IFE/KR/F-2013/123

Modelling an ambitious climate constraint with ETSAP–TIAM

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Report number	Availability	Revision number	Date
IFE/KR/F-2013/123	LIMITED		2013-11-14
Client/ Client reference: CenSES	Availability this page	Number of issues	Number of pages 22

Report title

Modelling an ambitious climate constraint with ETSAP–TIAM

Summary

The ETSAP-TIAM model is one of the global models available in CenSES, and the main purpose of this report is to give the CenSES partners a brief overview the characteristics of this model, and to address its possible area of application. In this report, results of two scenarios are presented; one scenario with no climate constraint and one scenario with a 450 ppm restriction of the CO_2 equivalents throughout the model period. These results are compared with results from the LinkS project, that are based on the the GCAM model, another global model available in CenSES.

Distribution

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Contents

1 Abbrevations

AFR	Africa
AUS	Australia-New Zealand
CAN	Canada
CCS	Carbon Capture and Storage
CenSES	Centre for Sustainable Energy Studies
CSA	Central and South America
CHI	China
EEU	Eastern Europe
ETSAP	Energy Technology Analysis Program
FSU	Former Soviet Union
GBL	Global
GCAM	Global Change Assessment Model
GDP	Gross Domestic Product
GDPP	Gross Domestic Product per capita
GHG	Greenhouse Gas Emissions
HOU	Households
IEA	International Energy Agency
IND	India
IFE	Institute for energy Technology
JPN	Japan
LinkS	Linking Global and Regional Energy Strategies
LP	Linear Programming
MARKAL	MARKet Allocation model
MEX	Mexico
MEA	Middle-East

ODA	Other Developing Asia
POP	Population
SKO	South Korea
TIAM	TIMES Integrated Assessment Model
TIMES	The Integrated Markal Efom System
SPROD-X	Production of sector X related to GDP
USA	United States
WEU	Western Europe

2 Introduction

In this report, the impact of an ambitious GHG emission reduction scenario on the development of the energy system is presented on a global and on a West European scale. This work is a part of the Research Area 2, Energy system and markets, in the Centre for Sustainable Energy Studies (CenSES). Europe is not isolated from the rest of the world, and future optimal investment strategies for Europe depend on the development of the energy system in the rest of the world. The activity in other continents influences the prices and the availability of traded energy carriers like fossil fuels and biofuels and affects the rate of technology learning. Also, in regards to future climate scenarios, the whole world needs to be taken into account since Greenhouse Gas Emissions (GHG) is a global problem.

The TIMES Integrated Assessment Model (TIAM) (Loulou, 2008; Loulou and Labriet, 2008) is a suitable tool used to investigate the consequences of the climate constraint on future energy and emission balances, and on new investments in upstream, transformation and end-use technologies. It is a global, technology rich, long-term model of the energy system that is developed by the Energy Technology Systems Analysis Program (ETSAP), an Implementing Agreement of the International Energy Agency (IEA) that uses the Integrated Markal Efom System (TIMES) modelling framework (Loulou et al., 2005a; Loulou et al., 2005b, c). TIMES is the successor of the MARKet ALlocation model (MARKAL), and gives a detailed description of the entire energy system including all resources, energy production technologies, energy carries, demand technologies and demand sectors. The model assumes perfect competition and has perfect foresight, and the total energy system cost for the whole model period is minimised to meet the final energy demand at a least cost. The ETSAP-TIAM version used in this report is available for all ETSAP partners where Institute for Energy Technology (IFE) is the Norwegian partner. There are done no changes to the model input or the model structure to the latest version of the ETSAP-TIAM model.

ETSAP-TIAM is a global model well suited to analyse climate constraints and endogenous technology learning, and the model, and variants of this model, is frequently used to address these issues, see (Anandarajah et al., 2013; Kesicki and Anandarajah, 2011; Loulou et al., 2009). The ETSAP-TIAM model is one of the global models available in CenSES, and the main purpose of this report is to give the CenSES partners a brief overview the characteristics of the model, and to address its possible area of application.

3 Model description

The time horizon of ETSAP-TIAM is 2005-2100 where the start-year is calibrated to the 2005 statistics. The annual time distribution is winter, summer, intermediate and day/night. Techno-economic parameters are described in the form of technologies that transform a commodity into others commodities (fuels, materials, energy services, emissions). The model can choose to invest in a rich set of both current and future technologies.

The 15 regions of ETSAP-TIAM are illustrated in Figure 1. The regions are Africa (AFR), Australia-New Zealand (AUS), Canada (CAN), Central and South America (CSA), China (CHI), Eastern Europe (EEU), Former Soviet Union (FSU), India (IND), Japan (JPN), Mexico (MEX), Middle-East (MEA), Other Developing Asia (ODA), South Korea (SKO), United States (USA) and Western Europe (WEU). Norway is a part of Western Europe together with Austria, Belgium, Denmark, Finland, France, Germany, Gibraltar, Greece, Greenland, Iceland, Ireland, Italy, Luxemburg, Malta, Netherlands, Portugal, Spain, Sweden and Switzerland.

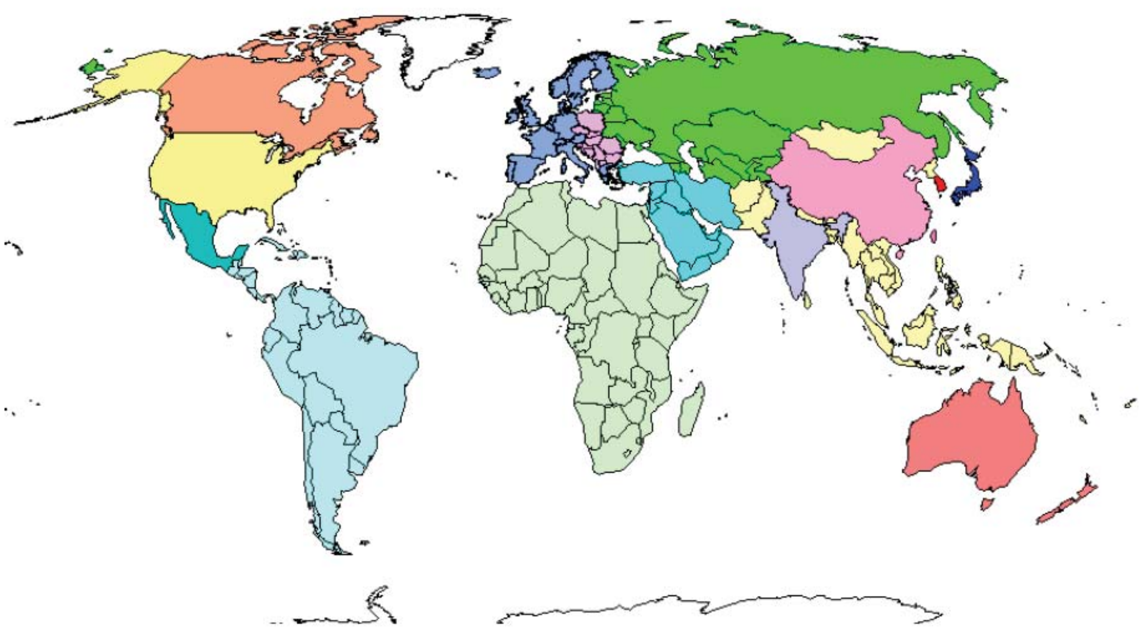

Figure 1: The regions of ETSAP-TIAM (Loulou and Labriet, 2007)

Inputs to the model are available resources and technology costs drivers for the end use demand, while outputs of the model are energy produced, energy consumed, energy prices, technology adoption, abandonment, emissions, emission prices, climate variables and demands for energy services. There is a various set of modelling options including stochastic programming (of most input parameters) (Loulou and Lehtila, 2012), endogenous technology learning and elastic end-use demand. The discount rate is a model input, and in the analysis described in this report a global discount rate of 5 % is used.

The decision variables of the model are optimised to satisfy the energy service demand at a least cost. The initial demand, drivers and demand elasticity are exogenous input to the model and set the basis for the final end use demand, see equation (1). The elasticity reflects the degree of decoupling between the drivers and the demands. It is also possible to include price elasticity on the service demand but this option is not used in the model results below.

Demand = (Initial demand * Driver) ^ elasticity Equation 1

The current drivers of the model are listed below:

- GDP – Gross Domestic Product
- GDPP – Gross Domestic Product per capita
- HOU – Households
- POP – Population
- SPROD-X – Production of sector X related to GDP

New drivers can easily be added or changed by the model user if the modeller finds it appropriate to use other drivers. Alternatively, the energy service demand can be directly set in the model.

The demand sectors are:

- **Transportation**; automobile travel, bus travel, 2 & 3 wheelers, rail passenger travel, domestic aviation travel, international aviation travel, trucks, freight rail, domestic navigation, bunkers
- **Residential**; space heating, space cooling, water heating, lighting, cooking, refrigeration and freezing, washers, dryers, dish washers, other appliances, other
- **Commercial**; space heating, space cooling, water heating, lighting, cooking, refrigeration and freezing, other electric demands, other
- **Agriculture**
- **Industry**; iron and steel, non-ferrous metals, chemicals, pulp and paper, non-metal minerals, other industries

To illustrate the detail level of the ETSAP-TIAM model, the final energy demand by end-use for the residential sector in Western Europe in 2005, 2030 and 2050 is shown in Figure 2. In the residential sector space heating has the largest end-use demand with a 54 % share in 2005 followed by hot water that has a 13 % share in the same year.

GDP is inter alia the driver of the commercial sector, heavy and medium sized trucks, and the relative GDP growth for all model regions from 2005 – 2100 is depicted in Figure 3. It is assumed a significant GDP growth in India (IND) and China (CHI) with a relative increase of 15.2 and 11.1 in 2050 and 30.1 and 22.0 in 2100 respectively. Population is inter alia the driver of hot water, residential cooking, rail and bus demand, and the relative population growth for all model regions from 2005 – 2100 is depicted in Figure 4. The population growth is expected to be highest in Africa (AFR) and in the Middle East (MEA) with a relative increase of 2.0 and 1.9 in 2050 and 2.6 and 2.5 in 2100 respectively. Towards 2050 in Western Europe the GDP is assumed to grow to 2.2 and the population is assumed be almost at the 2005 level.

ETSAP-TIAM endogenous trade oil, coal, natural gas, oil products and natural gas products between the 15 model regions. It is also included a possible electricity trade between Africa and Western Europe. In this current model version, it is not included a global market for any of these commodities meaning the commodity price can differ with region. The commodity price is equal the cost of producing one more unit of the given commodity, and the profitability of the trade, between two regions, depend therefore on the regional price differences, the regional demands and the trading cost.

The climate module of the ETSAP-TIAM model is detailed described in (Loulou et al., 2007), and include equations that calculates change in GHG concentrations, atmospheric temperature increase and radioactive forcing. Since the input parameter of the change in equilibrium atmospheric temperature induced by a doubling of CO_2 concentrations is highly uncertain, this parameter should therefore be treated by be probabilistic methods. This is possible to model in ETSAP-TIAM but is not done in this report.

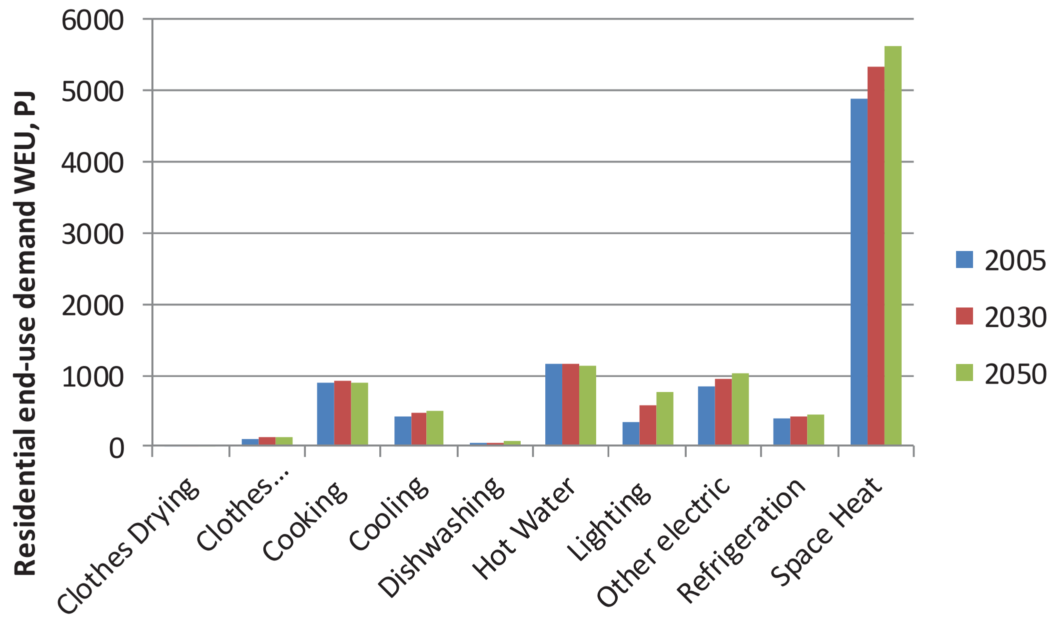

Figure 2: Residential end-use demand in Western Europe in 2005, 2030 and 2050

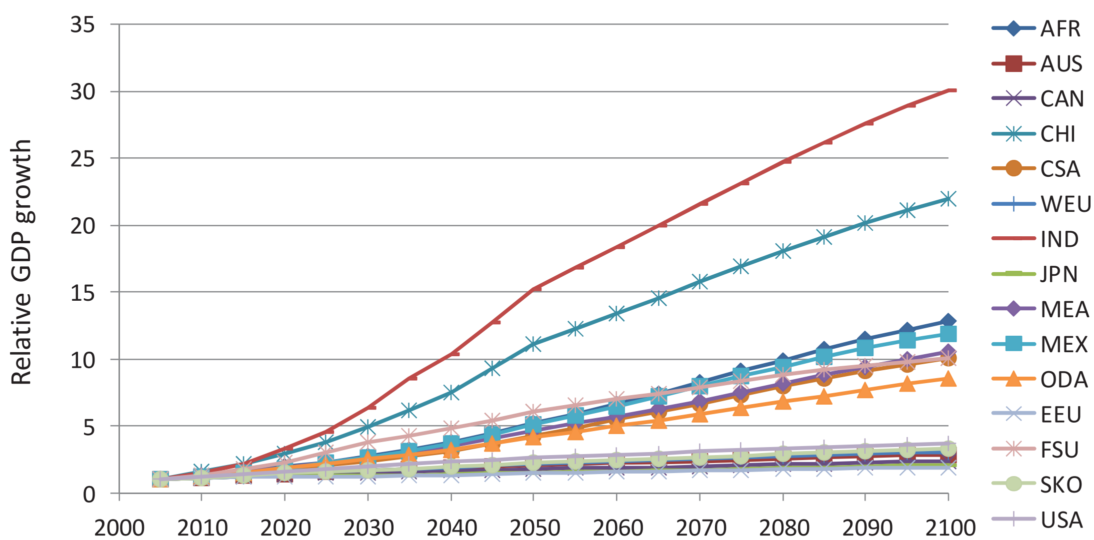

Figure 3: Relative GDP growth for all model regions from 2005 – 2100

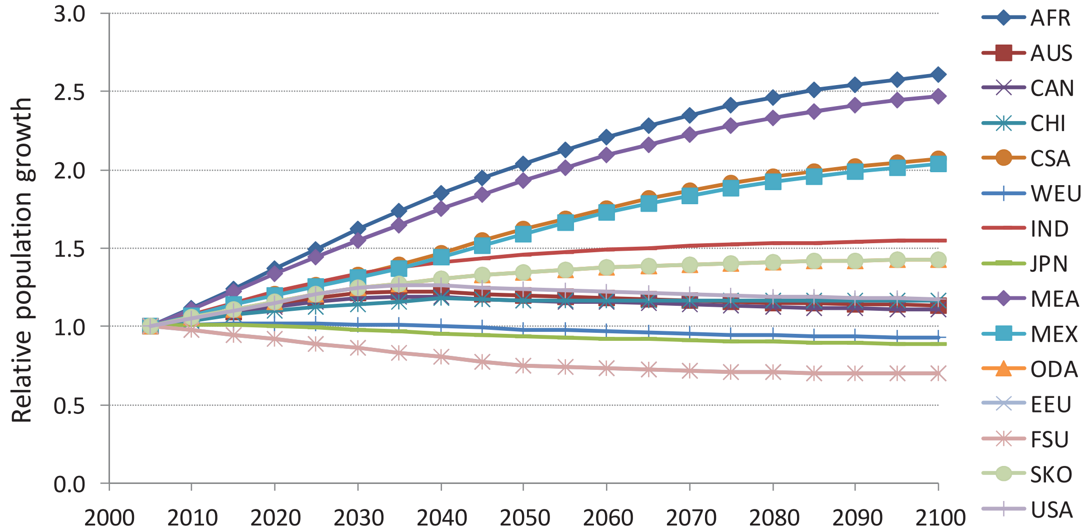

Figure 4: Relative population growth for all model regions from 2005 – 2100

4 Model scenarios and results

Results of the ETSAP-TIAM are presented in two scenarios; *BASE* with no climate constraints and *450PPM* with a 450 ppm restriction of CO_2 equivalents throughout the model period (2005 -2100). The 450 ppm target is also used in other global analysis, including the World Energy Outlook (IEA), where it is stated that the target is consistent with limiting a global increase in temperature to 2 ˚C. In the results presented below, the technological learning curves on efficiencies and costs is an exogenous input to the model that are based on external sources. This model assumption limits the model to capture the new market potential of emerging technologies.

Table 1: Scenario description

BASE	Reference scenario with no climate constraints
450PPM	The GHG concentration, expressed in ppm of CO_2 equivalent, is restricted to be below 450 ppm for the whole model period (2005 - 2100)

4.1 Climate variables

Figure 5 shows the CO_2 equivalents in parts per million (ppm) and the radiative forcing in W/m^2 for the two scenarios for the model period. In *BASE* the CO_2 equivalents exceed 450 ppm in 2040 and reach 648 ppm in 2100 where the corresponding radioactive forcing is 6.1 W/m^2. In *450PPM* the correponding radioactive forcing for 450 ppm is 3.6 W/m^2.

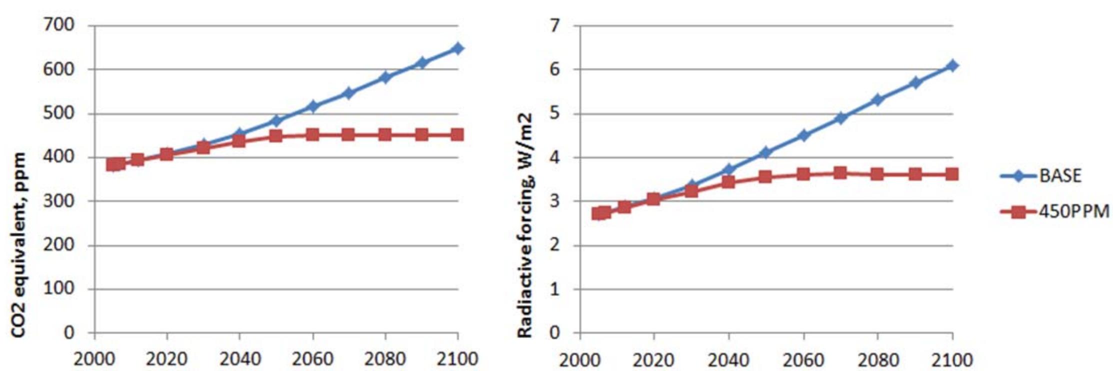

Figure 5: CO_2 equivalents (ppm) and radioactive forcing (W/m^2)

4.2 GHG Emissions

The GHG emissions include methane (CH_4), carbon dioxide (CO_2) and nitrous oxide (N_2O), and it is assumed that CH_4 have 25 times and N_2O have 298 times the global warming potential of CO_2. In the model, the emissions are split between energy-related emission from combustion and flaring, and non-energy related emissions from agriculture, manure, land fill, land use, waste water and industry.

The energy related GHG emissions, of CO_2 equivalents in Giga ton (Gt), for both scenarios on a global (GBL) scale and for Western Europe (WEU) are depicted in Figure 6. With no climate constraint the global energy related GHG emissions gradually increase from 40 Gt in 2005 to 90 Gt in 2100 while the GHG emissions in WEU increase slightly from 4.4 Gt in 2005 to 4.8 Gt in 2100. To achieve the 450 ppm target the global emissions is stabilised at the current emission level towards 2040 before it is further decreased to 26 Gt in 2100. For WEU the jumps in energy related CO_2 emissions from 2070 to 2100 are results of several model decisions. Inter alia, the production of unconventional gas in WEU has a significant increase from 2070 to 2080 before the production level is further reduced in 2090 and 2100. Sudden drops in activity of certain technologies can be a typical model result of a Linear Program (LP) model with perfect foresight where the activity of all capacity is optimised given a known future.

The share of GHG emission reductions of the model regions are set by global optimality, meaning the reductions are done where it is cost effective and no considerations regarding burden sharing is taken into account. The ETSAP-TIAM model is however flexible, and the model can easily include various burden sharing regimes. The difference in energy related GHG emissions, in CO_2 equivalents, between the two scenarios of all model regions are plotted in Figure 7. China is the region with largest emission cuts followed by the Former Soviet union, India and the United States.

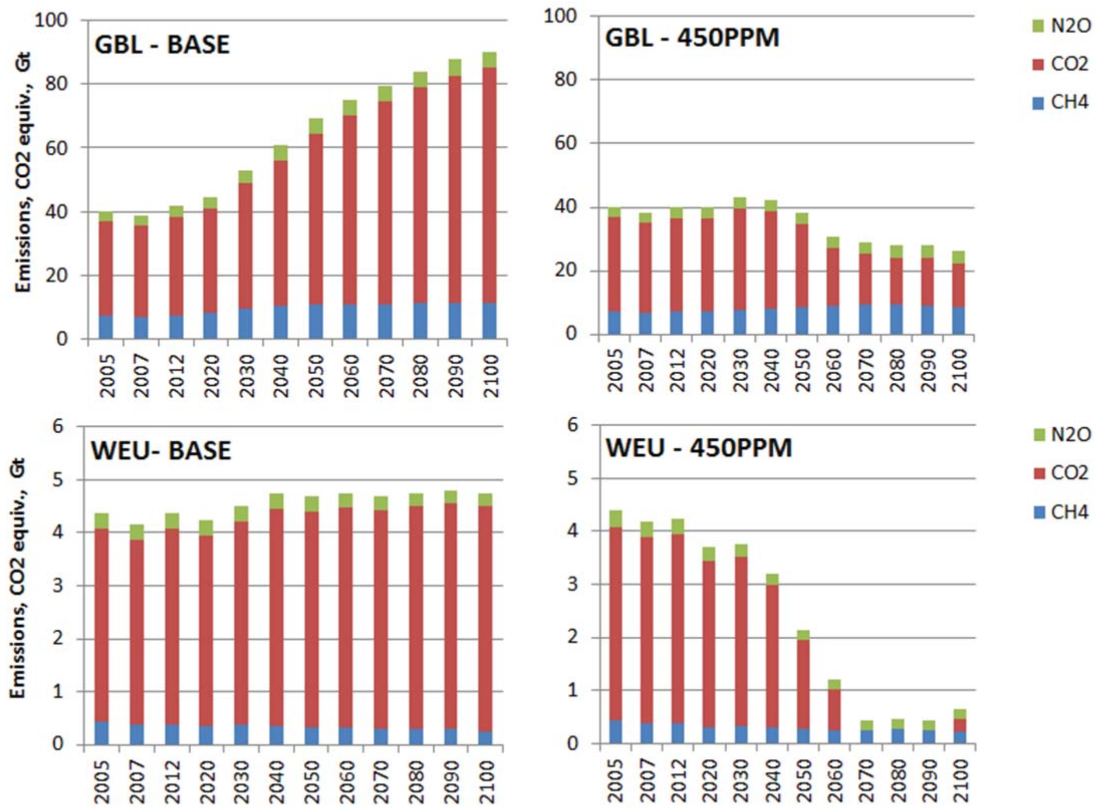

Figure 6: Energy related emissions in CO_2 equivalents, Gt

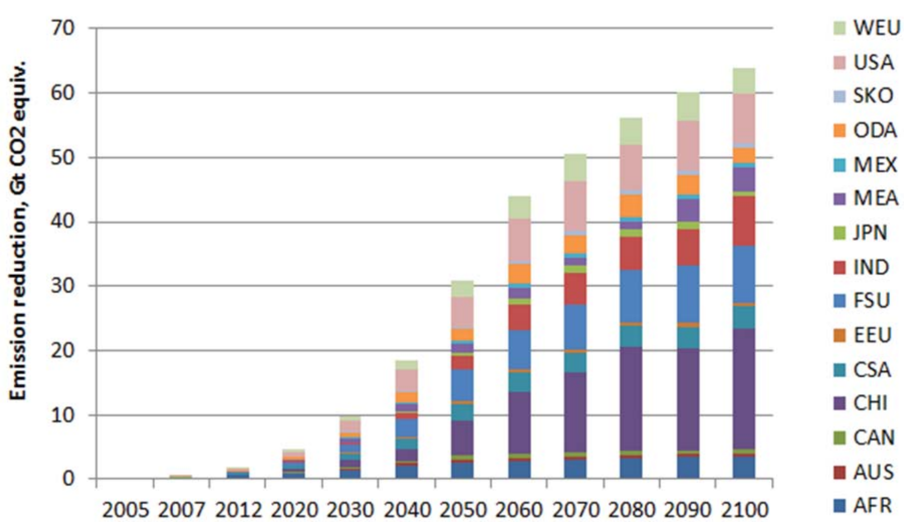

Figure 7: Energy related emission reductions between BASE and 450PPM for all model regions in CO_2 equivalents, Gt

4.3 Primary energy supply

The primary energy production, on a global level and for Western Europe, from 2005 – 2100 split by fuel is illustrated in Figure 8. With the climate constraint, the coal production is decreased and the natural gas and biomass production is increased on a global level. The total primary energy production is larger in *450PPM* compared to *BASE*, and in Western Europe this is partly due to the increase in renewable supply and natural gas extraction in *450PPM*. In both scenarios oil production in Western Europe is not considered profitable in the period from 2020 to 2050. This is in contrast to the projections of the Norwegian Petroleum Directorate, and further investigation of the related input parameters, like oil production and exploration costs, needs to be investigated to determine the reliability of these model results. Note that the drop in primary energy supply from 2005 to 2007 is mainly because the results of 2005 are calibrated to the statistics while the model decisions are free in 2007. The variations in natural gas production from 2007 – 2030 in Western Europe is due to how the natural gas resources are modelled. The conventional natural gas resources are split in several 9 technology classes; 3 steps for located reserves, 3 steps for reserve growth and 3 steps for new discoveries. All technology classes have different extraction costs with exogeneous technology learning over time, and different constraints on annual and cumulative production. In this model with perfect foresight, the model find it profitable to pospone some of the natural gas extraction to 2030 since the extraction cost, for a given technology class, is lower in 2030 compared to for example 2020. In 2020, with a lower activity on the natural gas production within Western Europe, the share of natural gas import is higher compared to for example 2012.

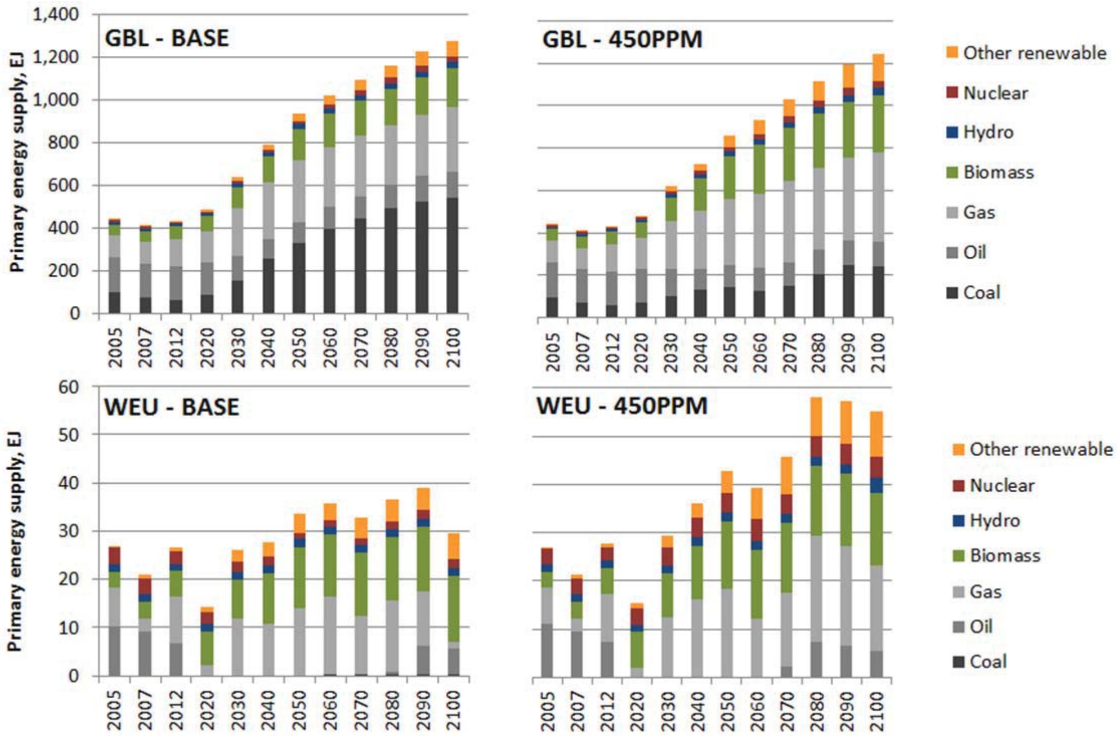

Figure 8: Primary energy production by fuel, EJ

4.4 Electricity production

Technology switch in the electricity sector is necessary to achieve significant future reductions of GHG emissions. Figure 9 show the electricity production, by fuel type, on a global level (GBL) and for Western Europe (WEU) from 2005 - 2100. With the climate constraint, conventional coal fired power plants are phased out and power plants with Carbon Capture and Storage (CCS) are a part of the electricity production mix from 2040. The CCS plants are fuelled with coal, gas and biomass where CCS with biomass is a favourable technology to reduce CO_2 emissions since this technology gives negative GHG emissions. In addition, electricity production from renewable technologies, as wind power and solar thermal, and nuclear power are higher in *450PPM* compared to *BASE*. Also in Western Europe the nuclear power production is increased from 2020 with the climate constraint. The electricity production is larger in *450PPM* compared to *BASE* from 2050 both globally and in Western Europe. Note that the model output on electricity production from PV in 2012 for WEU is lower than what was actually produced in 2012. This is mainly because the model currently do not include national specific subsidy scemes on solar technologies in for example Germany, and due to the exogeenous model assumption on technology learning.

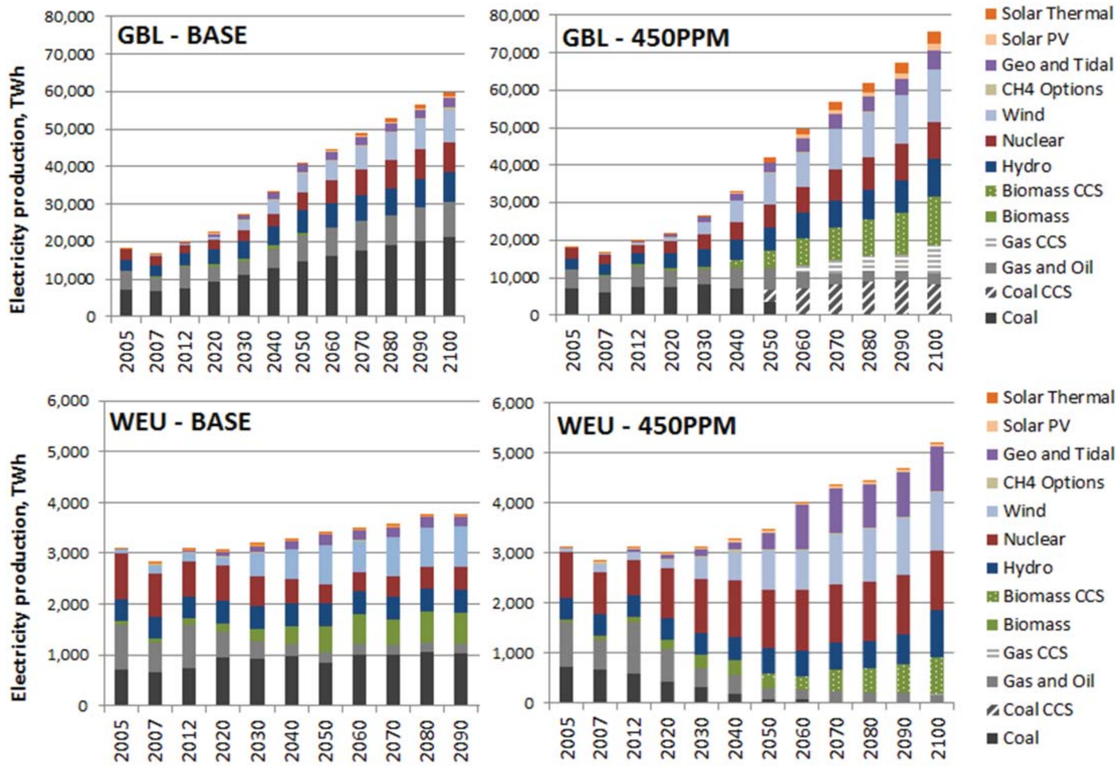

Figure 9: Electricity production by fuel, TWh

4.5 Prices

In *450PPM* the marginal price of CO_2 equivalents represent the global CO_2 price, and is shown Figure 10. The price increases exponentially with the model period to 430 USD per ton CO_2 equivalents in 2100. The carbon price reflects the cost of reducing the emissions in all energy sectors including transport, electricity production, housholds and industry.

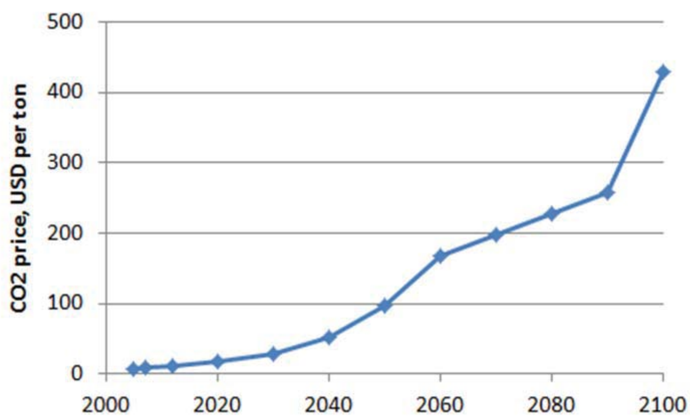

Figure 10: Global carbon price, USD per ton CO_2

In ETSAP-TIAM, the electricity grid is split between centralised and decentralised grid. The electricity price is the shadow price of the electricity balance equation. The annual average electricity prices in Western Europe for both scenarios are plotted in Figure 11. The electricity price is higher in *450PPM* compared to *BASE* in both the centralised and in the decentralised electricity grid; for example in 2050 the electricity price is 68 % higher with the climate constraint in the centralised grid and 31 % higher in the decentralised grid.

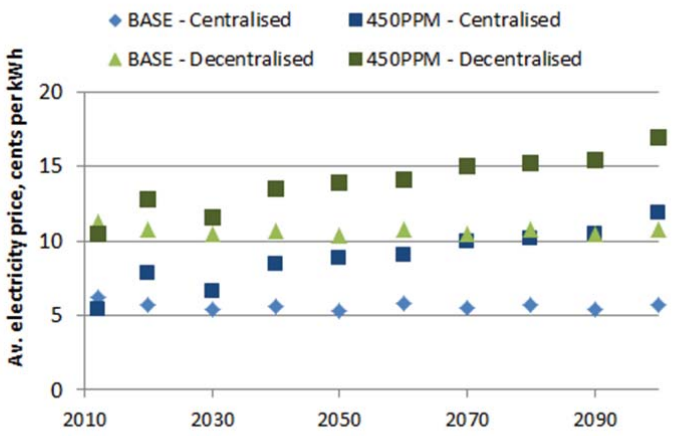

Figure 11: Average electricity price in Western Europe, USD cents per kWh

The price of coal, oil and natural gas for the two model scenarios in Western Europe are shown in Figure 12. The climate constraint gives a slightly increased oil and natural gas price and an approximate unaffected coal price. Please note that the llustrated fossil fuel price is a regional price for Western Europe and not global fossil fuel prices. In this ETSAP-TIAM version no global markets for any energy carriers are modelled, and the commodity price corresponds to the cost of supplying one more unit of the energy carrier in each region. The price difference between the two scenarios depend on the shape of the regional step-wise supply function for each energy carrier.

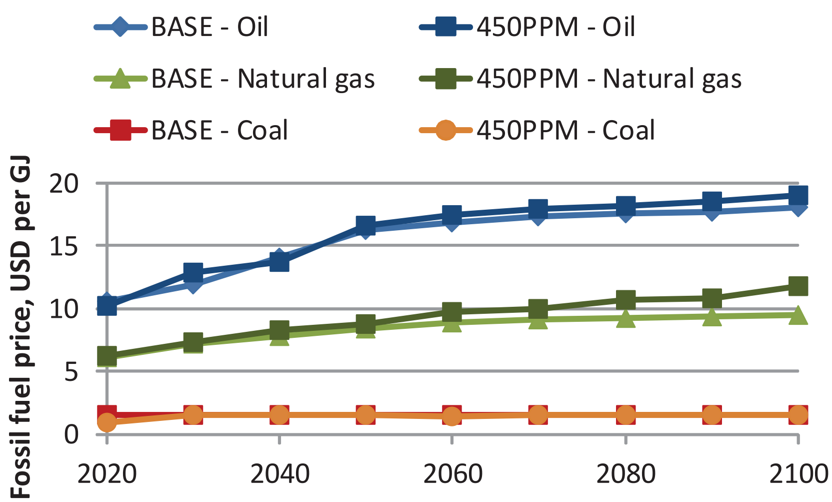

Figure 12: Fossil fuel price in West Europe, USD per GJ

5 Results comparison

The Global Change Assessment Model (GCAM) (Brenkert et al., 2003) is another global energy system model available in CenSES. In this section, selected results from the Linking Global and Regional Energy Strategies (LinkS) project, that is a project based on the GCAM model and management by SINTEF energy research, is compared with results from the ETSAP-TIAM model. The results of of the LinkS project are represented in several global scenarios, included a reference scenario and a scenario with a 450 ppm limit on CO_2 equivalents. These scenarios are compared with *BASE* and *450PPM*. The model results are not directly comparable since the model structure and presumptions of the models differ, but the purpose of this section is to show model results of two different models that have similar scenario descriptions. An essential difference between the two models are that ETSAP-TIAM assumes perfect foresight, where the model decicsions are base on a known future, and GCAM hasa myopic foresight where the model decisions are based on a unknown future. Perfect foresight is the most common assumption in TIMES models, but it is also possible to run ETSAP-TIAM and other TIMES model with a myopic foresight.

The primary energy supply, of GCAM and ETSAP-TIAM, for *BASE* and *450PPM*, are illustrated in Figure 13. For *BASE*, the total primay energy supply, have the similar trends in the two models; the primary energy supply increase from just above 400 EJ in 2005 to just above 1200 EJ in 2090. In 2090, the largest percentaual model difference is more nuclear and oil in GCAM while ETSAP-TIAM has more biomass and other renewable resurces. There is also significant more coal and gas in ETSAP-TIAM than in GCAM. The difference between the models are more significant in *450PPM* where the primary energy supply reduction, compared to BASE in 2090, is 3 % in ETSAP-TIAM and 26 % in GCAM. This demonstrates that the modelling of demand elasticity is different in the two models. In the ETSAP-TIAM version used in this work, it is not included any elastisities on the final energy demand, and consequently the only driving force for reducing the primary energy supply is a more efficient usage of energy carriers. In GCAM it is included both elasticities on price and on income. Since ETSAP-TIAM only cover the energy sector, it is not possible to include any income elasticity, and since ETSAP-TIAM endogenously capture the competition between the energy carriers, price elasticities cannot be directly implemented to the model. Another difference between the model results in *450PPM* is the fuel mix; despite a lower long-term energy supply in GCAM the model has more nuclear fuel supply from 2030 where GCAM has 4.5 times more nuclear supply compared to ETSAP-TIAM in 2090.

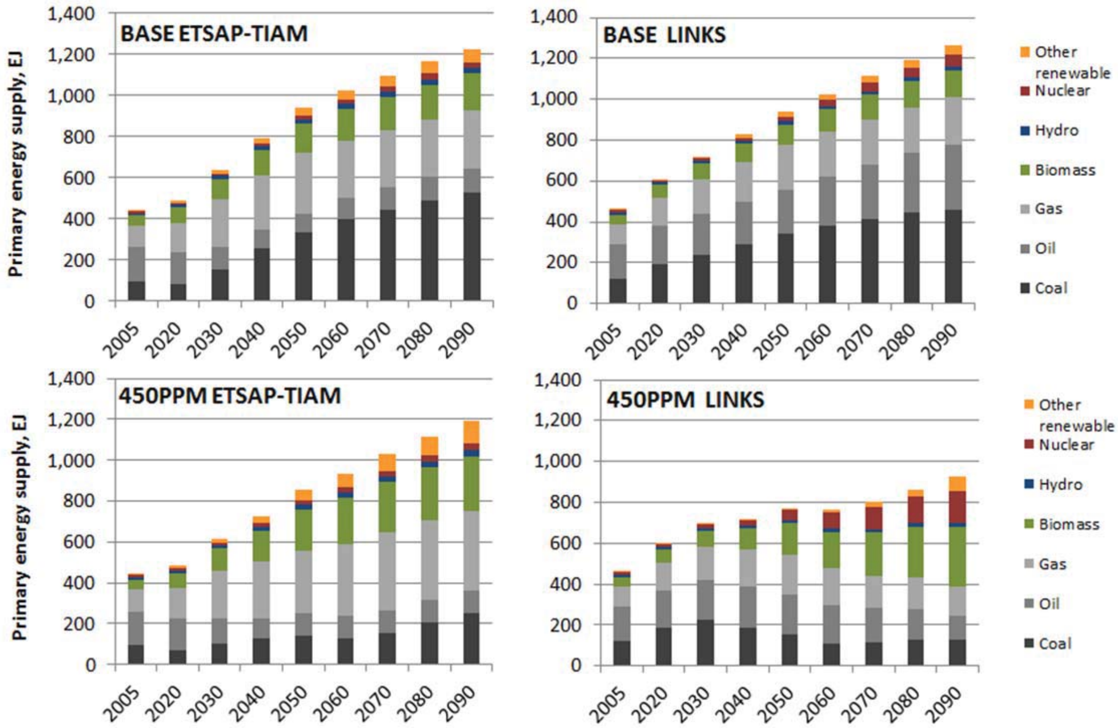

Figure 13: Global primary energy supply in ETSAP-TIAM and GCAM a reference scenario (BASE) and a 450 PPM limit scenario, EJ

The electricity production, split by fuel, for *BASE* on a global and a West European level for both models are depicted in Figure 14. Globally GCAM has a higher electricity production from 2020 compared to ETSAP-TIAM with 36 % more electricity production in 2090. Since the primary energy supply is in the same range these results indicate that GCAM find electrification of the energy sector more profitable compared to ETSAP-TIAM. The electricity production is also higher for GCAM in West Europe, and in 2050 the electricity production is 35 % higher in GCAM compared to ETSAP-TIAM. In spite of this, ETSAP-TIAM has more electricity production from wind, from 2030, and biomass, from 2020, compared to GCAM.

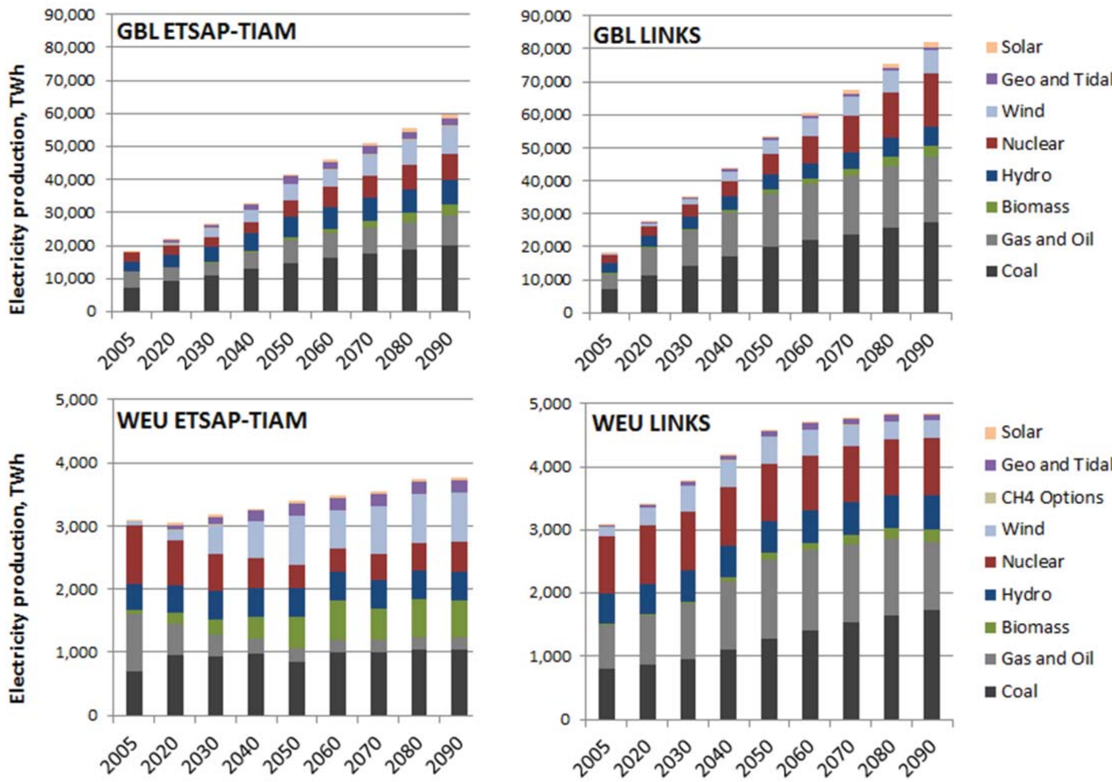

Figure 14: Electricity production in ETSAP-TIAM and GCAM, by fuel, on a global on a West European level, for a reference scenario (BASE), TWh

The electricity production, split by fuel, for *450PPM* on a global and a West European level for both models are depicted in Figure 15 and Figure 14. For both models the electicity production is increased with the climate constraint from 2050, and CCS is a part of the electricity production mix, from 2020 in GCAM and from 2040 in ETSAP-TIAM. Similarily the electricity production in *BASE*, the share of nuclear is larger on a global level in GCAM and the wind power production is higher in Western Europe in ETSAP-TIAM.

The CO_2 price in the 450 ppm scenario is compared in Figure 16. To make the prices comparable it is assumed that 1 USD in 2005 is worth 0.89 USD in 2000. The CO_2 price is in the same range towards 2070 before GCAM price significantly exceeds the ETSAP-TIAM price. In 2090, the CO_2 price, reflecting the cost of GHG reductions, is 117 % higher in GCAM compared to ETSAP-TIAM. There are several possible reasons for this difference, however a further comparison of the two models in regards of input data and model structure is required to get a better understanding of the cause.

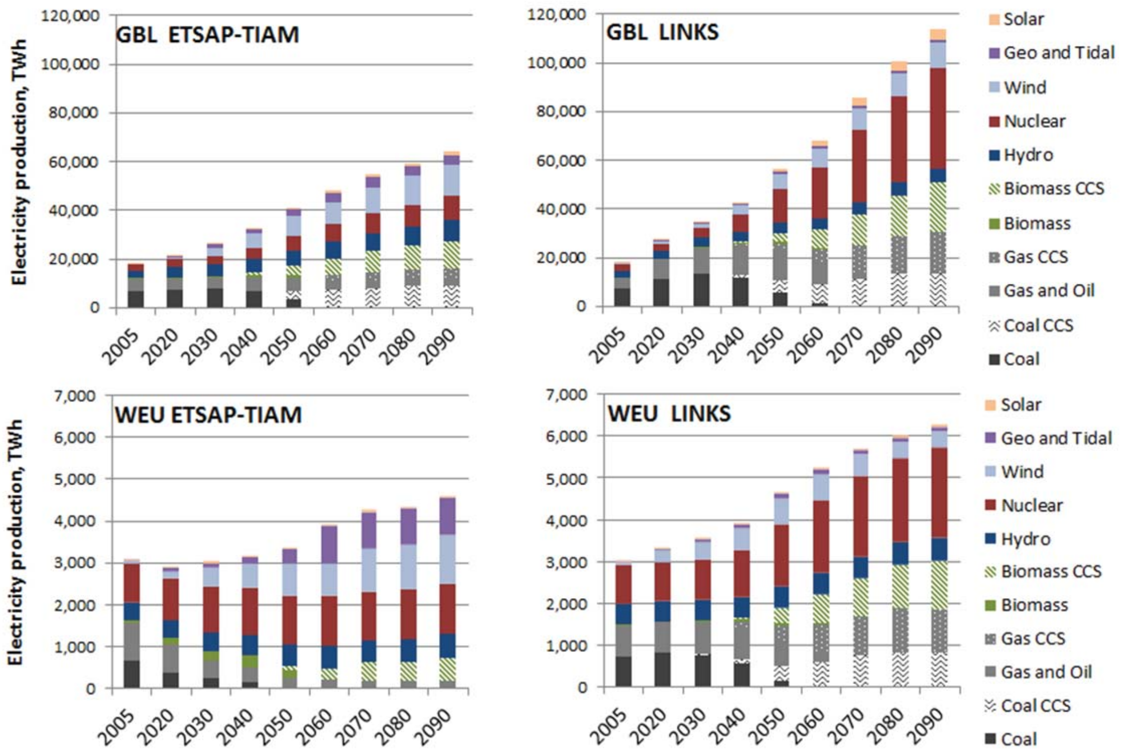

Figure 15: Electricity production in ETSAP-TIAM and GCAM, by fuel, on a global on a West European level, for a 450 ppm scenario, TWh

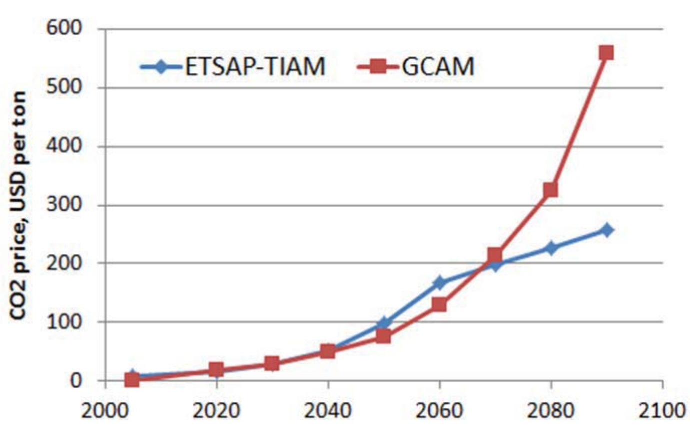

Figure 16: CO_2 price in a 450 ppm scenario for both models, USD (2000) per ton CO_2

6 Concluding remarks

The goal of this report is to give a brief overview of the characteristics of the ETSAP-TIAM model. Here, it is only presented the results of two climate scenarios, but the model is suitable to analyse a wide range of climate scenarios with various targets and burden sharing regimes. The ETSAP-TIAM model is primarily to study the long-term global energy system, and the results depend on the input data and the constraints added to the model. The model has a user friendly interface, and it is therefore easy to change the input and/or to add new linear constraints. This makes ETSAP-TIAM a suitable model to analyse different global energy issues in CenSES.

There are a set of global energy system models in the literature that is used to analyse constraints on future GHG emissions. Although the models address the same questions, the results presented can vary significantly due to different model structure and input. This is clearly illustrated in the *Result comparison* section of this report where a comparison of some model results from GCAM and ETSAP-TIAM are presented. Consequently, analysis of results needs to be in light of the properties of the model used.

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