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Cost of greenhouse gas mitigation - comparison between TIMER and WorldScan[*]

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Abstract

This paper describes the results of a comparison of two models which PBL uses to assess costs and effects of greenhouse gas mitigation: the bottom-up energy-system TIMER model (in combination with IMAGE and FAIR) and the top-down computable general equilibrium WorldScan model. For various carbon tax levels, the study compares both reduction potentials and estimated mitigation costs for energy-related CO_2 emissions in various regions.

We conclude that TIMER and WorldScan have their strengths and weaknesses on different aspects, which are all relevant for the assessment of climate policies. Given the detailed modelling of the energy system in TIMER, the strengths of TIMER mainly concern the analysis of technology-specific development, including 'learning by doing' and physical constraints. By taking inertia in the energy system into account, TIMER has projected substantially smaller emission reductions for Russia and China than WorldScan, which indicates that WorldScan was too optimistic about the mitigation potential in countries that had recently expanded their energy production sector.

By taking into account the indirect effects of climate policies and their consequences for international trade, the strengths of WorldScan are mainly in the analysis of changes in the demand for goods and services, as a result of climate policies, and the redistribution of costs over sectors and regions. In particular, in regions with previously no taxation or with low tax rates, WorldScan estimated substantial emission reductions, achieved through changes in the volume and structure of production, which are not considered by TIMER.

Exploiting the complementary insights of both models will provide a set of models that is very well suitable to assess the various impacts of climate change policies.

Keywords: Greenhouse gas mitigation; Marginal abatement cost curves; Bottom-up; Top-down

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1 Introduction

PBL uses several models to assess the costs and effects of global climate change policies. This paper provides a comparison of two models: TIMER (in combination with IMAGE and FAIR) and WorldScan. TIMER is a bottom-up model of the stocks and flows in the world energy system with detailed information on the costs and reduction potential of a large number of specific mitigation technologies (Van Vuuren et al., 2007). TIMER also accounts for several relevant characteristics of mitigation measures in the energy system, including the life cycle of capital goods and learning effects. WorldScan can be classified as a top-down Computable General Equilibrium (CGE) model of the world economy focusing on the sources of growth and international trade (Lejour et al., 2006). Its main aim is to build scenarios to assess structural policies including climate mitigation policies. WorldScan covers the main input markets (labour, capital, raw materials, energy), all sectors in the economy as well as their trade related international linkages.

Research questions to be analysed with both PBL models are sometimes closely related, in particular if they evaluate climate change mitigation policies in a global context and their associated costs. Therefore, we need to be able to explain and interpret differences in outcomes of the models in order to exploit their complementary insights. This paper describes the results of such a comparison of TIMER and WorldScan. Our focus is on comparing country- or region-specific mitigation costs. Potential factors that might be responsible for differences in outcomes, such as variations in underlying data and assumptions about policy scenarios, are eliminated as far as possible. The comparison is further restricted to mitigation of energy-related CO_2 emissions, which represent the largest part of total global greenhouse gas (GHG) emissions. This study aims to compare both (i) the reduction potentials and measures applied and (ii) the estimated mitigation costs of particular climate policy shocks, in particular for a given level of a carbon tax.

Section 2 provides some context for comparing TIMER and WorldScan by discussing the differences between bottom-up and top-down modelling traditions in general. Section 3 explains the methodological differences between TIMER and WorldScan in particular. Next, we present the marginal abatement cost curves obtained by both models in response to a carbon tax policy shock and discuss the different outcomes of the models. Section 5 compares and discusses the different cost measures used by TIMER and WorldScan. Finally, we draw conclusions and formulate actions for further research.

2 Bottom-up versus top-down models

In general, integrated assessment models not only simulate the impacts of climate change on the economy but also the economic consequences of global long-term climate policy strategies per se. Applied modelling efforts that study the economic consequences of climate policy strategies can be classified into two broad categories: (i) ‘bottom-up’ models, and (ii) ‘top-down’ models (e.g. Markandya et al., 2001; Van Vuuren et al., 2009; Vollebergh and Kemfert, 2005). Bottom-up models are typically built around the use of energy technologies and their technical as well as economic characteristics. Top-down models adopt an economy-wide perspective and provide a stylized representation of the whole economy and its underlying structure built around behavioural assumptions of both investment and consumption. TIMER belongs to the category of bottom-up models and WorldScan is an example of a top-down model. Major differences between these categories relate to how the energy system and the economy are modelled and which cost concept is used.

Representation of the energy system and the economy

Because bottom-up energy models are built around the energy system, these models take into account a lot of specific sector and technological details and physical parameters. They capture sector details and complexity both on the supply side (such as emission control technologies, substitution possibilities between primary forms of energy and physical restrictions) and on the demand side (the potential for end-use energy efficiency and fuel substitution). The key driver in these models is usually a cost minimization module where different options for investors in energy supply and demand technologies are weighed against each other, taking into account the availability of different resources along specific time paths. These assessments assume that only the technologies that satisfy existing demand for goods and services will change. For instance, if gasoline cars become more expensive, consumers will change their behaviour by buying more hybrid cars or using public transport, but the demand for the service 'transport' will not be affected.

Bottom-up models are able to assess possibilities for different technology futures with significantly different environmental impacts at a very detailed level. The actual circumstances in different countries or regions, such as the types of technology used to generate electricity, including its vintage structure, are relatively well represented. However, these models typically neglect interactions of the energy system with other sectors and have a partial equilibrium representation of the energy sector. Moreover, trade-related interactions are usually restricted to the energy input market and interactions with downstream sectors are not modelled at all. As a consequence, bottom-up models only provide a partial understanding of the long-run dynamics of the economy (Böhringer and Rutherford, 2008).

Top-down models aim to evaluate how particular policies affect the whole economy while respecting basic macroeconomic accounting rules. These accounting rules guarantee that expenditures (e.g. consumption) do not exceed income, and income, in turn, is determined by what factors of production (e.g. labour) earn. Accordingly, no surpluses can be created or lost (e.g. Piermartini and Teh, 2005).The economy-wide representation in these type of models allows to study climate or energy policy impacts on the energy sector as well as on other sectors in the economy, including trade impacts in both input (labour, capital and energy) and output (goods) markets. For instance, climate policies typically increase energy costs and therefore change the relative price of energy for all sectors. Accordingly, the model can study the direct but also the indirect impact of climate policies on supply and demand in all markets, including shifts in consumption and production away from GHG-intensive goods and services to goods and services with fewer or no GHG emissions. These *propagation mechanisms* imply that changes in one sector or region will have an impact on economic activities (and hence also emissions) in other sectors and regions (see, e.g., Böhringer et al., 2010). In the example of car use, top-down models not only show a shift in fuel type and type of transport used, but also a decrease in the demand for the service 'driving' accompanied by an increase in the demand for other goods and services, emitting less GHG emissions. Moreover, such impacts are likely to be affected through the trade channel as well, in particular if differences in climate policies exist between countries.

Top-down models particularly provide insight in economy-wide impacts of climate policies, but the representation of the energy system is generally less detailed. Energy use is just one of the major input factors, along with labour and capital, for most sectors in the economy. Energy resource availability is usually not modelled explicitly. Furthermore, possibilities for substitution and efficiency improvements are embedded in a (limited) number of parameters such as the elasticity of supply and demand. As a consequence, top-down models neglect interactions and complementarities of particular technologies and physical limitations that are relevant to the energy system.

Cost concept used

Bottom-up models focus on the direct mitigation cost of measures that are implemented. They estimate the additional cost for both energy supply and demand to adapt to the new constraint. For instance, if a carbon tax will be imposed, the cost of carbon intensive production and consumption will rise relative to carbon clean technologies which are usually more expensive. This difference in cost is labelled mitigation costs. It should be noted that the detailed specification of the energy system allows these costs to usually also account for the life-time of capital and country and sector specific turn-over rates, e.g. by including a vintage structure.

Top-down models focus on welfare effects; the additional cost of climate policy in sectors that are implementing reduction measures, such as direct engineering and financial costs, is only considered as a first step. These models also account for the effect of these costs on other sectors and regions through the propagation mechanisms. Initial higher cost in one sector, when large enough, raises the (output) price, which, in turn, is likely to have an impact on other sectors that exploit these products as inputs and now find their relative input prices changed. To what extent such price shifts have an impact on demand and supply of the inputs in different sectors depends on their relative importance in production as well as on the import and export positions of these sectors. These indirect effects may also imply a 'redistribution' of economic losses within an economy or across the border. As an example, consider mitigation policies that induce a reduced demand for fossil fuels. This would lead to an over-supply of fossil fuels and therefore to fuel trade related income losses for fossil fuel exporters, like OPEC countries and Russia and Canada. Welfare effects are generally measured by the change in consumers' utility level due to a change in consumption. Some models also include other factors that influence people's living standards, such as environmental pollution, which allows for a more comprehensive welfare analysis.

Comparison of bottom-up and top-down models

Clearly, the modelling structure between bottom-up and top-down models is very different. Whether this results in different mitigation cost estimates is still an open question. Van Vuuren et al. (2009) compare GHG emission reductions from different levels of carbon prices using various bottom-up and top-down models. Surprisingly, the results do not indicate a systematic difference in the reduction potential reported by bottom-up and top-down models used. However, the models only find comparable emission reduction levels at the global scale, because results at the sector level appear to diverge considerably. Nevertheless, they find that differences among top-down models are often of a similar order of magnitude as differences between top-down and bottom-up models.

Amann et al. (2009) compare estimates of GHG mitigation potentials of eight models. To this end, they required the different model estimates to account for differences in assumptions on baseline economic development, in the measures included in the baseline, and in the time window assumed for the implementation of mitigation measures. This correction allowed the remaining differences to be the consequence of the modelling approach only. In their analysis, the bottom-up models (i.e. models restricting their analysis to technical measures) show only half of the mitigation potential of the top-down models (i.e. including consumer demand changes and macro-economic feedbacks). Interestingly, the propagation mechanism seems to offer additional emission reduction potential. The extent to which this is the case critically depends on assumptions about the behaviour of firms and households, such as the ease with which GHG-intense activities can be substituted by low-GHG activities (see also Stern, 2006).

Clapp et al. (2009) compare model estimates by 19 models of national and sectoral GHG mitigation potential across six key OECD economies: Australia, Canada, the EU, Japan, Mexico and the USA. They also find that top-down models tend to find greater mitigation potential at specific carbon prices than bottom-up models "due to the capital movement between a wide range of economic sectors that allows for a more flexible response to carbon prices" (Clapp et al., 2009, Section 4.2).

3 Methodological differences between TIMER and WorldScan

This section presents more specific background information on methodological differences between the energy system model TIMER and the computable general equilibrium model WorldScan. This section first provides a rough sketch of both models. A more detailed description of the models is included in the Appendix. Next, we address more specifically the main differences in the mitigation measures modelled, including the role of learning-by-doing and inertia in the energy system, and in the cost concept used.

TIMER

TIMER is an energy system simulation model describing the long-term dynamics of the production and consumption in the world. The model's behaviour is mainly determined by substitution processes of various technologies based on long-term prices and fuel preferences. These two factors drive investments in new energy production and consumption capacity. The demand for new capacity is limited by the assumption that capital is only replaced at the end of the technical lifetime. Long-term prices are determined by resource depletion and technology development. Resource depletion is important for both fossil fuels and renewables (for which depletion and costs depend on annual production rates). The detailed specification of the energy systems accounts for the life-time of capital and country and sector specific turn-over rates, e.g. by including a vintage structure. Technology development is determined by learning-curves or through exogenous assumptions. Emissions from the energy system are related to energy consumption and production flows. A carbon tax changes relative prices and therefore induces a response such as increased use of low or zero-carbon technologies, energy efficiency improvement and end-of-pipe emission reduction technologies.

Compared to other energy system models, TIMER is relatively rich in technological detail, although not as detailed as real bottom-up models (Van Vuuren, 2006). Its relative strength compared to some of the other models is the integration within the IMAGE integrated assessment framework (Bouwman et al., 2006), the connection to the FAIR climate policy modelling framework (Den Elzen et al., 2013), the relatively well-advanced description of technological change, emissions of GHGs and air pollution, and its applications in the field of renewable energy. Combined with FAIR, the mitigation potential and costs of GHG emissions from the energy and land-use systems can be calculated.

WorldScan

WorldScan is a global computable general equilibrium (CGE) model that allows for simulations of the impact of climate policies on various world markets, including product markets and markets for factors of production, such as labour, capital, and energy. The model reflects the global economy with multi-region and multi-sector detail, the regions being connected by bilateral trade flows at industry level. Like all CGE models, WorldScan satisfies market equilibrium conditions, i.e. overall value added equals overall (input) cost. Policies change relative prices, which will induce supply and demand responses throughout the world economy. Equations specifying supply and demand behaviour of both firms and consumers are solved to guarantee full market clearing. Main parameters in these equations are substitution elasticities (reflecting the ease at which, e.g., energy can be substituted by capital and labour) and Armington elasticities (reflecting relative preferences for products from different countries). In addition to these changes in demand and supply, WorldScan also includes technical options to reduce emissions, such as the use of nuclear and renewable energy in the electricity sector and carbon-capture and storage (CCS).[1]

Like many CGE models used for climate policy analysis, such as ENV-Linkages (Dellink et al., 2011) and DYE-CLIP (Peterson et al., 2011), WorldScan is a recursive-dynamic CGE model: current period investment, savings, and consumption decisions are made on the basis of current period prices. Moreover, technology development usually follows an exogenous path which is derived from other models. This makes WorldScan less suitable for analysing the role of technical change and R&D and intertemporal flexibility of GHG mitigation. Examples of CGE models that are able to address these issues are WITCH (Bosetti et al., 2011), MERGE (Richels and Blanford, 2008) and the forward looking version of the EPPA model (Babiker et al., 2009).

Mitigation measures

In general TIMER and WorldScan include the same CO_2 emission reduction possibilities: changes in energy supply, energy efficiency improvements and end-of-pipe emission reduction technologies. A price on emissions (i.e. a carbon tax) induces investments in emission reduction measures. On the energy supply side, activities with high carbon emissions, such as use of coal, become more expensive compared to options with lower carbon emissions, such as renewable energy. The latter therefore gains in market share. On the energy demand side, investments in energy efficiency become more attractive.

In TIMER final demand for goods and services is to a certain extent exogenous[2], whereas emissions in WorldScan may also change through structural changes in demand. Changes in relative prices will affect the demand for inputs and final consumption, and induce in addition a shift towards less carbon-intensive products. Moreover, bilateral trade flows may change as a result of changes in relative prices between regions. WorldScan determines a new equilibrium after the policy shock where supply equals demand in all markets. The new equilibrium is likely to show a different economic structure in each region (including regions in which policies do not change) as well as different consumption and international trade patterns. Moreover, the final effect of a carbon tax on emissions in a specific region also depends on climate policies in other regions.

The options for reducing emissions in energy supply are modelled in more detail in TIMER than in WorldScan. TIMER includes detailed energy efficiency options like advanced heating technologies in the residential sector, reducing process emissions in cement production, and electric cars and high speed rail in the transport sector. Moreover, a total of 20 different power plant types are modelled in TIMER, each representing different combinations of i) conventional technology, ii) gasification and combined cycle technology, iii) combined heat-and-power, and iv) CCS. Also nuclear power and renewable energy options like bio-energy, wind power, hydropower en solar power are included.

In WorldScan, the possibilities to change energy supply (e.g. change the fossil fuel mix in the power sector) and improve energy efficiency are captured by the elasticity of substitution in the nested structure of production technologies (see Appendix). The elasticity of substitution differs between levels of the nesting structure and also differs between sectors (a distinction is made between agriculture, energy and other raw materials, and other sectors). Substitution occurs in all production sectors and also within households. The extent to which this will contribute to overall emission reductions depends on the (sector-specific) rate of substitution, but obviously also on the share of the polluting input in total production cost in the business-

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[1] The comparison of WorldScan and TIMER presented in Van Vuuren et al. (2009) is based on calculations by a previous version of WorldScan that did not include these technical options.

[2] As indicated before, in the case of the service 'transport', for example, not the demand for moving is affected, but the mix of means to satisfy this demand (e.g. by driving a gasoline car, a hybrid car or using public transport) may change.

as-usual scenario (BAU). The larger the share of fossil energy sources in total production cost, the larger the impact of a carbon tax on the production structure.

In addition to the structural changes, WorldScan also allows for implementing some technical mitigation options. These include the use of wind, biomass, nuclear energy and hydropower in power generation as well as the option of CCS for emissions from power plants. In the analyses presented here, the supply of nuclear energy and hydropower is not modelled endogenously in WorldScan. Supply curves for wind energy and CCS are derived from data in the TIMER model.[3]

An important difference between TIMER and WorldScan is that TIMER assumes technology development based on *learning-by-doing*. This implies that the cost of mitigation options will decrease over time when their installed capacity is built up. In WorldScan, elasticities of substitution and supply curves for technical options are constant over time and the cost of technical options is independent of the installed capacity. Van Vuuren (2006) shows that the effect of learning-by-doing on the cost of mitigation can be significant. In TIMER, a carbon tax of 300 USD/tC, implemented in a certain year, may yield emission reductions thirty years later that are 20-50% higher with learning-by-doing than without.

A final difference is that TIMER has a vintage structure. The implementation of mitigation measures depends on the vintage structure of the capital stock. As a consequence, *inertia in reducing emissions* is taken into account, as certain mitigation options only can be implemented at the moment of capital replacement. Note, however, that this inertia is reinforced because currently, the economic lifetime in TIMER is determined exogenously and hence independent of a price on emissions. WorldScan, on the other hand, does not model vintages explicitly and only estimates instantaneous adjustments in response to policies like a carbon tax, neglecting the cost of transition of the energy system. Hence, WorldScan is not able to provide insight into the adjustment process itself (e.g. timing of adopting new equipment), but examines the economy in different states of equilibrium.

Cost concept

In both models, the implementation of mitigation measures incurs cost for the sector or household directly affected. The cost of climate policies in the TIMER model is simply the sum of the direct cost of all measures implemented in a region. WorldScan accounts in addition for indirect effects in other markets. Moreover, as explained in Section 2, these indirect effects often have an international dimension due to international trade in both the factor and output markets. Such indirect effects may become dominant in scenarios with large differences between regions in terms of policies implemented or their pre-existing policies. For instance, if regions impose different targets, production will be expanded generally in regions with lax regulation relative to regions with more binding constraints. Obviously, such decisions will also affect emissions in different regions and might even lead to carbon leakage (Böhringer et al., 2010; Bollen et al., 2012). Moreover, distortions such as pre-existing taxes on energy use and market power cause indirect cost to be higher than direct cost. Therefore, welfare losses as calculated by WorldScan will deviate from the direct cost as calculated by TIMER, both in their total volume and distribution over regions.

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[3] It was not yet possible to incorporate in WorldScan data from TIMER on the use of bio-energy in the power sector. Hence, we used supply curves for biomass electricity based on Boeters and Koornneef (2011).

Table 1 Overview of main differences between TIMER and WorldScan

	TIMER	WorldScan
Type of model	Bottom-up	Top-down
Scope of the model	Energy system; within the IMAGE integrated assessment framework linked to the land-use system	Global economy including international trade
Response to climate policies	Investment in energy production and consumption capacity to meet a given aggregated demand for goods and services	Equilibrium of supply and demand and substitution between factors of production and goods and services consumed
Energy system	Detailed representation of specific energy technologies in all sectors	Energy system as part of entire economy, represented by major technologies and fuel types
Representation of dynamics	Recursive-dynamic, vintage structure of capital stock, learning-by-doing	Recursive-dynamic, flexible adjustment given the elasticity of substitution
Mitigation of CO_2 emissions	Investment in low-carbon energy technologies, taking into account physical constraints and installed capacity	Substitution between factors of production and goods and services consumed, technical mitigation based on supply curves derived from other data sources (e.g. TIMER)
Mitigation cost	Direct cost of investments in mitigation options	Direct cost of technical mitigation options, economic welfare losses taking into account indirect effects

4 Comparison of marginal abatement costs

Method

Marginal abatement cost curves (MACs) show the relation between the reduction of emissions (e.g. CO_2) and the marginal cost of abatement (reflected by an emission price, e.g. \$/ton CO_2). As such, a MAC for an economy can be seen as a reduced-form response of a more complex model to an emission tax (see e.g. Klepper and Peterson, 2006; Morris et al., 2008). Hence, MACs are frequently used to compare different models with regard to their climate policy response (e.g. Amann et al., 2009; Van Vuuren et al., 2009).

To compare responses of TIMER and WorldScan to a levy on CO_2 emissions, MACs are constructed for 2030 by plotting various levels of a CO_2 tax against the reduction in emissions of CO_2 estimated by the models. Combining the emission price levels and the resulting emission reduction levels provides an indication of the MACs implicit in the models. To guarantee consistency between both models on essential parameters, the same baseline developments in economic growth, energy use, global energy prices and emissions were used. These developments were taken from the business-as-usual (BAU) scenario of the OECD Environmental Outlook to 2050, as implemented in the IMAGE suite of models (OECD, 2012). Note that the response to a CO_2 tax in TIMER is driven by a minimization of the total direct cost, whereas responses in WorldScan also reflect indirect effects. As the indirect effects of climate policies in one region largely depend on what happens in other regions, WorldScan finds different MACs for different international climate policies (e.g. unilateral introduction of a CO_2-tax in Europe vs. a global uniform CO_2-tax). In our simulations we assume a uniform CO_2 tax in all regions in the world. As a sensitivity analysis we assess the effect of different international climate policy designs for emission reductions in Europe.

The levy on CO_2 emissions in both TIMER and WorldScan is translated into a tax on CO_2 emitting activities, mainly fossil fuel use. This CO_2 tax comes on top of fuel prices. These fuel prices differ between countries, partly because of differences in pre-existing taxes on fossil fuels. As a consequence, the relative impact of the CO_2 tax on fuel prices, and hence on fuel consumption, differs. The higher the fuel price, the smaller the relative impact of a CO_2 tax. Table 2 compares fossil fuel prices in the BAU in TIMER and WorldScan between various regions. As (tax-inclusive) fuel prices substantially diverge between sectors because of differences in pre-existing taxes, we present average prices for the respective fuels as observed in the sectors responsible for the largest share of fuel use (i.e. the power sector for coal and natural gas, transport for oil products). Moreover, to compare the overall price level of energy use between regions we also include the average price for the total of fossil fuels consumed (weighted for their volume of consumption).

Both models show relatively high average fuel prices in Europe and Japan, moderate prices in the USA and Oceania and relatively low prices in China, Russia and India. Prices in WorldScan diverge more between Europe and Japan on the one hand and China on the other hand than prices in TIMER. This might cause more pronounced differences in the results between these regions found by WorldScan than by TIMER. Table 2 also shows more specific differences between the models. In WorldScan, oil prices are relatively low in China and relatively high in India, whereas in TIMER oil prices are somewhat above global average in both countries. For natural gas, TIMER assumes relatively low prices in the USA and relatively high gas prices in Japan and China, whereas in WorldScan the opposite holds. As WorldScan is calibrated on 2004 data and currently assumes a globally uniform development of the price of gas, recent developments in the gas market, in particular the substantial decrease in the price of gas in the USA, are not well included in the model. The differences in relative prices may to some extent contribute differences in results of the models.

Table 2 Tax inclusive fossil fuel prices in 2030 in the BAU relative to global average (= 100) for power sector (coal and natural gas), transport (oil products) and overall weighted average for total fossil fuel consumption

	Coal		Oil products		Natural gas		Fossil fuels	
	TIMER	WorldScan	TIMER	WorldScan	TIMER	WorldScan	TIMER	WorldScan
USA	92	118	107	98	75	147	115	115
Europe	111	146	182	184	112	105	169	192
Japan	130	139	135	117	121	108	137	165
Oceania	77	94	116	116	85	97	118	126
Russia	110	86	89	84	63	81	76	71
China	97	91	111	55	120	56	70	48
India	85	68	106	141	114	110	72	95

Carbon taxes can be introduced over time in different ways. First, the carbon tax can be introduced immediately at the intended level (‘block tax’), keeping it constant afterwards. Second, the tax can be introduced more gradually over time. As WorldScan assumes more or less instantaneous adjustments, results for 2030 will be largely similar for a linearly increasing CO_2 tax and a block tax. In TIMER, however, inertia in the energy system (see previous section) induces different responses to different tax profiles (see also Van Vuuren et al., 2004). To compare the results of TIMER with the instantaneous adjustments in WorldScan, we use a block tax profile for the simulations in TIMER. By introducing the tax immediately in 2010, the energy system in TIMER starts to take into account this emission price in the investments in the energy system from 2010 onwards. By 2030 most of the changes are expected to have been implemented. The simulations by WorldScan assume the introduction of a CO_2 tax at a linearly increasing rate between 2010 and 2020, such that in 2020 the intended level is obtained, which will remain at this level until 2030. This is a pragmatic choice, to avoid WorldScan running into problems to find a numerical solution with high tax levels introduced immediately.

Marginal abatement cost curves

Figure 1 presents the MACs up to 100 USD/tCO_2 for the year 2030 for 7 world regions: Europe, USA, Japan, Oceania, Russia, China, and India. These were derived by plotting the incremental levels of a CO_2 tax introduced in the models as described above, against the corresponding reduction in CO_2 emissions estimated by the models. The cost curves presented here give a first impression of the agreement between TIMER and WorldScan on the costs of reducing emissions. In general, reductions tend to be larger in WorldScan than in TIMER for tax levels up to 50 USD/tCO_2, which is consistent with findings from other comparison studies (see Section 2). For higher tax levels, however, reductions in TIMER exceed those in WorldScan for several regions, indicating that further CO_2 emission reductions are much more expensive in WorldScan than in TIMER. In China and Russia, emission reduction rates are higher in WorldScan than in TIMER for the whole range of CO_2 tax levels analysed.

The MACs of both TIMER and WorldScan are not strictly convex, i.e. the additional emission reduction associated with an increase in the CO_2 tax level by 1 USD/tCO_2 is not continuously decreasing. This can simply be explained by the large potential becoming available at carbon prices around 40 USD/tCO_2, especially due to CCS employment (see Figure 1).

Both models show important regional differences. The results of TIMER and WorldScan largely differ for Russia. According to TIMER, Russia is the region with the lowest reduction potential, whereas WorldScan finds relatively high reduction potentials. The most important reason for the low emission reduction potential according to TIMER is the large overcapacity in current coal-fired power plants. This prevents the building of new, low-carbon intensive, power plants. After 2030, most of these power plants are at the end of their lifetime. At that time, replacement of these plants offers opportunities to reduce CO_2 emissions. Figure 2 shows that by 2040 the reduction potential for Russia is much closer to those of the other countries.

WorldScan shows the highest reduction potential for China (together with India), whereas according to TIMER, China’s reduction potential is much lower (similar to the average of the other regions). The reason for this lower reduction potential according to TIMER is similar to the reason for Russia: China has expanded its energy sector considerably in the past decade making replacement of or adjustments to these investments very expensive. Hence, moving to low-carbon technologies will be difficult for China. As indicated, WorldScan does not model vintages explicitly and allows for instantaneous adjustments of the energy system. Moreover, WorldScan finds high reduction potential because pre-existing taxes on energy are relatively low implying a relatively energy intensive production structure in the BAU. Hence, China and India have cheaper abatement options than, for instance, Europe, with its relatively high levels of existing taxes on energy. Moreover, with low levels of pre-existing energy taxes, the introduction of a CO_2 tax will have a comparatively large impact on energy.

Finally, TIMER shows a larger reduction potential for India than WorldScan because the energy sector in India will expand significantly in the coming decades. Introducing a carbon tax from 2010 onwards will immediately be taken into account such that the investments will be adjusted to low-carbon technologies at relatively low cost.

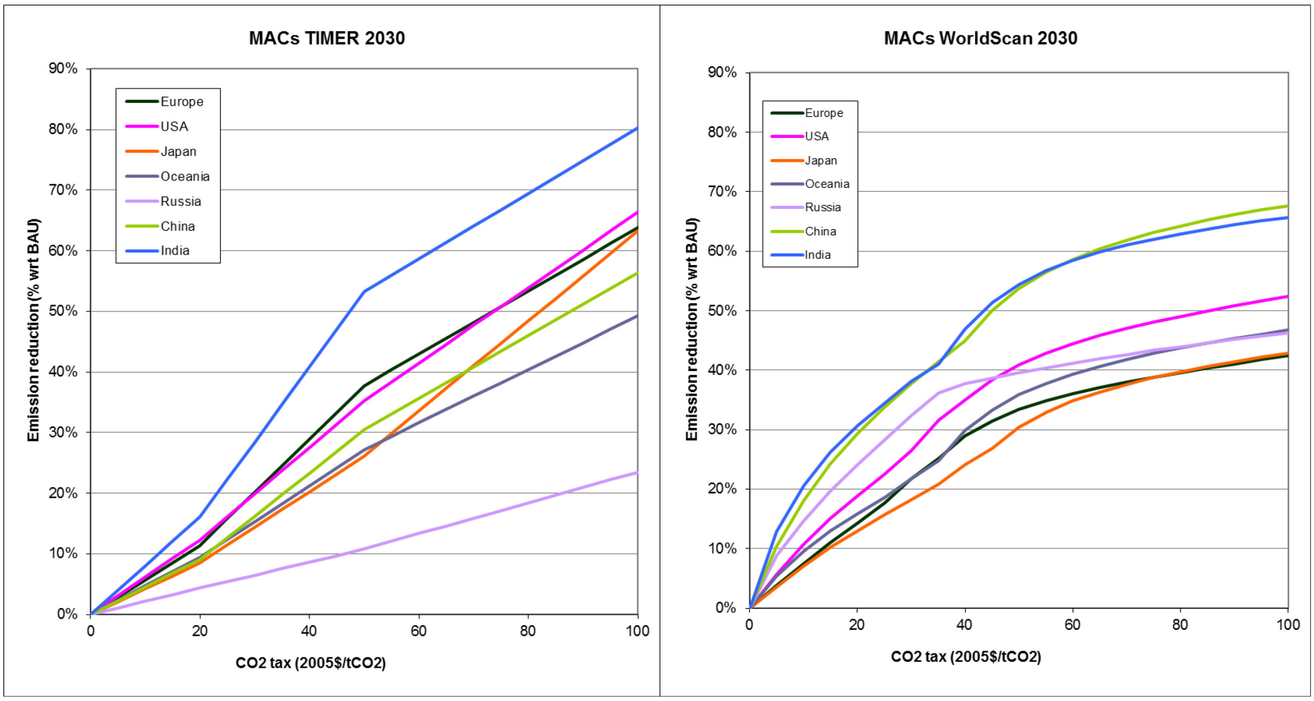

Figure 1 Marginal abatement cost curves for 2030 resulting from TIMER and WorldScan analyses

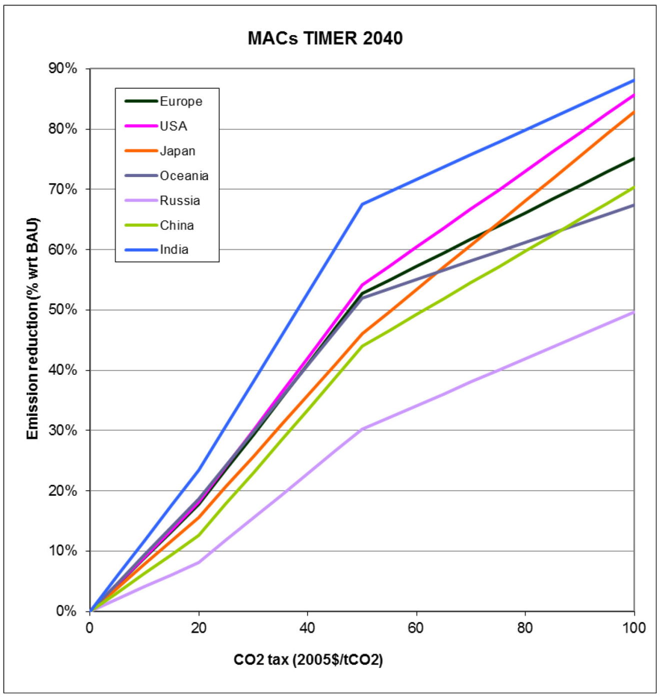

Figure 2 Marginal abatement cost curves for 2040 resulting from TIMER analyses

Reduction measures

The outcome of TIMER and WorldScan not only differs in the mitigation rates, but also in the underlying factors through which emission reductions are achieved. A comparison of the reduction measures taken at certain carbon prices provides insight in the differences in the MACs as shown above. Figures 3 to 5 present a decomposition of the emission reductions by 2030 for carbon prices at USD 20, 50 and 100 per tCO_2. In the decomposition, the *volume* effect refers to a reduction in emissions due to a decrease in the overall size of the economy; the *structure* effect refers to a reduction in emissions due to a change in the composition of the economy; the *efficiency* effect refers to a reduction in emissions due to more efficient use of energy; the *fossil switch* effect refers to a reduction in emissions due to a change in the fossil fuel mix.

At 20 USD/tCO_2, differences between TIMER and WorldScan are relatively small for Europe. For the USA, Japan and Oceania the emission reduction in WorldScan is about 50% higher than in TIMER, mainly because of a larger contribution of efficiency and structure effects. For Russia, WorldScan finds much larger reduction potential especially due to the implementation of renewable energy and biofuels and the volume and structure effects. These last two effects are not included in TIMER and the use of renewables and biofuels is limited as a result of the overcapacity in power supply. For China and India, WorldScan also finds much larger reductions at 20 USD/tCO_2, especially due to implementation of renewable energy, efficiency improvements, and volume and structure effects. TIMER simulates a substantial emission reduction in India due to increased use of nuclear energy, whereas in WorldScan we do not model endogenous supply of nuclear energy. As already explained above, the relatively large volume, structure and efficiency effects in Russia, China and India in WorldScan come from the relatively low rates of pre-existing energy taxes.

At 50 USD/tCO_2, CCS becomes an important mitigation measure in both models. This is not surprising, since the marginal cost and potential of CCS technology in WorldScan is calibrated according to TIMER results. In Europe, TIMER finds more potential for efficiency improvements, renewables and CCS and hence a larger overall emission reduction for 50 USD/tCO_2. For China, the differences between TIMER and WorldScan are smaller for 50 USD/tCO_2 than for 20 USD/tCO_2. For India, similar emission reductions are estimated by TIMER and WorldScan. The contribution of an increased use of bio-energy is larger in TIMER than in WorldScan, whereas volume and structure effects and an increased use of renewables are more important in WorldScan compared to TIMER.

At an even higher carbon price of 100 USD/tCO_2, a main difference is that emission reductions by CCS contribute relatively less to total reduction in WorldScan than in TIMER. As a result, total emission reductions are also smaller in most regions. Although the marginal cost and mitigation potential of CCS in WorldScan is based on the data in TIMER, the actual use of CCS as mitigation option differs, mainly because of differences in the use of coal for electricity generation. Actually, the volume, structure and efficiency effects in WorldScan cause a reduction in the production of electricity in general and the use of coal in particular.

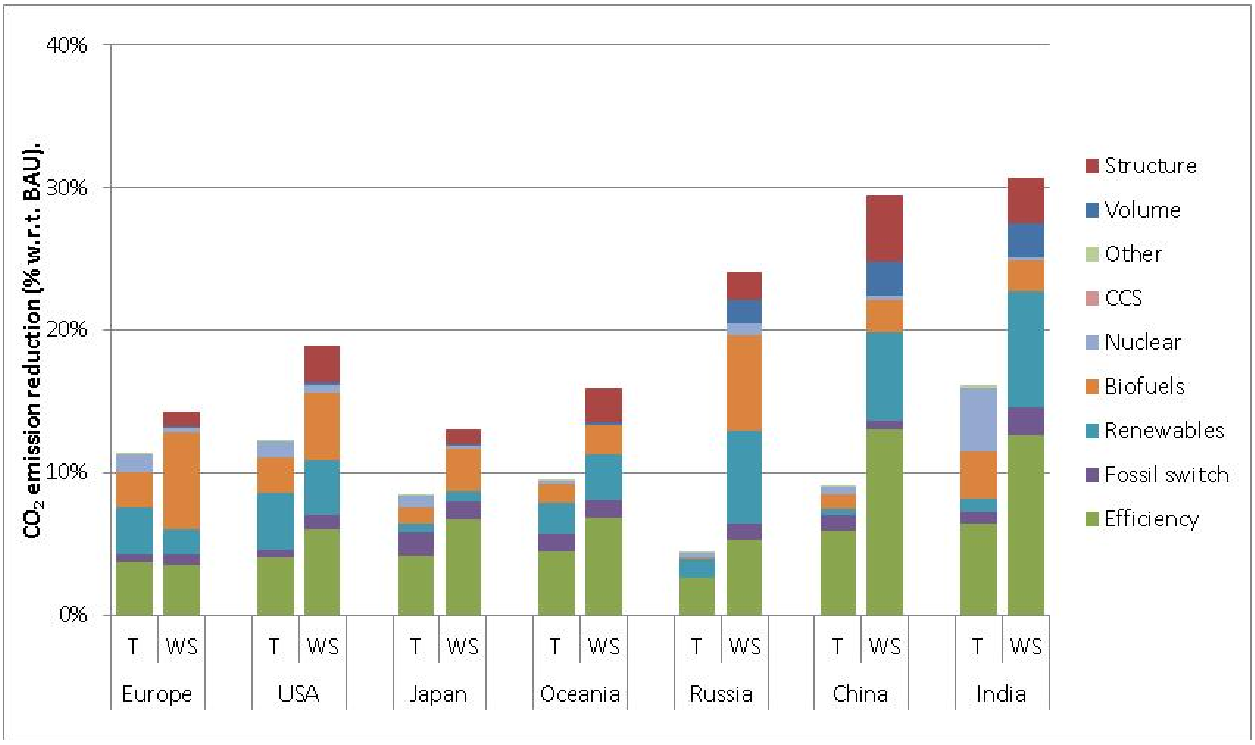

Figure 3 Decomposition of CO_2 emission reduction in 2030 at CO_2-tax of \$20/ton CO_2 – TIMER (T) compared with WorldScan (WS)

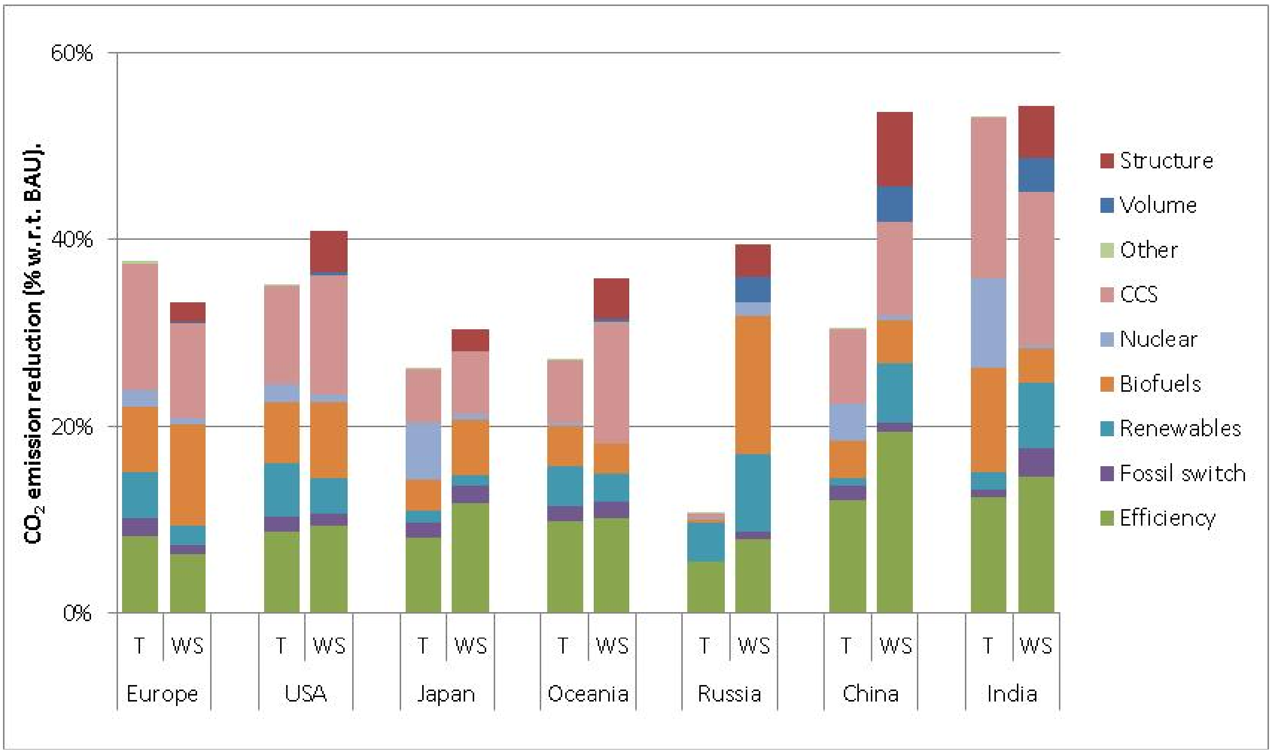

Figure 4 Decomposition of CO_2 emission reduction in 2030 at CO_2-tax of \$50/ton CO_2 – TIMER (T) compared with WorldScan (WS)

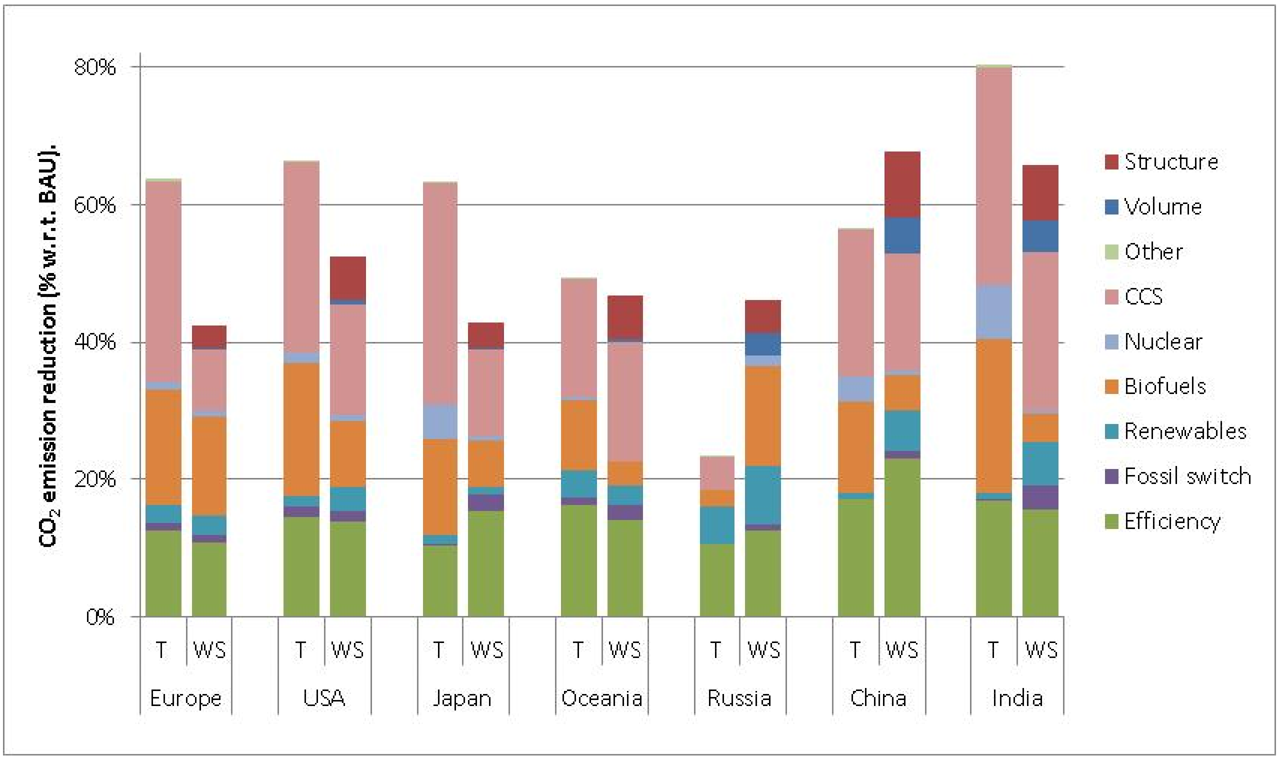

Figure 5 Decomposition of CO_2 emission reduction in 2030 at CO_2-tax of $100/ton CO_2 – TIMER (T) compared with WorldScan (WS)

Mitigation in different coalitions

Both in WorldScan and TIMER, emission reductions in one region depend on climate policies in the rest of the world. The reasons for this dependency are, however, different between the models. In WorldScan, the reason is that the net effect on CO_2 emissions as calculated for a specific region not only reflects the primary impact of the CO_2 tax through adjustments of domestic production and consumption patterns, but also secondary effects due to changes in exports and imports and hence in international prices. In TIMER, learning-by-doing plays an important role: with smaller coalitions there is less learning-by-doing on a global scale, which negatively impacts future potential at a given carbon price. On the other hand, in a smaller coalition there is less global demand for bioenergy, which means lower feedstock prices for bioenergy (either for fuel or power).

To provide some insight into the above effects, we analysed CO_2 mitigation in Europe for international climate coalitions different from a CO_2 tax introduced in all regions in the world (*Uniform*, as presented above). In particular, we consider a policy case in which Europe and all other Annex 1 countries introduce a CO_2 tax (*Annex1*), and a case in which Europe is the only region in the world introducing a CO_2 tax (*Unilateral*).

Figure 6 shows the results of WorldScan for these different cases for CO_2 emission reduction in Europe next to the results of TIMER for the *Uniform* case. The results show that in both WorldScan and TIMER, the *Annex1* and *Unilateral* scenarios lead to higher emission reductions in Europe at a carbon tax of 50 USD/tCO_2. In WorldScan, the main reason is that energy-intensive activities are outsourced, as reflected by the increasing contribution of the *structure* and *volume* effects in total mitigation. A worldwide introduction of a CO_2 tax (*Uniform*) makes production by the energy intensive sectors in Europe more competitive and production volumes in these sectors increase compared with the BAU. If other regions, such as China, will not introduce a similar CO_2 tax, European industry will face a loss of competitiveness and output levels will decrease in Europe because of a relocation of production to countries with no climate policies. Note that this outsourcing limits the effectiveness of climate policies in terms of reducing worldwide CO_2 emissions, as this causes carbon leakage to other regions (see Bollen et al., 2012). Moreover, emission reductions by efficiency improvements and the use of biofuels increases, which can be explained by the reduction in global fossil fuel prices due to climate policies, which is smaller with less countries joining the international climate coalition. In TIMER, the *Annex1* and *Unilateral* scenarios lead to (slightly) higher reductions due to the use of biofuels induced by lower feedstock prices for bioenergy. This effect is larger than the learning-by-doing effect, which results in less emission reductions by efficiency improvements.

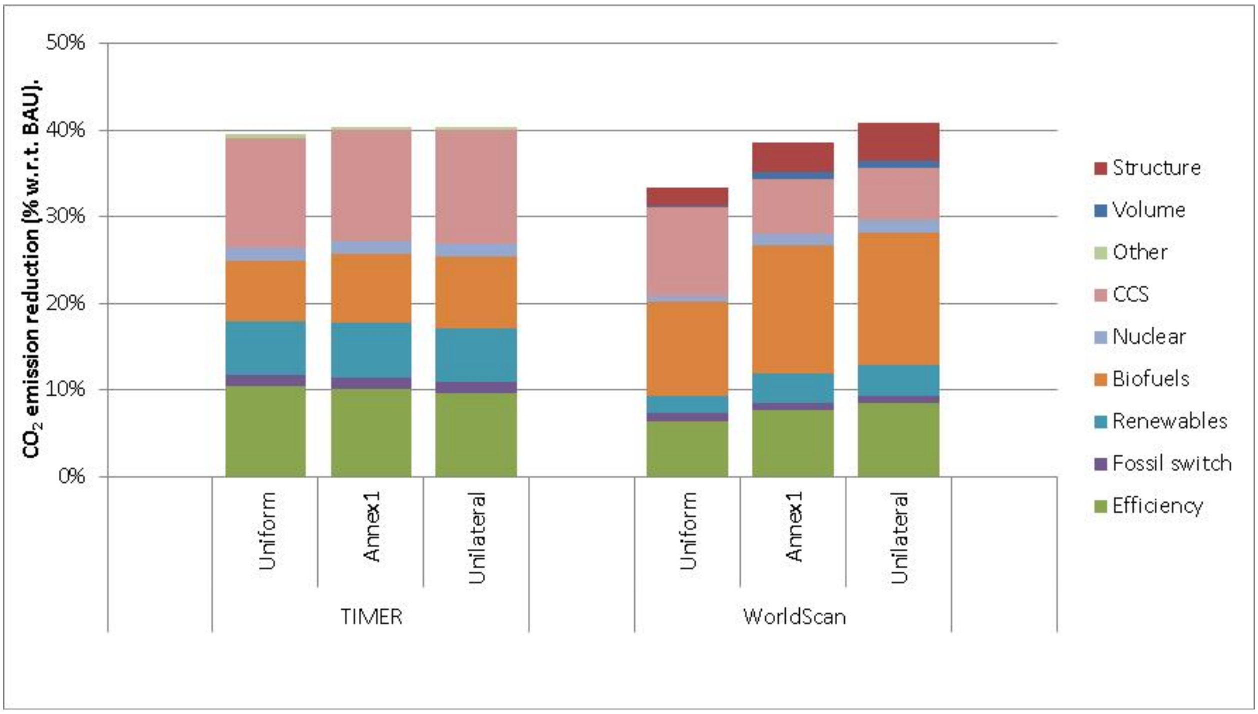

Figure 6 Decomposition of CO_2 emission reduction in Europe in 2030 at a CO_2 tax level of 50 USD/tCO_2 for different international climate coalitions (*Uniform*: CO_2 tax in all regions; *Annex1*: CO_2 tax in Annex 1 regions; *Unilateral*: CO_2 tax in Europe only)

5 Comparison of cost estimates

Different indicators can be used to analyse how policies affect social welfare. One (partial) indicator is the welfare costs of policies, i.e. the value of the resources society is willing to give up to take a given course of action, such as a predetermined reduction in CO_2 emissions (see e.g. Krupnick and McLaughlin, 2011). To evaluate overall welfare effects of emission reductions, also the benefits of this reduction should be included. Both FAIR and WorldScan provide estimations of the welfare cost of policies. In order to allow for analyses of both the benefits and the cost of climate policies, FAIR provides estimates of the benefits of reduced global warming (Hof et al., 2008) and the direct cost of mitigation measures. FAIR also calculates consumption losses due to climate policies, based on a simple Cobb-Douglas production function (see Appendix). WorldScan only includes welfare cost of climate policies, measured by the Hicksian Equivalent Variation. This measure is usually presented as a percentage of national income in the BAU showing the loss of welfare in terms of a reduction in national income.[4] As WorldScan does not provide a measure for the benefits of emission reduction, the model clearly provides a partial measure of the social welfare effects of policies.

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[4] The Hicksian Equivalent Variation of a policy case measures the amount of money by which the income of households in the baseline should change to attain the same change in utility level as caused by the policy measures in this case (see also Appendix).

The focus here is only on the various measures for welfare cost provided by FAIR and WorldScan. The outcome of WorldScan calculations includes various indicators to measure the economic impact of climate policies, including the change in GDP (as a measure for overall economic activity), consumption and national income. TIMER/FAIR present direct cost of mitigation measures as a percentage of GDP in the BAU and associated consumption losses. As these various indicators are not directly comparable, the main focus of the comparison here is on the distribution of the cost over regions according to the various measures.

As indicated, economic welfare effects are different from direct cost estimates. Indirect effects cause a redistribution of costs over economic actors and regions and may exceed the direct cost because of market failures. To analyse the relevance of this difference, in this section we compare the direct costs and consumption losses in various regions as estimated by TIMER/FAIR and the change in GDP, consumption and economic welfare of a comparable climate policy scenario as calculated by WorldScan. Note that in TIMER/FAIR the direct costs in a certain year do not take into account abatement action in previous years, in contrast to consumption losses.

Figure 7 compares the cost estimated by FAIR and WorldScan for a globally uniform CO_2 tax of 50 USD/tCO_2. Obviously, all regions face direct cost as a result of the introduction of a CO_2 tax. Both in FAIR and in WorldScan a CO_2 tax stimulates investments in mitigation which involves additional cost for producers and consumers. Graphically this is the area below the MACs in Figure 1 up to the level of 50 USD/tCO_2. In proportion to the level of GDP, direct costs are particularly high in regions with relatively high levels of CO_2 emissions in proportion to GDP, such as India and China. The economic impacts as calculated by WorldScan are somewhat different as they take into account a redistribution of the costs over regions as well as additional indirect effects (see Section 2). In terms of GDP losses, WorldScan results also show large effects in particular in India and China (5% and 4% below BAU respectively). An interesting finding of WorldScan is that GDP in Europe and Japan is hardly affected by the CO_2 tax, in contrast to FAIR. This can be explained by the fact that Europe and Japan are less energy- and CO_2-intensive than most other regions. As a result, the CO_2 tax will have less impact on production cost than in other regions, which makes producers EU and Japan more competitive. This results in more export of energy-intensive products, mitigating the negative pressure of the carbon tax.

Consumption losses as calculated by FAIR show a similar pattern of distribution over regions as the direct cost in relation to GDP. The change in consumption as calculated by WorldScan shows a somewhat different behaviour than change in GDP. In Russia the change in consumption is more than double the change in GDP. This follows from the fact that Russia, as a large oil and gas exporter, experiences a deterioration in its terms-of-trade because of decreasing fuel prices. To a lesser degree this also applies to Oceania as a major coal exporter. On the other side, Europe and Japan manage to increase their consumption, notwithstanding the CO_2 tax. This can be attributed to improvements in their terms-of-trade and competitiveness. Consumption losses as calculated by FAIR turn out to be much smaller than those found by WorldScan. Possible explanations for these differences are: (i) in FAIR, mitigation costs are only for a small part (~20%) deducted from investments, leading to relatively small indirect cumulative effects; and (ii) FAIR does not account for climate policy making consumption more expensive, which implies a lower reduction of consumption volume compared to WorldScan.

As welfare losses are related to consumption (see Appendix), the Hicksian Equivalent Variation as determined by WorldScan shows a similar pattern as the change in consumption: welfare losses are largest in Russia, India and China, and Europe and Japan are even better off in terms of economic welfare.

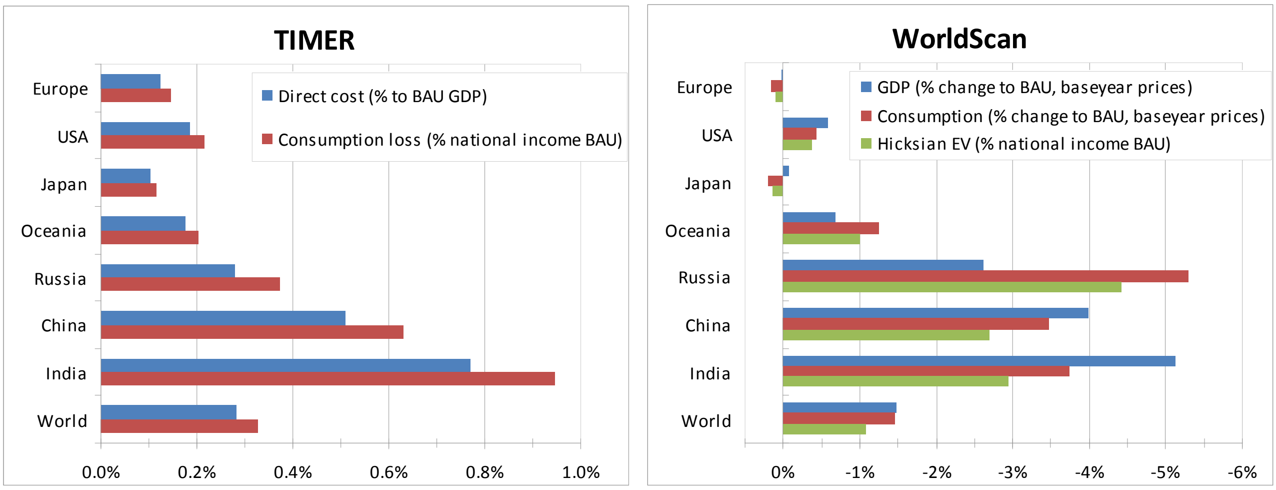

Figure 7 Comparison of cost measures in 2030 by TIMER and WorldScan for global uniform CO_2 tax of 50 USD/tCO_2. TIMER: direct costs as % of BAU GDP and consumption loss as % of BAU; WorldScan: welfare effects as Hicksian Equivalent Variation as % of BAU national income, GDP and national income as % change to BAU.

Comparison with other studies on cost of climate policies

Van Vuuren et al. (2009) found that for regimes that assume participation of developed and developing countries long-term direct abatement costs correlate strongly with macroeconomic costs for most regions. This was also shown for oil-exporting regions as in general these regions have highly carbon intensive economies leading also to high abatement costs. Still, Van Vuuren et al. (2009) acknowledge that there are economic impacts that are not included in the direct abatement costs such as the impact of income losses via changes in fuel trade.

Studies using CGE models to analyse the global impact of climate policies confirm that partial analyses based on direct cost of mitigation only, may lead to other conclusions than analyses of welfare effects in various regions using a general equilibrium framework. Böhringer et al. (2010) show climate policies in the USA and Europe only to cause large welfare losses in oil exporting regions. Other regions, including Japan and India, benefit from lower international fossil fuel prices. Morris et al. (2008) show that there is little correspondence between the marginal abatement cost and the marginal welfare cost. Moreover they show that the welfare effects in a region may largely diverge for different mitigation rates in the region and in the rest of the world. The analyses by Peterson et al. (2011), Dellink et al. (2011) and McKibbin et al. (2011) show comparable mechanisms as occur in WorldScan. As the policy cases simulated in these studies are not the same as the policy cases in this paper it is not possible to directly compare the results. This requires further analysis of welfare effects estimated by WorldScan, which was however beyond the scope of this study.

6 Conclusions and future work

Based on differences and explanation of differences between results of TIMER and WorldScan, we summarize the following:

- for CO_2 tax rates up to 50 USD/tCO_2 differences between estimated emission reductions are limited for developed regions, but large in some developing regions;
- the mitigation potential in WorldScan hardly changes over time, whereas TIMER shows changes resulting from the dynamics in the energy system as well as the effects of technological change due to learning by doing;

- inertia in the energy system as included in TIMER result in emission reductions estimated by TIMER to be substantially smaller than those estimated by WorldScan for Russia and China. In this regard, WorldScan seems to be too optimistic about mitigation potential of renewables and biofuels, particularly in regions which have substantially expanded their energy production sector recently;
- in case of a global uniform CO_2 tax, emission reductions through changes in the overall level of production and consumption in a region (volume effect) and through changes in the structure of the economy (structure effect) tend to be less important in developed economies. In regions with no or low rates of pre-existing energy taxes WorldScan estimates substantial emission reductions through volume and structure effects, which significantly contributes to mitigation rates being higher in WorldScan than in TIMER;
- for higher CO_2 tax rates, the use of biofuels as estimated by WorldScan is substantially smaller than estimated by TIMER;
- the mitigation rates in a specific region depend on the international context of climate policies. For a given carbon tax level, WorldScan and TIMER project higher emission reductions in Europe with smaller coalitions, but for different reasons. The reason in WorldScan is the impact of changes in international trade and other indirect effects, while feedstock prices for bioenergy and learning-by-doing are the main reason in TIMER.;
- the distribution of the direct cost of climate policies over regions is different from the distribution of the economic welfare losses as a result of indirect effects.

Strengths and weaknesses of TIMER and WorldScan
Based on these findings, we conclude that TIMER and WorldScan have their strengths and weaknesses on different aspects, which are all relevant for the assessment of climate policies. Given the detailed modelling of the energy system in TIMER, the strengths of TIMER are in the analysis of:

- consequences of climate policies for the entire energy system;
- technology specific development, including learning by doing and physical constraints;
- development of the responses to climate policies over time;
- long-term climate policies (>20 years);
- consequences of climate policies to specific economic actors;
- within the IMAGE integrated assessment framework, a combination of TIMER and FAIR allows to assess the mitigation potential and costs of GHG emissions both from the energy and land-use systems.

By taking into account indirect effects of climate policies and consequences for international trade, the strengths of WorldScan are in the analysis of:

- changes in demand for goods and services as a result of climate policies;
- redistribution of the economic welfare losses due to climate policies over sectors and regions;
- macro-economic consequences (structure of the economy, volume of production and consumption) of climate policies;
- global effectiveness of climate policies that do not encompass the whole world, by taking into account potential carbon leakage;

Table 3 Overview of strengths and weaknesses of TIMER/FAIR and WorldScan

	TIMER/FAIR	WorldScan
energy system	consequences of climate policies for the entire energy system at detailed, i.e. technology specific level	consequences of climate policies for entire economy, including energy system at high level of aggregation
feasibility of mitigation options in energy system	Accounting for physical constraints and data on installed capacity in the energy system	applicability of mitigation options exogenous to the model; no information on installed capacity, instantaneous adjustment at no cost
development of response to climate policies over time	dynamics in the energy system and technological change through learning by doing, dependent on installed capacity	exogenous change in cost and potential of wind, biomass and CCS, derived from TIMER
time horizon	well able to analyse long-term consequences of climate policies (> 20 years) by taking into account technological change and (physical) constraints to the energy system	best fit to analyse consequences of climate policies for global economy reaching a new equilibrium situation with time horizon of ~20 years; not able to analyse drastic changes in energy system so not very well suitable for long-term analysis of far-reaching climate policies
structural changes	behavioural changes due to changes in relative prices not included	both technical measures and structural changes are considered as mitigation options; in regions with no or low rates of pre-existing energy taxes behavioural changes significantly contribute to mitigation
international climate policies	effect of climate policies in other regions on mitigation rates in one region are negligible	mitigation in one region dependent on (climate) policies in other regions through indirect effects
distribution of costs and welfare effects	TIMER/FAIR only takes into account the direct cost, i.e. the cost of mitigation that actors initially incur	by taking into account the indirect effects, WorldScan estimates a redistribution of the cost (e.g. through terms of trade effects); moreover, market distortions, such as pre-existing taxes on energy, cause welfare effects to be significantly different from the direct cost
carbon leakage	effect of climate policies in one region on economic activities in the rest of the world are negligible	climate policies in one region will affect international trade and prices and hence economic activities and related emissions

In conclusion we can say that in cost assessments of climate policies, results by WorldScan complement the analyses made by TIMER, in particular with respect to the regional distribution of those costs. This effect will be even greater in analyses on climate coalitions that do not include all countries in the world. Moreover, analyses by WorldScan require a complementary assessment by TIMER on the technological aspects of the changes in the energy system. Exploiting the complementary insights of both models will provide a set of models that is very well suitable to assess the various impacts of climate change policies.

Future work

In addition to differences between the models that are the result of their different scope and structure, there are differences related to specific assumptions in the models that can, to some extent, be removed. Therefore, we propose a limited number of future actions to further align the models. These concern:

- tuning the data on cost and potential of biofuels use as included in WorldScan to the information in TIMER (or actually IMAGE) which not only takes into account issues with respect to the energy system, but also related to land use; given the observed differences in biofuel use at different CO_2 tax rates between TIMER and WorldScan this is expected to bring the WorldScan results closer to TIMER. This might also require changes to the way land-use activities are modelled in WorldScan;
- WorldScan currently assumes a globally uniform development of the price of natural gas. As this does not match recent developments of substantially decreasing gas prices in the USA compared with prices in Europe and Asia, WorldScan will be adapted to reflect regional differences in the development of fossil fuel prices;
- a further investigation of the impact differences in energy prices between TIMER and WorldScan may have on the effect of a CO_2 tax;
- in TIMER the lifetime of energy investments is exogenous; this causes the inertia in the energy system to be somewhat overrated, as high carbon taxes certainly will reduce the economic lifetime of carbon-intensive production facilities, such as inefficient coal-fired power plants. Considering this may result in larger reductions in emissions, in particular in Russia, and hence bring the TIMER results closer to WorldScan;
- the long-term effects of abatement costs on consumption losses are rather small in FAIR, due to default parameter settings in the economic growth module. Sensitivity analyses on these parameter settings could provide more insight into the uncertainty in long-term effects on consumption losses. Moreover, the economic growth module could be extended by, for instance, including the effects of fuel trade on consumption losses;
- it might also be useful to consider the adoption of vintages in WorldScan to take into account the existing inertia in the energy system.

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Appendix – description of the models used

TIMER and FAIR

TIMER is an energy-system simulation model, describing the demand and supply of 12 different energy carriers for a set of world regions. Its main objective is to analyse the long-term trends in energy demand and efficiency and the possible transition towards renewable energy sources. Within the context of IMAGE, the model describes energy-related GHG and air pollution emissions, along with land-use demand for energy crops. The TIMER model focuses particularly on several dynamic relationships within the energy system, such as inertia, learning-by-doing, depletion and trade among the different regions. The TIMER model is a simulation model, which means that the results depend on a single set of deterministic algorithms instead of being the result of an optimization procedure.

Model structure
The TIMER model describes the chain from demand for energy services (useful energy) to the supply of energy by different primary energy sources and related emissions (Figure A.1). The steps are connected by demand for energy (from left to right) and by feedbacks, mainly in the form of energy prices (from right to left). The TIMER model has three types of submodels: (i) the energy demand model; (ii) models for energy conversion (electricity and hydrogen production), and (iii) models for primary energy supply. Some of the main assumptions for the different sources and technologies are listed in Table A.1

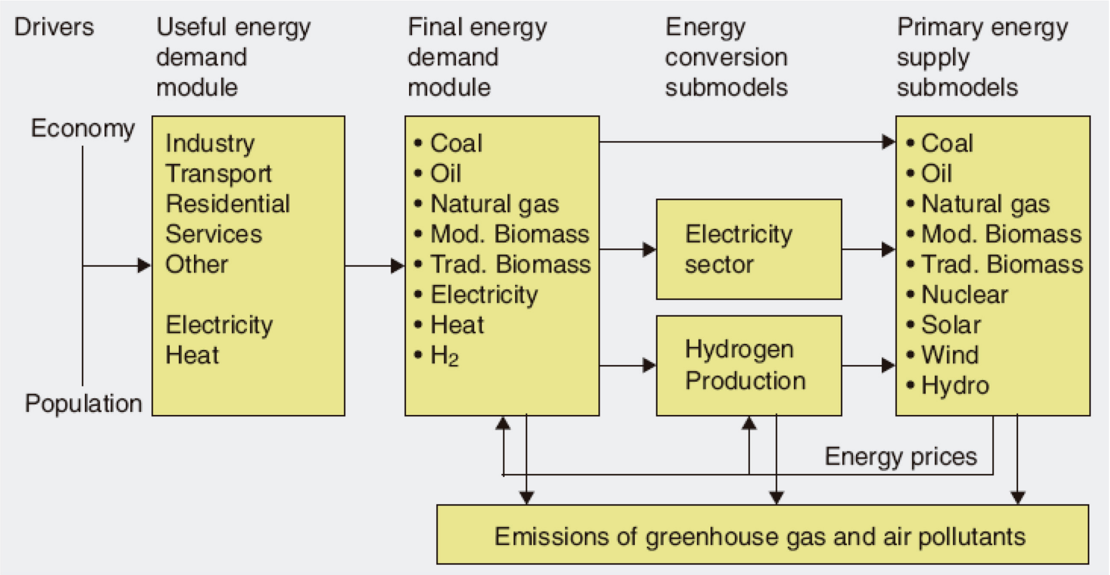
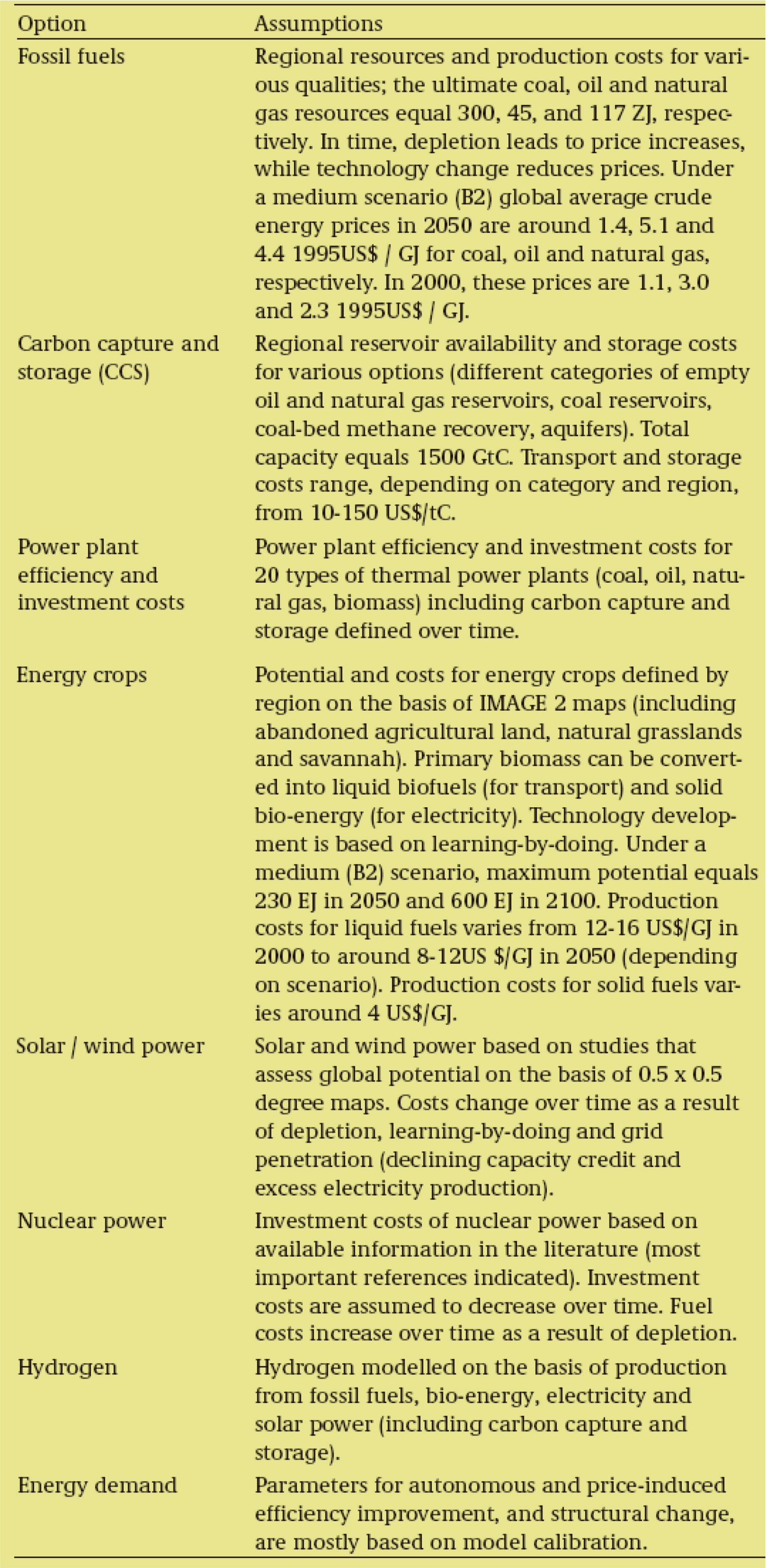


Figure A.1 Schematic representation of the TIMER model

Energy demand submodel
Final energy demand (for five sectors and eight energy carriers) is modelled as a function of changes in population, in economic activity and in energy intensity (Figure A.1). The model distinguishes four dynamic factors: structural change, autonomous energy efficiency improvement, price-induced energy efficiency improvement and price-based fuel substitution, which are discussed below.

Table A.1 Some main assumptions in the TIMER model



Option	Assumptions
Fossil fuels	Regional resources and production costs for various qualities; the ultimate coal, oil and natural gas resources equal 300, 45, and 117 ZJ, respectively. In time, depletion leads to price increases, while technology change reduces prices. Under a medium scenario (B2) global average crude energy prices in 2050 are around 1.4, 5.1 and 4.4 1995US$ / GJ for coal, oil and natural gas, respectively. In 2000, these prices are 1.1, 3.0 and 2.3 1995US$ / GJ.
Carbon capture and storage (CCS)	Regional reservoir availability and storage costs for various options (different categories of empty oil and natural gas reservoirs, coal reservoirs, coal-bed methane recovery, aquifers). Total capacity equals 1500 GtC. Transport and storage costs range, depending on category and region, from 10-150 US$/tC.
Power plant efficiency and investment costs	Power plant efficiency and investment costs for 20 types of thermal power plants (coal, oil, natural gas, biomass) including carbon capture and storage defined over time.
Energy crops	Potential and costs for energy crops defined by region on the basis of IMAGE 2 maps (including abandoned agricultural land, natural grasslands and savannah). Primary biomass can be converted into liquid biofuels (for transport) and solid bio-energy (for electricity). Technology development is based on learning-by-doing. Under a medium (B2) scenario, maximum potential equals 230 EJ in 2050 and 600 EJ in 2100. Production costs for liquid fuels varies from 12-16 US$/GJ in 2000 to around 8-12US $/GJ in 2050 (depending on scenario). Production costs for solid fuels varies around 4 US$/GJ.
Solar / wind power	Solar and wind power based on studies that assess global potential on the basis of 0.5 x 0.5 degree maps. Costs change over time as a result of depletion, learning-by-doing and grid penetration (declining capacity credit and excess electricity production).
Nuclear power	Investment costs of nuclear power based on available information in the literature (most important references indicated). Investment costs are assumed to decrease over time. Fuel costs increase over time as a result of depletion.
Hydrogen	Hydrogen modelled on the basis of production from fossil fuels, bio-energy, electricity and solar power (including carbon capture and storage).
Energy demand	Parameters for autonomous and price-induced efficiency improvement, and structural change, are mostly based on model calibration.

First, demand for useful energy (or energy services) is calculated according to:

$$UE_{R,S,EF} = Pop_R {}^* \ ACTpc_{R,S} {}^* \ SC_{R,S,EF} {}^* \ AEEI_{R,S,EF} {}^* \ PIEEI_{R,S,EF}$$

in which *Pop* represents population, *ACTpc* the sectoral economic activity indicator, *SC* a factor capturing sub-sectoral structural change, *AEEI* the autonomous energy efficiency improvement and *PIEEI* efficiency improvement in response to prices. The indices *R*, *S*, and *EF* indicate region, sector and energy form (heat or electricity), respectively. Both population and economic activity levels are exogenous assumptions to the model.

The energy-intensity development for each sector as a result of sub-sectoral structural change only (i.e. energy units per monetary unit in absence of efficiency improvement) is assumed to be a bell-shaped function of the per capita activity level (i.e. sectoral value added or GDP):

$$SC_{R,S,EF} = UEIbase_{R,S,EF} + 1/(\alpha + \beta {}^* \ DFpc_{R,S} + \gamma {}^* \ DFpc_{R,S}{}^{\delta})$$

in which *UEIbase* indicates a base intensity level, *DFpc* the per capita driving force indicator and α, β, γ and δ calibration parameters. The *SC* formulation can be interpreted as the income elasticity that is included in most energy-economics models (increase in energy demand for an increase in income levels), although the value of income elasticity is far from constant.

The Price-Induced Energy Efficiency Improvement (*PIEEI*), describes the effect of rising energy costs on consumers; this is formulated in TIMER on the basis of a simulated energy conservation cost curve. This multiplier is calculated using a sectoral energy conservation supply cost curve (characterized by a maximum reduction CC_{max} and a steepness parameter *CCS*) and end-use energy costs (*CostUE*).

$$EE_{opt} = CC_{max} - 1 \Big/ \sqrt{CC_{max}^{-2} + CostUE \, {}^* PBT / CCS}$$

Finally, the demand for secondary energy carriers is determined on the basis of the useful energy demand by the relative prices of the energy carriers. For each energy carrier, a final efficiency value (η) is assumed to account for differences between energy carriers in converting final energy into useful energy. This corresponds to:

$$SE_{R,S,EF} = \sum UE_{R,S,EF} {}^* \ \mu_{R,S,EC} / \eta_{R,S,EC}$$

in which *SE* is secondary energy demand, *UE* useful energy demand (see eq. 2.1), μ the market share of each fuel, and η the conversion efficiency from secondary to useful energy.

In simulating the market share of each fuel not only direct production costs are accounted for, but also energy and carbon taxes and so-called premium values. The latter reflect non-price factors determining market shares, such as preferences, environmental policies and strategic considerations. These premium values are determined in the calibration process of the model in simulating correct historic market shares on the basis of simulated price information. The same values are used in scenarios as a way to simulate assumption of societal preferences for clean and/or convenient fuels. The market shares are allocated using multinomial logit functions, which allows for niche markets (Figure A.2). This mechanism is based on the following equation:

$$IMS_i = \frac{\exp(-\lambda \, c_i)}{\sum_j \exp(-\lambda \, c_j)}$$

Where IMS_i is the share of total investments for fuel or production method *I*, c_i the price of production method *I* and λ the logit parameter, which reflects the sensitivity of markets relative to differences in production costs.

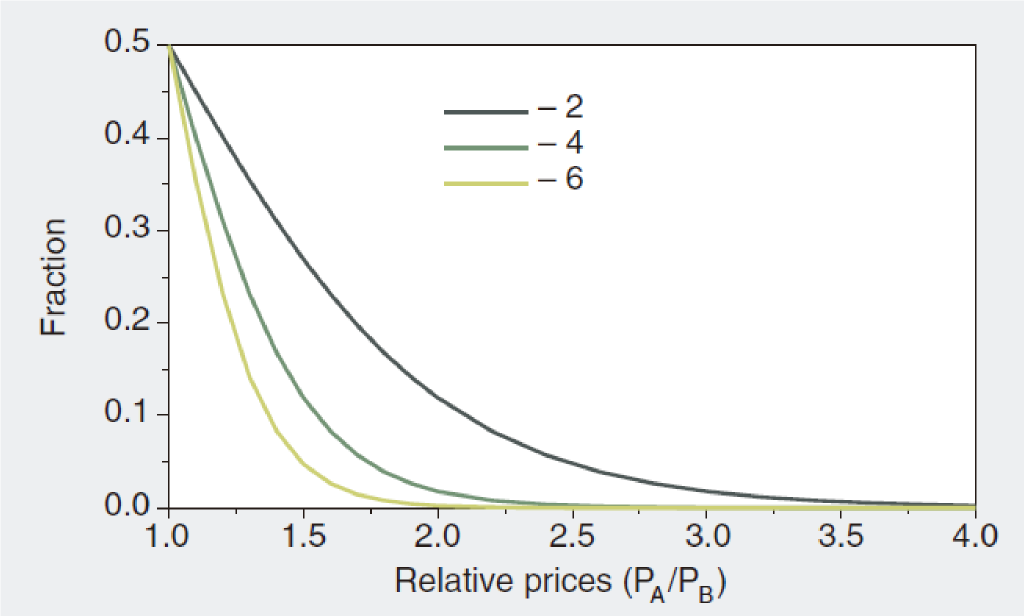


Figure A.2 Substitution of technologies in TIMER: multinomial logit equation. Outcomes for different values of the logit parameter λ, showing the fraction of technology, A, as a function of the price ratio between technology A and B.

Electric power generation submodel

The Electric Power Generation submodel simulates investments in various electricity production technologies and their use in response to electricity demand and to changes in relative generation costs. The demand for capacity is derived from the forecast for the simultaneous maximum demand and a reserve margin of about 10%. The simultaneous maximum demand is calculated on the basis of the gross electricity demand (*ElDem*) that equals the net electricity demand (*SE*(*Elec*)) plus electricity trade (*ElTrade*) and transmission losses (*TransLoss*):

$$ElDem = (SE(Elec) + Eltrade)\ ^{*}\ (1 + TransLoss)$$

The form of the Load Duraction Curve has been determined by region-specific factors such as heating and cooling degree days, daylight and assumed patterns of appliance use. In general, this results in a monthly variation with a maximum value of 20-30% above the average value and a minimum value 40% below.

Different technologies compete for a share in newly installed capacity on their total costs. Different cost categories are specified for each plant: i.e. investment costs, fuel costs, operational and maintenance costs and other costs. The last category may include costs for CO_2 storage and additional costs as a result of the intermittent character of solar and wind power (additional capacity, discarded electricity and additional spinning reserve requirements). The demand for new capacity equals the required capacity minus existing capacity, plus capacity that is going to be replaced (lifetime of plants varies from 30 to 50 years). Notably, an exception is made for hydropower. The capacity for hydropower is exogenously described, given the fact that here often other considerations than electricity production play a role.

The basic rule-of-thumb for the operational strategy is that power plants are operated in order of operational costs (merit order strategy). This implies that capital-intensive plants with low operational costs, such as for renewables and nuclear energy, will therefore in principle operate as many hours as possible. To some degree this is also implied for other plants with low operational costs (e.g. coal). In TIMER, the merit order strategy is simulated in three steps:

1. first intermittent renewable sources are assigned, followed by hydropower;

2. in the next step base load is assigned on the basis of the remaining capacity, using a multinomial logit model;
3. finally, peak load is assigned, again using a multinomial logit model.

For renewable energy sources with an intermittent character (wind and solar power), additional costs are determined for discarded electricity (if production exceeds demand), back-up capacity, additional required spinning reserve (both to avoid loss of power if supply of wind and solar power suddenly drops; spinning reserve is formed by power stations operating below maximum capacity, which can be scaled up in relatively little time) and depletion.

Models for primary energy supply
Production of all primary energy carriers is based on the interplay between resource depletion and technology development. Technology development is introduced either as learning curves (for most fuels and renewable options) or by exogenous technology change assumptions (for thermal power plants).

TIMER includes three fossil-fuel production sub-models for respectively solid, liquid and gaseous fuels. For each region these sub-models calculate the demand for secondary energy carriers, electricity generation, international transport (bunkers) and the demand for non-energy use and feedstocks. The calculated fuel demand accounts for losses (e.g. refining and conversion) and energy use within the energy system. In a next step, demand is confronted with possible supply, both within the region and in other regions by means of the international trade model.

Using TIMER in combination with FAIR
Figure A.3 shows how IMAGE, TIMER and FAIR are linked with each other. FAIR not only adds information on climate policy but also a relatively simple framework that allows for costs optimization of reduction of energy-related GHG emissions (as described in TIMER) against other forms of emissions.

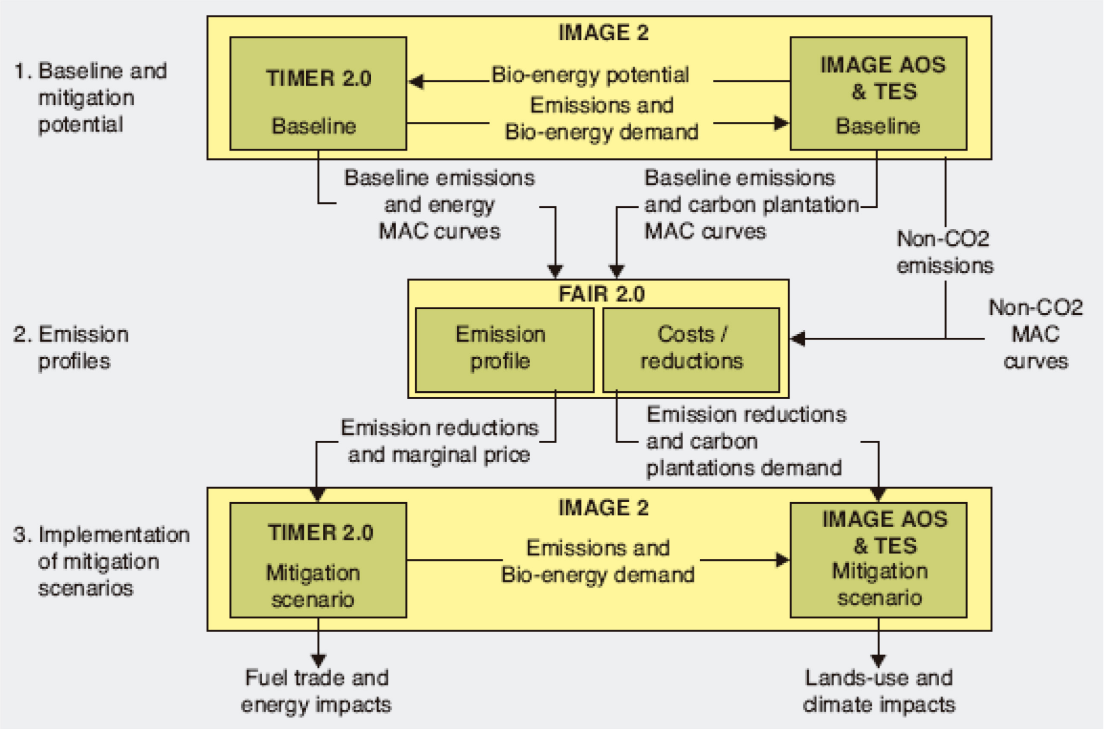


Figure A.3 FAIR within the IMAGE integrated assessment modelling framework

The scheme in which TIMER, and the rest of IMAGE and FAIR are often applied consists of three steps (Figure A.3):

1. a baseline emission scenario is constructed using the full IMAGE model, including TIMER. The terrestrial submodels of IMAGE and TIMER are also used to provide information on abatement through carbon plantation and measures in the energy system, respectively;
2. global emission pathways are developed using the FAIR model ; this leads to a stabilization of the atmospheric GHG concentration. The FAIR model distributes the global emission reduction across the different regions, gases and sources in a cost-optimal way, using the information on marginal abatement costs derived in step (1);
3. finally, the emission reductions and permit price determined in the previous step were implemented in the IMAGE/TIMER model to develop the final mitigation scenario (emissions, land use and energy system).

To estimate consumption losses of the direct abatement costs, a simple economic growth model based on a Cobb-Douglas production function is used. This approach has been commonly used for similar purposes in Integrated Assessment Modelling (Messner and Schrattenholzer, 2000; Nordhaus, 2008). The equations used are:

$$Y_t = AK_t^{\alpha} L_t^{1-\alpha}$$

where *Y* stands for GDP, *A* for technological progress, *K* for capital, *L* for labour, and α is the capital elasticity of production. *K* is equal to the capital stock of last year minus depreciation (η) plus investment (*I*):

$$K_{t+1} = K_t - \eta K_t + I_t$$

GDP can be used for consumption (*C*), investment (*I*), to pay for abatement cost (*EC*), or to pay for damage costs (*D*):

$$Y_t = C_t + I_t + EC_t + D_t$$

The parameterisation of these equations is as follows. We assumed that trends in labour follow from those in global population. Population estimates are taken from the long-term UN population projections (medium for B2 and low for A1). The initial capital stock in 2005 was set at USD 100 trillion, based on the IIASA growth study datasets (Miketa, 2004). The capital elasticity of production (α) indicates the importance of capital in the production function. In the DICE-2007 model, a value of 0.3 is used (Nordhaus, 2008). Other literature suggest higher values of around 0.5 (Richmond et al., 2007) or a somewhat lower value of 0.25 (Fankhauser and Tol, 2005). In FAIR, a value of 0.3 is used. The development of A was chosen in such a way that the GDP level corresponds with the exogenously calibrated baseline income development.

In the capital accumulation function, depreciation is set at 5% per year. Nordhaus' DICE-2007 model uses a depreciation rate of 10% per year, whereas the MERGE 5.1 model uses 40% per decade (3.4% annually). A 5% per year depreciation rate lies in between these values (runs with other savings rates show that the outcomes are not sensitive to the level of depreciation). For the sake of simplicity, we assumed that the savings rate (s) is constant over time at 21%. In comparison, the savings rate in Nordhaus' DICE-2007 model varies between 20% and 22% during the period 2005-2245.

The final equation states that damage and abatement costs reduce both consumption and investment. For abatement costs, we adopted the same methodology as used in the DICE-

2007 model. This means that the savings rate determines by how much abatement costs replace investment.

WorldScan

WorldScan is multi-region, multi-sector, recursively dynamic computable general equilibrium model with worldwide coverage. A detailed description of the model is given in Lejour et al. (2006). The model has been used for various kinds of analyses, in particular with respect to climate change policies (e.g. Boeters and Koornneef, 2011; Bollen et al., 2012; Hayden et al., 2010; Manders and Veenendaal, 2008). Bollen and Brink (2012) extended WorldScan to also include emissions of non-CO_2 GHGs and the possibility to invest in emission control by modeling abatement supply curves (i.e. marginal abatement cost curves) for emissions in each sector. These abatement supply curves represent the potential and cost of technical abatement measures. These are mainly 'end-of-pipe' abatement options, removing emissions largely without affecting the emission-producing activity itself.

WorldScan data for the baseyear calibration are to a large extent taken from the GTAP-7 database (Narayanan and Walmsley, 2008) that provides integrated data on bilateral trade flows and input-output accounts for 57 sectors and 113 countries. The aggregation of regions and sectors can be flexibly adjusted in WorldScan. The version used here features 25 regions (largely similar to the regions in TIMER) and 13 sectors, listed in Table A.2. Moreover, the electricity sector is split-up in 5 technologies: (i) fossil electricity with coal, oil and natural gas as imperfectly substitutable inputs, (ii) wind (onshore and offshore) and solar energy, (iii) biomass, (iv) nuclear energy, and (v) conventional hydropower (see Boeters and Koornneef, 2011). As part of the comparison between TIMER and WorldScan, the supply curves for wind energy and biomass were calibrated on the data on cost and potential of these technologies in TIMER. Moreover, the option of carbon capture and storage was included as an end-of-pipe option for mitigation of CO_2 emissions from power plants, using region specific data on CCS cost and potential in TIMER.

Table A.2 Production sectors and consumption categories in WorldScan

Production sectors	*Consumption categories*
Agriculture - crop products (incl. fishing)	Food
Agriculture - animal products	Beverages and tobacco
Minerals and mineral products	Clothing and furniture
Oil	Gross rent and fuel
Coal	Other household outlays
Petroleum and coal products	Education and medical care
Natural gas (incl. gas distribution)	Transport and communication
Electricity	Recreation
Consumer products	Other goods and services consumed
Energy intensive industry	
Capital goods and durables	
Transport	
Other services	

WorldScan is set up to simulate deviations from a "Business-As-Usual" (BAU) path by imposing specific additional policy measures such as taxes or restrictions on emissions. The BAU used here is calibrated on the time series for population and GDP by region, energy use by region and energy carrier, and world fossil fuel prices by energy carrier as assumed in the baseline of the OECD Environmental Outlook 2012 (OECD, 2012), which is also used in the TIMER simulations.

In WorldScan, environmental policies are simulated by the introduction of a price on emissions (Lejour et al., 2006). This emission price makes polluting activities more expensive and hence provides an incentive to reduce these emissions. For emissions directly related to the use of a specific input, such as fossil fuels, the emission price will in fact cause a rise in the user price of this input. Consequently, this will lead to a fall in the demand for this input (either by using less energy or by substituting more carbon emitting fuels for less emitting ones) and hence a reduction in emissions. As a result of these changes the production cost increases. For emissions related to sector output levels, the emission price will cause a rise in the output price of the associated product. The increase in the output price will lead to a fall in demand for this product (as consumers substitute goods that become more expensive by goods that have no price increase) and hence emissions will reduce. Moreover, if emission control options are available, these will be implemented up to the level where the marginal cost of emission control equals the emission price.

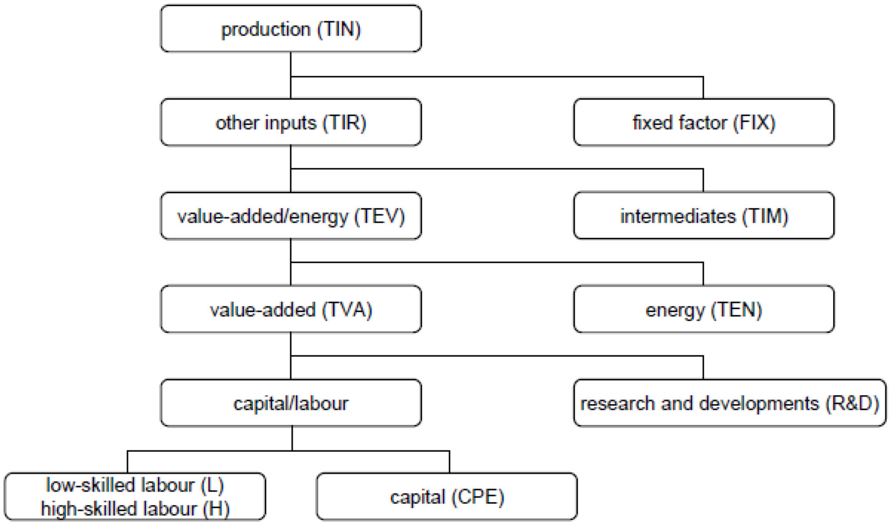
The production function

The production technology is represented by a production function which relates output to factor inputs and intermediate inputs. The main factor inputs are high- and low-skilled labour, and capital. Intermediate inputs are goods, services and energy. The inputs are to some extent substitutable. The relevance of each of these inputs for production and their substitutability is represented in the production function.

The production technology is modelled as a nested structure of constant elasticities of substitution (CES) functions. As in nearly all computable general equilibrium (CGE) models we assume the same production structure for all sectors and regions. The values of the substitution parameters reflect the substitution possibilities between inputs. These values may differ across sectors reflecting the different substitution possibilities of (factor) inputs within the producing sectors. Figure A.4 illustrates the nesting structure.

The production function can be expressed by equation (A.1) for the nesting at the top level. At the top level, an aggregate of all variable inputs q_{TIR} is combined with a fixed factor q_{FIX} to generate output q_{TIN}. The nests at the lower levels are analogously defined.

Figure A.4 Production structure of WorldScan



$$\begin{aligned} q_{TIN} &= CES\left(q_{TIR}, q_{FIX}; \rho_{TIN}\right) \\ &= \left(\alpha_{TIR}^{1-\rho_{TIN}} q_{TIR}^{\rho_{TIN}} + \alpha_{FIX}^{1-\rho_{TIN}} q_{FIX}^{\rho_{TIN}}\right)^{\frac{1}{\rho_{TIN}}} \quad 0 < \rho_{TIN} < \infty \end{aligned} \tag{A.1}$$

Consumption

In WorldScan, consumers save a fixed fraction of the level of their earned income. The income available for consumption is allocated to purchasing consumer goods and services. This is modeled as a Linear Expenditure System (LES) with consumers maximizing utility they derive from the consumption of goods and services, subject to a budget restriction and taking into account subsistence levels, i.e. the minimal quantity of consumption good *j* necessary to survive (see Lejour et al., 2006).

$$\max \qquad U_c\left(c_{c,1},\ldots,c_{c,n}\right) = B\prod_{j=1}^{n}\left(c_{c,j} - \gamma_{c,j}\right)^{\alpha_j}$$

$$\text{subject to} \qquad \sum_{j=1}^{n} p_{c,j} c_{c,j} = Y_c$$

with $c_{c,j}$ the demand for consumption category *j* by consumer *c*, p_j^c the corresponding price and C_c the total consumption budget of consumer *c*. Parameter $\gamma_{c,j}$ reflects the minimal quantity of consumption good *j* necessary to survive.

Welfare analysis

Welfare analysis concerns the evaluation of the effects of changes in the consumer's environment on his/her well-being. The most natural measure for evaluating welfare changes would be utility. As utility is, however, an ordinal concept, the magnitude of changes in utility is meaningless. Therefore, in economic analyses the concept of (Hicksian) equivalent variation (EV) is used to provide a cardinal welfare measure. The EV is defined as the amount of money by which the income of a household in the baseline situation *B* should change to attain the utility level of an alternative situation *V* in which prices have changed, e.g. due to policy measures:

$$EV\left(p^0, p^1, Y\right) = e\left(p^B, U^V\right) - e\left(p^B, U^B\right)$$

with $e(p^B,U)$ the expenditure necessary to attain utility level *U* at baseline prices p^B (which is price vector $\left(p_1^B,\ldots,p_n^B\right)$ for baseline prices of consumption goods and services). Obviously, not only changing prices but also changes in income will affect the utility level and hence welfare. Therefore, this welfare measure is related to other indicators that are often used, such as change in real GDP (i.e. at constant prices, providing insight into the change in overall economic activity), real consumption (i.e. at constant prices, providing insight into the quantity of goods and services consumed) and national income. However, Krupnick and McLaughlin (2011) conclude that "no macroeconomic metric is very closely correlated with, or provides very similar policy rankings to, welfare costs." The reason is that relative prices change and all kinds of indirect effects may occur. For example, a region's terms-of-trade[5] may improve, which causes welfare to increase while at the same time GDP might decrease as a result of reduced domestic demand. Moreover, pre-existing energy taxes may cause the introduction of a CO_2-tax to have additional welfare losses (see, e.g., Paltsev et al., 2007).

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[5] A region's terms-of-trade are determined by the prices received for its export compared to the prices paid for its imports.