CECILIA 2050

OPTIMAL EU CLIMATE POLICY

Choosing Efficient Combinations of Policy Instruments for Low-carbon development and Innovation to Achieve Europe's 2050 climate targets

Scenarios for a Low-Carbon Europe for 2050

Discussion of Results from the ETM-UCL Model, EXIOBASE Input-Output Model and the GINFORS Model

Funded by the European Union

This project has received funding from the European Union's Seventh Programme for Research, Technological Development and Demonstration under Grant Agreement no. 308680.

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Project coordination and editing provided by Ecologic Institute.

Manuscript completed in July 2014

This document is available on the Internet at: www.cecilia2050.eu.

Document title	Sectoral Scenarios for a Low-Carbon Europe for 2050
Work Package	WP3: Development of scenarios to 2030 and 2050
Document Type	Deliverable 3.4
Date	29 July 2014
Document Status	Final
Please Cite As	Drummond, Paul. 2014. Scenarios for a Low-Carbon Europe for 2050: Discussion of Results from the ETM--UCL Model, EXIOBASE Input--Output Model and the GINFORS Model. CECILIA2050 WP3 Deliverable 3.4. London: University College London (UCL).

ACKNOWLEDGEMENT & DISCLAIMER

The research leading to these results has received funding from the European Union FP7 ENV.2012.6.1-4: Exploiting the full potential of economic instruments to achieve the EU's key greenhouse gas emissions reductions targets for 2030 and 2050 under the grant agreement n° 308680.

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LIST OF ABBREVIATIONS

CCS	Carbon Capture and Storage
EU ETS	European Union Emissions Trading System
GWh	Gigawatt-Hour
HGV	Heavy Goods Vehicle
KWh	Kilawatt-Hour
LGV	Light Goods Vehicles
LNG	Liquid Natural Gas
LULUCF	Land Use, Land Use Change and Forestry
RCP	Representitive Concentration Pathway
SNA	System of National Accounts
UNFCCC	United Nations Framework Convention on Climate Change
WIOD	World Input-Output Database

Executive summary

The results of the aligned 'Decarbonisation' scenarios applied to the ETM-UCL, GINFORS and EXIOBASE IO Models indicate the difficulties an 80% reduction in CO_2 emissions by 2050 below 1990 levels in the European energy system. Indeed, scenarios applied to the latter two models do not achieve it. Broad sectoral developments in the Decarbonisation scenarios are:

- **Power Sector** – All scenarios experience an increase in electricity generation, both to satisfy increasing demand from existing electricity-using processes and to meet additional demand from increasing electrification in certain end-use sectors, particularly transport and buildings. Despite this, the power sector accounts for the largest (proportional and absolute) abatement across the economy in the scenarios applied to all three models, with CO_2 intensity decreasing to 31gCO_2/KWh in the EXIOBASE IO Model's Techno-Scenario by 2050, 25gCO_2/KWh in the GINFORS Global Cooperation scenario and to negative at -190gCO_2/KWh in the ETM-UCL Policy Success scenario. Although, how these reductions are achieved differs substantially with extremely varied levels of renewables and fossil fuels combusted with Carbon Capture and Storage (CCS)**.** The Policy Success scenario achieves negative emissions in the power sector by combusting biomass equipped with CCS, without which this scenario is also unable to achieve an 80% reduction in CO2 by 2050, from 1990 levels.
- **Industry Sector –** This is the most difficult major economic sector to decarbonise across all three Decarbonisation scenarios and models, for three reasons. The first is that demand for industrial products increases with projected GDP growth (and other drivers), increasing energy consumption and consequential emissions. The second is that energy efficiency measures for key industrial sub-sectors, such as iron, steel and cement, are relatively limited. Thirdly, price elasticities for energy carrier substitution are tight; meaning a significant shift to low-carbon fuel is difficult, particularly if a large proportion of renewable resource potential is directed to other sectors. Only the Policy Success scenario in the ETM-UCL and Global Cooperation in GINFORS achieves CO_2 reductions by 2050 over 2010 levels in the industry sector. The former achieves this primarily through the application of CCS to industrial processes, whilst the latter achieves reductions by encouraging material efficiency in downstream sectors, thereby reducing demand for industrial products and associated energy consumption and emissions production.
- **Transport Sector** – The road transport sector experiences a dramatic transformation in all Decarbonisation scenarios, but particularly in the Techno-Scenario and Global Cooperation scenarios. Significant electrification occurs in each, reaching 95% of all passenger cars in the former, and 80% of all land transport (including rail) in the latter. However, little action is taken in either on marine or aviation modes due to a lack of technical and fuel substitution potential. However, projections in future demand increase significantly more in the Techno-Scenario, particularly for aviation, as an exogenous assumption. In the Global Cooperation scenario, principally as a result of endogenous

dynamics in the GINFORS model, demand increases to a far lesser degree, and therefore energy consumption and CO_2 production, is much less significant. An increase in material efficiency across the economy also contributes to reducing transport demand in this scenario.

- **Buildings Sector** – Whilst both the Policy Success and Global Cooperation scenarios produce reductions in CO_2 by 2050 against 2010 in this sector, the EXIOBASE IO Model projects an increase against 2000. Three main components contribute to this. The first is attribution and accounting. Whilst the ETM-UCL accounts direct emissions from all buildings under this category, the EXIOBASE IO Model and GINFORS do not. The former reports direct emissions from non-residential properties under this category (with residential property direct emissions accounted for as 'direct' emissions), whilst the latter reports residential emissions only (with non-residential building direct emissions accounted for under the 'industrial' and 'agriculture' sectors). GINFORS also reports emissions from private vehicles under this category. The second is the extent to which efficiency measures are introduced. Building and product efficiency improvements are exogenously projected in the Techno-Scenario, whilst in Global Cooperation a policy measure is introduced to induce significant improvements building envelope efficiency. In the ETM-UCL only product efficiency improvements are taken up, with building envelope measures not considered. The third is differences in energy mix developments, particularly the extent of electrification. Relatively minor electrification of space heating occurs in Policy Success and Global Cooperation, although the extensive electrification of road transport influences produces substantial savings, and likely to be the key driver behind the abatement produced in this sector in that scenario. Very substantial electrification of space and water heating is assumed in the Techno-Scenario, however much of the CO_2 savings this achieves is reported as 'direct' emissions. If these are included in the calculations, a slight reduction in building CO_2 emissions is likely achieved by 2050 from the 2000 base year.
- **Agriculture Sector** – CO_2 emissions from the agriculture sector are minor compared to the rest of the energy system, with non-CO_2 emissions a much more prominent issue. However, such emissions are outside the scope of these models and scenarios. Whilst no measures are characterised and introduced to abate agricultural CO_2 in Policy Success or the Techno-Scenario, the Global Cooperation scenario applied to GINFORS achieves abatement via a carbon pricing mechanism and instruments applied to buildings and transport, for which those involved in agriculture are reported here.

A common lesson is the confirmation that projecting firm developments in different possible futures is an extremely difficult task, made more uncertain by the possibility of the unpredictable emergence of disruptive events or technologies. However, some broad conclusions may be drawn. The reduction of CO_2 emissions in Europe by 2050 to remain on a trajectory compatible with RCP2.6, or a 2°C pathway, is extremely difficult to achieve. Either complete decarbonisation (or the production of negative emissions) in a large CO_2-emitting sector is required (with the largest and most technical potential found in the power sector), with at least moderate abatement achieved in average across all other sectors, or all sectors of the economy must achieve substantial proportional reductions from existing levels, to a greater or lesser extent. This can only be achieved by a reduction in demand for the activities in a sector, energy efficiency measures or a low-carbon fuel mix – or combination of each. Such transformations must be driven by a policy mix able to withstand and adapt to future uncertainties. Carbon pricing alone, whilst important, is unlikely to deliver the level of decarbonisation required, even at high prices, due to the structure of the economy and uncertainties surrounding factors such as basic fossil fuel prices. It is likely that the CO_2 emissions produced by the EU will continue to decrease over time as a proportion of global emissions, regardless of whether the EU strives for decarbonisation. This highlights the importance of encouraging global efforts. However, regardless of international efforts, the total cost to the European economy of perusing the required level of CO_2 abatement by 2050 is likely to be small, and potentially positive if domestic supply chains are utilised and economic activity is stimulated.

1 Introduction

The European Union, along with other parties to the United Nations Framework Convention on Climate Change (UNFCCC) has stated its aspiration to limit any increase in average global surface temperatures to no more than 2°C, approximately equivalent to Representative Concentration Pathway (RCP) 2.6. Although such pathways relate to cumulative emissions, a trajectory that produces an 80% reduction in GHGs by 2050 relative to 1990s may be considered an appropriate milestone[1].

As part of the CECILIA2050 project, three modelling approaches were employed to determine the pathways and implications of pursuing such ambitious emission reductions in the European Union, with two of the approaches linking developments in the EU with the rest of the world. The objective of this report is to draw together the key results from each of these broadly co-ordinated modelling exercises to compare and discuss key similarities and differences, and draw out implications for the development of a low-carbon economy in the EU out to 2050.

Section 2 provides a description of the three modelling approaches, whilst Section 3 details the scenarios produced for assessment under each approach. Section 4 then compares the approaches and scenarios, to highlight key similarities and differences. Section 5 presents the key results of the key scenario, beginning with high-level results surrounding CO_2 emissions, energy consumption and carbon prices and economic impacts, before describing and comparing sector-level results and implications. Section 6 concludes.

A full description of each modelling approach, scenario design and consequential results is presented in further detail in three dedicated reports, as follows, with full references provided in the reference list. Each publication may also be found on the CECILIA2050 project website[2]:

- **European TIMES Model –** Solano & Drummond (2014)
- **EXIOBASE Input-Output Model** – De Koning *et al* (2014)
- **GINFORS –** Meyer *et al* (2014)

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[1] Representative Concentration Pathways (RCPs) are four greenhouse gas concentration trajectories adopted by the IPCC for its fifth Assessment Report (AR5). They are: RCP2.6, RCP4.5, RCP6.0, and RCP8.5, named after a possible range of radiative forcing values in the year 2100. Each RCP can be linked to a global GHG emission trajectory. RCP2.6, which links approximately to an 80% GHG reduction in 2050 relative to 1990, is unlikely to exceed a 2°C warming by the end of the 21st century, against pre-industrial levels. RCP4.5 is more likely than not to exceed 2°C, whilst RCP6.0 and RCP8.5 are highly likely to exceed it (Symon, 2013).

[2] www.cecilia2050.eu/publications

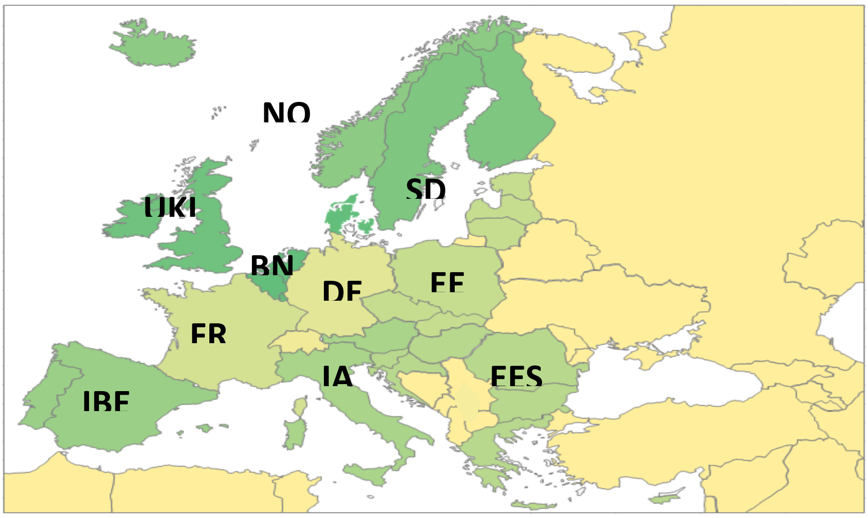
2 Modelling Approaches

2.1.1 European TIMES Model (ETM-UCL)

The European TIMES Model (ETM-UCL)[3] is a dynamic partial equilibrium energy system model with an inter-temporal objective function to minimise total discounted system costs, based on the TIMES model generator. It is a technology-rich, bottom-up model with perfect foresight and covers energy flows across supply-side and demand-side sectors. The model comprises a total of thirty-one countries (EU28 plus Norway, Iceland and Switzerland), grouped into eleven 'regions', as illustrated in Figure 1 and described in Table 1 along with a 'global' region.

Each region is modelled with supply, power generation and demand side sectors, and are linked through trade in crude oil, hard coal, pipeline gas, LNG, petroleum products, biomass and electricity. The 'global' region however is not characterised in the same way as the European regions, and may be considered simply as a 'basket of resources' from which other regions may import above products (except electricity)[4]. The model is calibrated to its base year of 2010, with energy service demand projected into the future using the key drivers of GDP, population, household numbers and sectoral output (linked to GDP), for each region. Elasticity of demand is not considered in this study to enable more direct comparison between scenarios and to remove concerns of overly ambitious demand responses. Measures and technologies to improve building envelope efficiency (such as insulation) are also not available. A standard annual discount rate of 3.5% is applied to all future monetary values, which are measured in US$2010[5].

Figure 1 - ETM-UCL Regions Map



[3] Refer to the following for more information Solano, B. and Pye, S. (2014) *European TIMES Model (ETM-UCL)*, Available at: www.ucl.ac.uk/energy-models/models/etm-ucl

[4] Exports to the global region are not enabled in the model, due to the import dependence of the EU.

[5] The ETM-UCL is calibrated to USD, for practical reasons. The average USD/Euro exchange rate over the period these results were produced was €0.73 per USD

Table 1 - ETM-UCL Regions Disaggregation

Region Code	Region Name	Countries Within Region
BNL	Benelux	Belgium, Netherlands and Luxembourg
SWZ	Switzerland	Switzerland
DEU	Germany	Germany
FRA	France	France
IAM	Italy, Austria, Malta	Italy, Austria and Malta
IBE	Iberia	Spain and Portugal
NOI	Norway and Iceland	Norway and Iceland
SDF	Sweden, Denmark, Finland	Sweden, Denmark and Finland
UKI	United Kingdom and Ireland	UK and Ireland
EEN	Eastern Europe – North	Estonia, Lithuania, Latvia, Czech Republic, Slovakia and Poland
EES	Eastern Europe - South	Slovenia, Hungary, Romania, Bulgaria, Greece, Cyprus and Croatia

2.1.2 EXIOBASE Input-Output Model

This global Input-Output (IO) model framework distinguishes forty-four trade-linked countries/regions with around 129 sectors per country (in practice not every sector exists in each country), drawing data from trade-linked supply-and-use tables in EXIOBASE – one of the most comprehensive IO datasets available - for the base year of 2000. EXIOBASE includes an environmental extension, which includes CO_2, CH_4 and N_2O emissions. However, only results regarding CO_2 emissions will be discussed in this report. This means that all sectors in each country/region are consistently linked to the supplying and using sectors in all other countries/regions. The forty-four regions in the model are for this study aggregated into four regions – the EU27, other High Income Countries (HI), Newly Developing Counties (largely BRICS), and the Rest of the World (RoW), including most African and Middle East Countries. Development of the energy system out to 2050 is based fully on exogenously defined adjustments. Therefore, endogenous dynamic relations are fully excluded, and no mathematical optimisation against an objective function in 2050 is involved. The overall goals of emission reduction are forced on the model, in a stepwise scenario procedure. This procedure is further elaborated in the description of the scenarios, discussed in the following section. Scenarios retain constant prices in Euro (for 2000), for all products[6].

2.1.3 GINFORS Model

GINFORS is a global economic-environmental model, and has a deep country (38 countries and 'Rest of the World) and sectoral structure (35 sectors), depicting international as well as the inter-sectoral interdependences with flexible price dependent structures for 59 product groups. Labour demand and wage determination are sectorally disaggregated. Gross fixed capital formation is estimated for each sector and drives final investment goods demand. Consumption demand for the 59 product groups is driven by disposable income of private households, and relative prices. Public consumption for 59 product groups is driven by

[6] More information regarding the model and data, including the open-source scenario tool, may be found here: http://cml.leiden.edu/research/industrialecology/researchprojects/projects/cecilia/cecilia.html

disposable income of government. The model contains a complete SNA (System of National Accounts) framework, including taxes on goods and income, and social security payments. This allows for endogenous calculation of the disposable income for households and government. Sector prices depend on unit costs, and the model calculates intermediate prices and prices for final use for producers (basic prices) and purchasers (including taxes), for all product groups.

Gross energy use for twenty energy carriers in physical units is calculated for heating and mobility purposes, with shares determined by relative prices. Electricity, heating and mobility demand drives gross production across all sectors, with energy intensity also price dependent. The same structure is given for private households. Here the activity variable is real disposable income. Physical energy demand drives the energy demand in monetary terms at constant prices. The structure of the electricity mix, unless fixed by an exogenous policy variable, is also determined by relative costs.

The central hypothesis is that agents make their decisions under conditions of bounded rationality on imperfect markets, which excludes rational expectations. Suppliers set their prices in relation to unit costs. The model clears the markets for price dependent demand. Insofar the model solution is driven by supply and demand elements. An exemption is made with the labour markets, where wages are determined by a Phillips-Curve approach and labour demand depends on sectoral production and wage development, allowing for a difference between labour supply and demand. The price elasticities on the different markets are all estimated econometrically.

3 Scenario Designs

3.1 ETM-UCL Scenarios

Common Assumptions

This sub-section presents assumptions common to all scenarios applied to the ETM-UCL. To produce consistency between modelling approaches, some of these assumptions are also applied to the EXIOBASE Input-Output Model and GINFORS, as far as possible. Such instances will be discussed under the relevant sections.

Table 2 - Key Common Assumptions (Source: IEA, 2012)

Driver	2015	2020	2030	2040	2050
Population	506m	511m	516m	515m	512m
Households	217m	-	238m	-	252m
GDP Growth	2% (2009-20)		1.8% (2020-30)	1.7% (2030-50)	

Table 2 presents common assumptions in GDP growth, absolute population numbers and number of households, as used by the IEA's (2012) *Energy Technology Perspectives 2012*, that form the drivers for various aspects of direct and indirect energy demand. It is also assumed that two of the three ’20-20-20’ targets contained in the EU’s 2020 Climate and Energy Package achieved – specifically 20% GHG reduction between 1990 and 2020 (implemented by contribution of CO_2 only), and 20% renewables in total gross final energy consumption. The energy efficiency target is not imposed, as it is widely considered unlikely to be achieved (Solano & Drummond, 2014). The 10% target for renewables in road transport by 2020 is also imposed. Constraints are also commonly applied on the potential for growth in nuclear power capacity. It is assumed that new nuclear capacity may only be introduced to replace existing capacity, with total capacity unable to grow beyond 2010 levels. This is based on existing capacities within Member States, expected shutdown dates and judgements on the political and legal feasibility of introducing new capacity across Member States (Solano & Drummond, 2014).

‘Reference’ Scenario – designed to provide a basis against which other scenarios may be assessed. As such, it is assumed that post-2020 efforts to curb emissions are abandoned at both a global and EU-level, producing a ‘business as usual’ emissions pathway largely consistent with an expected global average surface temperature increase of 6°C. As such, the ETM-UCL (acting in the role of a EU central planner with perfect foresight), will simply construct an energy system to meet demand at the cheapest total discounted cost (although constraints such as existing nuclear closure plans remain post-2020, where relevant). Fossil fuel price projections in each scenario described here are exogenous, and are also taken from the IEA (2012), which present prices for their global 2DS, 4DS and 6DS scenarios, as presented below in Table 3.

Table 3 - IEA Fossil Fuel Price Projections

Fossil Fuel	IEA Scenario	2010	2020	2025	2030	2035	2040	2045	2050
Crude Oil (2010 US$/bbl)	**2DS**	78	97	97	97	97	92	89	87
	4DS	78	109	114	117	120	119	119	118
	6DS	78	118	127	134	140	143	146	149
Steam Coal (2010 US$/tonne)	**2DS**	99	93	83	74	68	64	62	60
	4DS	99	106	108	109	110	109	109	109
	6DS	99	109	113	116	118	121	126	126
Gas (Europe) (2010 US$/Mbtu)	**2DS**	7	10	10	10	9	9	8	8
	4DS	7	10	11	12	12	12	12	12
	6DS	7	11	12	13	13	13	14	14

The different prices presented reflect the impact of global ambition of emission mitigation over time. If emission mitigation is no longer an ambition (at global or EU-level), demand for fossil fuels is likely to remain high and increase, an expected result of which would be higher prices for these products than in scenarios in which demand for these resources is constrained. If mitigation remains an ambition and is strengthened over time, the opposite would be expected.

‘Fragmented Policy’ Scenario – assumes that global and EU-level mitigation ambition is maintained and increased, with significant mitigation achieved by 2050 – but not to the level required to maintain a global 2°C (RCP2.6) trajectory. Instead, a path approximate to a long-term result of 4°C temperature change is achieved. For the EU this equates to an approximate GHG (and CO_2) reduction of at least 60% by 2050, from 1990 levels. In order to implement this constraint in the model an absolute cap equivalent to this reduction is applied to CO_2 emissions from the EU’s energy system for 2050. It is also assumed that the ‘firm’ emission and renewables targets in the UK and Germany will also be achieved in this scenario[7]. Fossil fuel prices are imposed to reflect the 4DS scenario prices presented in Table 3.

‘Policy Success’ Scenario – assumes that global and EU-level ambition is maintained and increased significantly from existing levels, with GHG (CO_2) emission mitigation in 2050 in the EU achieving at least an 80% reduction from 1990 levels – a common proxy for pursuing a 2°C (RCP2.6) pathway. The implementation of this constraint is via the same mechanism described above. The UK and German targets also remain. Fossil fuel prices are imposed to reflect the 2DS scenario prices presented in Table 3.

Four sensitivities on the ‘Policy Success’ scenarios were also developed, to reflect the significant uncertainty present in determining the most appropriate path for low-carbon development of the energy system.

EU ‘Goes it Alone’ - The first sensitivity opposes the assumption taken in the three ‘core’ scenarios that both global and EU-level ambition change in tandem by introducing the IEA’s 6DS fossil fuel import prices used in the Reference scenario - reflective of the EU ‘going it alone’ on mitigation.

No New Nuclear - The decision to construct (or indeed, retain operation of existing) nuclear power installations is as much (if not more) a political decision as an economic one. This sensitivity explores developments in a situation in which such factors act in a manner to prevent the construction of any new nuclear installations in the EU.

Delayed CCS - The ETM-UCL characterises several CCS techniques applicable to different power sector technologies[8], most of which are available for ‘selection’ from 2020 (although high initial costs often prohibits this). In this sensitivity the availability (and cost curve) of these technologies is delayed by ten years, to reflect uncertainty surrounding the rate of technological development.

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[7] The UK has a legislative obligation to reduce GHG emissions by 80% in 2050 (from 1990 levels), under the 2008 Climate Change Act. This is implemented in the model by requiring a minimum 80% reduction in CO_2 in the UK & Ireland region. Germany’s ‘Energy Concept’ also envisages a minimum 80% reduction in GHGs between 1990 and 2050, alongside an 80% renewable electricity target to be achieved as part of a wider ambition of 60% renewables across all energy consumption by 2050 (Buchan, 2012). These GHG targets were translated to CO_2 only for the purposes of this study.

[8] CCS technologies for application to industrial processes are also characterised, but are not altered in this sensitivity.

No Biomass CCS - This scenario sensitivity explores the implications for decarbonisation of the European energy system if this technology does not become available by 2050.

3.2 EXIOBASE Input-Output Scenarios

'Business-as-Usual' (BAU) – This scenario assumes projected GDP and population growth presented in Table 2 (with values for non-EU countries taken from the same source), along with the continued trend in energy efficiency observed between 1990 and 2000, with no additional climate policy ('additional' insofar as the impact of existing climate policy is reflected in continued efficiency improvements). Energy efficiency improvements are extrapolated based on country specific developments of the 30 most energy consuming sectors, as derived from the WIOD database (Timmer, 2012). These trends are not substantial in developed countries for some sectors, but and are much higher for some sectors in high-growth developing countries (e.g. in agriculture, an improvement of around 1% is projected in developed countries, whilst a 36% improvement is projected in high-growth developing countries). In this scenario there is no shift in developed countries towards the secondary and tertiary sectors, as occurred in the EU and other High Income countries (partly due to shifting abroad of material production from developed to emerging countries). At a global level it is assumed that such a shift is not possible; the primary products needed for an expanding economy have to be produced somewhere. Visions of re-industrialising Europe which entails "bringing back" primary industry like mining and manufacturing to Europe, are also not included in this and other scenarios as the structure of the global economy is not actively adapted in this sense.

'Techno-Scenario' – This scenario builds on the BAU scenario, but introduces specific emission abatement technologies, particularly in the demand sector, and shifts energy consumption in key final demand sectors and processes away from fossil fuels and towards electricity, including a substantial shift to electricity in final energy consumption, a considerable proportion of which is generated by a combination renewables and fossil fuel plants equipped with carbon capture and storage (CCS). Such renewables include a combination of principally wind, solar and biomass of different proportions. Specific definitions of these technologies and consumption shifts will be described and discussed in the relevant sections below.

'2-Degree World' (2DW) – This scenario further builds upon the above scenario via two broad changes. The first introduces a substantial shift from consumption of emission intensive goods and services, such as air travel, to low emission-intensity goods and services, such as music and theatre performances. The second reduces absolute levels of production and consumption, implying a reduction in economic growth.

3.3 GINFORS Scenarios

Common Assumptions

The three GINFORS scenarios also apply the population projections presented in Table 2, along with values for global regions also soured from the IEA (2012), whilst GDP is calculated endogenously (household growth projections are not applied). The 2020 target for renewables, as described above, is applied as an exogenous constraint in all scenarios. As CO_2 emissions are an endogenous variable, they cannot be explicitly constrained, and thus this target is not explicitly applied (although it is achieved, as will be discussed).

'Baseline' – It is assumed that policies currently active remain until 2020, with the EU ETS continuing to 2050, producing a real carbon price rising linearly to €47 in 2050 maintained at the average price produced by the EU ETS between 2005 and 2009. The share of renewables in gross final consumption is also assumed to increase to levels envisaged by the EU's 2013 Reference Scenario (European Commission, 2013b). Tax regimes remain constant. The presence of nuclear is also an exogenous assumption in all scenarios, but to different levels, as discussed in the relevant section below (reflecting the political rather than economic nature of its use). No policies exist in non-EU regions. As with the ETM-UCL 'Reference' scenario, 6DS prices as listed in Table 3 are applied.

'Middle of the Road' – This scenario aims to achieve an 80% reduction in CO_2 by 2050 in the EU (from 1990 levels), with non-EU countries also increasing to moderate abatement ambition. In the EU, the EU ETS remains as the central instrument, producing a linearly rising carbon price reaching €230 in real terms. A parallel cap-and-trade instrument is also applied to all remaining industrial and commercial activities (including agriculture), with an imposed price rising linearly to €460 by 2050, in real terms. Other policies, such as renewable purchase obligations for electricity suppliers, the promotion of electricity and renewables in transport, and policies promoting energy efficiency in buildings are introduced. All sectors of the economy are subject to policy measures, for which the specifics will be discussed in the relevant sections. In addition, an informational instrument is introduced that is assumed to produce a reduction of material inputs by 20% in all firms by 2050[9]. For non-EU countries, renewable electricity purchase obligations are introduced (with reduced ambition compared to the EU), along with the promotion of electricity and renewables in transport and the material input efficiency improvement. As with the ETM-UCL 'Fragmented Policy' scenario, 4DS prices as listed in Table 3 are applied.

'Global Cooperation' – This scenario aims to achieve significant reductions in CO_2 globally, to pursue a pathway 2°C. The same policy mix as above is applied for the EU, but with the policy mix applied globally. As with the ETM-UCL 'Policy Success' scenario, 4DS prices as listed in Table 3 are applied.

[9] See Meyer *et al* (2014) for more details.

4 Key Similarities and Differences between Modelling Approaches and Scenario Designs

It is clear that similarities, but also significant differences exist between each of the three modelling approaches employed. As an ensemble, these three approaches have added value. All models characterise different supply and end use sectors and technologies, the links between them and underlying costs. All consider the EU as a defined geographical entity (aggregated from Member State level or sub-regions), and hold CO_2 emissions as a product of the processes and activities contained therein. However, several significant and fundamental differences exist. Whilst the below is not exhaustive, it lists and describes key examples of such differences:

- **Objective** – Each model has a different objective purpose. The ETM-UCL projects the most cost-effective development pathway of the European energy system based on underlying data and within given constraints, whilst the EXIOBASE IO Model calculates the systemic impact of exogenous changes to highly detailed, globally integrated economic sectors, processes and products, along with consequential regional emissions. The GINFORS model also assesses the global impacts of exogenous inputs (e.g. policy packages) to economic sectors, processes and products, but with a much greater focus on macro-economic impacts and feedbacks (including labour demand and wage determination, for example).
- **Structure & Dynamics** – The structure and dynamics of each model relate to its purpose. Final product, process and energy service demand in each model are based on drivers (such as GDP and population growth), however how these drivers interact to produce the final outcome varies. Household income and government revenue drive consumption in GINFORS, along with basic prices and the imposed tax regime (along with the effect of other instruments imposed that alter absolute and relative prices). GDP is calculated endogenously in a consistent framework, and is the aggregate of sectoral value added. Individual agents (at the sectoral level) also take individual 'decisions', whilst the ETM-UCL assumes the role of a 'central planner'. The ETM-UCL considers basic prices in its system-level cost-optimisation (along with population, GDP growth and building floor space, for example), but does not directly consider the role of household and government income in its demand projections. The EXIOBASE IO Model considers GDP and population growth, and adds technological and behavioural changes exogenously, with no dynamic relations considered endogenously. Also, only GINFORS considers price elasticity of supply and demand in such calculations. Whilst GINFORS and the EXIOBASE IO Model characterise global and regional supply chains in significant detail, the ETM-UCL does not consider such relationships. These differences link with differences in;
- **Scope, Disaggregation and Definitions** – Whilst the EXIOBASE IO Model and GINFORS consider global interactions and impacts, the ETM-UCL assesses impacts in the EU only. This exclusion means that whilst the analysis can be effectively contained to the area of interest, assessment of the impact of the scenarios modelled on global CO_2 emissions,

amongst other things, cannot be assessed. This provides some benefit, in that any change in demand for industrial products, for example, must be met by domestic production, from which CO_2 emissions are also reported and constrained. In the IO and GINFORS models, 'carbon leakage' may occur. However, carbon leakage may still occur in the 'upstream' sector in the ETM-UCL, as energy products may be sourced from the basic 'global' region ('basket of resources'), producing zero territorial CO_2 emissions in the EU. Differences in disaggregation and definitions of different sectors of the economy are also present. For example, whilst the ETM-UCL disaggregates the 'Industry' sector into seven sub-sectors, GINFORS breaks this down into considerably higher detail, as fits with its objective purposes. The EXOBASE IO model adds further technological detail, including at sub-sectoral level, such as car drive systems and steel production technologies.

- **Data Sources & Projections** – Data on costs of technology, (and development over time), the availability of certain technologies, their physical, economic and other characteristics, and build rate constraints, to list a limited number of examples, will also vary widely between models and against projections in recent studies based on on-going developments. An example of this would be the continued rapid reduction in the cost of solar PV cells, which continually decrease at a higher rate than projected.

Whilst the conceptual design of each of the three scenarios are aligned (a 'business as usual' scenario, a globally co-ordinated '2-Degrees' scenario and a 'middle-ground' scenario), the fundamental differences between modelling approaches means that the implementation of scenarios must be necessarily different. Whilst efforts have been made to align scenario assumptions between models as far possible, only the population values listed in Table 2 are present across all three models and scenarios. Fuel prices are aligned between the scenarios in GINFORS and ETM-UCL, as are the EU's 2020 renewables and emissions targets (although in GINFORS, only the first is explicitly imposed). GDP values in Table 2 are aligned between ETM-UCL and the EXIOBASE IO Model, and are endogenously calculated in GINFORS. A key difference between the GINFORS and ETM-UCL, and the EXIOBASE IO Model scenarios is the base year. Whilst the former two begin their projection in 2010, from observed data for that year, the latter begins in 2000 (due to the availability of detailed, sector-level data). Developments in the energy system in the intervening decade are reflected in the EXIOBASE IO Model implicitly, in projected long-term developments. In addition, as the assessment horizon extends to 2050, the highly assumption-based nature of the projections mean this difference in base year is unlikely to produce significant differences in the presence of other model and scenario differences.

The combination of fundamental differences in model objective, structure, scope and dynamics, with necessary differences in scenario design and implementation means that the outputs from each model are likely to be significantly different in a number of ways. Such an outcome is to be expected, and serves to highlight the difficulty and complexity in projecting future developments. To allow discussion of the key results of each model above in context of each other, some general conventions will be observed throughout this report (unless otherwise stated). The baseline scenarios for all three models will be grouped collectively as the 'Reference' scenarios ('Reference' from ETM-UCL, 'BAU' in the EXIOBASE IO Model, and 'Baseline' in GINFORS), whilst the main scenarios presented in each of the three models will be termed the 'Decarbonisation' scenarios ('Policy Success' from ETM-UCL, 'Techno-Scenario'[10] in the EXIOBASE IO Model, and 'Global Cooperation' in GINFORS). The remainder of the report will focus on developments in these two groupings, particularly the latter, whilst the results of other scenarios developed under each study will be discussed when relevant. Similarly, the focus of all results will be the EU level. Member State level and global results, where available, will again be discussed when relevant. As discussed, the focus of each of the three studies is CO_2 emissions. As such, trends in CO_2 emissions will be the focus of this report.

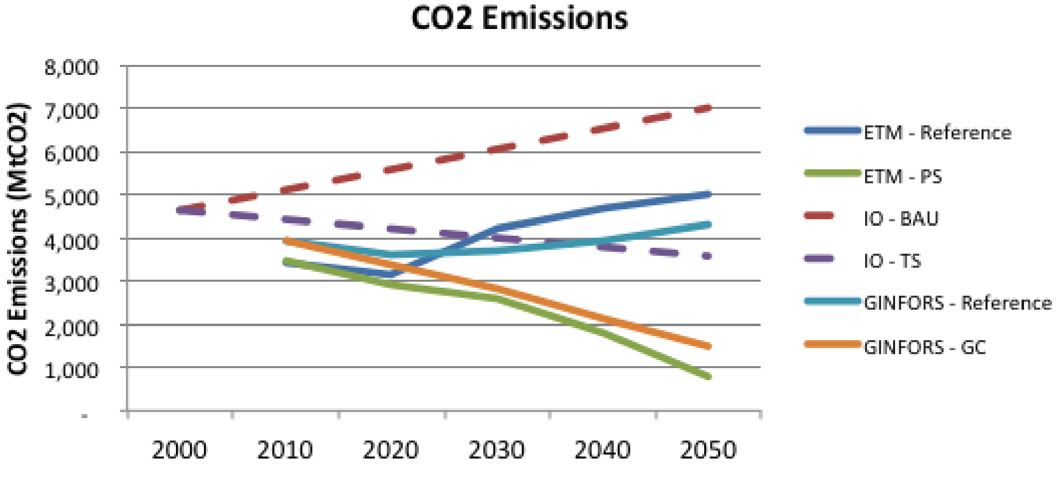
5 Comparison and Discussion of Key Results

This section compares and discusses the key results from the three modelling approaches. First, macro-level results such as CO_2 emissions, energy consumption, carbon prices and economic costs are discussed. Sectoral level results are then discussed.

CO_2 Emissions

Figure 2 illustrates differences in CO_2 emissions between the Reference and Decarbonisation scenarios produced by the three models. Developments over time are presented for the ETM-UCL and GINFORS results, whilst only 2050 emissions are presented for the EXIOBASE IO Model results, with linear interpolation.

Figure 2 - Total EU CO_2 Emissions



CO_2 emissions in Reference scenarios from all three models, as expected, increase from their respective base years – although at different rates, and with significantly different absolute emissions in 2050. Although the Reference scenarios in ETM-UCL and GINFORS are not significantly different in 2050, with CO_2 emissions of 5GtCO_2 and 4.3tCO_2, respectively, the

[10] This scenario is chosen, rather than 2DS, as the actions undertaken in this scenario are approximately in line with the 'Decarbonisation' scenarios, whilst actions undertaken in the 2DS scenario as a matter of policy are considered infeasible, as will be discussed.

growth rate from their 2010 base years varies substantially (45% and 9%, respectively). However, emissions in both decrease to 2020 to meet imposed 2020 targets, before increasing thereafter. Although the EXIOBASE IO Model produces much higher emissions of around 7GtCO_2 in 2050, the growth rate is relatively similar to the ETM-UCL at 52% from its 2000 base year. Whilst achieving the 2020 targets is likely to have reduced the overall growth of CO_2 emissions between 2010 and 2050 in the ETM-UCL and GINFORS Reference scenarios, the substantially reduced rate of CO_2 emission growth the GINFORS Baseline is likely due to the presence of a continued carbon price and continually rising share of renewables in Europe, along with other model dynamics leading to a slower growth in energy demand in the face of increasing fossil fuel prices.

Only the Decarbonisation scenario in the ETM-UCL achieves the target of a reduction in territorial CO_2 emissions of 80% from 1990 levels, reaching 0.8GtCO_2 by 2050 (with an 80% reduction value just below 0.9GtCO_2). The results of the Decarbonisation scenarios in both the EXIOBASE IO Model and GINFORS fail to reach the objective emissions target consistent with a 2°C (RCP2.6) pathway. 'Global Cooperation' reaches CO_2 emissions in the EU of around 70% below 1990 levels (1.5GtCO_2), although the Techno-Scenario scenario under the EXIOBASE IO Model achieves just a 20% reduction from 1990 emissions in the EU. At a global level, Global Cooperation reaches emissions of 16GtCO_2, whilst Techno-Scenario reaches 33.5GtCO_2. Whilst both are above the 12.4Gt limit required by 2050 to remain on the 2°C (RCP2.6) pathway, the results of Techno-Scenario are significantly higher, and much more consistent with the RCP 4.5 (along with the Middle of the Road scenario in GINFORS, which exhibits global emissions of 32.8GtCO_2 by 2050). Whilst the carbon pricing instruments introduced in the Global Cooperation scenario reach substantial real prices by 2050 compared with the baseline (illustrated in Figure 9 below), the reduced fossil fuel prices hamper their effectiveness. Other imposed instruments, such as the renewable electricity obligation discussed under the following section, are therefore much more important. However, the 2DW scenario in the EXIOBASE IO Model does manage to achieve global and European emissions in 2050 consistent with RCP2.6, however the very significant shifts in consumption from high to low carbon-intensive products and services, coupled with significantly reduced projections for GDP growth (approximately half those provided in Table 2 and applied in BAU and Techno-Scenario), in addition to the significant technological shifts produced under Techno-Scenario. Such developments render this scenario highly improbable.

These results suggest that under the EXIOBASE IO Modelling approach, and within the stated (still rather extreme) assumptions, sufficient abatement to remain on the RCP2.6 trajectory is not achievable by 2050. Although the required abatement is not achieved by GINFORS, the underachievement, whilst not negligible, is not significant. Although the ETM-UCL does reach the required emissions reductions by 2050 in the EU, calculations for non-EU emissions are not performed, thus removing the burden of achieving global effectiveness. However, as will also be discussed, the achievement of the required emissions target in the EU under the Policy Success scenario applied to the ETM-UCL is not achieved easily.

Figure 3, Figure 5 and Figure 4 present EU CO_2 emissions by sector, from the ETM-UCL, EXIOBASE IO Model and GINFORS models respectively, for the Reference and Decarbonisation scenarios.

Figure 3 - CO_2 Emissions Profile Development – ETM-UCL Scenarios

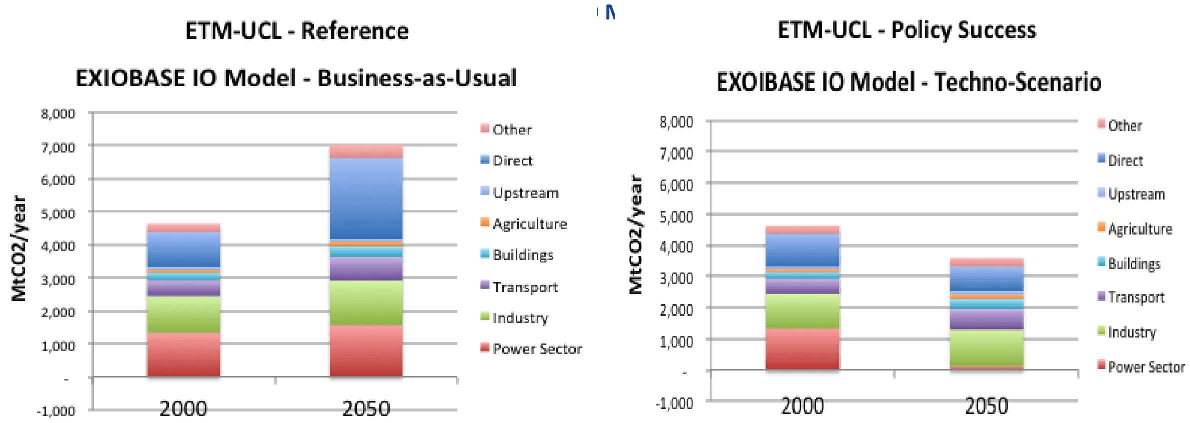
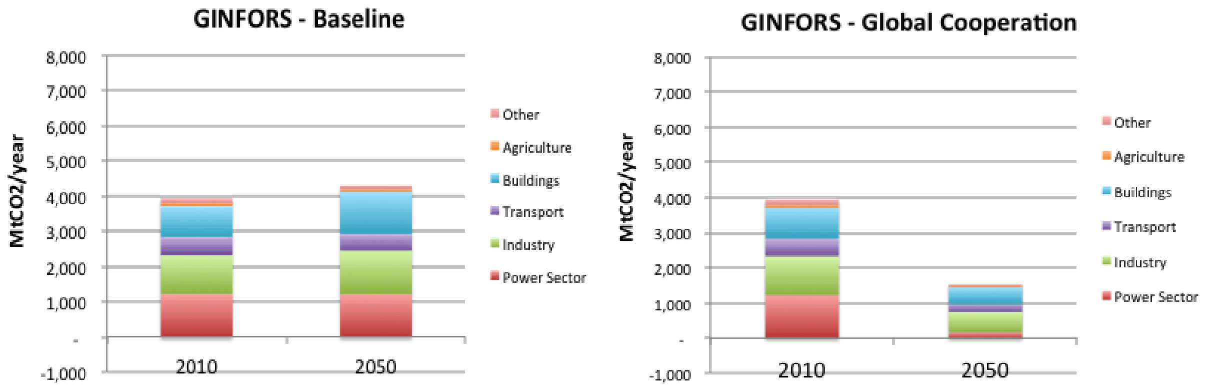


Figure 4 - CO_2 Emissions Profile Development – EXIOBASE IO Model Scenarios

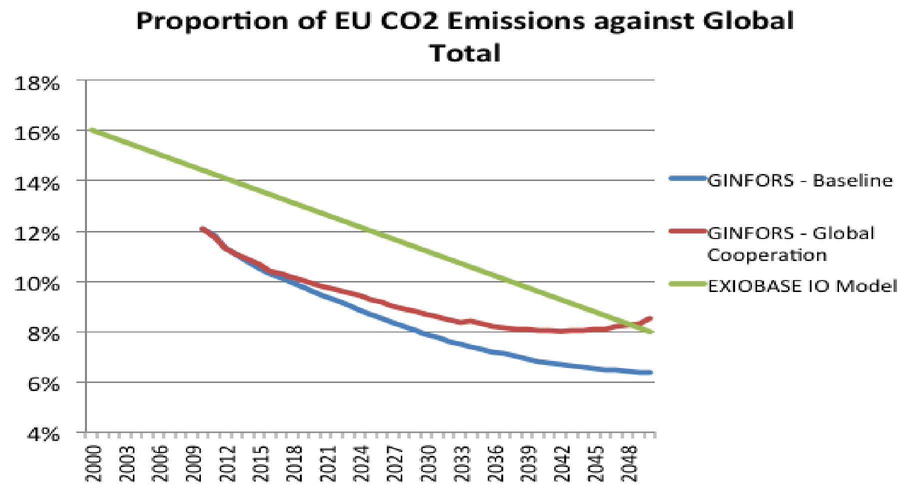


It is clear there are significant differences between the three models, both in sectoral contributions to emissions in both the Reference and the Decarbonisation scenarios and over time. The former is largely due to differences in emissions accounting between the models. For example, emissions from transport and buildings appear much lower in 2000 in the EXIOBASE IO Model compared to 2010 in ETM-UCL (approximately half, as with GINFORS), whilst the 'industry' sector appears approximately double (as in GINFORS). This is partly an issue as to which sector a process or activity is classified as, along with the whether or not an activity is included (for example, aviation and shipping emissions are excluded from the ETM-UCL scenarios), as discussed in the above section. The separation of 'direct' emissions in the EXIOBASE IO Model, which reflect direct emissions from final energy use in which there are no further links in the activity chain (approximately 50% domestic heating and 50% private transport), also has an impact. Under the ETM-UCL, such emissions are classified as buildings and transport related emissions, respectively. 'Other' emissions in Figure 5 and Figure 4 include emissions from processes such as construction and the collection and landfilling of waste. Another contributor to the difference are actual changes in emissions experienced between 2000 and 2010, however this clearly doesn't hold for differences between the ETM-UCL and GINFORS results, which hold the same base year.

The main driver for the increase in CO_2 emissions in the Reference scenario in the ETM-UCL is the power sector, which more than doubles in emissions between 2010 and 2050. The power sector is also the main driver for CO_2 reductions in the Policy Success scenario (achieving negative absolute emissions), although all sectors (except agriculture) play a role. The power sector is much less of a driver for the increase in emissions in the BAU scenario in the EXIOBASE IO Model (although a slight increase is experienced), with its 'direct' emissions by far the largest contributor (although all sectors contribute). Although, as with the Policy Success scenario in the ETM-UCL, the power sector is the largest contributor to CO_2 reductions between the base year and 2050. Indeed, all other sectors aside from 'direct' emissions experience a slight increase over time. As discussed, emissions in the GINFORS Baseline scenario only increases around 9% between 2010 and 2050, with proportional sectoral contributions remaining relatively stable. Again, with the ETM-UCL and EXIOBASE IO Model Decarbonisation scenario results, the power sector delivers the largest abatement in any sector in the Global Cooperation scenario (around half of total CO_2 reductions), with all sectors contributing.

Figure 6, below, illustrates the proportion of EU emissions against the global total projected to 2050, as calculated by the GINFORS and EXIOBASE IO Models. Whilst two trend lines are presented for GINFORS (Baseline and Global Cooperation), a single line is presented for the EXIOBASE IO Model results, as the results do not differ between the BAU and Techno-scenarios (in addition, only results for 2000 and 2050 are provided, with a linear interpolation). It is clear from both sets of results that the proportion of global CO_2 emissions produced by the EU is projected to continue decreasing, from around 16% in 2000 and 12% in 2020, to below 9% by 2050, regardless of the level of European and global mitigation ambition. This reflects the difference in economic growth projections between the EU and much of the rest of the world over the coming decades.

Figure 6 – Proportion of EU CO_2 Emissions Against Global Total



Energy Consumption

Figure 7 and Figure 8 illustrate the development of gross final energy consumption in the Reference and Policy Success scenarios applied to the ETM-UCL, and the Baseline and Global Cooperation scenarios applied to GINFORS, respectively. Such information is not easily extracted from the EXIOBASE IO Model, and so is excluded here.

Figure 7 - Gross Final Energy Consumption - ETM-UCL

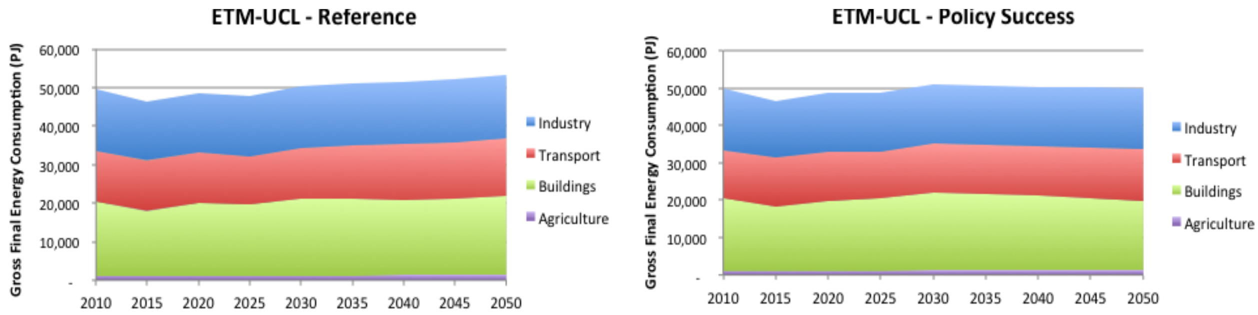
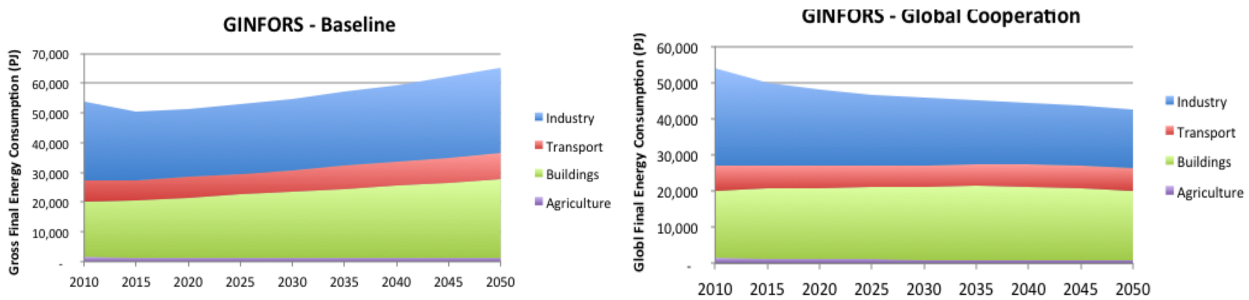


Figure 8 - Gross Final Energy Consumption - GINFORS

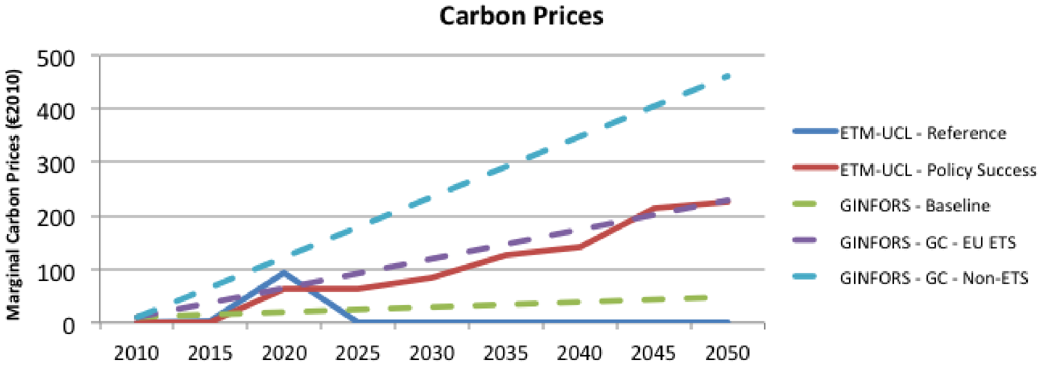


Total gross final energy consumption in 2010 is just under 50PJ in the ETM-UCL scenarios, and just over 54PJ in the GINFORS scenarios. The difference is due to the inclusion of marine and aviation transport in GINFORS, which is excluded in the ETM-UCL scenarios. The division between sectors is a function of sector definitions and scope, as highlighted above, but elaborated on below in sector-specific sub-sections. It is clear that the variation over time and between scenarios is greatest in the GINFORS scenarios than the ETM-UCL scenarios, with the ETM-UCL Reference scenario and GINFORS Baseline scenario increasing by 7% and 21% respectively over the assessment horizon, and approximately maintaining 2010 levels in the ETM-UCL Policy Success scenario whilst decreasing over 20% across the assessment horizon in the GINFORS Global Cooperation scenario. There are likely numerous contributions behind this difference, including differences in technological options available in each model, scenario (and policy) assumptions, and model structure and dynamics. The development of each end-use sector that builds to create this picture in the two figures above (plus those in the EXIOBASE IO Model), along with developments in the power sector, will be discussed in the relevant sub-sections below.

Carbon Prices and Total Economic Costs

Whilst the scenarios used in the GINFORS model use exogenous carbon prices, shadow marginal carbon prices are calculated endogenously in the ETM-UCL. The extraction of carbon prices is not possible from the EXIOBASE IO Model. Figure 9 illustrates the carbon prices from the ETM-UCL and GINFORS, for both the Reference and Decarbonisation scenarios (with two trajectories presented for the latter, one for the EU ETS, and one for the second cap-and-trade instrument introduced). Values are presented in €2010.

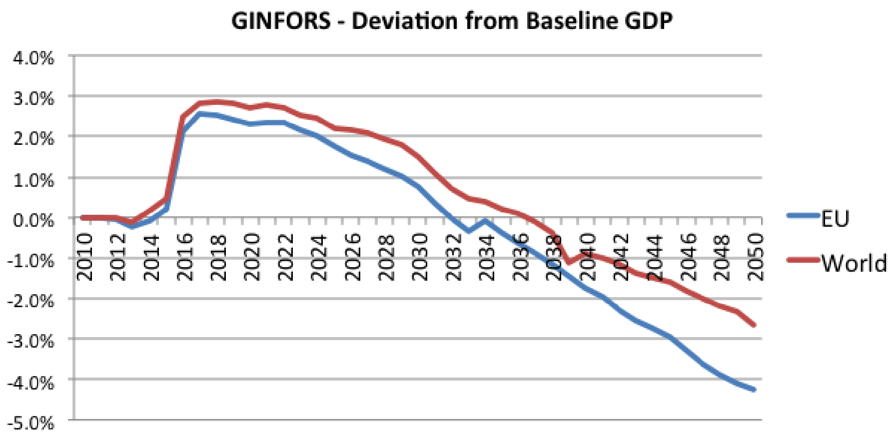
Figure 9 - Marginal Carbon Prices (€2010)



Whilst two distinct, linearly rising carbon prices are imposed for different sectors in the GINFORS Global Cooperation scenario, a single, economy-wide shadow marginal carbon price is produced by the ETM-UCL, with variations over time. Both ETM-UCL scenarios experience a peak in carbon price in 2020, reflecting the imposed 2020 targets. Whilst the Reference scenario price drops to zero immediately after (reflecting the lack of any restrictions on CO_2 emissions), the Policy Success trajectory rises relatively steadily to around €230 by 2050, matching the EU ETS price imposed in the GINFORS Global Cooperation scenario. The higher price imposed in the non-ETS cap-and-trade instrument suggests higher marginal abatement costs in the non-ETS industry sectors.

As an economic-environmental model, GINFORS is able to simulate the dynamic impact on the economy resulting from a given policy package and subsequent developments. Figure 10 illustrates the deviation in GDP in the Global Cooperation scenario from the Baseline, at both EU and global level.

Figure 10 - GINFORS - Global Cooperation GDP Deviation from the Baseline



At the global level, strong positive impacts on investment initially dominate, especially for the real estate sector and the electricity generation, increasing GDP against the baseline until around 2030 – after which such investments diminish. The worldwide information instrument for improving material efficiency improves efficiency of production for the sectors at the end of the supply chain whilst reducing production and value added for the sectors in the early stages of production. This produces a net negative on value added, which reduces consumption and the total circular flow of income and GDP. After 2030, the negative effects of this instrument begin to dominate, producing a total net negative impact on total global GDP (GWP). However, overall the difference between this scenario and the baseline is very small. In Global Cooperation a deviation of -2.6 % is projected by 2050, which means that the average annual growth rate for the period 2015 to 2050 would be 2.3 %, rather the 2.4 % projected for the baseline. If the absolute deviations are aggregated over the whole simulation period, this sum of deviations is zero and will be definitely positive if a time preference is implemented by a discounting factor.

Figure 10 also illustrates that deviations in GDP in the EU follow a similar pattern to the global trend, but with the negative component of the supply chain effect more prominent, with the positive deviations towards the beginning of the assessment horizon producing a weaker effect, despite an added positive influence from the reduction of fossil fuel imports. By 2050, the deviation is -4.5% against the baseline. Again, this effect is minor, meaning that the average annual growth rate would be 1.6 % under the Global Cooperation scenario, instead of 1.7 % in the Baseline. The reason for the stronger negative effect in the EU is that the industries in later stages of production, such as producers of investment goods and durable consumption goods, are much less material intensive than the same industries outside of the EU, meaning the positive dematerialisation effect for the industries in the later stages of production will be stronger for these industries outside the EU, boosting their competitiveness against their EU counterparts.

Whilst the ETM-UCL does not endogenously consider impacts on GDP, it does calculate the total cost of the physical energy system (investment and fuel costs), over the assessment horizon. The difference in total cost of the energy system Policy Success scenario is equivalent to 1.26% cumulative (exogenously) projected GDP in the EU between 2010 and 2050. There is little variation on this with the scenario sensitivities (except for the infeasible 'No Biomass CCS' scenario, for reasons discussed in the following sub-section. A net cost is to be expected under any constraining scenario over a non-constrained scenario under the EU ETS due to its cost-optimising approach, and lack of consideration of wider economic impacts. Results regarding total cost are not available from the EXIOBASE IO Model, and GDP projections, as with the ETM-UCL, are exogenous.

5.1 Power Sector

Total electricity generation in the EU in 2050 grows to around 3,850GWh in the Decarbonisation scenarios in the EXIOBASE IO Model and ETM-UCL, representing a 27% increase from 2000, and 20% from 2010, respectively. However, electricity generation in GINFORS increases to 6,650GWh by 2050 - an increase of 87% on 2010 levels. Each of these increases reflects both an increase in energy consumption overall, but also a shift to electricity in final demand in end-use sectors, although to highly varied extents between each model, as discussed in the following sections.

In the ETM-UCL, CO_2 emissions from the power sector increase to 2.4GtCO_2 in the Reference (a 213% increase from 2010), whilst in Policy Success they decrease to negative at -0.7GtCO_2 (a 165% decrease). In the EXIOBASE IO Model, CO_2 emissions increase to 1.6GtCO_2 in 2050 in BAU (a 37% increase from 2000), and down to 0.1GtCO_2 in Techno-Scenario (a nearly 90% decrease). In GINFORS, Baseline and Global Cooperation power sector emissions both decrease against 2010, to 1.2GtCO_2 (>1% decrease) and 0.2GtCO_2 (an 86% decrease), respectively. The emission intensity of the Techno-Scenario, Global Cooperation and Policy Success scenarios are 31gCO_2/KWh, 25gCO_2/KWh and -190gCO_2/KWh, respectively (from around 380gCO_2/KWh in 2000 and around 350gCO_2/KWh in 2010). Figure 12, Figure 12 and Figure 13 illustrate the development of the electricity mix for these three scenarios from their respective baselines.

Figure 11 - Electricity Mix – ETM-UCL – Policy Success

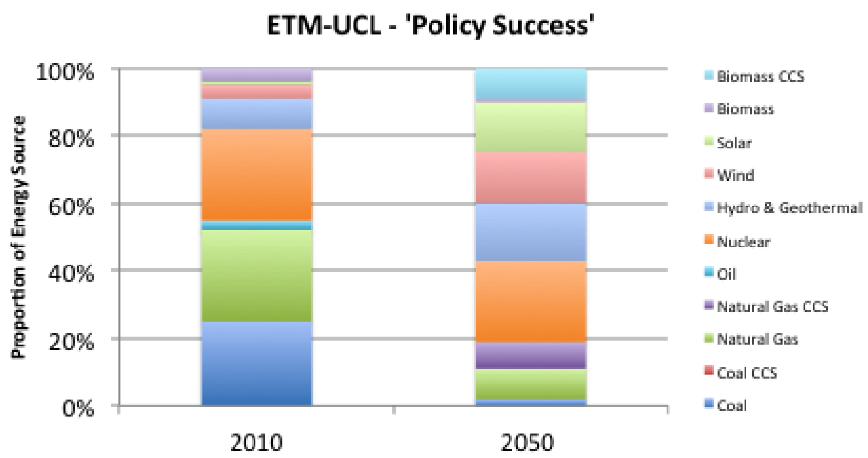


Figure 12 - Electricity Mix – EXIOBASE IO Model – Techno-Scenario

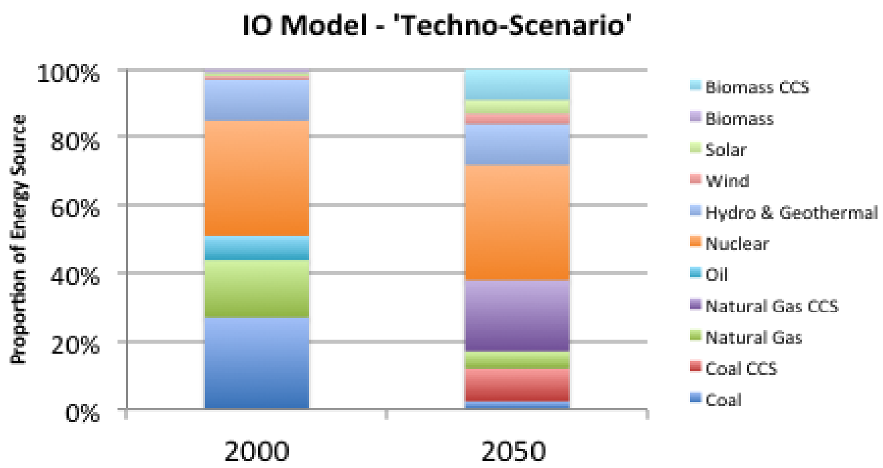
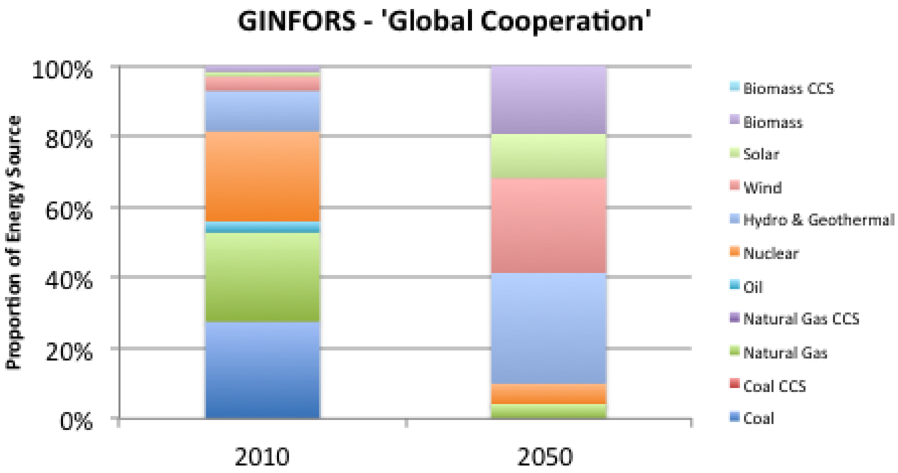


Figure 13 - Electricity Mix - GINFORS - Global Cooperation



Whilst the electricity mix in 2050 in Figure 11 (Policy Success) is determined by cost-optimisation within the context of the full energy system and the parameters imposed, the mix in 2050 illustrated in Figure 11 (Techno-Scenario) reflects fully exogenous assumptions based on the values presented in Jakeman & Fisher (2010). The GINFORS results, Figure 13, are also largely the result of exogenous assumptions. As is clear, there are significant differences in the electricity mix between the three models. The GINFORS model imposes a rising quota for total renewables reaching 90% by 2050. Suppliers of electricity have to fulfil this either with their own production or by purchasing electricity from other producers. Producers are free in their choice of renewable technology, with the distribution determined by their relative unit costs. There is a sharp increase in all types of renewables by 2050, particularly wind, which increases to 27% of generation. Hydroelectricity and geothermal power together produce 31%, whilst biomass and solar produce 19% and 12%, respectively. Penetration of renewables reaches 57% in Policy Success (with wind and solar accounting for 30% of total generation), but just 28% in Techno-Scenario (with wind and solar accounting for just 7% of total generation). The use of coal and natural gas retains a 40% share in Techno-Scenario, 19% in Policy Success, but just 4% in Global Cooperation. Whilst CCS is applied to around half the remaining fossil fuel generation in Policy Success and around 80% in Techno-Scenario, CCS is not available as a technological option in GINFORS for the Global Cooperation Scenario. The markedly reduced switch from fossil fuels to renewables experienced in the Techno-Scenario is justified by constraints imposed by observed penetration rates of renewable technologies (Kramer & Haigh, 2009), the long lifetime of coal plants currently under construction, the presence of shale gas in the USA (and potentially in Europe), and its depressing effect on the price of both coal and natural gas combining to suggest that fossil fuel-based generation may still play a substantial role in 2050 (de Koning *et al*, 2014).

The share of nuclear power changes little over time and between Policy Success and Techno-Scenario (producing 24% and 34% of electricity by 2050, respectively). In Global Cooperation however, nuclear generation decreases to just 4% of generation. The use of nuclear power by 2050 is the only power technology controlled by exogenous assumptions in all models, as its deployment is often a political choice rather than an economic one (Solano & Drummond, 2014). As with the ETM-UCL scenarios, nuclear generation is maintained at absolute 2010 levels in GINFORS. The dramatic proportional reduction of nuclear energy illustrated Figure 13 (25% in 2010 to 4% in 2050) is a result of the high growth rate of total generation in the Global Cooperation Scenario (87% across the assessment horizon).

The use of biomass CCS (which produces negative CO_2 emissions), despite a relatively minor share of proportional generation in both Policy Success and Techno-Scenario (9% in both), is a key technology in both models and scenarios (with CCS unavailable in GINFORS). Biomass used in all other final demand sectors is diverted to electricity generation in the Techno-Scenario, and whilst such a shift does not occur in Policy Success, the use of this technology facilitates the existence of the negative emission intensity (and absolute negative emissions), discussed above. The absence of this technology, as confirmed by the 'No Biomass CCS' Policy Success sensitivity, means the emission reduction objective imposed cannot be achieved under the Policy Success scenario in the ETM-UCL. The absence of new nuclear, or the delay of CCS availability to around 2030 however does not pose such difficulties, or any substantial differences in total system cost or other metrics, as confirmed by the 'No New Nuclear' and 'Delayed CCS' sensitivities (Solano & Drummond, 2014).

5.2 Industry Sector

Levels of 'industrial' emissions in the base years of Techno-Scenario and Global Cooperation are similar at around 1.1GtCO_2, whilst in Policy Success they are reported at around half this level (0.5GtCO_2). The difference is a result of differences in scope and accountancy. Whilst GINFORS and the EXIOBASE IO Model characterise the industrial sectors to a high level of detail, as required by the purpose of these models, the ETM-UCL characterises the industry sector as seven broad sub-sectors, as suited to its purposes. Some specific processes present in the former two models may not be present in the ETM-UCL. However, more significantly, GINFORS includes the transport and buildings-related CO_2 emissions associated with the industrial sectors in question under this category.

Industrial CO_2 emissions decrease by 39% and 53% between 2010 and 2050 in Policy Success and Global Cooperation scenarios, respectively, although an increase of 7% between 2000 and 2050 in projected in the EXIOBASE IO Model's Techno-Scenario. This increase is mainly due to limited options for abatement in steel and cement production, where despite the introduction of highly optimistic technology assumptions, increasing demand from economic growth projections counteracts their effects. The use of renewables in the industry sector does not increase, as the majority of renewables resources (particularly biomass) are applied in the power sector (with the use of CCS to produce negative emissions). For the EU, the share of global trade of industrial products remains roughly constant, as shifting production elsewhere does not produce CO_2 savings from a global perspective. Emissions from steel production include the substantial transport infrastructure required for CCS in the Techno-Scenario.

Although industrial CO_2 emissions in Policy Success decrease by 39%, total energy demand decreases by just 6%. The share of energy carriers remains largely constant, with relatively minor increases in the use of biomass and a corresponding decrease in the use of coal. A large proportion of the CO_2 reduction is delivered through the use of CCS on process emissions, not applied in either Techno-Scenario or Global Cooperation. In the absence of CCS, industrial emissions would have decreased by just 12%. However, unlike the EXIBASE IO Model, this projection does directly not consider the increase in steel demand from the use of CCS.

Despite the projected 53% reduction in CO_2 emissions from the industrial sector in the GINFORS Global Cooperation scenario, it remains the most problematic sector for achieving abatement in that scenario. The industry sector in GINFORS uses energy for mobility, heating and process heat like 'cooking' steel, producing ceramics and other basic goods. Energy use for mobility is influenced by the e-mobility program (see the following 'Transport' sub-section, whilst heating demand is influenced by the program to improve the energy efficiency of buildings (See the following 'Buildings' sub-section). The imposed carbon price influences all three categories of energy demand, but for process heat, a key source of emissions in this sector, it is the only direct influence. However, little abatement from process heat is produced from the imposed carbon price, as firstly, the price elasticities for energy intensity and carrier substitution are tight in the basic industries, and secondly, the relative prices for fossil fuels are very low in Global Cooperation, such that the shadow prices for energy are compared to the Baseline not much higher, despite rather high carbon prices. The information program for the reduction of basic material inputs in downstream industries, particularly small and medium size firms, thus reducing demand for these basic industrial products with consequential CO_2 emission reductions, is the most important factor in achieving the projected CO_2 trajectory for the industry sector in the Global Cooperation scenario. For a clear illustration of this we take a look at Germany - a country with high levels of industrial production. In 2010 the share of the basic metals industry in total gross production in Germany was 3.9%. In the Baseline it rises to 4.3% by 2050, whereas in the Global Cooperation scenario it reduces to 2.9% - a 42% difference. The difference in CO_2 emissions in the basic metals industry in Germany in 2050 between the Baseline and Global Cooperation scenarios is 60%, for which this reduction in demand is clearly a decisive influence. Although the effect of improvements in material input efficiency in downstream industries is the most prominent in the basic metals industry, demand reductions are achieved for all basic industries. Chemicals for example had a share of 3.1% of total gross production in Germany in 2010. In the Baseline this grows to 3.5%, but in Global Cooperation it reduces to 2.9% a difference of 32%. Again, this is clearly the largest contributor to the 48% difference in CO_2 emissions by 2050 between the two scenarios.

5.3 Transport Sector

Transport-related CO_2 emissions in 2010 in the ETM-UCL scenarios are just under 1GtCO_2, whereas CO_2 emissions reported as 'transport' in the base years of the GINFORS and EXIOBASE IO models are half this, at around 0.5GtCO_2. Again, this is due to differences in scope and accounting. In GINFORS, the transport sector is defined as a service sector delivering transport services to commercial activities and private households. Transport activities of the industry sector and of individual private use (e.g. private cars) are accounted for under 'industrial' emissions, above, and 'household' emissions (considered under 'buildings' emissions), below, respectively. Transport in the agriculture sector is also separated, as discussed in the following sub-section. CO_2 emissions from private car use is also separated out in the EXIOBASE IO Model, to form approximately half of 'direct' emissions (although emissions from industrial and commercial related transport are reported as transport emissions). Both GINFORS and the EXIOBASE IO Model report both aviation and marine transport CO_2 emissions, alongside surface transport. The ETM-UCL however only considers surface transport emissions, but reports all such emissions under the 'transport' category.

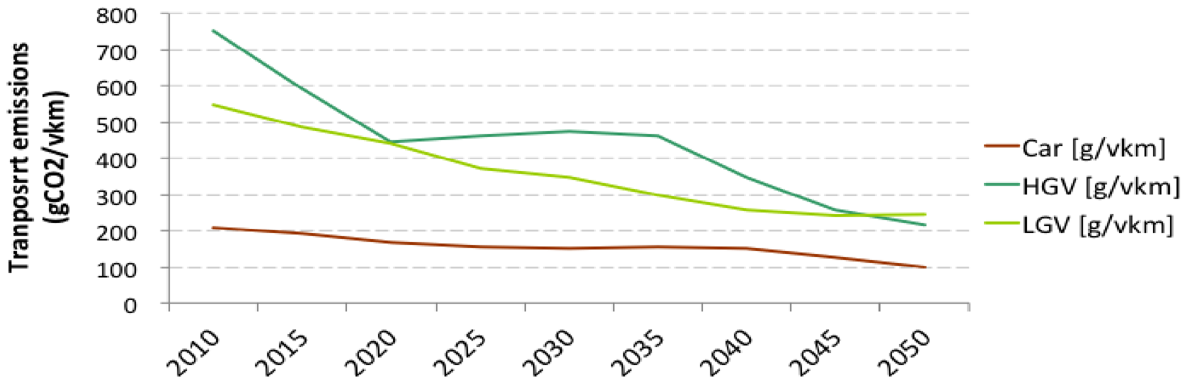
A similar pattern regarding CO_2 trends as the industrial sector emerges over time between the three models and scenarios. Whilst emissions decrease in the Policy Success and Global Cooperation scenarios between 2010 and 2050 (32% and 55%, respectively), an increase of 36% is projected in the EXIOBASE IO Model's Techno-Scenario.

In the GINFORS Global Cooperation and the ETM-UCL Policy Success scenario, the majority of abatement in the transport sector is delivered via road transport. The Global Cooperation scenario assumes the promotion of 'e-mobility', implemented through emission standards and taxation of fossil fuel combustion engines, the revenues from which are used for subsidies for the use of low emission vehicles (meaning that the sector in total is does not shoulder additional burden from this taxation), alongside imposed carbon taxation. Further, the use of electric cars is favoured in cities by improved parking conditions and exemptions from city taxes. Whilst the link from these policy assumptions to the energy structure of the land transport sector cannot be established explicitly, it is clear that the use of electricity will rise and that the use of diesel and gasoline will fall. To what extent this happens is a question of the intensity with which the policy instruments are implemented. However, the share of electricity in land transport (road and rail) rises to 80%, with electricity thus accounting for 39.3% of all transport emissions (as defined by GINFORS) by 2050 (from 2.5% in 2010), displacing the use of diesel, in particular. However, the data cannot provide information on the specific vehicle technologies employed, or the division between land transport modes. For air and water transport the imposed carbon price induces some improvements in energy intensity, but no significant technology shifts occur. Additionally, improvements in material efficiency in the economy delivered by the informational instrument for that purpose reduces demand for the transportation of materials, and thus transport energy demand. Overall, energy demand in the transport sector in Global Cooperation decreases by 10% over the assessment horizon, against a 28% increase in the Baseline scenario.

Transport sector energy demand in the ETM-UCL's Policy Success scenario increases by 4% (land transport only) – despite a 72% increase in road transport service demand, and a 34% increase in rail transport demand (although road transport accounts for 97% of land transport demand and energy consumption across the assessment horizon). The 32% reduction in CO_2 emissions is reflected by reductions in CO_2 intensity of cars, Light Goods

Vehicles (LGVs) and Heavy Goods Vehicles (HGVs) – particularly the latter, as illustrated in Figure 14, below.

Figure 14 - CO_2 Intensity of Road Transport Modes



Reductions in the CO_2 intensity of cars is delivered by a general switch from gasoline to other fuels, particularly diesel. Improvements in vehicle efficiency means that despite the 72% increase in transport demand from cars, energy demand increases by just 2% between 2010 and 2050. The use of petrol reduces from 64% of total fuel consumption by cars in 2010, to 32% in 2050. Diesel increases from 30% to 44%, whilst the use of biofuels increases to 18%, and electricity (through Plug-in Hybrid Electric Vehicles (PHEVs)) to 6%. A larger reduction in CO_2 intensity occurs in LGVs. Again, despite a uniform 72% increase in service demand, efficiency improvements produce a 25% energy demand reduction, with a slight shift away from diesel (92% to 78%) to electricity (7%, through PHEVs and Hybrids), but also gasoline (increasing from a 6% to a 12% share). Minor penetration of natural gas and biofuels also occurs). The largest improvement occurs in HGVs, despite a 37% increase in energy demand over the assessment horizon. However a much more dramatic shift occurs, with diesel moving from an effective monopoly to just 35% of HGV energy demand, replaced by biofuels at around 16%, and hydrogen to around 50% of demand. The use of biofuels increases rapidly from the beginning of the assessment horizon to 2020, and satisfies the imposed 10% target on renewables in road transport for 2020.

As such, the decarbonisation of the road transport sector is not as far-reaching in Policy Success as in Global Cooperation, described above (or in the Techno-Scenario, described below). Little electrification occurs (under 4% of road transport energy demand in 2050), although biofuels and hydrogen are relatively prominent (14% and 17% by 2050, respectively).

In the EXIOBASE IO Model's Techno-Scenario, although a 36% increase in transport emissions is experienced (as defined by this model), substantial savings are again achieved in the road transport sector. Similarly to Global Cooperation, passenger cars shift to a large majority electric drives (around 95% by 2050, by approximately equal shares of PHEVs and battery-electric), reducing CO_2 emissions from such sources substantially against both 2000 and the 2050 baseline projection, including from private vehicles reported as 'direct' emissions. However, Koning *et al* (2013) highlight that the imposition of electric drives over other low-carbon resources is an exemplary choice, and the use of hydrogen (produced from renewable sources) may also have been chosen. Such electrification accounts for around two-thirds of the 27% increase in total electricity generation projected between 2000 and 2050. However, it is assumed that goods vehicles do not experience a shift to electric or hydrogen drives, as additional storage systems are required, and non-fossil, non-biofuels are expensive and add additional weight. Such reasoning also applies to the lack of a shift in marine transport, which together with aviation accounts for around 75% of transport emissions in the EXIOBASE IO Model by 2050. Aviation demand is projected to rise substantially with rising income due to the high-income elasticity of demand, with an assumption of linear growth assumed in the Techno-Scenario. Although as with marine transport, no shift to low-carbon fuels are assumed. Electrification is not possible, and biomass is fully diverted to electricity generation with CCS. Despite assumed substantial improvements in transport efficiency (also assumed in the BAU scenario), coupled with an aggressive low-carbon shift in passenger cars, the (increasing) domination of transport modes for which no low-carbon shift occurs, produces increased emissions in 2050 over 2000 levels.

None of the three models or scenarios applied allow for a modal shift between, for example, private and public transport, or between types of transport, such as from road to rail. This is partly due to the design of the models, but also to allow the assessment of potential technological developments – the development of which may be more difficult to determine when considered alongside such factors.

5.4 Buildings Sector

Again, the difference in base year emissions reported as 'building' emissions in Figure 3, Figure 5 and Figure 4 are due to differences in scope and accounting. Whilst all direct CO_2 emissions from all buildings are included under the ETM-UCL definition (producing 0.64GtCO_2 in 2010), as discussed, divisions occur in GINFORS and the EXIOBASE IO Model. In GINFORS the 'buildings' emissions reported here are 'household' emissions, composed of direct emissions from dwellings and private vehicle emissions only. Emissions from buildings related to the industrial and commercial sector are included under the 'industrial' category, whilst those related to the agriculture sector are reported under that category. This produces total buildings-related emissions, as defined here, of around 0.88GtCO_2 in the 2010 base year. In the EXIOBASE IO Model, direct emissions from the heating of private households are considered under 'direct' emissions (comprising around 50% of such emissions). The produces building related emissions in the 2000 base year, as defined by the model (non residential buildings direct emissions), of around 0.22GtCO_2. Including 50% of 'direct' emissions (as the approximate proportion assigned to household emissions) increases this value to around 0.75GtCO_2.

A familiar pattern regarding the development of CO_2 emissions between the three Decarbonisation scenarios emerges for this sector. Whilst emissions reduce in both Policy Success and Global Cooperation between 2010 and 2050 (20% and 45%, respectively), they increase in the Techno-Scenario (41% between 2000 and 2050).

In the ETM-UCL, building envelope efficiency measures are not included as an option. The 20% savings are achieved through a combination of increasing energy efficiency of products and a changing fuel mix, particularly in space heating. In the residential sector (which accounts for around two-thirds of building emissions across the assessment period), although energy service demand for space heating increases by 14% over between 2010 and 2050 (due to increasing household numbers), final energy demand for space heating decreases by 13%. Increasing electrification is projected (5% to 18%), along with heat pumps (1% to 9%) and the use of natural gas (44% to 52%). This is compensated by a reduction in coal and other fossil fuel products, in particular. Energy service demand for commercial heating increases by 36% over the assessment period, but experiences a 25% reduction in final energy demand. Again, increasing electrification is projected (12% to 29%), along with the use of natural gas (41% to 51%) and heat pumps, but to an increased degree (4% to 20%). Again, this is compensated for by the reduction in the use of other fossil fuel products. Overall, final energy demand in buildings decreases by 4%.

Despite the 45% reduction in CO_2 emissions, energy demand in households (direct emissions and private transport) decreases by just 4% between 2010 and 2050 in the Global Cooperation scenario (against a 42% increase in the Baseline). For all buildings (including those associated with industrial emissions, discussed above and in the agricultural sector, discussed below), it is assumed that the German KFW program for subsidies to encourage investments in building efficiency measures is applied throughout the EU (and globally, in the Global Cooperation scenario). The program, which has been evaluated very positively by the European Commission[11], has the potential to reduce the energy intensity of buildings by up to 50% (PROGNOS, 2013). As 'household' emissions in GINFORS include those from private transport, the 'e-mobility' policy also has an impact on 'buildings' emissions, as defined here. Whilst it is not possible to definitively determine the contribution to energy demand and savings (or CO_2 production and savings) between direct household emissions and private transport emissions, some trends can be extrapolated from the fuel mix reported. It appears as though the division of energy demand in this sector between residential buildings and private transport remains largely constant over the assessment horizon, at around 60% and 40% respectively (meaning that absolute demand in both also remains largely stable). The division of energy carriers in building use also remains mostly constant, with a slight increase in electrification, compensated with corresponding minor reductions in the use of natural gas and other fossil fuels. This implies that residential building emissions have likely contributed little to the CO_2 reductions experienced in this category, with the energy efficiency program serving simply to prevent an increase in emissions with the growth in household numbers. The energy mix for private transport transforms rather rapidly however, with electrification reaching around 80% at the expense of traditional fossil fuels. As such, this is where the majority of the 45% CO_2 reduction is achieved.

[11] See European Commission (2013a), p20.

In the EXIOBASE Techno-Scenario, despite the increase in 'buildings' emissions (i.e. direct emissions from non-residential buildings), likely a result of increasing commercial and industrial demand over time overcoming introduced efficiency measures (as detailed in de Koning *et al*, 2013), direct emissions from households becomes less prevalent due to the substantial shift towards electricity consumption. If it is assumed that half of the reduction in 'direct' emissions illustrated in Figure 5 (Techno-Scenario panel) may be attributed to reductions in household direct emissions (and thus the other half attributed to reductions in private transport direct emissions), absolute emissions from buildings in 2050 are slightly below 2000 levels (around 6%, and around 75% lower than BAU CO_2 emissions from the sector, using the same attributions).

5.5 Agriculture Sector

CO_2 emissions from agriculture represent a minor share of total emissions in the EU (excluding LULUCF) in the base years of all three models (~2%). As no technologies are characterised in the ETM-UCL for abatement of such emissions, they increase by around 30% between 2010 and 2050, with no difference between scenarios. This means they account for 9% of CO_2 missions from the European energy system by 2050 in Policy Success (but decrease to around 1% in the Reference scenario, in the presence of rapid growth in other sectors). Similarly, in the EXIOBASE IO Model no significant shifts in consumption patterns and technological profile of the agriculture sector are characterised in the EU. As such, CO_2 emissions from agriculture also increase by the same magnitude across all scenarios – around 80% between 2000 and 2050. Such emissions remain at 2% of total CO_2 emissions in the BAU scenario, but increase to around 4% in Techno-Scenario

In the GINFORS Global Cooperation (and Middle of the Road) scenario, agriculture is influenced by the carbon price of the second (non-EU ETS) cap and trade system, the e-mobility policy and the policy for more building efficiency (both discussed in the 'Transport' and 'Buildings' sections, above). These policies (combine with broader dynamics) produce an approximate 60% reduction in agricultural CO_2 emissions between 2010 and 2050 in Global Cooperation, maintaining the share of 2% of total emissions. This share is also maintained in the Baseline scenario, where CO_2 emissions from the sector reduce by 20%.

However, CO_2 emissions are only a small proportion of GHGs associated with agriculture. Methane (CH_4) emissions, for example, are much more important, but lay outside the scope of the three models and scenarios presented and discussed here.

6 Conclusions

The results of the aligned 'Decarbonisation' scenarios applied to the ETM-UCL, GINFORS and EXIOBASE IO Models indicate the difficulties an 80% reduction in CO_2 emissions by 2050 below 1990 levels in the European energy system. Indeed, two of the scenarios – the Techno-Scenario applied to the EXIOBASE IO Model and the Global Cooperation Scenario applied to

GINFORS - do not achieve it (although the latter comes close, the former achieves just a 20% reduction). The Policy Success scenario, whilst achieving the abatement required, cannot do so without the production of negative emissions in the power sector through the use of Biomass combined with CCS. Broad sectoral developments in the Decarbonisation scenarios are:

- **Power Sector** – All scenarios experience an increase in electricity generation, both to satisfy increasing demand from existing electricity-using processes and to meet additional demand from increasing electrification in certain end-use sectors, particularly transport and buildings. The level of generation increase depends on the level of end-use demand increases produced by each model, and the extent to which electrification is assumed or occurs. Despite this, the power sector accounts for the largest (proportional and absolute) abatement across the economy in the scenarios applied to all three models, with CO_2 intensity decreasing to 31gCO_2/KWh in the EXIOBASE IO Model's Techno-Scenario by 2050, 25gCO_2/KWh in the GINFORS Global Cooperation scenario and to negative at -190gCO_2/KWh in the ETM-UCL Policy Success scenario. Although, how these reductions are achieved differs substantially. The use of renewables increases to just 28% in the Techno-Scenario, but increases to 90% in Global Cooperation. These developments are both exogenous assumptions. The endogenous calculation in the ETM-UCL produces a 'middle ground' of 57% renewables by 2050. The profile of different types of renewables (wind, solar, hydroelectricity, etc.) also varies significantly, however the use of biomass in electricity production is key in all three Decarbonisation scenarios. In both Policy Success and Techno-Scenario, around 9% of generation in 2050 is sourced from biomass equipped with CCS, producing negative emissions, and facilitating the production of absolute negative emissions from the power sector in Policy Success. As mentioned, the use of Biomass CCS in this scenario is essential in achieving the required CO_2 abatement, within the confines of the assumptions and model approach applied. The use of biomass for electricity generation reaches 19% in the GINFORS Global Cooperation scenario, but it is assumed CCS will not be available for use (with any fuel). The use of nuclear is across all three models and scenarios is the result of exogenous assumptions, reflecting the political nature of its application, in which it is assumed that absolute remains steady over time. This produces a significant proportional reduction in the GINFORS Global Cooperation scenario (from 25% to 6%), due to exceptionally rapid increases in total generation. The use of coal and natural gas for power generation remains significant in both Policy Success and Techno-Scenario, although with CCS applied to the majority. Fossil fuels become insignificant in power generation in the GINFORS Global Cooperation scenario.

- **Industry Sector –** This is the most difficult major economic sector to decarbonise across all three Decarbonisation scenarios and models, for three reasons. The first is that demand for industrial products increases with projected GDP growth (and other drivers), increasing energy consumption and consequential emissions. The second is that energy efficiency measures for key industrial sub-sectors, such as iron, steel and cement, are relatively limited (or at least limited in the three models employed here). Thirdly, price elasticities for energy carrier substitution are tight; meaning a significant shift to low-carbon fuel is difficult, particularly if a large proportion of renewable resource potential is directed to other sectors (particularly power production). Only the Policy Success scenario in the ETM-UCL and Global Cooperation in GINFORS achieves CO_2 reductions by 2050 over 2010 levels in the industry sector (39% and 53%, respectively). The former achieves this primarily through the application of CCS to industrial processes, whilst the latter achieves reductions by encouraging material efficiency in downstream sectors, thereby reducing demand for industrial products and associated energy consumption and emissions production.

- **Transport Sector** – The road transport sector experiences a dramatic transformation in the Decarbonisation scenarios, particularly in the Techno-Scenario and Global Cooperation. Significant electrification occurs in these two scenarios, reaching 95% of all passenger cars in the former, and 80% of all land transport (including rail) in the latter. These transformations are a result of exogenous assumptions and policy choices. However, the CO_2 emissions trajectory for the transport sector in these two scenarios diverge significantly, with Global Cooperation producing a 55% decrease on base year levels, and Techno-Scenario producing a 36% increase. This difference is due to two key reasons. The first is the assumed non-transformation of LGVs and HGVs (in particular) in Techno-Scenario, which in GINFORS are included in the 80% electrification of land-based transport. The second is the treatment of marine and aviation modes. Both the EXIOBASE IO Model and GINFORS models include consider such modes, and both Decarbonisation scenarios applied to these models assume or produce no technological transformation or significant increases in efficiency. However, projections in future demand increase significantly more in the Techno-Scenario, particularly for aviation, as an exogenous assumption. In the Global Cooperation scenario, principally as a result of endogenous dynamics in the GINFORS model, demand increases to a far lesser degree, and therefore energy consumption and CO_2 production, is much less significant. The increase in material efficiency across the economy also contributes to reducing transport demand in this scenario. An additional factor is the non-inclusion of CO_2 emissions from private transport in these values. For both of these models, such emissions are considered separately.

- The Policy Success scenario, applied to the ETM-UCL, considers just land-based transport. Whilst transport service demand increases substantially, land-transport CO_2 emissions decrease by 32% between 2010 and 2050. Increasing vehicle efficiency drives part of this, although whilst changes occur across passenger cars, LGVs and HGVs, they are less dramatic than in Techno-Scenario and Global Cooperation. Passenger cars shift mainly from gasoline to diesel, whilst some electrification occurs in LGVS. HGVs experience a relatively significant shift to two-thirds biofuels and hydrogen, displacing diesel. By 2050, electricity satisfies just 4% of road transport demand, with other non-fossil fuels meeting around 30% of demand.

- **Buildings Sector** – Again, whilst both the Policy Success and Global Cooperation scenarios produce reductions in CO_2 by 2050 against their base years in this sector (20% and 45%, respectively), the EXIOBASE IO Model projects an increase (41%). Three main components contribute to this. The first is attribution and accounting. Whilst the ETM-UCL accounts direct emissions from all buildings under this category, the EXIOBASE IO Model and GINFORS do not. The former reports direct emissions from non-residential properties under this category (with residential property direct emissions accounted for as 'direct' emissions), whilst the latter reports residential emissions only (with non-residential building direct emissions accounted for under the 'industrial' and 'agriculture' sectors). GINFORS also reports emissions from private vehicles under this category. The second is the extent to which efficiency measures are introduced. Building and product efficiency improvements are exogenously projected in the Techno-Scenario, whilst in Global Cooperation a policy measure is introduced to induce significant improvements building envelope efficiency. In the ETM-UCL only product efficiency improvements are taken up, with building envelope measures not considered. The third is differences in energy mix developments, particularly the extent of electrification. Relatively minor electrification of space heating (in particular) occurs in Policy Success and Global Cooperation, although the extensive electrification of road transport influences produces substantial savings, and likely to be the key driver behind the abatement produced in this sector. Very substantial electrification of space and water heating is assumed in the Techno-Scenario, however much of the CO_2 savings this achieves is reported as 'direct' emissions. If these are included in the calculations, a slight reduction in building CO_2 emissions is likely achieved by 2050 from the 2000 base year.

- **Agriculture Sector** – CO_2 emissions from the agriculture sector are minor compared to the rest of the energy system, with non-CO_2 emissions a much more prominent issue. However, such emissions are outside the scope of these models and scenarios. Whilst no measures are characterised and introduced to abate agricultural CO_2 in Policy Success or the Techno-Scenario, the Global Cooperation scenario applied to GINFORS achieves abatement via the 'second' carbon pricing mechanism, and instruments applied to buildings and transport, for which those involved in agriculture are reported here.

The extremely varied results achieved by each model and scenario depends on a plethora of factors regarding the assumptions and projections regarding economic development, population growth basic fuel prices and technological cost and availability (amongst others) the specific objective of each model and its design to meet this objective, and the operation of internal dynamics used to link factors (such as those described above) to produce results. For these reasons, the use of the three models described in this report is a complementary process, with each providing lessons that the others cannot necessarily provide. A common lesson is the confirmation that projecting firm developments in different possible futures is an extremely difficult task, made more uncertain by the possibility of the unpredictable emergence of disruptive events or technologies. However, some broad conclusions may be drawn with confidence. The reduction of CO_2 emissions in Europe by 2050 to remain on a trajectory compatible with RCP2.6, or a 2°C pathway, is extremely difficult to achieve. Either complete decarbonisation (or the production of negative emissions) in a large CO_2-emitting sector is required (with the largest and most technical potential found in the power sector), with at least moderate abatement achieved in average across all other sectors, or all sectors of the economy must achieve substantial proportional reductions from existing levels, to a greater or lesser extent. This can only be achieved by a reduction in demand for the activities in a sector, energy efficiency measures or a low-carbon fuel mix – or combination of each. Such transformations must be driven by a policy mix able to withstand and adapt to future uncertainties. Carbon pricing alone, whilst important, is unlikely to deliver the level of decarbonisation required, even at high prices, due to the structure of the economy and uncertainties surrounding factors such as basic fossil fuel prices. It is likely that the CO_2 emissions produced by the EU will continue to decrease over time as a proportion of global emissions, regardless of whether the EU strives for decarbonisation. This highlights the importance of encouraging global efforts. However, regardless of international efforts, the total cost to the European economy of perusing the required level of CO_2 abatement by 2050 is likely to be small, and potentially positive if domestic supply chains are utilised and economic activity is stimulated.

References

Buchan, D. (2012) The Energiewende – Germany's Gamble, Available at: http://www.oxfordenergy.org/wpcms/wp-content/uploads/2012/06/SP-261.pdf [Accessed 17th March 2014]

European Commission (2013a) *Commission Staff Working Document:. Accompanying the Document - Report from the Commission tot he European Parliament and the Council. Financial Support on Energy Efficiency in Buildings*, European Commission

European Commission (2013b) *EU Energy, Transport and GHG Emissions: Trends to 2050 – Reference Scenario 2013*, European Commission

IEA (2012) Energy Technology Perspectives 2012: Pathways to a Clean Energy System, IEA/OECD, Paris

Jakeman, G. & Fisher, B. (2010) Benefits of Multi-Gas Mitigation: An Application of the Global Trade and Environment Model (GTEM), 2006 updated 2010. In: EMF 21 Multi-Greenhouse Gas Mitigation and Climate Policy, F.C. De La Chesnaye & John P. Weyant (eds.)

Kramer G.J. & Haigh, M (2009) No Quick Switch to Low-Carbon Energy, *Nature*, 462 (7273), 568–569

De Koning, A., Huppes, G., Deetman, S. (2014) *Scenarios for 2050 for a 2-Degrees World*, Liden, Leiden University

Meyer, B., Meyer, M., Distelkamp, M. (2014) Macro-Economic Routes to 2050, GWS

PROGNOS (2013) *Ermittlung der Wachstumswirkungen der KFW Programme zum Energieeffizienten Bauen und Sanieren*, Basel.

Solano, B. and Drummond, P. (2014) Techno-Economic Scenarios for Reaching Europe's Long-Term Climate Targets, London, University College London

Symon, C (2013) *Climate Change: Action, Trends and Implications for Business: The IPCC's Fifth Assessment Report, Working Group 1*, University of Cambridge, Cambridge

Timmer, M.P. (ed.) (2012) *The World Input-Output Database (WIOD): Contents, Sources and Methods*, WIOD Working Paper Number 10