2. TIMER MODEL DESCRIPTION

Abstract. The TIMER model describes long-term development pathways in the energy system in the broader context of impacts on climate change, air pollution and sustainable development. TIMER is integrated into the integrated assessment modeling framework IMAGE via energy-related emissions of greenhouse gases and air pollutants, the use of bio-energy, and the role of the energy system in mitigation scenarios. In dynamic terms, the models describe the evolution of a set of energy technologies in different energy markets (most notably five end use sectors, electric power, hydrogen production) that compete for market shares on the basis of their relative costs and preferences. In time the costs of these technologies are driven by both technology development and depletion dynamics. The coupled TIMER-IMAGE-FAIR framework can be used to study different mitigation scenarios.

This chapter is based on: Van Vuuren, D.P, van Ruijven, B., Hoogwijk, M., Isaac, M., de Vries, B. (2006). TIMER 2.0: Model description and Application. In: Bouwman, L., Kram T. and Klein-Goldewijk, K. (2006). IMAGE 2.4: An overview, Netherlands Environmental Assessment Agency, Bilthoven.

2.1 Introduction

Energy forms a central component of discussions on sustainable development. The use of energy supports economic development; furthermore, securing affordable energy supply is an important element in the economic and energy policies of many countries. Fossil fuel resources, which currently account for more than three-quarters of the world energy use, are slowly being depleted. Especially oil and gas resources are becoming more and more concentrated in a limited number of supply regions. At the same time, renewable energy sources have limitations too. Secondly, fuel combustion is the single most important cause of both air pollution and greenhouse gas emissions. The future of global energy use is highly uncertain and depends on such uncertain factors as technological innovation and breakthroughs, as well as socio-economic development, resource availability and societal choices. Exploring different scenarios for the future energy system can thus provide crucial information to decision-makers.

The IMage Energy Regional model (TIMER) is an energy model that has been developed to explore different scenarios for the energy system in the broader context of the IMAGE environmental assessment framework (Integrated Model to Assess the Global Environment) (Alcamo et al., 1996, Bouwman et al., 2006). 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 analyze 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 greenhouse gas 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. As such, it can be compared to other energy system simulation models such as POLES (Criqui and Kouvaritakis, 2000). A description of the different types of energy models, and the position of the TIMER model within this field, can be found in Chapter 1 of this thesis.

The TIMER model was originally developed as a one-world model (TIME) for the TARGETS sustainable development model (Rotmans and de Vries, 1997). Between 1997 and 2000, a model version with 17 world regions was developed (TIMER 1.0) (de Vries et al., 2001). The TIMER 1.0 model was applied, amongst others, for the development of some of the IPCC SRES scenarios (de Vries et al., 2000), exploration of climate policies (van Vuuren and de Vries, 2001; Van Vuuren et al., 2003b), country-level scenario assessment and, together with IMAGE, global environmental scenario studies (UNEP, 2002; Carpenter and Pingali, 2006). The TIMER 1.0 model is used in Chapters 4, 8 and 9 of this thesis.

More recently, improved modeling of renewable energy sources, revision of the electricity model and the development of a hydrogen sub-model has led to the TIMER 2.0 model[i]. This model version was used to explore different stabilization strategies, as discussed in Chapter 7 of this thesis. The model is also used in the uncertainty analysis described in Chapter 5. While some interesting elements have been added to the model, the differences between TIMER 1.0 and TIMER 2.0 are not relevant for the main conclusions of the chapters where TIMER 1.0 has been applied.

In this chapter we present an overview of the TIMER model, including the most recent developments. Full documentation on the TIMER 1.0 model is available (de Vries et al., 2001). Section 2.2 overviews the model and discusses the sub-models on energy demand, conversion and supply. Section 2.3 discusses some crucial model elements, including technology development, and depletion and substitution. Section 2.4 indicates how the TIMER model can be used in combination with FAIR and IMAGE.

2.2 Model Outline and 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 2.1). 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 2.1.

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[i] Even more recently, the TIMER 2.0 model has been recalibrated for 26 regions.

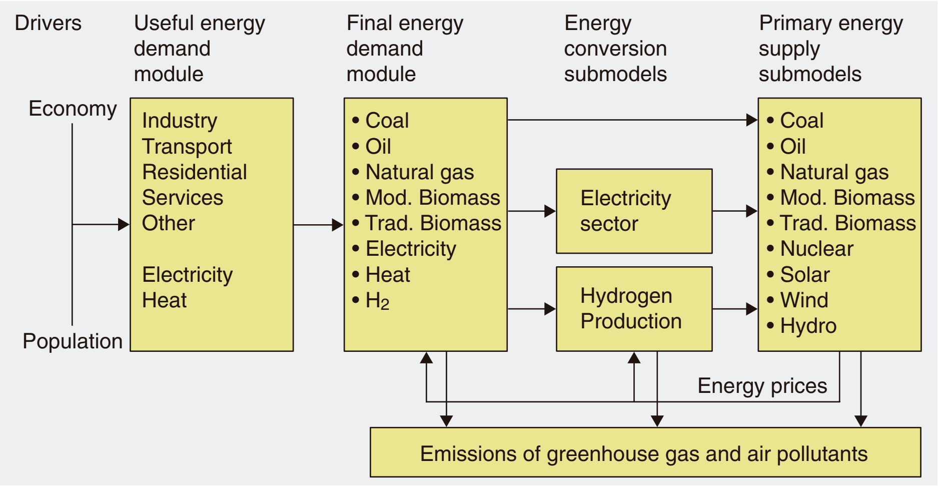

Figure 2.1 Overview of the TIMER model.

2.2.1 The 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 2.2). 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.

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

$$UE_{R,S,EF} = Pop_R{}^{*}\ ACTpc_{R,S}{}^{*}\ SC_{R,S,EF}{}^{*}\ AEEI_{R,S,EF}{}^{*}\ PIEEI_{R,S,EF} \tag{2.1}$$

in which Pop represents population, ACT pc the sectoral economic activity indicator (see Table 2.2), 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) (see equation 2.2):

$$SC_{R,S,EF} = UEIbase_{R,S,EF} + 1/(\alpha + \beta^{*}\ DFpc_{R,S} + \gamma^{*}\ DFpc_{R,S}{}^{\delta}) \tag{2.2}$$

in which UEIbase indicates a base intensity level, DFpc the per capita driving force indicator (see Table 2.2) and α, β, γ and δ calibration parameters. The SC formulation can be

Table 2.1 Some main assumptions in the TIMER model

Option	Assumptions	References
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.	Rogner (1997), TNO (2006)
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$/tC.	Hendriks et al. (2002a)
Power plant efficiency and investment costs	Power plant efficiency and investment costs for 20 types of thermal power plants (coal, oil, natural gas, biomass) including carbon capture and storage defined over time.	Hendriks et al. (2004)
Energy crops	Potential and costs for energy crops defined by region on the basis of IMAGE 2 maps (including abandoned agricultural land, natural grasslands and savannah). Primary biomass can be converted into liquid biofuels (for transport) and solid bio-energy (for electricity). Technology development is based on learning-by-doing. Under a medium (B2) scenario, maximum potential equals 230 EJ in 2050 and 600 EJ in 2100. Production costs for liquid fuels varies from 12-16 US$/GJ in 2000 to around 8-12US $/GJ in 2050 (depending on scenario). Production costs for solid fuels varies around 4 US$/GJ.	Hoogwijk (2004)
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).	Hoogwijk (2004)
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.	MIT (2003); Sims et al. (2003)
Hydrogen	Hydrogen modelled on the basis of production from fossil fuels, bio-energy, electricity and solar power (including carbon capture and storage).	Van Ruijven et al. (in press)
Energy demand	Parameters for autonomous and price-induced efficiency improvement, and structural change, are mostly based on model calibration.	De Vries et al. (2001)

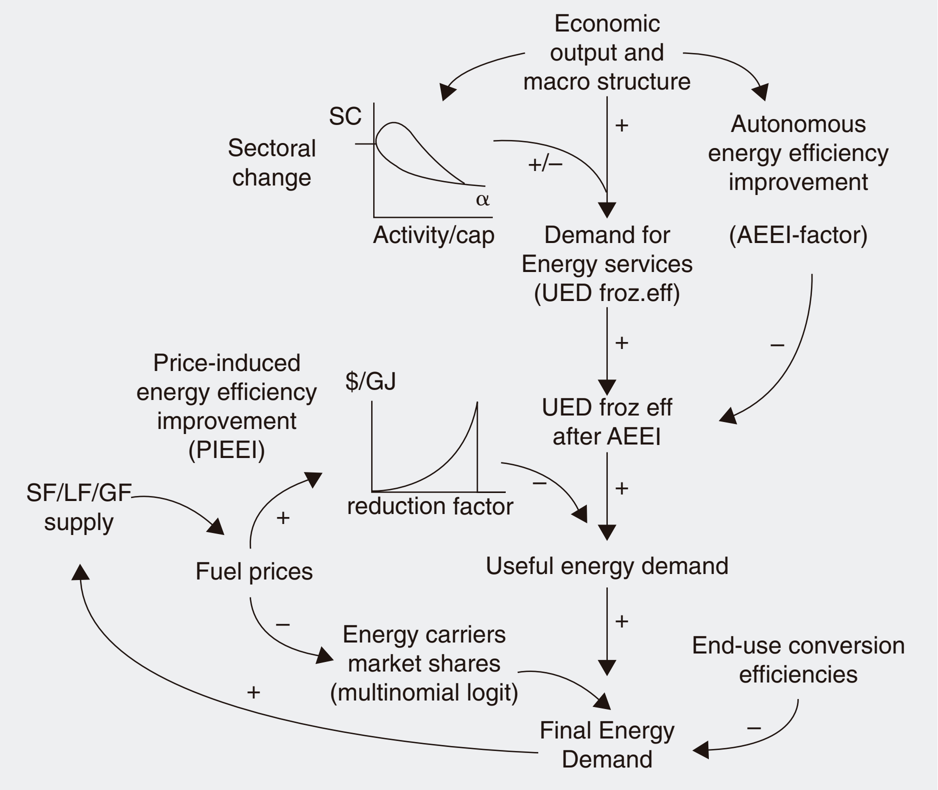

Figure 2.2 System dynamics representation of the Energy Demand submodel. UED is Useful Energy Demand, i.e. the energy services delivered; SF/LF/GF indicate Solid Fuel, Liquid Fuel and Gaseous Fuel respectively (+/- signs indicate positive/ negative coupling between parameters).

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 in equation 2.2 is far from constant.

The form of this equation is indicated on the left-hand side of Figure 2.3, while the right-hand side indicates the resulting trajectory for per capita energy use. The form reflects an empirical observation that a changing mix of activities with rising activity within a sector could first lead to an increase and then to a decrease in energy intensity (structural change). Evidence of this trend is more convincing in some sectors (e.g. industry) than in others (e.g. transport) (de Vries et al., 2001). The assumed formulation assumes saturation at a constant per capita useful energy use per sector – although the choice of parameters can actually imply that this occurs at activity levels that are unlikely to be reached during the scenario period. In any case, the actual shape of this function (defined by sector and region) has a large influence on the demand for energy services in the model. The activity indicator and the assumed drivers of structural change trends are indicated in Table 2.2.

Table 2.2 Sectors, activity indicators and driving forces of structural change, where the economic activity levels (activity and driving force) are both exogenous assumptions to the model

	Activity	Driving force	Intensification	Extensification	Heat/power
Industry	Industry VA pc	GDP pc	Growth of heavy industry	Shifts to high value-added industries	Eq. 2.2 for total demand; % electricity set externally
Transport	GDP pc	GDP pc	Rapid growth of freight and person transport	Saturation of transport	Eq. 2.2 for total demand; % electricity set externally
Residential	Priv. Cons pc	Priv. Cons pc	Rapid increase in heating/cooling demand + appliance use	Saturation	Eq. 2.2 applied to heat and power separately
Services	Service VA pc	Service VA pc	Rapid increase in heating/cooling demand + appliance use	Shifts to high value-added sectors	Eq. 2.2 applied to heat and power separately
Other	GDP pc	GDP pc	Intensification of energy use in agriculture	Saturation of agriculture energy demand	Eq. 2.2 for total demand; % electricity set externally

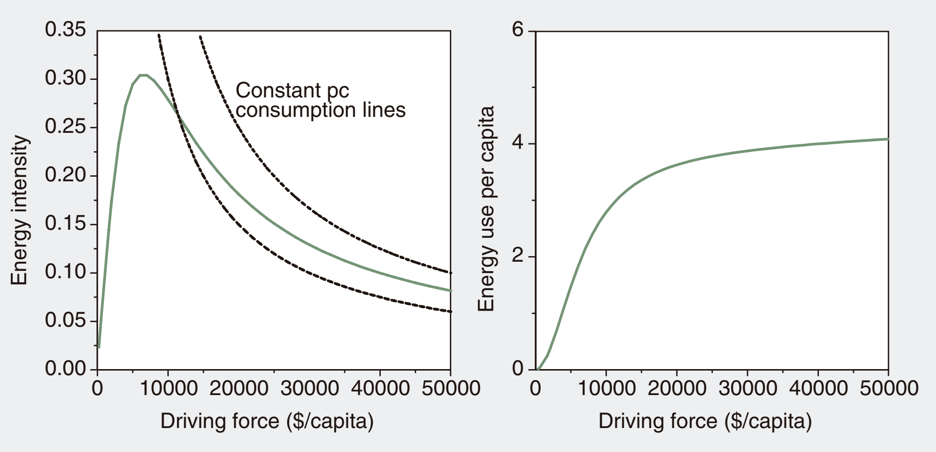

Figure 2.3 Assumed trend in energy intensity per sector (in GJ/$, either sectoral value-added, private consumption or GDP) as a result of structural change (SC) (left) and the corresponding energy use per capita (GJ/cap).

The Autonomous Energy Efficiency Increase (AEEI) multiplier accounts for efficiency improvement that occurs as a result of technology improvement independent of prices (equation 2.3).

$$AEEI(mrg)_{R,S,EF} = f * ACT_{R,S} / ACT_{R,S,t-1} \qquad (2.3)$$

The marginal AEEI, AEEI(mrg), is assumed to be a fraction (f) of the economic growth rate based on the formulation of Richels et al.(2004). The fraction in TIMER varies between 0.45-0.30 and is assumed to decline in time, as the scope for further improvement is assumed to decline (in a similar way, as included in learning curves, see Section 2.3). The marginal AEEI is implemented with the capital turnover rate assuming a vintage model. The current AEEI thus represents the weighted average (by investment rate) of the marginal AEEI over the capital lifetime. In other words, rapid economic growth leads to a more rapid decline in AEEI, both via a rapid decline in the marginal AEEI and via a larger share of the total capital stock that is relatively new. While, the existence of AEEI is somewhat controversial in economics literature, the AEEI is, from an engineering perspective, a logical representation of technological progress and, as such, a specific implementation of the total factor productivity improvement included in most economic models.

A next multiplier, 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 (Figure 2.4 and equation 2.4). 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).

$$EE_{opt} = CC_{\max} - 1 \Big/ \sqrt{CC_{\max}^{-2} + CostUE * PBT / CCS} \tag{2.4}$$

The calibration of this curve is described by De Vries et al. (2001). The basis is the assumption that investments into energy efficiency are made if they are equal or less than to the product of an apparent pay-back time and the current energy prices. The pay-back time formulation (a simplified investment criterion) states that all the investments made earn back the original investment within a given time period. The term “apparent” refers to the observation that while investors in energy efficiency indicate use of a certain pay-back time in their investment decision, in reality, lack of information (or other barriers) imply that not all investments meeting the pay-back criterion are made. Investments into efficiency lead to improvements in efficiency according to the sectoral energy conservation curve (see Figure 2.4). The whole curve slowly decreases over time as a result of technology improvement as a result of economies of scale and innovation lowering CCS (learning-by-doing; see 2.3). The improvement of the PIEEI factor is directly related to EE_{opt}, but includes some delay: it includes partly a direct response (equal to EE_{opt}) and partly to a delayed response via a vintage model. The PIEEI factor corresponds to the short- and long-term price elasticity in economic models. In TIMER different efficient levels between regions can be created by using different pay-back times. The pay-back times implied in developed nations vary from 1 year for transport, 2 years for other sectors and 3 years for industry (these values are low, given the fact they are apparent pay-back times). In modelling response to carbon prices, however, a pay-back time of 6 years is used to identify efficiency improvement responses that can be regarded as cost-effective compared to supply-side investments.

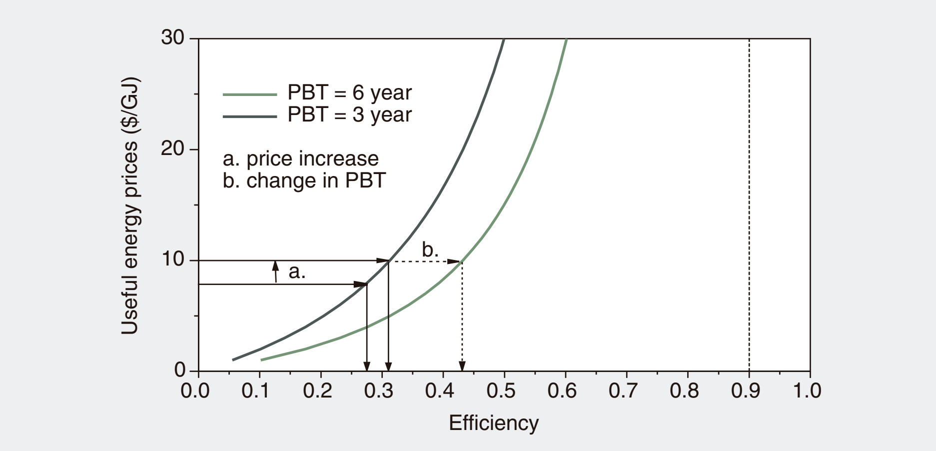

Figure 2.4 Assumed formulation for price-induced efficiency improvement (in other words, the conservation supply cost curve).

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 (see Figure 2.2). 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 equation 2.5:

$$SE_{R,S,EF} = \sum UE_{R,S,EF} * \mu_{R,S,EC} / \eta_{R,S,EC} \qquad (2.5)$$

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 (using a multinomial logit equation; see section 2.3) not only are direct production costs 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.

In TIMER, alternative approaches are used for traditional biomass and secondary heat. The market share of traditional biomass is assumed to be driven by per capita income, where a higher per capita income leads to lower per capita consumption of traditional biomass. The market share of secondary heat from, for instance, district heating is determined though an exogenous scenario parameter. Non-energy use of fossil fuels is modelled on the basis of an exogenously assumed intensity parameter (related to industry value-added) and on a price-driven competition of the various energy carriers.

Box 2.1 Ambiguity in model calibration

The behaviour of an energy model depends both on its structure and its parameter settings., Even under a given (simple) structure, different parameter settings for very uncertain factors may still lead to very different results, as is shown for learning in Section 2.3. At the same time, lack of historic information often allows for ultiple interpretations (and this parameter settings of the past).

2.2.2 The Electric Power Generation submodel

The Electric Power Generation submodel (Figure 2.5) simulates investments in various electricity production technologies and their use in response to electricity demand and to changes in relative generation costs (see also Hoogwijk, 2004).

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).

$$ElDem = (SE(Elec) + Eltrade) * (1 + TransLoss) \qquad (2.6)$$

The model determines a monthly load duration curve for each region by multiplying the electricity demand by the relative demand of 10 fraction of electricity ($Frac_{M,T}$). These together describe the load duration curve (LDC). 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. The SMD equals the highest value found each year (the annual pattern is indicated in Figure 2.6).

$$SMD = Max(ElDem * Frac_{M,T}) \qquad (2.7)$$

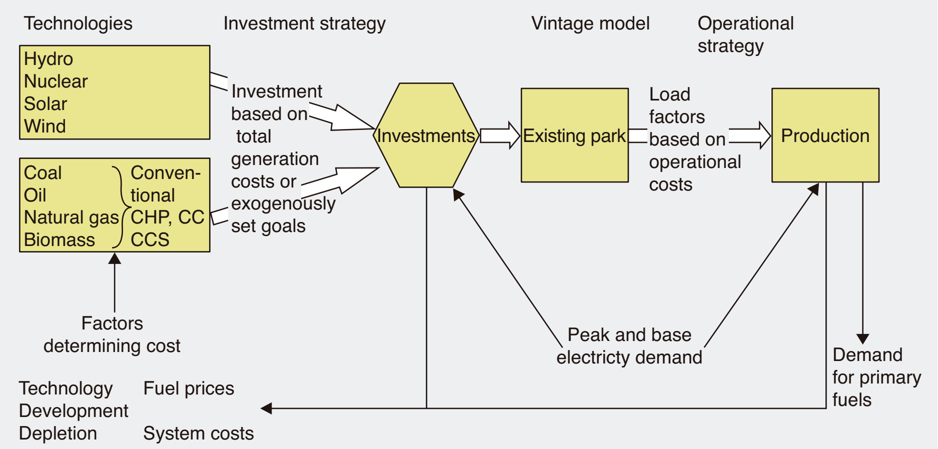

Figure 2.5 Schematic presentation of the Electric Power Generation model.

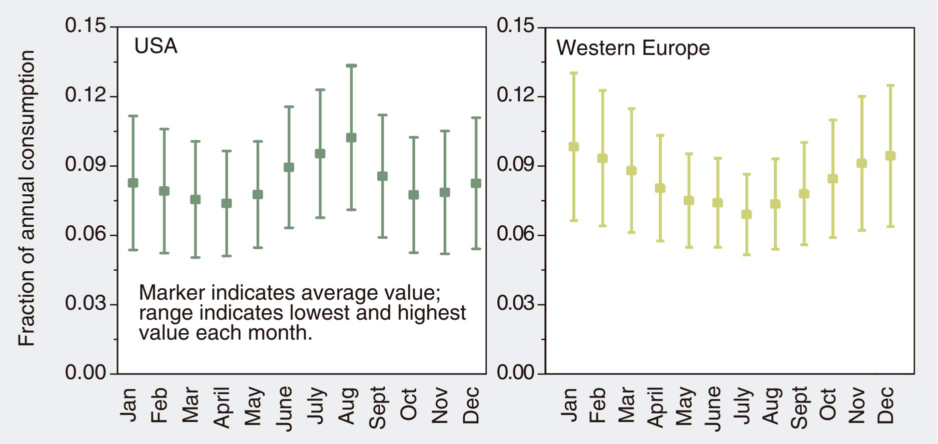

Figure 2.6 Annual pattern of electricity demand shown for two regions.

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 (see section 2.3);
3. finally, peak load is assigned, again using a multinomial logit model.

We realize that in reality, the merit order strategy is more complex, given all kinds additional requirements with respect to reliability and start-up times.

Fossil fuels and bio-energy can be used to generate electricity in a total of 20 different plant types that represent different combinations of (i) conventional technology; (ii) gasification and combined cycle technology; (iii) combined-heat-and-power and, (iv) carbon-capture and storage (see also Hendriks et al., 2004). The efficiency and capital requirement of these plant types are determined by exogenous assumptions that describe technological progress of typical component of these plants (the characteristics of the total set are derived from these typical components).

- For conventional plants, the coal-based plant is defined in terms of overall efficiency and investment costs into fuel handling, plant and fuel gas cleaning and operational costs. All other conventional plants (oil, natural gas and bio-energy) are derived by indicating differences for investments for a) desulphurization, b) fuel handling and c) efficiency.
- For Combined Cycle plants, the natural gas combined cycle plant is set as standard. Other plants are defined by indicating additional capital costs for gasification, efficiency losses for gasification and O&M costs for fuel handling.
- Carbon capture and storage plants are assumed to be Combined Cycle plants with correction (as a function of the carbon content of the fuel) for efficiency, investment costs, O&M costs (for capture) and storage costs.
- CHP plants can be based on Combined Cycle plants or conventional plants (the model selects the lowest costs option). In both cases a small increase in capital costs is assumed in combination with a lower efficiency for electric conversion and an added factor for heat efficiency (in other words, the model only includes large-scale CHP).

Table 2.3 provides, as illustration, some of the key parameters for the electric power technologies in Europe (B2 scenario).Apart from thermal plants, the model distinguishes hydropower, solar power, wind power and nuclear power. The costs of technologies are described in terms of learning and depletion dynamics.

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 (see also Hoogwijk, 2004).

- To determine discarded electricity for each load fraction a comparison is made between supply and demand. It is assumed that wind power can be either fully in-phase or fully out-of-phase with electricity demand: both situations are calculated and the average is used. For PV, it is assumed that supply mainly occurs during the central part of the LDC. If supply exceeds demand, this is assumed to be discarded, reducing the effective load factor of wind and solar electricity (and thus increasing their costs).
- Back-up capacity is added to account for the low capacity credit (its contribution to a reliable supply of electricity at any moment of time) of the intermittent sources (Figure 2.7). For the first 5% penetration of the intermittent capacity, the capacity credit equals the load factor of the wind turbines. If the penetration of intermittent sources increases further, the capacity credit decreases. The costs of back-up power (capacity with a high capacity credit but low capital costs) are allocated to the intermittent source.

Table 2.3 Power plants in the TIMER model and some assumed key characteristics (Western Europe, central scenario)

	Capital costs.		Electric Efficiency		OM costs	
	$/MW		%		$/kWh	
	2000	2050	2000	2050	2000	2050
PV	6102	1809	-	-	$ 0.015	$ 0.015
Wind	1377	555	-	-	$ 0.009	$ 0.010
Hydro	1355	1427	-	-	$ 0.017	$ 0.017
Nuclear	2319	2161	-	-	$ 0.008	$ 0.008
Coal (steam-electric)	1280	1113	41%	52%	$ 0.007	$ 0.005
Oil (steam-electric)	1138	1014	42%	53%	$ 0.006	$ 0.004
NG (steam-electric)	900	867	43%	54%	$ 0.004	$ 0.003
Biomass (steam-electric)	1469	1182	39%	51%	$ 0.006	$ 0.005
Coal (IGCC)	1696	1057	44%	54%	$ 0.010	$ 0.007
Oil (IG CC)	1696	1057	44%	54%	$ 0.010	$ 0.007
NG (CC)	716	562	54%	62%	$ 0.003	$ 0.002
Biomass (BIGCC)	3079	1145	42%	52%	$ 0.010	$ 0.007
Coal (CCS)	2180	1330	33%	46%	$ 0.012	$ 0.009
Oil (CCS)	2029	1245	33%	46%	$ 0.011	$ 0.008
NG (CCS)	1052	750	45%	55%	$ 0.005	$ 0.003
Biomass (CCS)	3612	1447	31%	44%	$ 0.014	$ 0.010
Coal (CHP)	1356	1170	34%	47%	$ 0.007	$ 0.008
Oil (CHP)	1259	1107	34%	45%	$ 0.006	$ 0.005
NG (CHP)	822	666	46%	53%	$ 0.003	$ 0.002
Biomass (CHP)	1524	1220	32%	45%	$ 0.007	$ 0.008
Coal (CHP/CCS)	2280	1430	27%	39%	$ 0.012	$ 0.009
Oil (CHP/CCS)	2129	1345	27%	38%	$ 0.011	$ 0.008
NG (CHP/CCS)	1152	850	37%	46%	$ 0.005	$ 0.003
Biomass (CHP/CCS)	3712	1547	25%	37%	$ 0.014	$ 0.010

Note: The use of CHP plants depends on exogenously subscribed heat demand. Progress for all these plants is determined by exogenous assumptions (see main text) except nuclear, PV and wind power that use learning curves.

- The required spinning reserve is assumed to be 3.5% of the installed capacity of the conventional park. If wind and solar photo-voltaic cells (PV) penetrate the market, the additionally required spinning reserve equals 15% of the intermittent capacity (but only after the additional spinning reserve exceeds the capacity already present in the system). These costs are allocated to the intermittent source.
- Depletion is modeled as a function of built-capacity. Hoogwijk (2004) has determined potential supply of solar and wind power at grid basis (0.5 x 0.5 degree) and the associated load factors. By combining this with an estimate of the proximity of the power grid, supply cost curves by region can be derived. These are used in TIMER (see Section on renewable energy supply).

For nuclear power, costs are determined by capital costs and fuel costs. Nuclear fuel (either uranium or thorium) is modeled in a similar way as primary energy.

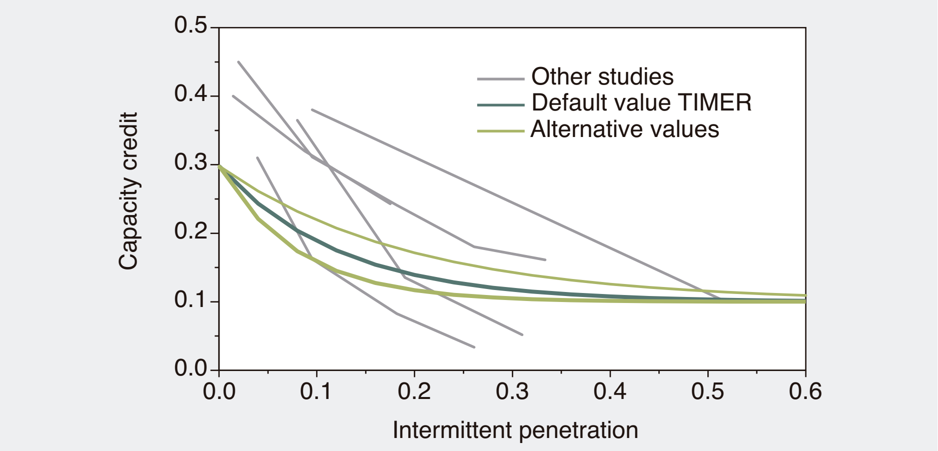

Figure 2.7 Capacity credit assumed in TIMER compared to other studies. It should be noted that actual value at zero penetration depends on the load factor which is time / region dependent. Grey curves indicate relationships found in literature (Namovicz, 2003; Giebel, 2005)

2.2.3 Hydrogen

The hydrogen sub-model simulates the demand for and production, infrastructure and technology dynamics of hydrogen-related technologies (see Figure 2.8). A detailed description is available elsewhere (Van Ruijven et al., in press). Hydrogen production costs are determined by capital and fuel costs and (if relevant) costs of carbon capture and storage. The costs of energy services from hydrogen for the end-user are equal to the production costs (taking into account end-use efficiency), and (additional) costs of end-use capital and infrastructure. The market-share of hydrogen is determined by a multinomial logit formulation, using the difference of the energy service costs from hydrogen and from other energy carriers. A feedback loop due to technological learning tends to lower the hydrogen production costs as cumulative installed capacity increases.

In TIMER 2.0, hydrogen can be produced by coal gasification, partial oxidation of oil, steam reforming of natural gas, gasification of biomass, electrolysis or direct solar-thermal production of hydrogen. For the production of hydrogen from natural gas, the model distinguishes between large-scale and small-scale steam methane reforming (SMR). In this way a transition period can be simulated in which there is no infrastructure and the more expensive small-scale SMR is the only available technology for stationary applications of hydrogen. The capital cost of production technologies declines through learning-by-doing (section 2.3).

Hydrogen can penetrate in all five end-use markets. Another option is mixing up to 5% hydrogen (on an energy basis) into the natural gas grid for use in the residential and service sectors (Hendriks et al., 2002b). We assume exogenous cost decline for fuel

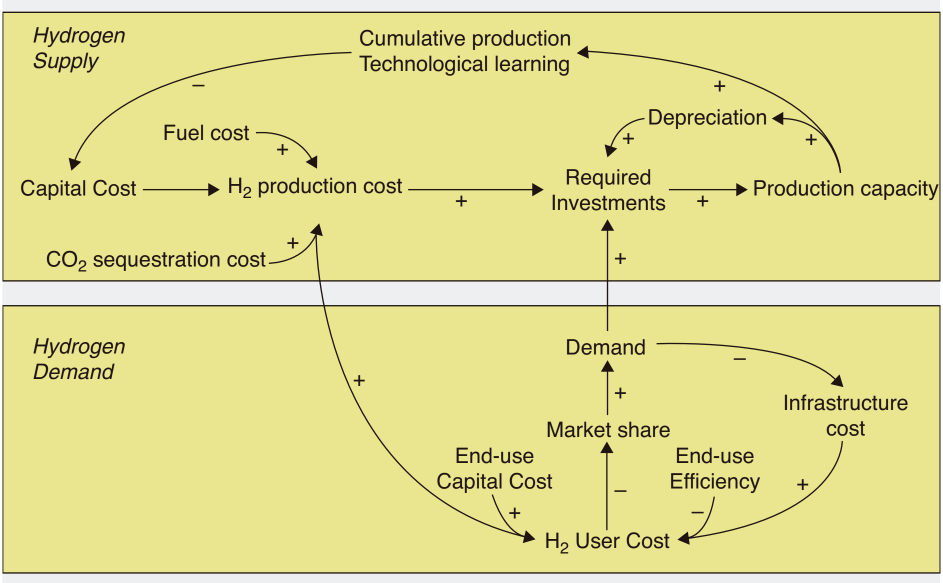

Figure 2.8 System dynamics representation of the TIMER-hydrogen model. Arrows indicate influence factors or inputs for calculation (Van Ruijven et al., in press).

cells, using Solid Oxide Fuel Cells in the industrial sector and Proton Exchange Membrane fuel cells in both stationary and mobile applications (Wurster and Zittel, 1994; Reijnders et al., 2001).

Transport and distribution of hydrogen is a major issue in the transition to a hydrogen energy system. Transport covers the distance from large-scale plants to residential areas or re-fuelling stations and is only considered for hydrogen produced at a large scale (this includes pipelines and trucks). Distribution includes the final distribution of hydrogen, i.e. the small-scale network in residential areas or the re-fuelling station itself. The costs of distribution are added to the cost of hydrogen. Since the development of a hydrogen transport infrastructure is expensive, hydrogen for stationary applications can initially only be produced by small-scale steam methane reforming plants near end-use locations. Investments in large-scale infrastructure (pipelines) will only be made when hydrogen demand density rises above a certain threshold. When this happens, stationary applications can be served by both small-scale and large-scale hydrogen plants. For the transport sector we assume that hydrogen can initially be produced at all scales, since demand is dispersed and transport can be provided by truck.

The implementation of the hydrogen model in the overall TIMER model show that under the default assumption, hydrogen is not likely to penetrate the world market before the mid-21st century, either with or without climate policy, if only costs are considered. Hydrogen could become a major secondary energy carrier later on, but only under optimistic assumptions (in particular breakthroughs are needed in fuel cell technology and infrastructure). The transport sector provides the earliest opportunities. Urban air pollution could provide an important incentive to the use of hydrogen. Coal and natural-gas-based technologies seem to be the most economically attractive to produce hydrogen. Partial oxidation of oil, biomass gasification, electrolysis and solar thermal hydrogen production are more expensive and hence show a lower degree of penetration. Under carbon constraints, the fossil-fuel based hydrogen production technologies are still the most attractive if combined with carbon capture and storage; if this is not available, the preferred hydrogen path shifts towards biomass and natural gas. These outcomes reveal an ambiguous role for hydrogen in relation to climate policy. On the one hand, the most cost-effective production route of hydrogen is from coal. As a result, CO_2 emissions from energy systems with hydrogen are likely to be higher than without hydrogen. On the other hand, energy systems with hydrogen can respond to constraints on CO_2 emissions more flexibly and at lower costs. This is because the use of hydrogen provides new and presumably cheap carbon emission reduction options in the form of centralized carbon capture and storage.

2.2.4 Supply of primary energy

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).

2.2.4.1 Fossil Fuels

To model resource depletion of fossil fuels and uranium, several resource categories are defined that are depleted in order of their costs (12 categories for oil, gas and nuclear fuels, 14 for coal). Production costs thus rise as each subsequent category is exploited (Figure 2.9).

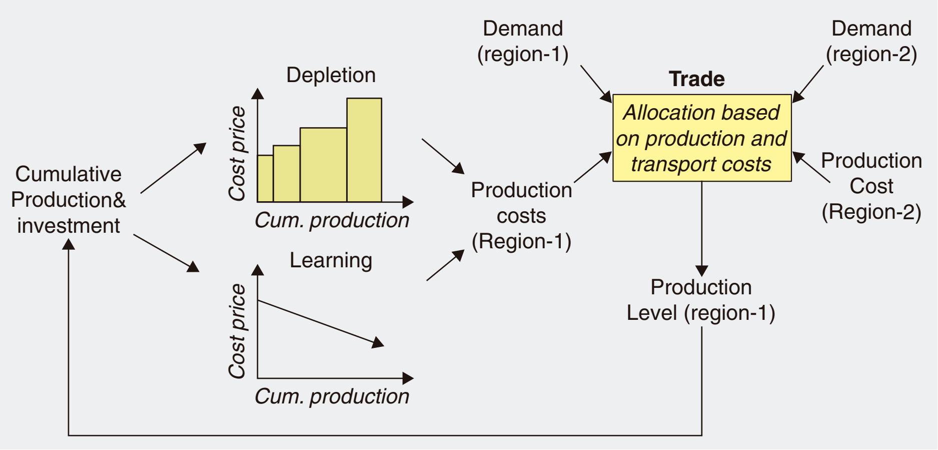

Figure 2.9 Schematic presentation of the sub-models for primary fossil energy production (2 regions are used to illustrate fuel trade).

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.

As indicated above, for each region supply of fossil fuels and nuclear fuels is specified in 12-14 categories, defined on the basis of increasing costs levels. Table 2.4 provides an overview of the assumed presence of each resource in default model conditions (aggregated into only 5 global categories). The table indicates that under default assumptions, supply of natural gas and oil is limited to only 2-8 times 1970-2005 production for all categories up to other unconventional sources (the first category of unconventional sources mainly includes reserves of oil from for tar sands and oil shales). For coal, however, even the current reserves equal several times the production of the last 3 decades. It should be noted that if price increases are high enough, also unconventional sources will be produced.

An alternative way of presenting this information is by showing the information aggregated into a long-term supply curve, as done for oil in Figure 2.10. All categories of oil for each region have been sorted on the basis of production costs and aggregated at the global scale. Supply is expressed in terms of 2000 production levels. The production costs shown here do not include technology progress. Figure 2.10 shows the result for low, medium and high assumptions, all three being used in scenario analysis.

The final production costs in each region are thus the combined influence of learning-by-doing and resource depletion. Depletion is determined by subsequent depletion of the 10-14 fuel classes. The learning parameter leads to lower costs with increasing cumulated production.

In the trade formulation, each region imports fuel from other regions depending on the ratios between the production costs in the other regions plus transport costs, and the production costs within the region considered (multinomial logit). Transportation

Table 2.4 Fossil fuels in TIMER under default assumptions aggregated into 5 global supply categories (ZJ) (based on (Rogner, 1997; Mulders et al., 2006))

	Oil	Natural gas	Underground coal	Surface coal
Cum. 1970-2005 production	4.4	2.1	1.6	1.1
Reserves	4.8	4.6	23.0	2.2
Other conventional resources	6.6	6.9	117.7	10.0
Unconventional resources (reserves)	2.9	6.9	25.0	233.5
Other unconventional resources	46.2	498.6	1.3	23.0
Total	65.0	519.2	168.6	270.0

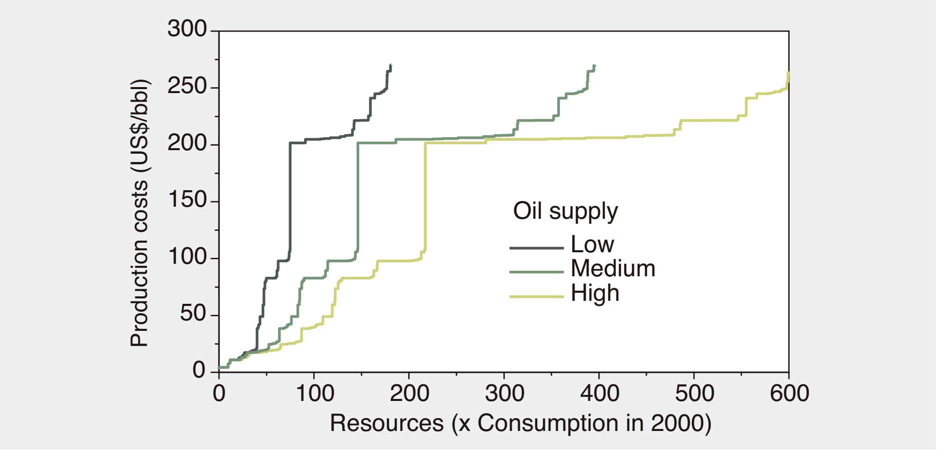

Figure 2.10 Implicitly assumed long-term oil supply cost curve under differ assumptions (based on resource estimates (Rogner, 1997; Mulders et al., 2006)) (the low, high and medium values used in the TIMER uncertainty analysis and are based on the underlying data.)

costs are the product of the representative interregional distances and time and fuel dependent estimates of the costs per GJ per km. To reflect geographical, political and other constraints in the interregional fuel trade, an additional parameter is used to simulate the existence of trade barriers between regions. Finally, a comparison is made between the production costs with and without unrestricted trade. In case some regions are able to supply at much lower costs than the average production costs of "demand" regions (a threshold of 60% is used), these regions are assumed to form a monopoly and will supply oil at a price only slightly below the production costs of the demand regions. Although the rule is implemented in a generic form for all energy carriers, it is only effective in the case of oil trade, where is assumed to simulate to some degree the behaviour of the OPEC cartel.

2.2.4.2. Bio-energy

The structure of the biomass sub-model is similar to that of the fossil fuel supply models but with a few important differences (see also Hoogwijk, 2004) (see Figure 2.11).

- First of all, in the bioenergy model depletion is not governed by cumulative production but by the degree to which available land is being used for commercial energy crops.
- The total amount of potentially available bio-energy is determined on the basis of calculations of the IMAGE crop model. These are able to provide information on bio-energy crop yields at a 0.5x0.5 degree grid under divergent land use scenarios for the 21st century and is based on IMAGE scenario calculations (see also supply cost curves for renewable energy). Potential supply is restricted on the basis of a set of criteria, most importantly bio-energy is only allowed on abandoned agricultural land and part of the natural grasslands. The costs of primary bio-energy crops (woody, maize and sugar cane) are described using a Cobb-Douglas production

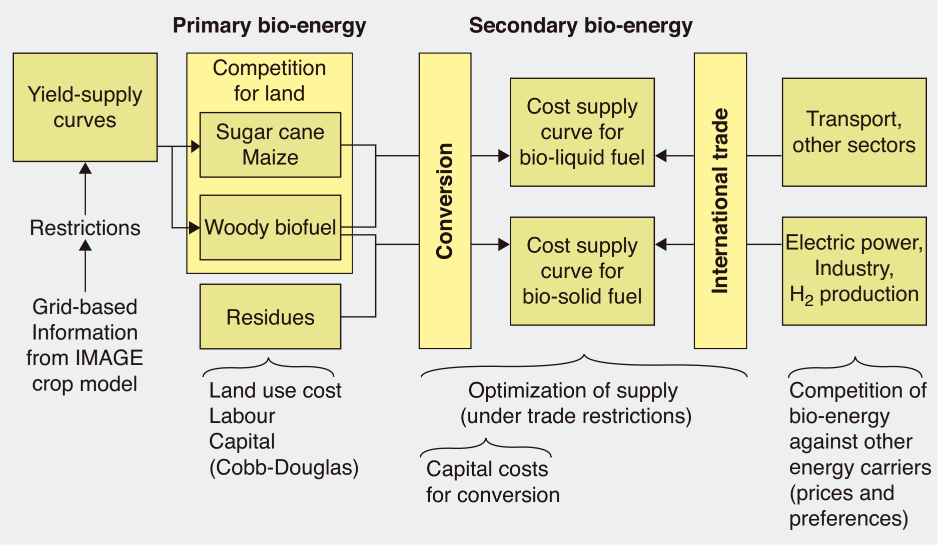

Figure 2.11 Overview of the bio-energy supply model.

function using labour costs, land rent costs and capital costs as input. The costs of land are based on average regional income levels per km², which was found to be a reasonable proxy for regional differences in land rent costs. These production functions are calibrated to empirical data as mentioned in Hoogwijk (2004).

- Next, the biomass model describes the conversion of biomass (in addition to wood crops, maize and sugar cane also residues) to two generic secondary fuel types: bio-solid fuels and bio-liquid fuels. The solid fuel is used in the industry and power sector, and the liquid fuel in other sectors, in particular transport.
- The trade and allocation of biofuel production is determined by optimization rather than by the multinomial logit equation used elsewhere in TIMER, to avoid unstable, oscillating model behaviour[ii]. The optimization finds an optimal combination of bio-solid and bio-liquid fuel supply across regions based on the demand for these products. Demand is determined in the end-use and energy conversion models on the basis of prices of the previous time step.

2.2.4.3. Costs Supply Curves for Renewable Energy

The potential of renewable energy (wind, solar photo-voltaic and bioenergy) has been estimated in a generic way on the basis of a methodology developed by Hoogwijk (2004) (an generic description is given by De Vries et al. (2007)).

(i) First, the relevant physical and geographical data for the regions considered are collected at the resolution of 0.5 by 0.5 degree. The wind and solar characteristics are taken from the digital database constructed by the Climate Research Unit (New

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[ii] The multinomial logit equation (discussed in more detail in Section 2.3) determines market share on the basis of current prices, without taking into account the form of the supply curve. As a result, relatively low prices may lead to high implementation rates, followed by steep increases in production costs and thus declining market shares. The alternative optimization approach is able to take the form of the supply curve into account (although oscillations may still occur).

et al., 1997; New et al., 1999). Land use information for energy crops is taken from the IMAGE land use model.

(ii) Subsequently, the model assesses which part of the grid cell area can be used for energy production given its physical-geographical (terrain, habitation) and socio-geographical (location, acceptability) characteristics. This leads to an estimate of the geographical potential. Several of these factors are scenario dependent. The geographic potential of biomass production by energy crops is estimated using suitability/availability factors accounting for competing land use options and the harvested rainfed yield of energy crops.

(iii) Next, the technical potential accounts for the fact that only part of the energy can be extracted in the form of useful secondary energy carriers (fuel, electricity), due to limited conversion efficiency and maximum power density.

(iv) A final step is to relate this technical potential to the on-site production costs. The information at grid level is finally sorted and presented as supply cost curves to TIMER. Supply cost curves are used dynamically and change over time as result of learning effect. Producing more renewable energy also leads to changes along this curve, and thus to higher costs.

The type of information that results from these steps are supply cost curves for wind and PV (used in the electric power model) and for bio-energy (used in the bio-energy submodel). As an example Figure 2.12 summarizes the information of these costs supply curves on global scale for wind and PV. The implementation of the wind and PV supply curves in the electric power model has been discussed already in the section on the electric power generation submodel.

As indicated in the previous section, for bio-energy, the TIMER model includes several routes from energy crops to liquid biofuel (ethanol and Fisher-Tropsch diesel) and solid biofuel. An example of bio-energy costs levels for transport fuel is shown in Figure 2.13.

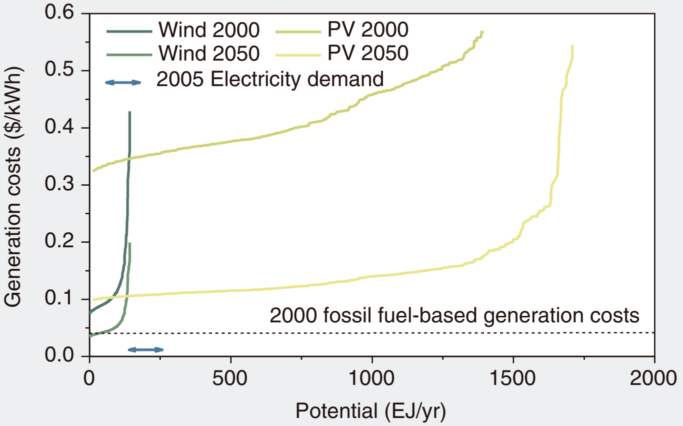

Figure 2.12 Representation of the supply costs curves for wind and solar PV (right) in the year 2000, as well as for the year 2050. Costs are expressed in terms of power production costs.

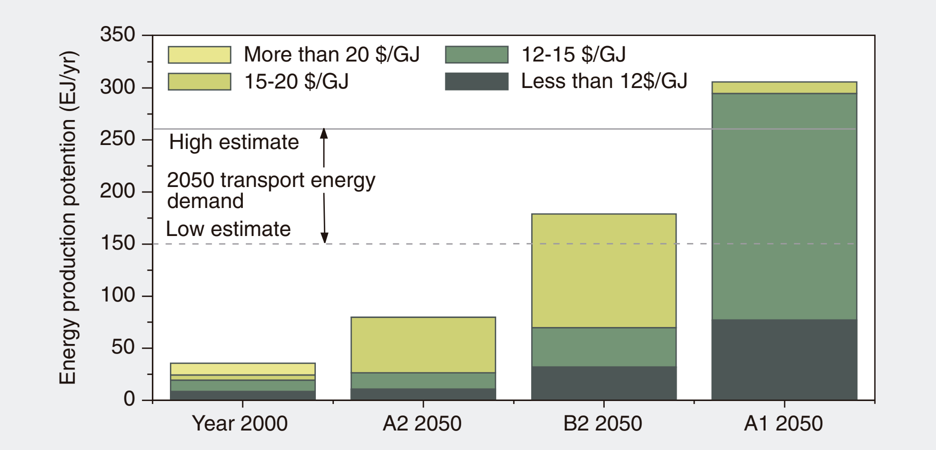

Figure 2.13 Supply costs curve for bio-energy in transport. The estimates vary strongly as a result of different land-use scenarios. The vertical lines indicate high and low estimates of transport energy demand.

2.2.5 The Emissions submodel

The TIMER Emissions Model (TEM) calculates the regional atmospheric emissions from energy and industry-related processes. The model covers carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), nitrogen oxides (NO_x), carbon monoxide (CO), non-methane volatile organic compounds (NMVOC), sulphur dioxide (SO_2) and emissions of halocarbons (CFCs, HCFCs, HFCs, etc.). Emissions are calculated by multiplying primary energy use fluxes and industrial activity levels with time-dependent emission coefficients:

$$Emis_{R,S,EC,Subst} = EnergyFlow_{R,S,ECt} {}^{*}\ EF_{R,S,EC,Subst} \qquad (2.8)$$

where Emis represents emissions (for regions, sectors, energy carriers and substances), energy flow the relevant energy flux (e.g. sectoral energy consumption or production level) and EF the emission factor. Changes in the emission factors represent technological improvements and end-of-pipe control techniques for CO, NMVOC, NOx and SO_2 (FGD in power plants, fuel specification standards for transport, clean-coal technologies in industry, etc.). The emission factors are determined exogenously and calibrated for historic time periods on the basis of the EDGAR emission model.

2.2.6 Carbon capture and storage (CCS)

For carbon capture and storage, three different steps are identified in the model: CO_2 capture and compression, CO_2 transport and CO_2 storage. Capture is assumed to be possible in electric power production, half of the industry sector and hydrogen production. Here, alternative technologies are defined that compete for market share with conventional technologies (without CCS). The former have higher costs and slightly lower conversion efficiencies and are therefore not chosen under default conditions;

however, these technologies increase much less in price if a carbon price is introduced in the model. Capture is assumed to be at a maximum 95%; the remaining 5% is still influenced by the carbon price. The actual market shares of the conventional and CCS-based technologies are determined in each market using multinomial logit equations. The capture costs are based on Hendriks et al. (Hendriks et al., 2002a; Hendriks et al., 2002b; Hendriks et al., 2004). In the electric power sector, they increase generation costs by about 40-50% for natural gas and coal-based power plants. Expressed in terms of costs per unit of CO_2, this is equivalent to about 35-45\$/tCO_2. Similar cost levels are assumed for industrial sources.

CO_2 transport costs were estimated for each region and storage category on the basis of the distance between the main CO_2 sources (industrial centres) and storage sites (Hendriks et al., 2002a). The estimated transport costs vary from 1-30 \$/tCO_2 – the majority being below 10\$/tCO_2.

Finally, for each region the potential for 11 storage categories has been estimated (in empty and still existing oil and gas fields, and on and off shore – thus a total of 8 combinations); enhanced coal-based methane recovery and aquifers (the original aquifer category was divided into two halves to allow more differentiation in costs). For each category, storage costs have been determined with typical values around 5-10\$/tCO_2 (Hendriks et al., 2002a). The model uses these categories in the order of their transport and storage costs (the resource with lowest costs first). Figure 2.14 summarizes the assumed default assumptions for storage capacity for aggregated regions and storage categories. It should be noted that the aquifer storage capacity is far more uncertain that the other categories (and thus in scenario studies, one may decide to use only part of this potential).

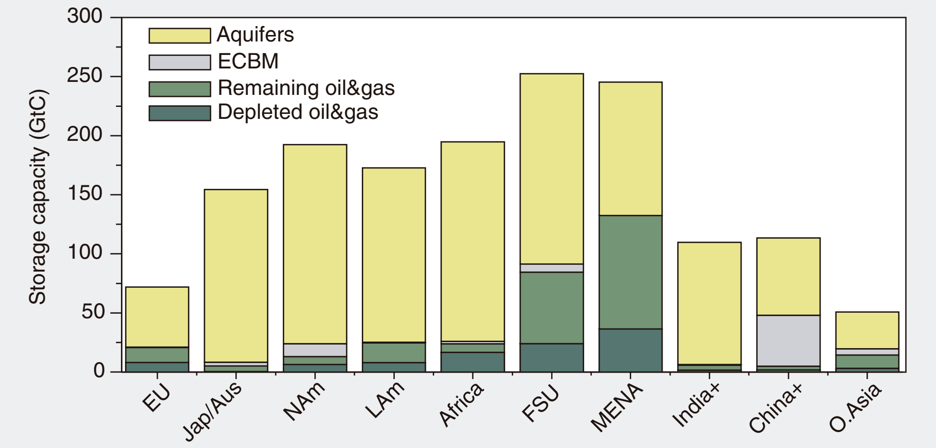

Figure 2.14 Summary of the assumed CO_2 storage capacity in TIMER (aggregated into larger categories and regions) (note: category ECBM refers to coal-bed methane; oil and gas refer to currently depleted fields and new fields).

2.3 Common Model Elements

The TIMER model has several elements that are included in various sub-models. Important elements include depletion, the capital vintage structure, technology development and substitution. Given the fact that depletion has already been discussed earlier, we only pay attention to the last three elements.

2.3.1 Capital vintage model

Throughout the model, capital stocks of production capital (e.g. oil production capacity, power plants and end-use equipment) are described using a capital vintage structure. This element describes the investment in and depreciation of capital stock on the basis of the assumed lifetime of different forms of capital stocks. Its use implies that changes in energy use and production can only be adopted by the system at a rate equal to new investment and the depreciation of existing capital. In other words, the vintage model forms an essential element of system inertia. The equations used for the vintage model are indicated below:

$$CapRq = FlowRq * COR \tag{2.9}$$

$$CapDepr = \sum_{n} {}^{1}\!/_{n} * Inv_{t-LT+n-5} \tag{2.10}$$

$$CapInv = CapRq - CapCr + CapDepr \tag{2.11}$$

Here, CapRq indicates the required capital level based on the required energy production level (FlowRq) and the ratio between capital and output (COR). The depreciated capital in each time period equals the capital that has reached the end of its lifetime (LT). To introduce some heterogeneity, in the model part of the capital has depreciated, in fact, a little earlier, while another part has depreciated a little later (n determines the number of years sampled around the average lifetime). CapInv, finally, equals the required capacity minus the existing capacity, but plus the depreciated capacity.

2.3.2 Technological development

An important aspect of the TIMER model is the endogenous formulation of technological development on the basis of “learning-by-doing”. This phenomenon is considered a meaningful representation of technological change in global energy models (Azar and Dowlatabadi, 1999; Grübler et al., 1999; Wene, 2000). The general formulation of learning-by-doing is that a cost measure, y, tends to decline as a power function of an accumulated learning measure, *Q*:

$$y = \alpha * Q^{-\pi} \tag{2.12}$$

where π is the learning rate, Q the cumulative capacity or output and α a constant. Often π is expressed by the progress ratio ρ, which indicates how fast the costs measure, y, decreases with the doubling of Q ($\rho=2^{-\pi}$). Progress ratios reported in empirical studies lie mostly between 0.65 and 0.95, with a median value of 0.82 (e.g. Argotte and Epple, 1990).

In the TIMER model, learning-by-doing influences the capital-output ratio of coal, oil and gas production, the specific investment cost of renewable and nuclear energy, the cost of hydrogen technologies and the rate at which the energy conservation cost curves decline. The value of ρ ranges between 0.7 and 1.0 based on historic values (see Figure 2.15). The actual values used depend on the technologies and the scenario setting. The ρ of solar/wind and bioenergy have been set at a lower level than those for fossil-based technologies, based on their early stage of development and observed historic trends (e.g. Wene, 2000; Junginger et al., 2005). There is evidence that in the early stages of development ρ is higher than for those technologies that have already been in use for long time periods. For instance, values for PV are typically below 0.8, while those for fossil fuel production are around 0.9-0.95 (see Figure 2.15). For technologies in early stages, other factors may also contribute to technology progress, such as relatively high investment in research and development (Wene, 2000). In TIMER, ρ values are exogenous, scenario-dependent assumptions. They are typically assumed to increase over time for technologies with values below 0.9 to represent maturation (but these pathways are typically strongly scenario-dependent).

It is an interesting question whether learning curves should be applied separately on the scale of regions or for the world as a whole. On the one hand, technologies developed in one region will often also be available in other regions. On the other hand, a significant part of cost reduction comes from experience gained by applying the technology and developing the associated infrastructure which may not be so easily transferred. In TIMER, we postulate the existence of a single global learning curve. Regions are then assumed to pool knowledge and “learn” together or, depending on the scenario assumptions, to be (partly) blocked from this pool. In the latter case, only the obviously smaller cumulated production within the region itself drives the learning process and costs will decline at a slower rate.

2.3.3 Substitution of fuels and technologies

The multinomial logit mechanism is used in TIMER to describe substitution among end-use energy carriers, different forms of electricity generation (coal, oil, natural gas, solar/wind and nuclear) and substitution between fossil fuels and bioenergy. This mechanism is also used to determine the production shares of different regions in international markets. The mechanism is based on the following equation:

$$IMS_i = \frac{\exp(-\lambda\, c_i)}{\sum_j \exp(-\lambda\, c_j)} \qquad (2.13)$$

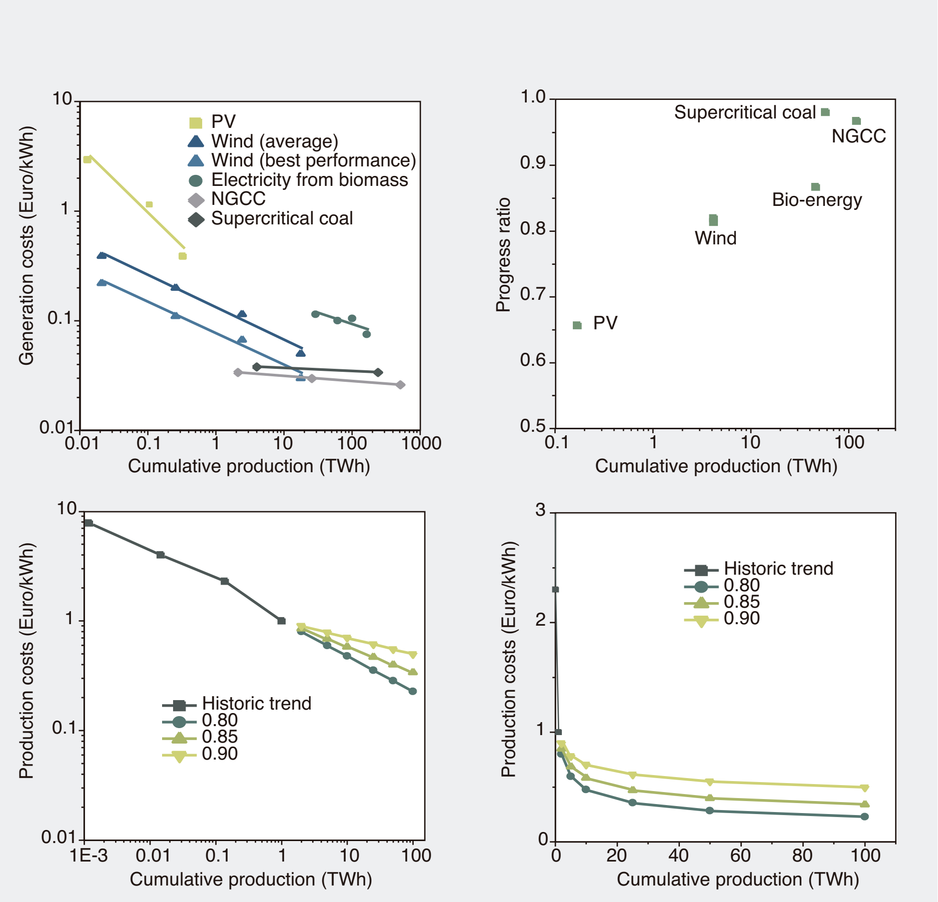

Figure 2.15 Learning curve and resulting dynamics. The upper panels shows empirical data from Wene for the 1970-2000 period. The lower left figure shows - on a logarithmic scale (for both x and y axes -) the potential technology improvement at different progress ratios (0.8-0.9) (historic data is based on the improvements of wind power plants). The same data is shown using linear axes on the right-hand side.

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 so-called logit parameter, which reflects the sensitivity of markets to relative differences in production costs. The "price" ci does not only encompass production costs but also other factors such as premium factors, additional investment costs and cost increases as a result of a carbon tax. These premium factors include all kinds of non-monetary preferences, such as convenience in handling or environmental consequences. For the calibration period, these premium factors are chosen so that historic market shares are reproduced on the basis of modeled prices.

The multinomial logit model implies that the market share of a certain technology or fuel type depends on costs relative to competing technologies. This is illustrated in Figure 2.16 for two competing technologies and for three different values for λ. The option with the lowest costs obtains the largest market share, but in most cases not the

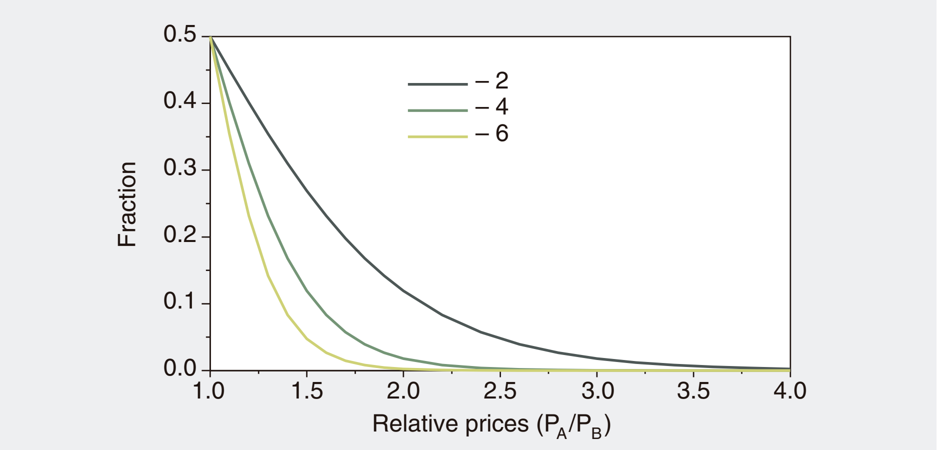

Figure 2.16 Multinomial logit equation. Outcomes for different values of the logit parameter λ, showing the fraction of technology, A, as a function of the price ratio between technology A and B.

full market. We interpret the latter as a representation of heterogeneity in the form of specific market niches for every technology or fuel. The value of the logit parameter determines the price sensitivity of the market and can be compared to substitution elasticities in economic models: a value of zero gives equal market shares to each technology, while a high value leads to full optimization. Given the fact that the preferences for different fuel types are not known in the quantitative sense for the historic situation, it is hard to determine the value of the logit parameter on an empirical basis. The value in TIMER is therefore determined by calibrating the formula against historically observed responses to price changes (but its value remains somewhat arbitrary).

2.3.4 The combination of innovation and substitution dynamics

Figure 2.17 shows how the learning curve formulation and the multinomial logit market share formulation interact.

The figure describes the competition between a rapidly learning technology using a learning curve, and a technology with a constant price. The combined behavior of technology learning and the market share formulation are shown in Figure 2.17. Technology B reduces its costs over time thanks to learning by doing. The market share of this technology increases in response, leading at first to further costs reductions – although this slows down once the technology has moved far enough along the learning curve. The resulting market share for technology B reflects a so-called logistic (s-form) penetration curve emerging from the combination of the two dynamic elements. Many engineering optimization models assume that penetration of new technologies occurs along such a curve using a exogenous formulation.

Obviously, the same uncertainties discussed for the learning curve and multinomial logit model separately also determine the outcomes of their combination. In Figure

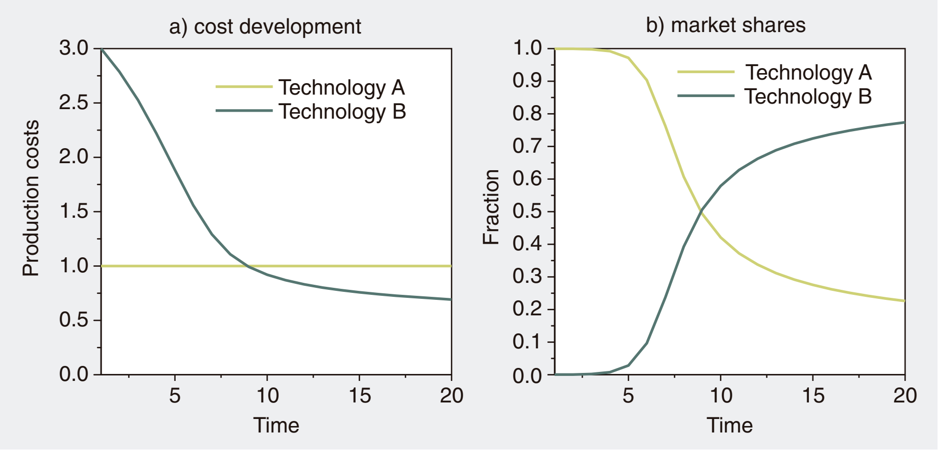

Figure 2.17 The combined behavior of a learning curve and the multinomial logit model for 2 technologies. Production costs (left) and market share (right).

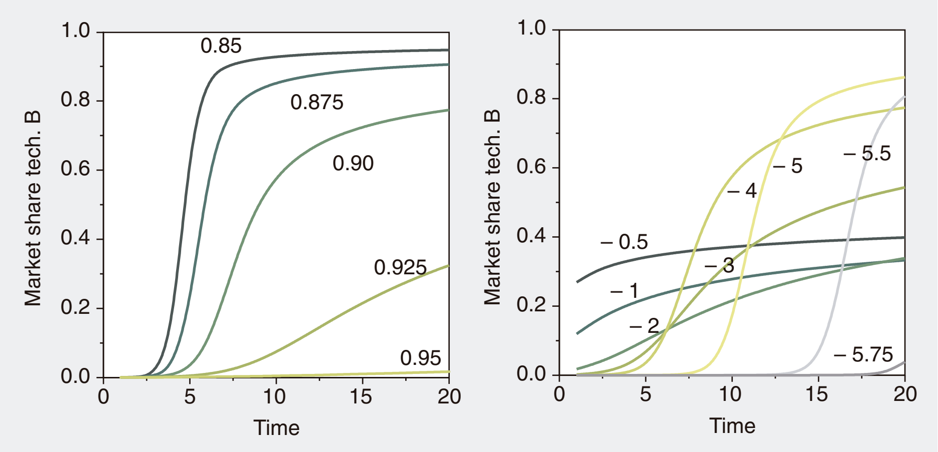

Figure 2.18 Market share of technology B in competition with technology A. The combined behavior of a learning curve and the multinomial logit model. Sensitivity to learning rate assumptions (left) and logit parameter assumptions (right).

2.18 the market share of technology B is now shown for different assumptions for the learning (ρ) and logit (λ) parameters. The results are demonstrated to critically depend on both parameters. Slower learning implies that technology B only penetrates the market slowly or even fails to do so, while faster learning results in a very rapid transition from technology A to technology B.

The impact of the logit parameter is more complex. Low values imply that technology B captures a large market share early on, but it also implies that the market is insensitive to price differences and thus, it can only capture half the market. Higher logit values (thus more price-sensitive markets) imply a low market penetration at first, but also imply that once technology B starts to benefit from learning (and its costs decrease), it is able to penetrate the market at a much more rapid rate.

2.4 Using TIMER in Conjunction with FAIR and IMAGE for Mitigation Analysis

The TIMER model is often used in combination with the FAIR model (den Elzen and Lucas, 2005) and the climate and terrestrial sub-models of IMAGE to develop scenarios that explore how such low greenhouse gas concentration stabilization levels could be reached. As TIMER forms part of the IMAGE modeling framework, a short description of IMAGE is first given. Next, the links between the sub-models for energy climate modeling are indicated.

2.4.1 IMAGE 2 Integrated assessment framework

IMAGE 2 is an integrated assessment modelling framework describing global environmental change in terms of cause–response chains (Alcamo et al., 1996, Bouwman et al., 2006). The most important subsystems are the “socio-economic system” and the “earth system” (Figure 2.19). In the socio-economic system, detailed descriptions of the energy and food consumption and production are developed using TIMER and agricultural trade and production models. The two main links between the socio-economic system and the earth system are land use and emissions. First, production and demand for food and biofuels lead to a demand for managed land. Second, changes in energy consumption and land-use patterns give rise to emissions that are used in calculations of the biogeochemical circles, including the atmospheric concentration of greenhouse gases and some atmospheric pollutants, such as nitrogen oxides and sulphur oxides. Changes in concentration of greenhouse gases, ozone precursors and species involved in aerosol formation form the basis for calculating climatic change. Next, changes in climate are calculated as global mean changes and downscaled to grid level.

The land-cover submodels in the earth system simulate the change in land use and land cover at 0.5 x 0.5 degrees (driven by demands for food, timber and biofuels, and changes in climate). A crop module based on the FAO agro-ecological zones approach computes the spatially explicit yields of the different crop groups and the grass, and the areas used for their production, as determined by climate and soil quality. Where expansion of agricultural land is required, a rule-based “suitability map” determines the grid cells selected (on the basis of the grid cell’s potential crop yield, its proximity to other agricultural areas and to water bodies). The earth system also includes a natural vegetation model to compute changes in vegetation in response to climate change. An important aspect of IMAGE is that it accounts for important feedbacks within the system, such as temperature, precipitation and atmospheric CO_2 feedbacks on the selection of crop types, and the migration of ecosystems. This allows for calculating changes in crop and grass yields and, as a consequence, the location of different types of agriculture, changes in net primary productivity and migration of natural ecosystems.

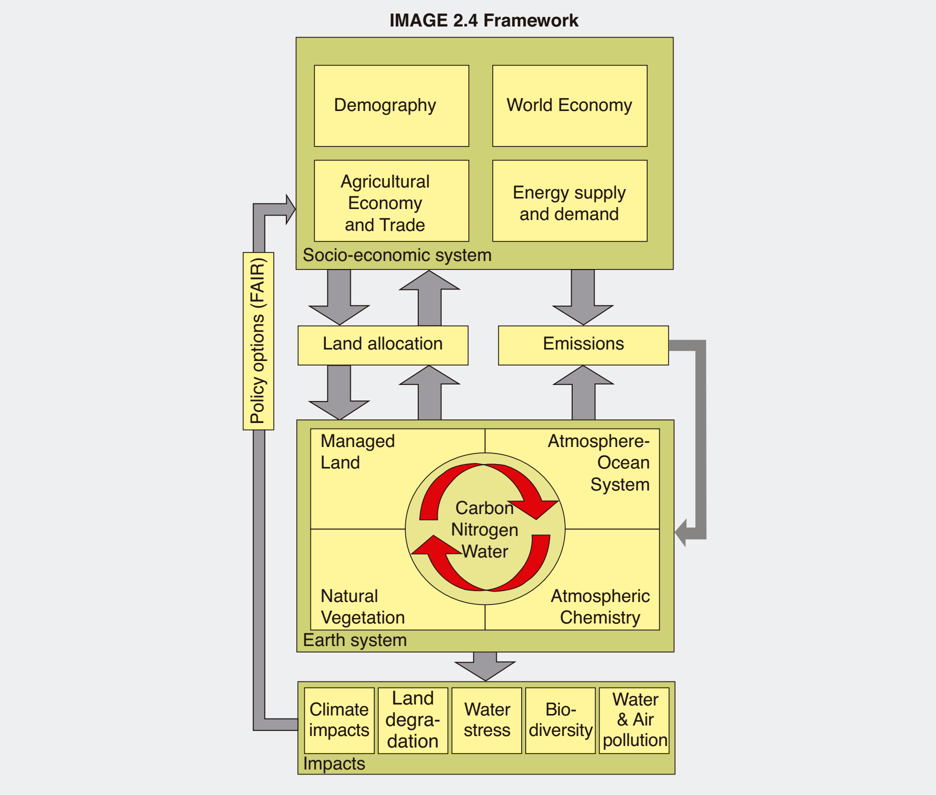

Figure 2.19 IMAGE 2 Integrated Assessment Framework.

2.4.2 Linkages between TIMER, IMAGE and FAIR for energy–climate modeling

The links between the sub-models are indicated in Figure 2.20. In the combination of the three models, FAIR not only adds information on climate policy but also a relatively simple framework that allows for costs optimization of reduction of energy-related greenhouse gas emissions (as described in TIMER) against other forms of emissions. IMAGE provides information for TIMER on the potential for bio-energy use, adds the ability to evaluate environmental and land-use impacts of different energy scenarios and, finally, describes other sectors that are relevant for climate change.

The scheme in which TIMER, and the rest of IMAGE and FAIR are often applied consists of three steps (Figure 2.20):

(i) 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;

(ii) global emission pathways are developed using the FAIR model ; this leads to a stabilization of the atmospheric GHG concentration. The FAIR model distributes

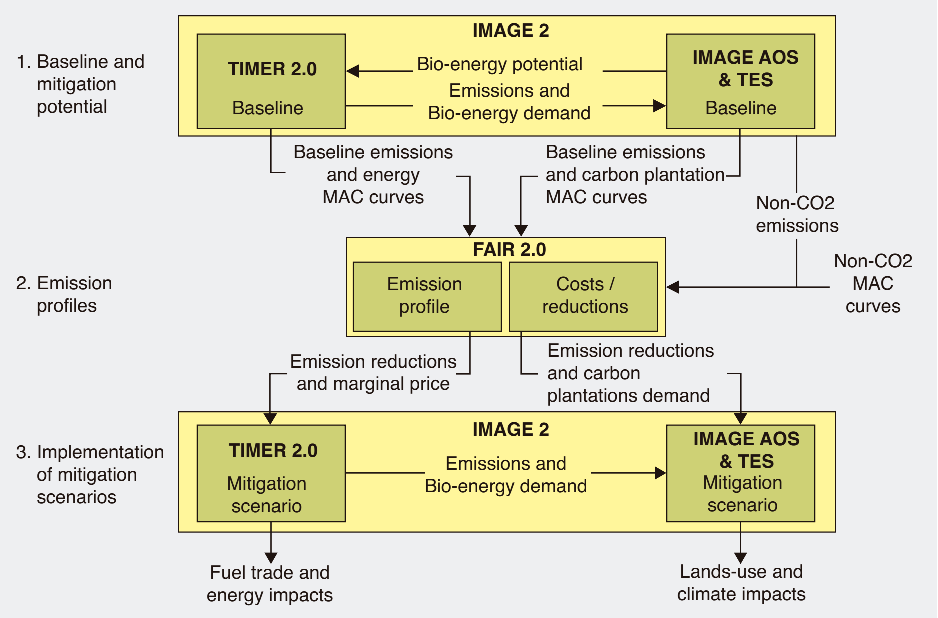

Figure 2.20 Linkage and information flows of the applied modeling framework integrating TIMER, IMAGE and FAIR (note CP = carbon plantations; MAC = Marginal Abatement Curve; AOS = atmosphere ocean system; TES = terrestrial ecosystem system).

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 (i);

(iii) 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).

In step (i) estimates for reduction costs and potential from TIMER are made by imposing an emission permit price (carbon tax) and recording the induced reduction of CO_2 emissions. TIMER responds to the addition of an emission permit price in several ways. On the energy supply side, options with high carbon emissions (such as coal and oil) become more expensive compared to options with low or zero emissions (such as natural gas, CCS, bioenergy, nuclear power, solar and wind power). The latter therefore gain in market share. On the energy demand side, investments in efficiency become more attractive. Technology change can strongly influence the results. Different sets of response curves to carbon tax levels are constructed to take this influence into account. Chapter 8 of this thesis discusses the construction of response curves in detail. Chapter 7 describes an analysis in which the overall framework is applied.

2.5 Concluding Remarks

The TIMER 2.0 model has been developed to explore different pathways of the global energy system in the context of climate change or long-term depletion of fossil fuel resources. Several applications of the model, mostly coupled to other elements of IMAGE, such as the land-use model and the FAIR model, have shown its capacity to fulfil this aim. However, the model can be improved further. Issues that merit our future research attention include: (i) the implication of the energy transition in developing countries. In most scenarios, increasing energy demand in developing countries represents the main driving force behind increasing global energy consumption. Nevertheless, representation of developing country energy issues in global energy models like TIMER is limited. We will explore whether improvements can be made; (ii) modelling physical drivers of energy demand. At the moment, primarily monetary indicators are used to determine energy demand. By modelling the underlying physical drivers (passenger kilometres or steel production), deeper insight can be obtained in opportunities to change the energy system.