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Abstract

This paper introduces the computable partial equilibrium energy model ‘Global Resource Extraction and Energy Transformation’ (GREET), its structure, assumptions and the outcomes of two exemplary scenarios. GREET is characterized by a comprehensive modelling of constraints on the diffusion of renewable energy, where physical constraints on the regional deployment of renewable energy technologies are complemented by the need to provide storage capacities for renewable production of electricity. The consumption of conventional primary energy carriers, on the other hand, is constrained by regional resource endowments as well as the need for capacity investments in primary energy carrier extraction-, trade- and transformation processes. In comparison to most contrastable global energy models, there is an explicit modelling of interregional trade flows in primary energy carriers, for which originating and destinating regions of the energy trades can clearly be specified. Thus, GREET, covering global primary energy trades for eleven world model regions, is very applicable for looking into future developments of energy trade flows. At the same time GREET doesn’t miss to cover the point that predominantly renewable based energy systems of the future are confined by constraints on renewable energy production technologies, such as the need to provide electricity storage capacities.

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1. Introduction

This paper introduces the computable partial equilibrium energy model ‘Global Resource Extraction and Energy Transformation’ (GREET), its structure, assumptions and outcomes of two exemplary scenarios. GREET is characterized by a comprehensive modelling of constraints on the diffusion of renewable energy, where physical constraints on the regional deployment of renewable energy technologies are complemented by the need to provide storage capacities for renewable production of electricity. The consumption of conventional primary energy carriers, on the other hand, is constrained by regional resource endowments as well as the need for capacity investments in primary energy carrier extraction-, trade- and transformation processes. GREET features explicit modelling of interregional trade flows in primary energy carriers and thus enables to investigate dynamics in future energy trades between the eleven world regions of the model.

The paper is organized as follows: Chapter 2 introduces the model structure, depicting underlying optimization problems and market clearing conditions, while in Chapter 3 constraints and associated data are specified and assumptions on regions, types of energy carriers, transformation technologies, cost functions, rates of technological learning and discount- and depreciation rates are illustrated. In Chapter 4 results of a baseline scenario and a global emission trading scheme scenario are shown. Next to general global trends, the chapter focuses on the developments within the model regions Europe, China and North America and in particular on the evolving primary energy trade patterns between these three regions and the rest of the world. Chapter 6 compares the settings of GREET to other computable energy models and concludes in highlighting advantages, disadvantages and the preferable application spectrum of the model. Thus, GREET determines scenario based evolvements of the global energy structure, exhibiting a significant focus on analyses of primary energy trade flows, while at the same time also taking different constraints on renewable and non-renewable energy production into consideration.

2. Model

2.1 Model Structure

GREET is a multi-energy, multi-period and multi-regional computable partial equilibrium description of the energy sector. The GREET model comprises the main relevant activities within the energy system: Extraction, trade, transformation and consumption. As the first upstream activity within the energy framework, extraction of natural resources is modelled within each region of the model. Extraction takes place, facing exogenous resource endowment constraints and taking endogenous investment decisions on extraction capacity expansions into future periods' extraction capacities into account. After extraction, the primary energy carriers are then passed on within each region to a trading unit that trades these energy carriers to the other regions considered in the model. The trading activity is also bound to initial trading capacities that can be enlarged by endogenous investments. Transportation costs between the different model regions are considered. Within each model region, there exists a transformation sector that transforms these primary energy carriers into final energy goods, which are then demanded by final consumption. Therefore, the transformation sector of each region is modelled to purchase the different primary energy carriers from the various primary energy traders of the other regions as well as its home region. After transforming the primary energy carriers into different forms of final energy products, these products are sold within the region. Concurrently, each region exhibits an initial amount of renewable energy production. The energy generated by renewable production technologies also serves as final energy and is sold within each region. Investments into different renewable technologies allow for an expansion of the various renewable sectors, while being limited by constraints on the creation of renewable production sites. Final consumption demands the overall amount of final energy, produced by renewable technologies and by the transformation of primary energy carriers into final energy goods within each region.

The following Figure 2.1 illustrates the general structure of GREET, depicted for a case of two regions A and B.

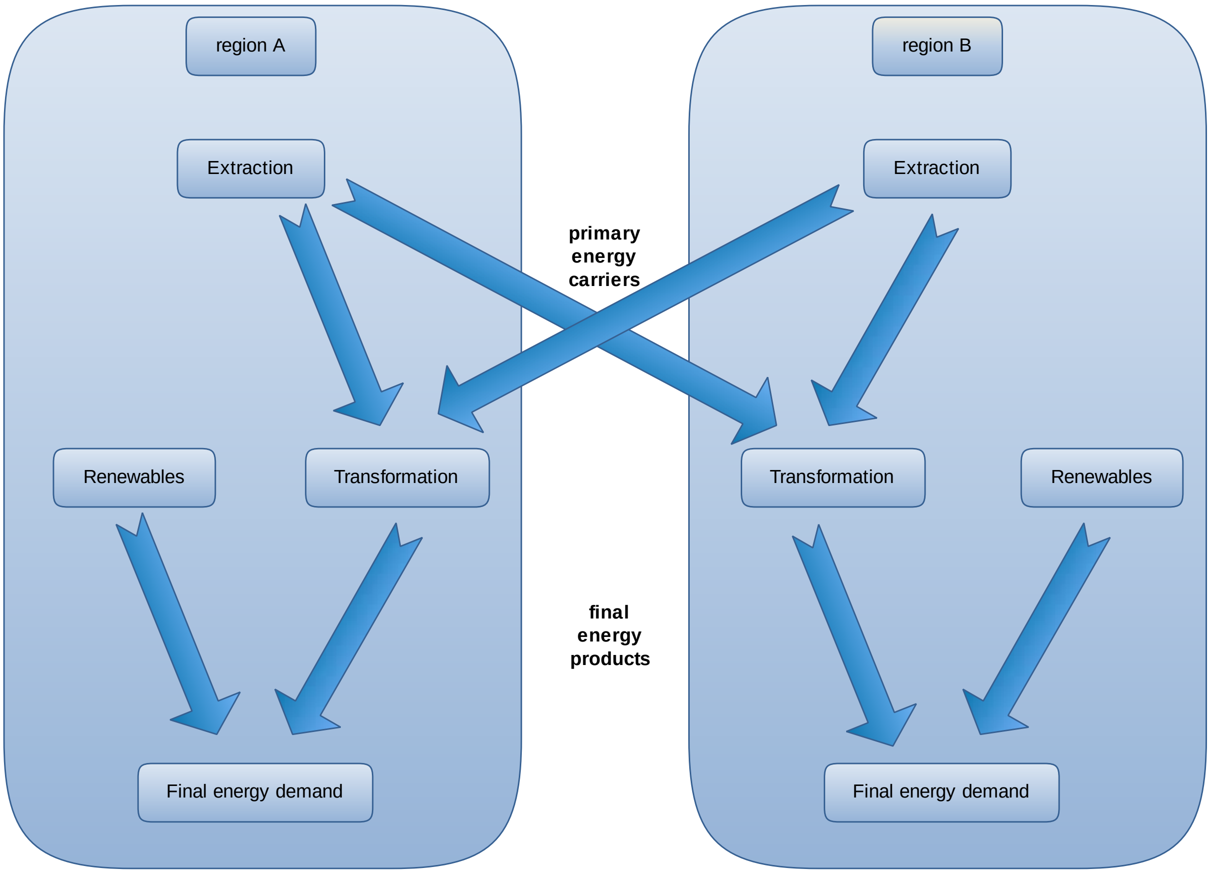

Figure 2.1: General structure of GREET

From this graph one can see that interregional trade of energy in GREET only takes place at the primary energy carrier level, while final energy products are produced and consumed only within a region itself. For means of the large size of the regions, incorporated in the model specifications of GREET, no trade of final energy goods is taken into account. This is a realistic simplification, once one compares the relative size of the trade volumes of primary energy carriers to those of final energy goods.[1]

Resulting from the above pictured interactions between the different decisive units within the overall energy framework, there are different markets arising from this structure. The first set of markets (Markets 1) contains all markets, where, within each region, all primary energy carriers are sold by extractors to domestic primary energy trading units. These markets are of minor importance and the trading units could also be regarded as parts of the extraction activities, as often seen in reality, where primary energy resources are globally marketed by

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[1] It can be seen that the bulk of transformation of primary energy carriers into final energy goods takes place in the region where the final energy is to be consumed. One rationale behind this is that it is e.g. cheaper to move crude oil than finished refinery products. The same logic applies to coal, natural gas and uranium.
(*EIA:* http://www.eia.doe.gov/pub/oil_gas/petroleum/analysis_publications/oil_market_basics/refining_text.htm)

the extractors themselves. Still, here, for structural purposes and the possibility to look into different effects, the two activities are conceptually separated.

The second layer of more important markets within GREET (Markets 2) are the global markets for primary energy carriers, where all of the primary energy carriers from all regions can be bought, to be later on transformed into final energy within the importing region. Prices are determined by the interplay of primary energy demands from the importing regions, the primary energy carrier supply possibilities of the exporting regions and different transportation costs between two regions. Market clearing is obtained, once a supply of one primary energy carrier traded from an exporting region *r* to one importing region *rr* $x^{trade}_{t,pe,r\rightarrow rr}$ equals the amount of this energy carrier, demanded by the transformation sector within the importing region *rr* $x^{trans\_purch}_{t,pe,rr}$. This condition has to hold for all primary energy carriers *pe* and all importing regions *rr* at all time-steps *t*. The markets then clear for the market prices $p^{pe\_down}_{t,pe,r\rightarrow rr}$.

The third layer of markets (Markets 3) then consists of the markets for final energy products within each region. Suppliers of final energy products are on the one hand the transformation sector, which produces final energy products *fe* from primary energy carriers, and on the other hand the renewable sector that produces final energy products by employing different renewable technologies *rt*. A market for a final energy product clears if the demanded amount of this product equals the sum of the amounts supplied from all transformation techniques $\sum_{pe} x^{trans}_{t,pe\rightarrow fe,rr}$ plus the sum of all forms of renewable energy production $\sum_{rt} x^{ren}_{t,fe,rr,rt}$. This condition has to hold for all final energy products *fe* in all regions *rr* and at all time-steps *t*. The resulting market prices are denoted by $p^{sec}_{t,fe,rr}$. Levels of market prices depend on the regions' final energy demands, the costs of energy transformation and renewable energy production within the regions, as well as on the regions' upstream costs of primary energy carrier supply. Figure 2.2 illustrates the interplay of the different actors on these markets.

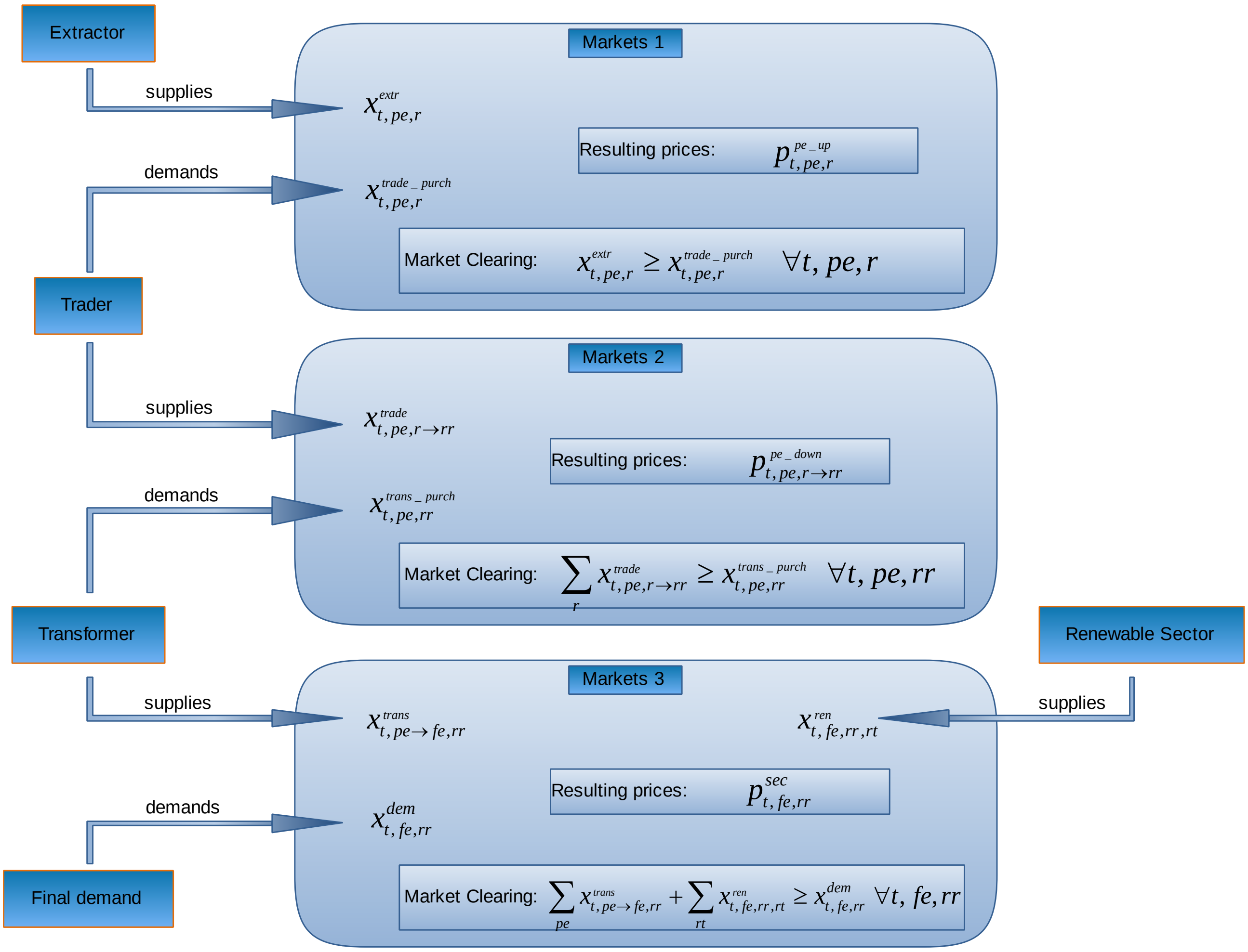

Figure 2.2: Markets in GREET

In the following subsections the definitions of the optimization problems of the different decisive activities (extraction, trade, transformation, renewable production) within the overall framework will be presented. Specifications of the particular cost functions applied for the various activities and investments will be given in Chapter 4. In the following, the general outline of the different sectors’ objective functions and constraints will be set out first.

2.2 Extraction Sector

The extraction sector maximizes profits from the extraction of the finite resources within the region. Its maximization problem is specified as follows:

$$\max_{x^{extr}_{t,pe,r},\, i^{extr}_{t,pe,r}} \quad \pi^{*}_{pe,r} = \sum_{t=1}^{T} \pi_{t,pe,r}\delta^{t} = \sum_{t=1}^{T} \Big[p^{pe\_up}_{t,pe,r} x^{extr}_{t,pe,r} - c^{extr}_{t,pe,r}(x^{extr}_{t,pe,r}) - c^{extr\_i}_{t,pe,r}(i^{extr}_{t,pe,r}) \ \Big] \delta^{t}$$

$$\begin{aligned} s.t. \quad & (1) \ \ x^{extr}_{t,pe,r} \le cap^{extr\_ini}_{pe,r} \ \rho^{extr^{t}}_{pe} + \sum_{\tau=1}^{t-1} i^{extr}_{t,pe,r} \ \rho^{extr^{t-\tau}}_{pe} && \forall t, pe, r \\ & (2) \ \ \sum_{t=1}^{T} x^{extr}_{t,pe,r} \le R_{pe,r} && \forall pe, r \\ & (3) \ \ x^{extr}_{t,pe,r} \ge 0 && \forall t, pe, r \\ & (4) \ \ i^{extr}_{t,pe,r} \ge 0 && \forall t, pe, r \end{aligned}$$

The overall profit of the extraction sector is determined as the sum of profits over all time-periods, whereby profits of future periods are discounted by a discount factor δ. Profits within each time-period consist of the revenues of the sales of the primary energy carriers $p^{pe\_up}_{t,pe,r} x^{extr}_{t,pe,r}$ minus costs of extraction $c^{extr}_{t,pe,r}(x^{extr}_{t,pe,r})$ and costs of investments into future extraction capacities $c^{extr\_i}_{t,pe,r}(i^{extr}_{t,pe,r})$. Production costs are a function of the amounts of primary energy carriers extracted, and investment costs are a function of the amount of capacity investments within the sector. Both cost functions will be further specified in the next chapter.

The decisions of the extraction sector on the amounts of primary resources extracted $x^{extr}_{t,pe,r}$ and amounts of investment into extraction capacities $i^{extr}_{t,pe,r}$ are constrained by: (1) a capacity constraint, which determines that the amount of primary energy carrier extraction cannot exceed the sum of initial extraction capacities $cap^{extr\_ini}_{pe,r}$ and capacity expansion investments $i^{extr}_{t,pe,r}$ in previous periods. Both initial extraction capacities and additional built up capacities are thereby subject to depreciation ρ^{extr}_{pe} of the extraction capacity stock for each type of primary energy carrier; (2) a resource endowment constraint, which states that the sum of extraction over all time periods cannot exceed the amount of resource endowment given for each primary energy carrier for each region $R_{pe,r}$; (3), (4) non-negativity constraints on extraction and investments.

Resulting from this optimization problem the following complementarity conditions are obtained:

$$(5)\quad \left(p^{pe\_up}_{t,pe,r} - c'^{extr}_{t,pe,r}(x^{extr}_{t,pe,r})\right)\delta^{t} - \lambda^{extr\_cap}_{t,pe,r} - \lambda^{resdepl}_{pe,r} \le 0 \qquad \perp \qquad x^{extr}_{t,pe,r} \ge 0, \qquad \forall t, pe, r$$

$$(6)\quad -\delta^{t} c'^{extr\_i}_{t,pe,r}(i^{extr}_{t,pe,r}) + \sum_{\tau=t+1}^{T} \lambda^{extr\_cap}_{\tau,pe,r} {\rho^{extr}_{pe}}^{\tau-t+1} \le 0 \qquad \perp \qquad i^{extr}_{t,pe,r} \ge 0, \qquad \forall t, pe, r$$

$$(7)\quad cap^{extr\_ini}_{pe,r}\ {\rho^{extr}_{pe}}^{t} + \sum_{\tau=1}^{t-1} i^{prod}_{t,pe,r}\ \rho^{t-\tau} {\rho^{extr}_{pe}}^{t-\tau} - x^{extr}_{t,pe,r} \ge 0 \qquad \perp \qquad \lambda^{extr\_cap}_{t,pe,r} \ge 0, \qquad \forall t, pe, r$$

$$(8)\quad R_{pe,r} - \sum_{t=1}^{T} x^{extr}_{t,pe,r} \ge 0 \qquad \perp \qquad \lambda^{resdepl}_{pe,r} \ge 0, \qquad \forall pe, r$$

Complementarity condition (5) depicts, that either the extraction activity $x^{extr}_{t,pe,r}$ has to amount to zero or the difference of discounted revenues minus the shadow prices on extraction capacity $\lambda^{extr\_cap}_{t,pe,r}$ and on resource depletion $\lambda^{resdepl}_{pe,r}$ has to amount to zero. This means that, if the sum of costs and shadow prices on extraction exceeds the revenues out of the sale of the primary energy carrier extracted, no extraction should take place. Vice versa, if the selling price for the primary energy carrier exceeds the associated costs of extraction, a positive amount of extraction should take place. Complementarity condition (6) depicts the same calculus for the extraction capacity investments: If discounted extraction costs exceed the sum of depreciated shadow values of capacity investments, no investments in capacity will be made. Complementarity conditions (7) and (8) align the constraints (1) and (2) to their respective shadow values.

2.3 Trade Sector

The resource trading sector maximizes profits from trade, subject to existing initial trade capacities. Investments into these trade capacities between regions are to be understood as an increase in physical transportation capacity and also as the setting up of trade agreements between partners from different regions, each associated with its specific costs. The trading sector maximizes the sum of discounted future profits from resource trade in form of revenues from its trade activities $x^{trade}_{t,pe,r\to rr}\, p^{pe\_down}_{t,pe,r\to rr}$ diminished by the investment costs associated with capacity expansions $c^{trade\_i}_{t,pe,r\to rr}(i^{trade}_{t,pe,r\to rr})$ and by the costs of the trade activity $c^{trade}_{t,pe,r\to rr}(x^{trade}_{t,pe,r\to rr})$ itself and the costs of the primary resource bought from the extraction sector $x^{trade\_purch}_{t,pe,r}\, p^{pe\_up}_{t,pe,r}$. Thus, the trading sector's optimization problem is specified as follows:

$$\max_{x_{t,pe,r}^{trade\_purch},\, x_{t,pe,r\to rr}^{trade},\, i_{t,pe,r\to rr}^{trade}} \pi^{*}_{t,pe,r} = \sum_{t=1}^{T} \left[x_{t,pe,r\to rr}^{trade} p_{t,pe,r\to rr}^{pe\_down} - x_{t,pe,r}^{trade\_purch} p_{t,pe,r}^{pe\_up} - c_{t,pe,r\to rr}^{trade} (x_{t,pe,r\to rr}^{trade}) - c_{t,pe,r\to rr}^{trade\_i} (i_{t,pe,r\to rr}^{trade}) \right] \delta^{t}$$

$$s.t. \qquad (9)\ \ x_{t,pe,r\to rr}^{trade} \le cap_{pe,r\to rr}^{trade\_ini} \, {\rho_{pe,r\to rr}^{trade}}^{t} + \sum_{\tau=1}^{t-1} i_{t,pe,r\to rr}^{trade} \, {\rho_{pe,r\to rr}^{trade}}^{t-\tau}, \quad \forall t, pe, r \to rr$$

$$(10)\ \ \sum_{rr} x_{t,pe,r\to rr}^{trade} \le x_{t,pe,r}^{trade\_purch}, \quad \forall t, pe, r$$

$$(11)\ \ x_{t,pe,r}^{trade\_purch} \ge 0, \qquad \forall t, pe, r$$

$$(12)\ \ x_{t,pe,r\to rr}^{trade} \ge 0, \qquad \forall t, pe, r \to rr$$

$$(13)\ \ i_{t,pe,r\to rr}^{trade} \ge 0, \qquad \forall t, pe, r \to rr$$

Decision variable for a trader is $x_{t,pe,r}^{trade\_purch}$, which denotes the amount of primary energy carrier *pe* bought from the extractor, $x_{t,pe,r\to rr}^{trade}$ which stands for the amount of primary energy carrier sold and exported from region *r* to region *rr* and $i_{t,pe,r\to rr}^{trade}$, the amount of investment into a specific trade option. For the constraints of a trader, (9) states the traders' capacity constraint and (10) describes, that, for each trader of a primary energy carrier in a region, the sum of all trades to all exporting regions $\sum_{rr} x_{t,pe,r\to rr}^{trade}$ is never allowed to exceed the purchased amounts from the extractor in its home region $x_{t,pe,r}^{trade\_purch}$. The constraint has to hold for all primary energy carriers *pe* from all exporting regions *r* at all time periods *t*. (11), (12) and (13) are the non-negativity constraints on the amounts of primary energy carrier bought and sold, as well as on the amount of capacity expansions. Capacity investments are modelled in a putty-clay fashion, such that once made investments in trade capacity are regarded as sunk costs and cannot be gained back by actively reducing capacity at a higher rate than its depreciation.

The resulting complementarity conditions, arising from the trading sector's optimization problem, incorporated into the overall model framework, are thus specified as:

$$(14)\quad \left(p_{t,pe,r\to rr}^{pe\_down} - c_{pe,r\to rr}^{'trade}(x_{t,pe,r\to rr}^{trade})\right)\delta^{t} - \lambda_{t,pe,r\to rr}^{trade\_cap} - \lambda_{t,pe,r}^{trade\_purch} \leq 0 \qquad \perp \qquad x_{t,pe,r\to rr}^{trade} \geq 0, \qquad \forall t, pe, r \to rr$$

$$(15)\quad \lambda_{t,pe,r\to rr}^{trade\_purch} - p_{t,pe,r}^{up}\delta^{t} \leq 0 \qquad \perp \qquad x_{t,pe,r}^{trade\_purch} \geq 0, \qquad \forall t, ec, re$$

$$(16)\quad \sum_{rre} x_{t,pe,r\to rr}^{trade} - x_{t,pe,r}^{trade\_purch} \leq 0 \qquad \perp \qquad \lambda_{t,pe,r\to rr}^{trade\_purch} \geq 0, \qquad \forall t, ec, re$$

$$(17)\quad cap_{pe,r\to rr}^{trade\_ini}\, {\rho_{pe,r\to rr}^{trade}}^{t} + \sum_{\tau=1}^{t-1} i_{t,pe,r\to rr}^{trade}\, {\rho_{pe,r\to rr}^{trade}}^{t-\tau} - x_{t,pe,r\to rr}^{trade} \geq 0 \qquad \perp \qquad \lambda_{t,pe,r\to rr}^{trade\_cap} \geq 0, \qquad t, pe, r \to rr$$

$$(18)\quad -\delta^{t}\, c_{t,pe,r\to rr}^{'trade\_capext}(i_{t,pe,r\to rr}^{trade}) + \sum_{\tau=t+1}^{T} \lambda_{t,pe,r\to rr}^{trade\_capext}\, {\rho_{pe,r\to rr}^{trade}}^{\tau-t+1} \leq 0 \qquad \perp \qquad i_{t,pe,r\to rr}^{trade} \geq 0, \qquad t, pe, r \to rr$$

2.4 Transformation Sector

For the transformation sector profit maximization is also assumed. The transformation sector maximizes profits stemming from revenues of sold final energy products $p_{t,fe,rr}^{sec} x_{t,pe\to fe,rr}^{trans}$ less the costs for the purchase of primary energy carriers from traders $p_{t,pe,r\to rr}^{pe\_down} x_{t,pe,rr}^{trans\_purch}$ less the costs of the transformation process itself $c_{t,pe\to fe,rr}^{trans}(x_{t,pe\to fe,rr}^{trans})$ less the costs of transformation capacity expansion investments $c_{t,pe\to fe,rr}^{trans\_i}(i_{t,pe\to fe,rr}^{trans})$. Future profits are discounted at discount rate δ. Constraints of the transformation sector are: (19) Amounts of final energy goods produced $x_{t,pe\to fe,rr}^{trans}$ are not allowed to exceed the depreciated sum of initial transformation capacities $cap_{pe\to fe,rr}^{trans\_ini}$ and transformation capacity expansion investments $i_{t,pe\to fe,rr}^{trans}$, for all transformation processes and in all periods. (20) the sum of all final energy products, generated from one type of primary energy carrier and divided by its specific transformation rate from primary energy carrier to final energy good $\alpha_{pe\to fe}$, is not allowed to exceed the amount of this energy carrier purchased. This condition has to hold for all types of primary energy carriers p*e* in all regions *rr* and at all times *t*, while conversion factors are assumed to be $0 \leq \alpha_{pe\to fe} \leq 1$, since parts of the energy content can get lost in the process of transformation from primary energy carrier to final energy good. (21), (22) and (23) are non-negativity constraints for production of final energy goods $x_{t,pe\to fe,rr}^{trans}$, purchases of primary energy carriers $x_{t,pe,rr}^{trans\_purch}$ and investments into transformation capacity expansion investments $i_{t,pe\rightarrow fe,rr}^{trans}$. The overall optimization problem can be written as:

$$\max_{x_{t,pe,rr}^{trans\_purch},\,x_{t,pe\rightarrow fe,rr}^{trans},\,i_{t,pe\rightarrow fe,rr}} \quad \pi_{pe,rr}^{*} = \sum_{t=1}^{T} \pi_{t,pe,rr}\delta^{t}$$

$$= \sum_{t=1}^{T} \Big[p_{t,fe,rr}^{sec} x_{t,pe\rightarrow fe,rr}^{trans} - p_{t,pe,r\rightarrow rr}^{pe\_down} x_{t,pe,rr}^{trans\_purch} - c_{t,pe\rightarrow fe,rr}^{trans}(x_{t,pe\rightarrow fe,rr}^{trans}) - c_{t,pe\rightarrow fe,rr}^{trans\_i}(i_{t,pe\rightarrow fe,rr}^{trans}) \Big] \delta^{t}$$

$$s.t. \qquad (19) \quad x_{t,pe\rightarrow fe,rr}^{trans} \leq cap_{pe\rightarrow fe,rr}^{trans\_ini} \rho_{pe\rightarrow fe,rr}^{trans}{}^{t} + \sum_{\tau=1}^{t-1} i_{t,pe\rightarrow fe,rr}^{trans} \rho_{pe\rightarrow fe,rr}^{trans}{}^{t-\tau}, \quad \forall t, pe \rightarrow fe, rr$$

$$(20) \quad \sum_{fe} \left(\frac{x_{t,pe\rightarrow fe,rr}^{trans}}{\alpha_{pe\rightarrow fe}} \right) \leq x_{t,pe,rr}^{trans\_purch}, \quad \forall t, pe, rr$$

$$(21) \quad x_{t,pe\rightarrow fe,rr}^{trans} \geq 0, \quad \forall t, pe \rightarrow fe, rr$$

$$(22) \quad x_{t,pe,rr}^{trans\_purch} \geq 0, \quad \forall t, pe, rr$$

$$(23) \quad i_{t,pe\rightarrow fe,rr}^{trans} \geq 0, \quad \forall t, pe \rightarrow fe, rr$$

Resulting from the transformation sector's optimization problem, we obtain the following complementarity conditions:

$$(24) \quad \left(p_{t,fe,rr}^{sec} - c'^{trans}_{t,pe\rightarrow fe,rr}(x_{t,pe\rightarrow fe,rr}^{trans}) \right) \delta^{t} - \lambda_{t,pe\rightarrow fe,rr}^{trans\_cap} - \frac{1}{\alpha_{pe\rightarrow fe}} \lambda_{t,pe,rr}^{trans\_conv} \leq 0 \quad \perp \quad x_{t,pe\rightarrow fe,rr}^{trans} \geq 0$$

$$, \quad \forall t, pe \rightarrow fe, rr$$

$$(25) \quad -\delta^{t} c'^{trans\_i}_{t,pe\rightarrow fe,rr}(i_{t,pe\rightarrow fe,rr}^{trans}) + \sum_{\tau=t+1}^{T} \lambda_{t,pe\rightarrow fe,rr}^{trans\_cap} \rho_{pe\rightarrow fe,rr}^{trans}{}^{\tau-t+1} \leq 0 \quad \perp \quad i_{t,ec\rightarrow fe,rre}^{trans} \geq 0$$

$$, \quad \forall t, pe \rightarrow fe, rr$$

$$(26) \quad \lambda_{t,pe,rr}^{trans\_conv} - p_{t,pe,r\rightarrow rr}^{pe\_down} \delta^{t} \leq 0 \quad \perp \quad x_{t,pe,rr}^{trans\_purch} \geq 0, \quad \forall t, pe, rr$$

$$(27) \quad cap_{pe\rightarrow fe,rr}^{trans\_ini} \rho_{pe\rightarrow fe,rr}^{trans}{}^{t} + \sum_{\tau=1}^{t-1} i_{t,pe\rightarrow fe,rr}^{trans} \rho_{pe\rightarrow fe,rr}^{trans}{}^{t-\tau} - x_{t,pe\rightarrow fe,rr}^{trans} \geq 0 \quad \perp \quad \lambda_{t,pe\rightarrow fe,rr}^{trans\_cap} \geq 0$$

$$, \quad \forall t, pe \rightarrow fe, rr$$

$$(28) \quad \sum_{fe} \left(\frac{x_{t,pe\rightarrow fe,rr}^{trans}}{\alpha_{pe\rightarrow fe}} \right) \leq x_{t,pe,rr}^{trans\_purch} \quad \perp \quad \lambda_{t,pe,rr}^{trans\_conv} \geq 0, \quad \forall t, pe, rr$$

2.5 Renewable Energy Sector

Renewable energy producers are also assumed to be profit maximizers. Their profit consist out of the revenues gained from the sales of renewable energies $p^{sec}_{t,fe,rr} x^{ren}_{t,fe,rr,rt}$, while they face production costs $c^{ren}_{t,fe,rr,rt}(x^{ren}_{t,fe,rr,rt})$ and costs of investments in capacity expansions $c^{ren\_i}_{t,fe,rr,rt}(i^{ren}_{t,fe,rr,rt})$. Crucial for the modelling of the diffusion of renewable technologies are assumptions on the constraints on renewables. One obvious constraint is (29), that production of renewable energies cannot exceed installed capacities. (30) and (31) are the non-negativity constraints on production and investment quantities. This is the very general outline of the maximization problem of the renewable sector. Further constraints on the diffusion of renewable energies will be introduced and specified in section 3.4.4, depicting physical constraints on renewable energy diffusion as well as storage constraints on electricity generation from fluctuating renewable sources.

$$\max_{x^{ren}_{t,fe,rr,rt},\, i^{ren}_{t,fe,rr,rt}} \quad \pi^{*}_{ec,re} = \sum_{t=1}^{T} \pi_{t,rr,rt} \delta^{t}$$

$$= \sum_{t=1}^{T} \Big[\, p^{sec}_{t,fe,rr} x^{ren}_{t,fe,rr,rt} - c^{ren}_{t,fe,rr,rt}(x^{ren}_{t,fe,rr,rt}) - c^{ren\_i}_{t,fe,rr,rt}(i^{ren}_{t,fe,rr,rt}) \,\Big] \delta^{t}$$

$$s.t. \qquad (29) \quad x^{ren}_{t,fe,rr,rt} \le cap^{ren\_ini}_{fe,rr,rt}\, {\rho^{ren}_{fe,rr,rt}}^{t} + \sum_{\tau=1}^{t-1} i^{ren}_{t,fe,rr,rt}\, {\rho^{ren}_{fe,rr,rt}}^{t-\tau}, \quad \forall t, fe, rr, rt$$

$$(30) \quad x^{ren}_{t,fe,rr,rt} \ge 0, \quad \forall t, fe, rr, rt$$

$$(31) \quad i^{ren}_{t,fe,rr,rt} \ge 0, \quad \forall t, fe, rr, rt$$

From this optimization problem, the following complementarity conditions are obtained:

$$(32) \quad \left(p^{sec}_{t,fe,rr} - c^{'ren}_{t,fe,rr,rt}(x^{ren}_{t,fe,rr,rt}) \right) \delta^{t} - \lambda^{ren\_cap}_{t,fe,rr,rt} \le 0 \qquad \perp \qquad x^{ren}_{t,fe,rr,rt} \ge 0, \qquad \forall t, fe, rr, rt$$

$$(33) \quad -\delta^{t}\, c^{'ren\_i}_{t,fe,rre,rte}(i^{ren}_{t,fe,rr,rt}) + \sum_{\tau=t+1}^{T} \lambda^{ren\_cap}_{t,fe,rr,rt}\, {\rho^{ren}_{fe,rr,rt}}^{\tau-t+1} \le 0 \qquad \perp \qquad i^{ren}_{t,fe,rr,rt} \ge 0, \qquad \forall t, fe, rr, rt$$

$$(34) \quad cap^{ren\_ini}_{fe,rr,rt}\, {\rho^{ren}_{fe,rr,rt}}^{t} + \sum_{\tau=1}^{t-1} i^{ren}_{t,fe,rr,rt}\, {\rho^{ren}_{fe,rr,rt}}^{t-\tau} - x^{ren}_{t,fe,rr,rt} \ge 0 \qquad \perp \qquad \lambda^{ren\_cap}_{t,fe,rr,rt} \ge 0, \qquad \forall t, fe, rr, rt$$

2.6 Final Demand

For the regional demand of final energy products $x_{t,fe,rr}^{dem}$ we assume that consumption in all final energies depends on the regional price of the specific final energy products. Equation (1) depicts the final energy demand structure in GREET. Since GREET is a partial equilibrium model, only covering the energy sector, while not modelling other sectors of economic activities, exogenous final energy demand paths for all model regions are assumed. These demand paths are depicted by the parameter $\theta_{t,fe,rr}$, which varies the growth of initial demands for final energies by region-specific exogenous demand growth rates. The demands of the specific final energy carriers and thus also the overall final demand, however, are sensitive to the development of prices of final energy carriers over time, which can vary quite significantly for different scenarios. Final demand for all forms of final energy is elastic to price deviations, compared to initial prices of the respective form of final energy. Thus, assuming an exogenous energy demand growth path, the price-elastic demand on individual final energies enables a light endogenization of the final energy demand structure, as final energy demands correspond to price changes within the energy system.

$$(35) \qquad x_{t,fe,rr}^{dem} = x_{fe,rr}^{dem\_ini} \theta_{t,fe,rr} \left(\frac{p_{fe,rr}^{sec\_ini}}{p_{t,fe,rr}^{sec}} \right)^{\rho} \qquad \forall t, fe, rr$$

3. Model Specification and Data

In this section, regions and energy carriers are specified and underlying data is described. Also specifications on the functional forms within the different optimization problems and choices of parameters are given.

3.1. Regions

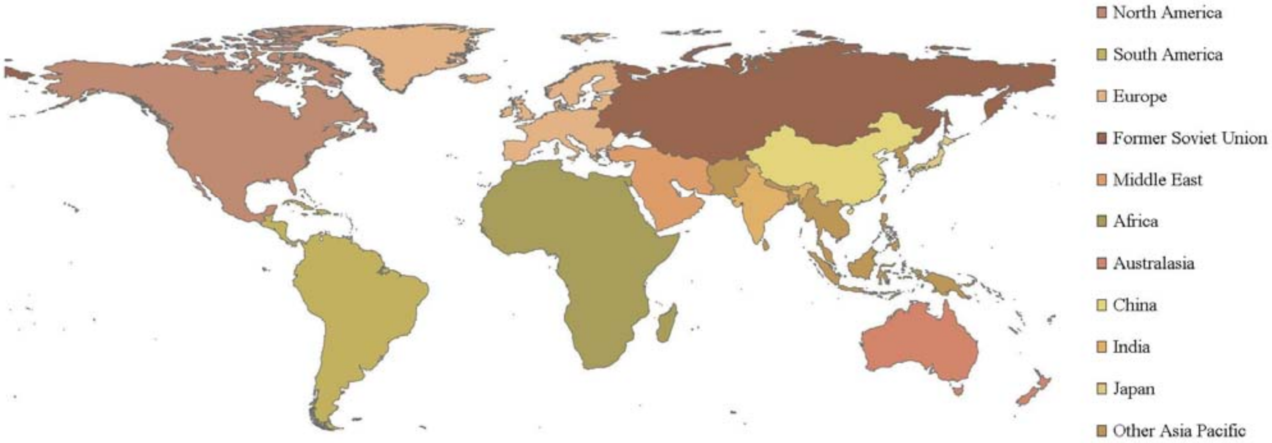

Figure 3.1: Regions in GREET

Figure 3.1 shows the aggregation of regions employed in GREET. For a detailed list of countries belonging to each of these regions, see Appendix A.3.1. Each of the regions employed in GREET either plays an important role in primary energy carrier production, primary energy consumption, or both. Such, the regions Former Soviet Union (*including Mongolia*), Middle East, South America and Africa are important producers and exporters of Natural Gas and Crude Oil. Japan, Europe, China and India are important current and future consumers and importers of these energy carriers. The regions Other Asia Pacific and North America play an important role in primary energy production as well as consumption, while the region Australasia e.g. has a significant importance as a producer and exporter of coal and uranium. Altogether these regions comprise more than 99% of the global production and consumption of primary energy carriers in 2007.

3.2. Energy carriers

Energy carriers in GREET are classified into primary energy carriers and final energy goods. Also, renewable technologies for the production of final energy goods are considered. Primary energy carriers in GREET are natural gas, crude oil, coal and uranium. Final energy goods are electricity, fuels (a composite liquid fuel category), heat and direct demands of natural gas and coal. Next to production from fossil fuels, the final energy good electricity can in this model also be produced by the renewable technologies wind, water, biomass, solar photovoltaics, tide-wave-ocean and geothermal energy. The final energy fuels can be generated using the renewable technology biomass and heat can be produced by geothermal and solarthermal renewable technologies as well as biomass. Within this representation of the energy system, we leave out traditional, non-commercial energies, such as animal waste or fuel wood, as described by Bhattacharyya (2010) and only focus on the commercial energy types as specified above.

3.3 Initial amounts in base year 2007

3.3.1 Initial amounts of final energy production and demand

Initial amounts for the production of final energy goods within the model regions of GREET for the base year 2007 are taken from OECD energy balances 2007. This way, initial amounts for transformation from primary energy carriers into final energy goods $x^{trans}_{'2007',pe \rightarrow fe,rr}$ as well as generation of final energy goods from renewable technologies $x^{ren}_{'2007',fe,rr,rt}$ are specified for all model regions for the model base year 2007. Accordingly, initial final demand in final energy goods is set to the amounts given by the OECD energy balances. Table 3.1 depicts initial values for 2007. All amounts are given in thermal values in million tonnes of oil equivalents, before transformation into final energy goods. Auto-production (self-generation) and associated auto consumption is included as a part of the overall demand of energy, e.g. power plants' auto consumption of electricity is termed as a part of the final energy demand in electricity.

	Africa	Australasia	Europe	FSU	India	Japan	MidEast	N-America	OtherAsia	China	S-America	sum
coal	**75,44**	**53,02**	**287,36**	**126,58**	**208,26**	**67,34**	**8,54**	**479,24**	**179,98**	**1000,64**	**12,5**	**2498,92**
Direct demand	13,98	3,26	38,24	14,04	40,52	10,86	0,48	26,66	63,58	260,28	5,4	477,32
electricity	61,48	48,88	208,64	53,2	167,74	56,46	8,06	445,14	110,22	662,34	7,08	1829,26
heat	0	0,88	40,48	59,32	0	0,02	0	7,44	6,18	78,02	0	192,34
Natural_gas	**63,28**	**22,1**	**446,98**	**502,62**	**31,04**	**87,02**	**217,22**	**594,02**	**158,7**	**48,84**	**91,12**	**2262,92**
Direct demand	26	13,94	293,12	224,02	16,2	33,34	109,22	389,86	67,84	40,42	62,36	1276,32
electricity	37,28	7	110,8	94,2	14,86	53,3	108	179,08	88,68	6,74	28,74	728,7
heat	0	1,16	43,06	184,38	0	0,4	0	25,08	2,18	1,66	0	257,9
crude_oil	**113,44**	**34,86**	**706,14**	**276,84**	**159,54**	**194,5**	**315,46**	**947,66**	**374,22**	**328,32**	**266,06**	**3717,08**
fuels	113,44	34,86	706,14	276,84	159,54	194,5	315,46	947,66	374,22	328,32	266,06	3717,08
Biofuels (fuels)	**0**	**0,46**	**14,94**	**0,06**	**0,14**	**0,14**	**0**	**25,26**	**0,36**	**6,22**	**4,54**	**52,1**
Geothermal (heat)	**0,88**	**2,16**	**9,6**	**0,44**	**0**	**2,82**	**0**	**16,48**	**14,82**	**0**	**2,46**	**49,66**
Hydro	**8,1**	**3,26**	**44,5**	**21,26**	**10,64**	**6,36**	**1,94**	**57,04**	**22,02**	**41,74**	**57,54**	**274,4**
Solar_photovoltaics	**0**	**0,02**	**0,6**	**0**	**0**	**0,18**	**0**	**0**	**0**	**0**	**0**	**0,8**
Solar_thermal (heat)	**0,02**	**0,16**	**1,46**	**0**	**0,14**	**0,5**	**0,86**	**1,74**	**0,24**	**4,3**	**0,14**	**9,56**
Tide_wave_ocean	**0**	**0**	**0,04**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0,04**
uranium	**2,94**	**0**	**245,24**	**66,48**	**4,42**	**68,76**	**0**	**245,12**	**48,62**	**16,2**	**5,1**	**702,86**
wind	**0,1**	**0,3**	**10,32**	**0,02**	**1**	**0,22**	**0,02**	**4,78**	**1,04**	**0,76**	**0,08**	**18,68**
sum	**264,2**	**116,34**	**1767,18**	**994,3**	**415,2**	**427,84**	**544,04**	**2371,36**	**800**	**1447,02**	**439,54**	**9587,04**

Table 3.1: Energy transformation energy inputs 2007 *(values in mtoe, primary energy is accounted for prior to conversion)*, source: OECD energy balances

3.3.2 Initial amounts of primary energy carrier trade

Initially traded amounts of primary energy carriers had to be taken from different sources: For natural gas and crude oil, data from the BP Statistical Review of World Energy 2007 (BP 2008) was taken, while for the amount of coal trades in 2007 data from ‘IEA Coal information (2010)’ (IEA 2010a) was used. Traded amounts of uranium were specified by data taken from www.wise-uranium.com. In cases where data for the year 2007 was missing or termed as unsecure, traded amounts were approximated by flows of previous years. For the flow of uranium from Russia to the European Union, the amount of 5406 metric tonnes of uranium in 2007, which by the authors is deemed as a “highly unreliable” figure, was reduced such that uranium imports from Russia into the European Union do not account for more than 25% of all European imports of uranium, as the European Union has a policy of importing not more than 25% of its uranium requirements from Russia. Tables depicting the amounts of interregional trade for the base year 2007 are given in Appendix A.3.2.

3.3.3 Initial production of primary energy carriers

Initial production (or extraction) of primary energy carriers is calculated as the sum of net-exports of primary energy carriers in a region and amounts of the primary energy carrier used within the region itself. The thus calculated amounts are checked to not significantly deviate from production amounts specified in OECD energy balances data for 2007 and BP statistical review data for 2007. Since transformation data from OECD energy balances are used, while traded amounts are taken from BP statistical review and other sources specified above, where already BP statistical review and OECD energy balances for the year 2007 are not perfectly consistent, small deviations in the primary resource extraction data, either from the amounts specified in BP statistical review or OECD energy balances are to be accepted.

3.3.4 Resource endowments

Primary energy carrier resource endowments for natural gas, crude oil and coal are set according to (BP 2008), while resource endowments of uranium are taken from ‘OECD Uranium 2009’ (Nuclear Energy Agency and OECD 2010), where data on endowments of identified resources extractable at less than 130$/kg were taken as the basis for endowments in 2007. Following Nuclear Energy Agency and OECD (2010), we assumed that one ton of uranium on average has an exploitable energy content of 12 thousand toe, since it is not clear in which region or type of reactor the uranium will be used later on. For model region Japan some small artificial endowments of crude oil and natural gas had to be constructed for computational issues, instead of the zero endowments found in BP (2008). This change, however, does not lead to any qualitative change in calculations. Table 3.2 shows the resource endowments assumed in GREET.

	coal	**crude oil**	**natural gas**	**uranium**	**sum**
Africa	21284	16929	13282	12314	63809
Australasia	37689	463	2769	14844	55765
Europe	13079	1588	3931	1212	19810
FormerSovietUnion	111683	16700	52853	19984	201220
India	37533	773	1004	871	40207
Japan	237	120	50	79	486
MiddleEast	924	102002	68564	19	171509
NorthAmerica	119793	10211	8242	9124	147370
Other Asia	3815	2310	8635	886	15646
China	58900	2026	2210	811	63947
South America	7323	28500	7252	3640	46716
sum	**412261**	**181648**	**168793**	**63784**	**826485**

Table 3.2: 2007 Resource endowments for model regions *(in mtoe).* Sources: BP (2008), Nuclear Energy Agency and OECD (2010).

3.4 Cost functions and cost data

Data on regionally broken down costs of extraction-, trade and transformation processes is in many cases hard to obtain. It becomes even more difficult, once one looks into costs of capacity expansions, for example of extraction processes. This is because, on the one hand, cost data often are business relevant information, kept confidential from clients and competitors, and on the other hand, future costs on e.g. extraction capacity expansions can be very unclear, due to e.g. geological conditions. Also, since the eleven regions covered in this global model are of huge size and often comprehend enormous heterogeneity, representative averages had to be taken, to, in the end, meaningfully depict the situation for a region. Where direct data on a region was not available, sometimes averages of by-country-costs within a model region were taken, or available cost data for one or several countries within a model region were assumed to be representative for that region. Where no cost data was available, assumptions had to be made. Generally, two sorts of costs apply for each of the sectors covered: Costs for the activity (production, trade, transformation) itself and costs of investments into capacities for these activities. Below, costs are specified for the different sectors.

3.4.1 Extraction costs

For crude oil and natural gas production, regional cost estimates by Reuters (2009) as well as cost estimates by the EIA (2009) (T-18. Production (Lifting) Costs by Region) were used. For coal extraction, cost estimates from Haftendorn et al. (2010) and Baruya (2007) were adopted. For regional uranium extraction costs, data from Nuclear Energy Agency and OECD (2010) was employed.

Harder to find are data or estimates on the costs of primary energy carrier extraction capacity expansion costs, i.e. costs for increasing production capacity of a primary energy carrier in a region. Since data for the regional differences in costs of capacity investments in extraction processes is not available, the regional costs for capacity expansions in resource extraction are configured according to the primary energy carrier specific regional ratio of resource extraction and resource endowments in the base year.

In addition to these linear costs of capacity expansion, a quadratic cost component, reflecting convex, increasing costs in rapid expansions of capacities, is included. Following Gould (1968), investment cost functions for capacity expansions in extraction processes are assumed to have the properties

$$c^{extr\_i}_{t,pe,r}(i^{extr}_{t,pe,r}) > 0, \qquad \frac{\partial c^{extr\_i}_{t,pe,r}(i^{extr}_{t,pe,r})}{\partial i^{extr}_{t,pe,r}} > 0, \qquad c^{extr\_i}_{t,pe,r}(0) = 0, \qquad \frac{\partial^2 c^{extr\_i}_{t,pe,r}(i^{extr}_{t,pe,r})}{\partial {i^{extr}_{t,pe,r}}^2} > 0$$

“reflecting the assumption that cost of adjustment will be greater on the average the greater the rate of (dis)investment” (Gould 1968). Within the specification of GREET, the simplest functional form of an investment cost function, representing these properties was chosen with

$$c^{extr\_i}_{t,pe,r}(i^{extr}_{t,pe,r}) = lc^{extr\_i}_{t,pe,r} i^{extr}_{t,pe,r} + qc^{extr\_i}_{t,pe,r} {i^{extr}_{t,pe,r}}^2$$

The extraction investment costs are thus a function of the amount of investments $c^{extr\_i}_{t,pe,r}(i^{extr}_{t,pe,r})$, with a linear cost component $lc^{extr\_i}_{t,pe,r}$ and a quadratic cost component $qc^{extr\_i}_{t,pe,r}$. For the parametrization of the quadratic extraction cost term we proceeded in a similar way, assigning the height of quadratic extraction capacity expansion costs according to the amount of resource endowment available in a region.

3.4.2 Trade costs

The trade costs function between regions is specified as a linear cost function of the average distances for representative seaborne trade routes, using ‘port world distance calculator’ (www.portworld.com). Abstracting from the high volatility of shipment prices and specifics of freight rates due e.g. frequentation of routes, we assumed a representative price of 1US$ per ton of cargo per day and an average daily cargo forwarding distance of 580 km. The resulting transportation costs are adapted to energy carrier specific freight rates, according to the primary energy carrier specific physical amounts of energy carrier per energy content. Distances are calculated allowing shipments via the Bosporus Strait, the Panama Canal and the Suez Canal, if reasonable. The parameter $lc^{trade}_{t,pe,r\rightarrow rr}$ depicts the linear costs of primary energy carrier trade. Additionally, trade costs also respond to fuel prices of importing regions, following formula (36):

$$(36) \qquad c^{trade}_{t,pe,r\rightarrow rr}\left(x^{trade}_{t,pe,r\rightarrow rr}\right) = lc^{trade}_{t,pe,r\rightarrow rr}\left(\frac{p^{sec}_{t,'fuels',rr}}{p^{sec}_{'t=1','fuels',rr}}\right)^{0,5} x^{trade}_{t,pe,r\rightarrow rr}$$

Investment costs in trade routes also vary according to distance and energy carrier, symbolizing costs of establishing contracts and additional capacity for a specific trade route. Costs of trade of primary energy carriers within a region, from their place of extraction to the place of conversion for smaller regions are assumed to be zero, however, for trade within the geographically larger or more scattered regions such as Other Asia Pacific, Former Soviet Union, Europe, Africa and North America, as well as for neighbouring countries on the same landmass, an average transportation distance of 1500 km is assumed. For an overview of the assumed trade distances between the regions in GREET see appendix A.3.4.

3.4.3 Transformation costs

For costs of transformation processes, investment and production cost data for electricity generating transformation processes are taken from ‘IEA Projected Costs of Generating Electricity 2010’ (IEA 2010b) and ‘IEA energy technology perspectives 2010’ (IEA 2010c).

Refinery production costs and investments costs in refinery capacity are taken from estimations form Kaiser and Gary (2007), Junginger et al. (2008) and by Reuters[2]. Junginger et al. (2008) show that specific investment costs for Gas combined cycle plants strongly depend on plant capacity. With a clustering of plants around the sizes of 100 MW and 300 MW, we assumed a typical plant investment cost of 1200$/kw (in 2007 dollars) as representative.

Costs for a non-manipulating transmission of a primary energy carrier, e.g. for the primary energy carrier coal, to become the final energy good coal that is directly demanded by final consumption, are assumed to be zero. The same accounts for the 'transformation' of the primary energy carrier natural gas into natural gas as a final energy good.

Analogical to the quadratic cost term in extraction capacity investments, a quadratic investment cost component is also introduced for transformation capacity investments, accounting for rising costs due to scarcities in cases of huge capacity investments, which might drastically change the structure of the energy system within a short time. Quadratic cost components correspond to the amounts of the specific linear investment costs. In contrast to other types of power plants, for investments in nuclear power plants, quadratic investment costs are increased by a factor 3, in order to account for an increased scepticism of civil societies to accept drastic increases in nuclear electricity production capacities after the Fukushima accidents. Conversion rates for the different transformation technologies are accounted on a regional basis, taken from input-output ratios calculated from OECD energy balances 2007. Future cost reductions in conversion processes are taken into account and further described in section 3.5.

3.4.4 Costs of renewable energy production

The modelling of the renewable energy sector in GREET considers different costs of and constraints on renewable energy production. Next to the direct costs of energy production and costs of investments into additional capacities, constraints on the regional potentials for renewable energy production are employed and costs for electricity storage from fluctuating renewable energy production is accounted for.

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[2] E.g.: http://www.reuters.com/article/2007/06/14/us-refinery-hyperion-idUSN1340544120070614
http://af.reuters.com/article/investingNews/idAFJOE71004620110201?pageNumber=1&virtualBrandChannel=0

3.4.4.1 Production and investment costs

As for non-renewable final energy production technologies, for renewable electricity production, costs for capacity investments and production of electricity were taken from IEA (2010b)’. For fuel production from sugarcane and corn, production costs were taken from studies from van den Wall Bake et al. (2009) and Hettinga et al. (2009).

For the parametrization of quadratic investment cost components, as for the quadratic costs of non-renewable transformation technologies, quadratic cost parameters were parametriced in relation to the particular costs of each renewable technology. However, due to the increasing costs of renewable production, once their employment approaches absolute physical potentials of a specific form of renewable energy production for a region, quadratic cost components were raised by a factor 2 compared to their non-renewable alternatives. This increase in quadratic costs is to depict the situation that massive investments into renewable technologies have an effect of increasing the costs, due to scarcities in factors such as places of location and other factors limiting the overall physical potential of a renewable technology. The opposite tendency of renewable energies, becoming, due to economies of scale, cheaper with more capacities installed, is also considered and described in section 3.5.

3.4.4.2 Constraints on renewables

Two types of constraints on renewable energy production are considered here. Firstly, for all forms of renewable energy production, regional potentials are derived from the literature, to depict the situation that regional production of renewable energy is not boundless. Secondly, as these constraints are not the most binding elements, when it comes to electricity generation from wind and solar technologies, an electricity storage constraint is introduced, to account for the additional costs of electricity generation from these fluctuating sources.

3.4.4.2.1 Renewable potentials

Data on resource potentials are taken from different sources, with the IPCC Special report on renewable energy sources (2011) as a major source on regionally differentiated potentials on renewable energy production from different renewable technologies. Thus, for potentials of geothermal energy production the lower estimates of the electric technical potential at depths to 10km are taken from IPCC (2011). Potentials for hydroelectricity also stem from IPCC

2011. The hydroelectric potential for China is taken from NDRC (2007). For tide, wave and ocean energies, regional potential for wave energy by Mørk et al. (2010) (also in IPCC (2011)) are employed. Wind energy potentials are generally based on Krewitt et al. (2009). Wind energy potentials for the region of the former Soviet Union are specified by results for Russia from Nikolaev et al. (2008) and data for China is specified by Xiao et al. (2010). For annual total technical potentials of solar energy, minimum estimates from Rogner et al. (2000) (also in IPCC (2011)) are employed.

Potentials on renewable energy generation from biomass are calculated using results from Fischer et al. (2009). Following Fischer et al. (2009), as a regional potential for renewable energy production, only “unprotected grassland and woodland (i.e., forests excluded) where land requirements for food production, including grazing, have been considered” (Fischer et al., 2009) are considered. On this basis, for this application in GREET, overall global biomass production potential is assumed to amount up to 222,3 EJ, spatially very unevenly distributed, however: Africa and Latin America exhibit the largest potentials for biomass production for energy usages, while the other world regions have smaller possibilities to enlarge their biomass production for energy use. For an overview of regional renewable energy potentials assumed in GREET, see Table 3.3.

Region\Technology	Biomass	Hydro	Geothermal	Solar	Tide, wave and ocean	Wind
Other Asia Pacific	155,2	25,0	71,9	918,6	257,2	147,0
China	93,1	115,7	152,4	1837,3	110,2	352,8
Former Soviet Union+	341,5	32,5	108,9	3656,2	55,1	734,9
India	62,1	24,9	63,1	716,5	147,0	165,4
South America	1397,2	188,9	36,1	2076,1	404,2	808,4
Middle East	3,1	3,9	35,7	2755,9	18,4	161,7
Europe	186,3	67,5	120,0	532,8	231,5	404,2
North America	589,9	109,7	50,0	3325,5	220,5	3395,3
Australasia	310,5	12,2	33,0	753,3	367,5	183,7
Africa	2142,4	77,7	20,8	11023,7	268,2	147,0
Japan	62,1	10,8	19,2	367,5	73,5	79,9

Table 3.3 Renewable energy potentials in GREET (in mtoe/year). Sources: IPCC (2011), NDRC (2007), Mørk et al. (2010), Krewitt et al. (2009), Nikolaev et al. (2008), Xiao et al. (2010), Rogner et al. (2000), Fischer et al. (2009)

These potentials, however, in many cases do not predominantly constrain the amounts of renewable energies employed, since physical potentials for many renewable technologies within the regions are abundant, especially for electricity generation from sun and wind. In the next section, the complementing constraint of electricity storage for fluctuating renewable electricity generation is introduced.

3.4.4.2.2 Electricity storage constraints

For the generation of electricity, absolute physical limits on the production by renewables, such as land use, are not the predominant constraint for the implementation of renewable energies. Different studies have shown that it is generally possible to supply 100% of electricity with renewable energies, e.g. SRU (2011). Taking this into account, we introduce the need to provide storage contingents, varying on the ratio of fluctuating renewable sources of electricity generation within the electricity system. The need to build up this storage also makes up an important share of costs of renewables. Here, we introduce the necessity to provide storage only for electricity generation from wind and photovoltaic technologies, while other renewable technologies are assumed to be adjustable.

Following Tröndle et al. (forthcoming), the necessary amount of electricity storage increases exponentially with the proportion of renewable electricity production. Tröndle et al. (forthcoming) depict that, starting from a renewable penetration rate of about 40%, the need for storage increases exponentially. Figure 3.4 depicts the need for electricity storage in the region Europe, for different renewable penetration rates.

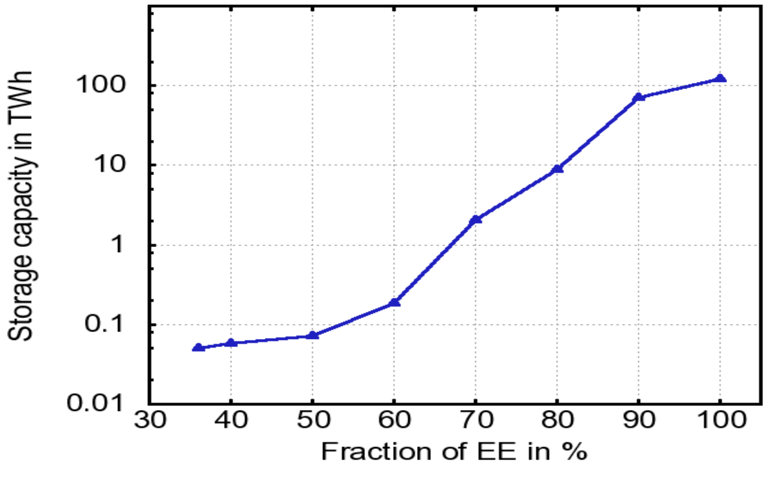


Figure 3.4: strorage requirements for different proportions of renewable electricity production. Source: Tröndle et al. (forthcoming)

Following the analysis of Tröndle et al. (forthcoming), we assume that the necessary amount of electrical storage capacity is an exponential function of the ratio of electricity generated from solar and wind technologies towards the amount of adjustable electricity production technologies. Thus, as an additional constraint for renewable energy production, an electricity storage constraint (37) is introduced, where the amount of storage capacity provided in one region and one period $s^{ren}_{t,rr}$ has to amount to an exponential function, with a region specific parameter β_{rr} specifying the maximum amount of storage for a case of an electricity supply from 100% renewable energy, and the amount the non-adjustable amount of electricity production serving as the argument of the exponential function. If this amount reaches 100% of the electricity generation, the required electrical storage capacity comes up to $e^{\beta_{rr}}$.

(37) $$s^{ren}_{t,rr} \geq e^{\beta_{rr} \frac{x^{ren}_{t,rr,'wind'} + x^{ren}_{t,rr,'solar'}}{\sum_{pe} x^{trans}_{t,pe \to fe,rr} + \sum_{rt} x^{ren}_{t,rr,rt}}}, \quad \forall t, rr$$

β_{rr} here is a region specific parameter to adjust the exponential function to the different sizes of the regional energy systems. Taking the analysis of Tröndle et al. (forthcoming) as a benchmark for the amount of electrical storage required, Table 3.5 depicts the different regional storage requirements for the regions in GREET, for the case of a completely renewable supply of electricity.

Region	Other Asia Pacific	China	Former Soviet Union+	India	South America	Middle East
Electrical storage	38,7	73,9	34,8	32,3	22,1	15,8
Region	**Europe**	**North America**	**Australasia**	**Africa**	**Japan**	
Electrical storage	72,2	79,4	15,1	19,9	32,3	

Table 3.5 Electrical storage requirements in case of a 100% renewable electricity supply (in mtoe)

The arising costs of electrical storage and generation of electrical storage capacity are shared proportionately between the fluctuating electricity generating renewable technologies wind and sun. With the storage needs introduced above, a constraint on the construction of storage capacity has to be introduced for the optimization problems of the electricity production from wind and sun. Thus, for these fluctuating renewable technologies the optimization problem becomes:

$$\max_{x^{ren}_{t,fe,rr,rt},\, i^{ren}_{t,fe,rr,rt},\, s^{ren}_{t,rr,rt},\, i^{store}_{t,rr,rt}} \quad \pi^{*}_{ec,re} = \sum_{t=1}^{T} \pi_{t,ec,re}\delta^{t}$$

$$= \sum_{t=1}^{T} \Big[p^{sec}_{t,fe,rr} x^{ren}_{t,fe,rr,rt} - c^{ren}_{t,fe,rr,rt}(x^{ren}_{t,fe,rr,rt}) - c^{ren\_i}_{t,fe,rr,rt}(i^{ren}_{t,fe,rr,rt}) - c^{ren\_store}_{t,rr,rt}(s^{ren}_{t,rr,rt}) - c^{i\_store}_{t,rr,rt}(i^{store}_{t,rr,rt}) \Big] \delta^{t}$$

$$s.t. \qquad (38) \quad x^{ren}_{t,fe,rr,rt} \le cap^{ren\_ini}_{fe,rr,rt}\, {\rho^{ren}_{fe,rr,rt}}^{t} + \sum_{\tau=1}^{t-1} i^{ren}_{t,fe,rr,rt}\, {\rho^{ren}_{fe,rr,rt}}^{t-\tau}, \quad \forall t, fe, rr, rt$$

$$(39) \quad x^{ren}_{t,fe,rr,rt} \ge 0, \quad \forall t, fe, rr, rt$$

$$(40) \quad i^{ren}_{t,fe,rr,rt} \ge 0, \quad \forall t, fe, rr, rt$$

$$(41) \quad s^{ren}_{t,rr,rt} \le cap^{store\_ini}_{rr,rt}\, {\rho^{store}_{rr,rt}}^{t} + \sum_{\tau=1}^{t-1} i^{store}_{t,rr,rt}\, {\rho^{store}_{rr,rt}}^{t-\tau}, \quad \forall t, rt, rr$$

$$(42) \quad s^{ren}_{t,rr,rt} \ge \frac{x^{ren}_{t,rr,rt}}{x^{ren}_{t,rr,'wind'} + x^{ren}_{t,rr,'solar'}}\, e^{\beta_{rr} \frac{x^{ren}_{t,rr,'wind'} + x^{ren}_{t,rr,'solar'}}{\sum_{pe} x^{trans}_{t,pe\rightarrow fe,rr} + \sum_{rt} x^{ren}_{t,rr,rt}}}, \quad \forall t, rt, rr$$

$$(43) \quad x^{ren}_{t,fe,rr,rt} \le P_{fe,rr,rt}, \quad \forall t, fe, rt, rr$$

Equation (42) depicts the need for storage, introduced above and proportionally shared between the two technologies, while (41) depicts the electrical storage capacity constraint and (43) stands for the general physical potential constraint, relevant for all renewable technologies. The resulting complementarity conditions are depicted in appendix A.3.5.

Data for the cost of provision of electrical storage are taken from VDE (2009). With the calculation of storage requirements of the electricity part of the energy system, we implicitly also account for the feasibility of the electricity supplies in terms of provision of electricity to comply with daily load curves. For the base year, decisive initial capacities for electrical storage are assumed to be nonexistent in the regions. However, enough storage capacity is provided to account for the minimal storage needs in the base year.

3.5 Technological learning

For the learning processes for the different technologies within GREET, we decided to not employ endogenous learning, but to lodge exogenous technological learning paths. Endogenous learning can be motivated from two different perspectives: (1) learning by searching effects, where R&D activities bring down production costs and (2) learning by doing effects, where bigger amounts of installed capacities bring down prices (compare Junginger et al. 2008). Reasons to not employ either form of endogenous learning within GREET are thus twofold: (1) For learning by searching effects, since GREET only is a partial equilibrium model and not a CGE, we cannot account for rivalry of R&D resources, such as scientists, between the energy sector and other sectors of an economy. Enabling endogenous investments in R&D might lead to an excessive use of R&D capacities within the energy sector and trade-offs to other sectors cannot be modelled here. (2) For learning by doing, the problem of endogeneity here is the rational of the investment decisions of the individual agents. In this perfect foresight model, once being able to account for an endogenous change in costs by producing higher amounts, costs will be brought down by increasing the aggregate amount of the technology employed. However, this is not rational from an individual agent's point of view, since he does not take into account the lowering of prices within his decision to install a certain device of one technology.

Another reason for not applying endogenous learning rates can be seen in the enormous variations in outcomes, where small changes in the estimation of a learning rate can produce disproportionately drastic changes in outcomes. As Junginger et al. (2008) states, especially for long term forecasts, small variations in the assumed rates of technological learning "can lead to significantly deviating cost reductions in scenarios or completely different model outcomes in energy and climate models" (Junginger et al.2008). This is (even more) true for endogenously applied learning rates, as an assumption of a comparatively high learning rate for a specific technology might lead to massive endogenous investments and thus change results drastically. For exogenous learning rates, the magnitude of such potential errors is decisively smaller.

Thus, in this model, we chose to implement exogenous learning rates for the different renewable and non-renewable technologies, using calculations of progress ratio data summarized in Junginger et al. (2008). For learning rates of fuel production from biomass, Junginger et al. (2008) concludes that it is very difficult to derive empirical experience curves, also due to a lack of data. Still, as an approximation for the biofuel sector, results from de Wit et al. (2010) are used, which predict a decrease in production costs of biomass to liquid Fischer-Tropsch fuels .

For the computation of technological learning of nuclear energy production, we looked into data computed by the University of Chicago (2004). As Junginger et al. (2008) indicates, the technological learning rates stated in the literature and also applied in GREET do not include limitations due to geographical potential constraints. Neither do these estimations of cost developments include the costs of storage technologies. Thus, as described in section 3.4, we modeled these additional cost factors separately. Figure 3.6 depicts the cost reduction assumptions for different technologies.

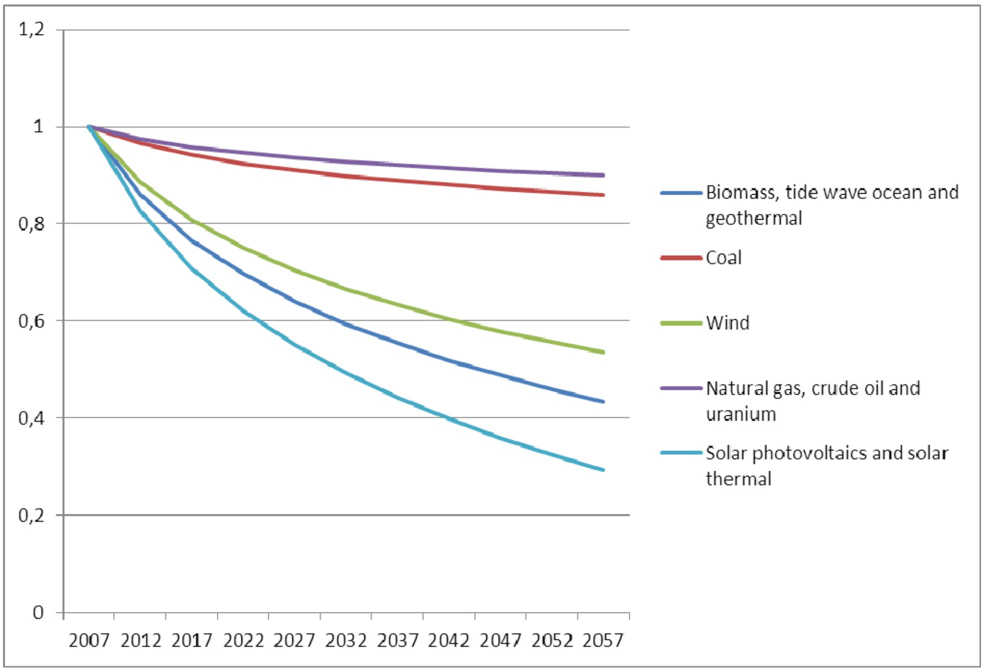


Figure 3.6: Cost reduction assumptions for different technologies

3.6 Final demand specification

As described in section 2.6, final energy demand in GREET grows by an exogenous growth path, however, elastic to final energy prices:

$$x_{t,fe,rr}^{dem} = x_{fe,rr}^{dem\_ini} \theta_{t,fe,rr} \left(\frac{p_{fe,rr}^{sec\_ini}}{p_{t,fe,rr}^{sec}} \right)^{\rho} \qquad \forall t, fe, rr \tag{35}$$

For the growth parameter $\theta_{t,fe,rr}$, the magnitude of regional differences in final demand growth are deduced from the Hawksworth (2006). Regional final energy demand growth, assuming constant final energy prices, is depicted in Table 3.7. The parameter ρ, determining price elasticity of final demand, was parameterized at 0,03.

Region	**Other Asia Pacific**	**China**	**Former Soviet Union+**	**India**	**South America**	**Middle East**
Growth rate	**1,17**	**1,95**	**1,38**	**2,65**	**1,95**	**1,17**
Region	**Europe**	**North America**	**Australasia**	**Africa**	**Japan**	
Growth rate	**1,02**	**1,23**	**1,39**	**1,17**	**0,81**	

Table 3.7 Yearly final energy demand growth rates in percent

3.7 Time steps, depreciation rates and discount factor

For the time steps within GREET, we chose time steps of 5 years, starting from the base-year 2007. Within the time of one such time step, we allow the model to construct new capacities in all parts of the energy system. Although, in some cases, such as the construction of nuclear power plants, this time span might be slightly too short, we believe that, for most fields, such as thermal power stations or refinery projects, is quite reasonable, as lead times tend to vary between two and four years (Bhattacharyya 2011). Yearly depreciation of production capacity is chosen to amount to 4% for all extraction-, transformation- and renewable energy production processes. No depreciation on trade capacities is assumed. The discount factor in GREET is chosen at 3% per year.

4. Results

4.1 Scenarios

The following two basic scenarios serve to depict the general results of GREET model runs. For both scenarios the general model specifications and assumptions, as depicted in Chapter 3, are adopted.

4.1.1 BAU – scenario 1

For this Business as usual scenario (BAU), no global framework on carbon emission reductions is assumed: globally, carbon emissions are costless. However, we have implemented the European ETS. In the form implemented in this scenario, the EU ETS caps and reduces CO_2 emissions from electricity generation for the model region Europe. Emissions are capped on the height of emissions in 2007, with the cap tightening by 1,74% every year from 2012 onwards. Within this model run, it is assumed that the cap keeps tightening at this speed until 2050. For the rest of the world, no restrictions on CO_2 emissions are assumed.

4.1.2 Global ETS – scenario 2

For this scenario, a binding global restriction on CO_2 emissions is assumed. The restriction is implemented in terms of a global CO_2 emission trading scheme, where all global carbon emissions resulting from combustion of fossil fuels within the energy system have to be covered by emission allowances. This includes all forms of energy obtained from the combustion of the primary energy carriers coal, crude oil and natural gas. The implementation within GREET takes place at the level of the transformation sector. For every amount of primary energy carrier transformed into final energy goods, emission offset allowances have to be purchased, matching the CO_2 content inherent to the primary energy carrier transformed. Thus, different to e.g. the EU ETS, refinery products like gasoline and other nonrenewable liquid fossil fuels are also covered by the carbon cap. For this scenario, global carbon emission allowances are set to the amount of energy related carbon emissions of the base-year 2007, at 25 billion tons of CO_2 per year. This effectively means that global CO_2 emissions from energy production are not allowed to rise above 2007 levels, with a market for CO_2

offset allowances determining for which purposes the emissions are used, and transformation sectors given the necessity to purchase CO_2 offset allowances and incorporating this as part of their economic optimization calculus.

Thus, the profit maximization problem of the transformation sector for scenario 2 becomes

$$\max_{x_{t,pe,rr}^{trans\_purch},\, x_{t,pe\to fe,rr}^{trans},\, i_{t,pe\to fe,rr}} \pi_{pe,rr}^{*} = \sum_{t=1}^{T} \pi_{t,pe,rr} \delta^{t}$$

$$= \sum_{t=1}^{T} \left[p_{t,fe,rr}^{sec} x_{t,pe\to fe,rr}^{trans} - p_{t,pe,r\to rr}^{pe\_down} x_{t,pe,rr}^{trans\_purch} - c_{t,pe\to fe,rr}^{trans}\left(x_{t,pe\to fe,rr}^{trans}\right) - c_{t,pe\to fe,rr}^{trans\_i}\left(i_{t,pe\to fe,rr}^{trans}\right) - p_{t}^{ea} ea_{t,pe\to fe,rr}^{trans} \right] \delta^{t}$$

$$s.t. \qquad (44)\ x_{t,pe\to fe,rr}^{trans} \le cap_{pe\to fe,rr}^{trans\_ini} \rho_{pe\to fe,rr}^{trans}{}^{t} + \sum_{\tau=1}^{t-1} i_{t,pe\to fe,rr}^{trans} \rho_{pe\to fe,rr}^{trans}{}^{t-\tau}, \quad \forall t, pe \to fe, rr$$

$$(45)\ \sum_{fe} \left(\frac{x_{t,pe\to fe,rr}^{trans}}{\alpha_{pe\to fe}} \right) \le x_{t,pe,rr}^{trans\_purch}, \quad \forall t, pe, rr$$

$$(46)\ ea_{t,pe\to fe,rr}^{trans} \ge x_{t,pe\to fe,rr}^{trans} em_{t,pe,rr}^{trans}, \quad \forall t, pe, rr$$

$$(47)\ x_{t,pe\to fe,rr}^{trans} \ge 0, \quad \forall t, pe \to fe, rr$$

$$(48)\ x_{t,pe,rr}^{trans\_purch} \ge 0, \quad \forall t, pe, rr$$

$$(49)\ i_{t,pe\to fe,rr}^{trans} \ge 0, \quad \forall t, pe \to fe, rr$$

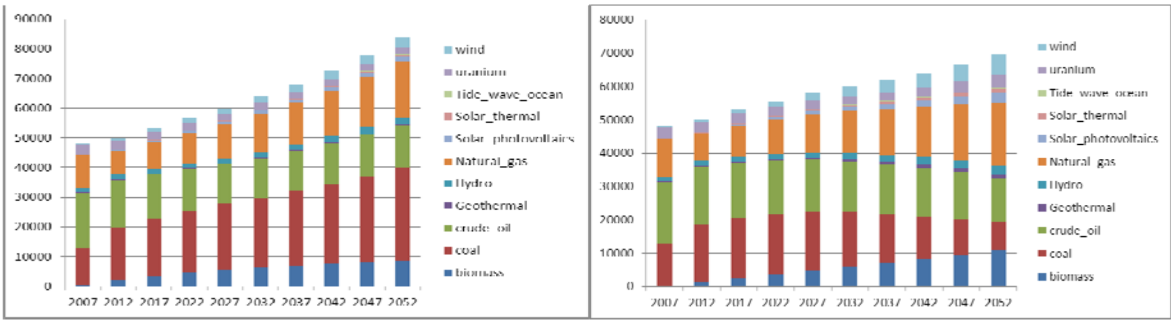
, with equation (46) determining the needs of the transformers to purchase emission allowances, where $em_{t,pe,rr}^{trans}$ expresses the CO_2 content inherent to the different forms of primary energy carriers, while $\sum_{pe\to fe} \sum_{rr} ea_{t,pe\to fe,rr}^{trans}$ is set to 25 billion tons of CO_2. Growth of final energy demand within the different regions of the world, as well as all other assumptions and parameters remain as specified in Chapter 3.

4.2 Primary energy consumption

For the two scenarios, significant differences in the evolvements of primary energy consumption can be detected. Even though a global carbon emissions cap at 2007 carbon emission levels is not a very ambitious restriction, shifts from the BAU-scenario, are remarkable.

4.2.1 Global primary energy consumption

Results for global primary energy consumption for the two scenarios are depicted in Figure 4.1. In scenario 1, global primary energy consumption almost doubles from 2007 to 2052. Coal most significantly increases its share in primary energy consumption. Natural gas over time becomes the second important primary energy carrier, also overtaking crude oil, which is consumed in slightly declining amounts. Renewable energies are further developed, but their share remains low. Nuclear energy is very slowly faded out, with new nuclear plants being built, while not completely replacing the amount of shut down ones.



Scenario 1 **Scenario 2**

Figure 4.1: Global primary energy consumption in two scenarios (in mtoe)

In scenario 2, overall primary energy consumption keeps growing, while overall global primary energy consumption for the year 2052, e.g., reduces by 17% compared to scenario 1. Thereby, the global carbon cap most significantly reduces coal consumption, while diffusion of renewable energies proceeds at a faster pace. Nuclear energy stays at almost constant shares and natural gas becomes the most widely consumed primary energy carrier.

4.2.2 Regional primary energy consumptions

Evolvements of primary energy consumption show different regional characteristics. Figure 4.2 depicts the primary energy consumptions for the two scenarios for the model regions China, Europe and North America.

In scenario 1, Chinese primary energy consumption more than doubles until 2052. Coal keeps being the dominant primary energy source, with absolute coal consumption also more than doubling. Natural gas is increasingly used, while renewable energies, except from some electricity generation from water and wind, are not significantly produced. The diffusion of nuclear technologies is precluded by cheap coal technologies. For scenario 2, this changes: Coal remains being the most important primary energy carrier, but, until 2052, the amounts of coal used diminish, in relative and also in absolute terms. Nuclear and renewable technologies are promoted, while the overall amount of primary energy carrier consumption reduces significantly, compared to scenario 1.

Differences between the two scenarios for the model region Europe are more subtle. Since, for scenario 1, the continuation of the EU ETS is assumed, already a stagnation of the use of coal technologies takes place, while renewable energies increase their shares, especially in electricity production. For both scenarios, overall primary energy consumption only increases at low rates. Renewable electricity production, e.g. from wind, increases to higher levels in the EU ETS case, with 'carbon leakage' taking place to other non-restricted sectors of the energy system. For scenario 2, however, as CO_2 emissions from liquid fuel combustion is also restricted by the carbon cap, fuel production from biomass increases to higher levels. Natural gas and crude oil keep playing important roles, with natural gas increasingly equaling crude oil in importance.

For the model region North America, differences between the two scenarios are again more significant. The carbon cap first of all reduces coal consumption. However, also in scenario 2, coal consumption first still increases, before starting to decrease from the 2020s onwards. Compared to the regions Europe and China, for North America, more fuel production from biofuels is possible and thus the amount of fuel production from biomass increases in both scenarios, with higher final increases for scenario 2.

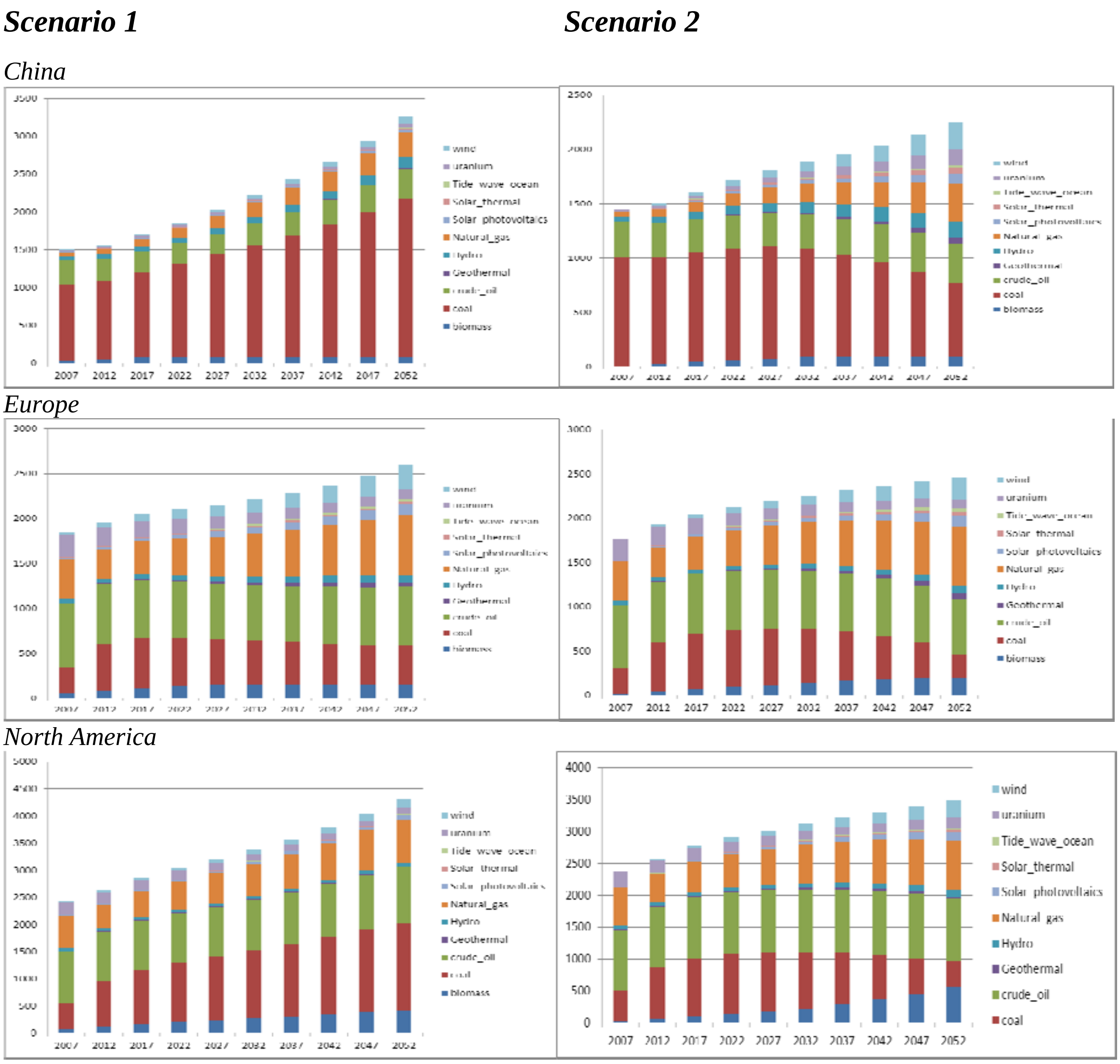


Figure 4.2 Primary energy consumption for China, Europe and North America in two scenarios

4.3 Primary energy carrier trade flows

Overall primary energy carrier trade flows show an increasing trend in both scenarios, however, sharply differing in types of energy carrier and regional trade patterns.

4.3.1 Global primary energy carrier trade flows

For the base year 2007, we accounted for interregional trade flows -between the regions employed in GREET- summing up to 14.720 mtoe. In Scenario 1, the sum of globally traded energy carriers triples and reaches 45.584 mtoe in 2052, while in scenario 2 the introduction of a global ETS makes primary energy carrier trade flows reach a height of 34.522 mtoe, still more than doubling compared to 2007 levels.

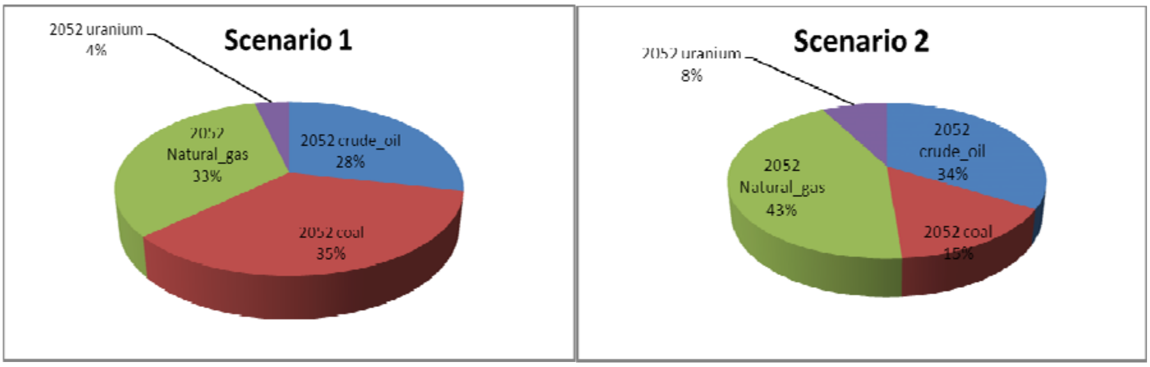


Figure 4.3: global primary energy carrier trade proportions (in energy content) in model year 2052

Figure 4.3 shows the relative shares of the different primary energy carriers in global trade for the two scenarios for the year 2052. For scenario 1, with the increasing primary energy consumption in coal, also an increasing trade in coal becomes rational. For the year 2052, coal trades amount to slightly more than one third of the globally traded primary energy carriers, becoming the most traded resource. Natural gas comes up to one third of trades, having overtaken crude oil trade amounts. Uranium does account for 4% of global primary energy carrier trades with regard to energy contents.

For scenario 2, the drastic reduction in coal trades, compared to scenario 1, essentially also accounts for the reduction of overall trade volumes. Coal trades reduce sharply, while gas, oil and uranium all increase their proportions. Compared to scenario 1, gas trades remain on stable absolute levels, while oil trade reduces in absolute terms and uranium trade increases in absolute terms. In both scenarios, natural gas trades show a sharp increase compared to 2007 levels.

4.3.2 Regional primary energy carrier trade flows

4.3.2.1 Coal trades

As the most significant overall differences between the two scenarios appear for the trades of coal, also the most obvious differences in regional trade flows are to be seen here. Figures 4.4 and 4.5 depict major coal trade volumes for the model year 2052 for the two scenarios, with changes from scenario 1 to scenario 2 indicated in brackets. For scenario 1, the by far largest interregional trade flow of coal takes place between the model regions Former Soviet Union (including Mongolia) and China. Additionally, China is provided with coal from Australasia and, to a smaller extent, from India. Australasia, the Former Soviet Union, Africa and also India evolve as main suppliers of coal. Next to China, as the biggest importer of coal, also North America, Europe, Other Asia Pacific and Japan import significant amounts of coal.

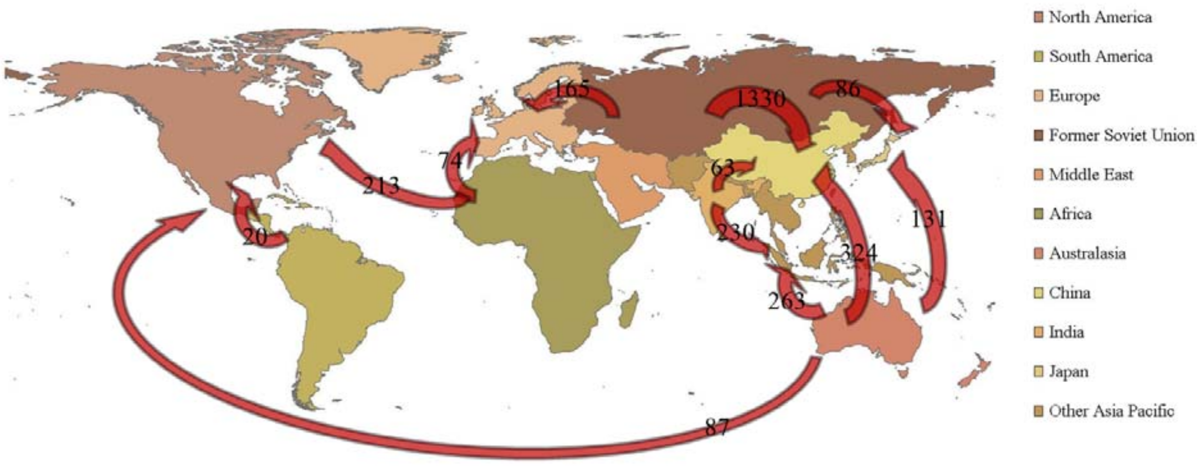


Figure 4.4 Major coal trades 2052 in mtoe – Scenario 1

In scenario 2, the sum of coal trades in 2052 reduces sharply. Trades from the Former Soviet Union to China still represent the largest interregional trade volume, while decreasing by 72% compared to scenario 1. Due to the rise in transport prices, some minor distance small trade flows increase, e.g. coal trades from South America to North America, while the sum of all coal imports decreases for all regions.

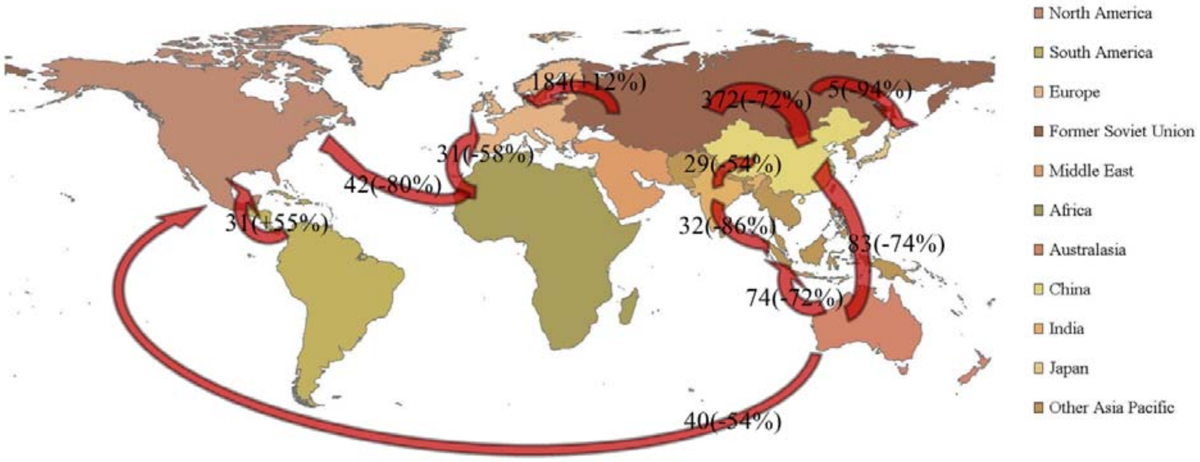


Figure 4.5 Major coal trades 2052 in mtoe – Scenario 2 (changes to scenario 1)

4.3.2.2 Crude Oil trades

Tables 4.6 and 4.7 depict major crude oil trade flows in the two scenarios. By 2052, the Middle East remains the major supplier for conventional crude oil. North America is additionally supplied with crude oil from South America, while Africa delivers smaller amounts of crude oil to North America, Europe and China. In Europe, as well as in the regions of the Former Soviet Union, all major amounts of conventional crude oil are by that time already depleted.

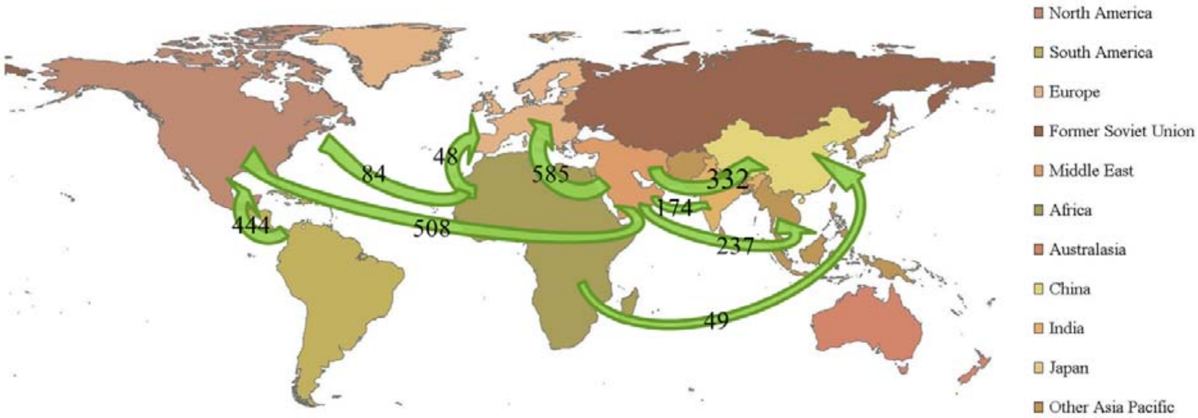


Figure 4.6 Major Crude Oil trades 2052 in mtoe – Scenario 1

This picture does not decisively change for scenario 2. For, with the global cap on carbon emissions, as depicted in scenario 2, global exploitation of crude oil still takes place in a comparable fashion, with the Middle East remaining as the main supplier of conventional crude oil resources. Still, overall traded amounts of crude oil reduce, with reductions in most individual amounts traded between regions comprising that trend.

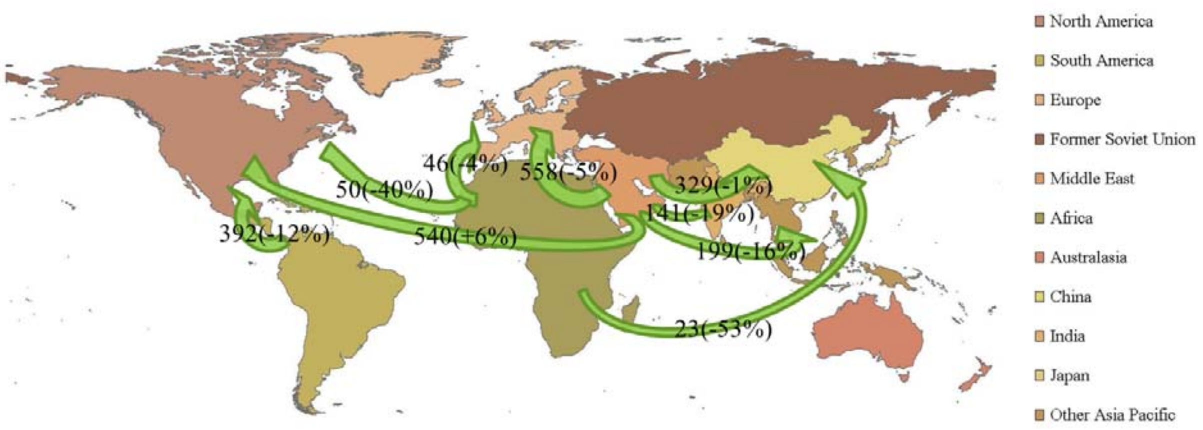


Figure 4.7 Major crude oil trades 2052 in mtoe – Scenario 2 (changes to scenario 1)

4.3.2.3 Natural Gas trades

In both scenarios, by 2052, natural gas becomes a globally traded primary energy carrier, traded in large volumes comparable to amounts of crude oil trades. Figures 4.8 and 4.9 depict that, by 2052, most of the exports of natural gas stem from the Former Soviet Union, the Middle East and Africa, while most of the other regions are importing from these two regions, relatively to the size of their energy systems and in most cases emphasizing geographic proximities.

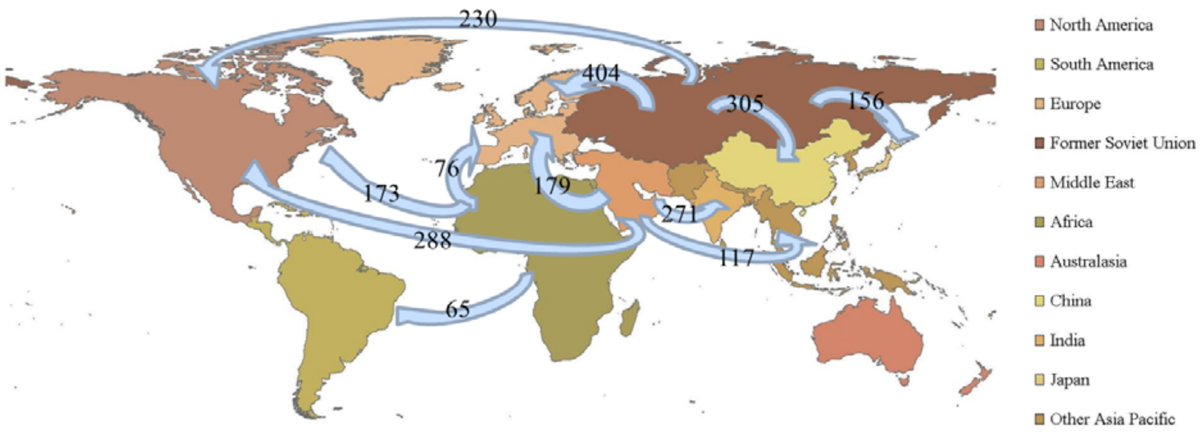


Figure 4.8 Major natural gas trades 2052 in mtoe – Scenario 1

Under the global carbon cap assumptions of scenario 2, natural gas has a high attractiveness, as its combustion is associated with comparably low carbon emissions. Still, changes from scenario 1 to scenario 2 are almost negligible, with a tendency that regions with big biomass production potentials produce more biomass in scenario 2, replacing natural gas imports with gas from biomass.

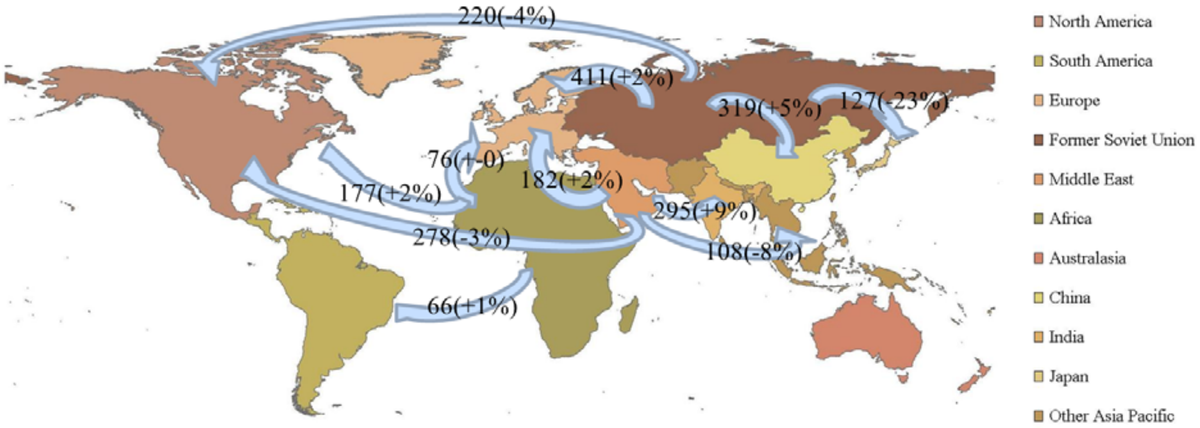


Figure 4.9 Major natural gas trades 2052 in mtoe – Scenario 2 (changes to scenario 1)

4.3.2.4 Uranium trades

Figures 4.10 and 4.11 show uranium trade flows for the year 2052. In scenario 1, main importing regions are Europe, China, Japan and also North America, which also produces significant amounts of uranium within the region itself. Suppliers of uranium are Africa, South America, Australasia and the Former Soviet Union. Europe has to import all of its uranium used, partially also importing uranium from North America.

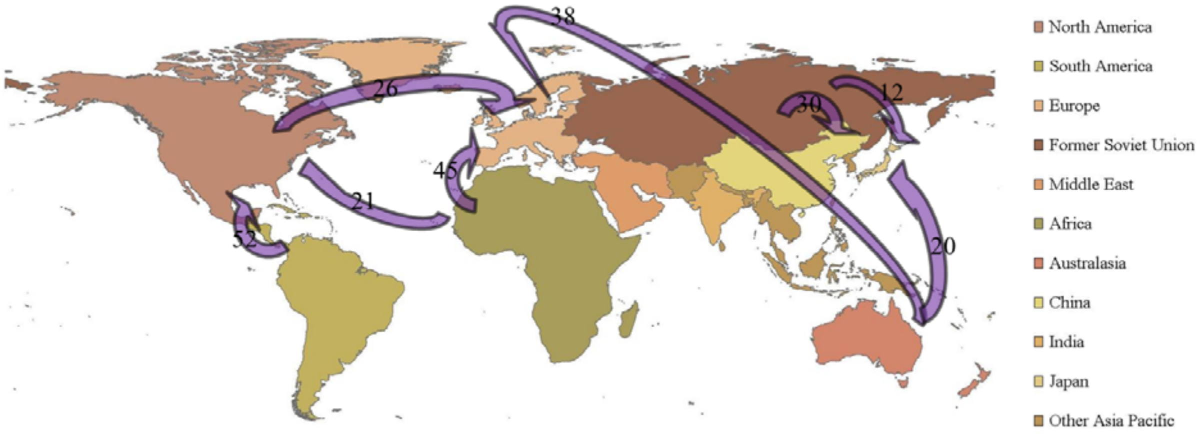


Figure 4.10 Major uranium trades 2052 in mtoe – Scenario 1

In scenario 2 the volume of uranium trades increases, as it is the only primary energy carrier not causing CO_2 emissions. All of the importing regions import more uranium than in scenario 1, with especially China more heavily relying on uranium imports from the Former Soviet Union and Australasia. Imports from the Former Soviet Union more than double. Effects on imports in Europe are rather insignificant, as the EU ETS was already in place in scenario 1. Still, as North America needs more uranium for own consumption and Australasia increases supplies to China, European imports from these two regions are reduced and compensated by imports from Africa.

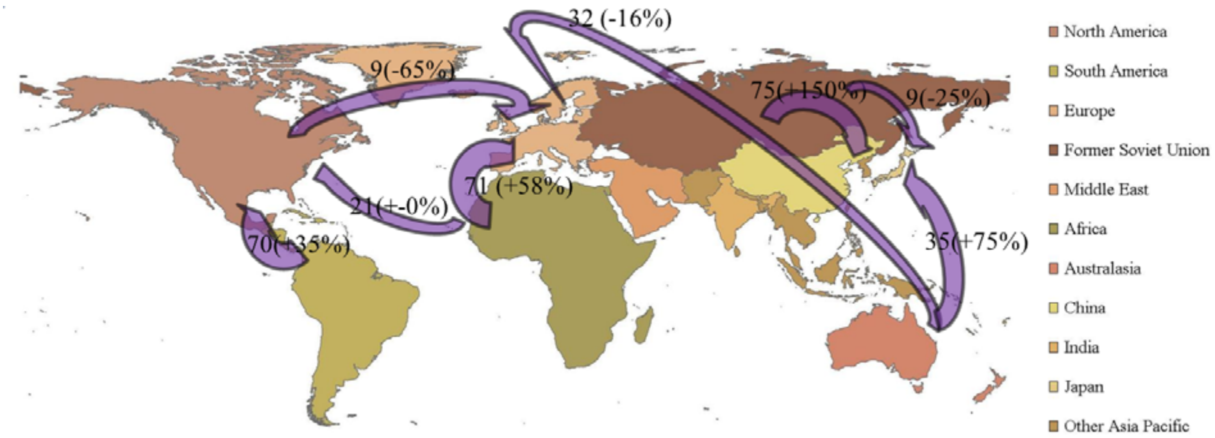


Figure 4.11 Major uranium trades 2052 in mtoe – Scenario 2 (changes to scenario 1)

Additional results on the evolvements of primary energy carrier trade flows are shown in appendix A.4.1

4.4 Electricity storage

Electrical storage needed to complement the fluctuations of non-adjustable renewable sources of electricity production is exponentially interlinked with the share of these non-adjustable renewables of the overall electricity generation. With rising shares of non-adjustable renewable energies, the need for electrical storage capacities becomes larger.

Figure 4.12 depicts the global electrical storage requirements for the two scenarios. For scenario 1, the increasing share of non-adjustable renewables leads to global electricity storage requirements of about 10 mtoe in 2052, which is about 116 TWh electricity storage capacity. For scenario 2, this amount only slightly increases for the near future, but more than doubles in later periods. As for the scenario 2, only a mediocre diffusion of renewable technologies occurred, this is already a remarkable difference. The reason for this comparably slow diffusion in wind and solar technologies, however, can also be seen in the cost associated with the electricity storage needs. Additionally, one also has to consider, that a big share of the global storage needs in scenario 1 are installed in Europe and have to be credited to the assumption of the continuation of the EU ETS there.

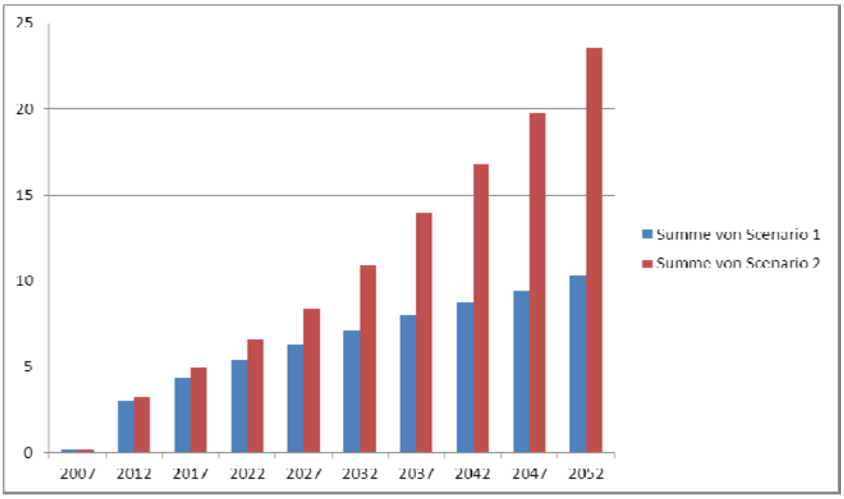
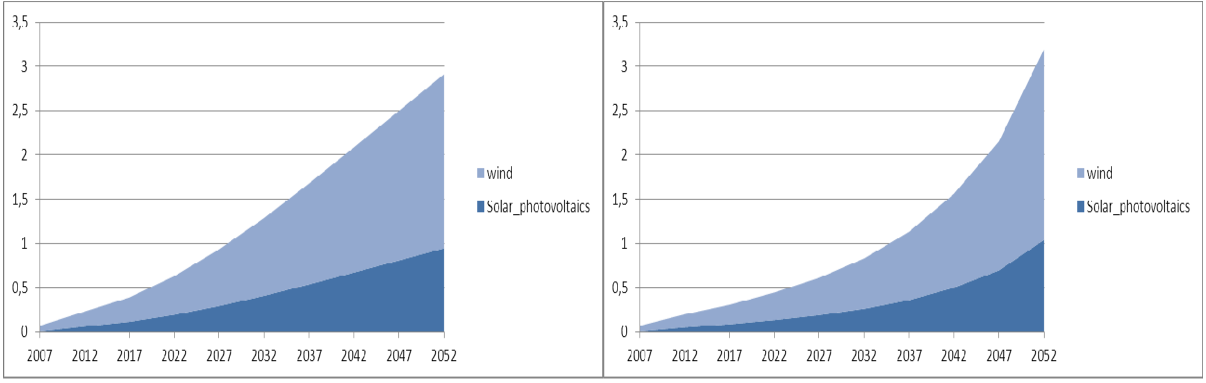


Figure 4.12 global electricity storage capacity (in mtoe)

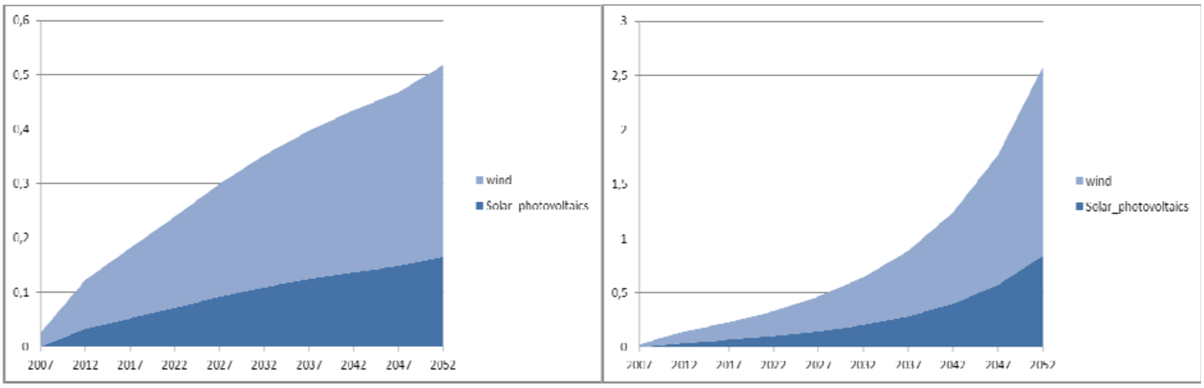
Figure 4.13 shows regional electricity storage capacity requirements for Europe, China and North America. Storage requirements are shared according to electricity amounts resulting from wind electricity and solar photovoltaic technology.

Scenario 1 ***Scenario 2***

Europe



North America



China

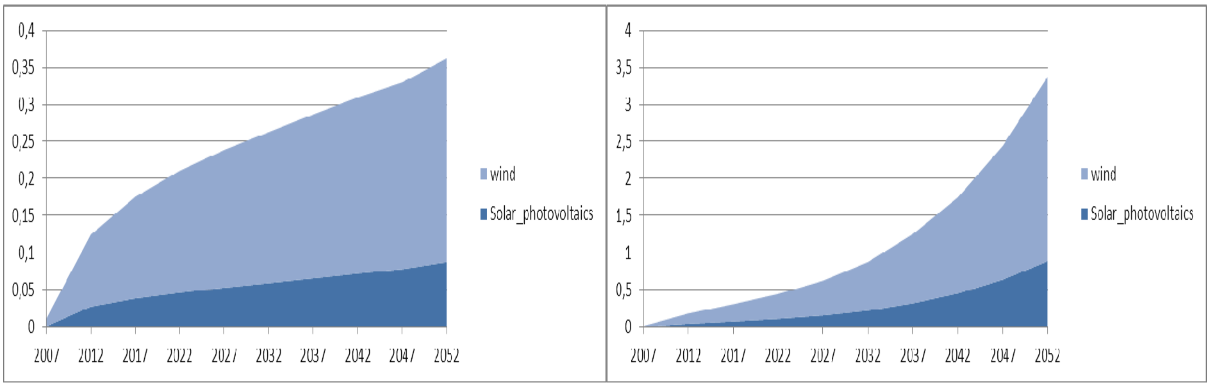


Figure 4.13 Electricity storage capacities (in mtoe)

Due to the specifics of the scenarios, the electricity storage demands for Europe sharply rise in both scenarios. The EU-ETS in scenario 1 leads to a more early diffusion in wind and solar technologies, such that electrical storage is already needed in earlier periods, while reaching about the same heights for the year 2052. In North America and China, comparably little electrical storage capacity is required in scenario 1, summing up to about 500 toe and 350 toe in 2052 in scenario 1. In scenario 2, electricity storage needs rise sharply. The storage needs for China in scenario 2 show the largest difference compared to scenario 1, as in scenario 1 only few renewable energy is installed in the very much coal based Chinese electricity system. From Figure 4.13 one can also see that comparatively worse conditions for sun, and comparatively better conditions for wind, compared to North America, lead to a stronger installation of wind power in China, where wind plays an even more dominant role among renewables than in Europe and North America.

5. Model comparison and discussion

Other well established models, such as PRIMES (Capros; Version 2 Energy System Model 2005), MERGE (Manne and Richels, 2004), WITCH (Bosetti et al., 2006) or REMIND-R (Luderer et al., 2010) made important contributions to the modelling of energy systems. Comparing GREET to these models, one has to notice that many of these models allow for integrated assessments, often combining a climate module with a bottom up energy model and a top down macro-model. Thus, these models can be used in a broader field of applications, having a stronger innate predictive power in overall developments. GREET so far only is a bottom up energy model and thus has to rely on e.g. exogenous assumptions in developments of overall final energy demands.

In most cases a noticeable difference between these long-standing models and GREET consists in their very detailed and extensive energy system formulation, with subtle distinctions between different technologies. An example for such a model is PRIMES, which was developed and enhanced since 1993. PRIMES, like GREET, is a partial equilibrium model, but with much more technical detail in the different technologies included, e.g a differentiation in four different types of investment decisions for the conversion sector. On the other hand, PRIMES ‘only’ focuses on Europe and such does not account for effects of e.g. global resource depletion dynamics or inter-regional global trade in primary energy carriers.
MERGE is a global model that comprises a Ramsey-Solow model of optimal long-term economic growth with sub-models calculating energy and non-energy related emissions of greenhouse gases and a global climate change model that feeds back market and non-market damages into long term economic growth considerations. Such, MERGE has a strong focus on damages from climate change, while not having the capability of looking into e.g. details of diffusion of renewable technologies or resource trades. GREET also considers CO_2 emissions, but does not consider feedbacks of climate change on the energy systems within the regions. WITCH is a global top-down Ramsey-type neoclassical optimal growth model comprising 12 world-regions, with an extensive modelling of the energy sector and also climate feedbacks on the economies in forms of damage functions. An advancement of WITCH can be seen in the incorporation of an inter-temporal investment in R&D game between the 12 regions and sophisticated technological learning modelling, comprising learning by doing and learning by searching as described in section 4.5. REMIND also hard-links a macro-economic Ramsey-type optimal growth model to an energy system module and

covers 11 world-regions. REMIND-R is distinguished from other models by a high technological resolution of the energy system and inter-temporal trade relations between regions. However, these trade relations are modelled as a common-pool trade, not allowing for the possibility to look into detailed trade flows between regions.

So far, these models have not taken the need to provide storage for the electricity subsystem of the energy system into account. GREET, is, as described, a global partial equilibrium energy model and thus does not take into account climate feedbacks on the energy system, nor does it endogenously compute growth in energy demands. Also, in its technological depth it does not reach the level of detail of other long-standing models. But we believe, that technical details are covered fair enough to make reasonable judgements and at the same time other very important features, like the constraints on renewables, are embedded. Also, in comparison to the models listed above, there is an explicit modelling of interregional trade flows in primary energy carriers, for which originating and destinating regions of the energy trades can clearly be specified. Thus, GREET is very applicable for looking into future developments of energy trade flows, also not missing the point that predominantly renewable based energy systems will feature a decisive demand in electricity storage capacities.

References

Baruya, P. (2007). *Supply costs for internationally traded coal*, London: IEA Clean Coal Centre.

Bhattacharyya, S.C. (2011). *Energy Economics – Concepts, Issues, Markets and Governance*, London, Springer London.

Bosetti V., C. Carraro, M. Galeotti, E. Massetti, M. Tavoni (2006). *WITCH A World Induced Techical Change Hybrid Model*. Working Paper of Department of Economics, Venice University, Italy.

BP (2008). *BP Statistical Review of World Energy*, Paris, France.

Capros P. (2005). *The PRIMES Energy System Model Summary Description,* National Technical University of Athens, Greece.

de Wit, M., M. Junginger, S. Lensink, M. Londo, and A. Faaij (2010). Competition between biofuels: Modeling technological learning and cost reductions over time. *Biomass and Bioenergy,* **34**(2), pp. 203-217.

Energy Information Administration (EIA) (2009). *Performance Profiles of Major Energy Producers 2008, Production (Lifting) Costs by Region* (database), Office of Energy Markets and End Use U.S. Department of Energy Washington, DC, USA.

ETG Task Force Energiespeicher (2009). *Energiespeicher in Stromversorgungssystemen mit hohem Anteil erneuerbarer Energieträger – Bedeutung, Stand der Technik, Handlungsbedarf*. Energietechnische Gesellschaft im VDE (ETG)

Fischer, G., E. Hizsnyik, S. Prieler, M. Shah, and H. van Velthuizen (2009). *Biofuels and Food Security*. The OPEC Fund for International Development (OFID) and International Institute of Applied Systems Analysis (IIASA), Vienna, Austria, 228 pp.

Gould, J. P. (1968). Adjustment Costs in the Theory of Investment of the Firm, *The Review of Economic Studies*, 35(1), 47–55.

Haftendorn, C., F. Holz & C. von Hirschhausen (2010). *COALMOD-World: A Model to Assess International Coal Markets Until 2030*, DIW Berlin Discussion Paper No. 1067.

Hawksworth, J. (2006). *Implications of global growth for carbon emissions and climate change policy*. PricewaterhouseCoopers LLP.

Hettinga, W.G., H.M. Junginger, S.C. Dekker, M. Hoogwijk, A.J. McAloon, and K.B. Hicks (2009). Understanding the reductions in US corn ethanol production costs: An experience curve approach, *Energy Policy*, **37**(1), pp. 190-203.

International Energy Agency (IEA) (2008): *World Energy Balances 2007*, OECD Publication, Paris, France.

International Energy Agency (IEA) (2010a). *Coal Information 2010*, OECD Publication, Paris, France.

International Energy Agency (IEA) (2010b). *Projected Costs of Generating Electricity - 2010*, OECD Publication, Paris, France.

International Energy Agency (IEA) (2010c), *Energy Technology Perspectives 2010 - Scenarios & Strategies to 2050*, OECD Publication, Paris, France.

IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation (2011). eds. O. Edenhofer, R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlömer, C. von Stechow, Cambridge University Press, Cambridge, UK and New York, NY, USA.

Junginger, M., P. Lako, S. Lensink, W. Sark and M. Weiss (2008). *Technological learning in the energy sector. Scientific Assessment and Policy Analysis for Climate Change,* WAB 500102 017. University of Utrecht, ECN.
http://www.rivm.nl/bibliotheek/rapporten/500102017.pdf

Kaiser, M. J. & J. H. Gary (2007). Study updates refinery investment cost curves, *Oil & Gas Journal*, 105(16), 84-94.

Krewitt, W., K. Nienhaus, C. Kleßmann, C. Capone, E. Stricker, W. Graus, M. Hoogwijk, N. Supersberger, U. von Winterfeld, and S. Samadi (2009). *Role and Potential of Renewable Energy and Energy Efficiency for Global Energy Supply*. ISSN 1862-4359, Federal Environment Agency, Dessau-Roßlau, Germany, 336 pp.

Luderer G., M. Leimbach, N. Bauer, E. Kriegler (2010). *Description of the ReMIND-R model*, Potsdam, Germany.

Manne A.S., R. G. Richels (2004). *MERGE: An Integrated Assessment Model for Global Climate Change*, Stanford University, EPRI, USA.

Mørk, G., S. Barstow, M.T. Pontes, and A. Kabuth (2010). Assessing the global wave energy potential. In: *Proceedings of OMAE2010 (ASME), 29th International Conference on Ocean, Offshore Mechanics and Arctic Engineering*, Shanghai, China, 6-11 June 2010.

National Development and Reform Commission (NDRC) (2007). *Medium and Long-Term Development Plan for Renewable Energy in China,* Information Office of the State Council of the People's Republic of China.

Nikolaev, V.G., S.V. Ganaga, and K.I. Kudriashov (2008). *National Kadastr of Wind Resources of Russia and Methodological Grounds for their Determination*. Atmograph, Moscow, Russia, 590 pp.

Nuclear Energy Agency and OECD (2010). *Uranium 2009: Resources, Production and Demand*, OECD Publication, Paris, France.

Reuters (2009). *FACTBOX – Oil production cost estimates by country,* Thomson Reuters.

Rogner, H.-H., F. Barthel, M. Cabrera, A. Faaij, M. Giroux, D. Hall, V. Kagramanian, S. Kononov, T. Lefevre, R. Moreira, R. Nötstaller, P. Odell, and M. Taylor (2000). Energy resources. In: *World Energy Assessment. Energy and the Challenge of Sustainability*. United Nations Development Programme, United Nations Department of Economic and Social Affairs, World Energy Council, New York, USA, 508 pp.

SRU Sachverständigenrat für Umweltfragen (2011). *Sondergutachten Wege zur 100% erneuerbaren Stromversorgung*. Berlin: Erich Schmidt Verlag.

Tröndle T., U. Platt, W. Aeschbach-Hertig and K. Pfeilsticker (forthcoming). Erneuerbare Energien in Europa - Elektrizitätsversorgung und ihr Bedarf an Energiespeicherkapazität, *Physik in unserer Zeit*, Wiley.

University of Chicago (2004). *The Economic Future of Nuclear Power*, Chicago, USA.

van den Wall Bake, J.D., M. Junginger, A. Faaij, T. Poot, and A. Walter (2009). Explaining the experience curve: Cost reductions of Brazilian ethanol from sugarcane. *Biomass and Bioenergy*, **33**(4), pp. 644-658.

Xiao, Z., Z. Rong, and L. Song (2010). *China Wind Energy Resource Assessment 2009*. China.

Appendices

A.1 List of Sets, Variables, Parameters and Cost functions

Sets

t, tt	time periods
pe	primary energy carriers
fe	final energy goods
r, rr	regions
rt	renewable technologies

Variables

$x^{extr}_{t,pe,r}$	quantity of primary energy carrier extraction
$x^{trade\_purch}_{t,pe,r}$	quantity of primary energy carrier purchased by trader
$x^{trade}_{t,pe,r\rightarrow rr}$	quantity of primary energy carrier traded
$x^{trans\_purch}_{t,pe,rr}$	quantity of primary energy carrier purchased by transformer
$x^{trans}_{t,pe\rightarrow fe,rr}$	quantity of primary energy carrier transformed to final energy good
$x^{ren}_{t,fe,rr,rt}$	quantity of final energy produced by renewable energy technology
$x^{dem}_{t,fe,rr}$	final energy demand
$i^{extr}_{t,pe,r}$	investment in extraction capacity expansion
$i^{trade}_{t,pe,r\rightarrow rr}$	investment in primary energy carrier trade capacity expansion
$i^{trans}_{t,pe\rightarrow fe,rr}$	investment in transformation capacity expansion
$i^{ren}_{t,fe,rr,rt}$	investment in renewable technology capacity expansion
$i^{store}_{t,rr,rt}$	investment in electricity storage capacity
$ea^{trans}_{t,pe\rightarrow fe,rr}$	emission allowances for energy carrier transformation
$s^{ren}_{t,rr,rt}$	amount of electricity storage capacity used
$\lambda^{extr\_cap}_{t,pe,r}$	shadow price for extraction capacity constraint
$\lambda^{resdepl}_{pe,r}$	shadow price for resource depletion of primary energy carrier
$\lambda^{trade\_cap}_{t,pe,r\rightarrow rr}$	shadow price for region by region trade capacity constraint
$\lambda^{trade\_purch}_{t,pe,r\rightarrow rr}$	shadow price for amount of purchases finally traded
$\lambda^{trans\_cap}_{t,pe\rightarrow fe,rr}$	shadow price of transformation capacity constraint
$\lambda^{trans\_conv}_{t,pe,rr}$	shadow price of conversion constraint
$\lambda^{ren\_cap}_{t,fe,rr,rt}$	shadow price for renewable energy generation capacity constraint
$\lambda^{store}_{t,rr,rt}$	shadow price for electricity storage constraint
$\lambda^{store\_cap}_{t,rr,rt}$	shadow price for electricity storage capacity constraint
$\lambda^{ren\_phys}_{t,fe,rr,rt}$	shadow price for physical renewable potential constraint

$p^{pe\_up}_{t,pe,r}$	price of primary energy carrier (extractor to trader)
$p^{pe\_down}_{t,pe,r\rightarrow rr}$	price of primary energy carrier (trader to converter)
$p^{sec}_{t,fe,rr}$	price of final energy good (transformation and renewables to demand)
p^{ea}_{t}	price of CO_2 emission allowances

Parameters

$R_{pe,r}$	resource endowment of primary energy carrier
ρ^{extr}_{pe}	depreciation factor of extraction capacity
$\rho^{trade}_{pe,r\rightarrow rr}$	depreciation factor of trade capacity
$\rho^{trans}_{pe\rightarrow fe,rr}$	depreciation factor of transformation capacity
$\rho^{ren}_{fe,rr,rt}$	depreciation factor of renewable energy technology capacity
$\rho^{store}_{rr,rt}$	depreciation factor of electricity storage capacity
$cap^{extr\_ini}_{pe,r}$	initial primary energy carrier extraction capacity
$cap^{trade\_ini}_{pe,r\rightarrow rr}$	initial primary energy carrier trade capacity
$cap^{trans\_ini}_{pe\rightarrow fe,rr}$	initial energy carrier transformation capacity
$cap^{ren\_ini}_{fe,rr,rt}$	initial capacity for final energy production by renewable technology
$cap^{store\_ini}_{rr,rt}$	initial capacity of electricity storage
$\alpha_{pe\rightarrow fe}$	conversion factor
$x^{dem\_ini}_{fe,rr}$	initial final energy demand
$\theta_{t,fe,rr}$	final energy demand growth
ρ	price elasticity of final demand
$em^{trans}_{t,pe,rr}$	CO_2 content in primary energy carrier
β_{rr}	electricity storage capacity requirement 100% renewable energy case
$P_{fe,rr,rt}$	physical potential of renewable technology
$lc^{extr\_i}_{t,pe,r} i^{extr}_{t,pe,r}$	linear costs of extraction capacity investment
$qc^{extr\_i}_{t,pe,r}$	quadratic costs of extraction capacity investment
$lc^{trade}_{t,pe,r\rightarrow rr}$	linear primary energy carrier trade costs

Cost functions

$c^{extr}_{t,pe,r}(x^{extr}_{t,pe,r})$	costfunction for primary energy carrier extraction
$c^{extr\_i}_{t,pe,r}(i^{extr}_{t,pe,r})$	costfunction for extraction capacity expansion investments
$c^{trade}_{t,pe,r\rightarrow rr}(x^{trade}_{t,pe,r\rightarrow rr})$	costfunction for primary energy carrier trade
$c^{trade\_i}_{t,pe,r\rightarrow rr}(i^{trade}_{t,pe,r\rightarrow rr})$	costfunction for trade capacity expansion investments
$c^{trans}_{t,pe\rightarrow fe,rr}(x^{trans}_{t,pe\rightarrow fe,rr})$	costfunction for energy carrier transformation

$c^{trans\_i}_{t,pe\rightarrow fe,rr}(i^{trans}_{t,pe\rightarrow fe,rr})$	costfunction for transformation capacity investment
$c^{ren}_{t,fe,rr,rt}(x^{ren}_{t,fe,rr,rt})$	costfunction for final energy production by renewable technology
$c^{ren\_i}_{t,fe,rr,rt}(i^{ren}_{t,fe,rr,rt})$	costfunction for renewable energy capacity expansion investments
$c^{ren\_store}_{t,rr,rt}(s^{ren}_{t,rr,rt})$	costfunction for usage of electricity storage capacity
$c^{i\_store}_{t,rr,rt}(i^{store}_{t,rr,rt})$	costfunction for investment in electricity storage capacity

A.3.1 Regions in GREET

Model Region	Constituting parts
Africa	African territories including the north coast of Africa from Egypt to Western Sahara and the east coast from Sudan to Republic of South Africa
Australasia	Australia, New Zealand
China	Peoples Republic of China, including Hong Kong
Europe	European members of the OECD, Albania, Bosnia-Herzegovina, Bulgaria, Croatia, Cyprus, Former Yugoslav Republic of Macedonia, Gibraltar, Malta, Romania, Serbia and Montenegro, Slovenia
Former Soviet Union+	Armenia, Azerbaijan, Belarus, Estonia, Georgia, Kazakhstan, Kyrgyzstan, Latvia, Lithuania, Moldova, Mongolia, Russian Federation, Tajikistan, Turkmenistan, Ukraine, Uzbekistan
India	India
Japan	Japan
Middle East	Arabian Peninsula, Iran, Iraq, Israel, Jordan, Lebanon, Syria
North America	USA, Canada, Mexico
Other Asia Pacific	Brunei, Cambodia, Indonesia, Laos, Malaysia, Mongolia, North Korea, Philippines, Singapore, Afghanistan, Bangladesh, Myanmar, Nepal, Pakistan, Sri Lanka, South Korea, Taiwan, Thailand, Vietnam, Papua New Guinea
South America	Caribbean, Central and South America

A.3.2 Initial primary energy carrier net trade flows for 2007 (in mtoe)

a) Crude oil

	Africa	**Australasia**	**Europe**	**FSU**	**India**	**Japan**	**MiddleEast**	**N-America**	**Other Asia**	**China**	**S-America**	**sum**
Africa	75,1	0,1	119,8	0,0	0,0	7,6	0,0	0,0	0,0	53,0	24,8	280,4
Australasia	0,0	26,7	0,0	0,0	0,0	1,8	0,0	0,0	0,0	1,3	0,0	29,7
Europe	0,0	0,2	87,9	0,0	0,0	0,0	0,0	53,9	0,0	0,0	0,0	142,0
FormerSovietUnion	0,2	0,0	332,1	276,8	0,0	8,2	0,0	24,7	11,1	26,3	1,7	681,2
India	0,0	0,0	0,0	0,0	159,5	0,0	0,0	0,0	0,0	0,0	0,0	159,5
Japan	0,0	0,0	0,2	0,0	0,0	20,3	0,0	0,7	0,0	1,9	0,0	23,0
MiddleEast	38,1	7,7	146,6	0,0	0,0	154,5	315,5	118,1	359,4	78,8	4,5	1223,2
NorthAmerica	0,0	0,3	3,7	0,0	0,0	1,6	0,0	638,8	0,0	0,4	6,8	651,5
Other Asia	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	3,3	0,0	0,0	3,3
China	0,0	0,0	0,4	0,0	0,0	0,0	0,0	0,4	0,4	155,4	0,0	156,6
South America	0,0	0,0	15,5	0,0	0,0	0,4	0,0		111,1 0,0	11,3	228,3	228,3
sum	**113,4**	**34,9**	**706,1**	**276,8**	**159,5**	**194,5**	**315,5**	**947,7**	**374,2**	**328,3**	**266,1**	**3717,1**

b) Natural gas

	Africa	Australasia	Europe	FSU	India	Japan	MiddleEast	N-America	Other Asia	China	S-America	sum
Africa	63,3	0,0	76,4	0,0	1,0	3,0	0,0	9,1	5,4	0,5	0,0	158,6
Australasia	0,0	22,1	0,0	0,0	0,0	14,4	0,0	0,0	15,2	3,0	0,0	54,8
Europe	0,0	0,0	217,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	217,0
FormerSovietUnion	0,0	0,0	144,3	502,6	0,0	0,0	5,5	0,0	0,0	0,0	0,0	652,4
India	0,0	0,0	0,0	0,0	22,1	0,0	0,0	0,0	0,0	0,0	0,0	22,1
Japan	0,0	0,0	0,0	0,0	0,0	7,4	0,0	0,0	0,0	0,0	0,0	7,4
MiddleEast	0,0	0,0	6,8	0,0	7,7	20,8	211,7	0,5	37,3	0,1	0,0	284,9
NorthAmerica	0,0	0,0	0,0	0,0	0,0	1,1	0,0	572,4	1,1	0,0	0,0	574,5
Other Asia	0,0	0,0	0,0	0,0	0,1	39,9	0,0	0,0	98,9	0,0	0,0	138,9
China	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	45,4	0,0	45,4
South America	0,0	0,0	2,4	0,0	0,2	0,5	0,0	12,0	0,7	0,0	91,1	107,0
sum	**63,3**	**22,1**	**447,0**	**502,6**	**31,0**	**87,0**	**217,2**	**594,0**	**158,7**	**48,8**	**91,1**	**2262,9**

c) Coal

	Africa	Australasia	Europe	FSU	India	Japan	MiddleEast	N-America	Other Asia	China	S-America	sum
Africa	75,3	0,0	31,4	0,0	5,5	0,3	3,3	0,4	2,4	0,0	0,6	119,2
Australasia	0,0	53,0	3,1	0,0	0,5	36,4	0,4	3,7	27,8	2,3	0,6	127,8
Europe	0,0	0,0	160,4	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	160,4
FormerSovietUnion	0,1	0,0	48,0	126,6	0,0	4,8	0,0	0,1	4,1	0,3	0,3	184,3
India	0,0	0,0	0,0	0,0	181,5	0,0	0,0	0,0	0,0	0,0	0,0	181,5
Japan	0,0	0,0	0,0	0,0	0,0	0,4	0,0	0,0	0,0	0,0	0,0	0,4
MiddleEast	0,0	0,0	0,0	0,0	0,0	0,0	4,7	0,0	0,0	0,0	0,0	4,7
NorthAmerica	0,0	0,0	5,6	0,0	0,0	1,3	0,1	452,1	0,0	0,0	0,0	459,1
Other Asia	0,0	0,0	12,6	0,0	17,1	15,3	0,1	1,9	145,7	1,2	1,3	195,2
China	0,0	0,0	1,9	0,0	0,3	8,8	0,0	0,0	0,0	996,9	0,1	1008,1
South America	0,0	0,0	24,4	0,0	3,2	0,0	0,0	21,0	0,0	0,0	9,6	58,3
sum	**75,4**	**53,0**	**287,4**	**126,6**	**208,3**	**67,3**	**8,5**	**479,2**	**180,0**	**1000,6**	**12,5**	**2498,9**

d) Uranium

	Africa	Europe	FSU	India	Japan	N-America	Other Asia	China	S-America	sum
Africa	2,9	67,1	0,0	0,0	0,4	21,1	4,2	0,0	0,0	95,7
Australasia	0,0	37,7	0,0	0,0	18,5	43,1	8,7	0,0	0,0	108,0
Europe	0,0	3,4	0,0	0,0	0,0	0,0	0,0	0,0	0,0	3,4
FormerSovietUnion	0,0	75,0	66,5	0,0	35,2	110,7	25,3	0,0	0,0	312,7
India	0,0	0,0	0,0	4,4	0,0	0,0	0,0	0,0	0,0	4,4
Japan	0,0	0,0	0,0	0,0	14,7	0,0	0,0	0,0	0,0	14,7
NorthAmerica	0,0	62,0	0,0	0,0	0,0	66,6	0,0	0,0	0,0	128,6
Other Asia	0,0	0,0	0,0	0,0	0,0	0,0	10,3	0,0	0,0	10,3
China	0,0	0,0	0,0	0,0	0,0	0,0	0,0	16,2	0,0	16,2
South America	0,0	0,0	0,0	0,0	0,0	3,6	0,0	0,0	5,1	8,7
sum	**2,9**	**245,2**	**66,5**	**4,4**	**68,8**	**245,1**	**48,6**	**16,2**	**5,1**	**702,9**

A.3.4 Assumed average trade distances between world regions in GREET (in 1000km)

	Other Asia Pacific	China	Former Soviet Union+	India	South America	Middle East	Europe	North America	Africa	Japan	Australasia
Other Asia Pacific	1,5	3,9	5,5	2,9	19,5	8,0	18,0	12,1	15,3	4,0	6,7
China	3,9	0,0	1,5	6,9	20,0	11,9	19,2	10,5	19,0	1,9	7,5
Former Soviet Union+	5,5	1,5	1,5	7,9	10,0	3,6	1,5	6,9	9,0	1,6	8,3
India	2,9	6,9	7,9	0,0	15,3	4,3	11,6	15,0	13,4	8,3	9,7
South America	19,5	20,0	10,0	15,3	0,0	11,0	7,7	5,4	5,1	15,6	13,1
Middle East	8,0	11,9	3,6	4,3	11,0	0,0	7,3	10,8	1,5	13,3	14,7
Europe	18,0	19,2	1,5	11,6	7,7	7,3	1,5	6,1	6,8	20,7	22,0
North America	12,1	10,5	6,9	15,0	5,4	10,8	6,1	1,5	8,2	9,0	11,6
Africa	15,3	19,0	9,0	13,4	5,1	1,5	6,8	8,2	1,5	20,3	12,0
Japan	4,0	1,9	1,6	8,3	15,6	13,3	20,7	9,0	20,3	0,0	7,2
Australasia	6,7	7,5	8,3	9,7	13,1	14,7	22,0	11,6	12,0	7,2	0,0

A.3.5 Complementarity conditions for electricity generation from wind and solar energy

$$
\begin{aligned}
(A1)\quad & \left(p^{sec}_{t,fe,rr} - c'^{ren}_{t,fe,rr,rt}(x^{ren}_{t,fe,rr,rt})\right)\delta^t \\
& - \lambda^{ren\_cap}_{t,fe,rr,rt} \\
& - \lambda^{store}_{t,rr,rt}\left(\left(\frac{\beta_{rr}}{\sum\limits_{pe} x^{trans}_{t,pe,rr} + \sum\limits_{rt} x^{ren}_{t,rr,rt}} - \frac{\beta_{rr}\sum\limits_{rt} x^{ren}_{t,rr,rt}}{(\sum\limits_{pe} x^{trans}_{t,pe,rr} + \sum\limits_{rt} x^{ren}_{t,rr,rt})^2}\right) e^{\beta_{rr}\frac{\sum\limits_{rte} x^{ren}_{t,rre,rte}}{\sum\limits_{ec} x^{trans}_{t,ec,rre} + \sum\limits_{rte} x^{ren}_{t,rre,rte}}} - \frac{s^{ren}_{t,rr,rt}}{x^{ren}_{t,rr,rt}} + \frac{s^{ren}_{t,rr,rt}\sum\limits_{rte} x^{ren}_{t,rr,rt}}{\left(x^{ren}_{t,rr,rt}\right)^2}\right) \\
& - \lambda^{ren\_phys}_{t,fe,rr,rt} \quad \le 0 \quad \perp \quad x^{ren}_{t,fe,rr,rt} \ge 0
\end{aligned}
$$

$$(A2)\quad -\delta^t\, c'^{ren\_i}_{t,fe,rr,rt}(i^{ren}_{t,fe,rr,rt}) + \sum_{\tau=t+1}^{T} \lambda^{ren\_cap}_{t,fe,rr,rt}\, {\rho^{ren}_{fe,rr,rt}}^{\tau-t+1} \quad \le 0 \quad \perp \quad i^{ren}_{t,fe,rr,rt} \ge 0$$

$$(A3)\quad -\delta^t\, c'^{ren\_store}_{t,rr,rt}(s^{ren}_{t,rr,rt}) - \lambda^{store\_cap}_{t,rr,rt} + \lambda^{store}_{t,rr,rt}\frac{\sum\limits_{rt} x^{ren}_{t,rr,rt}}{x^{ren}_{t,rr,rt}} \quad \le 0 \quad \perp \quad s^{ren}_{t,rr,rt} \ge 0$$

$$(A4)\quad -\delta^t\, c'^{i\_store}_{t,rr,rt}(i^{store}_{t,rr,rt}) + \sum_{\tau=t+1}^{T} \lambda^{store\_cap}_{t,rr,rt}\, {\rho^{store}_{rr,rt}}^{\tau-t+1} \quad \le 0 \quad \perp \quad i^{store}_{t,rr,rt} \ge 0$$

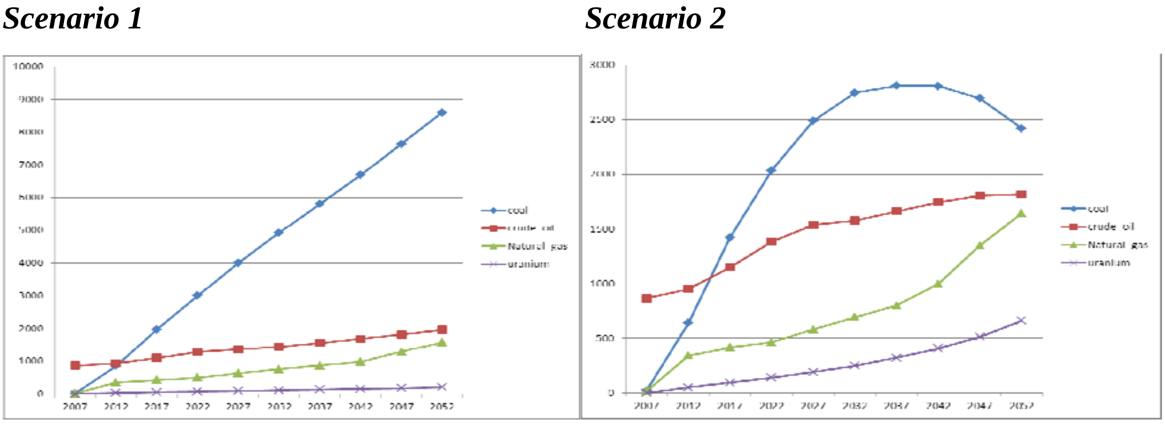
$$(A5)\quad cap^{ren\_ini}_{fe,rr,rt}\, {\rho^{ren}_{fe,rr,rt}}^{t} + \sum_{\tau=1}^{t-1} i^{ren}_{t,fe,rr,rt}\, {\rho^{ren}_{fe,rr,rt}}^{t-\tau} - x^{ren}_{t,fe,rr,rt} \ge 0 \quad \perp \quad \lambda^{ren\_cap}_{t,fe,rr,rt} \ge 0$$

$$(A6)\quad s^{ren}_{t,rr,rt} - cap^{store\_ini}_{rr,rt}\, {\rho^{store}_{rr,rt}}^{t} - \sum_{\tau=1}^{t-1} i^{store}_{t,rr,rt}\, {\rho^{store}_{rr,rt}}^{t-\tau} \quad \le 0 \quad \perp \quad \lambda^{store\_cap}_{t,rr,rt} \ge 0$$

$$(A7)\quad s^{ren}_{t,rr,rt} \ge \frac{x^{ren}_{t,rr,rt}}{x^{ren}_{t,rr,'wind'} + x^{ren}_{t,rr,'solar'}} e^{\beta_{rr}\frac{x^{ren}_{t,rr,'wind'} + x^{ren}_{t,rr,'solar'}}{\sum\limits_{pe} x^{trans}_{t,pe\to fe,rr} + \sum\limits_{rt} x^{ren}_{t,rr,rt}}} \quad \le 0 \quad \perp \quad \lambda^{store}_{t,rr,rt} \ge 0$$

$$(A8)\quad x^{ren}_{t,fe,rr,rt} \le P_{fe,rr,rt} \quad \le 0 \quad \perp \quad \lambda^{ren\_phys}_{t,fe,rr,rt} \ge 0$$

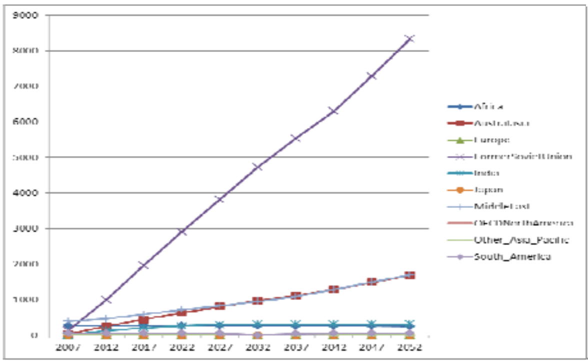
A.4.1 Development of primary energy carrier imports for model regions China, Europe and North America

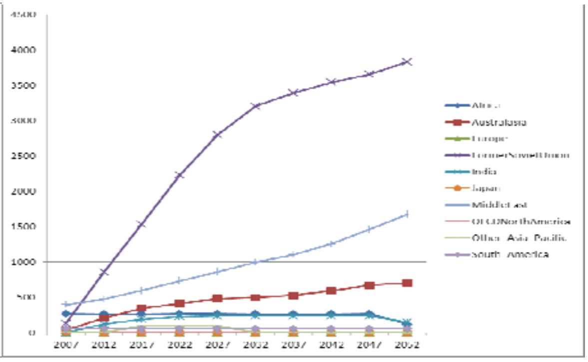

Scenario 1

Scenario 2

Chinese Imports by Energy carrier

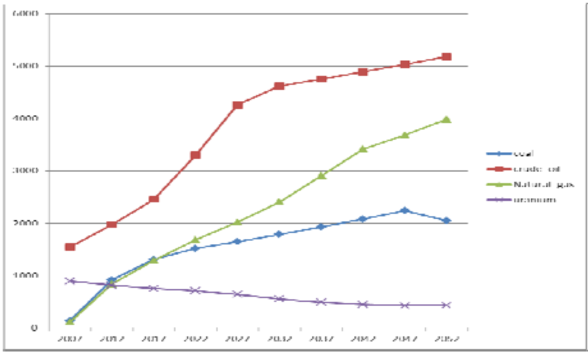
Scenario 1 ***Scenario 2***

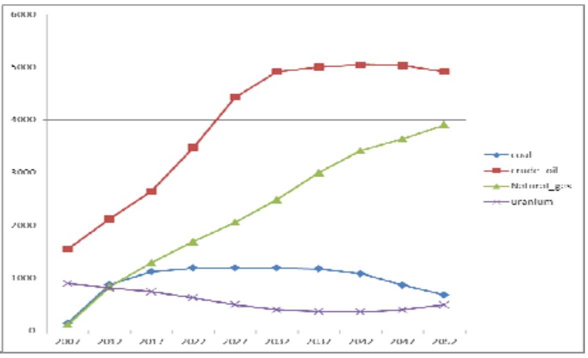




Chinese Imports by Region

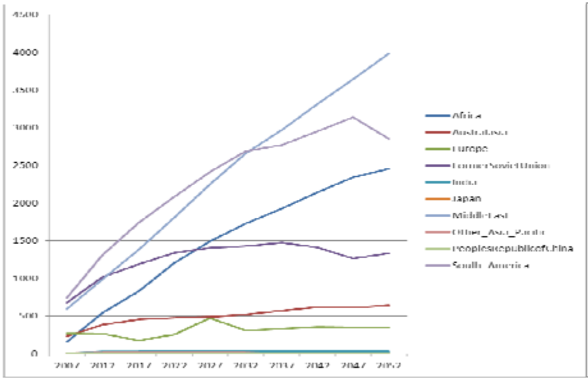
Scenario 1 ***Scenario 2***

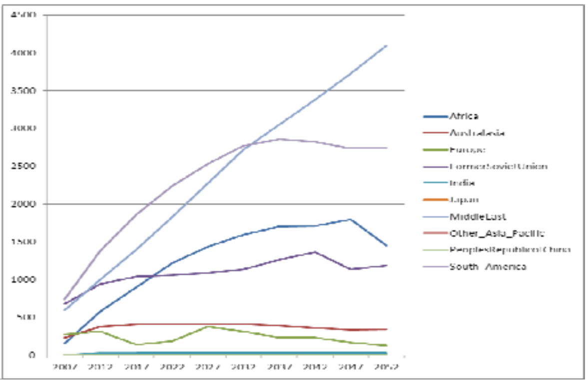




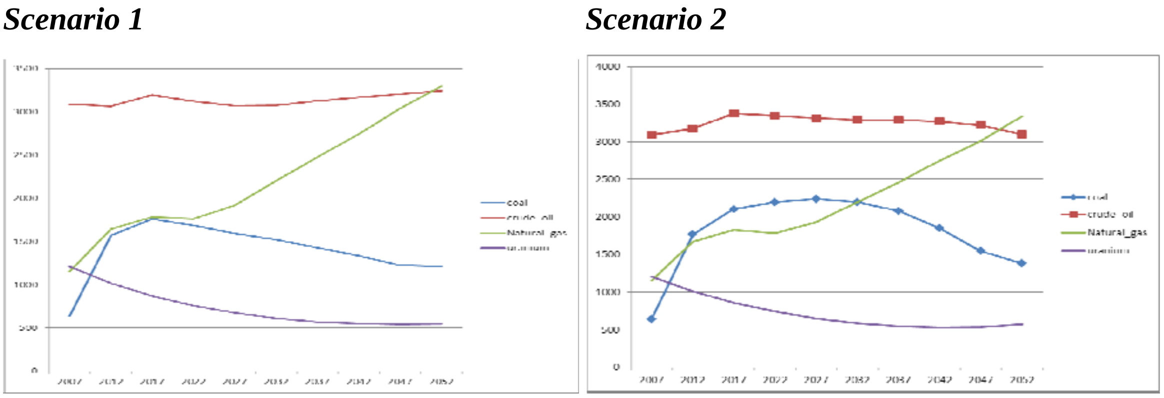
North American Imports by Energy carrier

Scenario 1 ***Scenario 2***





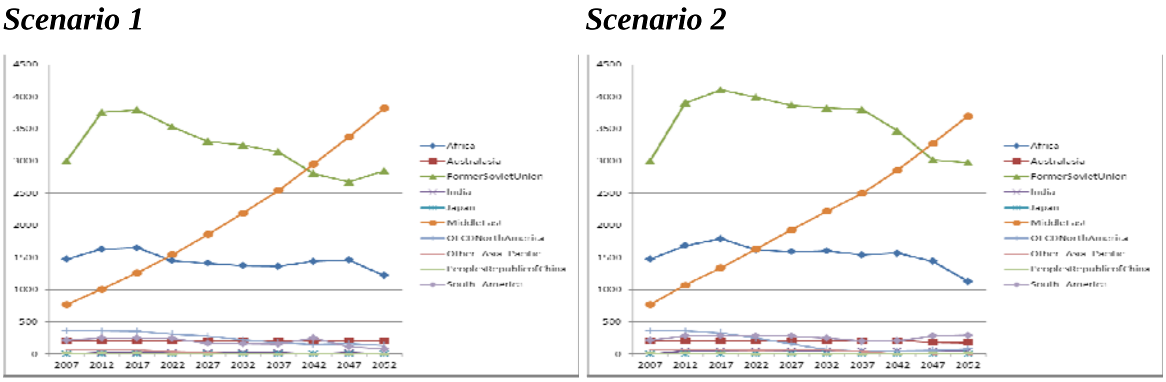
North American imports by Region



Scenario 1

Scenario 2

European Imports by Energy carrier



Scenario 1

Scenario 2

European Imports by Region

ZEW

Zentrum für Europäische
Wirtschaftsforschung GmbH

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- interdisziplinäre Forschung in praxisrelevanten Bereichen,
- Informationsvermittlung,
- Wissenstransfer und Weiterbildung.

Im Rahmen der Projektforschung werden weltwirtschaftliche Entwicklungen und insbesondere die mit der europäischen Integration einhergehenden Veränderungsprozesse erfaßt und in ihren Wirkungen auf die deutsche Wirtschaft analysiert. Priorität besitzen Forschungsvorhaben, die für Wirtschaft und Wirtschaftspolitik praktische Relevanz aufweisen. Die Forschungsergebnisse werden sowohl im Wissenschaftsbereich vermitteltals auch über Publikationsreihen, moderne Medien und Weiterbildungsveranstaltungen an Unternehmen, Verbände und die Wirtschaftspolitik weitergegeben.
Recherchen, Expertisen und Untersuchungen können am ZEW in Auftrag gegeben werden. Der Wissenstransfer an die Praxis wird in Form spezieller Seminare für Fach- und Führungskräfte aus der Wirtschaft gefördert. Zudem können sich Führungskräfte auch durch zeitweise Mitarbeit an Forschungsprojekten und Fallstudien mit den neuen Entwicklungen in der empirischen Wissenschaftsforschung und spezifischen Feldern der Wirtschaftswissenschaften vertraut machen.
Die Aufgabenstellung des ZEW in der Forschung und der praktischen Umsetzung der Ergebnisse setzt Interdisziplinariät voraus. Die Internationalisierung der Wirtschaft, vor allem aber der europäische Integrationsprozeß werfen zahlreiche Probleme auf, in denen betriebs- und volkswirtschaftliche Aspekte zusammentreffen. Im ZEW arbeiten daher Volkswirte und Betriebswirte von vornherein zusammen. Je nach Fragestellung werden auch Juristen, Sozial- und Politikwissenschaftler hinzugezogen.

Forschungsprojekte des ZEW sollen Probleme behandeln, die für Wirtschaft und Wirtschaftspolitik praktische Relevanz aufweisen. Deshalb erhalten Forschungsprojekte, die von der Praxis als besonders wichtig eingestuft werden und für die gleichzeitig Forschungsdefizite aufgezeigt werden können, eine hohe Priorität. Die Begutachtung von Projektanträgen erfolgt durch den wissenschaftlichen Beirat des ZEW. Forschungsprojekte des ZEW behandeln vorrangig Problemstellungen aus den folgenden Forschungsbereichen:

- Internationale Finanzmärkte und Finanzmanagement,
- Arbeitsmärkte, Personalmanagement und Soziale Sicherung,
- Industrieökonomik und Internationale Unternehmensführung,
- Unternehmensbesteuerung und Öffentliche Finanzwirtschaft,
- Umwelt- und Ressourcenökonomik, Umweltmanagement

sowie den Forschungsgruppen

- Informations- und Kommunikationstechnologien
- Wettbewerb und Regulierung

und der Querschnittsgruppe

- Wachstums- und Konjunkturanalysen.

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