REMIND – D

A Hybrid Energy - Economy Model of Germany

Project: ENCI-LowCarb
Engaging Civil Society in Low-carbon Scenarios

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Eva Schmid[1] (Potsdam Institute for Climate Impact Research)
Brigitte Knopf (Potsdam Institute for Climate Impact Research)
Nico Bauer (Potsdam Institute for Climate Impact Research)

[1]Corresponding Author:
Email address: eva.schmid@pik-potsdam.de, Telephone: +(49) 331-2674,
Fax: +(49) 331 299-2570, Mail: P.O. Box 60 12 03, 14412 Potsdam, Germany

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REMIND-D: A Hybrid Energy-Economy Model of Germany

Eva Schmid[*], Brigitte Knopf, Nico Bauer
Potsdam Institute for Climate Impact Research

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[*] Corresponding author: Tel. +49 331 288 2674, Fax: +49 331 288 2570, Email: eva.schmid@pik-potsdam.de, P.O. Box 601203,14412 Potsdam

1 Introduction

Global climate models indicate that a mitigation effort of ≈50% global greenhouse gas (GHG) emissions in 2050 relative to 1990 yields a likely chance of keeping global warming below 2°C (Meinshausen et al. 2009). Germany contributed nearly 5% of global GHG emissions in 2007 (UNFCCC 2009), of which carbon dioxide (CO_2) constituted the largest share with 87%. Figure 1 illustrates how German domestic CO_2 emissions can be attributed to the sectors land use, industrial processes[1] and the energy sector in the year 2007. The energy sector has been causing a stable share of ±80% of total German CO_2 emissions every year since 1990 (UBA 2010). Hence, decarbonizing the energy system is central to achieving cuts in German GHG emissions. A long-term CO_2 emission reduction target of 80-95% in 2050 relative to 1990 has been announced by the German Government (Bundesregierung 2010). Achieving such an ambitious mitigation target will require a structural transformation of the German energy system.

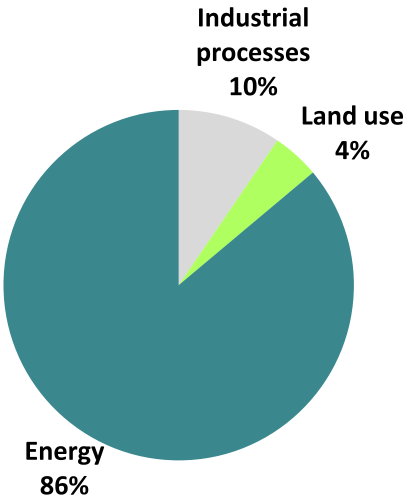

Figure 1: Shares in German CO_2 emissions in 2007 by source. Own illustration with data from UBA (2010).

Energy system transformations are large-scale processes subject to inertia, due to capital intensive infrastructure and conversion technologies as these usually have technical lifetimes of several decades. Long-term planning is necessary for enabling low carbon technologies in future energy system portfolios. An important tool for exploring the future and dealing with complexity and uncertainty are scenarios, especially when formalized by means of an energy-economy model. Ideally, such a model included all technological and socio-economic processes and systemic feedback loops that are observed in reality. Unfortunately, computational costs, data scarcity and data unobservability as well as a lack of conceptual frameworks and economic theories set limiting boundaries.

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[1] These are mainly emissions from mineral products, chemical industry and metal production.

Existing energy-economy models represent selected aspects of the energy-economy nexus and their results inherently reflect the adopted methodology of the model. Classification typologies vary greatly in the literature, e.g. according to (numerical) methodology (Nakata 2004) or descriptive versus normative argumentation structures (McDowall and Eames 2006). A widely agreed differentiation is to group energy-economy models into “top-down” versus “bottom-up” approaches. Top-down models follow an economic approach and endogenize behavioral relationships by calibrating on market data, assuming no discontinuities in historical trends. Bottom-up approaches, on the other hand, follow an engineering approach and contain detailed descriptions of technologies and technical potentials, assuming market adoption of the most efficient technologies (Hourcade and Robinson 1996).

In early global mitigation analyses, bottom-up models systematically indicated larger GHG reduction potentials than top-down models. Hence, Grubb et al. (1993) labeled top-down models as pessimistic and bottom-up models as optimistic. They attributed the difference to the existence of negative cost potentials, so called 'no regrets' options, in bottom-up approaches. These refer to emission reductions caused by the adoption of best available techniques whose costs are lower than the technologies currently in use, i.e. an efficiency gap. The size and meaning of this efficiency gap is subject to controversy in the debate between modeling approaches. It arises particularly due to the different approaches of modeling technological change.

Engineering-oriented bottom-up studies suggest that market forces do not operate perfectly and the policy implication is to remove barriers to adoption of the best available technique (Hourcade and Robinson 1996). Opposingly, economists argue that these postulated market failures are only apparent and can be explained in terms of two other factors: complexity and heterogeneity of consumer preferences and hidden costs, e.g. information costs or perceived risks associated with capital costs. In calibrated top-down models, this complex set of behavioral factors is captured in price and income elasticities. In a more recent analysis, Vuuren et al. (2009) find no systematic difference in the reduction potential reported by state-of-the-art top-down and bottom-up models at the global scale. However, the results at the sectorial level show considerable differences in terms of technical versus economical reduction potential. It is concluded that the two approaches are complementary in the sense that they add different types of information. While the bottom-up approach is stronger in terms of technology resolution, top-town models enable a sectorially integrated analysis by incorporating economic feedback loops.

For analyzing domestic CO_2 reduction potentials in Germany, bottom-up models dominate the literature, e.g. PERSEUS (Fichtner et al. 2001), TIMES-D (Blesl et al. 2007), IKARUS (Martinsen et al. 2006) and the Prognos model (Kirchner et al. 2009). They are demand driven and technology oriented. The models solve a partial equilibrium problem by minimizing an energy system cost metric, consisting of total fuel, maintenance and investment costs. Recently, some effort has been made to establish soft links between different models to consider feedback loops, e.g. Schlesinger et al. (2010) couple the bottom-up Prognos model with the top-down econometric PHANTA RHEI (Meyer et al.

2007) model and a detailed dispatch model of the German electricity sector. Soft-linking allows for some feedback, but the different models continue to individually optimize their objective functions. While the German GHG reduction potential has been extensively analyzed in terms of technical potential, the economic potential has received very little attention, due to a lack of models suitable for this type of analysis.

In order to fill this gap, a hybrid energy-economy model for Germany has been developed at the Potsdam Institute for Climate Impact Research: REMIND-D (Refined Model of Investment and Technological Development - Deutschland). Hard-link hybrid models integrate a detailed bottom-up energy sector into a top-down representation of the macro economy. In this manner, capital and resources for energy generation are allocated optimally with respect to the whole economy (Bauer et al. 2008). Hybrid models have been developed to overcome the drawbacks of pure top-down or bottom-up models and are well established in global integrated assessment exercises, e.g. WITCH (Bosetti et al. 2006) and REMIND-R (Leimbach et al. 2010). REMIND-D builds on the structural equations of the state-of-the art global integrated assessment model REMIND-R. All structural equations are reported in detail in Bauer et al. (2011)[2]. Hence, this document refrains from reproducing all equations in REMIND-D. Instead, it intends to provide an extensive documentation of the input data used to calibrate REMIND-D to the Federal Republic of Germany.

2 The Model REMIND-D

The basic purpose of REMIND-D is to provide a quantitative framework for analyzing long-term domestic mitigation scenarios for Germany, enabling a focus on the economic reduction potential. The technological reduction potential is considered explicitly by a detailed bottom-up energy system module. REMIND-D facilitates an integrated analysis of the long-term interplay between technological mitigation options in the different sectors as well as macroeconomic dynamics.

A stylized overview of REMIND-D's structure is illustrated in Figure 2. The top-down macroeconomic module resembles a Ramsey-type neoclassical optimal growth model (Cass 1965; Koopmans 1965; Ramsey 1928). Output is produced by aggregating the production factors capital, labor and energy via nested Constant Elasticity of Substitution (CES) functions. The production factor energy is subdivided so as to match the aggregated final energy demand of the industry and residential & commercial sector as well as the energy service demand of the transport sector. These quantities are provided by a bottom-up energy system module that considers the techno-economic characteristics of conventional and prospective energy conversion technologies explicitly. CO_2 emissions accounting is pursued via emission factors on fossil fuel consumption. For solving REMIND-D numerically, it is formulated as an intertemporal social planner problem

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[2] Accessible online via `http://www.pik-potsdam.de/research/sustainable-solutions/models/remind/remind-equations.pdf`

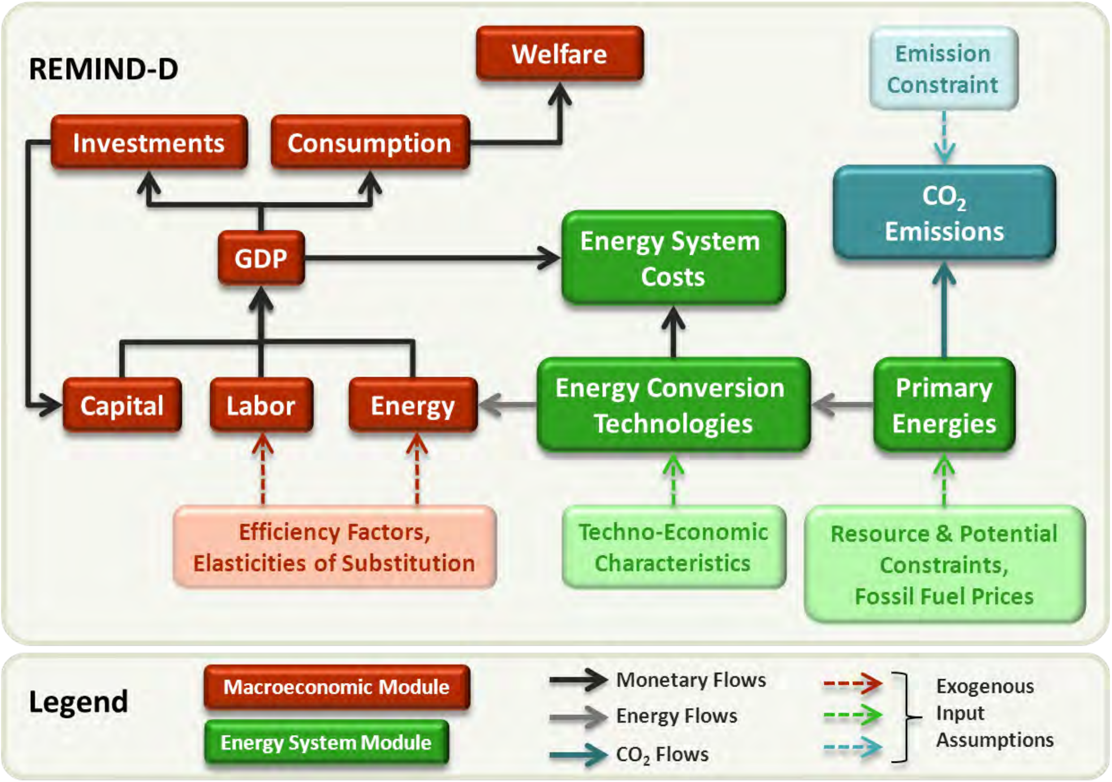

Figure 2: Stylized overview of REMIND-D's structure.

with perfect foresight. It maximizes an intertemporal social welfare function by determining optimal time paths of control variables subject to exogenous constraints. The control variables are investments into the macroeconomic capital stock, final energy and energy service demand, investments into energy conversion technologies and operation & maintenance as well as fuel costs.

The optimization space of the model is numerically constrained by technical resource and potential constraints of domestic primary energy supply (lignite, biomass, wind, solar and geothermal) and the energy conversion capacities' efficiency grades. Economically, it is constrained by fossil fuel prices, cost developments of low-carbon technologies as well as the exogenous efficiency factors and substitution elasticities in the production function. In the standard setting, mitigation policy is enforced in REMIND-D via a CO_2 budget that may be allocated intertemporally. Alternatively, specific carbon tax or emission trajectories can be imposed on the model. One particular set of constraints defines a scenario. The analysis of two scenarios that differ only with respect to the emission constraint allows for determining the differential effects of mitigation policy. In optimization models, the introduction of perturbation like a binding emission constraint or pricing carbon emissions will automatically lead to a non-optimal solution. Consequentially, mitigation costs will always be negative. Due to a lack of conceptual frameworks, positive co-benefits of mitigation are not included in the social welfare function.

Underlying assumptions of the optimization approach with a Ramsey-type growth model are discussed extensively in e.g. Maußner and Klump. (1996). The most important ones include that the economy is closed and no government exists that demands or supplies goods. The economy is comprised of two sectors: households and firms. Firms produce output by using the three production factors capital, labor and energy. Households are equal in initial endowments and preferences, which are ordinal. The assumption of representative households allows for an intragenerational aggregation of individual utilities. The ordinal preference orderings justifies the intertemporal aggregation of utilities, which is achieved by summing discounted utilities. Even though these assumptions are disputable, they are necessary simplifications for the analytical framework and relaxations incurred prohibitively high numerical costs due to the integration of the complex bottom-up energy system module.

An implication of these underlying assumptions is that a Ramsey-type growth model is only suitable for analyzing certain questions. For example, REMIND-D is ill-suited to analyze the distributional effects of climate policy. Originally, (Ramsey 1928) asked the question of "How much shold a nation save?" and operationalized it by asking "How much should a nation consume?" instead. By integrating energy as an additional production factor as well as a detailed representation of its supply chain and the carbon externality into the modeling framework, REMIND-D shifts the focus of analysis. The standard mode of analysis reads as: "Given the German energy system is subject to a specific carbon budget and set of scenario definition constraints, what is the most welfare-optimal mitigation strategy?".

The following summarizes fundamental information on REMIND-D. Calibration input for the macroeconomic and energy system modules is presented in Section 3 and Section 4. The calibration base year is 2007. Section 5 reports on the CO_2 emission accounting procedure. Finally, Section 6 provides a brief validation of model results.

2.1 Fundamentals

Programming Language and Solver The model is written in GAMS and uses the non-linear solver CONOPT.

Time The time horizon for the optimization is 2005-2100, with a discrete time step resolution of 5 years. The first time step, "2005", covers the period 2005-2009. The calibration of the model is performed for the year 2007, the median year in the range. Subject to analysis are the consecutive time steps from 2005 to 2050. The reason for excluding the later years from the analysis is the occurrence of undesirable "burn-out" effects towards the end of the simulation period. It is common practice in optimization models to cut off the period of analysis ahead of the end of the time horizon.

Fluctuating Renewables Variable renewable electricity generation fluctuates on very short time scales. Since the time resolution in REMIND-D is in 5 year time-steps, these effects cannot be modeled explicitly. However, neglecting the system requirements that arise from high penetrations of fluctuating renewables significantly understates the integration costs of renewables. In REMIND-D, a residual load duration curve approach captures most of the challenges that arise from high shares of fluctuating renewables without increasing the temporal resolution of the model. Ueckerdt et al. (2011) elaborates of the concept and validates the approach with a detailed dispatch model of Germany.

Geographical Resolution As a system boundary for REMIND-D, the geographical borders of Germany guide the cut-off since the focus of the model is on *domestic* mitigation. Imported energy carriers come at exogenous prices and Germany is assumed to act as a price taker. Within the model, the geographical dimension is parameterized in an appropriate way for covering geographic first-order effects, e.g. distribution technologies. REMIND-D is a single-region model.

Demand Sectors REMIND-D considers the aggregated demand sectors industry (IND), residential & commercial (RES&COM) and transport. Each sector demands different final energies, or in the case of the transport sector energy services. Elasticities of substitution determine the endogenous development over time.

Equilibrium The concept of equilibrium means that a system is in a state that will not change unless external influences change one or more variables. A market that is in equilibrium is in a state such that supply and demand match at the equilibrium price. There are many ways to find the equilibrium solution for a system. REMIND-D chooses to do so by maximizing the intertemporal welfare. According to the 2nd theorem of welfare economics, such a solution coincides with the market solution under the assumption of Pareto-efficiency. REMIND-D finds a simultaneous equilibrium in capital and energy markets.

Perfect Foresight The assumption of perfect foresight is a theoretical assumption necessary in the model setup for finding a solution to the equilibrium problem. Perfect foresight essentially means that the long-term consequences of a particular decision in a particular year are entirely foreseeable for the solution process. The solution process for REMIND-D is iterative, meaning the solver calculates a particular solution pathway over the time horizon and reaches a particular value for the optimization objective and stores it. In the next iteration, some alternative decision is made in the solution pathway and the solver compares the new value for the optimization objective to the one previously obtained. If it is higher, the older pathway is dropped and the new pathway serves as a benchmark. Again, some decision is altered and the objective value compared. This process repeats until the change in the optimization objective is continuously below a certain threshold, which is a very small number. In this case, the solution process ends and an optimal solution is reported. The concept of perfect foresight in REMIND-D implies that the results of the model represent optimal pathways and are not expert forecasts or simulations.

Myopic Behavior Fixing certain variables for a selected period of time on a pathway that does not coincide with the optimal solution is a means of introducing myopic behavior into the model. Upon comparing results from a complete perfect foresight model run with one that includes myopic behavior allows for distilling its effects.

Discounting The pure time preference rate in REMIND is rate is set to 1% in the standard setting. Endogenously, the interest rate adjusts to ±3%, depending on the scenario and time step. Thus, for the discounting of GDP losses, a discount rate of 3% is used in the standard setting.

Endogenous Learning REMIND-D draws on the concept of learning-by-doing (Arrow 1962) for modeling the cost functions of innovative low carbon technologies endogenously. The application of the concept to bottom-up energy system models was pioneered by Messner (1997) and Barreto (2001). For a critical discussion see Kahouli-Brahmi (2008) or Nordhaus (2008). The underlying idea is that, historically, the specific investment costs of technologies have been reduced significantly with increased installed capacity. Learning rates are a means to express how much the specific investment costs reduce upon a doubling of installed capacity. The innovative low-carbon technologies in REMIND-D are subject to non-linear, endogenous learning that is split into domestic and global components, implying the reasoning that for some components global capacities are the main drivers and for others national capacities.

Scenario The term scenario refers to one particular set of constraints of the optimization space, i.e. one set of exogenous assumptions.

Mitigation Enforcement In the standard setting, mitigation is enforced via a domestic CO_2 budget over the time horizon, inspired by Meinshausen et al. (2009) and WBGU (2009). Other possible implementations include prescribing a CO_2 tax or a specific annual emission trajectory.

Baseline Scenario In the Integrated Assessment community, often a baseline scenario is one that has unconstrained GHG emissions. For Germany, such a pure baseline is unlikely as emission reduction policies are already in place and commitments are high. The definition of a baseline scenario for REMIND-D consequently follows the idea that mitigation continues at a moderate level, i.e. reaches around 40% CO_2 domestic emission reduction in 2050 versus the 1990 level.

Policy Scenario In the context of REMIND-D a policy scenario is one that is subject to a stricter CO_2 emission reduction target than the baseline scenario.

Mitigation Costs Comparing the results of a baseline and policy scenario that differ only with respect to the emission constraint allows for determining the differential effects of mitigation policy. This implies a cost-effectiveness mode of analysis. Climate damages and positive co-benefits of mitigation are not considered in REMIND-D.

Mitigation costs are inherently negative and may be analyzed on all levels, e.g. from GDP losses to differences in electricity prices.

3 The Macroeconomic Module

The macroeconomic module of REMIND-D comprises the optimization objective, a social welfare function, and the production function. They are calibrated to represent the aggregate of German households and firms, respectively. While a hybrid economy-energy system model is theoretically intriguing, it is very challenging to calibrate it to a particular country. This is due to the fact that energy demand is represented endogenously by nested CES-functions, which require substitution elasticities, factor productivity growth rates and initial relative prices for calibration. The usual procedure for a Ramsey-type growth model is to operate under an input-validation paradigm and estimate them econometrically based on past data. However, for the most of the production factors in the case at hand, these data are unobservable. The time series which are potentially available only go back to 1991 for unified Germany. Such short time series yield insignificant econometric results. An alternative is to calibrate the model based on output-validation.

One means of providing output-validation is to rely on heuristics and calibrate the model behavior so it reproduces future developments that are judged as highly likely by expert consensus. Two heuristics serve for calibrating REMIND-D for Germany. (1) In a baseline scenario, with only moderate mitigation, historical trends in observable variables will continue smoothly. (2) In an ambitious mitigation policy scenario, energy demand will evolve in line with the predictions of detailed bottom-up energy system models. The calibration parameters in the macroeconomic module are adjusted through trial-and-error so as to fulfill these two heuristics as good as possible. The calibration was evaluated and improved in dedicated expert workshops within the ENCI LowCarb (Engaging Civil Society in Low Carbon Scenarios) [3] project.

3.1 Optimization Objective

The optimization objective of REMIND-D is an intertemporal social welfare function that depends on the intertemporal sum of logarithmic per capita consumption, i.e. utility U. For the underlying assumptions consult Maußner and Klump. (1996).

$$U = \sum_{t=t_0}^{T} \left(\Delta t \cdot e^{\xi(t-t_0)} L_t \cdot \ln\left(\frac{C_t}{L_t}\right)\right) \tag{1}$$

The variables L_t and C_t are population and consumption and the subscript t indicates time. We assume a pure rate of time preference ξ of 1%. The logarithmic functional

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[3] ENCI LowCarb is financed by the 7th Framework Programme for Research of the European Commission. For further information please visit www.lowcarbon-societies.eu.

Table 1: Assumed development of the German population in Million inhabitants (Kirchner et al. 2009).

2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
82.41	81.89	81.10	79.80	79.19	78.58	77.28	75.98	74.07	72.17

relationship between per-capita consumption and utility results from assuming the intertemporal elasticity of substitution to equal one. Via the steady state conditions and the Keynes-Ramsey rule, the endogenous interest rate amounts to around 3%; the exact value ultimately depends on the endogenous economic growth rate in the respective time step. If desired, the pure rate of time preference in the model can be altered. Table 1 reports the population forecast that is assumed in REMIND-D. It is derived from (Kirchner et al. 2009), who base their forecast on the prognosis from the national statistics bureau (Statistisches Bundesamt 2006).

3.2 Production Function

The backbone of the macroeconomic module is the production function, which ultimately determines the macroeconomic output Y, i.e. the gross domestic product (GDP). The production function applied in REMIND-D is a nested "Constant Elasticity of Substitution" (CES) production function. On the highest level, the production factor inputs considered are capital, labor and energy, with the latter being determined by several sub-nested CES-functions that are constructed according to the substitutability in terms of providing similar useful energy or energy services.

Formally, the production function is defined as follows for each layer described by the mapping M_{CES}, assigning the respective output factor $V_t(\upsilon_{out})$ to the available input factors $V_t(\upsilon_{in})$.

$$V_t(\upsilon_{out}) = \phi(\upsilon_{out}) \cdot \left(\sum_{M_{CES}} \left(\theta_t(\upsilon_{in}) \cdot V_t(\upsilon_{in})\right)^{\rho(\upsilon_{out})} \right)^{\frac{1}{\rho(\upsilon_{out})}} \qquad \forall t, \upsilon_{out} \tag{2}$$

$$M_{CES} = (\upsilon_{in} \times \upsilon_{out}) \in \mathfrak{M}_{CES}$$

The parameter $\phi(\upsilon_{out})$ is a scaling factor that represents total factor productivity and is set equal to one in REMIND-D. The parameter $\theta_t(\upsilon_{in})$ represents an efficiency factor that is determined endogenously for each production factor in the first time period based on its income share and the relative price of supplying one unit of the demanded production factor. The relative prices in the first time period are derived from the calibrated energy system. The growth rate of the efficiency factor is an exogenous input. The parameter

$\rho(\upsilon_{out})$ is determined by the elasticity of substitution σ defined for each CES-nest. The definition is according to Equation 3.

$$\sigma = \frac{1}{(1-\rho)} \tag{3}$$

For a graphical illustration of the production function mapping M_{CES} and elasticities of substitution σ see Figure 3. Note that all outputs (intermediate and GDP) represent monetary values. Table 2 reports the efficiency factors $\theta_t(\upsilon_{in})$ for each final energy demand.

The elasticities of substitution in the nested CES function have a techno-economic inter-

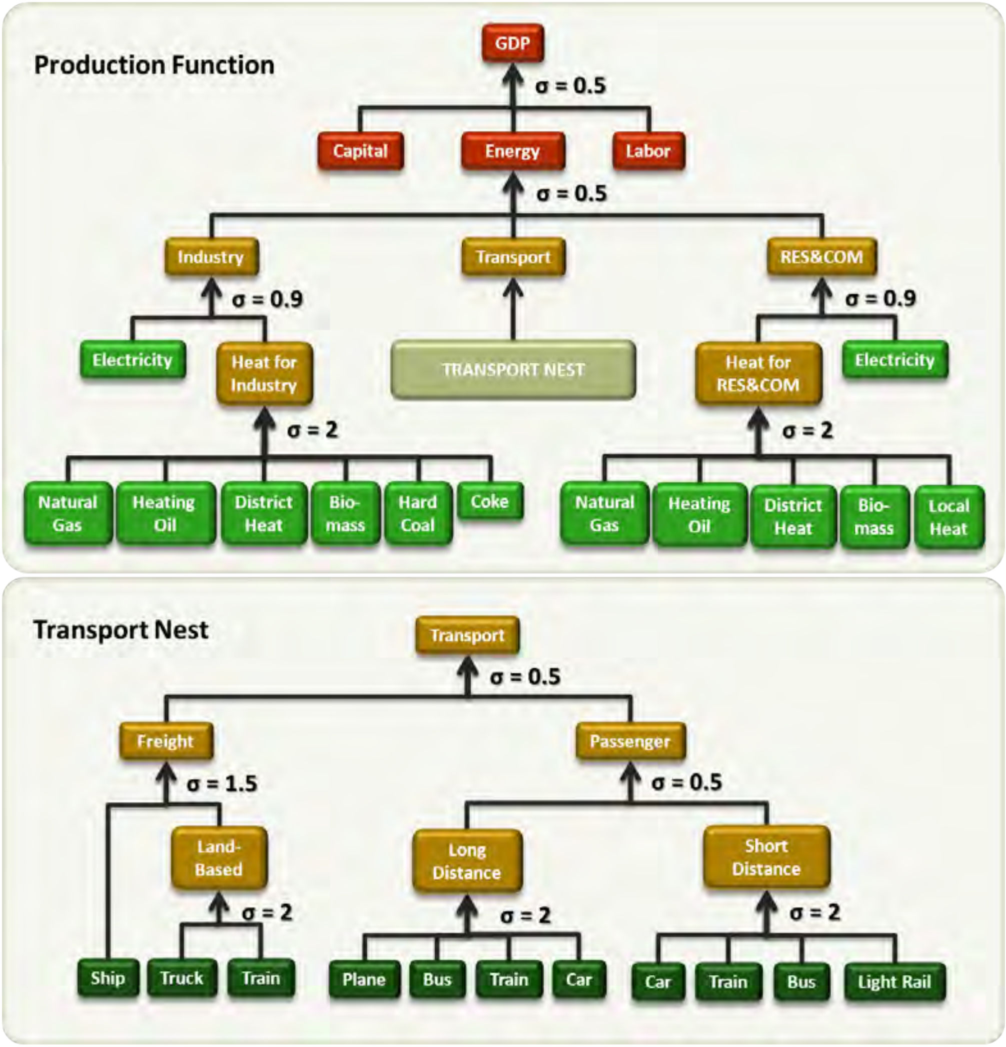


Figure 3: The nested CES-production function of REMIND-D with substitution elasticities σ. RES&COM = Residential & Commercial.

Table 2: Assumed growth rates of the efficiency factor $\theta_t(\upsilon_{in})$ in %.

%	Industry	RES&COM	Gt/Gp-km	Freight	PFD	PSD
Natural Gas	1.44	0.40	Ship	0.50		
Electricity	1.18	1.47	Truck	0.50		
District Heat	1.52	0.40	Train	0.50	1.50	1.50
Heating Oil	2.75	-9.00	Car		1.50	1.50
Biomass	1.18	0.60	Light Rail			1.20
Local Heat		0.60	Bus		1.50	1.20
Coke	2.65		Airplane		1.20	
Hard Coal	2.65					

pretation. For example, from an engineering point of view it is a simple task to substitute an oil furnace for a gas furnace in households. However, energy for industry and energy for transport are economic complements. In general, the substitutability increases with the level of detail in the branches. Depending on the substitution elasticity of the respective CES-nest, the effect of the efficiency growth rates is substantially different: If $\sigma < 1$, the production function demands relatively less from an input with higher $\theta_t(\upsilon_{in})$, and vice versa if $\sigma > 1$. This is also valid for aggregate intermediate factors. Assumptions about the growth rates of the efficiency factors $\theta_t(\upsilon_{in})$ are difficult to obtain from empirical data as these efficiency growth rates unify a variety of unobservable factors. The underlying idea is that over time more output may be produced from the same amount of input because the use of the final energy becomes ever more efficient. Essentially this argument rests on the idea of technological progress. However, the technological progress in the energy supply chain is represented explicitly in the energy system module. Separability of technological progress and demand reductions due to sufficiency is not measurable. Hence, the exogenous growth rates of the efficiency factors $\theta_t(\upsilon_{in})$ are chosen as to fulfill the two heuristics introduced above.

In the calibration year 2007, the GDP in Germany was 2428 billion € (Statistisches Bundesamt 2012) and the capital stock amounted to 10,206 billion € (Statistisches Bundesamt 2009). The production factor labor is assumed to be price-inelastic and population is used as a proxy. As a consequence of this simplifying practice, the labor force is assumed to develop proportionally to the total population. For this reason, REMIND-D is not suitable to analyze the labor market implications of mitigation.

3.3 Energy Demand

The energy demand in REMIND-D is modeled as an aggregate for each of the three end-use sectors industry, residential & commercial (RES&COM) and transport, as defined in the German energy balances (AGEnergiebilanzen 2010). In REMIND-D the sectors industry and the RES&COM demand final energy carriers; the specific appliances that convert these energy carriers to useful energy are beyond the scope of the model. This

Table 3: The left panel displays the final energy demand in Germany for 2007 in PJ, the data are from AG Energiebilanzen (2010). The right panel displays the energy service demand of the sectors domestic Freight and Passenger Transport in billion ton-km (Gt-km) and billion person-km (Gp-km), respectively. PLD stands for 'passenger long distance', PSD for 'passenger short distance'. Data are based on BMVBS (2008); Kirchner et al. (2009); UBA (2009).

PJ	Industry	RES&COM	Gt/Gp-km	Freight	PLD	PSD
Natural Gas	945	1316	Ship	65		
Electricity	850	985	Truck	476		
District Heat	151	290	Train	114	35	45
Heating Oil	136	863	Car		339	549
Biomass	64	189	Light Rail			17
Local Heat		21	Bus		17	37
Coke	169		Airplane		59	
Hard Coal	167					

is different for the transport sector – here energy services in terms of ton-km (t-km) or person-km (p-km) are demanded, since transport technologies are modeled explicitly in the energy system module. Table 3 reports the initial energy demands in the calibration year 2007. The Industry sector consists of the branches mining, stone & clay quarrying and manufacturing and is based on the classification by the Federal Statistical Office. The RES&COM sector is rather heterogeneous and includes private households, manufacturing firms with fewer than 20 employees not included in manufacturing industry, commercial properties and enterprise premises, agriculture, commercial enterprises and private and public service companies and organizations. In the transport sector, a general differentiation is made between freight transport and passenger transport. Passenger transport is further subdivided into modal split and long and short distance.

3.4 Hard Link

The cost side of the hard link between the energy system module and the macroeconomic module is ensured by the budget equation illustrated in Equation 4, posing that output Y_t has to cover the investments into the macroeconomic capital stock I_t and all costs incurred by the energy system E_t. Consumption C_t enters the social welfare function. The production factor part of the hard link operates via individually equating the final energy and energy service demands of the macroeconomic module with those generated by the bottom-up energy system module.

$$Y_t = C_t + I_t + E_t \qquad \forall t \tag{4}$$

4 The Energy System Module

The bottom-up energy system module (ESM) of REMIND-D is calibrated to represent the German energy supply chain. Figure 4 sketches the general structure. Technically, the different levels of primary, secondary and final energy / energy services are interconnected by a set of balance and transformation equations. This section presents the calibration input data, the equations are in Bauer et al. (2011).

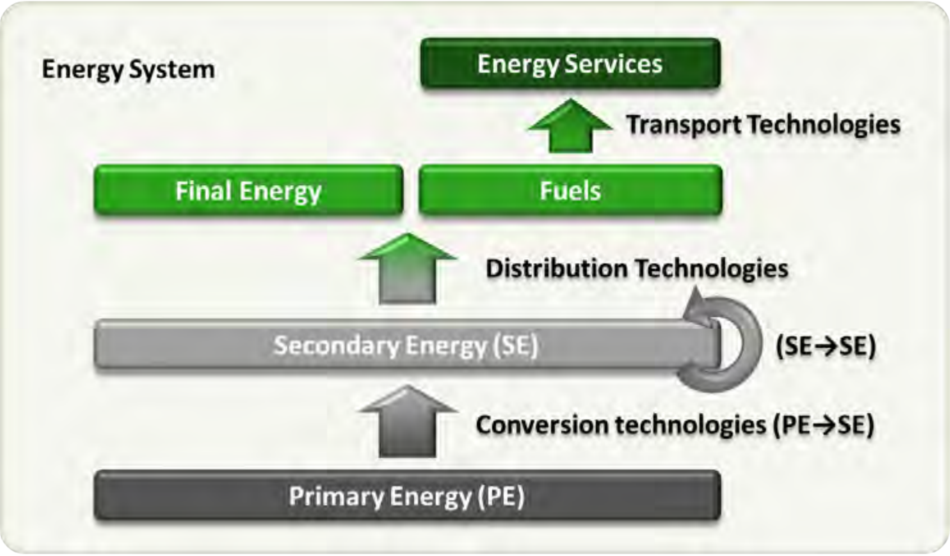


Figure 4: Schematic representation of the energy system module in REMIND-D.

Primary energy (PE) considered in REMIND-D are lignite, hard coal, crude oil, natural gas, uranium, wind power, solar irradiation, geothermal energy, hydro power and biomass. These constitute the plausible options for the German energy supply and are either imported or mined/used domestically. Section 4.1 elaborates on the potential, resource and price assumptions. PE is converted into SE by a multitude of energy conversion technologies. General characteristics of technologies in REMIND-D are introduced in Section 4.2. The detailed techno-economic parameterization is reported in Section 4.3, for both PE→SE conversion technologies (4.3.1) and SE→SE conversion technologies (4.3.2). SEs include electricity, hydrogen, district heat, coke, petrol, diesel, kerosene, heating oil, heavy fuel oil, biomass for industry and households, hard coal for industry, natural gas and local heat. To meet the final energy demand of the industry and RES&COM sector as well as fuel demand of the transport sector, the SEs are distributed with stylized technologies that proxy infrastructure requirements. These technologies are introduced in Section 4.4. Fuels are further converted into energy services by means of transport technologies, which are presented in Section 4.5.

4.1 Primary Energy

The ESM of REMIND-D considers renewable energy carriers, biomass and exhaustible fossil energy carriers. They characteristics differ in terms of associated CO_2 emissions and whether increased usage leads to an increase in fuel costs. Renewable energy is free of CO_2 emissions and free of fuel costs. Biomass is free of CO_2 emissions but increased usage leads to an increase in fuel costs. However, the use of renewable energies as well as biomass is limited to a specific technical potential. Exhaustible fossil energy carriers are CO_2 intensive and increased usage leads to an increase in fuel costs.

Renewable Energy Sources Renewable domestic primary energy sources include solar, wind onshore, wind offshore, deep geothermal, geothermal near-surface (for heat) and hydro. Table 4 gives an overview of the technical potentials estimated by different studies for Germany. Some differ substantially across the various studies. Reasons for the differences lie in differing assumptions on which the calculation of the technical potential rests. These are quite complex, including e.g. the size of the geographical region on which a primary energy carrier may be exploited and the distribution of wind speed or solar irradiation. In REMIND-D, each renewable potential is subdivided into different grades, representing the different quality classes of geographical sites with respect to average annual full load hours. Renewable energy technologies thus exhibit a gradual expansion with the best geographical sites exploited first, followed by those yielding less energy per area and year.

Table 4: Overview of technical potential estimates for renewable energy sources in TWh/a. The potentials assumed in REMIND-D are based further on BMU (2008) Scenario E-3, Nitsch et al. (2004) and Paschen et al. (2003).

TWh/a	BMU (2008)	UBA (2010)	SRU (2010)	REMIND-D
Solar-el.	105	248	112	105
Solar-th.	300	-	-	100
Wind-on.	68	180	90	90
Wind-off.	135	180	317	180
Geo-el.	150	50	223	64
Geo-th.	330	-	-	100
Hydro	25	24	28	28

Biomass Biomass differs from other renewable energy carriers in the sense that increased usage leads to an increase in fuel costs. This is represented by a biomass supply curve which is defined only up to a potential limit. As grown biomass is in competition with the food industry, the potential limit is up to political decisions on how much agricultural land may be used for energetic and how much may be used for food purposes.

Table 5 illustrates the assumed domestic higher-heating value potentials for Germany in 2005 and 2050, which are rather conservative. It is assumed that potentials for lignocellulose, sugar/starch and oily biomass linearly increase until 2050 and then stay constant. We assume that lignocellulose is only gained from scrap wood. The farmland used for the biomass potential may at most be quadrupled as compared to 2005. The potential for manure is already reached, as a major expansion of the livestock industry in Germany is not likely.

Table 5: Biomass potentials in REMIND-D for 2005/2050, from Nitsch et al. (2004) Variant "Naturschutz Plus" Scenario B. They are assumed to increase linearly between 2005 and 2050.

	BioLC (Lignocellulose)	BioSS (Sugar&Starch)	BioO (Oil)	BioM (Manure)
Potential[PJ/a]	450/700	40/250	60/200	150/150

Exhaustibles The fossil primary energy carriers crude oil, natural gas and hard coal are imported at exogenously set prices, based on the assumption that Germany acts as a price taker. This appears reasonable as the amount of fossil energy carriers used in Germany is relatively small compared to global volumes. Albeit hard coal and natural gas are also extracted domestically, these sources are neglected in REMIND-D. The reason is that the amount of natural gas extracted domestically is too small to make explicit modeling worthwhile. Shale gas is not considered. Hard coal mining is heavily subsidized, which will be phased-out until 2018. Table 6 reports the import price paths for the standard setting in REMIND-D.

Table 6: Import prices of fossil primary energy resources in €$_{2005}$ per GJ . Oil, natural gas and hard coal prices are from BMU (2008) Scenario "Maessig", uranium prices are from Du and Parsons (2009).

	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
Oil	7.51	8.66	9.56	10.54	11.52	12.49	13.29	14.08	14.60	15.12
Nat. Gas	4.66	6.92	7.65	8.43	9.22	9.99	10.63	11.26	11.68	12.10
Hard Coal	2.10	3.46	3.82	4.22	4.61	5.00	5.32	5.63	5.84	6.05
Uranium	0.45	0.50	0.59	0.71	0.84	1.00	1.18	1.41	1.67	1.99

Lignite is exclusively mined and consumed domestically, so we use an extraction cost curve approach in REMIND-D. The price of lignite rises with the cumulative extraction, which is limited to 6.1 Gt. This number corresponds to the amount of lignite that may still be extracted from already active open cast mines (DEBRIV 2009). Reserves are larger in Germany, but opening new mines will most likely be impeded by public protest.

The use of exhaustible fossil energy carriers leads to CO_2 emissions, whereby the application of Carbon Capture and Storage (CCS) technologies may contribute to significant reductions. Conversion technologies using biomass may also be used in combination with CCS, here it is possible to incur "negative" CO_2 emissions as biomass captures CO_2 from the atmosphere.

Nuclear energy is a highly controversial political topic in Germany. The atomic energy law (AtG) in Germany has undergone three major revisions in the past ten years. In 2002, the law was changed to ensure a nuclear phase-out until around the year 2020. In 2010, the law was revised to postpone the phase-out until around 2050. However, after Fukushima, the government decided in August 2011 to close down eight nuclear power plants immediately and subsequently decommission the remaining ones until 2022. In REMIND-D the nuclear phase-out according to AtG2011 is implemented.

4.2 Characteristics of Technologies

Main Input Each technology is assigned a main input energy carrier.

Other Input In case a technology needs some additional input for its process, this input is represented by means of a fixed input coefficient.

Main Product Each technology is assigned a main output.

Couple Product Some technologies inherently produce couple products in their process. In case their energetic share is not negligible, they are modeled by means of fixed couple product coefficients that relate the energetic couple product output to the main output.

Conversion Efficiency The conversion efficiency of a technology determines the ratio between energy input and output. Technologies that are considered to be technically mature have a constant conversion efficiency over time. Technologies that are expected to be refined in the future have time-dependent conversion efficiencies.

Capacities Historical capacity additions that have taken place in Germany since 1930 are an input to the model. Each vintage has a specific conversion efficiency. Over the optimization period, the stock of installed capacity is increased by investments and decreased when capacities reach the end of their technical lifetime.

Technical Lifetime Each technology is assigned a specific technical lifetime (TLT). Capacities built up in a certain time step t exist and produce output until the time step $t + TLT$. Optionally, lignite and coal power plants are exempted.

Full Load Hours Installed generation capacities produce output only in a fraction of the entire year due to maintenance or physical constraints. Hence, each technology has a characteristic full load hour ratio that relates the number of producing hours to the total hours in a year. For existing technologies, this number is derived from empirical observations. For renewable energies a discrete grade structure that differentiates between sites of different quality is implemented. For transport technologies this parameter is to be interpreted as person-km or ton-km per vehicle per year. For electricity generating technologies, the full load hours are endogenous to REMIND-D from 2010 onwards. Details on this issue are in Ueckerdt et al. (2011).

Investment Costs Building up capacities of a technology incurs investment costs. Each technology te is assigned a specific turnkey investment cost $in_{t,te}$ in €/kW, derived from the technical literature. Equation 5 defines the total investment costs IN_t incurred in a respective time step t, depending on the capacity additions $\Delta cap_{t,te}$.

$$IN_t = \sum_{te} (in_{t,te} \cdot \Delta cap_{t,te} + \gamma_{te} \cdot adj_{t,te}) \quad \forall t, te \tag{5}$$

For mature technologies, the specific investment costs are constant over time; for learning technologies they can decrease due to learning-by-doing effects. To prevent the model exhibiting excessively large expansion rates in a certain time step, investment costs are potentially increased by technology-specific adjustment cost $adj_{t,te}$, scaled with a scaling coefficient γ_{te}, set to 0.4. Adjustment costs are a means to increase model realism.

Learning Technologies For some technologies specific investment costs are expected to decrease with the cumulative installed capacity, according to the concept of "Learning by doing". In REMIND-D, a modified one-factor learning curve concept is used that is summarized in Equation 6, determining the specific investment costs, $in_{t,te}$, for the subset of learning technologies $tel \subset te$.

$$in_{t,te} = \alpha \cdot capcum^{\beta}_{t,te} + inF_{te} + inG_{t,te} \quad \forall t, tel \subset te \tag{6}$$

$$\begin{aligned} \alpha &= \frac{in_{2005,te} - inF_{te}}{in^{\beta}_{2005,te}} \\ \beta &= \frac{in_{2005,te}}{in_{2005,te} - inF_{te}} \cdot \frac{\ln(1 - l_{te})}{\ln 2} \end{aligned}$$

Especially for onshore and offshore wind as well as solar photovoltaic, the domestic cumulative installed capacity $capcum_t$ is expected to have only an impact on local components of the specific investment costs, like fundaments, grid connections, or assembly. Hence, the specific investment costs for these three technologies are split into an initial local component $in_{2005,te}$, that exhibits cost decreases with a learning rate l_{te} up to a certain floor cost inF_{te}, and a global component $inG_{t,te}$ that experiences cost decreases on an international level and represents the solar panel or the generator for wind turbines. For learning technologies other than wind and solar photovoltaic it is assumed, that domestic capacities are the dominant driver for investment costs.

Adjustment Costs To prevent the model from exhibiting excessive expansion rates that would not occur in the real world due to inertia and general bottlenecks, adjustment costs are implemented. The idea of adjustment costs is to force the model into more gradual expansion paths by punishing fast increases and decreases of relative capacity additions with scaled monetary costs $adj_{t,te}$ that are specific for each technology and depend on the relative capacity additions between two subsequent years. Equation 7 shows the functional relationship.

$$adj_{t,te} = \frac{(\Delta cap_{t-1,te} - \Delta cap_{t,te})^2}{\Delta cap_{t-1,te} + \epsilon_{te}} \quad \forall t, te \tag{7}$$

For each technology, a specific capacity threshold ϵ is defined, representing an estimate of realistic capacity additions, based on past observations. For any capacity increase beyond the threshold, adjustment costs would be incurred and thereby increased the specific investment costs for a specific technology in a specific year. However, the model minimizes adjustment costs to a negligible level and instead smoothens the expansion paths. So the concept is rather theoretical and a means to increase model realism.

Operation and Maintenance Costs Besides investment cots, each technology incurs variable and fixed operation and maintenance costs (O&M costs) retrieved from the technical literature. Fixed O&M costs, omf_{te}, are defined in €/kW for each technology; variable O&M costs, omv_{te} in €/MWh. Equation 8 shows how total O&M costs, OM_t, in a respective year t are determined by the installed capacities $cap_{t,te}$ and amount of main product $MP_{t,te}$ for each technology te.

$$OM_t = \sum_{te} (omf_{te} \cdot cap_{t,te} + omv_{te} \cdot MP_{t,te}) \quad \forall t, te \tag{8}$$

Fuel Costs Fuel costs are incurred by those technologies that need costly primary energies as an input. These are hard coal, lignite, natural gas, uranium and biomass; price paths are discussed in Section 4.1. Total fuel costs FU_t in a respective time step are determined by the primary energy demand of a technology $d_{t,te,PE}$ multiplied with the price of the primary energy $p_{t,PE}$.

$$FU_t = \sum_{te,PE} (p_{t,PE} \cdot d_{t,te,PE}) \quad \forall t, te \tag{9}$$

Energy System Costs Total energy system costs E_t in a respective time step t are depicted in Equation 10. They need to be covered by the GDP in each time step. This is the monetary part of the hard link between the energy system and the macroeconomic module in REMIND-D.

$$E_t = IN_t + OM_t + FU_t \qquad \forall t \tag{10}$$

4.3 Conversion Technologies

4.3.1 Primary to Secondary Energy

An overview of the PE→SE conversion technologies and their acronyms is given in Table 7. The respective abbreviations are reported in Table 8. Missing in this overview is, due to space constraints, the Thermal Nuclear Reactor (TNR) that converts uranium into electricity, ethanol production from Biomass Sugar&Starch (BioSS-ETN) and diesel production from Biomass Oil (BioO-DIE). In case technologies appear in several fields, this indicates that they are subject to co-production. A prominent example is combined heat and power. Co-production occurs also to a lesser extent with other technologies, yet for the sake of readability they are not considered in the overview table. As becomes evident, hard coal, lignite and lignocellulose are very flexible primary energy carriers as they permit the production of almost all types of secondary energy carriers. Renewable energy sources are especially applicable for producing electricity. The secondary energy carriers electricity, hydrogen, gas, district heat, coke and petrol are as such usable for an end-consumer once distributed to the place of consumption. Middle distillate is an intermediate product. The secondary energy local heat is a pseudo-energy carrier as local heat is generated at the place of consumption.

The structure of Table 7 is suggestive of a set of balance equations that relate the primary energy demand to secondary energy production via conversion efficiencies and full load hours on the technical side. On the economic side each technology has specific investment, variable and fixed maintenance costs and a technical lifetime. These parameters are presented in the following for each technology, organized by secondary energies that are the main product. The data is based on the referenced technical literature and represents best available technique values in most cases.

Electricity and District Heat All non-fluctuating electricity generation technologies' techno-economic parameters are reported in Table 9. Lig-PC and Coal-PC are conventional coal power plants with the highest CO_2 emission intensity of all electricity generating technologies. A minor improvement constitutes the construction of PC+ power plants, supercritical coal power plants that achieve a higher conversion efficiency. A combination with the Carbon Capture and Sequestration (CCS) technology allows for severely (80-90%) reducing the CO_2 emissions intensity but still use coal as a primary energy source, which could be of interest for the domestic lignite resources and considering the abundant global hard coal resources. Coal-PC/CCS and Lig-PC/CCS represent the post-combustion technology that separates the CO_2 from the flue gas in a chemical process after conventionally burning the pulverized coal. Two more CCS technologies are considered: Oxyfuel (PC/CCS-O) and Pre-Combustion (IGCC/CCS). The Oxyfuel process is different as the coal is burnt in an atmosphere that consists of re-circulated flu gas enriched with pure oxygen. Through the re-circulation process, the flu gas eventually consists to a very large extent of CO_2 and can conveniently be processed further.

Table 7: Overview of the primary to secondary (PE→SE) energy conversion technologies represented in REMIND-D.

Secondary Energy Carriers	**Primary Energy Carriers**					
	Hard Coal	Lignite	Gas	BioLC	BioM	RES
Electricity	Coal-PC Coal-PC+ Coal-PC/CCS Coal-PC/CCS-O Coal-IGCC/CCS Coal-CHP	Lig-PC Lig-PC+ Lig-PC/CCS Lig-PC/CCS-O Lig-IGCC/CCS Lig-CHP	Gas-TUR Gas-CC Gas-CC/CCS Gas-CHP	BioLC-COM BioLC-CCHP BioLC-GCHP BioLC-IGCC BioLC-IGCC/CCS	BioM-CHP	Solar-PV Wind-OFF Wind-ON Geo-HDR Hydro
Hydrogen	Coal-H2 Coal-H2/CCS	Lig-H2 Lig-H2/CCS	Gas-SMR Gas-SMR/CCS	BioLC-H2 BioLC-H2/CCS		
Gas	Coal-GAS	Lig-GAS	Gas-TR	BioLC-GAS	BioM-GAS	
District Heat	Coal-HP Coal-CHP	Lig-HP Lig-CHP	Gas-HP Gas-CHP	BioLC-HP BioLC-CCHP BioLC-GCHP	BioM-CHP	
Coke	Coal-COK					
Petrol				BioLC-ETN		
Middle-distillate	Coal-TL Coal-TL/CCS	Lig-TL Lig-TL/CCS		BioLC-TL BioLC-TL/CCS		
Local Heat						Solar-TH Geo-HPU

Table 8: Abbreviations in alphabetical order.

CC:	Combined Cycle	IGCC:	Integrated Gasification CC
CCHP:	Combustion with CHP	OFF:	Offshore
CCS:	Carbon Capture and Storage	ON:	Onshore
CHP:	Combined Heat and Power	PC:	Pulverized Combustion
COK:	Coking	PC+:	Supercritical PC
ETN:	Ethanol production	PV:	Photovoltaik
GAS:	Gasification	SMR:	Steam Methane Reforming
GCHP:	Gasification with CHP	TH:	Thermal Hot Water Generation
H2:	Hydrogen Production	TL:	Liquefication
HDR:	Hot-Dry-Rock	TR:	Transformation
HPU:	Heat Pump	TUR:	Turbine

Post-combustion achieves higher removal rates. The Pre-Combustion technology relies on the gasification of coal in a first step and then separates the CO_2 before combusting the hydrogen-rich synthetic gas in a gas turbine. In the model, separated CO_2 enters a stylized CCS-Chain that represents a CO_2-pipeline infrastructure and sequestration sites. The compression of CO_2 for sequestration requires electricity, the losses in this process are accounted for by reducing the conversion efficiency of the technologies facilitating CCS.

Apart from supercritical or CCS power plants, the combined heat and power (CHP) technology constitutes a mitigation option. In a CHP plant, the waste-heat is recycled by flowing through a district heat network and is used for warm water and heating in households or industry. A CHP plant can either produce heat or electricity as a main product. In Germany, they are generally producing more heat than electricity. In the extreme case of producing only district heat, they are then simply heat plants (HP).

Electricity generation from natural gas has the technical advantage over coal that gas power plants are able to ramp up and down within very short time scales and hence are a good complement to fluctuating RES, especially valid for gas turbines (Gas-TUR). Gas-TUR have the characteristic of very low specific investment costs but high fuel costs as conversion efficiencies are moderate and Gas is a relatively expensive primary energy carrier. Combined cycle plants (Gas-CC) have significantly higher conversion efficiencies, but are less flexible. They may also be constructed with post-combustion CCS, yet this option is more costly and possesses an even lower degree of flexibility. Electricity production from natural gas has approximately half the CO_2 emission intensity than from lignite and as such presents itself as a mitigation option. From a geopolitical point of view, the increased dependence on natural gas would make Germany more dependent on supply countries. A major possibility for domestic gas supply could be the methanation of hydrogen produced during temporary overproduction of electricity by RES; this option is not yet included into REMIND-D but work is in progress.

Lignocellulose is currently combusted for either only power generation (BioLC-COM), both heat and power (BioLC-CCHP) or only heat (BioLC-HP). Gasification of lignocellulosic biomass is a future technology that is still in a demonstration phase but may become very attractive in the future, both for co-generation (BioLC-GCHP) and sole electricity production (BioLC-IGCC). The latter may also be combined with CCS, it would then be possible to not only be CO_2 emission-neutral, as is the case for all BioLC technologies, but even create negative CO_2 emissions. The BioMCHP technology relies on manure that is being mixed with some parts of Sugar and Starch Biomass (BioSS) for achieving an anaerobic gasification. After cleaning this gas it is used with a normal burner and turbine to produce heat and power. Hydro represents a standard running water hydropower plant and Geo-HDR the production of electricity from hydrothermal resources. The full load hours reported are an average, as a discrete grade structure distributes the potential to slightly different quality sites with differing full load hours. DOT refers to a diesel oil turbine, which is actually a SE→SE technology, but is included into this overview table.

Table 9: Techno-economic parameterization of (PE→SE) energy conversion technologies represented in REMIND-D, that produce electricity or heat as main product and are non-fluctuating technologies. Full load hours are empirical values of 2007 and are only fixed in the first time step of REMIND-D. Sources: Hake et al. (2009), Schlesinger et al. (2010), IEA (2010), Bauer et al. (2009), MIT (2007), EC (2006),Nitsch et al. (2004), Schulz (2007), Konstantin (2009a),Konstantin (2009b), Thrän et al. (2009), BMU (2008), own calculations.

	TLT Year	Investment Costs €$_{2005}$/kW	Fix Costs €$_{2005}$/kW	Variable Costs €$_{2005}$/MWh	Conv. Eff. %	Full Load h/pa
Coal-PC	45	1150	22	6.85	44	6830
Coal-PC+	40	1800	36	7.99	50	6830
Coal-PC/CCS	45	1800	29	11.41	38	6830
Coal-PC/CCS-O	40	1900	34	13.7	41	6830
Coal-IGCC/CCS	40	2000	44	13.7	42	6830
Coal-CHP	40	430	9	4.57	$62_{th}/24_{el}$	5000
Coal-HP	45	350	11	2.76	93_{th}	4290
Lig-PC	45	1300	22	9.13	43	7000
Lig-PC+	40	1600	27	7.99	48	7000
Lig-PC/CCS	45	2100	29	14.84	35	7000
Lig-PC/CCS-O	40	2200	35	17.12	39	7000
Lig-IGCC/CCS	40	2300	46	17.12	40	7000
Lig-CHP	40	530	11	5.14	$57_{th}/18_{el}$	5700
Lig-HP	50	400	12	2.76	91_{th}	6750
Gas-TUR	30	300	9	1.84	32	1750
Gas-CC	35	500	30	0.53	55	1750
Gas-CC/CCS	35	850	34	1.87	51	1750
Gas-CHP	35	380	23	0.34	$50_{th}/30_{el}$	5000
Gas-HP	45	240	7	1.84	95_{th}	7890
BioLC-COM	40	2200	77	6.19	27	7010
BioLC-CCHP	40	3700	130	3.80	14	5960
BioLC-GCHP	40	4000	140	2.77	38	5960
BioLC-IGCC	40	1500	60	2.89	42	7010
BioLC-IGCC/CCS	40	2061	82	4.64	31	7010
BioLC-HP	40	450	12	1.20	85_{th}	4990
BioM-CHP	40	2700	135	1.70	38	7010
Hydro	80	5000	100	-	100	4820
Geo-HDR	35	4427	177	-	100	8000
DOT	40	322	10	0.92	30	800

Table 10: Techno-economic parameterization of the fluctuating learning technologies Sol-PV, W-OFF and W-ON. The first number given for investment costs refers to the local share, the second number to the global share. Floor costs and learning rates apply only to local components. The model takes the sum of both numbers as investment costs in each year. Sources: Neij et al. (2003), Nitsch et al. (2004), Junginger et al. (2004), Junginger et al. (2008), Konstantin (2009a), Schiffer (2008), Vrijmoed et al. (2010), own calculations.

	TLT	Investment Costs (in 2005)	Floor Costs	Learning Rate	Cumulated Installed Capacity (in 2007)	Fix Operating Costs
	Year	€$_{2005}$/kW	€$_{2005}$/kW	%	MW	€$_{2005}$/kW
Sol-PV	25	1600+2400	420	20	3811	40
W-ON	35	350+830	280	12	22247	22
W-OFF	25	1500+1000	580	25	0.001	125

Table 11: Development path of the exogenous global learning component in €$_{2005}$/kW. The data is retrieved from a REMIND-R 2° scenario.

	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
Sol-PV	2400	1459	1070	856	728	655	602	560	527	500
W-ON	828	705	627	602	589	583	578	573	570	566
W-OFF	1000	949	818	753	722	707	698	692	688	685

Fluctuating RES include Solar-PV, Wind-OFF and Wind-ON; their techno-economic parameters are reported in Table 10. They are implemented as learning technologies by means of the learning-by-doing approach, as described in Section 4.2. The idea is that the specific investment costs of these RES will decrease in the future due to cost efficiency developments in production and deployment with increasing installed capacities. As learning-by-doing effects operate on the global scale one cannot use exclusively German installed capacities for extrapolating future cost decreases. For all three technologies, some parts of the specific capital investment costs are related to local components, such as building the fundament or the grid connection of a solar panel or wind turbine. Such experiences have to be made within one country and domestic installed capacity is a good proxy driver for local components' cost reductions. However, the solar panel or the wind turbine's generator may be traded internationally and here global installed capacities' are an appropriate driver. The techno-economic parameterization for the fluctuating learning components is illustrated in Table 10. The development path of the global investment costs components are shown in Table 11, derived from a REMIND-R 2° scenario.

Table 12: Techno-economic parameterization of the primary to secondary (PE→SE) energy conversion technologies represented in REMIND-D that have hydrogen (H2) or gas as a main product. Sources: Yamashita and Barreto (2005), Gül et al. (2007), Hamelinck (2004), Nitsch et al. (2004), own calculatios

	TLT Year	Investment Costs €$_{2005}$/kW	Fix Costs €$_{2005}$/kW	Variable Costs €$_{2005}$/MWh	Conv. Eff. %	Full Load h/pa
Coal-H2	50	1020	31	0.42	59	7000
Coal-H2/CCS	50	1150	35	0.49	57	7000
Lig-H2	50	1015	31	0.42	57	7000
Lig-H2/CCS	50	1150	35	0.49	55	7000
Gas-SMR	45	400	12	12.70	73	7890
Gas-SMR/CCS	45	445	13	16.91	70	7890
BioLC-H2	45	1127	113	0.97	61	7880
BioLC-H2/CCS	45	1368	137	0.97	55	7880
Elec.-H2	17	241	12.05	0.25	62	7880
Coal-GAS	50	725	22	0.38	60	4800
Lig-GAS	50	725	22	0.38	58	7000
BioLC-GAS	40	2817	141	1.38	55	7450
BioM-GAS	40	2415	121	1.10	60	7450

Hydrogen and Gas The techno-economic parameterization of technologies producing gaseous secondary energy carriers are displayed in Table 12. Currently, hydrogen is mainly used for chemical processes but not as a source of energy. However, it could potentially be useful in the future for delivering process heat to industry or as fuel in nonstationary appliances like cars and buses. Conventional technologies for producing hydrogen is steam metane reforming (SMR) from natural gas and electrolysis, which is a SE→SE technology. SMR can also be coupled with CCS, then the hydrogen production would be almost carbon neutral. Other possible technologies for producing hydrogen include converting hard coal, lignite or lignocellulosic biomass first into synthetic gas and then into hydrogen, both with and without CCS.

Gas is currently imported to a large extent in the form of natural gas obtained from drilling. Yet this primary energy carrier could also be produced by the gasification of hard coal, lignite and lignocellulotic biomass. Under the EEG scheme, the production of biogas by fermentation of manure with grass or maize silage has been subsidized, hence, recently several biogas plants started operating in Germany (Thrän et al. 2009).

Liquids and Others The vast majority of fuels for transport was produced from fossil crude oil in 2007. REMIND-D features a refinery sector that is explained in detail in

Table 13: Techno-economic parameterization of the primary to secondary (PE→SE) energy conversion technologies represented in REMIND-D, that have raffinate, diesel, petrol, coke or local heat as a main product. Sources: Krey (2006), Yamashita and Barreto (2005), Gül et al. (2007), Hamelinck (2004), Ragettli (2007), Tijmensen et al. (2002), Nitsch et al. (2004), own calculatios

	TLT Year	Investment Costs €$_{2005}$/kW	Fix Costs €$_{2005}$/kW	Variable Costs €$_{2005}$/MWh	Conv. Eff. %	Full Load h/pa
ATDES	30	37	3.7	0.13	53	7880
Coal-TL	50	805	40	0.38	40	7450
Coal-TL/CCS	50	840	46	0.38	40	7450
Lig-TL	50	805	40	0.38	38	7450
Lig-TL/CCS	50	840	46	0.38	38	7450
BioLC-TL	45	2012	80	0.97	40	7970
BioLC-TL/CCS	45	2415	97	0.97	41	7970
BioO-DIE	45	104	5	0.46	93	7880
BioSS-ETN	45	394	45	3.58	55.3	7920
BioLC-ETN	45	1918	125	8.94	36.3	7920
Coal-COK	40	240	12	0.38	80	5250
Solar-TH	25	1127	34	-	100	867
Geo-HP	35	1610	48	-	100	4380

Section 4.3.2 as it conceptually belongs to the class of secondary to secondary energy conversion technologies. The first step in a refinery is the atmospheric distillation (ATDES), in which the crude oil goes through a fractional distillation at atmopspheric pressure. The main output of the ATDES process is raffinate, couple production yields 34.45% of middle distillate, 10.60%of petrol and 1.60% of heavy fuel oil. The gaseous fraction is neglected as it is only a small energetic fraction and often the refinery gas, at it is called, is re-used in the refinery itself for heating purposes in the distillation processes. Middle distillate is further refined to petrol, diesel or heating oil and can also be produced from hard coal, lignite or lignocellulosic biomass.

Due to several incentive schemes, biofuels had a minor share of 8% for diesel consumption and 2% for petrol consumption in Germany in 2007. Biosynthetic diesel can be directly produced from oily biomass, mainly rapeseed oil in Germany, by means of transesterification with methanol (BioO-DIE). Ethanol is produced from sugar and starch biomass (BioSS-ETN) and admixed recently with 5% to the standard petrol. Liquefaction of lignocellulosic biomass is known under the keyword second-generation biofuel production and may become a viable large-scale production of biofuels that is not subject to ethical problems in the future. On the contrary, oily as well as sugar and starch biomass may be used as food instead of energetic use, which leads to severe political discussions in Germany.

Other PE→SE technologies are the coking process that produces coke from hard coal that is mainly used in steel production and heat pumps for domestic use. As already mentioned, heat pumps produce local heat at the residential place of consumption. They use electricity as input, besides the solar thermal or low-pressure geothermal potential.

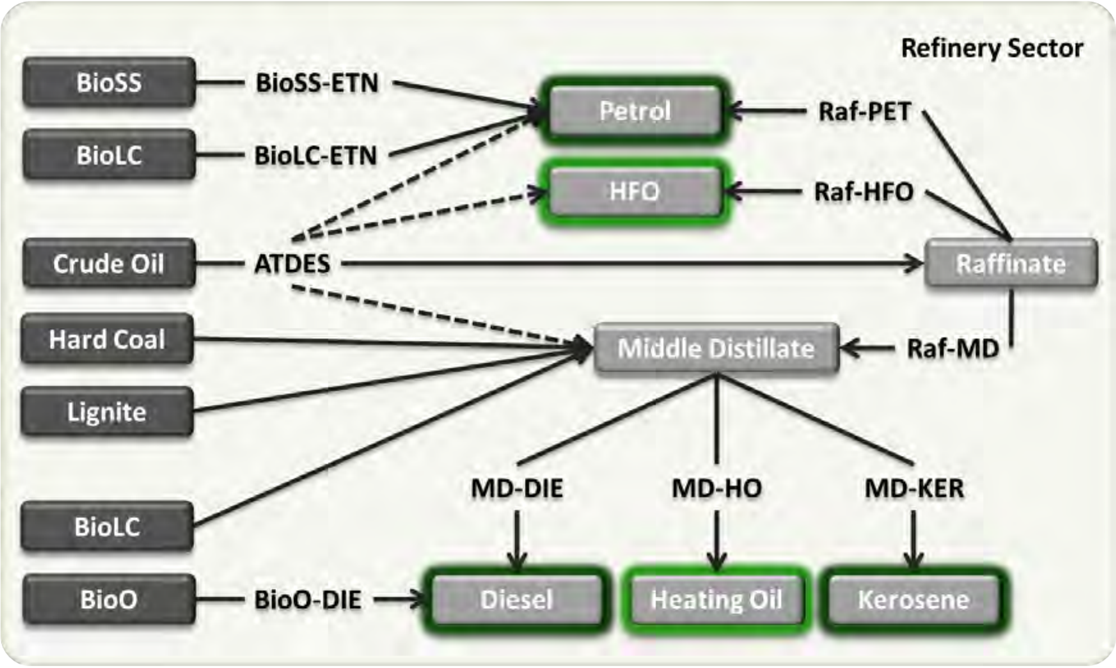
4.3.2 Secondary to Secondary Energy

Apart from the technologies electrolysis and diesel oil turbine, that were already discussed in the last section, the refinery sector is implemented as a set of SE→SE-technologies as illustrated in Figure 5. It is modeled in a stylized way to represent the complexity of a real-world refinery and permit the necessary degrees of freedom regarding the output mix. The first step in the conventional refinery process is the atmospheric distillation (ATDES), that produces raffinate as a main product, with fixed couple production of petrol, middle distillate and heavy fuel oil (HFO), as discussed in the last section. Raffinate and middle distillate represent intermediate products, that are further processed into usable fuels. The respective technologies have short technical lifetimes of 10 years, so the refinery sector does not per se dictate the model the fuel mix used in the transport sector. Raffinate may be converted in Petrol or HFO with the technologies Raf-PET and Raf-HFO, these technologies represent the vacuum distillation in a real-world refinery. Middle Distillate may be converted into diesel (MD-DIE), Heating Oil (MD-HO) or Kerosene (MD-KER). The techno-economic parameterization of these technologies is derived from aggregation of the very detailed refinery representation in Krey (2006) and reported in Table 14

Table 14: Techno-economic parameterization of the intermediate refinery processes. Sources: Krey (2006), MWV (2008), own calculatios

	TLT Year	Investment Costs $€_{2005}$/kW	Fix Costs $€_{2005}$/kW	Variable Costs $€_{2005}$/MWh	Conv. Eff. %	Full Load h/pa
Raf-PET	10	157	7.85	0.504	90	7880
Raf-HFO	10	41	2.05	0.104	90	7880
Raf-MD	10	134	6.70	0.447	90	7880
MD-KER	10	24	1.20	0.919	90	7880
MD-HO	10	16	0.80	0.919	90	7880
MD-DIE	10	8	0.40	0.919	90	7880

Figure 5: The refinery sector in REMIND-D. Dashed arrows indicate couple production. Abbreviations are explained in the text.



As has been discussed in the last section, to substitute the crude oil in the fuel production process, Middle Distillate may also be produced from hard coal, lignite or lignocellulose by means of liquefaction. Furthermore, Diesel may be produced from oily biomass and petrol may be produced from sugar and starch (first-generation biofuels) or lignocellulose (second-generation biofuels).

4.4 Distribution Technologies

In the single region model REMIND-D, distribution technologies are a means of representing distribution networks and infrastructure requirements in a parameterized way, since the spatial dimension is not applicable. Table 15 presents the considered technologies and their acronyms, Table 16 the techno-economic parameterization.

The distribution technologies capacities are expressed in capacity per energy unit of energy carrier that needs to be distributed. For the RES&COM sector, the distribution is generally more costly than for the IND sector, as distribution networks need to be highly branched. For the transport sector, the distribution technologies consider the fuel station network. In the model, the existing distribution technologies need not necessary to be used at full capacity to prevent the phenomenon that they dictate the choice of final energies or energy services in climate policy scenarios.

Table 15: Overview of the distribution technologies in REMIND-D.

Secondary Energy Carriers	Industry	RES&COM	Transport
Natural Gas	D_Gas-IND	D_Gas-RES&COM	D_Gas-Trans
Electricity	D_El-IND	D_El-RES&COM	D_El-Trans
District Heat	D_DHeat-IND	D_DHeat-RES&COM	
Heating Oil	D_HeatOil-IND	D_HeatOil-RES&COM	
Local Heat		D_LHeat-RES&COM	
Coke	D_Coke-IND		
HFO	D_HFO-IND		
H2	D_H2-IND		D_H2-Trans
Petrol			D_Pet-Trans
Diesel			D_Die-Trans
Kerosene			D_Ker-Trans

Natural gas networks consist of major long-distance pipelines and local distribution infrastructure, especially for the RES&COM sector. For the transport sector is assumed that only the fuel-filling infraststructure and the access to the pipeline-system is required additionally and existing gas stations can be retrofitted. Electricity grids in Germany exist in three different formats: maximum voltage (220 or 380 kV), medium voltage (6 to 30 kV) and low voltage (240 or 400 V) and need to be extended for coping with a large share of RES in the system, which is necessary in climate policy scenarios. Of course, a proper representation of grids needs a fine geographical resolution in the energy system. In REMIND-D the expenses for electricity grids are approximated. For the electrification of the transport sector, eventually a network of charging stations is necessary. Since charging requires up to several hours, it is unlikely that the existing petrol station network may be the core of the future charging infrastructure. District heating networks are pipeline systems that are either under or above ground. Heating Oil and HFO is assumed to be transported with trucks and has very low upfront investment costs that represent the costs for special fuel trucks with short technical lifetimes. On the distribution of coke there is very little information available, it is assumed that coke is produced spatially close to the site of industrial consumption, so distribution costs are very small.

The built-up of a hydrogen network for delivering process heat for the industry sector required pipeline infrastructure. For the transport sector, not only the pipelines are needed, but also a retrofit of existing petrol stations with H2-filling devices. Due to fast fill-up of the tank, the existing petrol stations may be maintained. For petrol, diesel and kerosene the reasoning is similar as with heating oil - fuels are transported with fuel trucks to their place of consumption and upfront investment costs are low. The infrastructure of gas stations already exists and only needs to be maintained.

Table 16: Techno-economic parameterization of the distribution technologies represented in REMIND-D. Own calculations.

	TLT Year	Investment Costs €$_{2005}$/kW	Fix Costs €$_{2005}$/kW	Conv. Eff. %	Full Load h/a
D_Gas-IND	55	161	0.02	90	7010
D_El-IND	55	1006	0.10	97	7010
D_DHeat-IND	55	161	0.02	95	3500
D_HeatOil-IND	55	20	0	100	6570
D_HFO-IND	55	20	0	100	6570
D_Coke-IND	55	20	0.01	100	7880
D_H2-IND	55	241	0.02	100	7010
D_Gas-RES&COM	55	322	0.10	90	4380
D_El-RES&COM	55	1529	0.76	94	4380
D_DHeat-RES&COM	55	161	0.02	95	3500
D_HeatOil-RES&COM	55	40	0.02	100	4380
D_LHeat-RES&COM	55	0.0001	0	100	8760
D_Gas-Trans	55	161	0.02	90	7010
D_El-Trans	55	1500	0.08	100	6130
D_H2-Trans	55	241	0.12	100	5260
D_Pet-Trans	55	80	0.08	100	6130
D_Die-Trans	55	80	0.08	100	6130
D_Ker-Trans	55	80	0.08	100	6130

4.5 Transport Technologies

The transport sector, converting fuels to energy services in the form of spatial relocation of goods and passengers, is explicitly included in REMIND-D. To fulfill mobility requirements, conventional and innovative transport technologies of various modes are considered, see Table 17.

Long-distance passenger transport is provided by domestic aviation (Plane-KER), Intercity and ICE trains (Train-EL) and long-distance buses (Coach-DIE), as well as by motorized private transport (MPT). In Germany, a large share of the car fleet consists of diesel cars, which are characterized by somewhat higher upfront costs, but diesel is relatively less taxed than petrol. Consequently, those who need to frequently travel long distances choose diesel cars. Obviously, one can also travel short distances with diesel cars, as well, and vice versa one can travel long distances with petrol cars that are owned mainly for the purpose of short commuting. In REMIND-D, this fact is accounted for by defining a main purpose for a class of cars and then ensuring a second purpose techni-

Table 17: Overview of transport technologies in REMIND-D. Abbreviations are Hybrid (Hy), Plug-in Hybrid (PHy) and Fuel Cell (FC).

Secondary Energy Carriers	**Energy Services** Passenger Long Distance (PLD)	Passenger Short Distance (PSD)	Freight (F)
Petrol		Car-PET Car-PET/Hy Car-PET/PHy	
Diesel	Car-DIE Car-DIE/Hy Coach-DIE	Car-DIE/PHy Train-DIE Bus-DIE Bus-DIE/Hy	Truck-DIE Train-DIE Ship-DIE
Natural Gas	Car-GAS Car-GAS/Hy		
Electricity	Train-EL	Car-EL Train-EL LightRail-EL	Train-EL
H_2		Car-H_2/Hy Car-H_2/FC Bus-H_2	
Kerosene	Plane-KER		

cally by means of 'couple production' of the transport technology. The classification of Table 17 reflects the main purposes of the respective transport technologies. For MPT transport, there are additionally various innovative car technologies. Local trains represent regional or medium-distance trains that either run on diesel or electricity. Inner-city public transport is covered by light rail trains and diesel, as well as innovative buses. The freight transport sector consists of trucks, trains and inland navigation.

Table 18 presents the techno-economic parameterization for all MPT car technologies with initial investment costs per car, fuel demand, yearly short- and long-distance performance and variable costs. Fixed costs are not considered as data is very case-specific and also scarce, especially for public transport and commercial trucking technologies. The investment costs of innovative car technologies can be reduced over time by two means: Technology-specific learning-by-doing by building up capacities or cluster-learning for batteries. For hybrid, plug-in hybrid and electric technologies, an increasing share of the specific investment costs is caused by the battery pack and related technology. In the battery sector, substantial cost reductions can be expected. As learning-by doing effects are occurring at a battery-level, the capacity additions of all technologies that use batteries are contributing to the learning. The investment costs for batteries are again

Table 18: Techno-economic parameterization of MPT technologies in REMIND-D. SD/LD indicates the yearly short/long-distance driving. Investment costs are split into chassis/drivetrain + battery-related costs, with the latter exhibiting cluster learning across all technologies. Car-H2/Hy and Car-H2/FC additionally have learning in the chassis/drivetrain investment costs by 6.7 and 13.8 Tsd.*e*, respectively, with a learning rate of 5%. Sources: Wietschel et al. (2010), Edwards et al. (2008b), Edwards et al. (2008a), Gül (2008), Kirchner et al. (2009), Krey (2006), own calculations.

	TLT Year	Investment Costs Tsd.€$_{2005}$ /car	Fuel Demand kWh /100 km	LD Tsd.km /a	SD Tsd.km /a	Variable Costs €$_{2005}$ /km
Car-ETN	12	19.5	68.00	2.4	9.6	0.027
Car-ETN/Hy	12	19.5+6.4	41.65	2.4	9.6	0.033
Car-ETN/PHy	12	19.5+8.1	44.90	2.4	9.6	0.073
Car-DIE	10	21.4	67.32	15.4	6.6	0.025
Car-DIE/Hy	10	21.4+6.4	38.61	15.4	6.6	0.030
Car-DIE/PHy	11	21.4+8.1	39.00	2.4	9.6	0.073
Car-GAS	12	21.6	52.00	17.6	4.4	0.027
Car-GAS/Hy	12	21.6+6.43	38.70	17.6	4.4	0.030
Car-H2/Hy	12	26.8+6.4	39.30	3.0	12.0	0.030
Car-H2/FC	12	33.3+1.6	23.30	3.0	12.0	0.075
Car-EL	10	19.6+17.7	15.00	0	15.0	0.099

split into a local and global component. In the future, the fuel demand of conventional car technologies is expected to follow the declining trend on a per 100km basis. Table 19 illustrates the techno-economic parameterization for the public transport technologies and Table 20 for the freight transport technologies

The dynamics of the transportation sector are very difficult to be represented in an energy system model that follows the logic of implicitly minimizing costs. For passenger transport, non-quantifiable factors such as minimizing travel time or maximizing travel comfort are frequently more influential for choosing a particular kind of transportation mode than pure cost calculations. Urbanization tendencies and general demographic developments do have an influence, too. In the case of motorized private transport (MPT) car owners often do not base their investment choices on clean cost calculations, but consider their car as fulfilling other purposes than just the technical transportation, e.g. status symbol, self-expression. As regards freight transport, the growth rate of transported ton-km has historically been very closely correlated to the growth rate of GDP (Feige 2007). As the underlying drivers of this link are rather complex, there is no direct link between GDP and freight transport volume in REMIND-D. In principle, they could become decoupled in the future, if the economy became more efficient in

Table 19: Techno-economic parameterization of public transport technologies in REMIND-D. The top panel displays technologies that serve short distance driving, the bottom one long distance driving. For Bus-H2, the 70Tsd.e are subject to learning with a rate of 5%. Sources: Krey (2006), Wietschel et al. (2010), own calculations.

	TLT	Investment Costs Tsd.€$_{2005}$ /vehicle	Fuel Demand kWh /100 km	Number of Passengers	Yearly Range Tsd. km /a	Fix Costs %	Variable Costs €$_{2005}$ /km
Bus-DIE	13	280	416	20	612	-	0.412
Bus-DIE/Hy	13	328	291	20	612	-	0.412
Bus-H2	13	280+70	400	20	612	-	0.405
Train-DIE	26	2270	1530	80	2960	0.02	1.9
Train-EL	26	2090	914	80	5600	0.02	1.8
LightRail-EL	26	2030	811	55	4125	0.02	1.8
Coach-DIE	13	280	240	25	875	-	0.412
Train-EL	26	16710	2100	223	66900	1.5	2.5
Plane-KER	17	22600	8000	115	28750	0.013	3.72

Table 20: Techno-economic parameterization of freight transport technologies in REMIND-D. Source: Krey (2006), own calculations.

	TLT	Investment Costs Tsd.€$_{2005}$ /vehicle	Fuel Demand kWh /100 km	Load Capacity t	Yearly Range Tsd. km /a	Fix Costs %	Variable Costs €$_{2005}$ /km
Truck-DIE	10	33.6	225	5	125	-	0.0724
Train-DIE	27	3500	2780	434	30380	0.076	3.01
Train-EL	27	3700	1250	434	30380	0.05	3.02
Ship-DIE	47	2340	11000	918	24235	0.07	1.94

terms of transport-km per GDP. To account for these factors, the yearly total amounts of demanded ton-km and passenger-km for long- and short-distance travelling are part of the scenario definition in REMIND-D and are exogonous, if not explicitly stated otherwise. Without these constraints, the model has a tendency to severely decrease freight and short-distance passenger transport and increase long-distance passenger transport in the presence of a stricter CO_2 emissions budget. This can be easily understood from an energy-efficiency point of view, however, it does not reflect reality due to the missing non-quantifiable drivers in the model. Table 21 presents the assumed future developments in a standard setting.

Table 21: Assumed development paths of freight and passenger energy services demand. Source: Lenz et al. (2010).

	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
Freight	7.51	8.66	9.56	10.54	11.52	12.49	13.29	14.08	14.60	15.12

5 CO_2 Emissions

REMIND-D considers only CO_2 emissions from the energy sector that stem from the combustion of fossil fuels. The standard operating mode of REMIND-D is via a CO_2 emission budget over the entire optimizing time horizon. This method yields the maximum freedom for the model to allocate the emissions over time. REMIND-D can also be operated by implementing a specific CO_2 emission path or a CO_2 tax path. The CO_2 emission accounting in REMIND-D is implemented via the primary energy demand of CO_2-intensive energy carriers and their emission factors. These are 56 tCO_2/TJ for Gas, 72 tCO_2/TJ for Hard Coal, 113 tCO_2/TJ for Lignite and 72 tCO_2/TJ for Crude Oil (Strogies and Gniffke 2009). These are the emission factors used in the calculation of the Kyoto protocol reporting. All other primary energy carriers come without CO_2 emissions. In principle, the use of fossil and biomass energy carriers leads to CH_4, SO_x, NO_x emissions etc., which are, however, not considered in REMIND-D at the moment.

6 Model Validation

Validating causal-descriptive models that generate projections well into the future is an inherently challenging task. The concept of validity as such has been subject to a lengthy academic debate, strongly tied to philosophy of science issues. Barlas (1996) suggests that a model is valid if it demonstrates 'the right behaviour for the right reason'. Hence, a valid model produces results that are at once trustworthy, justifiable and meaningful for the problem under analysis. In fact, the validation of a model must be understood as a process, which is not separable from the modeling process itself (Landry et al. 1983). As a full-fledged validation exercise is beyond the scope of this document, this Section intends to give a brief indication of how model results obtained with REMIND-D relate to empirical data.

Figures 6, 7 and 8 display CO_2 emissions from energy use, GDP and final energy demand for Germany. Historical data is plotted together with model results from two scenario runs, for which the configuration of REMIND-D differs only with respect to the emission budget. Displayed model data are from two runs of the 'continuation' scenario, elaborated in Schmid and Knopf (2012). The 'Model Baseline' run achieves moderate 40% CO_2 emission reduction in 2050 relative to 1990, the 'Model Policy' run ambitious 88%.

Figure 6: German CO_2 emissions from energy use. Data from 1990-2009 are empirical (UBA 2010). Model results are obtained with REMIND-D for the years 2007-2050.

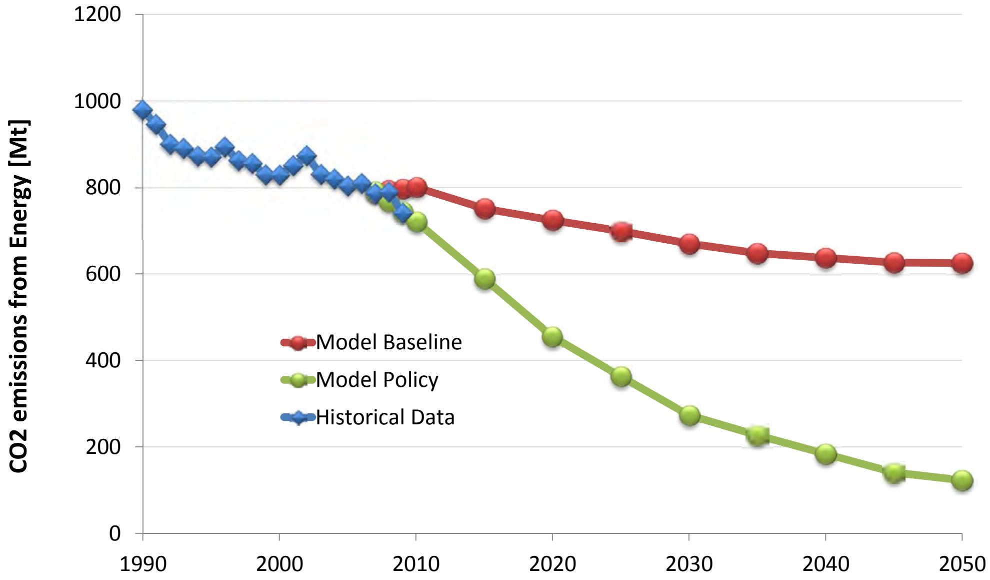


Figure 7: German Gross Domestic Product (GDP) in Bn €. Data from 1990-2009 are empirical (Statistisches Bundesamt 2012). Model results are obtained with REMIND-D for the years 2007-2050.

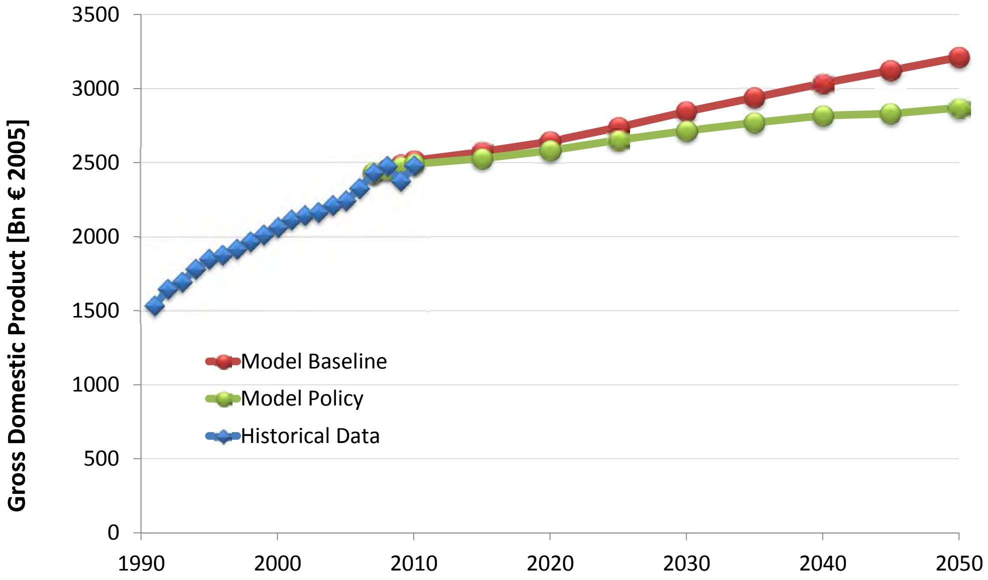
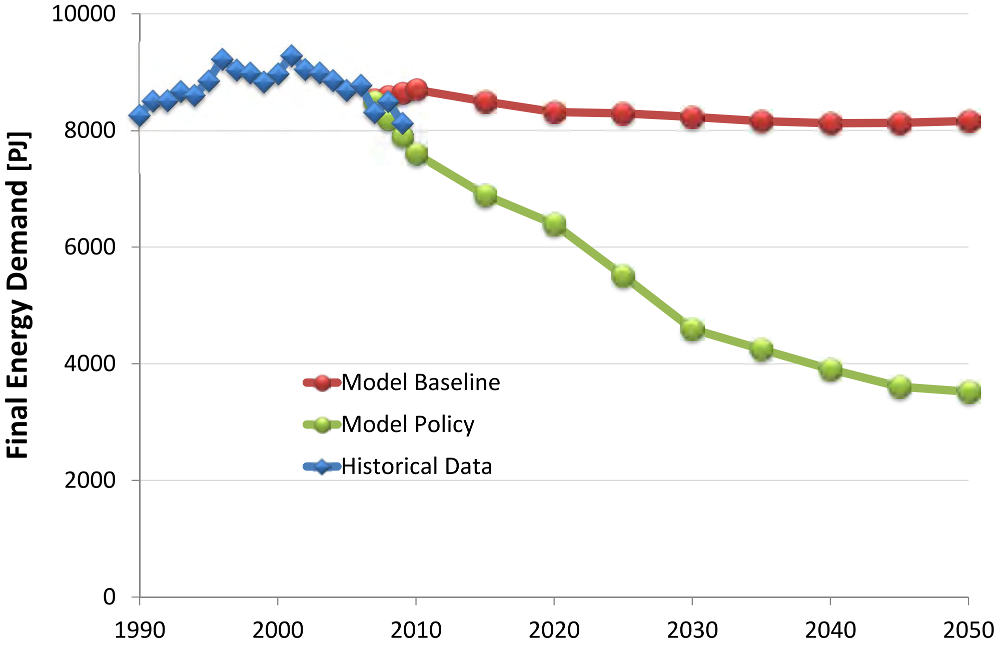


Figure 8: German final energy demand in PJ. Data from 1990-2009 are empirical(AG Energiebilanzen 2010). Model results are obtained with REMIND-D for the years 2007-2050.



The CO_2 emissions from the energy sector in the calibration year 2007 are reproduced well by the model results of REMIND-D. Since they are an outcome of the calibration procedure, the good fit is an indication for the validity of REMIND-D's structure. Interestingly, the empirical CO_2 emission in 2009 lie on the trajectory of the 'Model Policy' scenario, which leads to an ambitious mitigation mitigation target of 88% CO_2 emission reduction in 2050 relative to 1990. However, CO_2 emissions were particularly low in 2009 due to the financial crisis and it is unclear whether this trend continues. The 'Model Baseline' trajectory performs well in extrapolating the historical trend in emission reduction. GDP and final energy demand are reproduced by REMIND-D exactly in 2007 as they are a calibration input. GDP growth is slightly slower in the model results than observed historically. The reason why GDP trajectories are diverging between the two model runs is the additional and binding CO_2 budget constraint in the 'Model Policy' run. The historical trend in final energy demand is reproduced well by the 'Model Baseline' trajectory. Again, as is the case for total CO_2 emissions, the overlapping years 2007-2009 coincide with the 'Model Policy' data. A more extensive model validation, including the structured comparison between the results of REMIND-D and those of other models of Germany, will be addressed in future work.

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