CICERO Report 2009:02

Disaggregating the Electricity Sector in the GRACE Model.
(GRACE-EL)

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Version 1.0

January 2009

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Tittel: Disaggregating the Electricity Sector in the GRACE Model	**Title:** Disaggregating the Electricity Sector in the GRACE Model
Forfatter(e): CICERO Report 2009:02 18 sider **Finansieringskilde:** **Prosjekt: ADAM** **Prosjektleder:** Gunnar S. Eskeland **Kvalitetsansvarlig:** Hans Asbjørn Aaheim **Nøkkelord:**	**Author(s):** CICERO 18 pages **Financed by:** European Commission **Project:** ADAM **Project manager:** Gunnar S. Eskeland **Quality manager:** H. Asbjørn Aaheim **Keywords:** macroeconomic model, electricity sector, policy analysis
Sammendrag:.	**Abstract:** This report presents an extension of the GRACE CGE model, with a disaggregation of the electricity sector into unique generation technologies. The goal of this extension is to allow closer analysis of interactions between the electricity sector and the wider economy. An additional extension presented in this report is a treatment for capital vintaging.
Språk: Engelsk	**Language of report:** English
Rapporten kan bestilles fra: CICERO Senter for klimaforskning P.B. 1129 Blindern 0318 Oslo	The report may be ordered from: CICERO (Center for International Climate and Environmental Research – Oslo) PO Box 1129 Blindern 0318 Oslo, NORWAY
Eller lastes ned fra: http://www.cicero.uio.no	Or be downloaded from: http://www.cicero.uio.no

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Acknowledgements

This project was funded by the European Commission under the ADAM Project. Thanks to Asbjørn Aaheim, Gunnar Eskeland, Steffen Kallbekken, Ian Sue Wing, and Thure Traber for help and discussions.

1 Introduction

The model for Global Responses to Anthropogenic Change in the Environment (GRACE) is a multi-sector, multi-region, recursively dynamic global computable general equilibrium model (CGE), which is mainly based on the Solow-Swan neoclassical growth model (Solow, 1956), written in GAMS. The model has been applied to integrated air quality and climate policy analysis (Rypdal et al., 2007), and analysis of climate change impacts on the forestry sector (Rive et al., 2005). In the latter, a special forestry growth module was developed in GRACE, which coupled with a simple climate model, allowing for integrated climate-economic-environment assessment.

Recent additions have been made to the model, warranting this documentation. First and foremost is the disaggregation of the electricity sector into unique generation technologies, indicated by the suffix '-EL' in the GRACE-EL acronym. This documentation describes the GRACE-EL model, along with additional developments and applications beyond those described in the previous version of the model described in Aaheim and Rive (2005).

The rest of the document is organized as follows. The next section describes the new features in the current version. Section 3 describes our data sources. Section 4 describes the general structure and flows within the model. Section 5 describes the final demand and production structures in the model, the treatment of income and trade, and the price structure. Section 6 outlines the greenhouse gas emissions inclusion, Section 7 describes the dynamics of the model, and treatment of investments, and Section 8 describes the disaggregation of the electricity sector.

The model code is available upon request.

2 Change Log

The following changes have been made to the model since the initial version presented by Aaheim and Rive (2005).

- The model is now constructed as a mixed complementary problem (Mathiesen, 1985) and written in MPSG/E (Rutherford, 1998). The model is still solved in GAMS (Brooke et al., 1988).
- The underlying data has been updated to GTAP v6 (Dimaranan, 2006), with 2001 as the base year (see Section 3).
- GRACE-EL now employs considerably simpler production and consumption structures, taken from the MIT EPPA model (Paltsev et al., 2005). Associated substitution elasticities are also taken from EPPA.
- A treatment for capital vintaging has been employed with cross-sector capital transformation to limit the intra-period flow of sunk capital between sectors (see Section 7).
- The electricity sector for countries within the European Union (EU) regions have been disaggregated into electricity technologies using bottom-up data (Section 8).

3 Data

GRACE-EL is calibrated around the Global Trade Analysis Project (GTAP) v6 database which represents the global economy in 2001 using the input output table of 87 regions for 57 sectors. As the previous data base versions, this data base contains bilateral trade and transport along protection data representing the linkages among the 87 regions of the global economy. Updating the database is aimed at exploiting the advantages that the latest data offers in terms of disaggregation of different regions, improvement of domestic data base for different countries, improvements in the treatment of government consumption, income taxes, domestic supports, tariff coverage, trade estimates, and energy use data.
The original data base is converted into a GAMS readable format using the GTAP6inGAMS conversion tool (Rutherford, 2006). These data are then aggregated in order to create a full social accounting matrix (SAM) for each region. A SAM is a general and consistent macroeconomic accounting framework. In GRACE, the global SAM consists of input-output matrices for each region (inputs of primary factors to sectors, and output of consumption and investment), and with trade between the regions. We make adjustments to the SAM to make the initial capital stock and investments in the base year consistent with the growth assumptions. These adjustments are described in Section 7. GRACE-EL also employs a database for CO_2 emissions from combustion in the GTAP production and consumption sectors associated with GTAP6 (Lee, 2007). The GRACE-EL model employs an aggregated set of regions and sectors; there are 12 regions, 16 production sectors, three final demand sectors, and three primary factors (Table 1 below).

Regions		**Production Sectors**		**Final Demand**	**Primary Factors**
BAL	Baltic 3 + Poland	ATP	Air transport	Investment (INV)	Capital (CAP)
BNL	BeNeLux Region	COL	Coal	Private (PRI)	Labor (LAB)
FRA	France and Switzerland	CRP	Chemicals	Public (PUB)	Nature (RES)
GER	Germany and Austria	CRU	Crude oil		
GRE	Greece	ELC	Electricity		
IBE	Spain and Portugal	FOO	Food and agriculture		
ITA	Italy and Malta	GAS	Gas		
NOR	Nordic Region	HEA	Heavy industry		
UKI	UK and Ireland	I_S	Iron and steel		
REE	Rest of EU Accession	OMN	Mining		
DVD	Rest of Developed World	PPP	Paper and pulp		
ROW	Rest of World	NFM	Non-ferrous metals		
		NMM	Non-metal minerals		
		REF	Refined oil products		
		SER	Services and dwellings		
		R_T	Surface transport		

Table 1: Regional, sector, and factor aggregation in GRACE-EL

4 General Structure

The structure of production and consumption of GRACE-EL is based on a number of other models. The quantity and price flows within the economy are based around the GTAP6 database. The structure of production and consumption (i.e. the demand trees) is based on the MIT EPPA model. The disaggregated electricity sector is based on work by Sue Wing (2006b) (see Section 8). The dynamics and treatment of investments were adapted from the GTAP-Dyn model (Ianchovinchina et al., 2007).

The GRACE model consists of six main elements: production sectors, final demands, an Armington aggregation of domestic goods and imports, the regional household, and a global bank and trust. The flow of payments between these elements associated with expenditures and production is embedded in the GTAP6 database, and is shown in Figure 1.

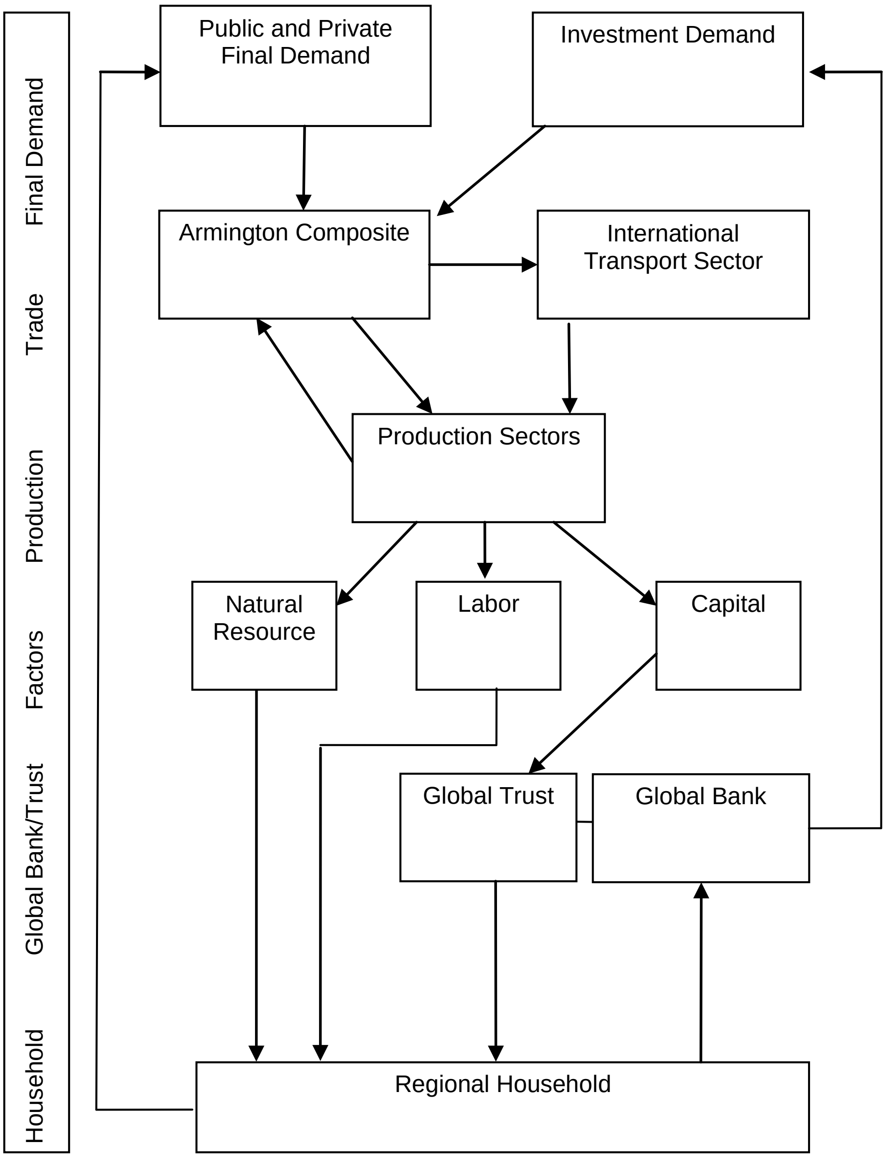

Figure 1: Flow of payments in the GRACE-EL, based around GTAP6 database. The flow of goods/factors occurs in the opposite direction to the payments.

As the figure illustrates, the factors of production are owned by the Regional Household. This Regional Household, which also collects tax, seeks to maximize welfare by distributing its budget to savings and private and public private demands. Trade occurs bilaterally, with an

Armington composite good, which minimizes the cost of combining domestically produced and imported versions of each good. The production sectors seek to maximize profit subject to their production structure (see Section 5), and demand factor and composite goods. Final demand sectors seek to maximize welfare subject to their budget constraint, and demand composite goods.

All factor endowments at equilibrium are fully employed by the production sectors. Each sector output is produced in consistency with what the regional household demands for the final demand sectors. Thus, regional as well as global economic activity satisfies the principles of income balance, market clearing, and normal remuneration of real capital and land in competitive equilibrium (zero profits).

5 Detailed Structures in GRACE-EL

5.1 Production Structures

The structure of production in each sector identifies the demand for factors and intermediate Armington good inputs, and the substitution between these inputs. These are modeled as nested constant elasticity of substitution (CES) functions.

Figure 2 illustrates the standard structure of production in GRACE, used in all sectors except primary energy producers and European electricity sectors. The top level nest is a Leontief (fixed fraction) input of the factor/energy nest (VA-Energy) and non-energy inputs ranging from air transport (ATP) to surface transport (R_T). The next nest is a substitution between value added (VA) factor inputs and the energy nest, followed by substitution between electricity and non-electric energy inputs. The elasticity of substitution at each nest is adopted from EPPA.

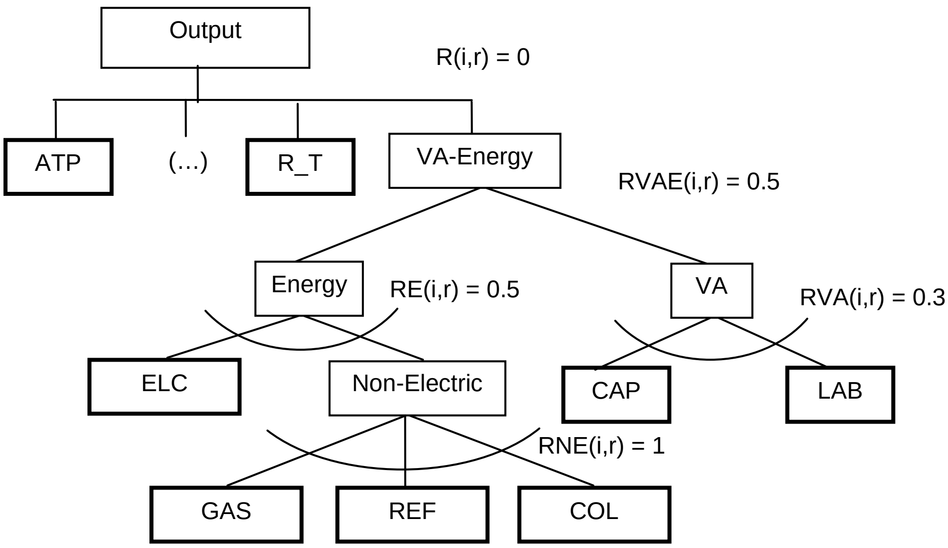

Figure 2: Standard production structure in GRACE-EL

The electricity sectors in ROW and DVD employ this standard production structure, however electricity production in European regions is given particular treatment with a different tree. This is detailed in Section 8.

The production structure for primary energy producton sectors – coal, gas, and crude oil – is illustrated in Figure 3. At the top level is a substitution between the natural resource and a nest of remaining inputs. The remaining inputs combine a Leontief technology of intermediate goods and a value added nest.

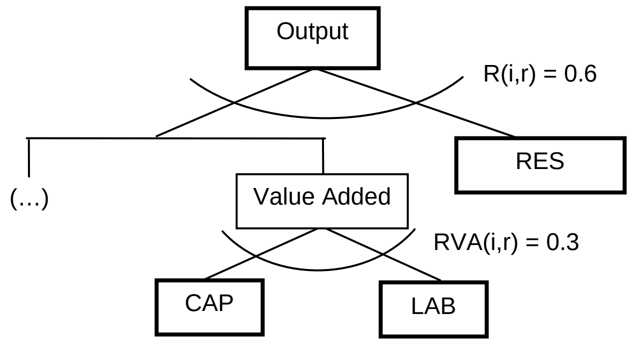

Figure 3: Production structure of primary energy producers

5.2 The Regional Household, Global Bank, and Final Demand Structure

As in the GTAP model and database, GRACE includes a Regional Household to which tax revenue and factor income accrues. In addition, there exist three final demand sectors: private consumption, public consumption, and savings (see Figure 4). Income to the private and public consumption sectors and savings is allocated by the Regional Household maximization problem (see the description of savings and investment Section 7). The Global Bank allocates regional savings to investment across regions.

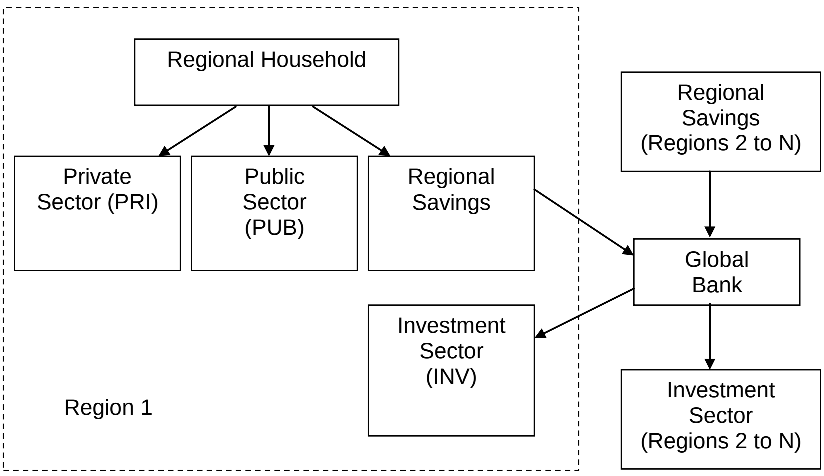

Figure 4: The Regional Household and the Global Bank. Based on Hertel (1997).

Like the production structures, the demand structures of the final demands are made up of nested CES functions adopted from the EPPA model (see Figure 5 below). At the top level of the demand structure, substitution is made between the energy and non-energy nests. Substitution between these respective nests occurs with an elasticity of substitution of 0.25; within the nests the elasiticity of substitution is 0.4.

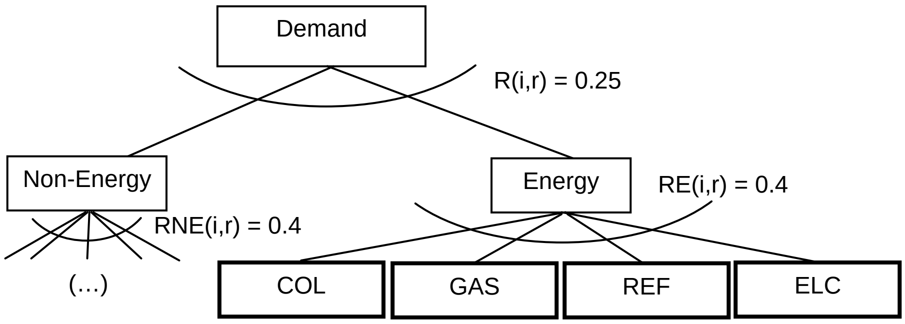

Figure 5: Final demand structure in GRACE-EL

5.3 Trade and International Transport

In GRACE, the regional economies are linked through bilateral trade flows. All goods can be traded internationally, with the exception of the primary factors. Rather than assuming that goods are exported to a global pool, trade occurs between countries. Bilateral imports of the same good from different regions are combined into an import aggregate. This is aggregated with domestically produced goods into a single Armington composite good which is then demanded by the production and final demand sectors. Substitution between bilateral imports of the same good and between domestic and aggregate imports is modeled through a CES function (Figure 6). The substitution elasticities are denoted in the figure with prefix ‘RI’, and are based on those in the EPPA model. Exceptions to the listed substitution elasticities are made for the following sectors: (a) REF (RIM = 6), (b) ELC (RIM = 0.5; RIMR = 0.3), and (c) GAS and COL (RIMR = 4).

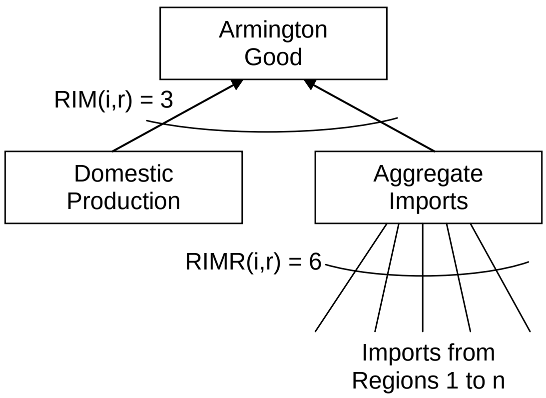

Figure 6: Bilateral imports and the Armington aggregate

When a good is traded, a price premium is paid by the importing country to the international transport sector. This price premium is determined by a fixed transport factor derived from the base year data. The transport is provided by a Cobb-Douglas composite of the transport services goods from each of the regions.

5.4 Price Structure

For simplicity, we have until now avoided discussion of prices in the economy. The pricing structure in GRACE is identical to that in the GTAP model (Hertel, 1997). In a CGE framework, there are no commodity unit "prices" as they are understood in the real world – the model only solves for relative prices. We thus initially set a basis price (typically 1) of our choosing for the market prices. However, the actual price of each good faced by each agent in the economy will differ from this market price due to 'price wedges'. Within each region, these price wedges are brought about by taxes (or subsidies), which either raise (or lower) the price faced by each agent relative to the market price. Figure 6 illustrates the price differentiation between agents. A price wedge occurs between the seller's price and the market price of domestic outputs, brought about by an output tax. There is a second price wedge between this market price and the final and intermediate demand agents' prices, as a result of consumption and intermediate taxes.

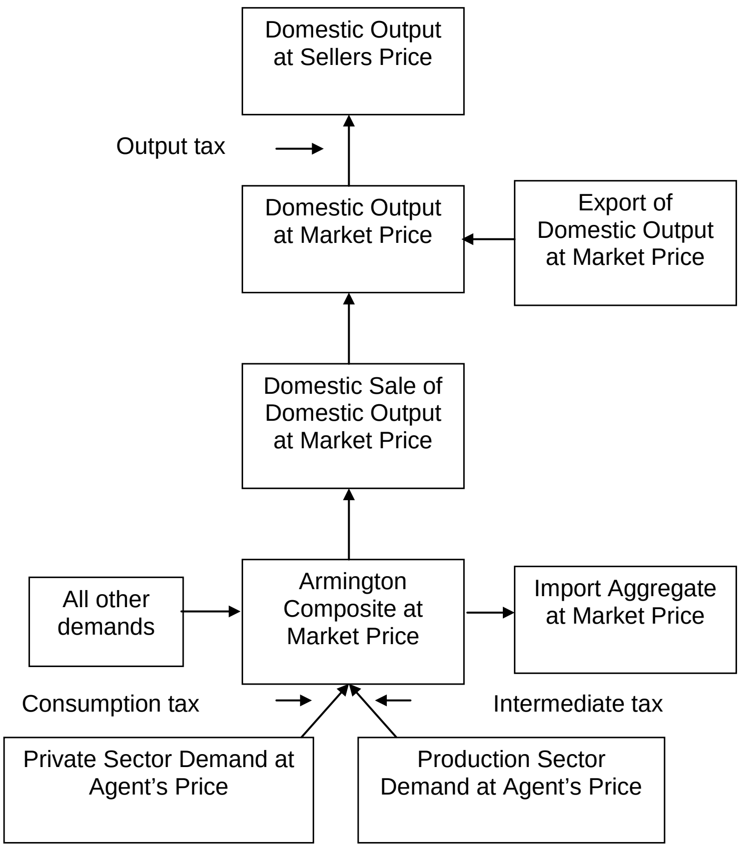

Figure 7: Price structure within each region. Arrows denote payment flows. Based on Hertel (1997)

In trade, price wedges are brought about by tariffs and transport margins (see Figure 8 below). Market and region-specific world prices of bilateral export goods are differentiated through an export tax. This price is further differentiated into the world price of import through a transport margin, and the market price of import through an import tariff.

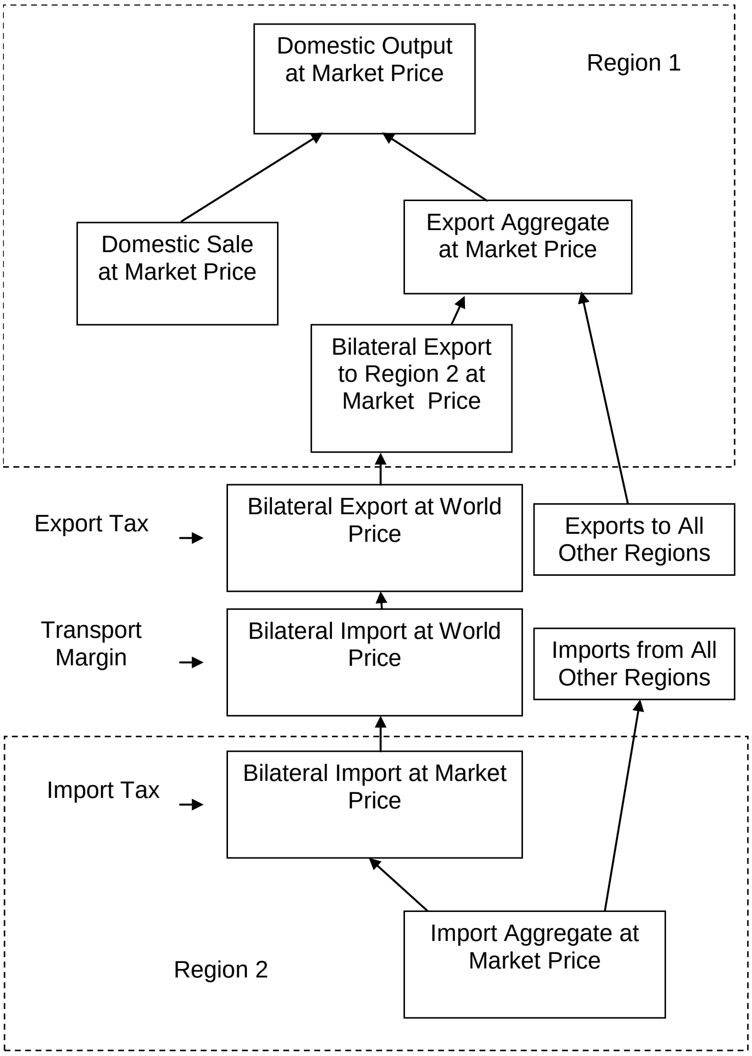

Figure 8: Pricing structure in trade. Arrows denote payment flows. Based on Hertel (1997)

6 Greenhouse Gas Emissions

The GRACE-EL model includes combustion emissions of CO_2 from industrial and household sources. These emissions are relatively simple to model, as they are emitted at a roughly fixed rate of fossil fuel use. GRACE uses emissions data provide by GTAP themselves (Lee, 2007) for version 6 of the database.

The database provides CO_2 emissions from intermediate use of each of the six GTAP energy commodities, in each of the original GTAP regions and sectors, with differentiation for either domestic or imported energy sources. The database also provides emissions for energy use in the household sector. In GRACE-EL, the emissions are aggregated to three energy sources (oil, gas, and coal) with no differentiation for domestic or imported energy emission factors.

CO_2 emissions are modeled as fixed-factor inputs to their associated energy use inputs. As shown in the production and final demand structures above, CO_2 may be reduced via reduced production output, fuel switching, or efficiency improvements (i.e. increased capital/labor inputs).

7 Investment and Dynamics and Intersectoral Mobility of Capital

7.1 Dynamics of Capital Stock

The GRACE model is a recursive dynamic model, wherein time-recursive static equilibria are solved to model the development of the economy over time. Each equilibrium represents a single year, and is connected to the next by the growth in the primary inputs of labor, natural resources, and capital stock. Each time period is solved independently and thus unlike intertemporal dynamic models, computation complexity does not increase when time periods are added. The model is typically run for five 5-year periods from its base year (2001).

In the model, economic growth is driven by growth in the effective labor force and the level of income is determined by capital stock. The value of the capital stock at the end of each time period is given by the value of the stock at the beginning of the period (net of depreciation) plus the value of investments made. This end of period capital stock is then available at the beginning of the next time period.

Investments in each region are made by the model's Global Bank. We follow the investment theory of the GTAP-Dyn model (Ianchovinchina et al., 2007), where investors seek to equalize expected rates of return across all regions. If an imbalance arises, and one region develops a higher expected rate of return than the others, investments will be shifted toward that region until the expected rate of return is again equalized. In a recursive dynamic setup, investors expectations follow the martingale property and thus investors use the current prices as the best proxy for future prices when making their investment decisions.

As expected, we find that the base year data does not conform to our investment theory. In reality, investment choices are affected by a multitude of factors, including risk aversion, information availability, and preferences. As a consequence, we make an adjustment to the database initial capital stocks so that the expected rate of return is equalized across all regions – and conforms to our theory from the start. While such an adjustment may not be preferable, and very stylized, it is simple and acceptable when we are less concerned with the very short-term. Possible alternative treatments are discussed by Ianchovichina and McDougall (2007).

In our basic version of GRACE-EL, we assume an annual depreciation rate of 4%, and an interest/discount rate of 5%, both values taken from the GTAP6 data.

We make assumptions about the 'normal' rate of growth in the capital stock over time. This does not determine the actual rate of growth, but rather guides investments into each region via the expected rate of return in each region. We are able to change this value for alternative scenarios for each region. As we expect, this 'normal' rate of growth is different from the growth rate found in the GTAP6 base year data. As such, we make a second adjustment to the base data, related to this assumed growth rate such that it does conform. While this is again somewhat stylized, it ensures that the growth in the first year is consistent with the following years in our scenario runs.

Payments to capital (i.e. income from investments) are distributed to the Regional Households by the Global Trust based on ownership, rather than the location of capital. This ensures any foreign investments are accounted for. Income from capital in each region first accrues to the Global Trust at the global rate of return. This income is then distributed back to the regional households based on the cumulative value of each region's savings over time. The distribution of income from the Global Trust to the regional households is based on each region's share of the total global cumulative (and depreciated) savings.

We must make an exception to this treatment, however, for the base year capital stock. In the GTAP database, the income from the capital stock in each region accrues only to its own regional household. Thus, the households own the base year capital stock within their region, thereby violating our assumption that capital ownership is not location specific. As we wish for our first time period to replicate the base year data, we must account for this anomaly by assuming that (i) the base year capital stock is only owned by the region where it is located, and (ii) from only the second time period onwards is capital ownership not location-specific. This means that the Global Trust must track the depreciating value of the base year capital stock along with the value of the cumulative savings.

7.2 Intersectoral Mobility of Capital Stock

A new extension of GRACE-EL is the treatment of mobility of existing capital stock between sectors. The modeling literature often treats any available capital and new investment as perfect substitute, and assumes perfect mobility of capital from one sector to the other. In many occasions, this assumption does not cost substantial insights – particularly under scenarios with long timescales.

However, with regard to sectors that deeply tied to climate policies, it has a number of drawbacks. First and foremost, an already installed capital investment, say hydro turbine can not perfectly be serve as a nuclear plant or vice versa. Although in sufficiently long time, say 100 years, cumulative depreciation makes the issue worthless, most climate policies aim at sending signals the change behavior both in the short and long run. Moreover, in the absence of any frictions, a small change in expectation about policy can shift generating technology from coal fired power to nuclear or hydro power plants. Even though there have been even sharp frequent changes in expectations, such a complete shift, or what is technically know as corner solution, has not been observed. Hence, if the intention of models is to replicate reality and simulate the consequences of changes in exogenous variables, then perfect inter-sectoral capital mobility may be a weak assumption.

Dissatisfaction about this assumption first emerged in late 1950s, with suggestion that capital is perfectly mobile ex-ante but it is immobile ex-post (the "Putty-Clay" model). A number of recent attempts have tried to take into account adjustment costs and frictions in intersectoral capital mobility in a given region in a CGE framework. In GRACE-EL, we follow Sue Wing (2006b) based on its generality and simplicity.

We model the supply of the existing capital stock to the production sectors (and each individual electricity generation technology) in each period with a constant elasticity of transformation (CET) function. The function will seek to supply capital to each sector/technology at the highest price, substituting away from sectors where the capital price is low (i.e. coal production under climate policy). This substitution, however, incurs some cost, which is moderated by the elasticity of transformation. If the elasticity is large, it is "cheap" for capital to move from one sector to another sector. If the transformation elasticity collapses to zero, the CET technology resembles the Putty-Clay model.

We have no clear empirical ground for the choice of the value of the elasticity in transformation in GRACE-EL, and thus simply set it at unity, as is done by Sue Wing.

8 Electricity Sector Disaggregation in GRACE-EL

The GRACE-EL model is based around the GTAP6 database, which offers national-level accounts of aggregate sectoral inputs and output flows. On its own, the database does not feature detailed characteristics about sector processes or the use of particular technologies – a weakness of many top-down macroeconomic models. Technological information is particularly interesting in the case of the electricity sector, which is likely to have a key role in emissions reduction in the coming decades due to its large emissions base and wide range of generation technologies.

With the intent of exploring the role of the electricity sector of the climate policy, the GRACE model has been modified to include explicit treatment of electricity generation technologies. This modification is done only for the regions within the European region (see Table 1); however the methodology could be applied to the rest of the world. It includes fossil fuel and non-fossil fuel generation technologies, as well as some technologies that are not yet in widespread use. A number of other CGE models feature similar treatments (Frei et al., 2003;Bohringer et al., 2005;Paltsev et al., 2005), and in particular we draw heavily on the model developed and applied by Sue Wing (2006a;2006b); this model is referred to below as SW2006.

In short, the modification involves the merger of ‘bottom-up’ technology information into the ‘top-down’ framework of GRACE. The production structure of the electricity sector must be rearranged to incorporate the alternative technology options. Additionally, technology-specific information about inputs, generation, and efficiencies are incorporated into the GTAP database. This involves a disaggregation of the electricity sector data, but for simplicity does not require a rebalancing of the GTAP6 input-output matrix.

The final result is a disaggregation of the following generating technologies (Table 2). These technologies represent the aggregate characteristics of the existing generating capacity. We have explicitly excluded carbon capture and storage (CCS) technologies, as the model will only be used to generate scenarios to 2020. The model, however, is flexible to accommodate such extensions, as well as further disaggregation into more specific technology types such as those featured in SW2006.

Fossil fuel technologies	Carbon-free technologies
Coal	Nuclear
Natural Gas	Hydro
Oil	Renewables (Solar/Wind)

Table 2: GRACE-EL disaggregated electricity technologies**.**

8.1 Production structure for disaggregated electricity sector

The starting point of the disaggregation is the reorganization of the electricity sector production structure (illustrated below in Figure 9), which is a nested CES function divided into generation activities (GEN) and transmission, distribution, and network overhead activites (TD). This is a similar to SW2006, which features a three-way split between generation, transmission and distribution, and overhead. For GRACE, lacking the data to make the distinction between transmission and network overhead, we simply combine them.

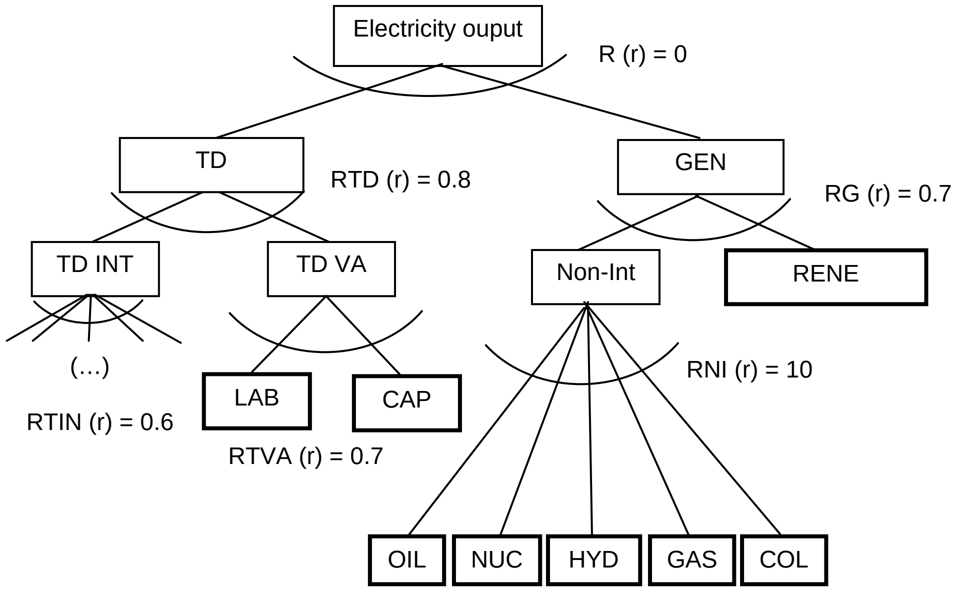

Figure 9: Nested CES production structure of disaggregated electricity sector in European regions. The r index refers to the set of regions.

GEN and TD activities are separated into two branches as complementary (Leontief technology) inputs. The TD nest separates intermediate (TD INT) and factor (TD VA) inputs, which are modeled as nested CES functions with low elasticity of substitution. The GEN branch of the production tree features two nests: intermittent sources, and non-intermittent sources. Renewable generation represents the sole intermittent generation technology, while the remainder of 'traditional' generation technologies make up the non-intermittent sources.

Each of the generation technologies is itself a Leontief technology of inputs. The fossil fuel technologies are made up of complementary inputs of fuel, labor, and capital; non-fossil fuel technologies are made up of complementary inputs of labor, and capital. The shares of each of these are determined in the calibration described below. The capital represents the investment, and the labor the overhead required for each technology.

The non-intermittent technologies are modeled to be highly substitutable to each other (elasticity = 10). This represents the homogeneity of their collective outputs, but avoids corner solutions that would arise from perfect substitutability. Of course, this elasticity is still extremely high, and under price shifts the model would over time likely change the makeup of the electricity sector quite drastically. However, there are two mechanisms in place to prevent drastic inter-period changes to the power sector.

Firstly, our capital vintaging treatment (Section 7) provides a brake on the movement of capital between technologies within each period. Secondly, we apply a capacity constraint on the production from each technology. This prevents the complete dominance over time (in effect, a corner solution) of one technology. This constraint is modelled as a shadow price on expansion for each generation technology in each region – which is zero when the production is within this constraint. This constraint can be intepreted as a physical constraint (e.g. limitations on suitable hydro locations) or socio-political constraints (e.g. concerns over dominance of nuclear or gas as energy sources).

The intermittent and non-intermittent sources are modeled as imperfect substitutes to each other. This is because the variable output of intermittent sources such as solar and wind means they must be backed up by additional capacity of non-intermittent sources. As such, intermittent sources are substituted with non-intermittent sources using an elasticity of 0.7.

8.2 Data calibration

The next step is to consolidate the existing top-down GTAP data with the more detailed bottom-up data for the electricity sector. This involves the use of a calibration technique seen in SW2006, which seeks to disaggregate input and output values for TD and each GEN technology from the existing GTAP electricity sector. The calibration model is made up of two sets of equations:

The first set of equations ensures that the disaggregation result is consistent with the original sector data. The factor and intermediate input totals across TD and GEN activites are constrained to the total inputs of the original GTAP electricity sector1. Fixed value parameters are denoted with a horizontal line above them, while the rest are variables.

$$\overline{IO}_{ELC}(i) = IO_{TD}(i) + \sum_{tech} IO(i, tech) \qquad \text{Equation 1}$$

$$\overline{IF}_{ELC}(f) = IF_{TD}(f) + \sum_{tech} IF(f, tech) \qquad \text{Equation 2}$$

The parameters *IO(i)* and *IF(f)* refer to the value of baseline inputs of commodities *i* and factors *f* (listed in Table 1) used by the electricity sector. The *ELC* suffix denotes the original aggregate electricity sector, while *tech* represents the set of disaggregated GEN technologies (listed in Table 2).

The next set of equations restricts the total output of the *TD* and *tech* activities to the total output of the original electricity sector, and the activity outputs ($a = \{TD, tech\}$) must equal the sum of their respective inputs:

$$\overline{XD}_{ELC} = XD_{TD} + \sum_{tech} XD(tech) \qquad \text{Equation 3}$$

$$XD(a) = \sum_{i} IO(i, a) + \sum_{f} IF(f, a) \qquad \text{Equation 4}$$

XD refers to the value of outputs of either the original sector or the disaggregated activities or technologies.

Additional restrictions are placed on the distribution of commodity inputs across the activities. As highlighted earlier, electricity generation technologies are only comprised of fuel and factor inputs. All other inputs to the electricity sector in GTAP – such as services, or

[1] Note that these equations refer to the outputs and inputs within a given region, so are implicitly indexed by region.

machinery – are assumed to contribute to the *TD* activities. These inputs, as such, are thus unconnected to particular electricity generating types. This is represented in Equation 5 and Equation 6 below.

$$IO(ne, tech) = 0 \qquad \text{Equation 5}$$

$$IO_{TD}(e) = 0 \qquad \text{Equation 6}$$

Where *ne* = {non-energy *i*}, and *e* = {final energy *i*}. Final energies (from Table 1) are refined oil (REF), coal (COL) and natural gas (GAS). It should be noted that within Equation 5, it is also assumed that technologies may only use fuels for which they were designed. Coal plants may only use coal, and so forth.

In the above equations, XD_{ELC}, $IO_{ELC}(i)$, and $IF_{ELC}(f)$ are informed by the GTAP database, as signified by the bars on top. The remaining values are calculated by the calibration, which in addition to satisfying the above constraints, seeks to closely match them with electricity output, input, and efficiency values from the bottom-up literature. This is done using what is termed a "positive mathematical programming" approach similar to that used in SW2006. The objective of the calibration is not to seek an exact fit, but rather to minimize the divergence between the actual bottom-up data characteristics and the disaggregated GTAP data.

The first of these characteristics is the share of total electricity production contributed by each technology type. Our starting point is the electricity production data for year 2001 from Eurostat (European Commission, 2008), shown in Table 3. The renewables category represents solar and wind power. In this disaggregation, we have disregarded biomass energy. While this is a notable sacrifice in light of recent attention towards bio-energy, the model does not yet feature the necessary treatment of land and resource opportunity costs associated with this technology. As such, we leave it for future work.

Source	NOR	UKI	FRA	GER	BNL	BAL	IBE	ITA	GRE	REE
Nuclear	91	83	427	162	48	10	61	0	0	71
Coal	35	136	20	278	32	130	79	30	33	100
Oil	7	10	6	6	5	3	32	71	8	14
Gas	22	147	19	71	74	6	30	95	6	25
Hydro	212	7	121	68	3	8	58	53	3	28
Wind/Solar	5	3	2	17	2	0	9	10	1	0

Table 3: Electricity production by type (TWh) in 2001. Source: Eurostat (European Commission, 2008)

The divergence (*EPS*) between the calibrated share of generation from each technology type and the share informed by Eurostat is captured here:

$$EPS_1(tech) = \frac{1}{\overline{\overline{GEN}}(tech)} \frac{XD(tech)}{\overline{\overline{PG}}(tech)} \Bigg/ \sum_{techs} \frac{XD(techs)}{\overline{\overline{PG}}(techs)} - 1 \qquad \text{Equation 7}$$

As before, the sets *tech* (and alias *techs*) refers to the set of standard aggregate generating technologies seen in Table 2. As with the previous equations, the fixed parameters are denoted by a horizontal line above them. The baseline production level GEN is taken from the Eurostat data in Table 3. The parameter *PG* refers to the unit generating cost of each technology, and is calculated in part using data from NEA et al. (2005) and Reinaud (2004). The generating price is calculated from capital investments and upkeep, overhead and maintenance, and fuel costs.

The capital and labor cost components are taken from the literature, with capital costs annualized at 5% over 30 years. The fuel cost component is calculated using fuel price and thermal efficiency data. To ensure consistency, the fuel price (*PF*) is calculated from the GTAP database itself. The unit price the fuels (including taxes) is calculated simply by dividing the value (in 2001$) and volume (in Mtoe) of the original GTAP electricity inputs. The aggregate thermal efficiency value for each fossil fuel tech is calculated from a 2005 table of generating capacity and efficiency in Europe (Traber, *forthcoming*), which makes distinctions between old and new coal and lignite power stations, and numerous types of gas and oil facilities. The *PG, PF*, and efficiency (*EFF*) values used in the calibration are shown in Table 4 and Table 5 below.

	Efficiency (EFF)			**PF ($/Mbtu)**			**PG ($/Mbtu)**		
	Gas	**Oil**	**Coal**	**Gas**	**Oil**	**Coal**	**Gas**	**Oil**	**Coal**
NOR	0.41	0.36	0.38	3.44	4.81	2.22	12.71	16.68	11.24
UKI	0.53	0.37	0.35	2.57	5.18	1.79	8.98	17.51	11.20
FRA	0.36	0.38	0.34	2.95	4.64	1.70	11.38	15.39	11.33
GER	0.44	0.37	0.37	3.84	5.01	1.73	11.54	16.36	9.92
BNL	0.48	0.37	0.39	3.09	6.56	2.00	10.63	21.92	10.74
BAL	0.40	0.38	0.35	3.02	5.64	1.26	10.04	17.32	9.34
IBE	0.50	0.37	0.36	3.10	4.58	1.62	9.28	15.46	9.73
ITA	0.45	0.38	0.38	3.12	4.44	1.74	8.45	13.19	9.38
GRE	0.53	0.36	0.36	3.01	5.18	1.69	7.88	16.57	9.92
REE	0.43	0.34	0.36	2.81	4.62	1.11	9.01	16.06	8.83

Table 4: Thermal efficiency, fuel price (including intermediate taxes), and unit generation prices for fossil technologies. Sources: Traber (*forthcoming)*, GTAP6 database, NEA et al., and Reinaud.

The second divergence equation relates to the actual and calibrated thermal efficiency of each of the fossil technologies:

$$EPS_2(ftech) = \frac{1}{\overline{EFF}(ftech,e)} \frac{\overline{PF}(e) * IO_{ftech}(e)}{\overline{PG}(ftech) * XD_{ftech}} - 1 \qquad \text{Equation 8}$$

The set *ftech* is a subset of *tech* containing only the fossil technologies.

The final divergence equation relates to the capital and labor inputs of each technology. It compares the labor to capital expense ratio from the literature, to the ratio in the calibrated disaggregated technologies:

$$EPS_3(tech) = \frac{1}{LKratio(tech)} \frac{IFZ(LAB,tech)}{IFZ(CAP,tech)} - 1$$ Equation 9

The elements *LAB* and *CAP* refer to the labor and capital factor inputs to each tech. The labor to capital ratio (*LKratio*) used in the calibration is calculated at the same time as *PG* above. It compares the overhead and maintenance (treated as labor) and capital investment and upkeep (treated as capital) portions of total electricity production; the values are shown Table 5. The large differences seen in some technologies (i.e. gas in France vs. UK) is a consequence of the use of several sources of data with differing qualities of country coverage.

Region	**Generation Price (PG) $/Mbtu**			**Labor:Capital Expense Ratio (LKratio)**					
	Hydro	**Nuclear**	**Renewable**	**Hydro**	**Nuclear**	**Renewable**	**Gas**	**Coal**	**Oil**
NOR	5.00	7.47	13.00	0.3	0.29	0.2	0.53	0.51	0.53
UKI	5.00	8.04	13.00	0.3	0.44	0.2	1.40	0.66	1.40
FRA	5.00	7.13	13.00	0.3	0.34	0.2	0.60	0.74	0.60
GER	5.00	8.04	13.00	0.3	0.44	0.2	1.08	1.07	1.08
BNL	5.00	10.35	13.00	0.3	0.33	0.2	0.52	0.66	0.52
BAL	5.00	6.47	13.00	0.3	0.58	0.2	0.55	0.74	0.55
IBE	5.00	7.13	13.00	0.3	0.34	0.2	0.74	0.47	0.74
ITA	5.00	-	13.00	0.3	-	0.2	0.56	0.53	0.56
GRE	5.00	-	13.00	0.3	-	0.2	0.49	0.47	0.49
REE	5.00	6.47	13.00	0.3	0.58	0.2	0.55	0.73	0.55

Table 5: Non-fossil technology generation price and labor:capital expense ratio. Source: NEA et al., and Reinaud.

Finally, the objective of the calibration seeks to minimize the divergence across all *EPS* values.

$$MIN = \sum_{tech} EPS_1(tech)^2 + \sum_{tech,f} EPS_2(ftech)^2 + \sum_{tech} EPS_3(tech)^2$$ Equation 10

The resulting calibrated electricity production levels are shown in Table 6 (fossil fuels) and Table 7 (non-fossil fuels). The calibrated thermal efficiencies of the fossil technologies are also presented.

Region	**Gas**		**Oil**		**Coal**	
	Production (TWh)	**Efficiency**	**Production (TWh)**	**Efficiency**	**Production (TWh)**	**Efficiency**
NOR	24	0.41	7	0.38	39	0.36
UKI	172	0.53	15	0.35	138	0.36
FRA	11	0.36	6	0.33	18	0.37
GER	87	0.44	10	0.38	308	0.36
BNL	83	0.50	12	0.40	37	0.33
BAL	11	0.30	7	0.19	93	0.33
IBE	24	0.50	33	0.36	79	0.37
ITA	95	0.45	78	0.38	32	0.38
GRE	7	0.50	8	0.31	30	0.34
REE	43	0.31	20	0.28	107	0.29

Table 6: Calibrated fossil fuel technology production in GRACE-EL

	Nuclear (TWh)	**Hydro (TWh)**	**Renewables (TWh)**
NOR	96	223	5.8
UKI	103	8	3.8
FRA	325	79	1.3
GER	242	92	22.5
BNL	94		2.3
BAL	6	5	0.3
IBE	58	55	8.5
ITA	-	56	10.2
GRE	-	2	0.7
REE	12	19	0.3

Table 7: Calibrated non-fossil fuel technology production in GRACE-EL

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