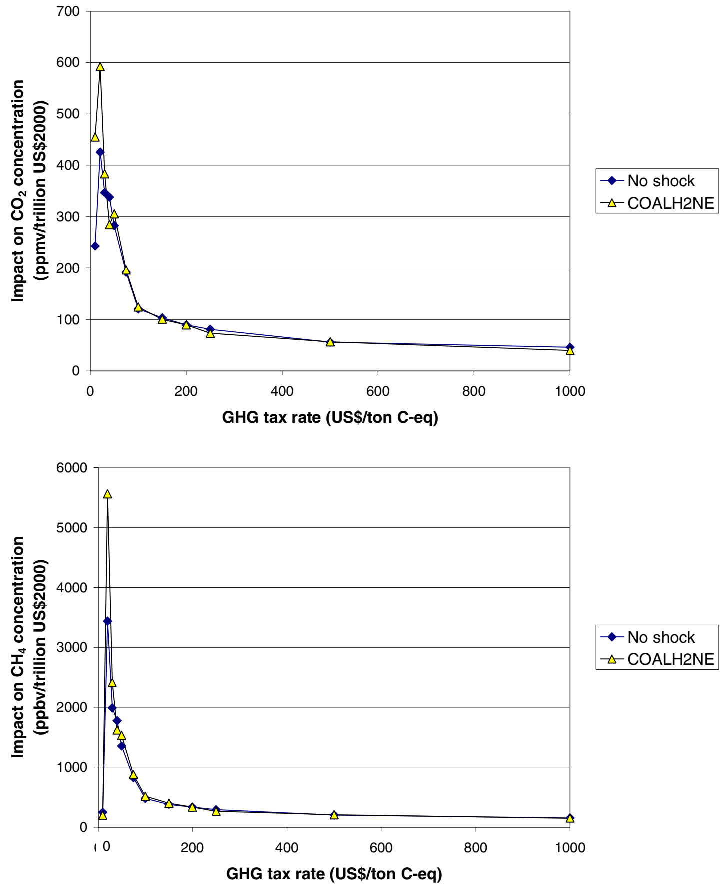
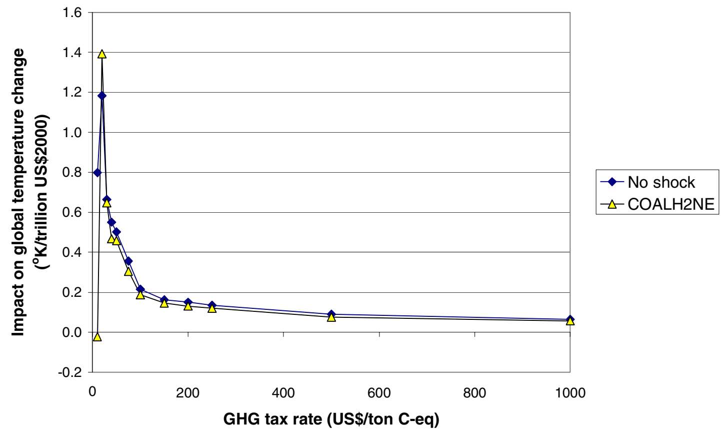


Figure 37: Impact of a carbon-equivalent (C-eq) tax on atmospheric CO_2 and CH_4 concentration in the year 2100 for the no shock and D&D shock scenarios. The impact measure is computed as the ratio between the change in the indicator (between zero tax scenario and the C-eq tax case) and the corresponding instrument cost (difference in total discounted energy-system costs plus D&D shock cost, subtracting the C-eq tax revenue). By convention, a positive impact means an improvement in the indicator (in this case a reduction in atmospheric concentration).

However, it is unlikely that the entire impact on technologies that use the gasifier (and related complementary or competing technologies) is confined to the range of $40-50/ton C-eq. Instead, this result implies that very few of these occur in the range $50-60/ton C-eq.

This is consistent with the results presented in Section 7.1, which implied the existence of GHG tax thresholds at which particular technologies become competitive, and below which they exert only a small influence on the development of the energy system. The hypothesis is that a D&D shock is able to lower the competitiveness threshold. In the example presented here, a likely interpretation is that the shock moved the threshold for a particular technology from somewhere between $40 and $50/ton C-eq to somewhere below $40/ton C-eq. However, an alternative or coincident interpretation is that the D&D shock resulted in the displacement and slower development of another competing technology that had in the absence of the shock provided cost-effective abatement for between $40 and $50/ton C-eq. As discussed, there are many interactions in each scenario combining a D&D shock and GHG tax, and the purpose of this section is not to examine these in detail for every scenario, but rather to illustrate trends.



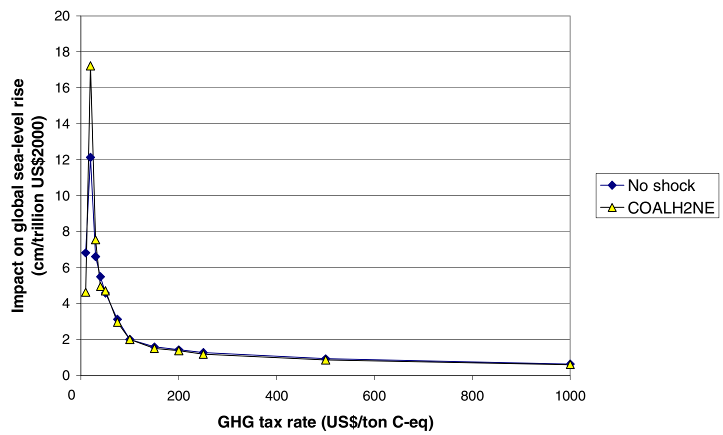


Figure 38: Impact of a C-eq tax on global annual temperature change and global annual sea-level rise in the year 2100, with and without D&D shock. The impact measure is computed as the ratio between the change in the indicator (between zero tax scenario and the C-eq tax case) and the corresponding instrument cost (difference in total discounted energy-system costs plus D&D shock cost, subtracting the C-eq tax revenue). By convention, a positive impact means an improvement in the indicator.

We next consider the impact on energy security of supply of adding a GHG tax to a D&D shock. Figure 39 presents the impact of the GHG tax with and without an underlying D&D shock on the coal-to-H_2 production technology. It should be remembered that in Section 6.2 a D&D shock to the COALH2NE technology alone was reported to have almost no impact on global Ru:P for oil, and reduce very slightly the global Ru:P ratio for gas. In comparison, the combination of the D&D shock and GHG tax appears to provide benefits to Ru:P ratios, especially for gas, compared to the tax-only scenario. This is not surprising for a technology which assists in converting a relatively inconvenient fuel (coal) into a highly flexible fuel (H_2) that can readily substitute for gas and oil, and thereby enhance long-term supply availability. For oil, there is once again a point of inflexion between $40 and 50/ton C-eq, although for gas the main effect of the shock is to reduce the extent to which the GHG tax encourages additional gas use (which reduces the Ru:P ratio), by providing a substitute for gas. However, it should be pointed out that because the shock to the COALH2NE technology in the zero tax scenario decreases the Ru:P ratio, the effect observed with the addition of the C-tax is partly a catch-up back to the levels under the no-shock scenario.

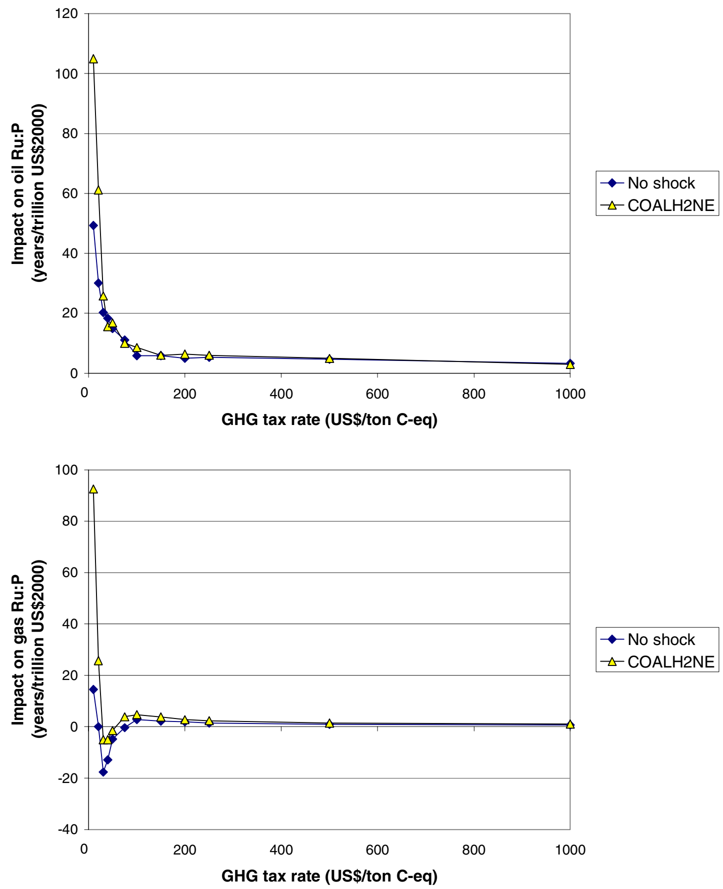


Figure 39: Impact of the C-eq tax on the long-term resources-to-production ratio (Ru:P) of oil and natural gas for the year 2050, for no-shock and D&D shock scenarios.

7.3 Impact of combined D&D shock and carbon-equivalent tax on climate change

The analysis in Sections 7.1 and 7.2 presents cross-sections of the 'impact surface' of the combined D&D shock and C-e tax for the sustainability indicators. We now present a summary of the entire surface for selected indicators and impacts. Again, we will discuss primarily the impacts and not the indicators, but it is useful to present one indicator to illustrate general patterns and trends.

Figure 40 presents the absolute impact on CO_2 concentration in the year 2100 of the combined D&D shock and GHG tax. Compared to the impact of the GHG tax alone (presented in the left-hand column of Figure 40), the D&D shocks have a relatively small impact on CO_2 concentration. This is consistent with the result presented in Figure 29.

However, Figure 40 provides additional information on the consistency of the results presented in Figure 29 and Figure 30 under different GHG tax levels, most notably for the two technologies with the largest positive and negative impact on concentration (HCA and NNU). In the absence of a GHG tax HCA increases concentration relative to the baseline (0.5%) and NNU decreases it (-2.7%). However, Figure 40 shows that the result for NNU is sustained under all carbon tax levels and that the application of this D&D shock reduces atmospheric CO_2 concentration by at least as much as increasing the GHG tax to the next level. This is explained by the fact that this technology is relatively attractive over the longer term, and the D&D shock accelerates take-up. A D&D shock to the HCA technology, on the other hand, has much less impact on concentrations at higher GHG tax levels, presumably because this technology can both increase (by displacing lower emissions generation) and decrease (by displacing conventional coal generation) CO_2 concentration.

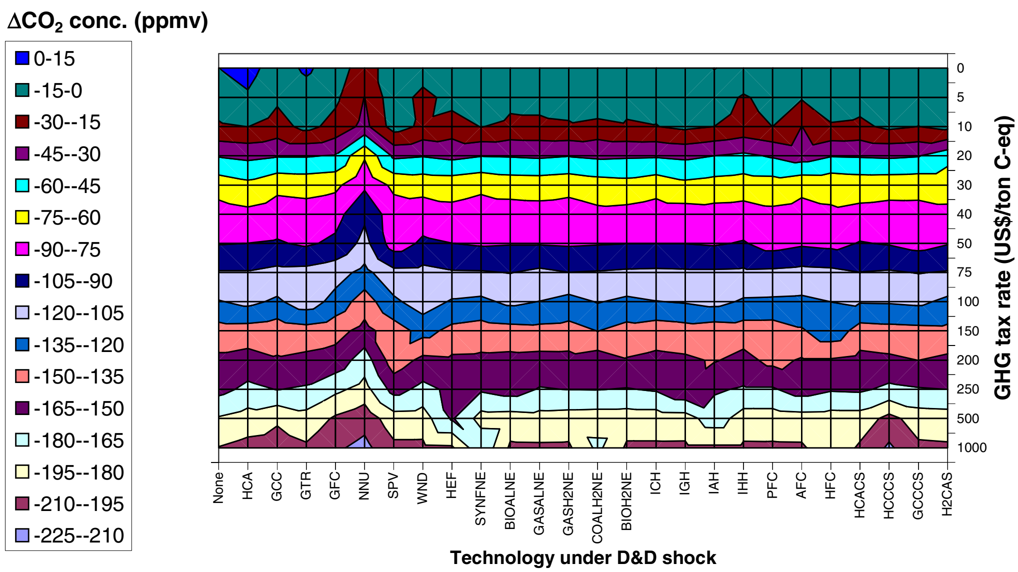


Figure 40: CO_2 concentrations in the atmosphere in the year 2100 for the set of technology demonstration and deployment (D&D) shocks conducted in this study combined with different levels of carbon equivalent tax. For the abbreviations of the technologies see Table 1 and Table 2 above or the appendix. The label "None" refers here to the baseline scenario, i.e., the case without D&D shocks.

In Section 7.1 impacts were presented per unit of direct initial cost for the D&D shock. This presentation compared the effectiveness of a once-off D&D investment on a range of technologies in terms of improving the sustainability indicators. On the other hand, in Section 7.2 the impact of different GHG tax levels was presented per unit of net system discounted cost. Therefore, before looking at the combined impact surface (which is calculated per unit of combined instrument cost) it is necessary to calculate policy cost on a consistent basis.

To do this, the impact of the D&D shock on discounted system cost is determined and added to the initial cost of the shock and the impact on system cost of the GHG tax. By accelerating the development of a technology and lowering its cost, the D&D shocks are expected to reduce total discounted system cost,[17] offsetting some of the cost any GHG tax. In some cases, particularly at low GHG tax rates, this may result in a net reduction in system cost. For these cases it makes little sense to report the impact on an indicator per dollar of cost, because costs are negative, and hence these results are excluded.

Figure 41 presents the impact surface for temperature change. The figure shows that the general pattern – that is, the impact declines at higher rates of GHG tax – is roughly the same irrespective of the D&D shock applied, although some notable exceptions exist. For example, a D&D shock to most CCS technologies results in an impact spike around \$50/ton C-eq. In addition, the impact response with a D&D shock on NNU (new nuclear generation) is more subdued at lower tax rates, presumably because much of the impact on CO_2 concentrations occurs also at a zero GHG tax[18] (see Figure 40 above), and also because this technology tends to displace those coal-based technologies which emit large quantities of SO_2.

We will not go into further detail in the discussion of the combined shock-tax scenarios because of the complex nature of interpreting the results.

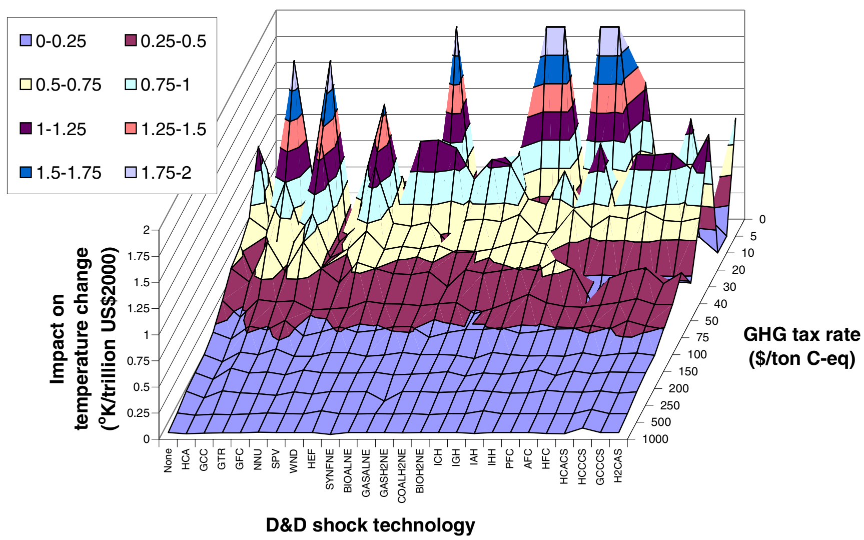


Figure 41: Impact on temperature change in the year 2100 for the set of technology demonstration and deployment (D&D) shocks combined with different levels of carbon equivalent tax. For the abbreviations of the technologies see Table 1 and Table 2 above or the appendix. The label "None" refers here to the baseline scenario, i.e., the case without D&D shocks.

[17] However, there will be cases where a D&D shock has no significant impact on the energy system, because the targeted technology is extremely uncompetitive. In this case, the shock will force installation of some additional capacity but may have no positive impact on energy costs.

[18] Note, the zero GHG tax case is not included in Figure 41 for the reasons in the previous paragraph; being that net cost is negative and hence impact (Δindicator/cost) takes on a completely different interpretation.

8. Conclusions

This report presents an assessment of the impacts of two representative policy instruments, namely a carbon-equivalent tax and energy-technology demonstration and deployment (D&D) programs, on sustainability indicators in the areas of climate change and security of energy supply. We have concentrated on the role of technological change in the global energy system in achieving sustainability goals in these two areas.

The analysis has been conducted with the modeling framework developed at IIASA-ECS for the MINIMA-SUD project. The main elements of this modeling framework are the "bottom-up" energy-systems ERIS model, linked with the climate model MAGICC (Turton and Barreto, 2004). Among others, the energy-systems ERIS model incorporates the effects of clusters of learning technologies, the competition between non-CO_2 GHG abatement opportunities and energy system abatement, forest sinks and carbon capture and storage (CCS) and an adequate representation of technology choices in the passenger-car sector.

Several insights can be derived from this exercise. A carbon-equivalent (C-eq) tax appears as an effective climate-change policy instrument, leading to positive impacts along the causal chain from GHG emissions to concentrations and, subsequently, temperature change and sea-level rise. However, due to the inertia of the climate system, the C-eq tax appears more effective in reducing GHG concentrations than in reducing global temperature change and sea-level rise, which are processes with much longer time scales. It appears that, in order to produce a sizeable effect on these climate variables, a strong C-eq tax signal is required. Since strong C-eq taxes may not be politically feasible, it may be wise to combine the C-eq tax with other policy instruments.

The impacts of the C-eq tax on global security-of-energy-supply indicators can be summarized as follows. The tax appears to have a positive impact on the long-term resources-to-production (Ru/P) ratio of oil, since the global energy system moves away from oil consumption as the tax rate is increased. With oil consumption playing a key role in anthropogenic greenhouse gases (GHG) emissions to the atmosphere and being at the same time one of the main concerns for security of energy supply in OECD regions, there could be room for synergies between climate change and security-of-energy-supply policies.

However, a different impact can be observed for natural gas. Low C-eq tax rates tend to increment the consumption of natural gas, thus reducing its long-term global resources-to-production ratio. Intermediate C-eq tax levels produce an increase in the Ru/P ratio of gas, as non-fossil-based technologies or fossil-based technologies in combination with CO_2 capture and storage (CCS) become cost-effective. After C-eq taxes surpass a given level, no subsequent gains in the long-term gas availability can be observed. This result suggests that, when it comes to natural gas, the application of a carbon-equivalent tax may bring a trade-off between climate-change and security-of-energy-supply objectives.

We also examined the impact of demonstration and deployment (D&D) programs in energy technologies. D&D programs can be an effective instrument for gathering experience with a technology or cluster of technologies in the marketplace. Market experience is necessary in order to achieve cost reductions and performance improvements that could increase the competitiveness of emerging technologies.

For the examination of the impacts of D&D programs, we have followed the so-called "shock" methodology. That is, the imposition of small one-off incremental variations in the cumulative capacity of a given technology. In this study, we have performed D&D shocks for a number of technologies in the electricity generation, fuel production and passenger-car sectors.

The results of the D&D shocks can be summarized as follows. As expected, low-carbon or carbon-free technologies tend to have a positive impact on climate-change indicators, while carbon-intensive technologies have a negative impact on them. However, impacts tend to decrease as one moves along the cause-effect chain of climate change, from GHG concentrations to global temperature change and sea-level rise. This is mainly due to, on the one hand, the large inertia of climate and oceanic systems but, in some cases, the effects that the deployment of some technologies have on SO_2 emissions play also a role. When, for instance, a D&D program in a specific technology strongly displaces coal production, CO_2, CH_4 and SO_2 emissions decrease. The decrease in CO_2 and CH_4 is reflected in lower atmospheric concentrations of these two GHGs, and consequently, in a lower associated radiative forcing. However, since SO_2 has a negative radiative forcing, the decrease in SO_2 emissions offsets some of the impact of lower CO_2 and CH_4 emissions. This has a negative impact in both global temperature change and sea-level rise (i.e., a smaller decrease or possibly an increase).

As for the global indicators of security of energy supply considered here, i.e., the long term global resources-to-production (Ru/P) ratios for oil and natural gas, for the most part of our set of D&D programs, positive (or zero) impacts were observed on the oil Ru/P ratio and negative (or zero) impacts were observed on the gas Ru/P ratio. With our assumptions on the fossil-resource base and technology dynamics in our baseline scenario and given the set of energy-related technologies that were examined in this study, the global energy system tends to move away from oil consumption under the D&D shocks.

On the contrary, D&D shocks on this set of technologies tend to stimulate the consumption of natural gas, which in our baseline scenario, is a valuable, relatively limited resource. Several of the technologies examined here were gas-based technologies and, thus, this is not a surprising result. For other technologies, the changes induced by the D&D shock displaced consumption of natural gas in a given sector (e.g., electricity generation) making it available in other sectors (e.g., stationary applications or transportation).

There also appears to be a strong case for combining demonstration and deployment shocks with a carbon (equivalent) tax. It appears that D&D shocks have the potential to lower the GHG tax threshold at which particular technologies become competitive. Accordingly, a well targetted D&D shock in the context of a GHG abatement policy may be able to provide more cost-effective abatement opportunites. Moreover, because a GHG tax may be arbitrary in terms of its impact on other policy goals, applying D&D

shocks may help promote the development of those technologies that provide more synergies, thereby mitigating risk.

Demonstration and deployment programs in some technologies, such as new nuclear power plants, lead to improvements in indicators of both climate change and security of energy supply, as measured here. In other cases, such as with advanced coal-based electricity generation, there is a trade-off between these two sustainability objectives. This suggests the possibility of identifying robust technologies, i.e., those that may contribute simultaneously to both objectives. However, the identification of robust technologies requires a much more detailed analysis than the exploratory exercise conducted here. In addition, our analysis did not consider other dimensions of sustainability that could be important when defining synergies and trade-offs and would play a role when comes to the choice of technologies that should be supported.

In summary, our results concerning the impact of the carbon-equivalent tax and energy-technology demonstration and deployment programs suggest that there could be both synergies and trade-offs between climate-change and security-of-energy-supply policies. Our analysis, however, has followed a global perspective in these issues. At the regional level, other elements may play a role. Specifically, regional security-of-energy-supply considerations may introduce a so-called "how" inefficiency in the mitigation of GHGs. A "how" inefficiency arises "when individual countries or regions reduce their GHG emissions based on criteria that do not depend solely on a fuel's GHG content" (Brown and Huntington, 2003; Huntington and Brown, 2004). Specifically, a country or region may follow a strategy to reduce more the fuels that it imports than those the country exports. Doing so, it could have gains both in terms of security-of-supply and balance of trade, but it would be doing so at the expenses of its trade partners. Also, such strategy would not necessarily coincide with the least-cost GHG mitigation strategy for the world as a whole (Brown and Huntington, 2003). These and other aspects should be analyzed in more detail.

These results depend, of course, on our specific assumptions and methodological approach. Among other factors, the clusters approach to technology learning used here plays an important role. Through the clusters approach we represent the fact that technologies do not evolve in isolation, but related and/or complementary technologies co-evolve and there are learning spillovers across them (Silverberg, 1991; Nakićenović, 1997). Because of the interrelations between technologies implied by the clusters approach, the choice of both the key components shared by different technologies, the technologies assumed to be members of a given cluster and the degree of spillovers assumed affect the model outcome.

On the other hand, the same clusters approach to technology used in this analysis provides an important policy insight. Given the uncertainties associated with technological change, it appears sensible to target clusters of related technologies, rather than individual technologies, while stimulating cross-technology learning spillovers and new combinations of technologies.

Results also depend on the developments in the baseline scenario, which provide the context in which changes in the technology choices take place. Consequently, these developments also influence the levels of the sustainability indicators induced by the application of a specific policy instrument. In addition, impact assessment is sensitive to the way the sustainability indicators are defined and how the costs of the policy instrument are estimated.

The exercise highlights the need of further developing methodologies for impact assessment of alternative policy instruments, such as the one applied here, given that they can provide an important input to the policy development process of the European Commission, in particular for the definition of sustainable development strategies in the long run (EC, 2002). Among others, it is necessary to extend and refine the relevant sustainability indicators in these two areas, improve the representation of causal chains from policy instruments to indicators, advance on the representation of mechanisms of technological change and extend the coverage to other sustainable-development areas and associated indicators.

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Appendix: Learning Components and Technologies

Table A1: Learning components and technologies. Shading indicates a learning technology, and a cross indicates membership of the cluster corresponding to the component in the column heading.

			Learning components										
			FC	SFC	GT	GA	SR	AN	AP	AW	HY	CA	AG
Technologies			fuel cell	stationary fuel cell	gas turbine	gasifier	steam or autothermal reformer	advanced nuclear	PV plants	wind turbines	hybrid battery system	absorption and stripping (SELEXOL)	gas non-electric
Electricity generation	HCC	Conventional coal											
	HCA	Advanced coal			×	×							
	OLC	Conventional oil											
	GCC	NG combined cycle			×								
	GSC	Gas steam cycle											
	GTR	Gas turbine			×								
	GFC	Gas fuel cell	×	×			×						
	BIP	Biomass power plant											
	NUC	Nuclear conventional											
	NNU	New nuclear						×					
	HYD	Hydro											
	STH	Solar thermal											
	STC	Solar thermal cogen											
	SPV	Solar PV							×				
	WND	Wind								×			
	ORE	Other renewables (geothermal etc.)											
	HEF	Hydrogen fuel cell	×	×									
Non-electric stationary	GASNE	Gas non-electric											×
	COALNE	Coal non-electric											
	OILNE	Oil non-electric											
	BIONE	Biomass non-electric											
	SALNE	Alcohol non-electric											
	SH2NE	Hydrogen non-electric											
Heat techs	COALDHNE	Coal district heating											
	GASDHNE	Gas district heating											
	OILDHNE	Oil district heating											
	BIODHNE	Biomass district heating											
	STHDHNE	Solar thermal heating											
	OREDHNE	Geothermal heating											
Fuel synthesis	OILREF	Conventional oil refining											
	SYNFNE	Fisher-Tropsch from coal				×							
	BIOALNE	Alcohol from biomass				×							
	GASALNE	Alcohol from gas					×						
	GASH2NE	Hydrogen from gas					×						
	COALH2N	Hydrogen from coal				×							
	BIOH2NE	Hydrogen from biomass				×							
Carbon capture	HCACS	Capture from advanced coal electricity generation and F-T fuels production										×	
	HCCCS	Capture from conventional coal										×	
	GCCCS	Capture from GCC										×	
	H2CAS	Capture from hydrogen production										×	
Cars	ICC	Internal combustion conventional											
	ICG	Internal combustion gas											
	ICA	Internal combustion alcohol											
	ICH	Internal combustion hybrid									×		
	IGH	Internal combustion gas hybrid									×		
	IAH	Internal combustion alcohol hybrid									×		
	IHH	Internal combustion hydrogen hybrid									×		
	HFC	Hydrogen fuel cell	×								×		
	PFC	Petroleum fuel cell	×				×				×		
	AFC	Alcohol fuel cell	×				×				×		
Air	AIRC	Air transport conventional											
	AIRH	Air transport hydrogen											
Other transport	COALTR	Other transport - coal											
	GASTR	Other transport - gas											
	OILTR	Other transport - oil											
	ALTR	Other transport - alcohol											
	H2TR	Other transport - H2											