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

Techno-Economic Scenarios for Reaching Europe's Long-Term Climate Targets

Using the European TIMES Model (ETM-UCL) to Model Energy System Development in the EU

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LIST OF ABBREVIATIONS

CCS	Carbon Capture and Storage
EJ	Exajoule
ER2050	Energy Roadmap 2050
ESD	Effort Sharing Decision
ETM-UCL	European TIMES Model
EU ETS	EU Emissions Trading System
FP	Fragmented Policy
GDP	Gross Domestic Product
GHG	Greenhouse Gasses
HGV	Heavy Goods Vehicles
IEA	International Energy Agency
LGV	Light Goods Vehicles
Mtoe	Megatonne of Oil Equivilent
NPV	Net Present Value
PJ	Petajoule
PS	Policy Success
RED	Renewable Energy Directive
VKM	Vehicle Kilometres

1 Executive summary

This objective of this study is to examine the long-term implications for the EU's energy system if an 80% reduction in CO_2 emissions is to be achieved by 2050 against 1990 levels, using the European TIMES Model. (ETM-UCL). The key conclusions are the following:

- **Power Sector** - Negative emissions in the power sector via the use of biomass CCS is essential in producing a technically feasible pathway (down to a CO_2 intensity of -190gCO_2/KWh by 2050), in the absence of both demand response actions and building envelope efficiency measures. In addition, 70% of generation sourced from a mixture of renewables and nuclear by 2050 is required, with CCS attached to the majority of remaining fossil fuels. Wind and solar PV replace nuclear when no new nuclear capacity is constructed to replace retirement of the existing fleet, at negligible additional cost.
- **Industry, Transport & Buildings** – CCS is also essential in the industrial sector, helping to achieve a CO_2 reduction of 65% by 2050 from 1990 levels. The transport sector achieves just a 10% reduction by 2050, delivered by a switch from gasoline to diesel (with some biofuels and electrification) in cars, along with increasing hybridisation of LGVs and biofuels and hydrogen becoming significant in HGVs. However, this study does not consider modal optimisation or consumer demand response. The building (residential and commercial) sector achieves a 36% reduction in CO_2 by 2050, delivered primarily through increasing end-use product efficiency, with (some) space heating electrification and the use of heat pumps in commercial properties. Again, a lack of demand response, high investment costs and no building envelope efficiency measures mean further decarbonisation is difficult to achieve in this sector under the given scenario constraints.
- **Marginal CO_2 Price & Energy System Costs –** Average EU-wide carbon prices reach \$300/tCO_2 in 2050. The total cumulative energy system cost of decarbonisation between 2010 and 2050 is projected at around \$4.33 trillion (NPV), equivalent to 1.26% of projected GDP between 2010 and 2050 - 14% over the Reference scenario system cost. In the 'EU Goes it Alone' sensitivity, in which the EU takes unilateral action to achieve emissions abatement, an additional cost equivalent to 0.31% of cumulative EU GDP is experienced.

Many uncertainties unavoidably pervade attempts to project future energy system developments, under given circumstances. The most significant technical uncertainty in this study is the future availability of biomass CCS. The purpose of this study is to determine the most appropriate low-carbon energy system development pathway on a cost-optimal basis only, however other uncertainties remain. Alongside technical, economic and demographic development uncertainties to 2050, public and political acceptability issues with the low-carbon transformation may present barriers to be overcome. An appropriate policy mix to implement such a low-carbon transition must consider these aspects, and mitigate or adapt to them as necessary.

2 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. As has become commonplace in interpreting what this aspiration practically requires, this study assumes that this implies a reduction in global GHG emissions of at least 80% by 2050, from 1990 levels[1].

This paper examines the implications of imposing an 80% reduction in EU CO_2 emissions[2] on the Union's energy system, and attempts to project the most cost-effective transformation pathway to achieve this goal using the recently developed European TIMES Model (ETM-UCL), a technology-rich, bottom-up linear optimisation model.

Firstly a description of the model is provided, followed by a discussion of the scenarios and assumptions applied to the model. We present a reference scenario, alongside 'Fragmented Policy' and 'Policy Success' scenarios, with various sensitivities applied to the latter. We then present the results of the scenarios, including trends in energy production and consumption, CO_2 emissions, marginal CO_2 costs and whole system costs. An overview of sectoral developments is also provided, followed by a discussion of the results and conclusions.

A follow-up report will characterise the sector-level results in more detail, and synthesise them with results from a parallel Input-Output Framework modelling activity.

3 The 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

[1] Although it is cumulative GHG emissions that are important in the climate system, such proportional reduction targets in certain years represent appropriate milestones.

[2] An 80% reduction in GHG emissions is likely to require an 80% reduction in CO_2 at a minimum.

[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

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 exogenously calculated 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. 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

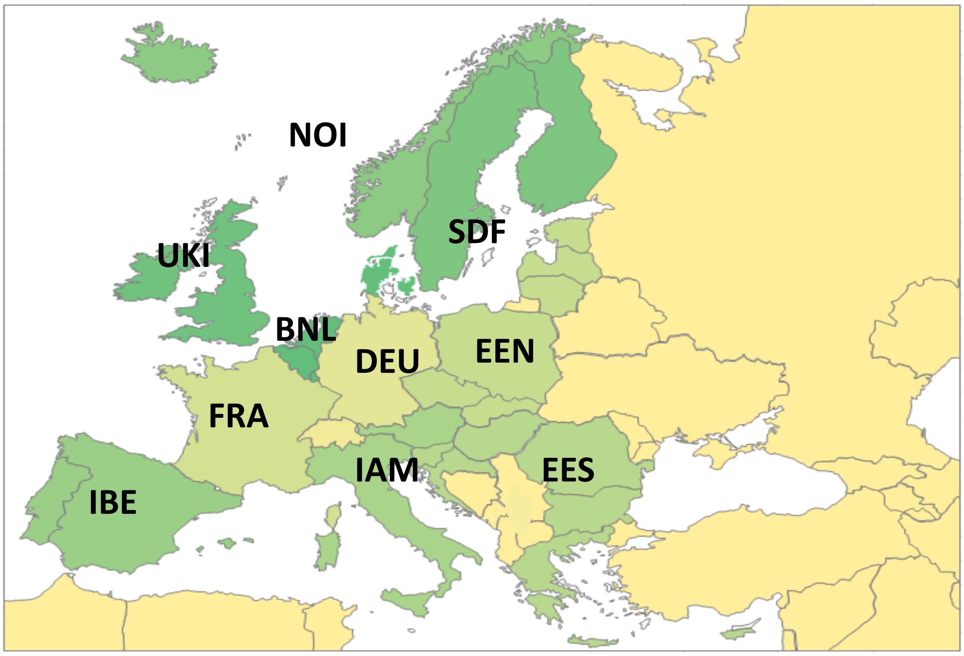

Table 1 ETM-UCL Regions - Disaggregation

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

[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.

4 Scenario Design and Assumptions

4.1 Scenario Commonalities

Each scenario designed and run as part of this study has an assessment horizon of 2050, with projections beginning in the base year of 2010. Results are reported for five-year time period. In order to limit the analysis to EU Member States only (EU28), the Switzerland, Norway and Iceland regions are excluded from the scenario runs.

The scenarios described below, whilst exhibiting key differences, hold a number of common assumptions. The first are in the trajectory of the key drivers of GDP, population growth and number of households. These exogenous values drive energy service demand in the economy. These values are taken from the IEA's '*Energy Technology Perspectives 2012'* for the European Union, and are tabulated in Table 2. These trajectories are also common across the different mitigation ambition scenarios (2DS, 4DS and 6DS) presented by the IEA (2012).

Table 2 Key Energy Service Demand Drivers (Source: IEA, 2012)

Driver	2015	2020	2030	2040	2050
Population	506m	511m	516m	515m	512m
Households	217m	-	238m	-	252m
GDP Growth[6]	2% (2009-20)		1.8% (2020-30)	1.7% (2030-50)	

Each scenario also assumes that the GHG emissions (translated to CO_2 only in this study) and renewable targets of the EU's 2020 Climate and Energy Package are achieved – two of the '20-20-20' targets. The energy efficiency target is not imposed, as it is widely considered unlikely to be achieved. The details of the draft 2030 policy framework for climate and energy, announced by the Commission on 22nd January 2014, are not considered in the modelling[7]. However, the implications of the results on the broad proposals of this framework are discussed where relevant.

GHG (CO_2) Emissions

Two mechanisms are currently in place in the EU in order to achieve a 20% reduction in GHG emissions by 2020, from 1990. The first is the EU Emissions Trading System (EU ETS), which places a cap on CO_2 emissions from power (and parallel heat) generation, along with various emission-intensive industries (e.g. iron, steel, glass, cement). The EU ETS currently covers around 11,000 installations, accounting for around 55% total CO_2 emissions (45% total GHGs) (European Commission, 2014b)[8]. In Phase 3 of the EU ETS (2013-2020), the emissions cap

[6] Actual values used in the model calculated are by Cambridge Econometrics for the E3ME model, and vary by region, but match the values presented in the table for the EU as a whole.

[7] The framework proposes at 40% domestic (EU) GHG reduction target by 2030 (delivered via a 43% and 30% reduction in EU ETS and non-EU ETS sectors respectively) from 2005 levels, along with a EU-wide target of 27% renewables in gross final energy consumption (European Commission, 2014a).

[8] N_2O emissions from the production of nitric, adipic, glyoxal and glyoxalic acids, and PFCs from aluminum production are also covered from 2013, but are minor and not included in this study.

declines annually by 1.74% of the average total quantity of allowances issued annually in Phase 2 (2008-2012). This means the total cap in 2020 will be 21% below that in place at the beginning of the EU ETS in 2005 (European Commission, 2014b). In order to implement this within the scenarios, emissions limits are set in 2015 and 2020 equal to the ETS cap for these years[9], across the power and heat generation and 'industry' sectors[10].

The second instrument employed is the Effort Sharing Decision (ESD). The ESD establishes binding annual GHG emission caps for each Member State between 2013 and 2020 (Annual Emission Allocations (AEAs)), covering all non-EU ETS sectors[11] such as surface transport, buildings, agriculture and waste, and all six Kyoto GHGs[12]. The average of these Member State caps produce an EU GHG reduction of 10% by 2020, from 2005 levels from the obligated sectors (European Commission, 2014c). The ESD is implemented in the model by capping all remaining non-ETS CO_2 emissions[13] in 2015 and 2020 at the legally mandated level – controlled for the removal of non-CO_2 GHGs.

The combined influence of these constraints ensures results for proportional CO_2 emissions reductions that meet or exceed the 2020 target for overall GHG mitigation (20% below 1990 levels).

Renewable Energy

The Renewable Energy Directive (RED) (2009/28/EC) establishes a common framework for the promotion of energy from renewable sources[14]. It imposes upon each Member State a binding target to ensure a certain proportion of their gross final energy consumption is obtained from such renewables by 2020, with the EU average equalling 20%. Table 3 presents these targets by Member State, aggregated to a regional level. A sub-target requires that 10% of final energy consumption in transport is renewable by 2020, and is equally applicable across all Member States. For implementation in the model this target is mapped to require at least 10% of liquid transport fuels to be biofuel (by which the vast majority of this target is likely to be achieved).

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[9] Scaled down to account for the removal of Norway and Iceland from the study.

[10] 'Industry' is disaggregated in the model to Chemicals, Iron & Steel, Non-Ferrous Metals, Pulp & Paper and 'Other' Industry. 'Other' industry (responsible for around 37% industrial energy consumption in 2010) includes other EU ETS sectors such as cement, lime and ceramics aggregated with a small proportion of non-ETS industrial sectors, included under the EU ETS cap for ease of analysis. Aviation (domestic and international) emissions are excluded from the modeling, as accurate redefinitions of 'international' and 'domestic' associated emissions for the purposes of the ETM-UCL have not yet been undertaken. This does not affect the pre-2020 constraints, as aviation is subject to a sub-system within the EU ETS, distinct from the caps described in the text. The removal of these three sectors is unlikely to significantly impact the post-2020 trends, as CO_2 emissions from these sectors within or directly attributable to the EU are relatively minor, and few options currently exist in the model for mitigation.

[11] Excluding Land Use, Land Use Change and Forestry (LULUCF) and international shipping emissions.

[12] Carbon dioxide, methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons and sulphur hexafluoride.

[13] Emissions from LULUCF and international shipping are removed from the model.

[14] Defined as energy from wind, solar, aerothermal, geothermal, hydrothermal and ocean energy, hydropower, biomass, landfill gas, sewage treatment plant gas and biogases.

Table 3 Renewable Energy Directive Targets

Region	Member State	Member State Target	Regional Target
BNL	Belgium	13%	13%
	Netherlands	14%	
	Luxembourg	11%	
DEU	Germany	18%	18%
EEN	Estonia	25%	22%
	Lithuania	23%	
	Latvia	40%	
	Czech Republic	13%	
	Slovak Republic	14%	
	Poland	15%	
EES	Slovenia	25%	18%
	Hungary	13%	
	Romania	24%	
	Bulgaria	16%	
	Greece	18%	
	Cyprus	13%	
	Croatia	20%	
FRA	France	23%	23%
IAM	Italy	17%	20%
	Austria	34%	
	Malta	10%	
IBE	Spain	20%	26%
	Portugal	31%	
SDF	Sweden	49%	39%
	Denmark	30%	
	Finland	38%	
UKI	United Kingdom	15%	16%
	Ireland	16%	

Common assumptions are also applied regarding nuclear capacity. Constraints are applied that reduce existing capacity in different regions in line with expected shutdown dates according to the World Nuclear Association (2013), as of October 2013. This includes the German phase-out plan introduced in the wake of the Fukushima disaster in 2011, culminating in the removal of all German nuclear capacity by 2022 (Bruninx *et al*, 2013). Constraints are also applied to the introduction of new capacity in different regions, to reflect differences in public opinion and expected government strategies. Again, such judgements are based on World Nuclear Association assessments of the existing landscape across these regions. The constraints applied, based on the position of constituent Member States, are the following (Table 4).

Table 4 Constraints on New Nuclear Construction

Region Code	New Nuclear
DEU	No new build permitted
IAM	
BNL	Permitted to reach total 2010 capacity (e.g. permitted to replace closing domestic installations)
FRA	
IBE	
SDF	
UKI	
EEN	New build permitted, but capped to total EU capacity in 2010 (e.g. permitted to replace reduced capacity seen in other regions)
EES	

As such, total EU nuclear capacity is limited to 2010 levels at any time over the assessment horizon, but the location of such capacity may change over time (e.g. from Germany to Eastern European Member States). Such assumptions may be contested, but are judged reasonable constraints for the purposes of this study.

4.2 Reference Scenario

The 'Reference' scenario is 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).

However, as 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. Table 5 presents projected import prices for key fossil fuels used by the IEA (2012) in their 6°C (6DS), 4°C (4DS) and 2°C (2DS) scenarios. For the Reference scenario in this study, the 6DS prices are imposed.

Table 5 IEA Fossil Fuel Price Projections (Source: IEA, 2012)

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

Import prices for different types of biomass range approximately between $5-10/PJ in 2010. These prices remain static in the Reference and Fragmented Policy scenarios, but roughly double by 2050 in the Policy Success scenario (and sensitivities), discussed below, to reflect increasing demand. Based on previous in-house modelling, this might be considered relatively conservative.

4.3 'Fragmented Policy' Scenario

The 'Fragmented Policy' (FP) 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 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. The model will then produce the cost-optimal energy system development in order to achieve this constraint. Whilst no other explicit targets are implemented between 2020 and 2050 in this scenario (other than the common constraints and assumptions discussed above), in order to produce informative results some 'realism' constraints are applied, in order to maintain scenario feasibility. In summary, annual CO_2 emissions (post-2020) are not permitted to exceed the 2020 levels, renewable energy consumption may not reduce below 2020 levels, and annual CO_2 mitigation may not exceed a 3.5% reduction on emissions from the previous year between 2010 and 2040, and 8% between 2040 and 2050[15]. The combination of these constraints prevents the unrealistic 'backloading' of almost all investment in and utilisation of mitigation technologies and measures to the last few years of the assessment horizon, as a result of assumed technology cost reductions in the model and discounting of future costs.

It is assumed that the 'firm' emission and renewables targets in the UK and Germany will also be achieved in this scenario. The UK has a legislative obligation to reduce GHG emissions by 80% in 2050 (from 1990 levels), enshrined in the Climate Change Act 2008. This is implemented in the model by requiring a minimum 80% reduction in CO_2 in the UK & Ireland region[16]. 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). Again, the GHG target has been translated to CO_2 only for the purposes of this study. No other comparable Member State policies, where present (i.e. existing or upcoming policy instruments beyond simply a stated ambition), were judged to be of a robust enough nature to include in this study. As with the Reference scenario, fossil fuel prices should reflect the

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[15] The 3.5% value generally represents the upper end of possible annual reduction rates produced by the literature (den Elzen *et al* (2011)), whilst the increase to 8% maintains the ability for the model to produce a solution.

[16] As the UK accounts for the vast majority of CO_2 emissions in this region (501MtCO_2 in 2010, against Ireland's 41MtCO_2 (European Environment Agency, 2014)), it is reasonable to constrain the region as a whole.

influence of changing absolute and relative demand. As such, the 4DS prices listed in Table 5 are used.

4.4 'Policy Success' Scenario

The 'Policy Success' (PS) 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 – the minimum requirement for remaining in line with a 2°C trajectory. The implementation of this constraint is via the same mechanism described above. The UK and German targets also remain. Again, retaining the assumption that global and EU mitigation efforts evolve in tandem, the 2DS fossil fuel prices in Table 5 are implemented for this scenario.

4.4.1 'Policy Success' Sensitivities

As with any study attempting to determine the most appropriate path for the development of a low-carbon energy system, significant uncertainties exist. As such, four sensitivities on the Policy Success scenario are presented.

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 rapid development and commercial realisation of carbon capture and storage (CCS), for the power sector in particular, is often a backbone of low-carbon development plans. The ETM-UCL characterises several CCS techniques applicable to different power sector technologies[17], 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.

No Biomass CCS

As will be discussed, the development and deployment of CCS technology to power generation from biomass feedstock, and the negative emissions this generates, is often cited

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

as the key technology to producing significant decarbonisation of the EU's energy system. This scenario explores the implications for decarbonisation if this technology does not become available by 2050.

5 Core Scenario Results

This section presents and discusses the results of the above-described 'core' scenarios, as applied to the ETM-UCL. The results of the Policy Success sensitivities will be discussed in a separate section. As the objective of this paper is to discuss EU-level developments, this will be the focus. Regional level results will be presented and discussed in further detail where necessary. Sectoral-level results will also be discussed. A more detailed discussion of sectoral level results, and their implications, may be found in a subsequent publication in this series.

5.1 CO_2 Emissions

Figure 2 to Figure 4, below, present the direct CO_2 emissions profile for the three core scenarios (Reference, Fragmented Policy and Policy Success), with sectoral breakdown.

Figure 2 CO_2 Emissions by Sector - Reference

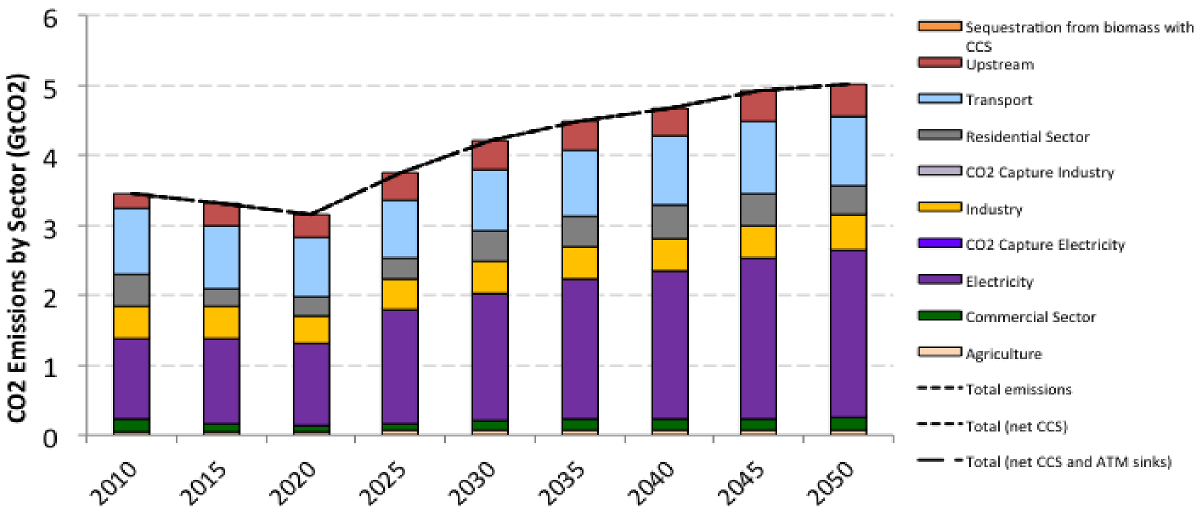


Figure 3 CO2 Emissions by Sector - Fragmented Policy

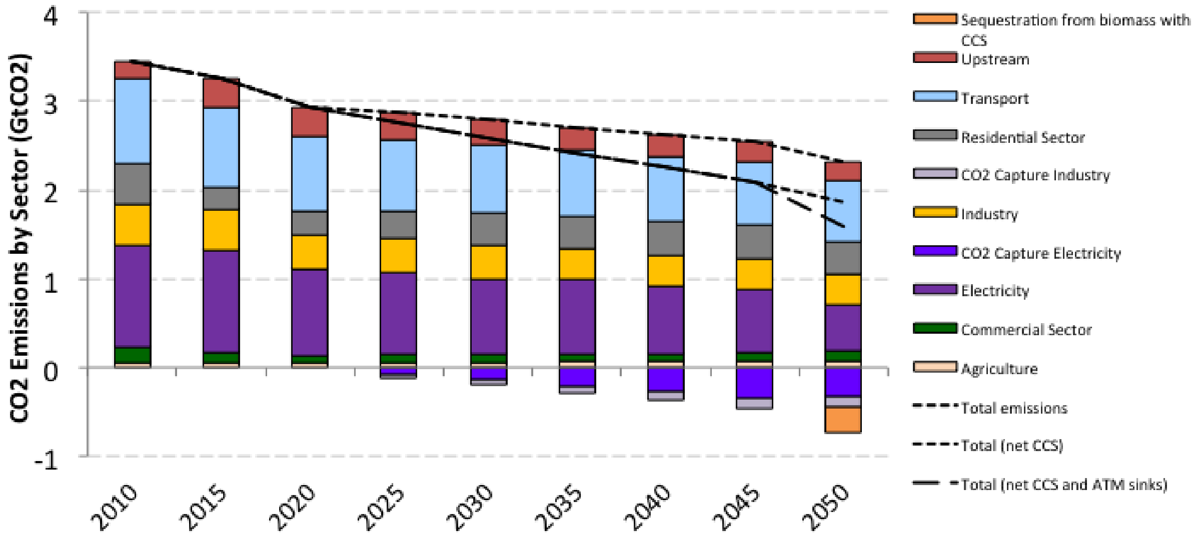
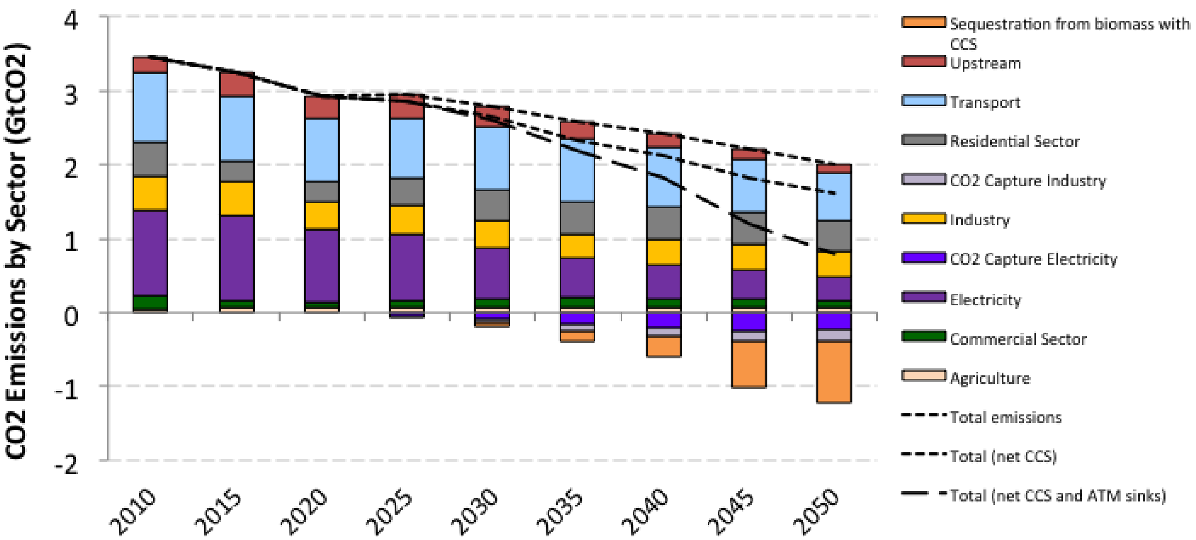


Figure 4 CO2 Emissions by Sector - Policy Success



Across all three scenarios emission trends between 2010 and 2020 are largely similar – both overall and in sectoral contribution. Whilst 2020 CO_2 emissions in the Reference scenario in 2020 are 9% lower than 2010, they are around 15% lower in the FP and PS scenarios. This equates to an approximate 29% reduction on 1990 levels, and 34% in the constrained scenarios - exceeding the 2020 GHG (CO_2) target in all cases.

Whilst most sectors make a contribution to CO_2 mitigation by between 2010 and 2020, the residential sector achieves the largest absolute savings in all instances (~180MtCO_2). The commercial sector achieves the largest proportional reduction however, with a reduction of around 54% in all three runs (~97MtCO_2). Power sector emissions reduce by 15% and 14% in the FS and PS scenarios respectively (~160MTCO_2), but increase in the Reference by around 4%. Whilst CO_2 emissions from agriculture also increase slightly in all scenarios to 2020 (~4%), ‘upstream’ sector emissions (e.g. resource extraction and refining) increases markedly, from 58% in PS (114MtCO_2), to 68% (133MtCO_2) in the Reference.

However, whilst these values are of importance, the purpose of this study and the structure of the ETM-UCL are designed to assess medium and longer-term developments in the EU’s energy system. As such, short-term (pre-2020) results are not the focus of assessment.

As expected, CO_2 emission profiles between 2020 and 2050 are much more heterogeneous. With no emission or renewable energy constraints from 2020, the Reference scenario rapidly increases to around 5GtCO_2 in 2050 (13% above 1990 levels), driven largely by rapid increases in power sector emissions (1.2GtCO_2 from 2020). The FP scenario on the other hand reduces annual net CO_2 emissions to around 1.6GtO_2 in 2050, whilst PS scenario emissions reduce to under 0.8GtCO_2. These reductions are 54% and 77% below 2010 levels, and 64% and 86% below 1990 levels, respectively. As the proposed 2030 Framework does not contain a CO_2-only target a direct assessment against the results presented here cannot be made. However, under both constrained scenarios a 41% CO_2 reduction is achieved below 1990 levels by 2030. The Reference scenario also retains a reduction of 5% by this point.

In FP and PS, as with the Reference scenario, the key driver behind these long-term emission trajectories is the power sector. As illustrated in Figure 2 and Figure 3, power sector CCS is introduced (at any significant level) from 2025 in both the FP and PS scenarios, with sequestration from biomass entering into use by 2050 in the former, and much earlier (2030) in the latter - becoming highly significant by 2050. This combination produces negative power sector emissions by 2050 and 2040 in FP and PS respectively, with the levels of biomass sequestration in the latter approximately equalling total CO_2 emissions remaining unabated from the entire energy system in 2050 (~0.8GtCO_2). CCS is also applied to industrial processes in the FP and PS scenarios in 2025, responsible for the majority of the 54% and 61% reduction in industrial CO_2 emissions projected by 2050 from 2010, respectively. Upstream emissions continue their increasing trend in the Reference and more than double by 2050, whilst they return to 2010 levels in FP and to half this in PS.

Although the residential and commercial sectors are decisive contributors in abatement to reach the 2020 emissions target across these scenarios, annual emissions in FP and PS from both sectors in 2050 are higher than 2020 values (but remain below 1990 levels). The increase is particularly prevalent for the residential sector; emissions in 2050 are only 20% and 9% lower than 2010 in FP and PS, respectively. CO_2 emissions from agriculture continue to grow to 2050 at an equal rate across all scenarios, reaching 74MtCO_2 annually. Transport emissions alter little to 2020, and remain stable to 2050 in the Reference. In the constrained scenarios however, 2050 transport emissions (chiefly road transport, as aviation and shipping emissions are excluded from this analysis), reduce by around 30% between 2020 and 2050. Due to the relative significance of this sector, this equates to a reduction of around 300MtCO_2.

Figure 5 to Figure 7 illustrates the contributions of the nine regions of the model to overall CO_2 emissions, across the three scenarios.

Table 6 describes the proportional change of CO_2 emissions by 2050 from 1990 by region and EU-wide, for each scenario.

Figure 5 CO_2 Emissions by Region - Reference

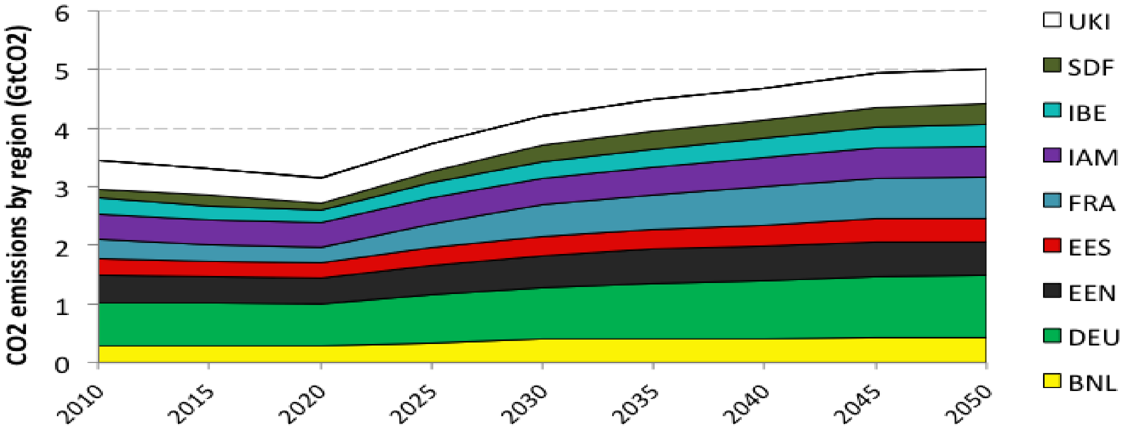


Figure 6 CO_2 Emissions by Region - Fragmented Policy

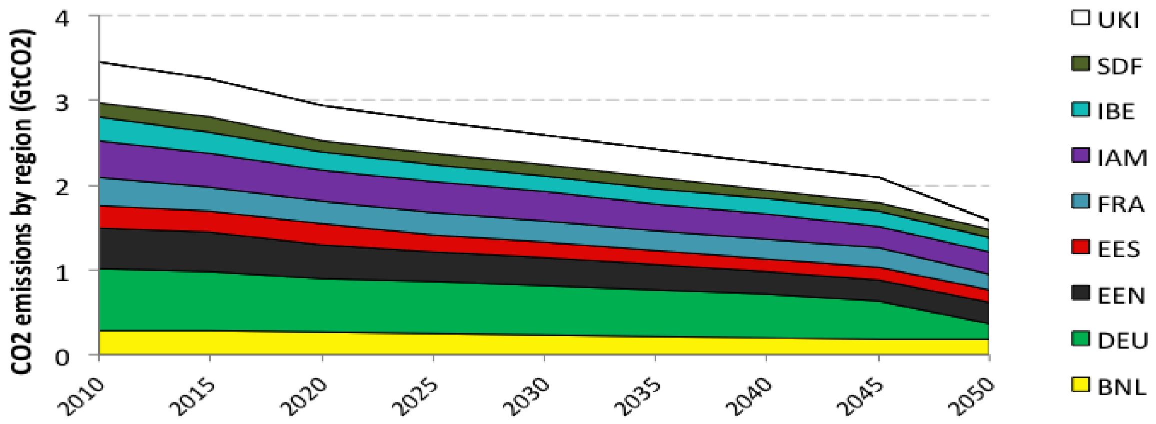


Figure 7 CO_2 Emissions by Region - Policy Success

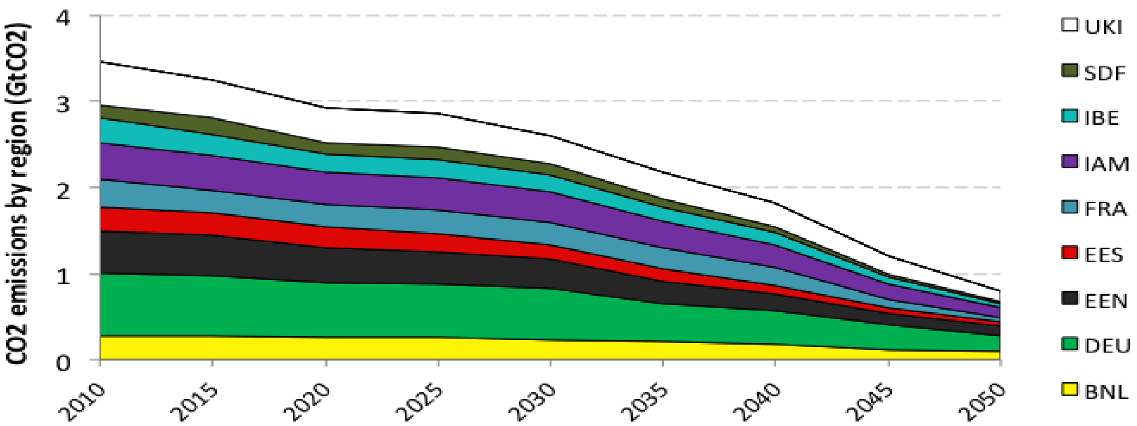


Table 6 CO_2 Reduction in 2050 from 1990 - EU and Regional

Region	% Change in 2050 CO_2 emissions from 1990 levels - Reference	% Change in 2050 CO_2 emissions from 1990 levels – Fragmented Policy	% Change in 2050 CO_2 emissions from 1990 levels – Policy Success
BNL	49%	-37%	-67%
DEU	2%	-82%	-82%
EEN	-17%	-64%	-84%
EES	-12%	-69%	-90%
FRA	78%	-51%	-87%
IAM	0%	-49%	-76%
IBE	44%	-36%	-83%
SDF	104%	-47%	-87%
UKI	-2%	-81%	-81%
EU-Wide	**13%**	**-64%**	**-86%**

The overachievement in EU-wide CO_2 reduction targets in the two constrained scenarios is likely a result of simple cost-efficiency – once certain investments have been made in the energy system to achieve the minimum constraints, it is cheaper to utilise them to the full and achieve further abatement as a consequence.

The regional change in CO_2 emissions in the Reference scenario is extremely varied, ranging between -17% and 104% by 2050. In the constrained scenarios, and particularly PS, the range of developments is much smaller (but still present), with all regions experiencing significant reductions. Germany and the UK & Ireland regions both meet (and exceed) 80% reductions as required, although Germany remains the largest single emitter in both instances. The most significant proportional reduction by a region without a pre-defined target is EES, achieving -67% in FP and -90% in PS (in which it holds the largest proportional contribution to abatement efforts overall). The Benelux region contributes the least proportional reduction by 2050 in PS (-67%), and marginally the second-least in FP (-37%, slightly more than Iberia at -36%). However, this region is a minor contributor to EU CO_2 emissions in all scenarios.

5.2 Primary and Final Energy Consumption

Figure 8 to Figure 10 present developments in primary energy consumption across the EU for the Reference, FP and PS scenarios.

Figure 8 EU Primary Energy Consumption - Reference

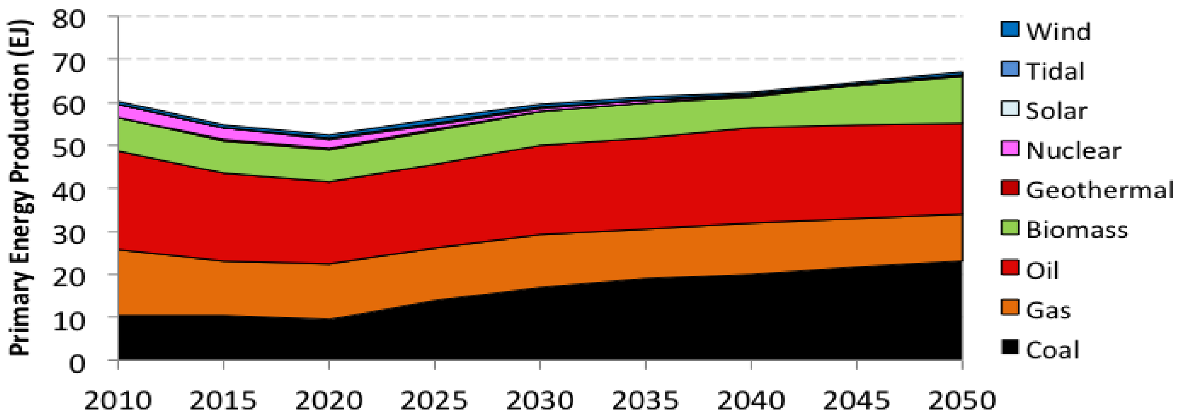


Figure 9 EU Primary Energy Consumption - Fragmented Policy

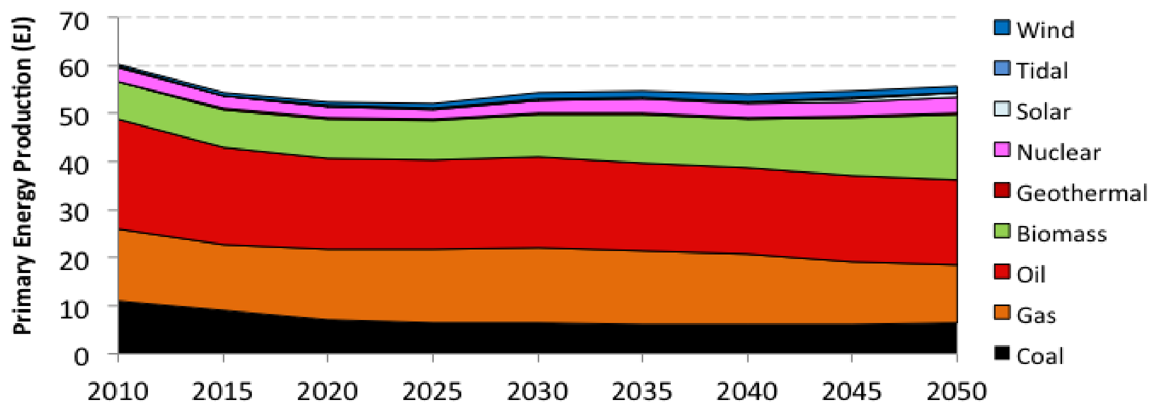
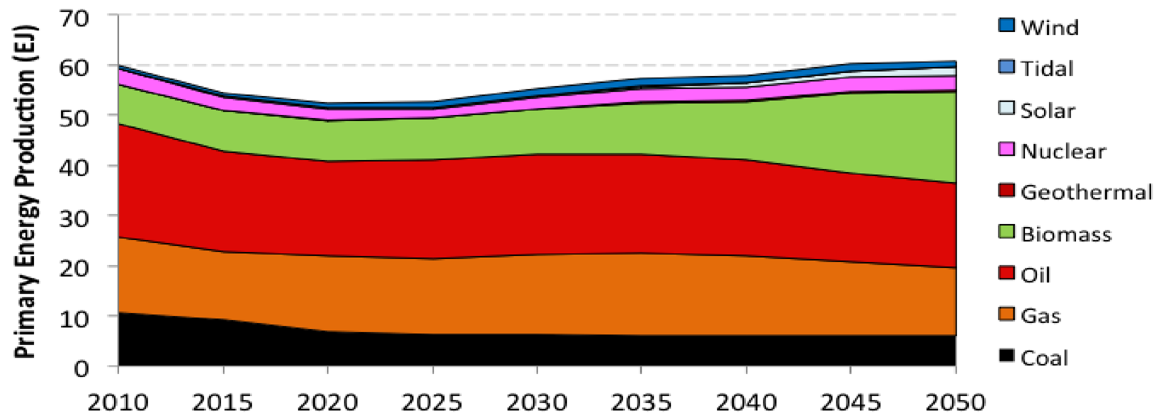


Figure 10 EU Primary Energy Consumption - Policy Success



Trends in primary energy consumption across the three scenarios are again similar between 2010 and 2020, with a general decrease in total demand of around 9% (mainly due to reducing oil and coal demand in FP and PS, and oil and gas demand in the Reference). This equals a 29% reduction against the projected baseline calculated under the Energy Efficiency Directive, thus 2020 EU energy efficiency target of 20% is exceeded despite no explicit model constraint. Post-2020 trends again diverge. In the Reference overall demand increases, driven by rapidly rising coal demand – more than doubling by 2050 from 2010 levels. Demand for gas drops by around a third, with biomass experiencing an increasing share from 2040 to roughly equal that of gas by 2050. Supply of nuclear is eliminated by 2045, as no new capacity is constructed. The FP and PS scenarios both experience decreasing trends in the primary consumption of coal, gas and oil, and similar increasing trends in primary consumption of wind and solar (with nuclear remaining largely constant). Whilst overall annual primary consumption post-2020 remains largely stable at around 57EJ in the FP scenario, demand increases to around 62EJ in PS, satisfied by an increasing consumption of biomass (to around 29% of total EU primary energy consumption in 2050, from 13% in 2010).

Figure 11 and Figure 12 illustrate the trends in EU imports of fossil fuel products[18] and biomass across the assessment horizon, for the three core scenarios[19].

Figure 11 EU Fossil Fuel Imports

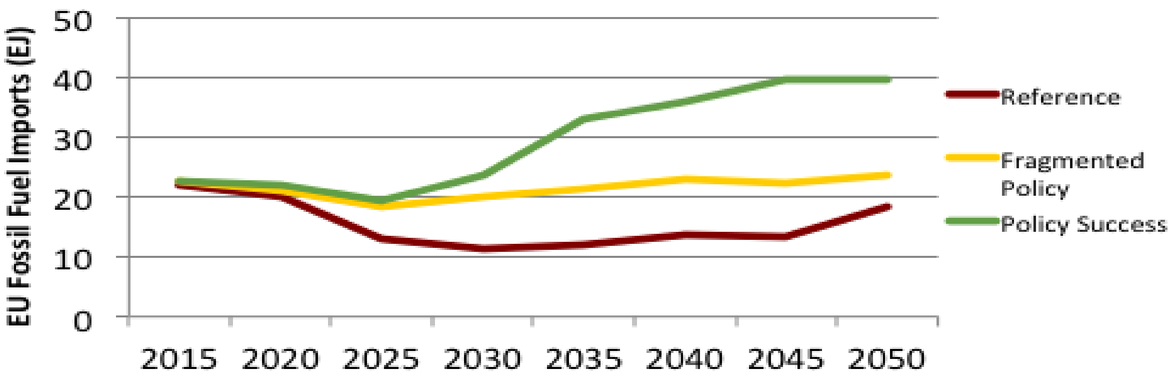
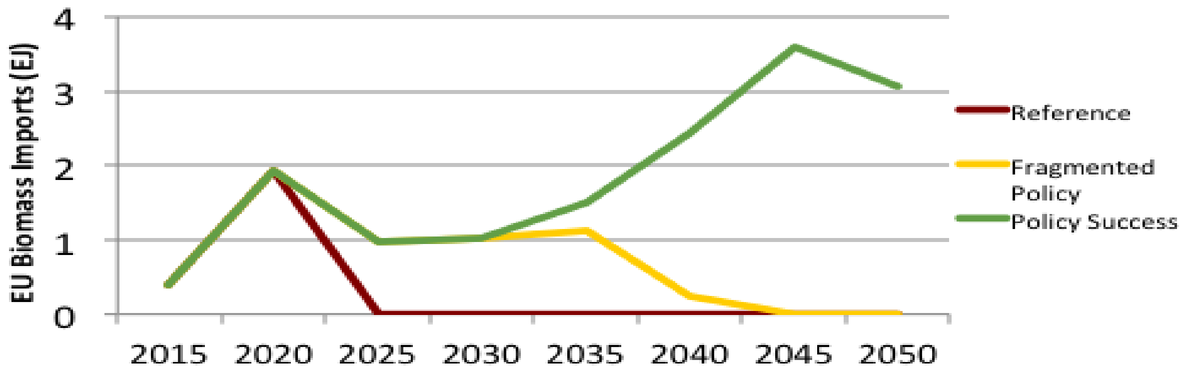


Figure 12 EU Biomass Imports



Trends for fossil fuel imports diverge from around 22EJ in 2020, dropping to 18EJ in the Reference and increasing to nearly 40EJ in PS. Increasing imports with tightening emission constraints is incentivised by reduced import prices coupled with reducing domestic production to achieve a reduction in upstream emissions. Biomass imports also increase with tighter emission constraints to meet the increasing demand described above, despite higher import prices in the Policy Success scenario.

[18] Coal, gas and oil products (e.g. gasoline, diesel, kerosene).

[19] 2010 base year values are not shown as these are fixed 'actual' values, rather than optimised values projected for subsequent years, which of are interest in this study. Such reasoning is applied to other figures in this report that do not present 2010 values.

Table 7 EU Final Energy Consumption - Reference

Final Energy Carrier (PJ)	2010	2020	2030	2040	2050
Coal	1,481	979	1,023	841	811
Natural Gas	11,851	9,586	11,782	11,327	10,618
Electricity	10,229	10,780	10,964	11,452	12,361
Oil Products	25,352	21,116	22,037	23,341	23,605
Direct Biomass	2,769	4,393	3,328	3,212	4,371
Biofuels	166	1,359	1,239	705	488
Heat	1,941	1,618	1,541	1,295	1,274
Hydrogen	9	44	17	11	38
Other Renewables	96	94	99	65	55
Total	**53,878**	**49,976**	**53,087**	**54,238**	**56,001**

Table 8 EU Final Energy Consumption - Fragmented Policy

Region	2010	2020	2030	2040	2050
Coal	1,478	988	1,061	785	727
Natural Gas	11,840	9,476	11,655	12,009	11,420
Electricity	10,233	10,690	11,325	11,905	12,350
Oil Products	25,361	21,267	20,557	19,456	19,168
Direct Biomass	2,770	4,956	4,674	4,207	4,196
Biofuels	166	1,364	1,611	1,974	1,844
Heat	1,940	1,624	1,588	1,452	1,494
Hydrogen	7	51	197	237	512
Other Renewables	103	94	119	75	30
Total	**53,898**	**50,509**	**52,788**	**52,100**	**51,742**

Table 9 EU Final Energy Consumption - Policy Success

Region	2010	2020	2030	2040	2050
Coal	1,481	979	1,023	841	811
Natural Gas	11,835	9,546	12,174	12,941	12,709
Electricity	10,233	10,787	10,612	11,324	12,238
Oil Products	25,363	21,184	21,785	20,787	18,458
Direct Biomass	2,770	4,744	4,545	3,494	2,372
Biofuels	165	1,363	1,284	1,485	1,787
Heat	1,940	1,620	1,577	1,571	1,723
Hydrogen	6	55	47	421	2,269
Other Renewables	103	94	121	101	99
Total	**53,896**	**50,371**	**53,169**	**52,965**	**52,465**

Table 7 to Table 9 present projected trends in final energy consumption for the three scenarios (presented in table form for readability). Again, trends to 2020 are generally equal between scenarios. The 2020 renewable target slightly exceeded in all cases, with renewables accounting for around 21% of final energy consumption. Trends begin to diverge by 2030 (although total final energy returns to around 2010 levels in all cases, from the reduction by 2020), with the proportion of renewables dropping to around 16% in the Reference, and remaining at 2020 levels in the constrained scenarios. As such, the proposed 2030 target of 27% renewables in final energy consumption is not achieved in any scenario. Total final energy consumption in the constrained scenarios remains stable between 2030 and 2050, whilst the Reference scenario experiences an increase to around 2EJ above 2010 levels. By 2050 the proportion of renewables drops further to around 14% in the Reference, and increases to around 28% and 30% in FP and PS, respectively.

5.3 Overview of Sectoral Developments

This section describes the sectoral developments of the European energy system in the Reference, FP and PS scenarios. Sectors are presented in order of significance of CO_2 emissions.

5.3.1 Power Sector

Figure 13 to Figure 15, below, illustrate the development of the EU's electricity generation profile across the three core scenarios.

Figure 13 EU Electricity Generation Profile - Reference

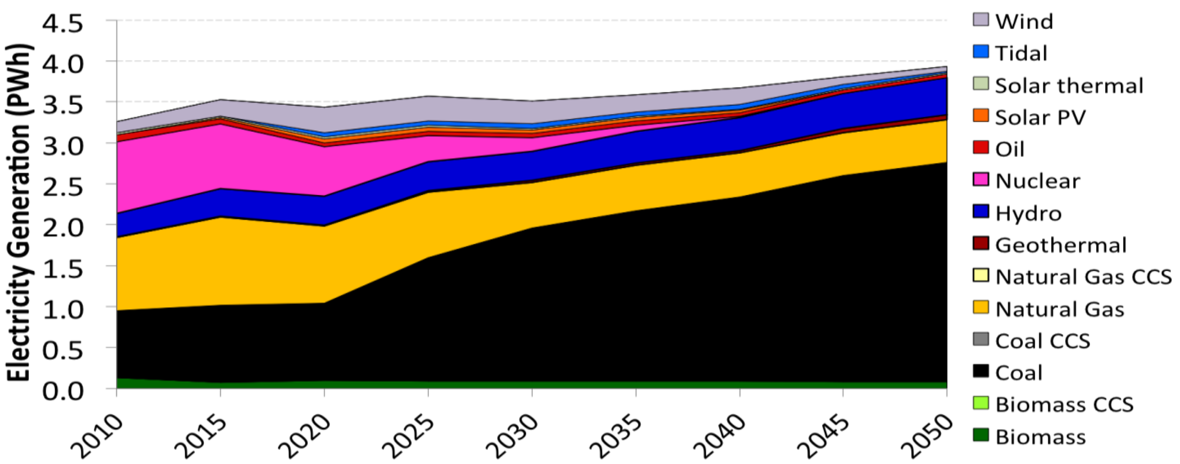


Figure 14 EU Electricity Generation Profile - Fragmented Policy

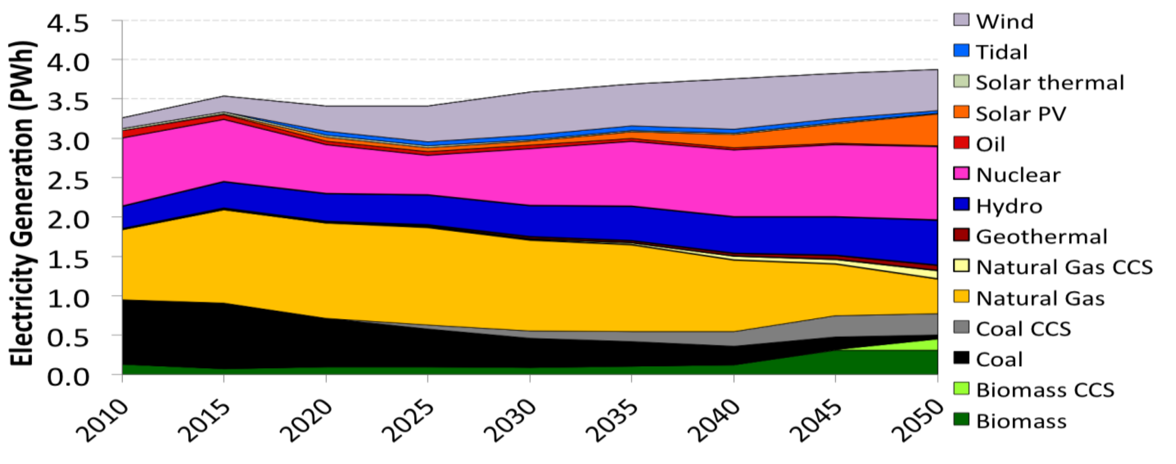
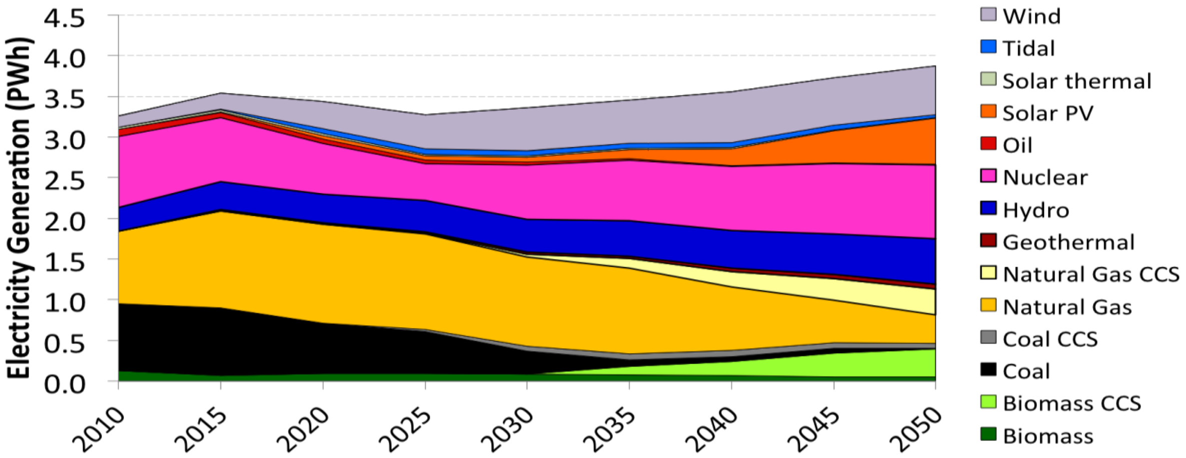


Figure 15 EU Electricity Generation Profile - Policy Success



Total generation increases across all scenarios at a relatively equal pace, from around 3.3PWh in 2010 to approximately 3.9PWh in 2050. By 2020, renewable electricity (RES-E) accounts for around 26.5% of generation (largely hydro and wind) in all scenarios (up from around 18% in 2010), but with significant divergence post-2020. The Reference scenario (Figure 13) rapidly turns to coal post-2020 for the majority of electricity supply (68% by 2050, accounting for the majority of the growth in coal in primary energy demand seen in Figure 8), with gas and hydropower accounting for much of the remainder (13% and 11% of total generation in 2050, respectively), despite significant increases in imposed fossil fuel costs. Non-hydro renewables (mainly wind and biomass) retain a 6% share by 2050, with nuclear generation absent by 2045. The development of the generation profile in the FP and PS scenarios (Figure 14 and Figure 15), are clearly very different from the Reference scenario, but largely similar to each other. There are three key differences between the constrained scenarios and the Reference. The most significant departure concerns coal generation, which experiences a relatively steady decline. In FP coal declines to an 8.3% share of generation by 2050, with only around fifth of this remaining unabated (without CCS). In PS, coal (including both abated and unabated), becomes relatively insignificant by 2050 (1.8% of generation). The second main departure is the investment in nuclear in the constrained scenarios, which retains 2010 generation levels (around 0.9PWh), aside from a 'pinch point' around 2025, with generation briefly reducing to around 0.45PWh as a result of lead-time constraints (planning and construction) for new capacity[20]. However, nuclear reduces from around 27% to 24% as a proportion of total generation in both FP and PS – a function of increasing total generation. The third crucial difference is the increasing prevalence of non-hydro renewables in the constrained scenarios, which by 2050 accounts for 38% and 43% of generation in FP and PS, respectively. In both scenarios wind power[21] is the largest single non-hydro renewable generation source by 2050 (this remains true inclusive of hydro in the PS scenario, in which, behind nuclear and gas, it also the third largest electricity resource overall). Solar PV is also highly significant in both scenarios, and exhibits rapid growth from 2035 to reach 10% of total

[20] A lead time of 10 years is required for nuclear technologies in ETM-UCL.
[21] Onshore and offshore wind is not disaggregated.

generation by 2050 in FP, and 15% in PS – almost equivalent to wind generation in the latter. The use of biomass for power generation, with CCS in particular, has important ramifications. As tabulated below in the form of CO_2 emission intensity of generation (Table 10), biomass sequestration leads to negative emissions by 2050 in FP and from 2040 in PS. Whilst more generation from biomass is projected for the FP scenario by 2050 (450TWh compared to 400TWh for PS), a higher proportion of biomass generation in PS is with CCS (87% compared to 33% in FP), producing the significant differences seen in the trends in Table 10.

Table 10 CO_2 Intensity of EU Power Generation

gCO_2/KWh	2010	2015	2020	2025	2030	2035	2040	2045	2050
Reference	348	344	342	453	520	554	574	600	612
Fragmented Policy	348	327	283	248	199	171	132	96	-19
Policy Success	348	326	285	264	170	63	-12	-132	-190

Despite significant power sector changes over time and between scenarios, the proportion of different energy resources in total primary energy supply directed to power generation remains largely unchanged (although, as discussed, absolute supply of these resources does vary). Power generation demands around three-quarters of primary coal supply, and a third of natural gas. Whilst clearly all renewable power resources in primary supply are used to generate electricity, the proportion of biomass in primary consumption directed to power generation is the only commodity that varies with any significance, beginning at around 20% in 2010, rising to around 60% in the Reference by 2050, and around 40% in the constrained scenarios. Under 2% of oil and oil product primary supply is used in electricity production.

Figure 16 to Figure 18 illustrate the corresponding changes in electricity capacity profiles that enable the generation profiles discussed above. Due to the low load factor of wind and solar PV, very considerable capacity is required in the FP and PS scenarios by 2050. For wind this growth begins immediately, and from 2030 for solar PV. By 2050 wind and solar capacity combined reaches 53% (617GW) and 60% (785GW) of total capacity in FP and PS respectively. This is a very substantial increase (13%) from the EU-wide combined capacity of 95GW in 2010.

Figure 16 EU Total Installed Electricity Capacity - Reference

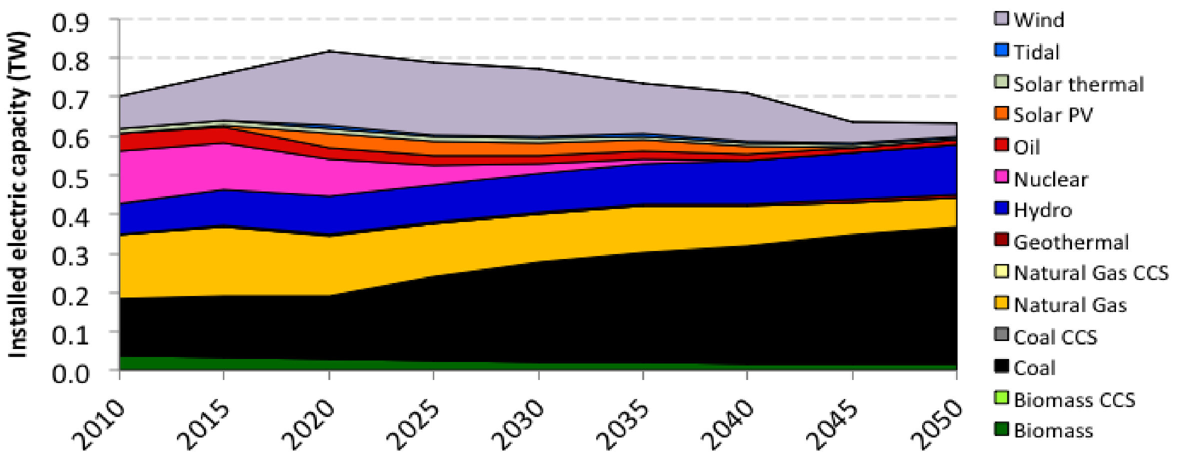


Figure 17 EU Total Installed Electricity Capacity - Fragmented Policy

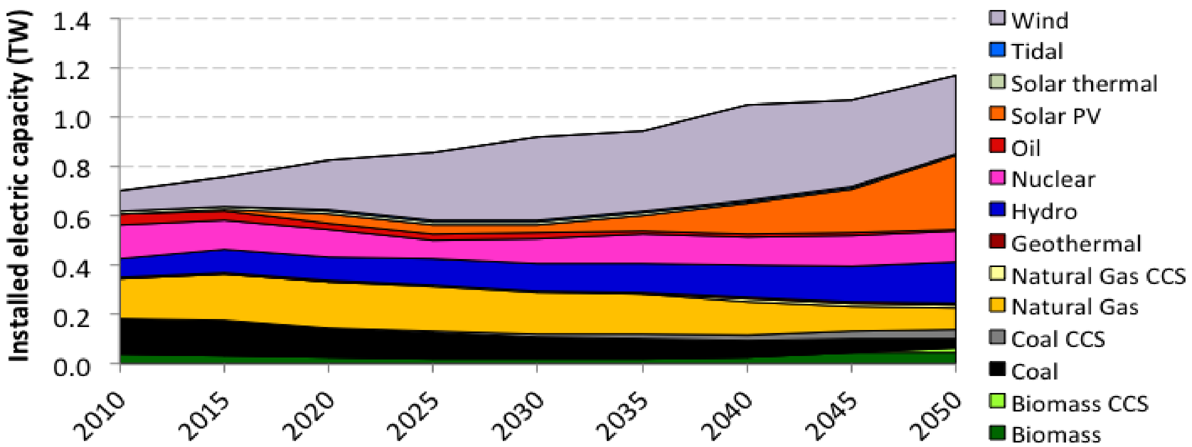
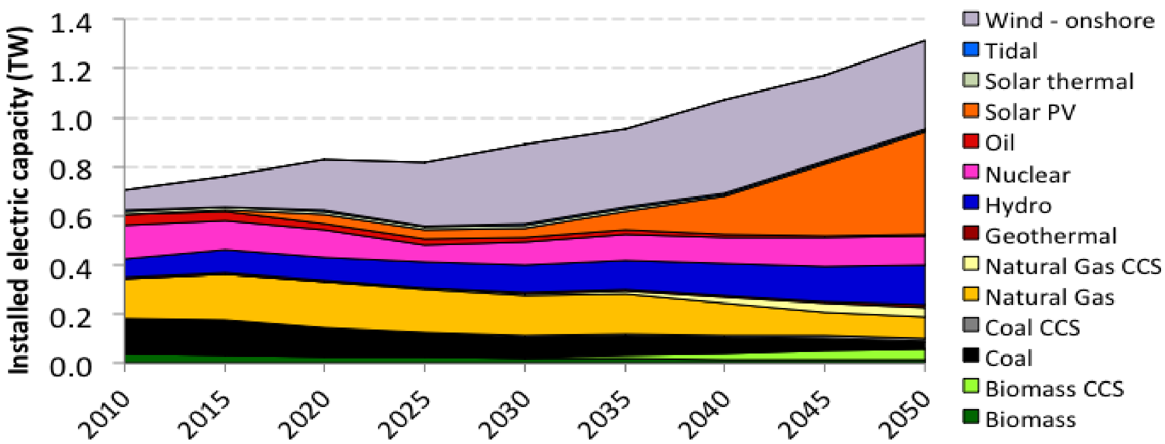


Figure 18 EU Total Installed Electricity Capacity - Policy Success



Figures illustrating regional differences in electricity generation profiles for the Policy Success scenario (the primary focus of this report) may be found in Annex 1. All regions (except Germany) project increased electricity generation by 2050 from 2010 levels. The overall reduction in coal-based generation is also driven by a common trend across all countries in which it holds significance in 2010 (all except France and Iberia), but with reductions in Germany and EEN holding the largest influence. By 2050 the EEN, SDF and IAM regions account for nearly 80% of remaining coal generation - the vast majority of which uses CCS technology. Nuclear capacity pushes up against the imposed constraints in all regions (Table 4), with the EEN and EES together replacing the corresponding reduction in German capacity. The 2025 nuclear 'pinch point' is driven particularly by France, but also the BNL, IBE and UKI regions, in which lead times mean new capacity cannot come online in time to replace the retirement of the existing fleet to maintain a constant level of generation. The use of wind grows to be significant in 2050 in most regions except France, EEN and EES, but with Germany and the UK & Ireland accounting for over half of all European wind generation. Wind also appears to be the shorter-term technology of choice to replace nuclear generation when pinch-points are experienced. Trends in the use of solar in different regions appear to follow that of wind, but with rapid growth beginning later (around 2035). As with wind, Germany accounts for the most generation from solar PV of any region by 2050 (in both proportional (30% of German generation) and absolute terms (32% of total EU solar PV generation)). Wind and solar PV combined produce 64% of the Germany's generation by 2050. The use of Biomass with CCS appears in all regions from 2035, and grows to roughly equal proportions in each by 2050 (between 7% and 10% of total regional generation). The use of gas and hydroelectricity remains relatively constant over time in most regions (except for significant growth in gas in EEN, and hydro in EES and SDF), but with gas increasingly used in conjunction with CCS from 2030.

Generation trends in individual regions are volatile in comparison to the aggregate EU trend. This is in large part due to different regional characteristics, but the presence of inter-state electricity trading, and the differences in trade volumes over time, is also a factor. Electricity trade reduces by 23%, 22% and 31% between 2010 and 2050 in the Reference, FP and PS scenarios respectively. This is in opposition to expectations, as additional trade helps facilitate increasing penetration of intermittent renewables. However, electricity trade dynamics are characterised in only basic terms in ETM-UCL, and as such may not produce trends that reflect expectations or results of other models in which such dynamics are more specifically modelled.

5.3.2 Transport Sector

Road transport accounted for over 70% of total EU transport CO_2 emissions in 2010 (and around 20% of all EU CO_2 emissions), and as such is the focus of transport sector analysis in this report. Figure 19 to Figure 21 illustrate the CO_2 emission intensity of key transport categories for the three scenarios. Figure 22 to Figure 24 display corresponding fuel consumption trends[22].

[22] These figures also include consumption by buses and motorbikes, in addition to the three key vehicle categories presented in Figure 19 to Figure 21 however these vehicle types consistently account for under 4% of total road transport fuel consumption.

Figure 19 CO_2 Emission Intensity of Road Vehicles - Reference

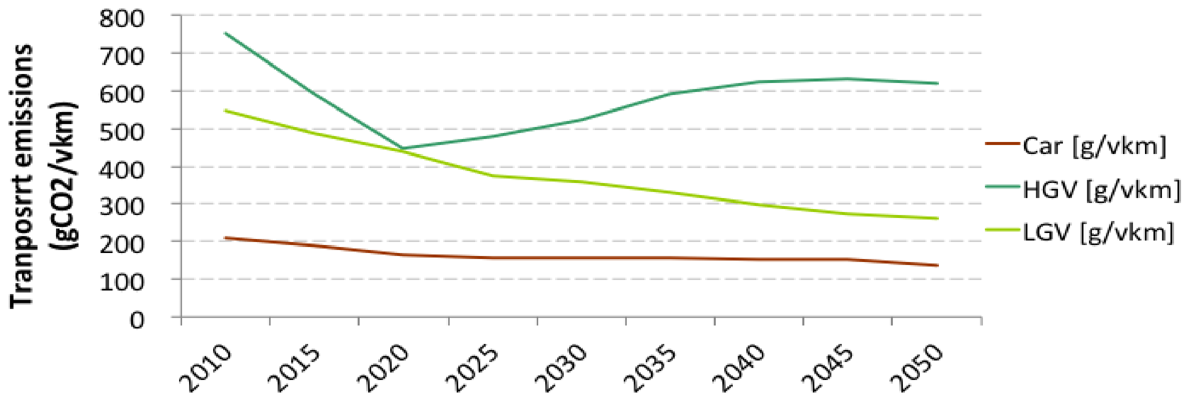


Figure 20 CO2 Emission Intensity of Road Vehicles - Fragmented Policy

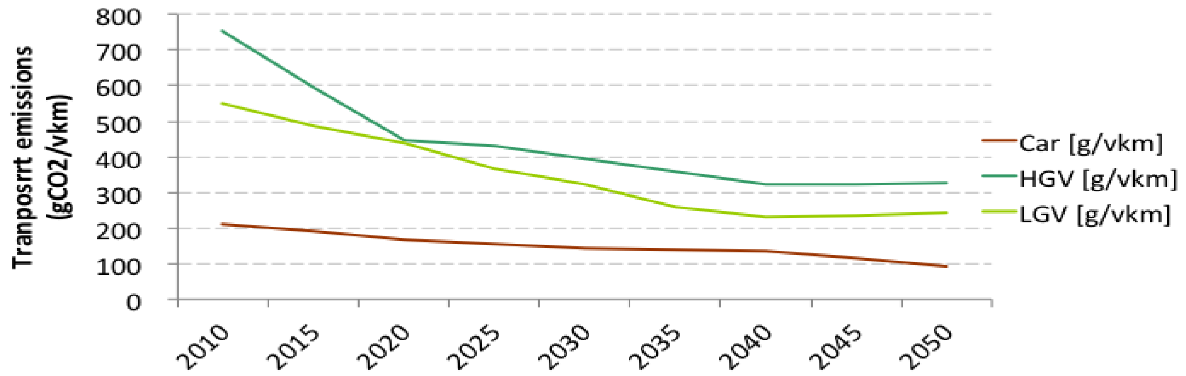


Figure 21 CO2 Emission Intensity of Road Vehicles - Policy Success

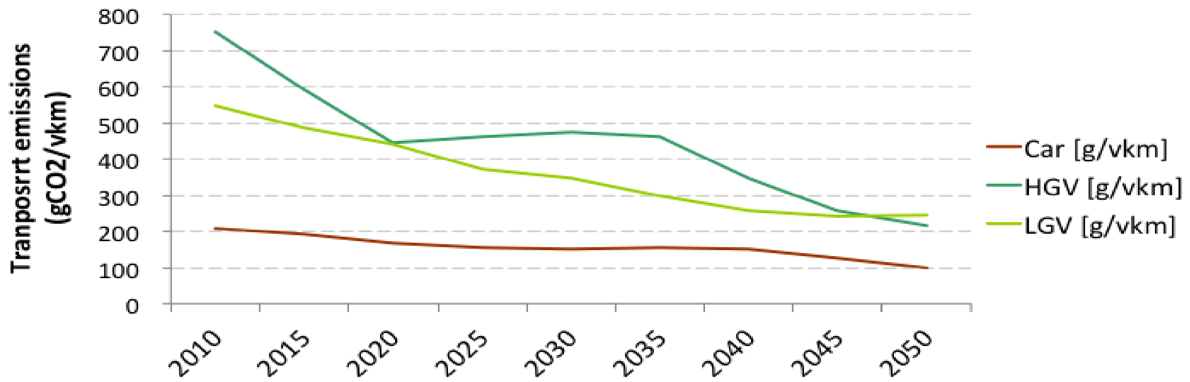


Figure 22 Fuel Consumption by All Road Transport - Reference

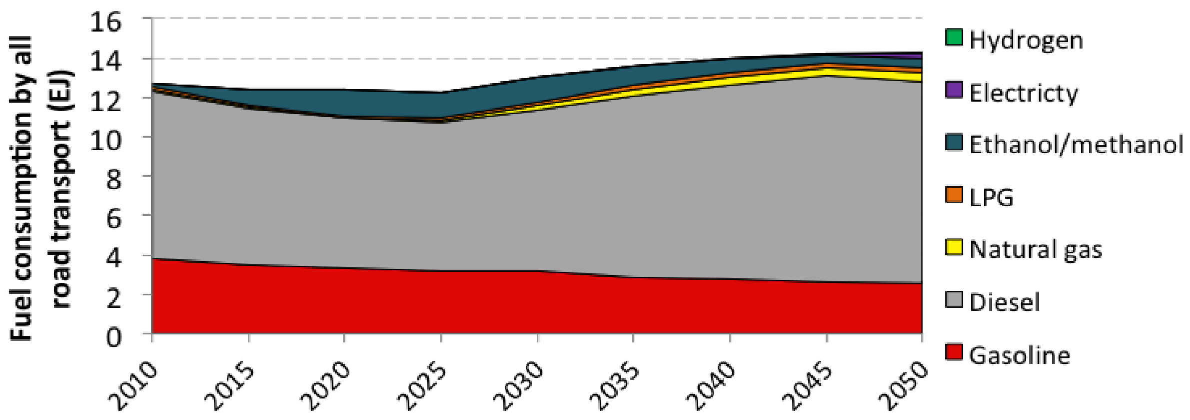


Figure 23 Fuel Consumption by All Road Transport - Fragmented Policy

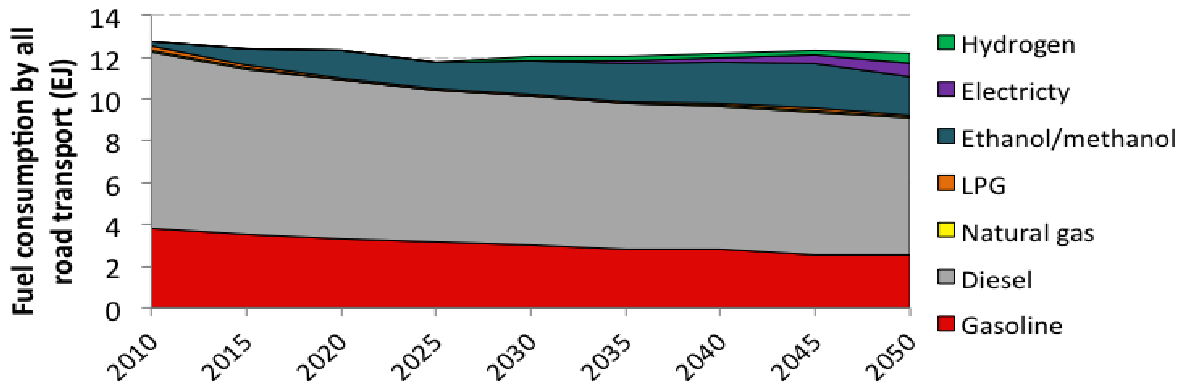
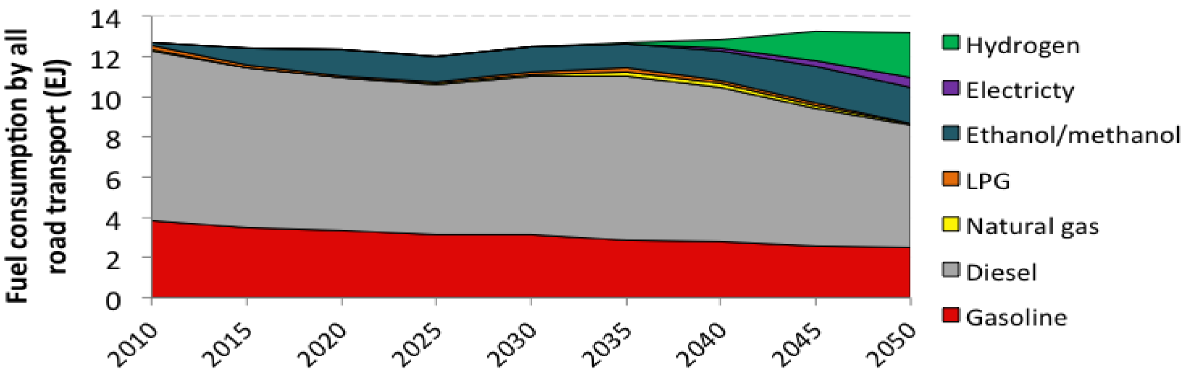


Figure 24 Fuel Consumption by All Road Transport - Policy Success



In all scenarios road transport demand grows from around 2,600 billion vehicle kilometres (bvkm) in 2010 to around 4,400bkvm in 2050. As the model does not optimise modal split, the proportional contribution remains roughly equal at 70% of demand car travel, 13% from Heavy Goods Vehicles (HVGs) and 17% from Light Goods Vehicles (LGVs, which includes vans and medium-sized commercial trucks). Trends in total transport emissions vary across the three scenarios (from a 5% increase in the Reference between 2010 and 2050, to a 32% reduction in Policy Success), are driven almost entirely by changes in the CO_2 emission intensity of these three types of road vehicle.

The CO_2 intensity of cars experiences the least change overall in all three scenarios, decreasing from around 190gCO_2/vkm in 2010 to 135gCO_2/vkm in the Reference, and around 95gCO_2/vkm in the constrained scenarios by 2050. The continued decrease in CO_2 intensity after 2020 in the Reference is due partly to the broad switch to more efficient diesel vehicles, but also to the availability over time of more efficient vehicles and technologies overall, that are cost-optimal to deploy even in the absence of other constraints. This is also the case for other transport modes, and for other end-use technologies in other sectors. In FP and PS, further reductions are in part due to a more extensive gasoline to diesel switch. Additionally, the use of hybrid cars also becomes significant from 2025 in FP, with plug-in hybrids (PHEVs) entering the mix significantly from 2040 - the combination of which is responsible much of the 'wedge' of electricity use visible in Figure 23. In PS, biofuels (ethanol/methanol) are also introduced (with some PHEVs), accounting for over half of the growth in ethanol and methanol consumption illustrated in Figure 24 (with the remainder consumed in HGVs, discussed below). In PS, conventional cars continue to satisfy 54% of car transport demand by 2050, and 45% in FP.

LGVs experience relatively significant CO_2 intensity reductions across all scenarios, down to around 260gCO_2/vkm in the Reference, and around 245gCO2/vkm in the two constrained scenarios (from around 550gCO_2/vkm in 2010). These trends are achieved via similar methods (including improved vehicle efficiency over time, as discussed above). All scenarios experience a rapid increase in PHEVs post-2020. In the Reference and PS scenarios this begins around 2035, and around 2025 in FP. By 2050 PHEVs account for 46% of LGV demand in the Reference, and 41% in the constrained scenarios. Interestingly, whilst gasoline and diesel internal combustion engine (ICE) vehicles retain an approximate 40% share of LGV travel demand in the Reference scenario by 2050, this value is 50% in the constrained scenarios – with the difference likely due to differences in oil import prices (lower in the constrained scenarios). The remainder of LGV demand is satisfied by a combination of hybrid, biofuel, LPG and natural gas vehicles. LGVs account for the entirety of LPG and natural gas consumption seen in Figure 22 and Figure 24.

All scenarios produce a rapid increase in biofuels for HGVs between 2010 and 2020, producing the sharply decreasing trend in CO_2 intensity between these years seen in the figures above. This accounts for almost all the increase in biofuel consumption up to 2020 presented in the figures above for all scenarios, and satisfies the 2020 renewable transport constraint (at least 10% biofuels). The post-2020 trend in HGV CO_2 intensity is clearly the most sensitive to the constraints imposed. Whilst CO_2 intensity is lower in 2050 than 2010 in all cases, the extent varies from a reduction to 620gCO_2/vkm in the Reference, to 215gCO_2/vkm in PS (from 750gCO_2/vkm in 2010). Whilst in the Reference case biofuels are phased out in favour of a return to diesel, they remain in the HGV fuel mix at roughly the same 2020 level out to 2050 in the constrained scenarios (around 1.3PJ). Hydrogen fuel cells are also introduced to HGVs in the constrained scenarios from around 2030, becoming significant by 2050 - especially in PS (satisfying around half of HGV energy demand, compared to 11% in FP). HGVs account for the entirety of hydrogen use in road vehicles, as seen in Figure 23 and Figure 24, with almost all hydrogen in the energy system in these scenarios (Table 7 and Table 9), produced from a combination of biomass gasification and electrolysis.

Road transport consistently accounts for around 24% of total final energy demand in the EU, in all three scenarios. In addition to almost all hydrogen, this includes around half of all oil products, and all biofuels. The use of natural gas in LGVs reaches 4% of total final consumption in 2050 in the Reference scenario, whilst road transport in the constrained scenarios demands 4%-5% of final electricity consumption (mainly via cars).

5.3.3 Residential and Commercial Sectors

The residential and commercial sectors together accounted for around 19% of EU emissions in 2010, and around 36% of total final energy consumption.

Residential

Figure 25 to Figure 27 Illustrate developments in final energy consumption in the residential sector in proportional terms, for the three core scenarios.

Figure 25 Residential Final Energy Consumption - Reference

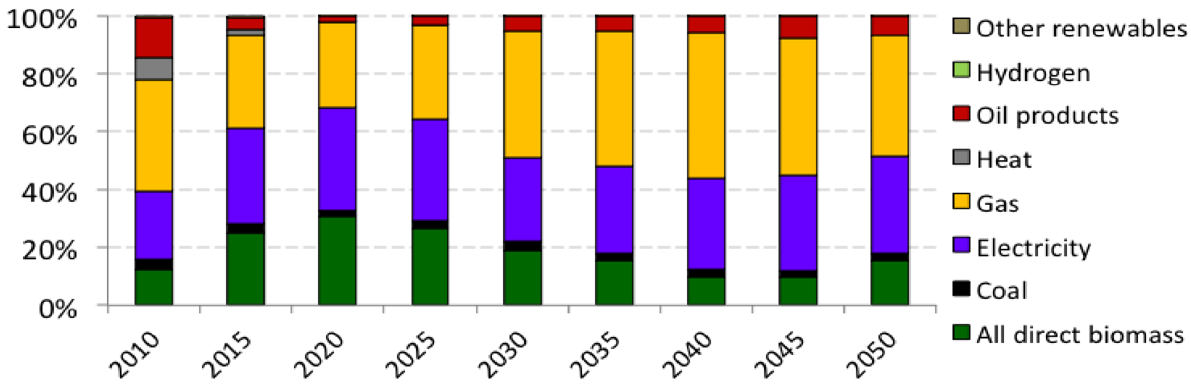


Figure 26 Residential Final Energy Consumption – Fragmented Policy

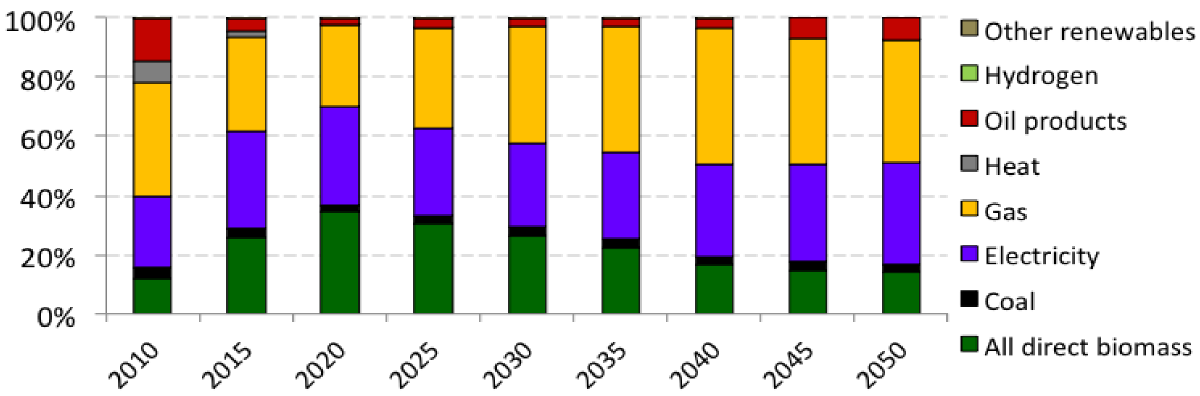
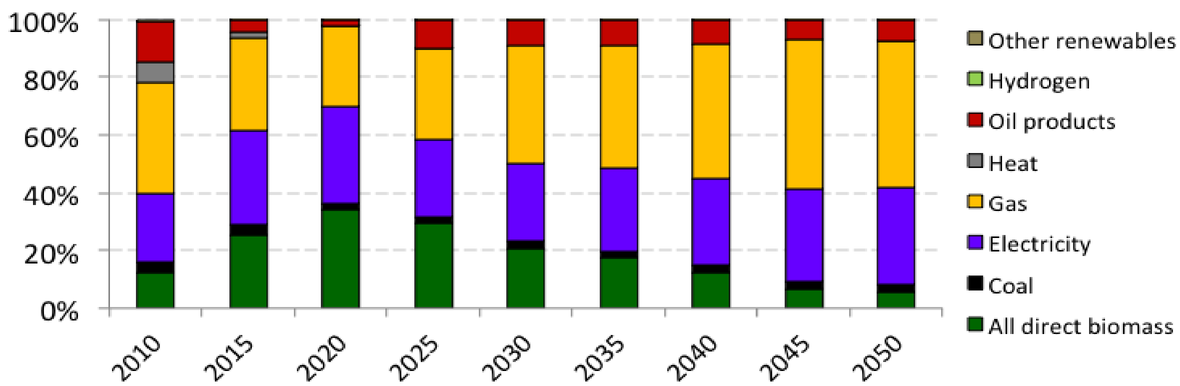


Figure 27 Residential Final Energy Consumption - Policy Success



Once again, the development of final energy consumption in the residential sector is relatively similar between the scenarios, beginning at around 13EJ in 2010, with slight divergence occurring form 2030 with Reference demand rising to around 13.5EJ, and the constrained scenarios both reducing to just below 12EJ. There is also significant similarity in fuel profiles. Coal maintains a minor share, whilst oil products decrease from 14% to 7% of total domestic consumption by 2050 (temporarily reducing to around 2% in 2020), and electricity increases from 3EJ to 4EJ (24% to 34% of the total) between 2010 and 2050, in all scenarios. The proportion of biomass and natural gas is more turbulent. Biomass accounts for around 12% of residential energy consumption in 2010, increasing rapidly to around 33% by 2020. In each case this proportion drops by 2050, returning to 2010 levels in the Reference and FP scenarios (both proportionally and in absolute terms). In the PS scenario, biomass reduces to around 5% of total residential consumption by 2050 - about a third of 2010 levels in absolute terms. Natural gas experiences the opposite fortunes to biomass by 2020, reducing from 39% in 2010 to 29%. It then increases in absolute terms in all cases to above 2010 levels, and proportionally to a 42% share by 2050 in the Reference and FP scenarios, and up to 51% in PS. The use of direct heat is removed by 2020 in all scenarios.

Table 11 Proportion of Total Final Energy Consumption - Residential Sector

Fuel	2010	2050		
	All Scenarios	Reference	Fragmented Policy	Policy Success
Coal	30%	11%	41%	36%
Oil Products	7%	4%	5%	5%
Natural Gas	42%	53%	44%	47%
Biomass	57%	47%	41%	25%
Electricity	30%	37%	33%	32%
Heat	49%	0%	1%	0%

Table 11 displays the proportion of total final energy demand by fuel accounted for by the residential sector. The changing values largely reflect changing absolute use of these energy products in total final energy consumption, rather than a change in the consumption profile of the residential sector. It is clear that residential energy consumption is, and remains out to 2050, a key demand sector for natural gas, biomass and electricity, but also coal (despite the minor contribution). Space heating demand is the largest single component of residential energy demand (61% in 2010, and up to 65% in 2050 in the Reference), and the key driver behind residential energy trends.

In 2010 around 70% of residential natural gas demand, and over 90% of direct residential heat demand (via district heating), but only around 14% of domestic electricity was used for space heating. The significant reduction in total residential natural gas and oil product demand in 2020, and parallel increase in biomass, is due to changes in space heating – as is the subsequent reversal of this trend out to 2050. The reduction of direct heat in residential energy (in favour of other sectors, as discussed below), also contributes to the decreasing 2020 demand trend. The use of electricity for space heating increases steadily from 2010, to around 20% by 2050 in all scenarios. In the Reference this represents around 50% of all domestic electricity consumption in 2050, and around 30% in the two constrained scenarios. In both FP and PS scenarios the 1EJ increase in electricity in total domestic consumption is accounted for by this increased electrification of space heating, along with electrically powered heat pumps.

The lack of significant difference between in domestic energy consumption profiled in 2010 and 2050 in all three scenarios explains the lack of significant changes in long-term emissions in the residential sector (Figure 2, Figure 3 and Figure 4). However, this must be considered in context of the increasing number of households in the EU. There were approximately 206 million domestic properties in the EU in 2010, covering around 19.5 billion m^2. This is projected to increase to 252 million households covering 24.7 billion m^2 by 2050 (IEA, 2012), with space heating energy service demand alone increasing from 5.6EJ to 6.4EJ. Using a crude estimation, Table 12 presents the projected change in energy intensity of residential buildings over time.

Table 12 Energy Intensity of Residential Buildings

Metric	2010	2050		
	All Scenarios	Reference	Fragmented Policy	Policy Success
Household (MWh/dw)	17.4	14.9	13.2	12.9
Floor space (KWh/m^2)	183.3	152.5	135.1	131.4

Household energy intensity decreases by around 15% in the Reference and up to 25% in PS, and by slightly higher proportions in terms of floor space (17% and 29%). As the ETM-UCL does not consider building envelope efficiency measures, this is driven entirely by improving efficiency of end-use products (boilers, air conditioning units, white goods, etc.).

This reducing energy intensity (along with a changing energy supply mix, particularly increasing electrification) leads to residential direct CO_2 emission intensity decreasing from 2.23tCO_2/dwelling in 2010 (0.024tCO2/m^2), to 1.66tCO_2/dwelling in Reference and PS in 2050 (0.017tCO2/m^2), and 1.45tCO^2/dwelling in FP (0.015tCO2/m^2). Reference and PS intensities are roughly equal as a higher proportion of residential energy in PS is satisfied by natural gas at the expense of biomass, raising emissions despite reduced overall energy demand. FP achieves a lower intensity through an almost identical proportional split between energy carriers, but with around 11% less final energy demand.

As expected, there are significant regional differences in residential energy demand requirements. For example, energy consumed for space cooling is a much more significant concern in lower latitudes than in northern Member States – however such detailed discussion of regional variation is outside the scope of this report.

Commercial

Figure 28 to Figure 30 illustrate developments in total final energy consumption in the commercial sector in proportional terms, for the three core scenarios.

Figure 28 Commercial Sector Final Energy Consumption - Reference

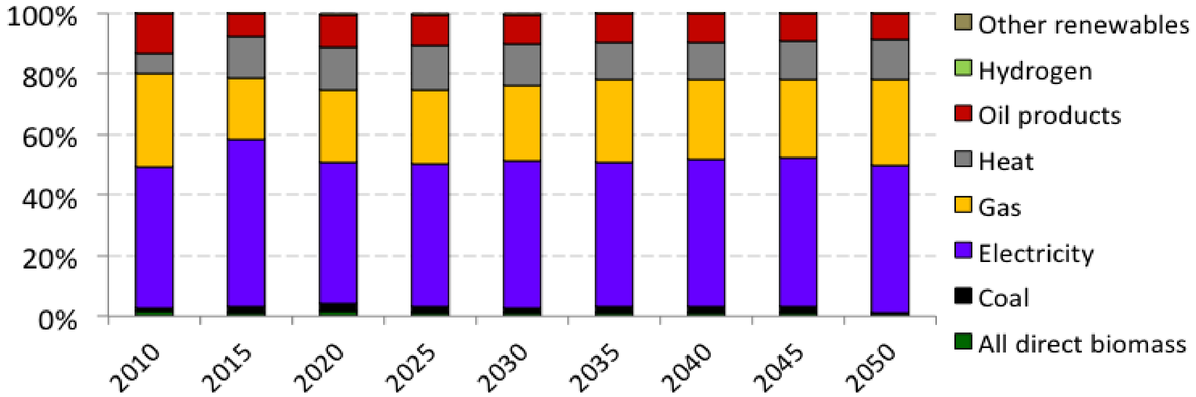


Figure 29 Commercial Sector Final Energy Consumption - Fragmented Policy

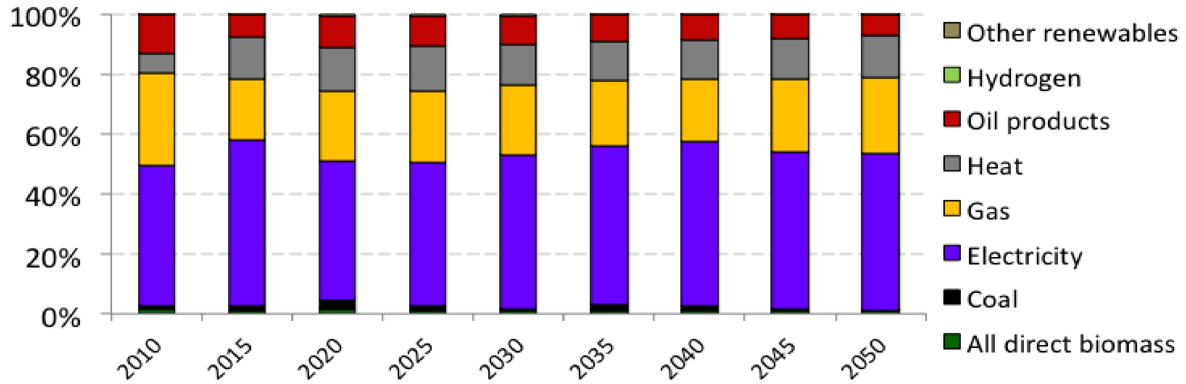
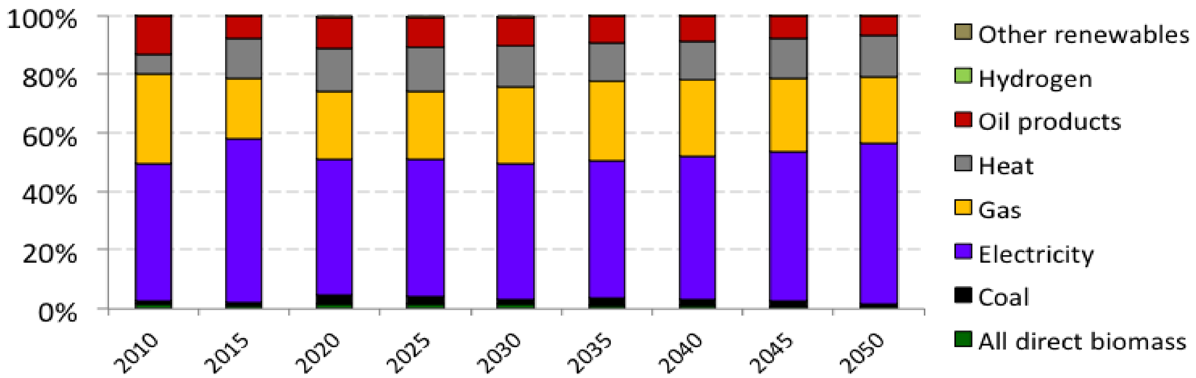


Figure 30 Commercial Sector Final Energy Consumption - Policy Success



The EU's commercial sector consumes about half the energy as the residential sector between 2010 and 2050, (approximately increasing from 6.5EJ to 7EJ), delivered again with a remarkably similar (and static) energy carrier profile across all three scenarios. As with residential consumption, electricity and natural gas are the two key energy carriers, with the former clearly dominant (at a 47% share in 2010, against a 31% share for the latter). Oil products and the direct use of heat are not insignificant at 13% and 7% in 2010, respectively. The use of natural gas and oil products decreases slightly over time, with a steeper gradient with tighter emission constraints - replaced by an increasing share of electricity. The use of heat also increases slightly (to around 13%).

Similarly to residential, the commercial sector consumed around 30% of total electricity supply in 2010, and maintains this approximate share across time in all scenarios. Around 17% of final energy natural gas consumption in 2010 was used in the commercial sector, increasing in the Reference to 19% in 2050, but decreasing to 12% in PS (and 15% in FP). The proportion of total direct heat in the energy system used for commercial purposes increases in all instances from 22% of the total in 2010, to nearly three-quarters in the Reference, around two-thirds in FP, and around half in PS. Oil products and biomass in the commercial sector retain a minor proportion of the total supply, although the sector does account for an increasingly large share of final energy coal in the constrained scenarios – up to 9% in PS in 2050 (from 4% in 2010), but down to around 1% in the Reference (in context of a rapid increase in the use of coal in other final demand sectors).

Again, space heating is a key component of overall commercial energy requirements, accounting for 41% of the total in 2010 - although this proportion decreases over time in all scenarios (down to 36% in the Reference, and to 29% in the constrained scenarios), with other uses (such as water heating), increasing proportional demand. In all scenarios a relatively significant electrification of space heating occurs to 2020, before slowly declining to 2050. Only around 11% of total commercial electricity consumption was for space heating in 2010. This proportion increases in all scenarios by 2050, but all remain below an 18% share. The use of heat pumps is much more prevalent than in the residential sector, satisfying around 20% of final space heating demand by 2050 in the constrained scenarios (and 10% in the Reference). The extended use of heat pumps contributes to a reduction in overall space heating final energy demand in these scenarios (around 25% between 2010 and 2050 – 2.6EJ to 2EJ), as heat pumps exhibit a coefficient of performance (COP) of more than 1 (e.g. higher than 100% efficiency). As with the residential sector, the trend in the use of natural gas alters direction over the assessment horizon, but by 2050 returns to approximately 2010 levels in absolute terms in all cases. However, the slight decline in overall commercial gas consumption is enough to raise the proportion demanded to satisfy space heating demands from 55% in 2010, to 83% in the Reference, and 65% in the constrained scenarios.

Again, the trends discussed must be considered in the context of increasing commercial activity and associated energy service demands. Commercial floor space in the EU in 2010 was around 7.25 billion m^2, and is projected to rise to around 10.11 billion m_2 by 2050 (IEA, 2013). As such, energy intensity decreases from around 245KWh/m^2 in 2010 to around 195KWh/m^2 in the Reference and 186KWh/m^2 in the constrained scenarios. This is a reduction of around 20% and 24%, respectively – again delivered by increasing efficiency of end-use products rather than building envelope improvements. CO_2 intensity reduces from 25kgCO_2/m^2 to 17KgCO_2/m^2, 11KgCO_2/m^2 and 9KgCO_2/m^2 in Reference, FP and PS respectively.

5.3.4 Industry, Upstream and Agriculture Sectors

The industrial, upstream and agriculture sectors together accounted for around 25% of EU CO_2 emissions in 2010.

Industry

Figure 31 to Figure 33 illustrate the trends in energy consumption in the industrial sector for the three core scenarios.

Figure 31 Industrial Final Energy Consumption - Reference

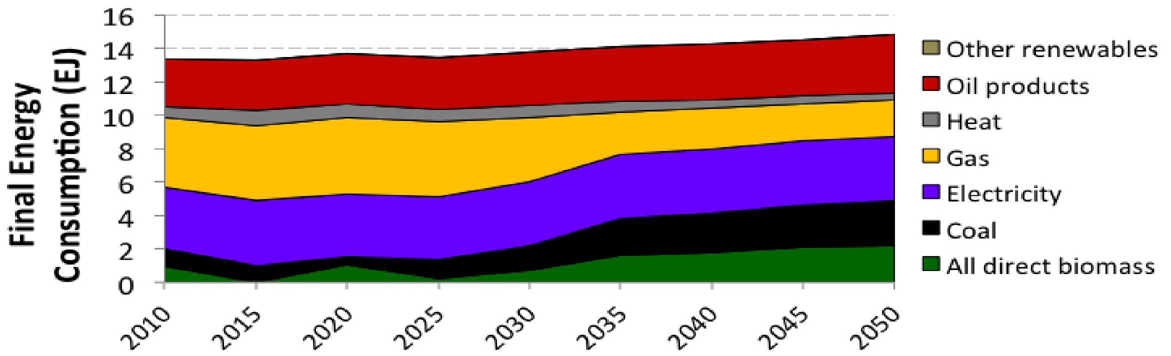


Figure 32 Industrial Final Energy Consumption - Fragmented Policy

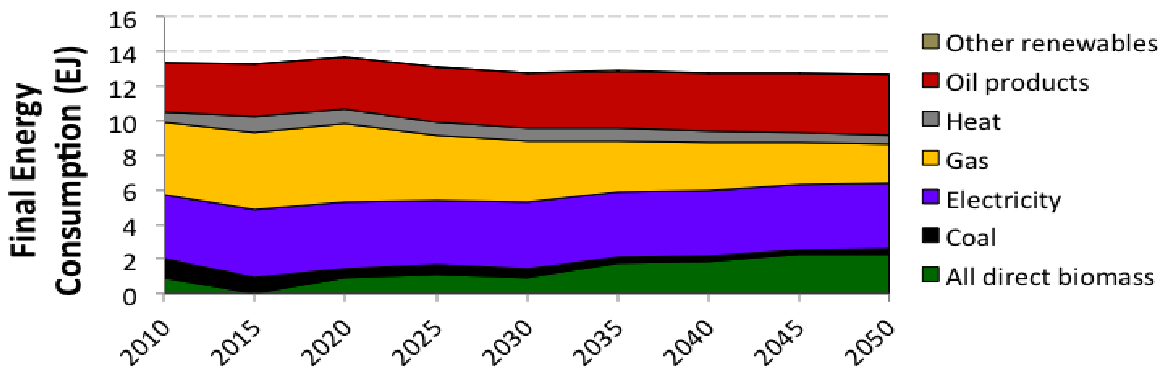
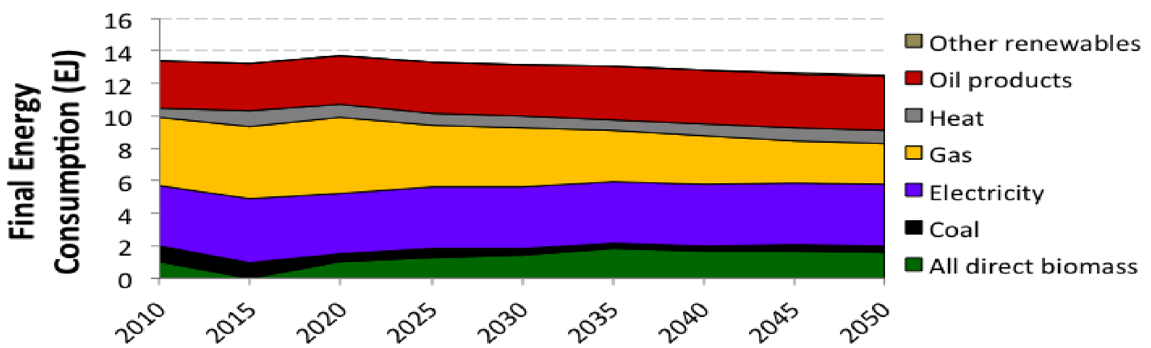


Figure 33 Industrial Final Energy Consumption - Policy Success



As in other demand-side sectors, the Reference scenario experiences slightly increasing energy consumption with the constrained scenarios experiencing a slight decrease, as more CO_2 and energy (and cost) efficient technologies are deployed. In 2010, industry accounted for around 25% of total EU final energy consumption. This value increases slightly to 26% by 2050 in the Reference, and decreases to 24% in the constrained cases. Once again, the consumption profile is largely similar between the three scenarios. The only significant difference is in the use of coal, which satisfies the increase in demand in the Reference to equal 19% of industrial final energy consumption by 2050, as opposed to around 3% in the constrained scenarios. Table 13 presents the proportion of energy carriers in final energy consumption demanded by industry, across the three scenarios and over time.

Table 13 Proportion of Total Final Energy Consumption by Fuel - Industry Sector

Fuel	2010	2050		
	All Scenarios	Reference	Fragmented Policy	Policy Success
Coal	69%	87%	48%	50%
Oil Products	11%	15%	18%	18%
Natural Gas	35%	20%	19%	20%
Biomass	36%	49%	46%	68%
Electricity	36%	31%	30%	31%
Heat	31%	35%	38%	46%

Again, aside from coal, the changing proportions in Table 13 largely reflect changing contributions of these energy products to total final energy consumption, rather than a change in the consumption profile of the industry sector. The distribution of these fuels between sub-industries remains largely static over time and between scenarios. Iron and steel is the most significant consumer of coal, whilst the chemical industry is responsible for around half of industry's gas consumption and a large proportion of biomass by 2050 (from pulp and paper in 2010), but almost all oil products (<99%) used in industry across the full horizon. Electricity consumption is relatively well distributed between sub-industries, whilst the direct use of heat is largely with chemical and 'other' industries.

The modest differences in total industrial energy consumption and fuel split over time and between scenarios do not reflect the significant differences in industrial emission developments between them – increasing by around 3% in the Reference between 2010 and 2050, but decreasing by 54% and 61% in the FP and SP scenarios, respectively. Whilst the difference in the use of coal is a significant explanatory variable, the use of CCS in capturing industrial process emissions (in the iron and steel industry, in particular), from 2025 in the constrained scenarios is much more important, sequestering around half of industry's CO_2 emissions by 2050.

Upstream

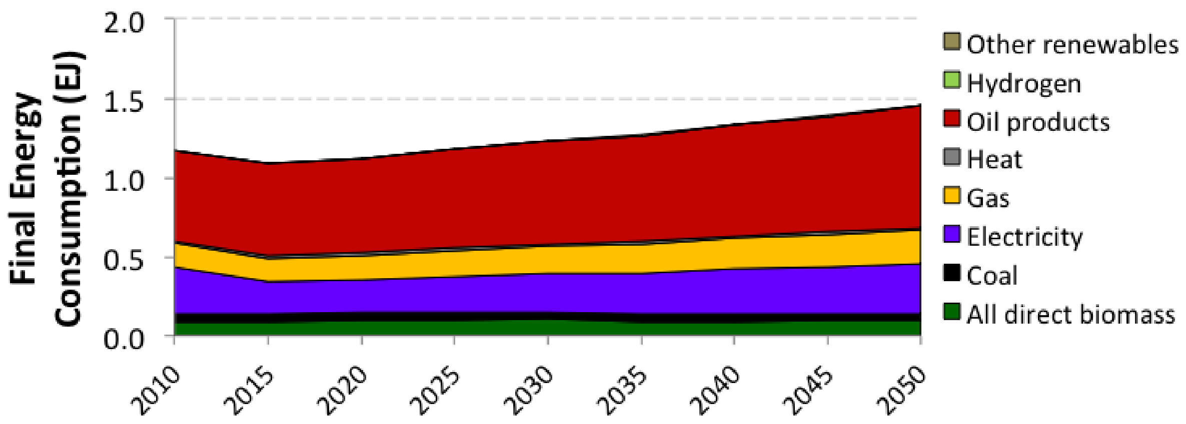
There is a significant difference in upstream emissions between the three core scenarios. This is accounted for mostly by differences in the development of the domestic production of fossil fuels. Domestic production of natural gas in the Reference increases by around 60% between 2010 and 2050, whilst coal production more than trebles. In contrast, domestic coal production reduces by around two-thirds between 2010 and 2050 in PS, whilst domestic gas production almost ceases entirely. As highlighted, fossil fuel imports increase as CO_2 emissions are further constrained in order to replace domestic production and associated emissions, and maintain the still very high demand for fossil fuel products in primary energy consumption. In each scenario natural gas is the most-imported fossil fuel (on an energy content basis), with coal the least traded. Oil products experience the greatest variation in import volumes between the three core scenarios, with imports reducing significantly post-

2020 in the Reference (to under 1EJ in 2050), and increasing rapidly to over 16EJ in 2050 in PS (whilst remaining roughly static at around 6EJ in FP).

Agriculture

Figure 34 presents the final energy consumption for the agriculture sector. There is no variation in the fuel consumption profile and subsequent CO_2 emissions between the scenarios.

Figure 34 Agriculture Final Energy Consumption - All Scenarios

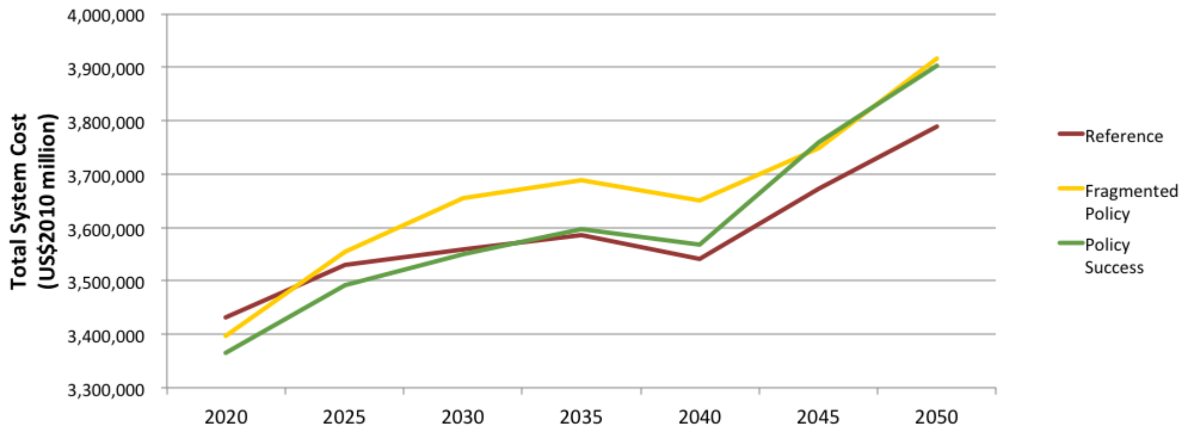


In 2010 agriculture accounted for around 2% of final energy consumption in the EU, and just over 1.5% of total CO_2 emissions. By 2050, agriculture increases to around 3% of final energy consumption in all scenarios, but with significant differences in the proportion of total CO_2 emissions attributable to this sector, ranging from 1.5% in the Reference to over 9% in PS. The growth experienced over time reflects increasing demand for agricultural production against the drivers presented in Table 2. Whilst in other sectors final energy demand changes are not linear as efficiency measures and other influences may be taken up, the agriculture sector in the model lacks such a range of efficiency or CO_2 abatement options, and where they are available, it is often cost-minimising to focus efforts on other sectors.

5.4 Energy System Costs and Shadow Marginal CO_2 Prices

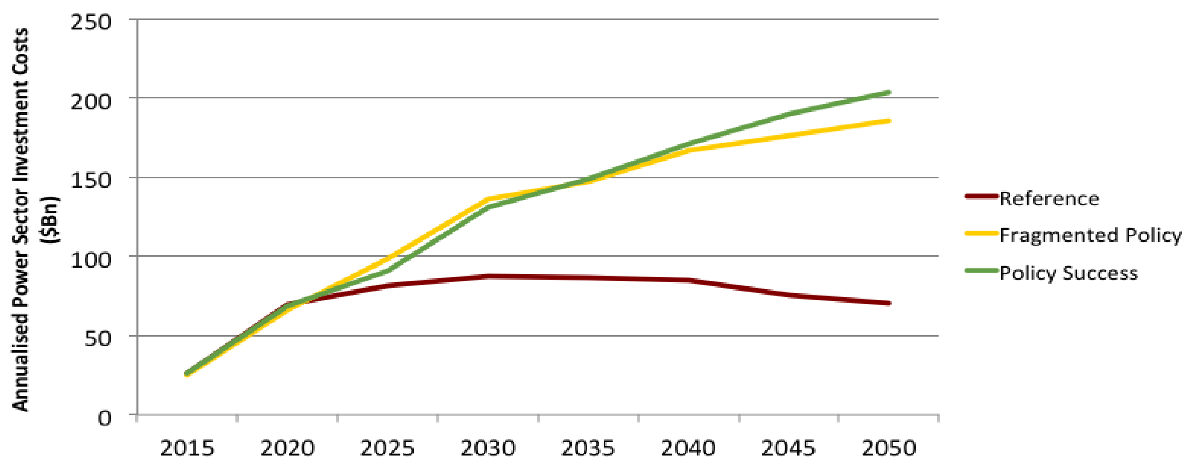
Figure 35, below, illustrates total energy system costs for the three core scenarios. This includes capital cost, maintenance and operation and fuel costs. Pre-2020 values are not presented, as system costs are largely equivalent in 2015 at around $2.58 trillion, the inclusion of which would render subsequent differences between scenarios less clear.

Figure 35 Total Energy System Cost



However, from 2020 onwards it is immediately clear that there is still relatively little difference between the scenarios. A significant factor in this is the assumption of differing fuel costs between the scenarios (Table 5). The net present values (NPV), the objective function the model attempts to minimise, are \$29.17 trillion for the Reference, \$33.5 trillion for Fragmented Policy and \$33.2 trillion for the Policy Success scenario. As such, it appears that the investment in the European energy system required to reach an 80% CO_2 reduction by 2050 (from 1990 levels) is around 14% higher than if decarbonisation efforts in the EU were abandoned post-2020. Reaching a lower target of a 60% CO_2 reduction actually costs slightly more (around 15%).

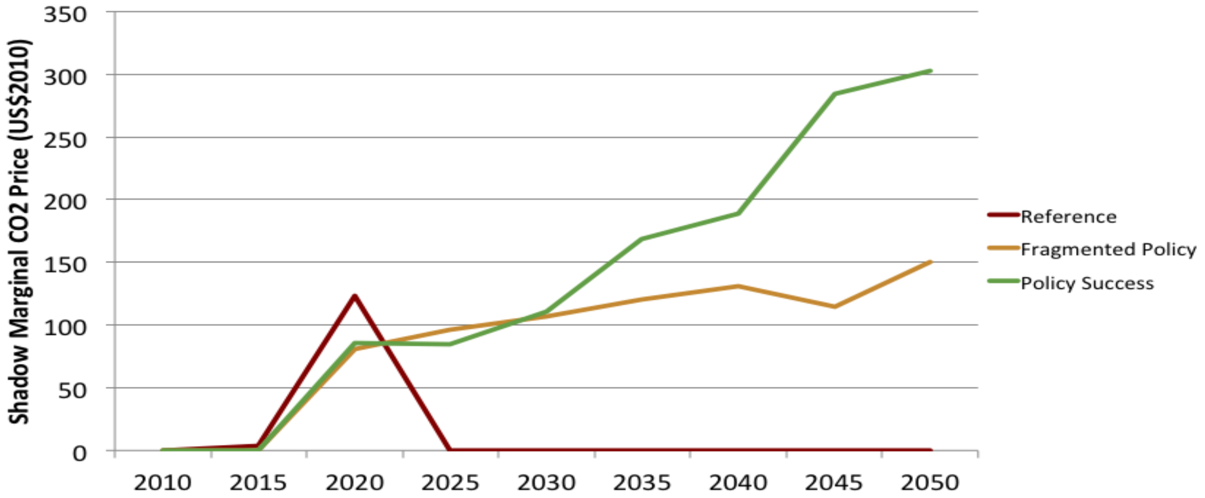
Figure 36 Annualised Power Sector Investment Costs



Required investments in the power sector are less uniform than overall system costs, as Figure 36 indicates. Reference scenario annualised investment costs peak in around 2030 at approximately \$88bn, whilst FP and PS costs steadily increase to a peak in 2050 at around \$185bn and \$203bn, respectively. The profiles of investment are as expected, with coal the focus in the reference scenario, and wind, solar and nuclear, with higher capital costs, comprising the bulk of investment in the constrained scenarios.

In working to meet a given CO_2 emission constraint, the model produces a marginal abatement cost of CO_2. Figure 37 illustrates the average shadow price trajectory for the three core scenarios.

Figure 37 Marginal CO_2 Abatement Cost



The Reference scenario price peaks in 2020 at around $120/t$CO_2$ before decreasing to zero, reflecting the lack of continued emission constraints. The Reference price is higher than the constrained scenario price of around $80/t$CO_2$ in 2020 as it appears the most cost-efficient path to achieving the 2020 targets with no subsequent abatement requirements is to invest in technologies with slightly higher short term abatement cost, and shorter technical lifetimes. For the two constrained scenarios prices increase roughly in tandem to around $110/t$CO_2$ by 2030, after which they diverge to reach $150/t$CO_2$ and $300/t$CO_2$ in 2050 in the FP and PS scenarios, respectively. These marginal costs are average EU values. The specific CO_2 constraints placed on the UK & Ireland and Germany produce higher marginal prices in these regions than others - up to $470/t$CO_2$ for Germany and $300/t$CO_2$ for the UK & Ireland in PS in 2050. The influence of these regions in the model raises the value of $280/t$CO_2$ experienced in all other regions to reach the weighted average of $300/t$CO_2$ shown in the Figure 37.

6 Policy Success Sensitivities – Results

This section presents the key differences to the core Policy Success scenario generated by the four sensitivities. Figure 38 illustrates the variation in energy system cost and marginal carbon price on the central Policy Success scenario, over time. The trend lines illustrate marginal CO_2 price (left axis), whilst the bar values represent system cost (right axis). It is clear that the sensitivities produce only modest departures from the core scenario marginal CO_2 price over time. The Biomass CCS trend ceases in 2040 in Figure 38 as it is technically infeasible in the model after this date. It is also apparent that maximum additional system cost for any sensitivity is relatively minor, but increases over time. The sensitivities responsible for this will be discussed in the relevant sub-sections below. The NPV values for each sensitivity are presented in Table 14 (except Biomass CCS, as a technically infeasible scenario).

Figure 38 Marginal CO_2 Prices and System Costs - Sensitivities

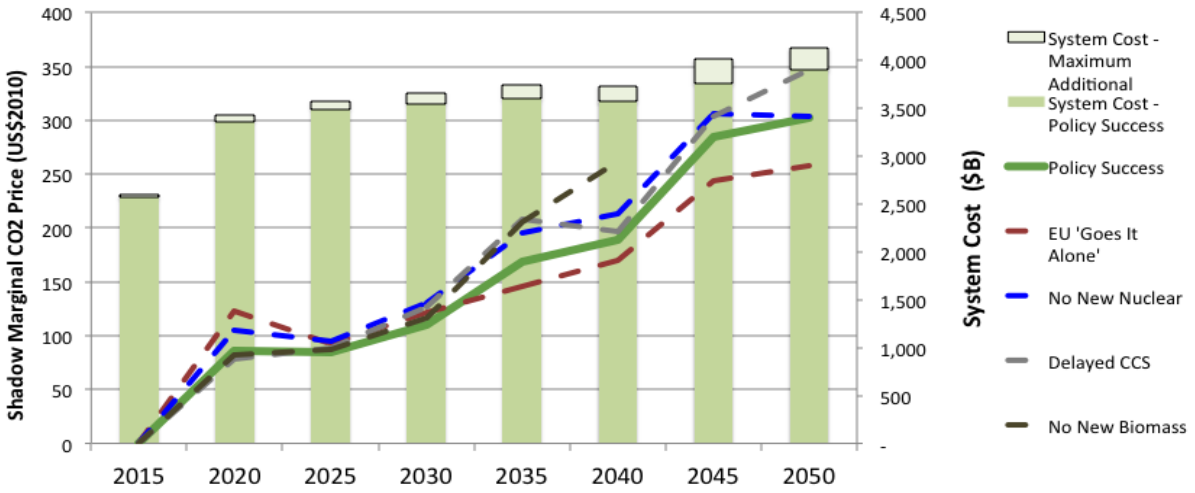


Table 14 System Cost Net Present Values - Sensitivities

Sensitivity	Net Present Value ($2010 trillion)
Policy Success	**$33.20**
EU 'Goes it Alone'	$34.22
No New Nuclear	$33.32
Delayed CCS	$33.23

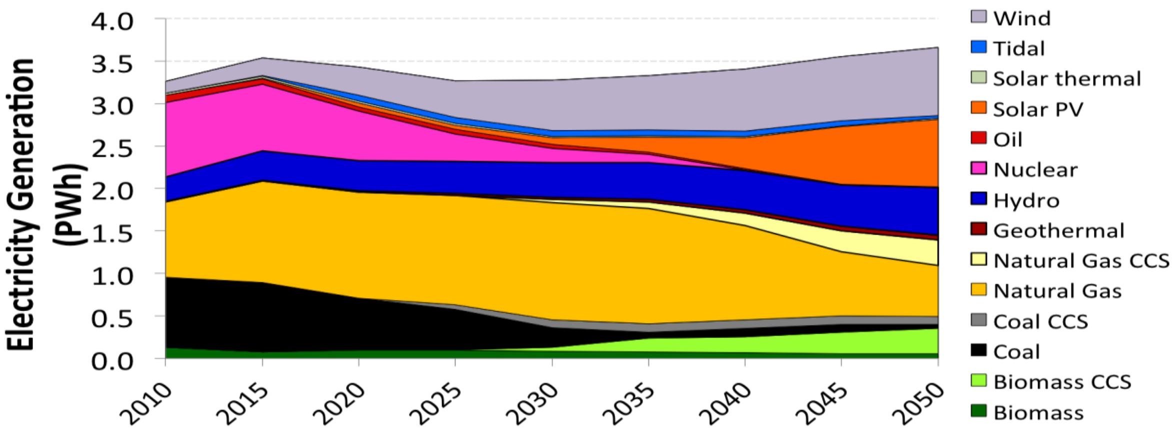
6.1 EU 'Goes It Alone'

There is very little difference in energy system development between the core Policy Success scenario, in which collective global action is assumed and fossil fuel prices reflect reduced demand, and the EU 'Goes it Alone' sensitivity, in which the EU works to decarbonise unilaterally amid global fossil fuel price increases, reflecting increasing global demand. Decarbonisation begins slightly earlier, and some sectors, such as transport, experience marginally more decarbonisation. Fossil fuel retains a slightly larger share of electricity generation by 2050, but with additional deployment of CCS. However, upstream sector emissions in 2050 are around double in this sensitivity compared to the core scenario. This reflects the increased value of domestic production of energy products. The NPV of this sensitivity is the largest at over $1 trillion higher than the central scenario – and also produces the highest additional annual system cost between 2015 and 2050, as represented by the 'system cost – maximum additional' data in Figure 38. The marginal CO_2 price is initially higher than the central trend, but dips below the central trend at around 2035 to reach around $260/t$CO_2$ by 2050.

6.2 No New Nuclear

In this sensitivity, the only significant difference to the core PS scenario may be found in the power sector. Figure 39 illustrates the development of electricity generation.

Figure 39 EU Electricity Generation Profile - No New Nuclear Sensitivity



In the core PS scenario, nuclear generation remains reasonably consistent between 2010 and 2050 (with a pinch-point around 2025), up to the imposed (capacity) constraint. In this sensitivity, as no new nuclear capacity is permitted, nuclear generation is replaced by additional generation from wind, solar PV and natural gas (with total generation remaining approximately the same). Due to the low load factor inherent in wind and PV, total installed electric capacity reaches over 1.5TW by 2050 (over 200GW higher than the core PS scenario). The precise development of electric capacity and generation to replace nuclear varies by region. In the central PS scenario, the three regions in which nuclear power is central by 2050 are the EES and EES regions, and France. With no new build nuclear permitted, nuclear power is eliminated by 2045 in France, with wind and PV each accounting for around 24% of generation by 2050. Natural gas accounts for around 21% of generation by 2050 (with around 50% having CCS). Collectively, these sources account for around 2% of French generation in 2050 in the core PS scenario. In EEN the growth of solar PV is similar in both the core scenario and this sensitivity, whereas wind becomes more prominent (from negligible in core PS in 2050, to around 10% of generation by 2050 with no new nuclear). Natural gas appears to be the primary substitute for nuclear by 2050, increasing from 33% to 45% of generation by 2050 in the sensitivity (with around 10% of this attached to CCS in both instances). The use of natural gas also increases in the EES region (from 9% in PS to 21% by 2050 in the sensitivity – with CCS accounting for more than half of this in both), however solar PV, which is entirely absent in the core PS scenario in EES, now accounts for 21% of generation by 2050.

In all three regions total generation remains largely unchanged from the core PS scenario. As with the previous sensitivity, gross power sector emissions are increased but are countered by additional CCS deployment. Overall, renewable energy reaches only marginally higher levels than in the central PS scenario (although this difference is larger in terms of renewable power only, which increases from around 57% to 71% by 2050). Total system cost NPV is around $120 billion higher in this sensitivity (0.4% increase), with annualised EU power sector investment actually slightly reduced. Marginal CO_2 prices are around $25/t$CO_2$ higher for most of the assessment horizon, but converge to around $300/t$CO_2$ by 2050.

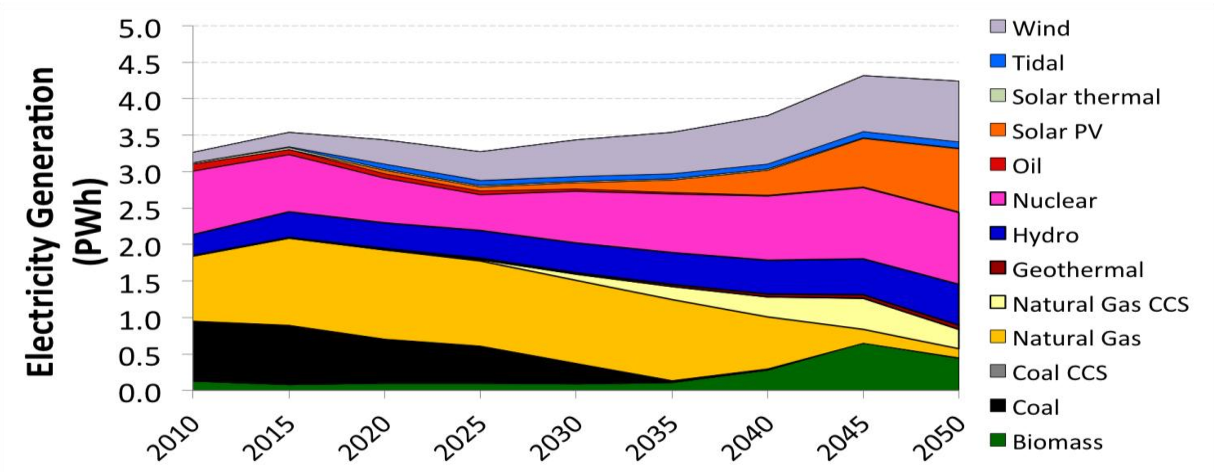
6.3 Delayed CCS

As with the EU 'Goes It Alone', there is little difference between this sensitivity and the core scenario results. The only departure of any significance is the doubling of coal CCS generation by 2050 (although from only 0.81PWh to 1.64PWh), at the expense of natural gas CCS generation. Total system cost NPV is $30 billion higher (just under 0.1%), with the marginal CO_2 cost peaking above the core trend in 2035 and 2050, reaching around $350/t$CO_2$.

6.4 No Biomass CCS

As mentioned, the Biomass CCS sensitivity is technically infeasible after 2040. After this date a 'backstop' technology is introduced. This technology is undefined, and is intended to allow the model to solve when it otherwise could not. It is available at $5,000/t$CO_2$ abated, and is called upon to abate nearly 270MtCO_2 in 2050. However, whilst noting this, it remains interesting to assess the overall system development. As with 'No New Nuclear', the most direct impact of this sensitivity is on the power sector. Figure 40 illustrates the electricity generation profile if biomass CCS is unavailable.

Figure 40 EU Electricity Generation Profile - 'No Biomass CCS' Sensitivity



When compared with Figure 15 there is clearly a significant impact. Total generation is about 350TWh higher in 2050 in this scenario than in PS (an increase of 10%), with relatively significant changes to the profile. The overall consumption of biomass remains roughly the same (although all unabated), whereas the use of natural gas halves but with the remaining majority (two-thirds) generated with CCS. Coal is almost entirely removed from the mix. Wind and solar both increase by around 300TWh each, and now account for 40% of generation by 2050 (against 30% in PS). Concurrently, total electrical capacity in the EU reaches nearly 1.8TW by 2050 against 1.3TW in PS, with the difference almost entirely driven by additional wind and solar PV capacity.

Table 15 CO2 Intensity of EU Power Generation - Policy Success and 'No Biomass CCS' Sensitivity

gCO_2/KWh	2010	2015	2020	2025	2030	2035	2040	2045	2050
Policy Success	348	326	285	264	170	63	-12	-132	-190
No Biomass CCS	348	327	284	263	182	101	56	4	1

As Table 15 illustrates, electricity generation still almost completely decarbonises (with just 3MtCO_2 total emissions in 2050) - although in absence of biomass CCS, negative emissions are unattainable. This means other sectors must make additional efforts to achieve the 80% CO_2 reduction target (up to a marginal abatement cost of $5,000/t$CO_2$, after which the backstop technology is more cost-effective). As such, the commercial, residential and transport sectors all making significant additional decarbonisation investments. Until around 2040 the overall rate of decarbonisation matches the central PS scenario, and appears to be achieved at reasonable expense - within the range of other sensitivities for total system cost and marginal carbon prices (see Figure 38).

7 Discussion

This section discusses the key results from this study and their implications, and briefly compares these results (primarily of the Policy Success scenario) with that of previous studies – particularly the EU's Energy Roadmap 2050.

The Energy 2050 Roadmap (ER2050) was produced in 2011 to explore the challenges posed by reducing the EU's GHG emissions to 80-95% below 1990 levels by 2050, including an 85% reduction in CO_2 from the energy system in the EU27. The results of seven scenarios were produced using the PRIMES energy system model, with a base year of 2005. This includes a Reference scenario[23] (ER-Ref), a 'Current Policy Initiatives' (CPI) scenario, and five decarbonisation scenarios with different emphases on the manner of decarbonisation[24]. For more information on the specific details of these scenarios, other assumptions, the PRIMES model and specific results, refer to the ER2050 Communication and Impact Assessment (European Commission, 2011a and European Commission, 2011b, respectively).

Table 16, below, presents the difference in CO_2 emissions in 2030 and 2050 from 1990 levels for the Policy Success scenario in this study, and the range of results for the decarbonisation scenarios in ER2050.

[23] Includes policies implemented by March 2010. 2020 targets for GHG reductions and RES shares are implemented, with no further targets post-2020, except the annual EU ETS cap reduction (1.74%).

[24] ***'High Energy Efficiency'***, in which the focus rests with reducing final energy demand, '***Diversified Supply Technologies***', in which all energy sources compete on an open market with no specific support measures, '***High Renewable Energy Sources***', in which strong support measures for RES are provided, '***Delayed CCS***', in which the availability of CCS technology is delayed, and '***Low Nuclear***', in which no new nuclear capacity is permitted.

Table 16 CO_2 Emissions - Comparison with EU 2050 Energy Roadmap

Sector	EU 2050 Energy Roadmap (All Decarbonisation Scenarios) – change from 1990 CO_2 Emissions			ETM-UCL Results - Change from 1990 CO_2 Emissions		
	2020	2030	2050	2020	2030	2050
Power	-33% to -37%	-48% to -65%	-96% to -99%	-34%	-62%	-152%
Transport[25]	+22%	+5% to +9%	-60% to -62%	+17%	+18%	-10%
Residential & Commercial	-28% to -40%	-40% to -46%	-86% to -88%	-55%	-31%	-36%
Industry	-43% to -44%	-45% to -48%	-77% to -79%	-51%	-64%	-65%

Sectoral developments are relatively similar to 2030 between the two studies, with the electricity, industry, and residential and commercial sectors reducing emissions significantly against 1990 levels, with transport emissions rising. However, significant divergence occurs between 2030 and 2050. The ER2050 decarbonisation scenarios project almost full decarbonisation of the power sector, with a relatively even proportional CO_2 reduction in the remaining sectors (between 60% and 79%). The results of the present study suggests a more weighted distribution of abatement efforts, with the power sector clearly bearing by far the largest burden, reducing emissions by 152% in 2050 from 1990 levels (made possible by the use of biomass CCS). As a consequence, whilst abatement efforts in the industry sector between the studies are generally comparable, the decarbonisation efforts required in the residential, commercial and transport sectors in particular are significantly lower. The ER2050 study does not present CO_2 emissions from the upstream sector or disaggregate CO_2 emissions in agriculture, and so cannot be compared with results from this study.

A principal difference between the decarbonisation scenarios in this study and the ER2050 is that the latter implements various policies post-2020, such as a continuation of the EU ETS, CO_2 standards for vehicles and certain infrastructure measures, that may bias results away from the purely-cost optimal, as produced by this study. As such, a level of divergence between results is to be expected at the outset. Before other key reasons behind these sectoral differences are discussed, macro-trends should be summarised and compared. In the Reference scenario in this study total primary energy demand decreases by 4% from 1990 levels by 2050, and by 10% in Policy Success (although 2050 values are 11% and 1% higher than the base year 2010 values for these scenarios respectively). The ER2050 ER-Ref scenario projects a 6% increase in total primary demand between 1990 and 2050, whilst the Diversified Supply Technologies (DST) scenario (largely equivalent to Policy Success)[26], projects a 27% decrease over the same period. In both studies a key driver in determining trends in both final and primary energy demand is GDP growth. The ER2050 scenarios assume annual growth of 1.7% from 2005, whilst this study assumes initial growth rates of 2% from 2010, reducing to 1.7% later in the assessment horizon (Table 2). However, if GDP exerted the largest influence over total primary demand in both studies, then a reduction of 27% would be unexpected. As such, the significant difference between the decarbonisation

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[25] Excluding aviation and shipping.

[26] Hereafter, the DST is the ER2050 decarbonisation scenario with which comparisons to Policy Success are drawn, unless otherwise stated.

scenarios in the two is likely to be due in large part to the effect of demand response (and building envelope efficiency measures, to be discussed), which is considered in PRIMES model used for the ER2050, but is absent in ETM-UCL. An increase in the cost of energy and the energy system over time reduces end-user final energy demand in accordance with a given elasticity, and thus in turn reduces primary energy demand. This is influenced by differences in primary fossil fuel prices (oil, coal and gas) over time, and relation to each other – which also influences the proportional contribution of primary energy fuels used to fulfil this supply. Table 17 presents fuel import price assumptions used in the ER2050 scenarios (refer to Table 5 for the values used in this study).

Table 17 ER2050 Fossil Fuel Price Projections (Source: European Commission, 2011b)

ER2050 Scenario	Fuel	2010	2020	2030	2040	2050
Reference	**Oil (2008 US$/bbl)**	85	88	106	116	127
	Coal (2008 US$/tonne)	103	130	148	148	152
	Natural Gas (2008 US$/Mbtu)	9	11	13	15	17
Decarbonisation Scenarios	**Oil (2008 US$/bbl)**	85	84	79	75	70
	Coal (2008 US$/tonne)	105	114	118	105	95
	Natural Gas (2008 US$/Mbtu)	9	11	11	9	8

In the Reference scenarios in both studies, all fossil fuel import prices increase from (similar) 2010 levels in line with global demand (Table 5 and Table 17). However in ER2050 the oil price reaches a lower peak, whilst coal and natural gas prices attain higher levels than IEA values. In the ER2050 decarbonisation scenarios oil prices decrease from 2010 levels, whilst the IEA values used in this study for a decarbonising world still project an increase of nearly 12%. Coal prices decrease in both studies between 2010 and 2050, around 10% in ER2050, but by around a third in the IEA values. Natural gas prices in both scenarios peak at around 2030 then fall back to roughly (similar) 2010 levels by 2050. Differences between the values are due to different modelling approaches used to produce them, the scenario assumptions applied, when they were produced, and the specific units they are measured in (e.g. 2008 and 2010 US$).

Primary fuel supply in the Reference scenario for this study is dominated by coal and oil by 2050 (two-thirds of the total), with natural gas and renewable sources sharing the remaining third. Nuclear power is eliminated by 2045. In Policy Success around a third of primary energy is satisfied by renewables by 2050, with gas and oil around a quarter each. Coal and nuclear retain a 10% and 5% share, respectively. Total energy import dependency for the EU in 2010 was around 54% in 2010 (EUROSTAT, 2012). This decreases to 49% in the Reference scenario by 2050, but increases to 59% in Policy Success. This is reflected by Figure 11, in which fossil fuel imports increase with increasing emissions constraints, in order to replace reduced domestic production. Such a result indicates cost-effectiveness only, and not consideration of potential energy security issues (or net global emissions, as will be discussed).

The EU2050 ER-Ref scenario projects similar proportions of oil, natural gas and renewable resources to the ETM-UCL Reference scenario by 2050, but the use of coal drops to just 11%

of the total, with nuclear retaining a 16% share. In the ER2050 DST scenario, renewables and nuclear both take shares higher than in Policy Success, at 41% and 15% respectively. Coal and oil consequently take smaller shares of 6% and 14%. Natural gas supplies a similar proportion of around a quarter of total primary energy consumption. Total energy import dependency increases to 58% in 2050 in ER-Ref, and decreases to 40% in DST. The 20% difference in import dependency in the respective decarbonisation scenarios is due to the difference in proportional contributions of renewables and nuclear energy.

The level of biomass consumption in primary energy is a topic currently receiving significant academic and political attention, due to issues surrounding indirect land-use change and biodiversity impacts, amongst others. The European Environment Agency (2006) estimates that by 2030, annual primary consumption of biomass could reach 295Mtoe (12.3EJ) whilst remaining 'environmentally compatible'. At just under 9EJ primary biomass consumption in 2030, the Fragmented Policy and Policy Success scenarios remain within this limit (along with the Reference, at just under 8EJ).

The presence of nuclear in 2050 in the ER-Ref scenario implies either that the difference in projected coal price in the two Reference scenarios makes retaining nuclear generation at the expense of high coal supply cost-optimal in ER-Ref, or that the cost of new nuclear capacity in the PRIMES model is lower than the ETM-UCL – or a combination of the two. These arguments also hold for the decarbonisation scenarios, in which coal prices are significantly higher in ER2050. However, despite a higher proportion of nuclear generation in primary supply in DST than in the Policy Success scenario, absolute nuclear supply decreases by around a fifth between 2010 and 2050 (but remains stable in Policy Success, up to the imposed constraint). These seemingly opposing trends are due to the significant reduction in total primary energy demand in DST, not experienced in this study.

Whilst primary fuel costs are a key determinant of the projected size and profile of primary energy supply in these studies, numerous other factors hold influence and serve to produce changes over time and differences in projections between different studies. This includes projected technology costs, their availability, efficiencies and build rates for different sectors, and assumed renewable resource potentials, along with specific model design (including the base year, geographical scope and objective function), and specific scenario design.

The size and structure of the power sector is by far the largest factor in the relationship between primary and final energy profiles[27]. With the power sector consuming around three-quarters of primary energy coal, a third of natural gas and from 20% to 40-60% of biomass across time and between scenarios in this study. Differences in primary energy consumption profiles between scenarios are almost entirely due to differences in projected power sector development. Overall generation grows from around 3.3PWh in 2010 to around 3.9PWh by 2050 in both the Reference and Policy Success scenarios, but to around 4.9PWh in both the ER-Ref and DST scenarios in ER2050, to satisfy increased electrification of final

[27] Although other transformative processes, such as biomass to biofuels, and oil to petrol/diesel, are also important.

demand sectors. Generation from fossil fuels in the Reference scenario in this study exceeds 80%, with the remainder shared between hydro and other renewable sources. In ER-Ref however, fossil fuels only account for around 30% of generation, with renewables accounting for over 40% (including 7% hydro), and nuclear claiming over 26%. The generation profile of the respective decarbonisation scenarios are largely similar to each other, with Policy Success producing electricity from around 20% fossil fuels, 24% nuclear and 56% renewables. DST uses 25% fossil fuels, 16% nuclear and 59% renewable sources.

Although, there are differences within these categories - particularly renewables, clearly, the key technology for decarbonisation in the power sector (and in the energy system overall) in this study in the Policy Success scenario (and Fragmented Policy), within the constraints imposed, is biomass CCS – enabling negative emissions and absorbing a significant level of the CO_2 reduction burden. The essential nature of this technology is confirmed by the 'No New Biomass' sensitivity, and by previous modelling studies, including Azar *et al* (2006), Van Vuuren *et al*, (2007) and Edenhofer *et al* (2010). However, many other studies do not consider biomass CCS to be vital for decarbonisation, and often do not allow its use at all – including the ER2050 decarbonisation scenarios. For example, a recent study by Capros *et al* (2014), which tested seven different decarbonisation scenarios for the EU with seven large-scale energy-economy models, found technically feasible solutions across all scenarios and models in absence of biomass CCS. Another recent study by Knopf *et al* (2013), which similarly applied EU decarbonisation scenarios to thirteen macroeconomic and energy system models, also found that biomass CCS was not an essential component for a technically feasible solution in all but one model (indeed, only three of the models used allow it an option). However, the ability to project demand reduction is a significant factor in producing a feasible scenario in the absence of biomass CCS.

Whether a given scenario is technically feasible in a particular model depends on implicit differences in model structure, objective function and assumptions about future technology developments and availability, basic fuel costs, and others. Inevitably such assumptions will differ between models and explicit scenario design, and serves to demonstrate that such efforts to project future developments are inherently uncertain. This extends not only to technical feasibility, but also to social, political, economic, legal and administrative aspects that are not considered as part of the cost-optimising approach taken in these models. Such factors pervade all supply and demand sectors of the energy system. However, a near-universal conclusion from studies projecting pathways for decarbonisation of the EU's energy system is that even if biomass CCS and negative emissions are not produced, a near complete decarbonisation of the power sector is still required if an 80% reduction in CO_2 below 1990 levels (or even 60%, as suggested by the results of the Fragmented Policy scenario) is to be achieved.

Another key difference between the Policy Success and DST scenarios is the use of wind and solar PV. Wind is the dominant source of renewable power in DST by 2050 (around 32% of all generation), with solar PV contributing less than 10%. In Policy Success, wind and solar PV both account for around 15%. The increase in solar PV at the expense of wind in this study is, again, due to differences in technology cost projections. The cost of PV systems has dropped very considerably between the base years of 2005 and 2010 (and even since 2011, when the ER2050 study was conducted). Whilst the most recent costs and projections are factored in to the ETM-UCL, such a cost profile is unlikely to have been used in the ER2050 study. Additionally, whilst the use of nuclear power declines in DST over time, it would likely have increased significantly under Policy Success (and Fragmented Policy) in the absence of capacity constraints (the imposed constraints are indeed binding).

As seen in Table 9, total final energy demand and the profile of final energy carriers used to satisfy this demand changes relatively little over time and between scenarios in this study. Total final energy demand and energy carrier profile in the ER-Ref scenario in 2050 is comparable to the Reference scenario in this study, although in the DST scenario total final demand falls to around 34EJ – approximately 35% lower than 2050 demand in Policy Success, due to the reasons cited above (demand response – and building envelope efficiency measures, to be discussed). The energy carrier profile is also different in DST, with fossil fuels accounting for under a third of final consumption, and electricity accounting for around 40% (rather than around 23% in Policy Success). The presence of renewables in final consumption (including renewable electricity) is also higher in 2050 in DST, reaching around 50% (against around 30% in Policy Success).

Total final demand by sector, and the (proportional) sectoral consumption per energy carrier also exhibits little variation over time and between the Reference and Policy Success scenarios. Around half of all oil products are consumed in the transport sector (with the remainder distributed roughly equally between the remaining end use sectors), which also consumes virtually all biofuels and hydrogen (in the constrained scenarios, where it is deployed). Industry consumes around a third of electricity generation and natural gas, and around two-thirds of coal in final energy. The residential sector consumes most of the remaining coal in final demand, around half of natural gas, and around a third of electricity. The commercial sector consumes much of the remainder of these energy carriers. The only energy carrier that varies in any significance in sectoral distribution over time is biomass, which in 2010 was channelled mostly to the residential and industrial sectors in roughly equal proportions. In all scenarios in this study the rapid increase of biomass for residential heating by 2020 (which accounts for the spike in biomass in final energy around this time), means over 90% of final energy biomass is used for residential purposes, and is a key factor in meeting the 2020 renewable and emissions targets. In all scenarios, both total biomass demand in final consumption and the proportion used in the residential sector decreases (to around 25%, with industry accounting for most of the remainder by 2050). This general lack of variation in final energy profiles between scenarios and over time again highlights the importance of transformations in the power sector.

However, despite the small variation in energy profiles emission reductions are achieved in every end-use sector (except agriculture[28]) in the Policy Success scenario by 2050 against 1990 (and 2010) levels. Transport CO_2 emissions are projected to remain above 1990 levels to at least 2030 (despite continuously decreasing from the 2010 base year), eventually achieving a 10% reduction on 1990 by 2050 through the increasing use of biofuels and hydrogen-fuelled HGVs, plug-in hybrid LGVs, and a steady switch from gasoline to diesel in cars. In many other studies transport often contributes more significantly to decarbonisation efforts. In the ER2050 for example, a 60%-62% CO_2 reduction is achieved, largely through electrification of cars and LGVs (to 65% of energy demand for these modes), but also a reduction in overall demand coupled with modal shift in the remainder (mostly in freight transport) – partly enabled and driven by the inclusion of post-2020 measures contained in the Roadmap to a Single Transport Area (COM (2011) 144) (European Commission, 2011b). As this study does not consider either demand-side responses or opportunities for modal shift (or any pre-defined measures post-2020), and due to the cost-optimising nature of ETM-UCL, a comparable level of abatement is not achieved for this sector. The absence of significant electrification of road transport is likely due to the relatively high investment costs and discount rates for this sector, making decarbonisation, especially in the face of increasing rather than falling demand, highly expensive. As such, the EU target for CO_2 intensity of 95gCO_2/km for new cars in 2020 is only achieved as a total fleet average in 2050 in the two constrained scenarios.

Relatively significant decarbonisation occurs in the building stock by 2020 (55% below 1990 levels), largely driven by rapidly increasing proportions of electricity and biomass, and increases in residential space heating efficiency from 2010, as old boilers are replaced with more (cost) efficient units. Direct heat moves from the domestic (space heating) sector to the commercial sector. Total energy demand in the building stock returns to around 2010 levels by 2050, with emissions increasing to reach just 36% below 1990 levels by 2020 (20% below 2010), driven by an increasing residential and commercial building stock (although of decreasing average energy and CO_2 intensity - 25-30% reduction between 2010 and 2050). In other studies (including as the ER2050), much more significant efficiency decarbonisation is achieved through improved building envelope efficiency. As this options is not available in the ETM-UCL, average energy intensity of the building stock remains much higher in 2050 than would be expected if the Energy Performance of Buildings Directive (2010/31/EU) ambition of all new buildings being ‘nearly zero energy’ from 2020 is achieved. The continuing (and even increasing) role for natural gas in space heating and other building demand purposes is unexpected in a scenario where CO_2 emissions are highly constrained. As with decarbonisation of transport, a more significant switch to electricity, for example (a common result in other studies – including ER2050), is likely prevented by the high

[28] The agriculture sector will not be discussed further due to the lack of variation between scenarios and the inability to consider non-CO_2 GHGs in this study, which are of significantly more importance than agricultural CO_2.

investment costs associated with substituting the established infrastructure. However, the use of heat pumps becomes relatively significant in commercial space heating by 2050.

CO_2 reductions in the industrial sector are driven in part by increasing process efficiency, but more importantly, by the introduction of CCS on industrial processes. As the ETM-UCL does not consider changes to trade balances of non-energy products between the EU and the rest of the world, the increasing demand for industrial sector output in line with GDP growth in the model means that such additional demand must be met domestically. As such, the model does not consider the potential for carbon leakage under a carbon-constrained regime. However, an analysis of such issues is not the purpose of this study. The 65% reduction industrial CO_2 emissions by 2050 in this study are similar to the 77-79% achieved in the ER2050 decarbonisation scenarios, also achieved through a combination of efficiency and CCS, but also increased electrification.

Although carbon leakage is not a possibility in the industrial sector, it may occur in the upstream sector where domestic production of energy products is substituted for imports from outside the EU, as occurs in the constrained scenarios. As discussed, whilst this may be cost-optimal approach, it contributes to the reduction of EU energy security without reducing global CO_2 emissions.

Long-term marginal carbon prices reaching \$300/tCO_2 (approximately €220) in 2050 (with a range of around \$50/tCO_2 either side in the feasible sensitivity scenarios) are within the range of the results projected by other studies analysing comparable decarbonisation scenarios. The median value from the combination of various scenarios and models studies by Knopf *et al* (2013) is €521/tCO_2 by 2050, whilst values produced by the various models in Capros *et al* (2014) range between €243/tCO_2 and €565/tCO_2. Other recent studies by Capros *et al* (2012) and Hubler & Loschel (2013), for example, produce marginal carbon prices of €190/tCO_2 and €164/tCO_2, respectively. The marginal carbon price for the ER2050 DST scenario by 2050 is similar to that produced by the Policy Success scenario, at €265/tCO_2. Also akin to the Policy Success scenario, the carbon price trajectory is non-linear for most comparable scenarios in other studies; with the curve steepening towards 2050 as the potential for low cost abatement options are exhausted.

Total energy system cost in the Reference scenario is equal to around 9.1% of (exogenously) projected GDP between 2010 and 2050, rising to 10.44% and 10.34% in Fragmented Policy and Policy Success, respectively. This suggests that the additional cost of decarbonisation of the EU energy system is approximately equal to 1.26% of cumulative GDP between 2010 and 2050. As discussed, these costs are based on different basic fuel price assumptions. However, the most costly Policy Success sensitivity, the EU 'Goes it Alone' scenario (in which fuel prices are equal to those applied in the Reference), suggests a system cost equal to 10.66% of GDP between 2010 and 2050 – just a 0.31% increase on the core decarbonisation scenario. Results from other studies compared to GDP produced by other studies are difficult to compare as GDP is often calculated endogenously (and thus vary between scenarios), using different growth rate assumption or present annualised costs rather than cumulative or NPV values. The ER2050 study, which similarly assumes no difference in GDP growth between scenarios, calculates a cumulative energy system cost relative to GDP of 14.37% for the Reference, and 14.11% for the DST scenario – suggesting an energy system cost saving with decarbonisation equivalent to 2.6% cumulative GDP between 2011 and 2050, achieved through a significant reduction in fossil fuel requirements and associated costs. This is at odds with both this study and much of the literature, which suggest decarbonisation presents a positive, albeit a relatively small additional cost (Capros *et al*, 2014). The scenarios and models used by Capros *et al* (2014) suggest such additional cost to be equal to between 0.2% and 1% of cumulative GDP between 2015 and 2050, whilst Capros *et al* (2013) calculates a 0.26% equivalent cost. Although there is variation between studies (as expected with a plethora of different assumptions and other variables), the difference is generally small.

As discussed, the results of this study are cost-optimal on an NPV basis only, optimised within the boundaries of projected parameters. As such, along with necessary uncertainties regarding projected technical and other developments, the political, legal or administrative feasibility or desirability of implementing these results, along with the policy instruments and mixes that would be required, are not considered. Such considerations are the subject of future reports in the CECILIA2050 study.

8 Conclusions

This objective of this study is to examine the long-term implications for the EU's energy system if an 80% reduction in CO_2 emissions is to be achieved by 2050 against 1990 levels. This was carried out by using the recently-developed European TIMES Model (ETM-UCL) to project a least-cost pathway (in Net Present Value terms) for energy system development that meets this CO_2 constraint ('Policy Success'), along with milestone targets for 2020 and other connected parameters. A 'Fragmented Policy' scenario (60% CO_2 reduction by 2050 from 1990 levels), and a 'Reference' scenario (no CO_2 constraints post-2020), along with sensitivities of 'Policy Success', were also analysed to allow for comparison. The key conclusions are the following:

- **Power Sector** - The achievement of negative emissions in the power sector via the use of biomass CCS is essential in producing a technically feasible pathway (down to a CO_2 intensity of -190gCO_2/KWh by 2050), in the absence of demand reduction options (via demand elasticity or building efficiency options). Alongside biomass CCS (~9%), around 70% of generation sourced from a combination of wind, solar PV, nuclear and hydropower generation of similar proportions by 2050 is the most cost-effective pathway for power system decarbonisation within the context of the broader energy system, with CCS attached to the majority of remaining fossil fuels. Wind and solar PV replace nuclear when no new nuclear capacity is constructed to replace retirement of the existing fleet, at negligible additional cost.
- **Industry, Transport & Buildings** – CCS is also essential for extensive decarbonisation of the industrial sector, alongside efficiency measures, to achieve a CO_2 reduction of 65% by

2050 from 1990 levels. However, the transport sector achieves just a 10% reduction by 2050, delivered by a switch from gasoline to diesel (with some biofuels and electrification) in cars, along with increasing hybridisation of LGVs and biofuels and hydrogen becoming significant in HGVs. However, further reductions in line with other studies (such as the 60-62% projected in the ER2050) are not achieved, as this study does not consider modal optimisation or consumer demand response, and has high investment costs relative to others. The building (residential and commercial) sector achieves a 36% reduction in CO_2 by 2050 (reflected by improved energy and CO_2 intensity - 25-30% between 2010 and 2050), delivered primarily through increasing end-use product efficiency, and some shift to space heating electrification and the use of heat pumps in commercial properties. Again, with a lack of demand response and high relative investment costs, and as building envelope efficiency measures are not considered in the model, further decarbonisation comparable with other studies is not achieved (e.g. up to 88% below 1990 in the ER2050).

- **Marginal CO_2 Price –** Average EU-wide carbon prices reach \$300/tCO_2 in 2050, following a relatively steady increase from 2015 onwards (with a steeper curve between 2040 and 2050). Such a value is within the (wide) range of marginal carbon prices produced by comparable scenarios in other studies.
- **Energy System Costs** – The total energy system cost of the Policy Success scenario is projected at around \$33.2 trillion (NPV), equivalent to 10.34% projected GDP between 2010 and 2050. This is approximately \$4.33 trillion (NPV) (14%) higher than the Reference scenario system cost, implying that decarbonisation of the EU's energy system by 2050 would require an additional cost equivalent to around 1.26% cumulative GDP over this time. The highest cost Policy Success sensitivity (in NPV terms) is the EU 'Goes it Alone' scenario (in which the EU takes unilateral action, and increasing fossil fuel import prices reflect continued rapid demand outside the EU), which projects a possible further additional cost in such a circumstance equivalent to around 0.31% cumulative GDP.

Many uncertainties unavoidably pervade attempts to project future energy system developments, under given circumstances. The most significant technical uncertainty in this study is the future availability of biomass CCS – an apparently essential technology in achieving CO_2 mitigation ambitions, certainly in the absence of strong reductions in consumer end-use energy demand - particularly in transport and buildings. Whilst the purpose of this study is to determine the most appropriate pathway for the development of a low-carbon energy system in the EU on a cost-optimal basis only, uncertainties surrounding numerous other factors regarding implementation of this pathway remain. Alongside technical, economic and demographic development uncertainties to 2050, public and political acceptability issues with the low-carbon transformation may present barriers to be overcome. An appropriate policy mix to implement such a low-carbon transition must consider these aspects, and mitigate or adapt to them as necessary.

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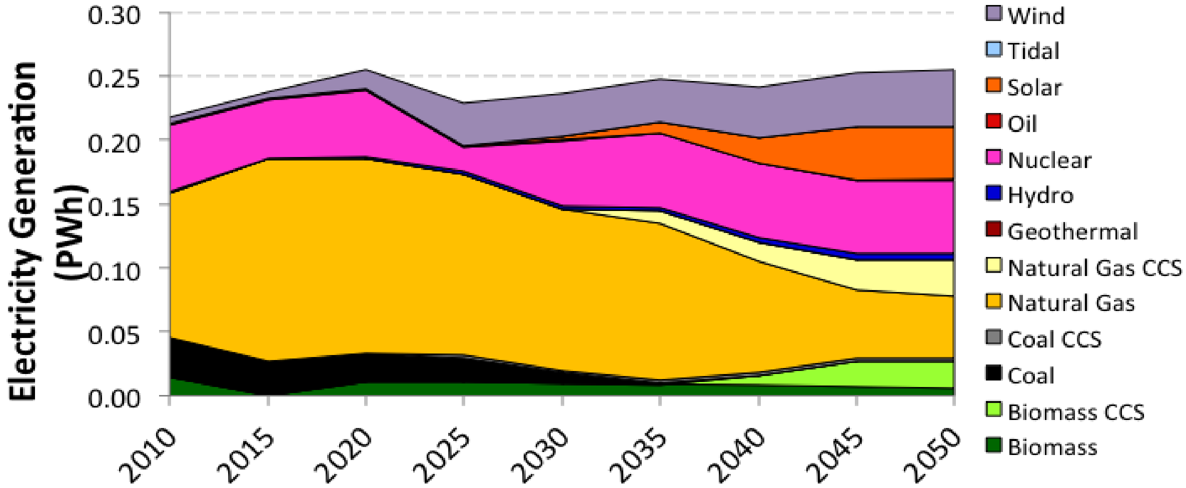
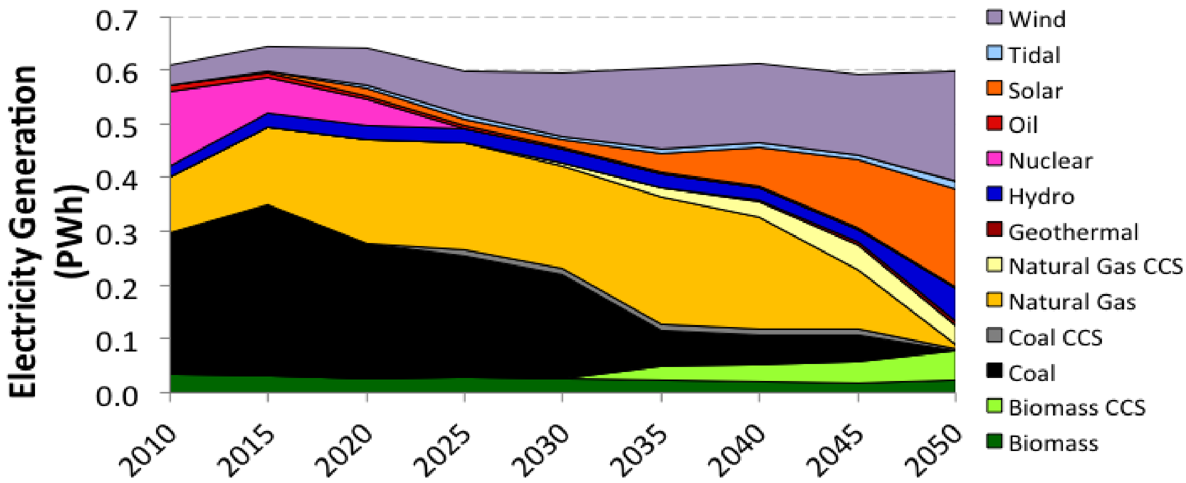
Annex 1 – Regional Electricity Generation Trends in 'Policy Success'

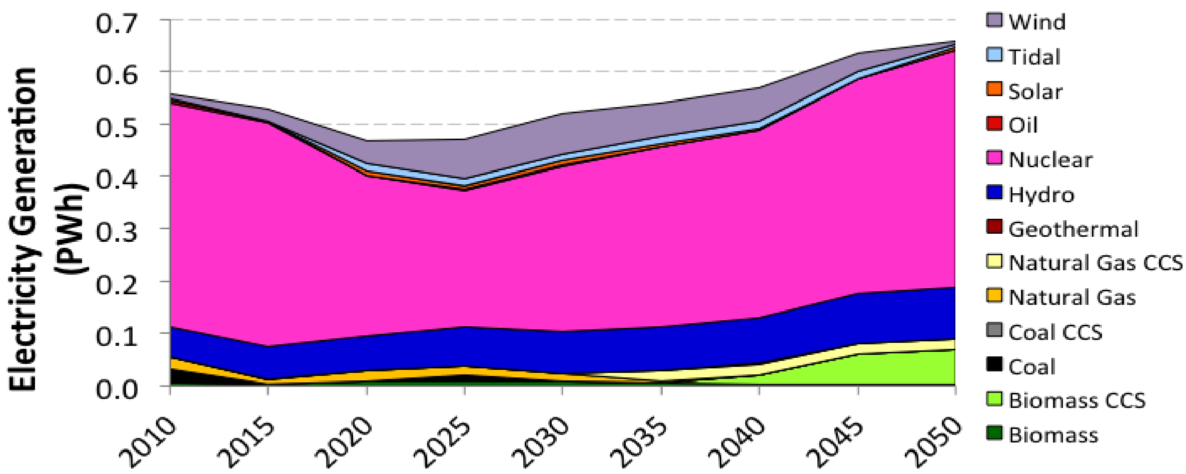
Benelux



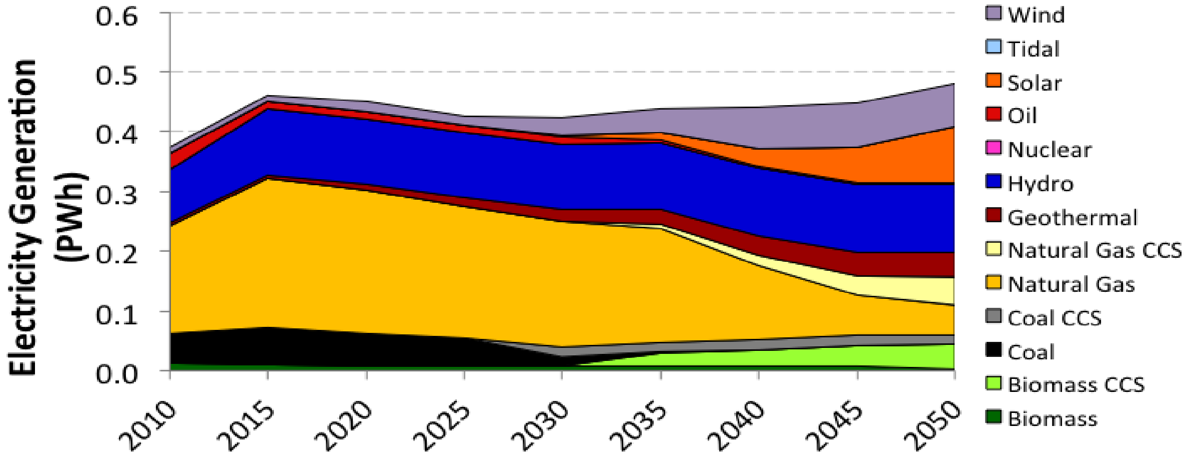
Germany



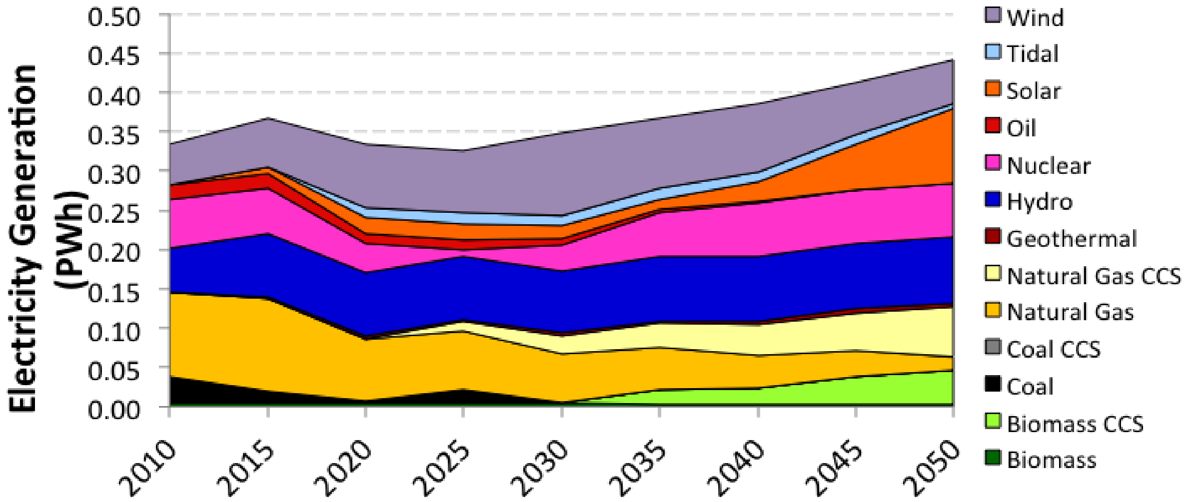
France



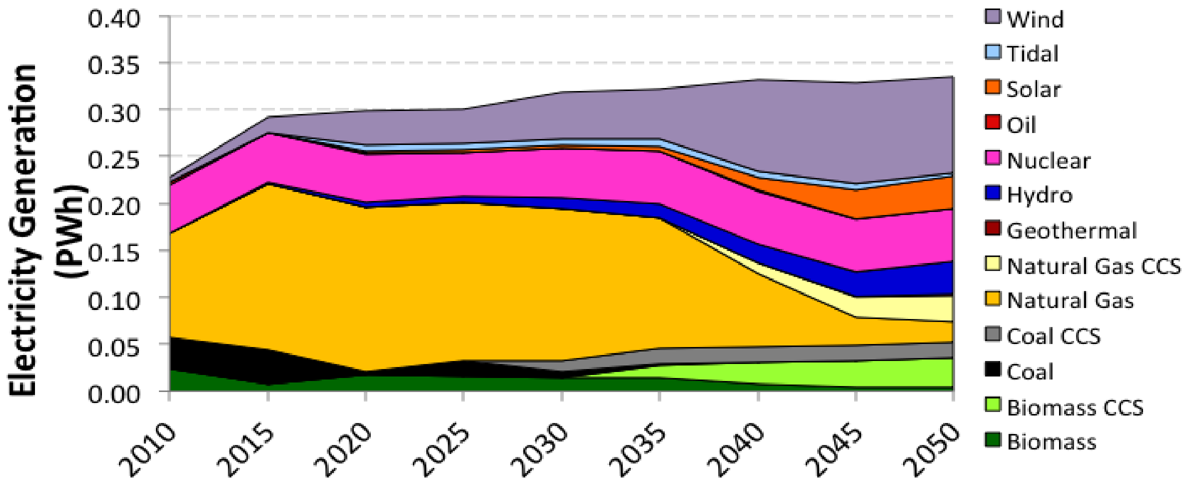
Italy, Austria and Malta



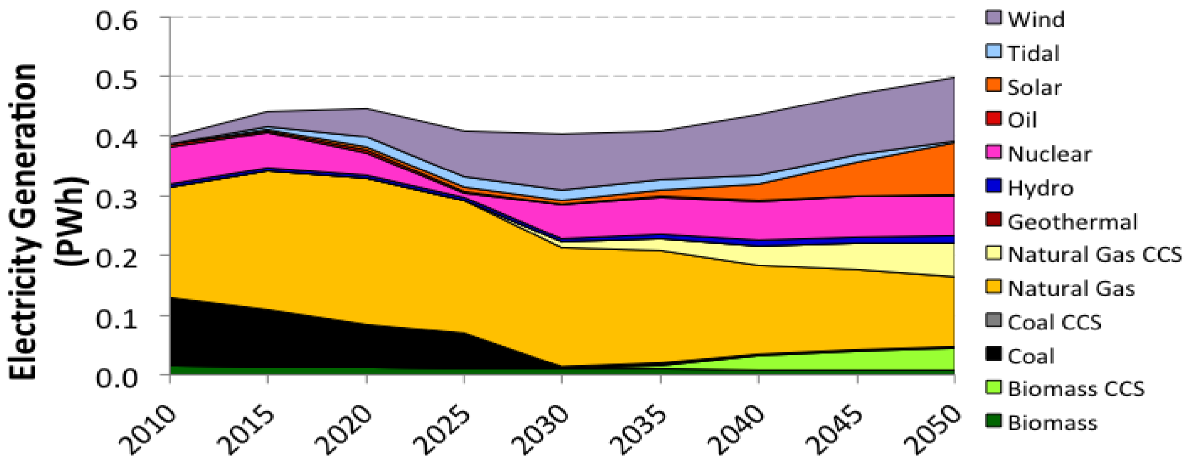
Iberia



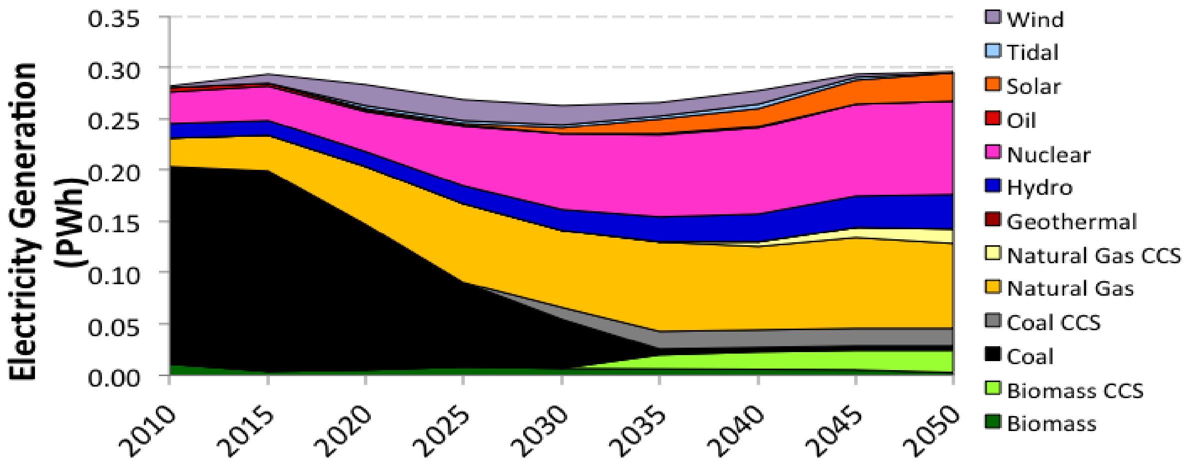
Sweden, Denmark, Finland



United Kingdom and Ireland



Eastern Europe – North



Eastern Europe - South