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

Policies to Deliver a Low-Carbon Energy System in Europe

Examining Different Policy Pathways

Funded by the European Union

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LIST OF ABBREVIATIONS

AFV	Alternatively-Fuelled Vehicles
BAT	Best Available Technology
CCGT	Closed-Cycle Gas Turbine
CCS	Carbon Capture and Storage
CEF	Connecting Europe Facility
EED	Energy Efficiency Directive
EEOS	Energy Efficiency Obligation Scheme
EITE	Energy Intensive Trade Exposed
EPBD	Energy Performance of Buildings Directive
EPC	Energy Performance Certificates
ER2050	Energy Roadmap 2050
ESCo	Energy Saving Company
ETD	Energy Taxation Directive
EU ETS	European Union Emissions Trading System
HGV	Heavy Goods Vehicle
HVAC	High Voltage Alternating Current
HVDC	High Voltage Direct Current
KWh	Kilowatt Hour
LCOE	Levelised Cost of Electricity
LEZ	Low Emission Zone
LGV	Light Goods Vehicle
LRF	Linear Reduction Factor
MSR	Market Stability Reserve
OCGT	Open Cycle Gas Turbine
PAYS	Pay As You Save
PHEV	Plug-in Hybrid Electric Vehicle
PTP	Personalised Travel Planning

RES-E	Renewable Electricity
RHI	Renewable Heat Incentive
TCO	Total Cost of Ownership
TSO	Transmission System Operator
TYNDP	Ten-Year Network Development Plan
VA	Voluntary Agreement

Executive summary

It is clear that a substantial shift in the physical characteristics of the EU's energy system is required to achieve an 80% reduction in CO_2 emissions by 2050 (from 1990 levels), with various interdependencies presenting themselves. Principal among these is the decarbonisation of electricity generation, to allow for increased electrification of key demand sectors (buildings and transport, in particular).

Three stylised policy pathways have been presented; a 'market-based' pathway, a 'technology-based' pathway, and a 'behaviour-based' pathway. The market-based policy pathway principally employs carbon pricing and other pricing mechanisms to drive decarbonisation. It is likely that such a pathway has a substantial chance of achieving significant decarbonisation across many sectors, however the potential for price instability and unknown technological cost development produces a great deal of uncertainty. Principal-agent issues, along with information asymmetries and behaviour and psychological issues (at both the individual and organisation level) present other barriers to technological shifts. The technology-based policy pathway focuses on the use of direct regulatory instruments. As with the market-based policy pathway, upon initial inspection it would appear this option also holds a reasonable chance of achieving the required objectives. However, whilst issues of uncertainty and principal-agent problems, for example, are reduced compared to the market-based pathway, issues of monitoring and enforcement of regulations may become prominent, calling this conclusion into question. In the behaviour-based policy pathway technological change is likely to be driven primarily by remaining pricing and regulatory instruments, rather than information and other behavioural instruments. The evidence suggests that information and other instruments designed to modify and overcome barriers to behaviour change have thus far proven largely ineffective – although this may change over time with awareness, culture, and improved scope and instrument design.

It is evident that any effective policy mix for decarbonisation of the EUs energy system must include components from all three approaches, to counter the drawbacks inherent in focussing on a single paradigm, and to produce synergies that would otherwise not arise. However, the particular configuration of policy instruments must consider issues other than assumed 'effectiveness'. Issues of cost-efficiency, both static and dynamic, must be considered. In the longer term, dynamic incentives for innovation are particularly important in order to deliver key technologies that are expected to play a substantial role (e.g. CCS), and produce cost reductions (e.g. renewable and low-carbon vehicle technologies). Additionally, of course, policy instruments and instrument mixes must be feasibly introduced and complied with. This includes the interrelated issues of public and political acceptability, legal compatibility and administrative ability.

Some aspects may be summarised from this report that may be classified as key 'bottlenecks'; issues for which if progress if not made or solutions not found within the near future, they may act as significant hurdles or even barriers to achieving the CO_2 emissions reductions sought in the required timeframe. The most prominent of such bottlenecks are:

- **Electricity grid expansion and interconnection**. An annual increase of around 1% in electricity transmission network length is likely required between now and 2030, along with substantial investment to upgrade existing transmission and distribution infrastructure, to enable an approximate doubling of (largely renewable) electricity capacity to come online (both centralised and decentralised). This includes an on average doubling in interconnector capacity between Member States. Such objectives must be achieved to enable rapid, cost-efficient decarbonisation of the electricity generation, whilst maintaining electricity security. This includes consideration of methods of financing and authorisation procedures, discussed below.
- **Electricity market design**. The existing EU electricity markets, with increasing renewable electricity capacity, are expected to produce an inherent 'missing money' problem, where renewable, nuclear and fossil fuel generators alike cannot generate sufficient revenue from the market to cover their levelised costs. This prevents investment in any installation that does not receive enough external subsidy to substitute for this (particularly fossil fuels), risking security of supply issues. Electricity market designs, either a single EU integrated market or aligned national markets, must be reformulated or complemented (e.g. with capacity markets) in the near future to account for this.
- **Streamlined, integrated and permissive administration and authorisation procedures.** Authorisation and planning procedures have proven to be significant barriers to the development of low-carbon or enabling infrastructure – particularly transmission infrastructure and renewable electricity installations. Such barriers must be removed to permit the development of such essential infrastructure.
- **Incentives to transition to low-carbon electricity generation and capacity profile.** Although an expanded, interconnected grid and suitable electricity market design allows for the development of a low-carbon power sector, it will not (necessarily) drive it. Other incentives will be required, which will likely include reforms to the EU ETS to produce a higher, more predictable carbon price, and depending on the specific design of a future electricity market, the presence of some form of renewable electricity support mechanism (either centralised at the EU level, or more likely harmonised to a substantial degree across Member States). It is unlikely that decarbonisation of the power sector would be successfully delivered without such instruments working in tandem, particularly in the short term. Although which of these, or any other instruments, is the driving force, may vary depending on the particular policy mix employed.
- **Decarbonisation of the existing residential building stock.** Over 80% of the residential building stock expected to be present in 2050 in the EU is already in existence. Energy consumption by these buildings must reduce by at least 0.6% per year between 2015 and 2050. Whilst the Energy Efficiency Directive currently requires energy savings of 1.5% per year (across both residential and commercial consumers), this requirement ends in 2020, and evidence suggests that of the 17 Member States that have chosen to implement Energy Efficiency Obligation Schemes to fulfil this obligation, 14 have credibility concerns.

Issues such as appropriate financial incentives, the landlord-tenant dilemma, access to and cost of capital, the 'hassle factor', discounting of costs and benefits and other behavioural issues are persistent problems that often prevent the voluntary installation and introduction of energy efficient and low-carbon technologies and behaviours. At present, the EU policy mix does not sufficiently tackle these issues in order to produce conditions conducive to long-term reductions in energy consumption and CO_2 emissions from this sector. In order to achieve the average annual reduction outlined above over the coming 35 years, and given the long life of such infrastructure and investments, this should be addressed as a matter of urgency.

For the (road) transport and industrial sectors, no particular issues were identified that constitute urgent bottlenecks of a similar nature to those outlined above (in terms of instrument 'effectiveness', as used in this paper, at least). For example, the passenger car stock is fully replaced approximately every 15 years, meaning that substantial decarbonisation under an effective policy mix results may be delivered relatively quickly. Additionally, requirements are already in place to ensure electric vehicle charging networks are established to allow circulation of such vehicles in urban and suburban conglomerations by 2020. In the industrial sector, as energy is a major cost liability for the most energy- and CO_2-intensive sectors, the reform of the EU ETS may produce relatively rapid increases in efficiency and low-carbon measures. However, one such measure is the widespread introduction of CCS on industrial processes. This is heavily dependent on the availability and associated cost of such technology. Whilst this paper assumes it will be commercially available when it is required, efforts are needed to ensure that this will indeed be the case, along with technological availability and cost reductions in other sectors, although such issues are outside the scope of this report. However, substantial action is still required in order to meet and exceed the minimum requirements outlined for all sectors discussed, driven by improvements and changes that will be required to the existing climate policy mix, over the short-, medium- and long-term.

1 Introduction

It is clear that to enable the EU and its constituent Member States to achieve a reduction of GHG emissions of 80-95% by 2050 (against 1990 levels), a substantial transformation of the energy system – from power stations and energy transmission and distribution networks to vehicle filling stations and the vehicles that require them - driven by enhanced effective, cost-efficient and feasible policy instruments, is required. The objective of this report is to propose and assess the effectiveness of typified policy packages with coverage across the European energy system to facilitate this transformation.

Chapter 2 first details the medium (by 2030) and long-term (by 2050) key infrastructure requirements and characteristics based on energy system modelling, by both supply and end-use sectors. A 'low-carbon energy infrastructure' is defined here as the key physical stationary and mobile assets required across the power generation and transmission, other energy and CO_2 distribution, industrial, buildings and transport sectors, to enable an 80% reduction of CO_2 emissions from the EU's energy system by 2050. The agriculture sector is excluded from this discussion, due to the minor contribution to energy-related CO_2 emissions in the EU. Discussion of upstream fossil fuel-related infrastructure (e.g. extraction, refining and importing infrastructure) is also excluded.

Chapter 3 then presents three policy packages for delivering this infrastructure, based on three different policy paradigms. Key policy instruments will be presented; along with a discussion of specific benefits and challenges presented, and potential 'bottlenecks' that may occur. Explicit discussion of policy instruments to directly encourage technological innovation is excluded, along with detailed discussion of institutional and legal arrangements, material resource constraints, availability and sources of finance, carbon leakage, distributional impact and public and political acceptance. Such aspects are addressed in separate publications in the CECILIA2050 project[1], however they are raised in this report when they are of particular importance. Issues external to the EU are also not considered. Chapter 4 summarises and concludes.

2 Low-Carbon Infrastructure Requirements

The projected profiles of a low-carbon infrastructure and economy in the EU by 2050, and the pathways to achieving it, vary substantially between specific scenarios and modelling activities - all of which consider different projections of energy demand, technology and resource development and cost evolution (amongst innumerate others), along with different model objectives, structure and dynamics. Such a situation is inevitable, as future

[1] See www.cecilia2050.eu/publications for all publications from the CECILIA2050 project.

developments are inherently uncertain. However, this chapter presents the common key infrastructure requirements produced and inferred by the following key low-carbon scenarios and modelling exercises:

- **CECILIA2050 Modelling**[2] - Three aligned, complementary modelling activities to project pathways for a low carbon energy system were undertaken as part of the CECILIA2050 project. The first employs the cost-optimising European TIMES energy system model (ETM-UCL), the second employs the global economic-environmental model GINFORS, whilst the third employs the global EXIOBASE Input-Output model framework. The 'central' decarbonisation scenario results of all three models will be employed in this report, although the focus will largely rest with those of the ETM-UCL 'Policy Success' scenario, which lends itself most appropriately to discussions of specific infrastructure requirements.
- **Energy Roadmap 2050**[3] - The ER2050 was produced in 2012 at the request of the European Council. It produces and assesses five pathways for EU energy system decarbonisation to reach an 85% reduction in CO_2 emissions from 1990 levels by 2050 (along with a Reference and 'Current Policy Initiatives' scenario). This report will assess the conclusions from the central 'Diversified Supply Technologies' decarbonisation pathway, under which no specific technology is preferred, with cost-optimisation determining deployment.
- **IEA 2012 Energy Technology Perspectives**[4] - The IEA 2012 ETP presents global energy system pathways under a '6°C Scenario' (6DS), in which current trends are generally extrapolated to 2050, a '4°C Scenario' (4DS), in which country-level emissions pledges are enforced and stepped-up, along with efforts to improve energy efficiency, and a '2°C Scenario' (2DS), in which the global energy system reduces CO_2 emissions by 2050 consistent with an 80% change of limiting average global temperature increase to 2°C (approximately a 50% decrease from 2009 levels). This report will assess conclusions drawn in the 2DS scenario for the European Union.

Figure 1 illustrates and compares the CO_2 emissions trajectory for the EU produced by these modelling exercises (with all three outputs from the CECILIA2050 modelling illustrated). It is immediately clear that there are significant differences between the individual CECILIA2050 modelling outputs, reasons for which are explored in detail in Drummond (2014). The ETM-UCL results match most closely to the ER2050, which both achieving a CO_2 reduction of 80% below 1990 levels. The GINFORS results match largely with the IEA CO_2 projections, achieving CO_2 emissions approximately 65% below 1990 levels by 2050. For IEA, this is due to the global nature of the modelling approach and objectives, rather than region specific. For GINFORS, this largely a result of reduced fossil fuel prices hampering mitigation efforts (see Drummond

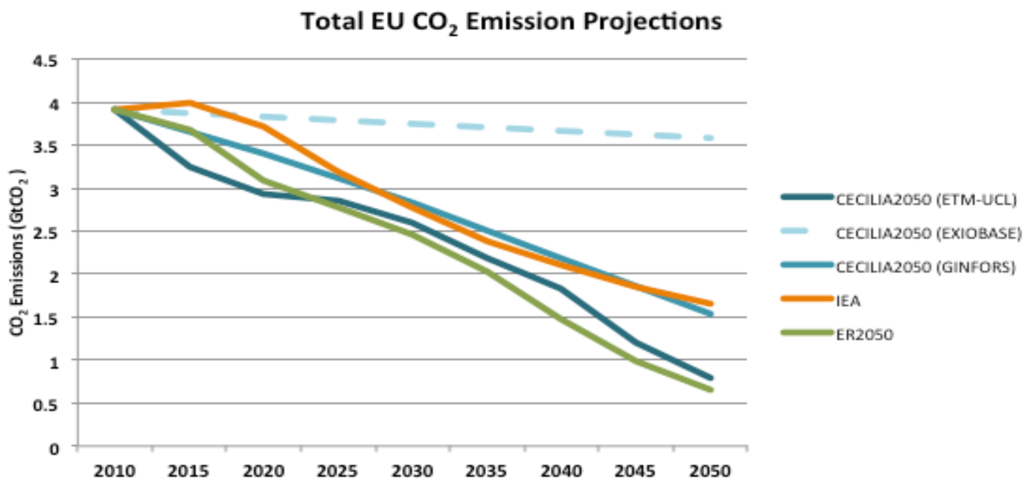
[2] See Drummond (2014) for a synthesised discussion of the results of the results of these three modelling activities. For more information regarding specific modelling approaches, scenario design and results, see Solano & Drummond (2014) for ETM-UCL results, Meyer *et al* (2014) for GINFORS results, and De Koning *et al* (2014) for EXIOBASE I-O Model results.

[3] See European Commission (2011) for more information.

[4] See IEA (2012) for more information.

(2014) and Meyer *et al* (2014)). The EXIOBASE projection achieves CO_2 emissions in 2050 just 20% below 1990 values. This is a result of the associated modelling approach and assumptions applied, which are again discussed in Drummond (2014), and De Koning *et al* (2014).

Figure 1 - Total EU CO_2 Emission Projections



The discussion will be divided into the key sectors of 'power generation', 'industry', 'buildings' and 'transport' and 'energy and CO_2 transmission and distribution networks', with each sub-section providing a general description of current circumstances and a discussion of key common requirements by 2030 and 2050, based on the results of the above modelling activities. As the specific requirements and possible developments across Member States is likely to be extremely heterogeneous, the focus here is necessarily at the EU level. However, specific issues of difference between Member States with different characteristics are raised when of clear importance. Additionally, the infrastructure requirements, and therefore the policy instrument packages proposed to deliver them, are not comprehensive, and represent the projected key requirements only.

2.1 Power Generation Infrastructure

Power generation is the greatest contributor to European CO_2 emissions, accounting for 33% of total CO_2 emissions in the EU28[5] in 2012 (European Environment Agency, 2014). Despite, and partly because of this, the power sector is the greatest contributor to abatement in the majority of medium and long-term low-carbon scenarios. Each of the low-carbon scenarios discussed here project a CO_2 reduction of at least 90% by 2050 from 1990 levels (88% from 2010 levels) in the power sector. The ETM-UCL projects the power sector becoming a net sink for CO_2 emissions via the use of biomass combustion with carbon capture and storage (CCS).

[5] All such values are exclusive of Land Use, Land Use Change and Forestry (LULUCF). CO_2 emissions from sources such as international transport, upstream activities (e.g. petroleum refining) and waste (accounting for approximately 14% of CO_2 emissions in the EU28 in 2012 (European Environment Agency, 2014), are not considered in this report).

By 2030, a reduction of at least 60% from 1990 levels (52% from 2010) is projected in order to meet these levels in 2050.

This decarbonisation is projected in tandem with (often significantly) increasing electricity generation, driven by increasing demand from existing end-users, and increasing electrification of other sectors and sub-sectors (discussed below). Total generation in the EU in 2010 was 3,373 TWh. Low-carbon scenarios project this to increase by an average of around 35% by 2050 (varying from 15% to 50%, depending on the particular scenario assumptions). This means CO_2 intensity of power generation must reduce to around 150gCO_2/KWh by 2030, as a milestone to reaching at a maximum of around 10gCO_2/KWh by 2050 (from around 350gCO_2/kWh in 2010). Methods of achieving such decarbonisation in the power sector very substantially between different scenarios and the assumptions therein.

Figure 2 illustrates projected proportional contributions to the European electricity mix by 2030 and 2050 from the IEA, ETM-UCL and ER2050 studies, whilst Figure 3 presents associated electricity capacity projections from the ER2050 and ETM-UCL studies[6].

Figure 2 - Projected EU Electricity Generation Profile

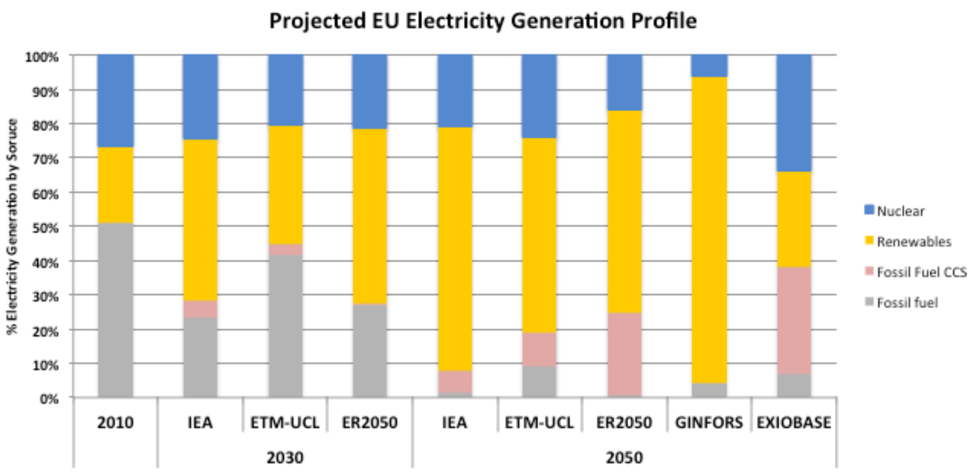
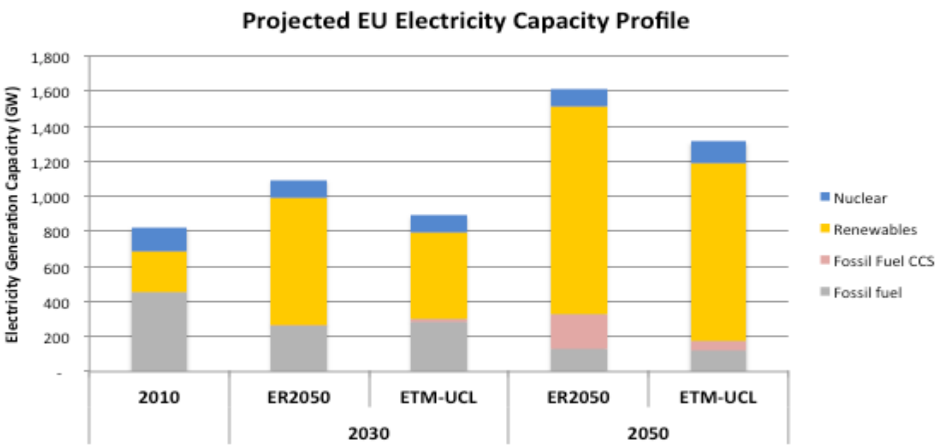


Figure 3 - Projected EU Electricity Capacity Profile



[6] Electricity capacity data is unavailable for the IEA, GINFORS and EXIOBASE studies, and as such are excluded from Figure 3.

Fossil Fuels and CCS

In 2010, unabated fossil fuels accounted for around 51% of European electricity generation, and around 56% of generation capacity (with an approximately equal share between coal and natural gas). It is clear that such generation must reduce drastically by 2050, as confirmed by Figure 2, in which it retains a share of between just 1% (ER2050) and 9% of total generation (ETM-UCL). In all cases, unabated coal is almost entirely removed, with any remaining fossil-based generation sourced from natural gas. As such, unabated fossil fuel generation (from natural gas) should account for a maximum of 10% of total electricity generation in the EU in 2050 (and a maximum of 40% by 2030) Associated generation capacity should decrease to around half 2010 levels (and less than 25% of total generation capacity) by 2030, before reducing again to a quarter of 2010 levels (and less than 10% of total generation capacity) by 2050.

Generation from fossil fuels with CCS is introduced in all studies (except GINFORS[7]), but its projected contribution to total generation by 2050 varies significantly – from 6% (IEA) to 31% (EXIOBASE). This difference is a function of variations in scenario assumptions, technology and fuel availability and costs, amongst other variables[8], that act to favour certain low- or zero-carbon generation technologies (including fossil fuel CCS, nuclear and renewables), over others. A value of at least 10% generation by fossil fuel CCS installations (at any combination of gas or coal) by 2050 (implying a capacity equal to at least 5% of total generation capacity) appears reasonable based on the studies considered in this report. CCS technologies are commonly projected to have achieved only relatively minor deployment by 2030 (as illustrated in Figure 2, the most optimistic is up to 5% of total generation). As such, a target contribution of over 2% by 2030 appears reasonable (with a capacity target of around 1% of the total). Additional infrastructure requirements concerning CCS are discussed in Section 2.5.

Nuclear

In 2010, nuclear accounted for around 27% of European electricity generation (and the majority of its zero-carbon generation), and around 16% of its total generation capacity. As illustrated in Figure 2, all studies considered project a largely stable proportional contribution to generation out to 2050 (except GINFORS, which projects a decrease to 6%), with capacity also remaining largely equal in absolute terms (as illustrated in Figure 3 for the ETM-UCL and ER2050).

However, the distribution of nuclear generation is likely to change somewhat over this time horizon. For example, Germany, which in 2010 sourced around 25% of its generation from nuclear power (16% of total EU generation from nuclear, and around 5% of total EU power generation), has committed to becoming nuclear free by 2022[9]. France, which in 2010

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[7] GINFORS assumes CCS will be unavailable, as an exogenous model constraint. See Meyer & Meyer (2013) for details.
[8] See respective publications for details, listed in Footnotes 2 to 4.
[9] For more information, see: http://www.world-nuclear.org/info/Country-Profiles/Countries-G-N/Germany/

sourced around 90% of its generation from nuclear power (48% of total EU generation from nuclear, and around 14% of total EU power generation), has committed to reducing the contribution from nuclear to 50% by 2025[10]. A number of other non-nuclear states also committed to remaining so. As such, if nuclear-based generation is to maintain its existing proportional contribution to the EU generation mix, new capacity will be required in Member States that are pro- (or not anti-) nuclear, such as the UK, and some Baltic States.

Renewables

In 2010, renewables[11] accounted for around 22% of European electricity generation, and around 28% of its total generation capacity. The largest individual contributor was hydroelectricity (43%), with wind and biomass (including renewable wastes) both accounting for approximately another 25% each, and solar around 5% (Eurostat, 2015). As expected, renewables experience the greatest increase in generation in all models to between 57% (ETM-UCL) and 90% (GINFORS) of generation by 2050 (except EXIOBASE, which projects 28% of generation from renewables). In all cases wind and solar are the largest contributors to renewable generation (with approximately equal shares).

As illustrated in Figure 3, renewables also account for the largest growth in capacity (in both absolute and proportional terms), to account for approximately 75% of installed capacity by 2050 in the ER2050 and ETM-UCL studies (from around 28% in 2010). The proportion of projected renewable capacity is often greater than the proportion of projected electricity sourced from renewables due to reduced capacity factors[12] compared to conventional generation, produced by intermittency (particularly with wind and solar installations). Whilst nuclear commonly operating in Member States with a capacity factor above 70%, the annual average for wind generation in the EU in 2012 was 22.1% (European Commission, 2014a). As such, to generate an equivalent level of electricity, greater levels of capacity are required. However, this is less of a problem with, for example, biomass and hydropower, which are not subject to such short-term intermittency.

The deployment of renewable electricity (RES-E) may follow the current 'centralised' power generation paradigm, in which electricity is generated at large installations before entering the transmission and distribution system for delivery to consumers, or a shift towards 'decentralised' generation may occur, in which electricity is produced by smaller installations for autoproduction[13], or when (surplus) electricity enters the grid through the distribution network (bypassing the transmission system, discussed under Section 2.5)[14]. Decentralised installations may range from solar photovoltaic systems on individual residential or

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[10] For more information, see: http://www.world-nuclear.org/info/Country-Profiles/Countries-A-F/France/

[11] In this report 'renewables' includes hydropower and biomass combusted with CCS.

[12] Defined as the ratio of actual generation in a given period to the maximum possible (i.e. if output was continuously a at full nameplate capacity) (Eurelectric, 2011b)

[13] Defined as the generation of electricity for the generators own use, on a single premises.

[14] Decentralised generation may also known as 'distributed' generation. Various specific definitions of this type of generation exist, but all contain the requirement that if the owner is not the sole consumer of the electricity generated, the installation must be connected to the distribution network, rather than the transmission network. A review of definitions may be found in L'Abbate *et al* (2007).

commercial properties, to community-based installations supplying local demand, and those satisfying the demand of large industrial sites.

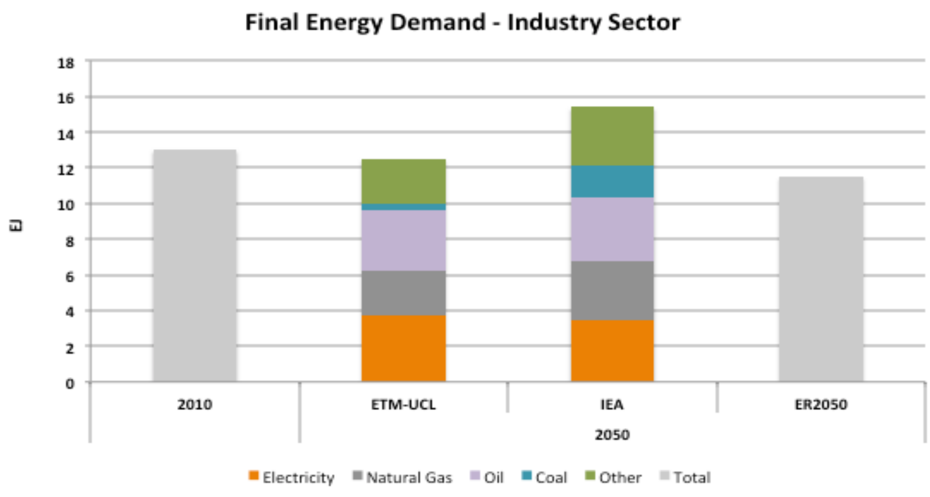
Based on the modelling studies considered, a minimum target generation from renewables in the EU is 40% by 2030, and 60% by 2050. This implies a share of total generation capacity of around 60% and 75% by 2030 and 2050, respectively.

The development of the electricity mix over time, in terms of specific technologies employed and the profile of their deployment (e.g. centralised or decentralised) will vary significantly by Member State. This determines, and is determined by, developments required in electricity transmission, distribution and management infrastructure (Section 2.5), along with market design for effective operation (Section 3.5).

2.2 Industry Sector

Emissions from the Industry sector accounted for around 13% of total CO_2 emissions in the EU28 in 2012 (European Environment Agency, 2014), with the manufacture of chemicals, iron and steel responsible for over half of this (and over half on all industrial energy consumption). CO_2 projections to 2050 from the industrial sector are relatively consistent between the ETM-UCL, IEA and ER2050 results at 77%, 67% and 78% below 1990 levels respectively (63%, 49% and 66% below 2010 level respectively). This is delivered despite increasing demand for industrial products[15], and achieved through a combination of energy efficiency, fuel switching and the use of CCS on industrial processes. Figure 4 illustrates total industrial energy consumption projected by these modelling activities by 2050[16].

Figure 4 - Final Energy Demand - Industry Sector



As illustrated in Figure 4, both the ETM-UCL and ER2050 project a decrease in final energy consumption between 2010 and 2050 (4% and 12% respectively), whilst the IEA projects an

15 Growth in demand for industrial products is driven primarily in all studies discussed by GDP growth, but the profile of growth depends on the structure, scope and assumptions present in each model employed. Refer to Solano & Drummond (2014), IEA (2012) and European Commission (2011) for details and discussions of these assumptions.

16 'Other' fuels include biomass, direct heat and other renewables.

18% increase. Each of these projections is significantly below the energy consumption projections in their 'reference' scenario counterparts (between 15% and 30%), indicating a relatively significant increase in energy efficiency in each result as demand for industrial products increases[17]. This is may be achieved through the use of existing Best Available Technologies (BAT) (which alone are estimated to have the potential to reduce industrial energy demand by around 10% from current levels (IEA, 2012)), but also through the increased use of combined heat and power (CHP) units and district heating. Whilst the potential for energy efficiency varies significantly by the specific industrial sub-sector in question, such detail is beyond the scope of this report.

In 2010, energy consumption in the industrial sector in the EU was dominated by oil, natural gas and electricity (with an approximate 25% share each). The remainder is composed in large part by coal, with direct heat and biomass also contributing. As illustrated in Figure 4 for the ETM-UCL and IEA results (such data is unavailable for the ER2050 results), fuel switching to carriers with lower CO_2-intensity (such as biomass) is likely to be a minor contributor to abatement in this sector. This is due to assumed price elasticities rendering substantial energy carrier substitution a relatively expensive option (although again, whilst beyond the scope of this report, the specific existing and projected energy mix varies between sub-sectors and studies). Therefore the major driver for abatement in the industrial sector in each of these studies is the application of CCS on industrial processes. It is responsible for over half of the projected abatement in the sector between 2010 and 2050 in the ETM-UCL results, and nearly two-thirds in the IEA projections.

The GINFORS and EXIOBASE model results project significantly different results to those discussed above, but also to each other. GINFORS projects a CO_2 reduction of 26% by 2050 from 1990 levels (an increase of 16% from 2010), whilst the EXIOBASE results project at 51% increase (137% from 2010). The difference is due in large part to sector accountancy (for example, the 'Industrial' sector in GINFORS also includes industry-related buildings[18] and transport activities, and therefore energy consumption and emissions, which are subject to the associated assumptions described in the related sections below) along with model structure and scope[19]. Also, significantly, neither study considers the use of CCS in industry.

Based on these studies, it is clear that the industrial sector is likely to be the most difficult sector to decarbonise significantly. Total energy consumption (and the energy carrier mix) is likely to remain stable to 2050 (indicating increasing energy efficiency), with CCS sequestering at least 50% of CO_2 emitted from industrial processes.

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[17] Each study applies the same GDP growth assumptions in both their 'reference' and 'decarbonisation' scenarios, indicating comparable growth for industrial products in both projections for each study. Although, the extent to which this is the case will vary between each model employed.

[18] Developments in industrial-related building are discussed under the 'buildings sector' sub-section, although policies for industry-related buildings are discussed as part of the industry sector under Chapter 3.

[19] See Drummond (2014) for a more detailed explanation.

2.3 Buildings Sector

Direct emissions from the buildings sector accounted for around 16% of total CO_2 emissions in the EU28 in 2012 (European Environment Agency, 2014), with residential emissions accounting for around 70% of this. The ETM-UCL, GINFORS and IEA results are largely consistent in their projected abatement from buildings, averaging at around 42% below 1990 levels by 2050 (35% below 2010). The ER2050 however projects much deeper CO_2 reductions, at 86% below 1990 levels by 2050 (84% below 2010 levels), with the EXIOBASE results projecting CO_2 emissions from buildings remaining largely stable between 2010 and 2050[20]. Reasons for the difference between the first three projections and the latter two are elaborated below. Figure 5 illustrates the CO_2 intensity of the residential and commercial building stock by 2030 and 2050, based on projections by the ETM-UCL and ER2050 results.

Figure 5 – Average CO_2 Intensity Projection - Residential and Commercial Buildings

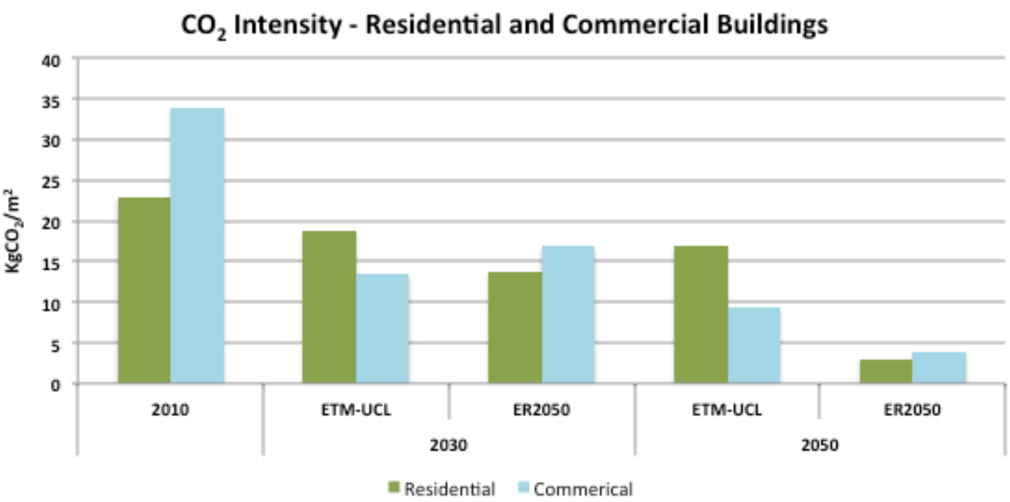


Figure 5 illustrates the average CO_2 intensity of the EU residential building stock decreasing to $17kgCO_2/m^2$ by 2050 under the ETM-UCL projections (from $23kgCO_2/m^2$ in 2010), whilst the ER2050 projects a reduction to just $3kgCO_2/m^2$ (a reduction of 26% and 87% on 2010 levels, respectively). Commercial properties[21] are projected to decrease in CO_2 intensity to $9kgCO_2/m^2$ and $4kgCO_2/m^2$ by 2050 by the ETM-UCL and ER2050 respectively, from $34kgCO_2/m^2$ in 2010 (a 73% and 88% reduction, respectively). The IEA results (not included in Figure 5 due to a lack of disaggregated data for 2030), project a residential and commercial CO_2 intensity of $11kgCO_2/m^2$ and $23kgCO_2/m^2$ by 2050 (a 53% and 33% reduction on 2010 levels, respectively). Although disaggregated data for GINFORS and EXIOBASE are not

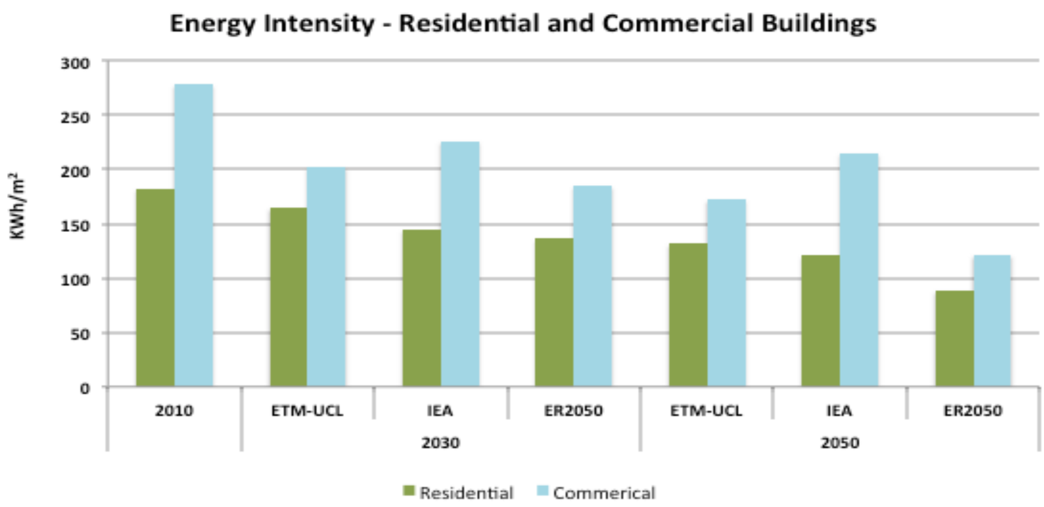
[20] Refer to Drummond (2014) for discussion of emissions accountancy in the GINFORS and EXIOBASE models. Values employed in this section from the results of these models are calculated as a close approximation for all non-industrial buildings due to the dominance of the residential sector in CO_2 emissions and energy consumption of all buildings, by considering 50% of 'direct' CO_2 emissions in the EXIOBASE results as 'residential' emissions.

[21] For the purposes of this report, projections and trends for commercial properties also applied to publicly owned and industrial properties. However, policies related to industrial buildings are dealt with under the industrial sector.

available, CO_2 intensity for all (non-industrial) buildings reaches approximately 14kgCO_2/m^2 and 20kgCO_2/m^2 by 2050. Although these results are rather varied, reasonable targets appear to be a maximum average CO_2 intensity of 10kgCO_2/m^2 and 12kgCO_2/m^2 for m^2 for residential and commercial properties across the EU by 2050, with a 2030 target of around 16kgCO_2/m^2 for all buildings (the average value of results illustrated in Figure 7, and the IEA projections for 2050). For residential properties, this equals approximately 1.54tCO_2/hh by 2030 and 1tCO_2/hh by 2050, from around 2.16 in 2010. However, given the significant variation in household size across the EU (an average of 50m^2 per capita in Northern and Southern Europe, and 25m^2 per capita in Central and Eastern Member States) (BPIE, 2011), this average value is likely to vary significant across the Union.

These results are produced in the context of an increase in total energy service demands in buildings (by 14% in residential, and 36% in commercial buildings as projected by the ETM-UCL between 2010 and 2050), driven by increasing household numbers and floor area (both residential and commercial)[22]. However, all models (except EXIOBASE[23]) project a decrease in final energy consumption in buildings (between 3% and 8% reduction between 2010 and 2050). Therefore, it is clear that the abatement described above is delivered at least in part through increasing energy efficiency. Whilst is likely to be delivered in part by behavioural actions (such as closing windows and turning off appliances when not in use)[24], the majority will likely be delivered through infrastructure alterations. Figure 6 illustrates the energy intensity of the residential and commercial building stock by 2030 and 2050, based on projections by the ETM-UCL, IEA and ER2050 results.

Figure 6 – Average Energy Intensity Projection - Residential and Commercial Buildings



[22] The IEA (2012) project household numbers in the EU to increase from 206 million in 2009 (around 64% single family houses, 36% apartment blocks (BPIE, 2011) to 252 million in 2050, with an associated floor space increasing from 19.5 billion m^2 to 24.7 billion m^2. Commercial floor space is projected to increase from 7.3 billion m^2 to 10.1 billion m^2. Both trends are mostly driven by an increase in commercial value added and residential income rather than population growth (projected to increase modestly from 500 million in 2009 to 512 million in 2050). These figures are employed in the calculation of values in Figure 7 and Figure 8.

[23] Not included, as disaggregated energy consumption data is not easily extracted from these results.

[24] The deployment and use of smart meters and related issues are discussed under 'Energy Transmission and Distribution Networks', below.

Figure 6 illustrates the average energy intensity of the residential building stock decreasing to 132kWh/m^2, 121kWh/m^2 and 89kWh/m^2 by 2050 in the ETM-UCL, IEA and ER2050 results respectively from 183kWh/m^2 in 2010 (a reduction of 28%, 34% and 51% respectively). Commercial properties are projected to decrease in energy intensity to 173kWh/m^2, 215kWh/m^2 and 122kWh/m^2 by the ETM-UCL, IEA and ER2050 respectively, from 278kWh/m^2 in 2010 (a reduction of 38%, 23% and 56% respectively). As with CO_2 intensity, although disaggregated data is not available for the GINFORS results, the average energy intensity for all (non-industrial) buildings is projected at 153kWh/m^2 by 2050[25]. Once again, the average value of the projections in Figure 6 appear to be reasonable targets for maximum average energy intensity for 2030 at 150kWh/m^2 and 200kWh/m^2 for residential and commercial properties respectively, and for 2050 at 115kWh/m^2 and 170kWh/m^2 for residential and commercial properties, respectively. For residential properties, this equates to a reduction in average per-household energy intensity from around 17.3kWh/hh in 2010 to 14.1kWh/hh in 2030, and 11.1kWh/hh in 2050. However, to due to reasons described above, this average value is likely to vary significantly across Member States.

This reduction in energy intensity is likely to be delivered via increasing both the efficiency of building envelopes (insulation, multi-glazed windows, air-sealing, the avoidance of thermal bridging and efficient thermal and lighting design, for example) and of energy-using products within the building (from boilers and air conditioning units and design, to lighting, white goods and consumer electronics).

The remainder of CO_2 abatement from buildings is likely to be delivered through a shift in the energy mix employed to match the remaining energy demand to satisfy increasing service demands. Space heating is typically the largest energy end-use in buildings, averaging at around 68% of total residential energy consumption in the EU (ranging between approximately 35% and 85%) (European Environment Agency, 2011). As such, it is the key energy service demand in buildings for decarbonisation. At present, natural gas is the largest contributor to space heating in European buildings at around 45% (both residential and commercial), with much of the remainder delivered by other fossil fuels (such heating oil and coal), although this varies very significantly across Member States. A commonly projected method of achieving decarbonisation in space heating is electrification (a significant contributor to projected increases in electricity demand and generation described above), primarily via ground and air source heat pumps producing zero CO_2 emissions at the point of use, and increasingly low CO_2 emissions indirectly through decarbonisation of electricity generation. Heat pumps may also produce zero-carbon (at point-of-use) space cooling, particularly important in southern Member States. Other options for space heating are also available, such as biomass boilers. Such technologies may simultaneously reduce the CO_2 intensity of water heating (along with options such as solar thermal systems) – the second largest energy end-use in buildings (at an average of around 14% of residential energy

[25] As EXIOBASE building-related energy consumption values are not available, energy intensity projections cannot be calculated.

consumption of the EU) (European Commission, 2011b)[26]. Based on the modelling results examined here, a minimum of 40% of EU space heating and cooling demand (both residential and commercial) should be satisfied by non-fossil (direct) energy by 2050 (and at least 20% by 2030), with natural gas providing much of the remaining fossil fuel-based energy[27].

There is likely to be significant difference in how CO_2 intensity and energy demand and consumption profile in residential and commercial buildings develops to 2050 between Member States. Alongside the factors listed above, developments will be dictated by, for example, differences in climate (impacting the time and intensity of heating and cooling demands), developments in the proportion of buildings rented or owner-occupied (including private residential and commercial renting, and social housing), the size and type of individual buildings (such as single-family housing, apartment blocks or shopping malls), along with the existing profile of the above, current energy intensities and energy mixes. The age of existing buildings, and the proportion the 2050 building stock already constructed is also highly important. Around 75% of buildings across the EU likely to be in use in 2050 are likely to already exist (Boermans *et al*, 2012)[28]. A number of measures cannot be retrofitted to existing buildings for technical reasons, whilst others may be prohibitively expensive.

2.4 Transport Sector

The transport sector was the second largest contributor to EU CO_2 emissions in 2012, accounting for around 24% - with road transportation accounting for the vast majority of this (~95%) (European Environment Agency, 2014). The transport sector also accounts for the second largest CO_2 abatement by 2050 in most scenarios. Whilst two of the CECILIA2050 scenario results (ETM-UCL and GINFORS) project average abatement of around 25% below 1990 levels by 2050 (approximately 40% below 2010 levels), the EXIOBASE results project an increase of 38% by 2050 from 1990 levels (15% increase from 2010 levels)[29], largely due to assumed linear growth in aviation demand (and associated emissions), and a focus on transformations in passenger cars only (discussed below). The IEA and ER2050 both project a more aggressive abatement trajectory, achieving a 40% and 60% reduction in CO_2 by 2050 from 1990 levels, respectively (50% and 70% below 2010, respectively). In order to meet these abatement projections, 2030 CO_2 emissions must be limited to around 2010 levels (an increase of around 15% above 1990 levels). The reasons behind the longer-term differences presented may be explained by variations in projections and assumptions concerning

[26] Cooking is the only remaining energy end-use in buildings that is not almost fully electrified. However, due to its relative insignificance (~3% of residential energy use across the EU), it is not considered further here.

[27] With coal, heating oil and similar products removed from use. Gas heating may be also be provided by renewable sources, however such options are not considered further in this report.

[28] Whist the IEA (2012) values presented in Footnote 22 may initially suggest that 82% of residential properties and 79% of commercial floor space in use by 2050 already exists; a proportion of this will reach retirement before 2050 and must therefore be replaced, alongside construction to satisfy new demand.

[29] See Drummond (2014) for a discussion surrounding accountancy of 'transport' emissions for the GINFORS and EXIOBASE Models. The ETM-UCL scenario did not consider aviation or marine transport emissions.

transport demand (total and by modal split), technologies deployed and energy required in meeting this demand.

Whilst all scenarios either assume or project a significant increase in both total passenger and freight travel demand between 2010 and 2050 (e.g. around 40% in ER2050, 70% in the ETM-UCL), total energy demand is commonly projected to remain stable or reduce (ranging from a slight increase of 4% and a reduction of 46% from 2010 levels, given by the ETM-UCL and ER2050, respectively – with the GINFORS and IEA results falling within this range). Such a phenomenon may be explained by either mode shifting to more efficient transport modes, shifting energy carriers within a mode, making the use of existing carriers more efficient, or a combination of such factors. The three CECILIA2050 modelling exercises do not consider modal shift (although GINFORS and the EXIOBASE model produce varied demand changes by mode), and whilst the ER2050 and IEA scenarios assume some modal shift (largely from aviation and private cars to public transport and rail), the majority of projected abatement is achieved by changing the fuel mix of road transport (with some improvement in efficiency of conventional carriers). As such, infrastructure requirements in the road transport sector are the focus of this report.

Figure 7 - Projected EU Road Transport Energy Mix

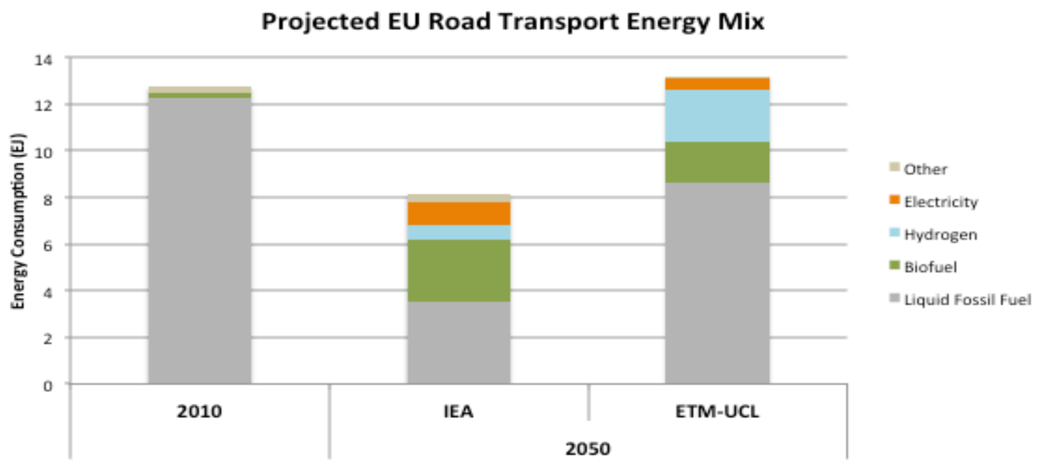


Figure 7 illustrates total energy demand by energy carrier for the EU road transport sector in 2010, and projected developments by 2050 from the IEA and ETM-UCL results[30]. In 2010, total demand was 12.7EJ, with liquid fossil fuel (petrol and diesel) accounting for nearly 97% of this. By 2050, the IEA projects a 36% reduction in road transport energy demand (slightly less than the ER2050 projection), with liquid fossil fuel retaining a 43% share. Biofuels, electricity and hydrogen account for 32%, 12% and 8% respectively (with 'other'[31] fuels accounting for the remaining 4%). By comparison, the ETM-UCL projects a 4% increase in road transport energy consumption by 2050, with liquid fossil fuels retaining a larger 65%

[30] 2030 values are not presented, as they are not available for the IEA results.

[31] 'Other' fuels refer primarily to natural gas and LPG.

share. Biofuels, electricity and hydrogen account for 13%, 4% and 17% respectively (with 'other' fuels accounting for just 1%).

Figure 8 illustrates the CO_2 intensity of passenger cars, light goods vehicles (LGVs) and heavy goods vehicles (HGVs) projected by the ETM-UCL (total fleet, rather than just new vehicles). Such disaggregated data is not available for the IEA projections. The CO_2 intensity of passenger cars decreases from around 210gCO_2/km in 2010 to around 100gCO_2/km in 2050. A significant contributor to this is a continued long-term switch from petrol to diesel (petrol decreases from 64% to 31% of passenger car energy consumption between 2010 and 2050, whilst diesel increases from 30% to 44%). Passenger cars account for around 50% of total road transport liquid fossil fuel consumption in 2050 (from 43% in 2010) illustrated in Figure 7. Biofuels and electricity increase from negligible levels in 2010 to 18% and 6% of passenger car energy consumption respectively, accounting for around 60% of both biofuel and electricity consumption for all road transport in 2050 in the ETM-UCL projections in Figure 7. This projection of relatively modest change is in stark contrast to the assumptions and results associated with the other modelling activities considered. In the EXIOBASE scenario, passenger cars are almost entirely electrified (95%) by 2050 (although, no significant change is projected for other road (and non-road) transport modes), whilst the GINFORS results assume 80% of all surface transport (including rail) is electrified by 2050 (with no further distinction between modes). The ER2050 results produce 65% electrification of passenger cars and LGVs by 2050 (with around 13% biofuels).

Figure 8 - CO_2 intensity of EU Vehicle Fleet - ETM-UCL Projection (Source: Solano & Drummond, 2014)

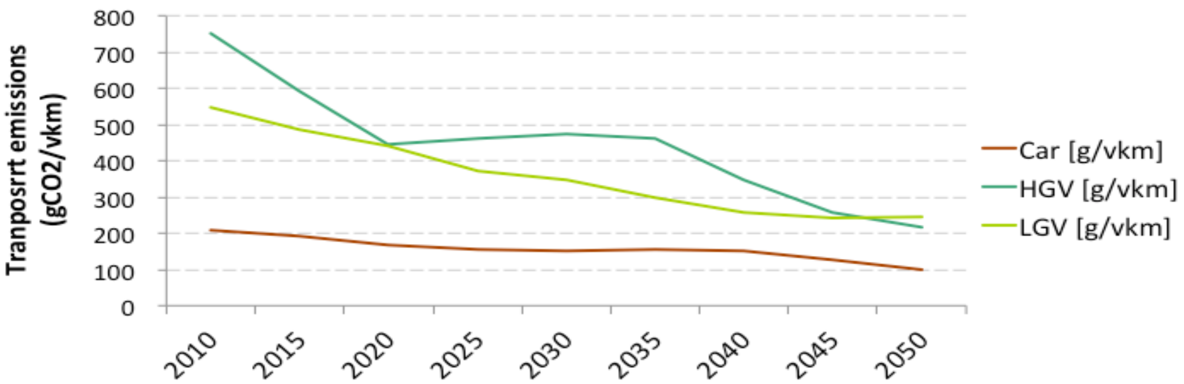


Figure 8 projects the CO_2 intensity of LGVs and HGVs to decrease from around 550gCO_2/Km and 750gCO_2/km respectively in 2010 to around 240gCO_2/km and 215gCO_2/km respectively in 2050. The LGV trend is driven largely by a 25% reduction in energy consumption through rapid increases in vehicle efficiency (travel demand grows linearly by nearly two-thirds), with the fuel mix remaining largely unchanged (with diesel by far the largest contributor). The HGV trend is driven by a shift to biofuels (at 16%, and accounting for 41% of biofuel in road transport as illustrated in Figure 7) and hydrogen (49%, accounting for all hydrogen use projected by the ETM-UCL and illustrated in Figure 7) by 2050, from almost entirely diesel in 2010. Related projections and assumptions from the EXIOBASE and GINFORS models for these modes are discussed above. The ER2050 projects a 41% contribution to freight transport energy consumption from biofuels.

As is clear, there are relatively significant differences in the projected energy mix in road transport by 2050, both overall and between modes. However, some conclusions may be drawn. The majority of road transport CO_2 abatement is likely to be driven by changing the fuel mix of passenger cars, with a fleet CO_2 intensity of 100gCO_2/km by 2050 as illustrated in Figure 8 likely to be the minimum requirement[32]. At least half of total passenger car energy consumption is likely to be required to be zero-carbon at the point of use, with remaining conventional fuels continuing to shift from petrol to diesel. Although electrification (via the use of plug-in hybrids (PHEVs) or pure electric vehicles (EVs)) appears to be the preferred non-conventional energy carrier, other carriers such as biofuels and hydrogen are likely to be part of the mix to some extent. For road freight transport, an expansion in the use of biofuels coupled with hydrogen fuel cells is likely to be preferred over electrification – although the transformation is likely to be less dramatic than for passenger vehicles. However, the most appropriate proportion of each carrier (including conventional fuels) for each passenger and freight mode at the EU and Member State level by 2050 depends on technological, cost and other developments that may only be speculated from our current vantage point. Also, whilst demand for passenger and freight road transport is likely to increase substantially by 2050, it is not certain to what extent this demand will be satisfied by factors of, amongst others, increasing vehicle numbers, increasing the lifespan of individual vehicles, increasing journey lengths, vehicle sharing, increasing load size, or modal shift. The model results discussed in this report do not deal explicitly with this question[33]. As such, policy instruments employed to encourage a low-carbon shift in road transport should allow for flexibility in absorbing and encouraging such specific developments.

The deployment of low-carbon passenger and freight private road vehicles will require significant supporting infrastructure – particularly electric vehicle (or PHEV) charging (or battery-swap) and hydrogen filling infrastructure. Such requirements are discussed under Section 2.5.

As discussed, whilst the most transformative projected change to deliver significant CO_2 abatement from the road transport sector is a shift to low-carbon energy carriers (particularly in passenger cars), a modal shift from private to public road transport is likely to deliver a contribution (particularly in large urban areas). As such, public transport modes (particularly busses) must also reduce in CO_2 intensity, in order to maximise potential benefits. Additionally, a shift to active transport (walking and cycling) may also contribute (again, particularly in urban areas). Increasing both public road and active transport modes is likely to require dedicated stationary infrastructure such as bus and cycle lanes, cycle parking (potentially including bike sharing infrastructure), and pedestrianised routes. Neither the modelling studies examined here or the wider literature tackle in detail specific requirements for reduced CO_2 intensity of public transport (e.g. energy carrier mix) or active transport

[32] As discussed in Solano & Drummond (2014), the ETM-UCL is likely to be conservative in projecting decarbonisation in the transport sector, due to high investment costs and a lack of demand response dynamics.
[33] However, the IEA (2012) concludes that as passenger car market in the EU is close to saturation, vehicle sales are projected to remain largely constant.

infrastructure needs at the EU level[34], and as such they are largely omitted here. Requirements that are not directly related to the delivery of a low-carbon transport infrastructure, such as the construction of new roads to absorb increased demand that would likely develop regardless of the decarbonisation imperative, are outside the scope of this report.

2.5 Energy and CO_2 Transmission and Distribution Networks

This section considers the requirements for infrastructure that enable the technological shifts in both the demand and supply side sectors of the energy system described above. In particular, the focus is on infrastructure requirements for electricity transmission, distribution and management, infrastructure for 'fuelling' low-carbon vehicles, and infrastructure for dealing with CO_2 sequestered using CCS technologies. As the studies used in this report do not investigate such requirements (at least to any level of detail), alternative publications and resources are drawn upon. Additionally, as fossil fuel-only infrastructure is not the focus of this report, requirements for natural gas distribution networks, for example, are not discussed.

Electricity Transmission, Distribution and Management

Numerous studies indicate that the existing European electricity grid is unsuitable for future needs (Battaglini *et al*, 2009). The projected increase in electricity demand and generation, along with changes in the characteristics of both electricity supply and demand, will require significant changes to existing transmission and distribution[35] infrastructure, from generating installations to the point of consumption. However, the magnitude and profile of this change depends on how six elements of related infrastructure and trends develop, and their interaction. The first element, on the demand side, regards the extent to which end-use sectors electrify, and how (particularly buildings and road transport). For example, Figure 9 illustrates the variability between electricity and heat demand in buildings (commercial and residential) in the UK.

With increasing electrification of space and water heating, the relatively low variability in electricity demand illustrated in Figure 9 will increase to satisfy both the daily and seasonal variation in heat demand in Member States with climates that produce such demand. The issue is also present for Member States in which space cooling experiences high variability (although with inverted seasonal demand to that illustrated in Figure 9). Although parallel developments such as increasing thermal efficiency in buildings and the high coefficient of performance heat pumps experience over gas electric resistance boilers would reduce final energy demand for heating over time (although in turn, this is likely to be countered to a

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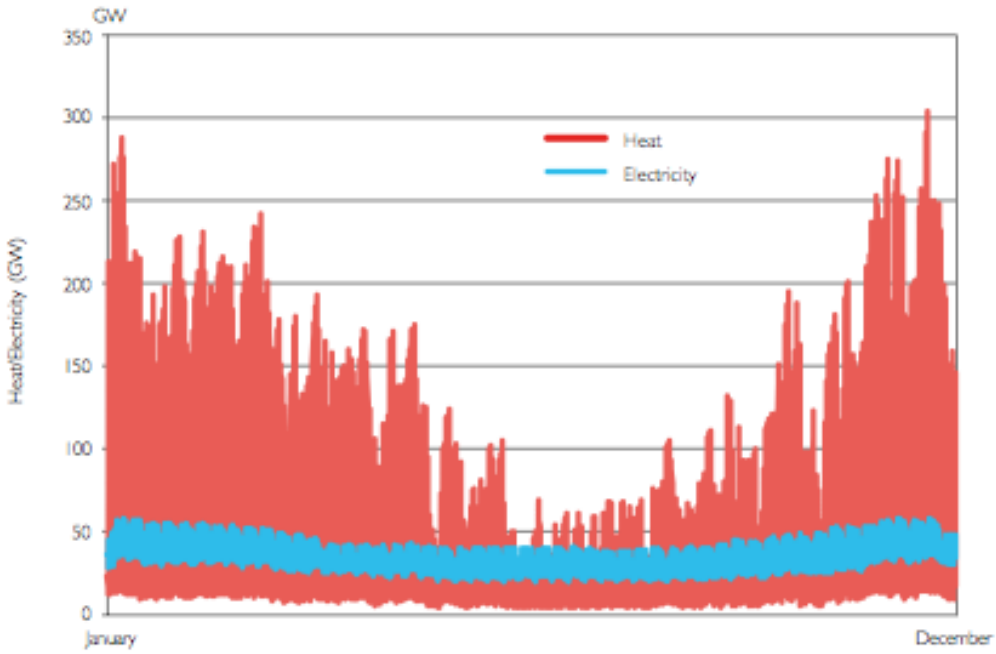
[34] Requirements between Member States, regions and between urban and rural areas are likely to vary substantially.

[35] The 'transmission' network carries high voltage electricity from generators for transmission over long distances. The 'distribution' network draws electricity from the transmission network via substations (that 'step-down' voltage levels), for delivery to final consumers (although some large industrial consumers are served directly by the transmission network).

significant degree by increasing number and size of buildings, as discussed in Footnote 22). However, it is unlikely that additional connections from residential and commercial properties to the distribution network will be required, due to already-ubiquitous access[36]. Requirements for (and consequences of) electric vehicle charging infrastructure are discussed below.

Figure 9 - Comparison of Heat and Electricity Demand Variability Over Time (Source: DECC, 2012a)



The second element, on the supply side, concerns the extent to which generation capacity is provided by, and electricity demand is satisfied by, decentralised installations. Decentralised generation reduces demand for long-distance transmission networks, and if used for autoproduction, also reduces requirements for distribution capacity. Decentralised generation may also increase energy efficiency; reducing transmission requirements also reduces transmission losses[37]. The third element is the extent to which new centralised generation becomes cited in new, and particularly remote 'unconventional' locations (e.g. offshore wind), where existing grids are absent or weak (Battaglini *et al*, 2009). As discussed, such requirements likely to vary significantly by Member State.

The fourth element is the extent to which electricity interconnection increases between Member States[38]. Interconnectors allow for the development of a European 'supergrid'[39] and a single European market for electricity. This allows electricity generated in one Member State to be consumed in another, facilitating the integration of intermittent RES-E capacity,

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[36] Connections to new-builds will be necessary, although this is a requirement regardless of the decarbonisation imperative.

[37] In 2013, transmission and distribution losses averaged 6.4% of gross generation in the EU (EUROSTAT, 2015)

[38] Along with how interconnection develops between Member States and non-Member States. However, this aspect is outside the focus of this report.

[39] Defined as 'a pan-European transmission network facilitating the integration of large-scale renewable energy and the balancing and transportation of electricity, with the aim of improving the European market' (Friends of the Supergrid, 2014).

reducing total capacity requirements (aggregated from each Member State ensuring adequate capacity margins individually), improving energy security in the EU, and reducing costs (both capital and wholesale electricity costs). Additionally, the development of a supergrid allows remote generation (particularly offshore wind), which are currently connected to the grid using point-to-point connections[40], to be interconnected with each other within and between Member States, reducing gross transmission capacity requirements and issues of local congestion (described above). Key design requirements for a single electricity market are discussed in Chapter 3.

The fifth element is the development and deployment of electricity storage capacity. Storage allows for ’load levelling’ (electricity storage in times of excess generation for consumption when demand increases), which may also reduce aggregate generation capacity requirements, although requirements for storage capacity with increasing penetration of intermittent renewables may be reduced with increasing interconnection. Storage capacity may be provided by conventional options such as pumped hydro[41] or batteries (from large-scale to household level units) or more unconventional options such as electric vehicles (which may retain the charge, or return it to the grid for other purposes), or the production of hydrogen (which may also be used as a transport propellant (in HGVs, for example, as discussed above), or combusted to return electricity to the grid). Various other possible options exist[42]. The sixth and final element concerns the development of intelligent management of electricity generation and demand through ‘smart grid’[43] infrastructure components, which allows for efficient integration of the above options (regardless of the eventual relative importance of each).

It is clear that there are interdependencies and trade-offs between each of these factors, each of which is subject to uncertainty, producing ambiguity surrounding specific electricity transmission, distribution and management infrastructure required by 2050. Indeed, it is a relatively neglected area in energy transition studies (Andersen, 2014). However, some broad requirements may be elucidated.

The 2014 ‘10-Year Network Development Plan’ (TYNDP) (ENTOSE, 2014) outlines key developments to the European transmission network likely to be required by 2030. The TYNDP identifies around 100 physical ‘bottlenecks’ to achieving a European grid compatible with long-term requirements (ENTSOE, 2014):

[40] Point-to-point (or ‘radial’) connections connect the individual generator to the grid at a single point. As such, when the generator is not producing power, or producing below capacity, the connection capacity is left unused (or underused). Similarly, if the grid at the point of connection becomes congested, the generated electricity cannot be transferred elsewhere for consumption.

[41] In which excess generation is used to elevate water to achieve gravitational potential, to be realised trough turbines at times of peak demand or low generation. Around 45GW of installed capacity exists in the EU, concentrated largely in Italy, France, Germany, Spain and Austria (USEIA, 2015).

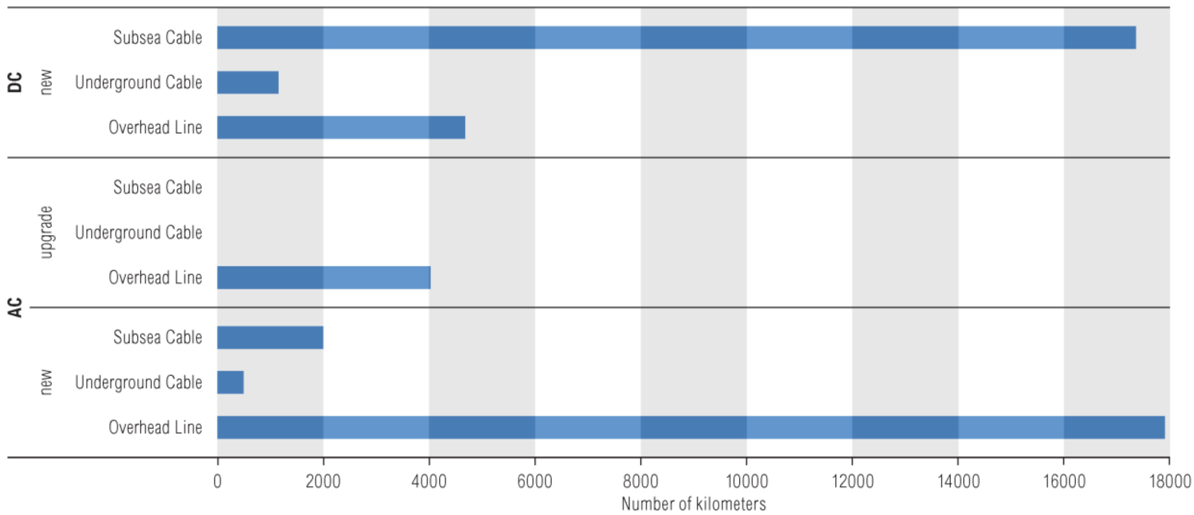
[42] Including compressed air, batteries, flywheels and thermal storage.

[43] Defined as ‘an electricity network that can cost efficiently integrate the behaviour and actions of all users connected to it – generators, consumers and those that do both – in order to ensure an economically efficient, sustainable power system with low losses and high levels of quality and security of supply and safety’ (European Commission, 2011a)

- **Security of Supply** – when some specific areas may not be supplied according to expected quality standards (around 10% of bottlenecks).
- **Direct Connection of Generation (and Storage)** – to the grid from both thermal and renewable installations (around 30% of bottlenecks).
- **Market Integration**[44] – if inter-area balancing is at stake, bottlenecks internal to a price zone (e.g. internal grid infrastructure), and bottlenecks between price zones (e.g. interconnectors) (around 60% of bottlenecks, with 40% cross border and 20% internal).

Projected security of supply bottlenecks centre around Luxembourg and the West and South of Germany, the Baltic States, Italy, the UK and Ireland and Spain and Portugal. The latter two regions, along with Greece, Romania, Bulgaria, Poland and the Nordic countries are projected to be the key areas for bottlenecks surrounding grid connection from generators (and storage sites – particularly pumped hydro), and market integration. Figure 10 presents a breakdown of additional transmission capacity (of pan-European significance) likely to be required by 2030 in the EU, in order to overcome these bottlenecks.

Figure 10 - Additional Electricity Transmission Capacity Requirements by 2030 (Source: ENTSOE, 2014a)



As illustrated by Figure 10, around 44,00km of new transmission lines are likely to be required by 2030 (compared to around 300,000km already in existence[45] (Eurelectric, 2013)) – an increase in total transmission network length of around 1% per year until 2030 (ENTSOE, 2014a). High-Voltage Alternating Current (HVAC) lines are expected to remain the prominent technology (at around half of new capacity), with new overhead HVAC lines, for inland applications, particularly prominent (18,000km). Around 4,000km of existing overhead HVAC lines are also likely to require upgrades. However, such values do not consider existing transmission lines that will require replacement. The average age of the European high-voltage transmission system is 30-40 years, against a mean lifetime of high voltage equipment of 30-50 years (Battaglini et al, 2009), meaning a high proportion of existing capacity must be replaced by 2030 alongside the upgrades and additions outlined above.

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[44] Where a 'bottlenecks' may overlap between these three categories, they are considered an issue of market integration foremost.

[45] However, 97% (10 million km) of the electricity grid is distribution network.

High-Voltage Direct Current (HVDC) lines, accounting for the remaining half of new transmission lines, are projected to be particularly prominent for subsea connections (for the integration of offshore renewable generation, and interconnection between Ireland and the UK with mainland Europe, in particular).

Although HVAC are currently the most widespread technology due to its technical maturity, HVDC lines are often more appropriate for long distance transmission in both overhead and subsea, but also underground transmission (over 50km for underground and subsea, and over 100km for overhead). HVDC cables produce much reduced transmission losses, and the charging current of long-distance HVAC cables often requires compensation by 'shunt reactors' (absorbers of reactive power). Additionally, the transmission corridor for HVDC lines is much reduced compared to HVAC lines, reducing issues such as right-of-way requirements (Friends of the Supergrid, 2013; Andersen, 2014). As such, long distance HVDC lines are more cost effective and practical to implement than their HVAC counterparts. As illustrated in Figure 10, around 1,000km and 500km of HVDC and HVAC lines are projected to be underground, to avoid impacting environmentally sensitive areas (around 10% of the projected lines in Figure 10 are projected to route through protected areas, presenting associated issues (ENTSOE, 2014a)). Underground lines also offer increased system resilience to external disruption, such as extreme weather or sabotage (Andersen, 2014).

Figure 11 - Net Interconnector Capacity between Member States and non-EU Countries (2013) (Source: ENTSOE, 2014)

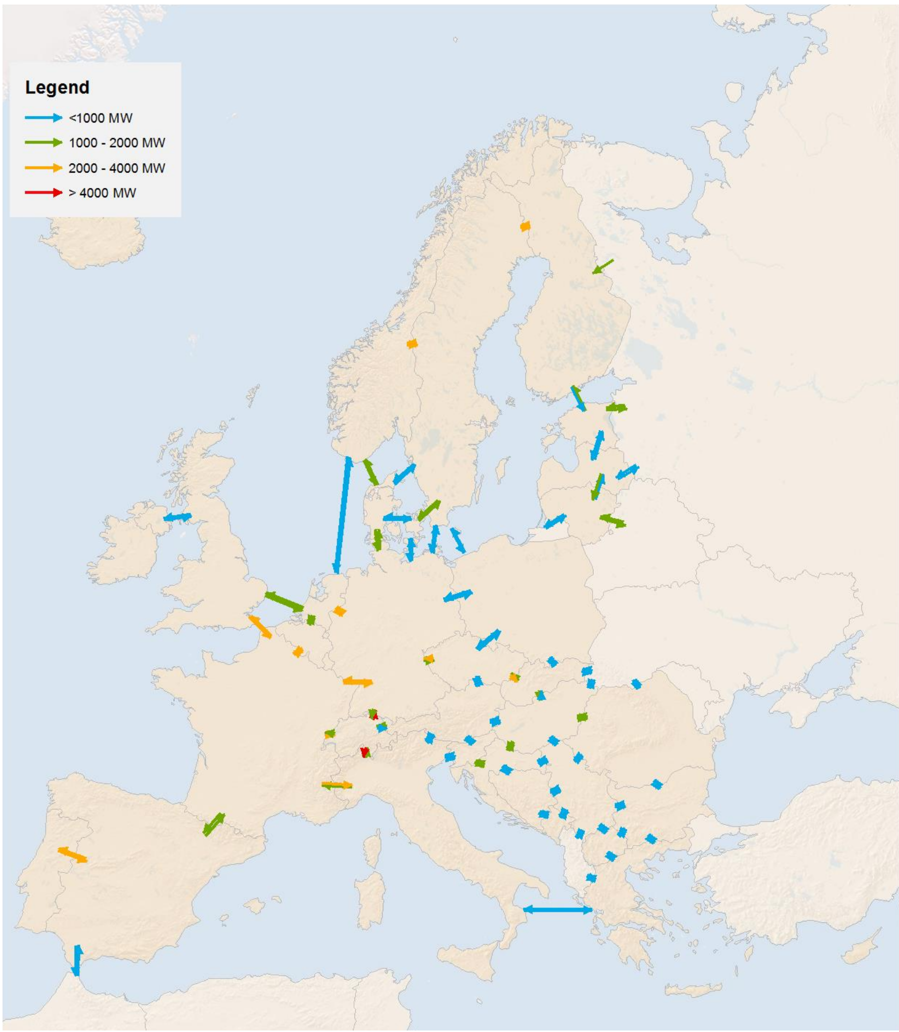


Figure 11 illustrates existing interconnector capacities between Member States, and neighbouring non-EU countries. It is clear that the majority of existing interconnector capacities are under 1,000MW. The TYNDP projects that interconnector capacities should on average double by 2030, although there are large discrepancies between regions, with some requiring much greater capacity increases. Connection between the Iberian Peninsula and mainland Europe may require up to a tenfold increase (to 10GW), with interconnection between the three Baltic States (Estonia, Latvia and Lithuania) and the rest of the EU, trebling. Interconnection between Ireland, the UK and continental Europe is also projected to require doubling, if not trebling (ENTSOE, 2014a).

Regardless of the particular development and combination of the first five aspects influencing the magnitude and profile of the development of grid infrastructure across the EU, it is likely that the (at least partial) introduction of 'smart' infrastructure to allow intelligent management of the grid will be required. A central component of a smart grid is the deployment of smart metering systems[46]. Commission Recommendation 2012/148/EU, on preparations for the roll-out of smart metering systems, provides minimum common technical requirements for electricity smart metering systems:

- Provide 'real-time' readings (at least every 15 minutes) and visualised consumption data directly to the consumer (and any designated third party), using a standardised interface.
- Allow remote reading by the operator, and frequently enough to be used for network planning.
- Provide two-way communication between the smart metering system and external networks for maintenance and control of the metering system.
- Support advanced tariff systems through the use of time-of-use registers and remote tariff control.
- Provide the option import/export and reactive metering, which may be activated and deactivated in accordance with the wishes and needs of the consumer.
- Allow remote on/off control of the supply and/or flow of power limitation.
- Provide secure data communications and allow for fraud detection and prevention.

These functionalities particularly allow for the integration of decentralised generation, and for advanced demand response measures. For example, real-time consumption data matched with advanced tariff systems that implement dynamic pricing to supply and demand interactions provides the consumer with the incentive and required information to alter their electricity consumption patterns to minimise costs. As discussed above, electric cars may be charged when supply is plentiful (or demand is reduced) and prices are low (and with export metering allowing the potential for the return of this power to the grid when supply is restricted (or demand is heightened), and prices are high. With the potential development of 'smart' appliances, this may become an automated process.

At least 45 million smart meters are already installed across the EU (European Commission, 2014b). Due to the importance of smart systems in enabling the effective deployment and

[46] Defined by the Energy Efficiency Directive (2012/27/EU), Article 2(28) as 'an electronic system that can measure energy consumption, providing more information than a conventional meter, and can transmit and receive data using a form of electronic communication'.

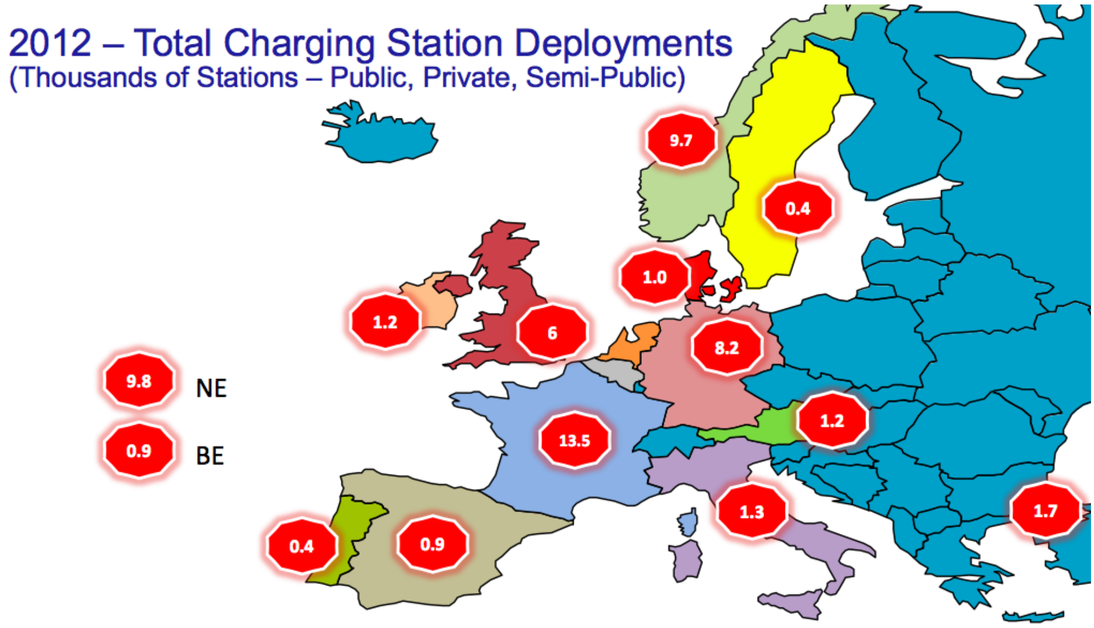
operation of low-carbon infrastructure the electricity system, a rapid rollout of smart meters is required. The existing target of an 80% deployment by 2020 (for electricity only), as set by the Third Energy Package[47], appears suitable. This target, along with other policy-related issues, is discussed in Section 3.5.

Low-Carbon Vehicle Energy Supply Infrastructure

The deployment of electric vehicle charging infrastructure (particularly for passenger vehicles) and hydrogen filling infrastructure (particularly for freight vehicles), are critical in facilitating the deployment of low-carbon transport.

There are two main options for plug-in electric vehicle charging[48]; alternating current (AC) and direct current (DC) charging points, used for conventional and semi-fast, and fast charging[49], respectively (Bakker, 2013). However, whilst DC allows a vehicle to charge in a matter of minutes rather than hours, it does not permit the use of variable tariffs to encourage charging when in off-peak load hours and it may reduce battery life (ARF, 2014).

Figure 12 - Total EV Charging Station Deployment in the EU in 2012 (Source: Hayfield, 2012)



Charging points may be private (e.g. situated in households or privately owned parking areas), public (e.g. situated along public roads or filling stations), or semi-public (e.g. retail park car parks). Figure 12 illustrates the total deployment of charging stations from all three categories across Europe in 2012. As is clear, the majority of existing charging points are in

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[47] The Third Energy Package contains various measures, including smart-meter roll-out targets, 'electricity generator and supplier 'unbundling', and the establishment of independent system operators See European Commission (2015b) for more information.

[48] This includes 'pure' electric vehicles, and 'hybrid' electric vehicles – the latter of which also partially charge from the parallel internal combustion engine.

[49] Fast charging may provide charge at a rate over five times that of conventional charging (Eurelectric, 2011).

Western Europe, with France, the Netherlands, Germany and the UK experiencing the largest deployment[50].

The majority (80%) of existing charging points are private (domestic), followed by semi-public (15%) and public stations (5%) (ARF, 2014). Residential charging often does not require any equipment in addition to standard sockets, however this limits residential connections to conventional AC charging (Eurelectric, 2011). It is likely that domestic charging will remain dominant as the deployment of electric vehicles moves from the 'early adopter' to 'mass rollout' stage in the EU (60% of all charge points), however for private vehicle owners without access to a garage, or other private or semi-private parking, public charging points will be required (with a share of around 20% of all charging points). Public charging points will also be required along intercity or international roads, to ensure vehicles can be charged when required, and to reduce 'range anxiety'. Around 5% of existing public charging points are fast-charging DC connections, and whilst it is likely that this proportion will increase over time, AC is likely to remain dominant. In addition to residential and public charging, semi-public charging points at places of work, for example, is likely to be required (and account for the remaining 20% of charging points in the EU) (ARF, 2014). The specific profile of charging point distribution requirements is likely to vary significantly between Member States, and between rural and urban areas. For example, in Germany around two-thirds of households have a garage or other private parking space; in London this value is only a third (ARF, 2014).

At present, various interfaces exist between charging points and electric vehicles. For example, whilst the largest proportion of charging points in the EU offers Type 2 socket connections, there are differences both within and between Member States. For example, charging points in the UK offer both three-pin and Type 2 sockets. In Belgium, Denmark and Germany, although Type 2 connections are dominant, the implementation of various pilot projects has produced variance (Bakker, 2013). Whilst such variety has not thus far been a significant obstacle, increasing electric vehicle deployment may be hindered by interoperability. As such, vehicles and charging points should be standardised so that 'all electric vehicles [may] be charged…and communicate with the electricity grid anywhere in the EU' (Eurelectric, 2011a). Whilst it is possible for dedicated charging points to be supplied directly by decentralised electricity generation, it is likely that the majority will be grid-connected (particularly public, fast-charging installations).

The use of 'battery swapping' stations, at which empty batteries are swapped for fully-charged units (thus providing an advantage over waiting for a vehicle to charge), has been piloted on a small scale in the EU, but it is unlikely to be introduced at scale in future. Indeed, most new EV models do not support battery swapping.

At present, little infrastructure exists for the refuelling of hydrogen vehicles. Around 80 hydrogen fuelling stations exist (H_2stations.org, 2014), largely serving public transport demonstration projects in Western Europe. Hydrogen refuelling points may be installed at existing stations for conventional fuelling, with specific requirements varying depending on

[50] In addition to significant deployment in Norway, which falls outside of the EU.

whether the hydrogen is delivered in a liquid or gaseous form. Whist the former holds the same as natural gas refuelling, the latter requires the use of 'fuelling robots' for maintain safety in the presence of extremely low temperature hydrogen. However, the filling time for each is comparable to that for conventional fuels. Hydrogen, produced by a variety of means[51], may be transported to fuelling stations either via pressurised tanks (on refuelling tankers, for example), or via pipeline. Whilst such pipelines are already in use for transporting hydrogen for industrial purposes, it is likely that pressurised tanks will be the primary method employed, due to the high cost of pipeline construction and operation. As hydrogen vehicles presently have a lower range than conventional vehicles (due to a lower energy density in hydrogen then fossil fuels), as with electric charging infrastructure, a network of fuelling stations will be required at such intervals along public highways, particularly intercity and international routes, as to reduce range anxiety. However, such a widespread deployment is unlikely to be required until at least 2030.

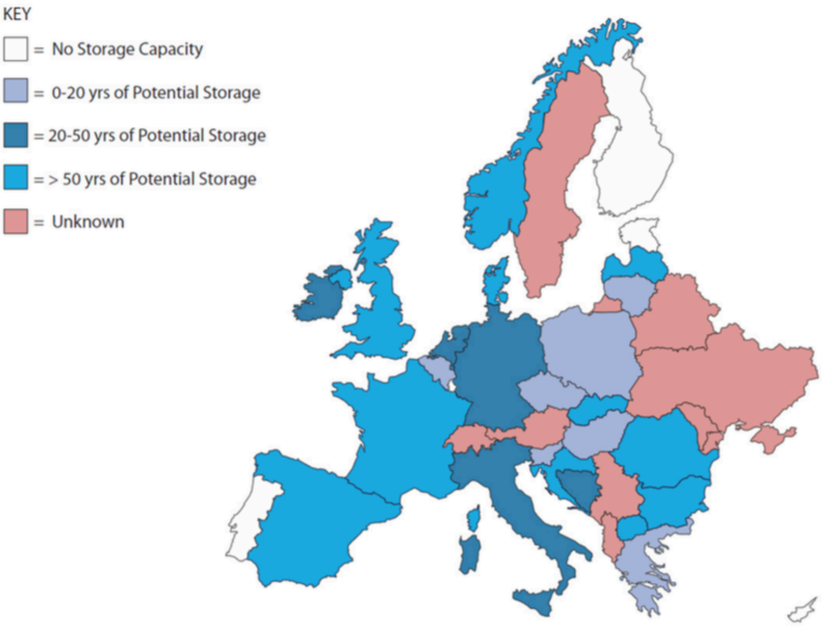
Carbon Capture & Storage – CO_2 Transportation and Storage

Once CCS technology captures the CO_2 from fossil fuel or biomass electricity generation installations, it must be transported and stored. The manner by which it is transported from a particular 'source' to a particular 'sink' depends on the volume of CO_2 to be transported, the planned lifetime of the CO_2 source (the generation plant), distance between the CO_2 source and storage site (and whether the storage site is onshore or offshore), and the availability of existing infrastructure (such as road networks) (Leung *et al,* 2014). Three key options exist; pipeline (onshore or offshore), ship (offshore) or truck (onshore). As trucks do not have the capacity to transport substantial volumes of CO_2, they are unlikely to be widely utilised. Similarly, whilst there are no technical challenges presented for the transportation of CO_2 by ship[52], this medium is only applicable when CO_2 volumes are relatively small (less than 200,000 ton/year) and the 'source to sink' distance is long (Mallon *et al*., 2013). As such, whilst CO_2 transportation by truck and ship may find applications for specific projects, the use of pipelines is widely considered to be the primary conduit for 'source to sink' CO_2 transportation (ARUP, 2010; Wellenstein & Slagter, 2011). Figure 13 illustrates estimated potential for CO_2 storage across Europe.

[51] Not discussed in this report.

[52] Transportation of CO_2 with ships only exists in a small-scale today, but the vessels in operation have very similar designs to other gas transporting ships like Liquefied Petroleum Gas (LPG) carriers and thus present no technical challenges (Neele *et al*, 2013).

Figure 13 - European CO_2 Storage Potential (Source: ARUP, 2010)



As is clear, whilst the data in Figure 16 contain varies assumptions (such as the rate at which CO_2 it captured, and where), CO_2 storage potential varies significantly across Europe. As such, it is likely that an extensive, cross-border pipeline network will be required (Morbee *et al.*, 2010). Figure 14 illustrates the projected CCS transportation network required by 2050 across Europe, whilst Figure 15 quantifies its development over time.

Figure 14 - Projected CCS Transportation Network by 2050 (Source: Morbee *et al*, 2010)

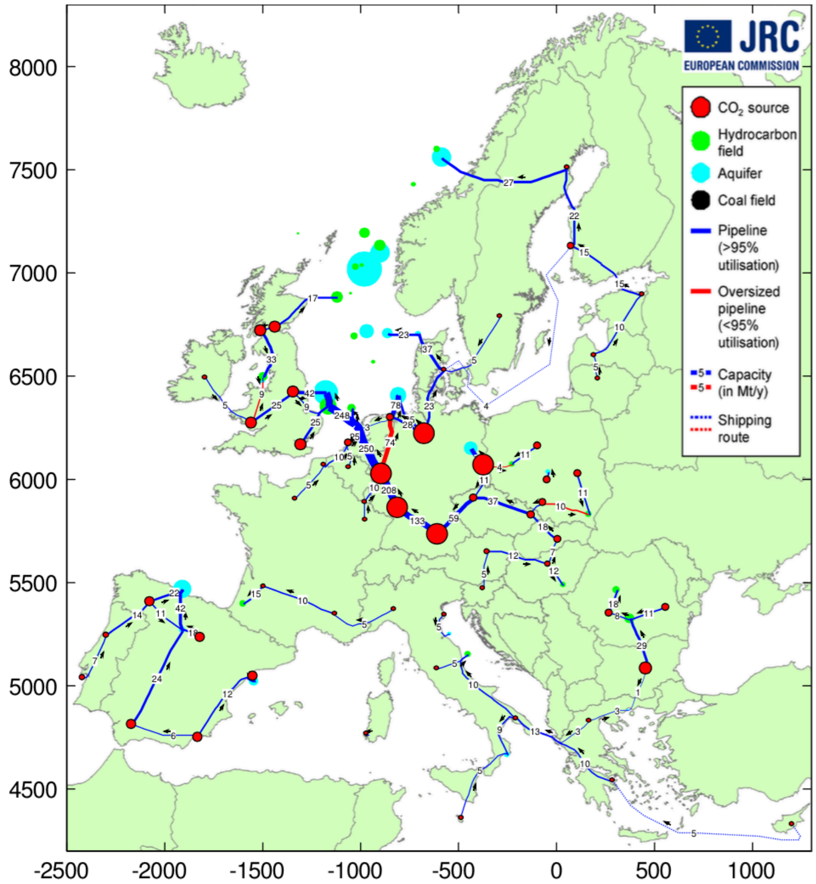
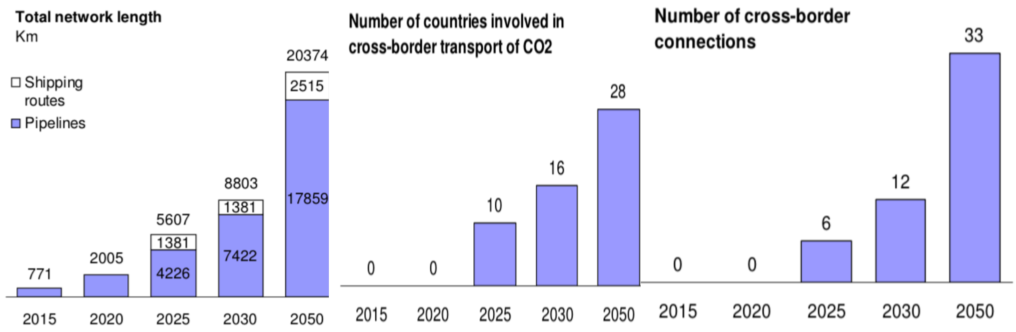


Figure 15 - CCS Transportation Network Development - 2015 to 2050 (Source: Morbee *et al*, 2010)



By 2050 the total network length is projected to be over 20,000km (around 90% pipelines), with the most active region for both transport and storage (in saline aquifers and depleted hydrocarbon reservoirs) of CO_2 is projected to be North-West Europe, particularly surrounding Germany, the UK and the North Sea regions. However, almost all Member States are projected to be involved in CO_2 transport to some degree, with over 30 cross-border connections. The majority of pipeline construction is projected to occur between 2030 and 2050, with the rate of construction at up to 1,200-1,500 km/yr in some regions. Transport via shipping will likely have a more significant role during initial network development, particularly during the 2020s, with pipelines restricted to local point-to-point projects (Neele *et al*, 2013).

Pipelines (constructed of carbon steel) have the possibility of connecting one sink to one source, or connecting one or more sources to one or more sinks (Wellenstein & Slagter, 2011). It is likely, as illustrated in Figure 14, that pipelines will carry CO_2 from multiple sources to a single regional sink (Coleman, 2009). Whilst there are various parallels with the natural gas network, there are three key differences. First, the flow is reversed – natural gas flows from a few sources to countless end-users (down to individual buildings). Secondly, and due to the first key difference, CCS networks are likely to be less 'invasive' than natural gas networks. Finally, there are key technical differences to consider. For example, CO_2 pipelines will be required to operate at higher pressures than most existing natural gas pipelines, and with fewer impurities, to prevent the creation of carbonic acid, which may corrode the pipeline (ARUP, 2010).

3 Three Policy Pathways

3.1.1 Policy Pathways

In order to assess the potential benefits, challenges and bottlenecks associated with different potential evolutions of the European climate policy mix, three policy 'pathways' have been developed, each focussing on a different policy paradigm. Each pathway follows the three 'pillars of policy', designed to produce developments across the three 'domains of change' developed by Grubb (2014). The summary of each pathway is as follows, as initially proposed and further discussed in Rey *et al* (2014):

- **'Market-Based' Policy Pathway**

This pathway focuses on the use of economic instruments to encourage the development of a low-carbon energy infrastructure, principally via the use of technologically neutral, equalised carbon price signals (thus focussing on static cost-efficiency). Non-market based instruments are gradually removed. Although government intervention is minimised in this paradigm, some non-market based instruments remain to overcome market failures (e.g. principal-agent problems).

- **'Technology-Based' Policy Pathway**

This pathway, conversely, experiences significantly increased government intervention through the principal focus on the use of technology support instruments and standards to deliver a low-carbon energy system. A carbon price signal remains, but mainly to help prevent rebound effects.

- **'Behaviour-Based' Policy Pathway**

This pathway focuses on encouraging a change in behaviour in actors in the energy system – principally in energy-using individuals, households and organisations. The key instruments in this paradigm are those that encourage, facilitate and co-ordinate a low-carbon transition by raising awareness, overcoming information failures and addressing other market failures, including principal-agent problems and access to capital. A carbon price signal again remains to reinforce behavioural change and to prevent rebound effects.

The following sections discuss the three typified policy packages developed, and their suitability to deliver the infrastructure elaborated above for the key sectors of power generation, industry, buildings and transport. Instruments concerning deployment of energy and CO_2 transmission and distribution infrastructure are discussed separately, as there is likely to be little variation in approach between the three policy paradigms considered. Instruments that attempt to address behavioural issues only, and which do not impact infrastructure choices and development (or only very indirectly), are not considered. Where relevant, key differences in instrument design or potential effectiveness depending on whether European policymaking competencies become increasingly 'centralised' with EU institutions, or remains largely at currently levels division, are discussed. For the purposes of this assessment, political acceptability and commitment is broadly assumed as inherent in each policy package. It is also assumed that each policy package is deployed within the context of appropriate long-term frameworks and targets. Differences in international climate mitigation efforts and policy are not considered.

3.2 Market-Based Policy Pathway

3.2.1 Power Generation Infrastructure

Table 1 presents a brief summary of the policy instruments proposed for the 'power generation' sector under the 'market-based' policy pathway. Carbon pricing via the EU

Emission Trading System (EU ETS) is the sole instrument in this sector. Other policy instruments, particularly dedicated RES-E support mechanisms, are removed.

Table 1 - Market-Based Policy Pathway – Power Generation

Policy Instrument	Description
EU ETS	The EU ETS is substantially reformed to produce a robust, increasing price over time, along with scope increasing to the road transport sector.

The EU ETS is 'cap and trade' tradable permit system, which places an aggregate cap on CO_2 emissions from the power sector, energy intensive industrial sector and domestic aviation[53], N_2O emissions from the production of nitric, adipic, glyoxal and glyoxalic acids, and Perfluorocarbons (PFCs) from aluminium production, in all EU Member States, plus Iceland, Lichtenstein and Norway. Around 11,000 stationary installations are obligated under the system, and around 45% of GHGs from the EU28 are covered (European Commission, 2015). Whilst the permit price was relatively steady in the first year of operation in 2005 (at around €25/tCO_2), prices have rarely reached such levels since, and have experienced significant volatility. Various factors have contributed to this, at different times and to different extents. The primary issue at present, however, is the presence of a permit surplus of around 2.1 billion allowances in the system, which has lead to a price maintained at well below €10/tCO_2 since late 2011. Whilst various factors have contributed to this surplus, a significant factor is almost certainly reduced demand for electricity and industrial products (and therefore the emissions associated with generation and production), stemming from the 2008 financial crisis. Further discussion surrounding price volatility and associated issues and drivers may be found in Agnolucci & Drummond (2014).

Without intervention (or a significant deviation from projected exogenous developments), it is projected that a permit oversupply will remain until the late 2020s. As (largely equalised) carbon price is relied upon as the most significant driver of decarbonisation across the economy in the market-driven policy pathway, with the EU ETS central to delivering this, four items of structural reform are proposed to increase the price to more 'appropriate' levels (discussed below), and to reduce volatility and improve long-term predictability. Each reform discussed below was broadly presented as initial options for structural reform in European Commission (2012)[54]:

- The introduction of a **Market Stability Reserve (MSR)**. Adjustments to annual auction volumes would be triggered when the total number of allowances in circulation falls outside a predefined range, by placing allowances in, or releasing them from, the MSR. The objective is to address imbalances between supply and demand, and thus indirectly

[53] 'Domestic' aviation is defined as any flight internal to an Individual Member State, or any intra EU28+3 flight. 'International ' aviation, defined as any flight to or from any EU28+3 airport originating or terminating outside the EU28 +3 are technically obligated, but with compliance requirements currently suspended until 2016. As only road transport is considered in this report, aviation is not discussed further.

[54] The 2012 'State of the Carbon Market' report aimed to 'analyse the functioning of the carbon market, and to consider whether regulatory action is needed to 'strengthen the EU ETS…and make it more effective' (European Commission, 2012).

influencing allowance prices. The MSR is a proposal that is currently being taken forward, with a legislative proposal[55] suggesting introduction at the beginning of Phase 4 (2021).

- **The permanent retirement of 'back-loaded' allowances**. As a short-term measure to address the oversupply, a total of 900 million allowances are being withdrawn from auction across 2014-2016, to be auctioned instead in 2019-2020. Whilst there is some discussion surrounding the immediate entry of these allowances into the proposed MSR, in this policy pathway, it is proposed that these allowances are fully retired, permanently reducing the supply of allowances.
- **Early revision of the Linear Reduction Factor (LRF)**. The LRF is the rate at which the total availability of allowances decreases annually – currently 1.74% from 2010 levels (i.e. a constant absolute reduction each year from 2010). At present, the EU ETS Directive (2009/29/EC) foresees a review of the LRF after 2020, with any decision to alter it implemented by 2025. However, in the second of the structural reform proposals attempting to be taken forward by the Commission, it is proposed that the LRF increases to 2.2% from 2021. An additional driver behind this is the achievement of the proposed target of a 40% reduction in EU GHG emissions by 2030 (from 1990 levels), as contained in the 2030 Framework for Climate and Energy Policies (European Commission, 2015a). Under this pathway, this proposal is adopted in this policy pathway.
- **Expansion of the scope of the EU ETS to other sectors.** This approach takes a demand-side rather than a supply-side approach to addressing the oversupply issue. In this policy pathway, it is proposed that the EU ETS is expanded to include fossil fuels from road transport, applied upstream at the point of production of import. This also allows for an equalised carbon price to be expanded. This is further discussed under the 'Transport' section, below (Section 3.2.4).
- **Remove (or heavily limit) the use of international credits**. The ability to use international credits for compliance under the EU ETS has contributed significantly to the current oversupply – it is likely that the surplus by 2020 would be only 25% that of projected levels if such access were removed (European Commission, 2012). This policy pathway implements a banning (or heavy reduction) in the use of international credits from the beginning of Phase 4 (2021).

The objective of these reforms is to produce a stable and relatively predictable carbon price upon which investments may confidently be made, by removing the existing oversupply and attempting to manage such risks in the future. Although the direct objective of the EU ETS is not to produce a pre-determined carbon price, but rather to achieve the mandated cap through the lowest-cost options (and therefore produce the lowest carbon price possible against this objective), an examination of a price level and trajectory that may be considered 'suitable' to drive the transition to a low-carbon infrastructure (and as an indicator of success of the instrument), is useful.

[55] See European Commission (2014c) for the legislative proposal.

Numerous modelling studies have sought to determine the shadow marginal (or explicit) carbon price produced with (or required for) significant decarbonisation of the European energy system by 2050. Although the ETM-UCL and ER2050 project similar shadow prices of €220/tCO_2 and €265/tCO_2 by 2050, respectively (with the ETM-UCL projecting a price of €80/tCO_2 by 2030), other modelling studies often produce a wide range results depending on individual model structure and dynamics, technology and fuel price assumptions, and scenario design. Knopf *et al* (2013) applies European decarbonisation scenarios[56] to thirteen different models[57], with resulting marginal carbon prices ranging from €61-169t/CO_2 in 2030 (with a median of €76/tCO_2), and €240-1127/tCO_2 in 2050 (with a median of €521/tCO_2). These values represent equalised-economy wide values, rather than reflecting marginal abatement costs in existing EU ETS sectors - which are considered to be those with the lowest marginal abatement costs. For example, the GINFORS projects a carbon price for the EU ETS sectors of €230/tCO_2 by 2050, with non-EU ETS sectors requiring a carbon price of €460/tCO_2[58].

However, as this pathway foresees an expansion of the sectoral scope of the EU ETS to transport (a sector often considered the most expensive to decarbonise (Knopf *et al*, 2013)), and as other carbon pricing mechanisms are to be aligned with the EU ETS (as discussed under the 'Buildings' sector (Section 3.2.3), below), the prices here may be considered as projections of 'suitable' explicit carbon prices produced by the EU ETS under a market-based policy pathway. Therefore, it would seem reasonable to suggest that a minimum carbon price of around €75/tCO_2 in 2030 and around €250/tCO_2 in 2050, is required under this pathway.

As the above-mentioned structural reform proposals are all targeted at altering the dynamics of the supply of and demand for permits, rather than directly targeting the price itself (as is appropriate for a quantity-based instrument), the extent to which they may achieve and maintain these 'appropriate' price levels, and a relatively predictable manner, is unclear and difficult to assess *ex ante*. This will depend on the specific design and implementation of the measures proposed, individually and in combination, and exogenous developments that act to influence permit demand (overall and across time). Such developments may include economic shocks (such as that experienced in 2008, and a significant contributor to the current permit oversupply and consequential low price), deviations from expected rates of electrification in end-use sectors (which would both increase electricity demand and reduce demand for convention fuels in transport, which are now within the scope of the EU ETS), and unexpected technological (or social) developments that may rapidly reduce marginal abatement costs in a singe sector, sub-sector or Member State. The impact of parallel instruments may also exert an influence over such developments, although as in this policy pathway dedicated RES-E support mechanisms are removed, this risk is reduced. Whilst the

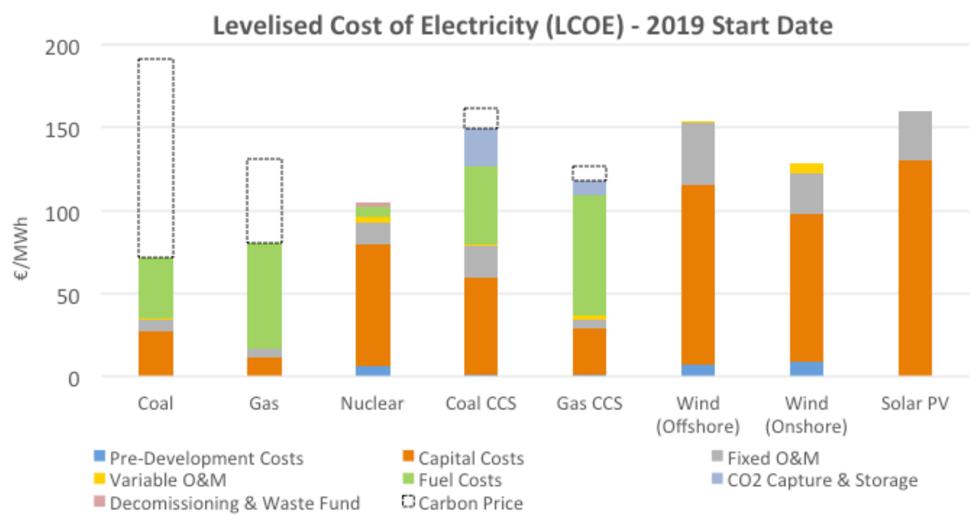
[56] All scenarios reach an 80% reduction in CO_2 emissions below 1990, but with differences in international co-operation, trade and other linkages. See Knopf *et al* (2013) for more detail.
[57] Partial equilibrium energy system, macroeconomic computable general equilibrium (CGE) and growth models, with different geographic and temporal resolutions, and sectoral definition and coverage. See Knopf *et al* (2013) for more details.
[58] Carbon prices for the EXOBASE Model are not extractable.

MSR, in particular, is designed to maintain effective function of the instrument in light of such (particularly demand side) developments, the pre-defined rules by which the MSR would operate may not be suitable to deal with the effects of such aspects developing to an extreme, or if they occur in parallel. Further alteration of the operating rules of the MSR, or a repeat of 'one-time' fixes such as those outlined above, may in itself damage the stability and predictability of future carbon prices. Although abatement may be achieved, and the EU ETS cap maintained, through a variety of means – both expected and unexpected, and both induced by the EU ETS and as a consequence of other developments, regardless of the particular mechanism, a significant reduction or banning of the use of international credits ensures that abatement will be produced in within the EU28 (plus 3).

In the power sector, if it is assumed that the reforms outlined above produce a suitable, stable and predictable carbon price (with no significant, unexpected exogenous developments), abatement has been, and may be delivered via two key mechanisms. The first is 'fuel switching' (encouraging generation from low- rather than high-CO_2 intensity existing fossil fuel capacity), and the second is through longer-term investments in lower-carbon generation capacity (including renewables), than would otherwise have been the case. Fuel switching, whilst the primary driver for the modest levels of abatement induced by the EU ETS thus far (Agnolucci & Drummond, 2014), is a short-term operational phenomenon rather than an infrastructural development, and thus is not explored further here.

In order to drive a change in European electricity capacity profile towards that discussed in Section 2.1. (i.e. an increase in renewables at the expense of fossil fuel generation capacity), the carbon price must be such to make the levelised cost of electricity (LCOE), the total average cost of generation of a electricity across the lifetime of the installation, favour such capacity. Figure 16 illustrates recent projections of the LCOE for various key generation technologies in the UK, with a project initiation date of 2019[59].

Figure 16 - Levelised Cost of Electricity - 2019 Start Date (Source: DECC, 2013; DECC, 2012b)



[59] The LCOE for Biomass with CCS is projected at €218.4/MWh (for a project start date of 2025), but as the source does not provide a breakdown, it is not represented in Figure 16. A conversion rate of 1.3 is used for GBP to EUR. All values have a 10% discount rate applied by the source.

Various components comprise the LCOE, and as is clear from Figure 16, each component holds different levels of importance in different generation sources. Capital costs are by far the largest contributor to the LCOE for nuclear and renewable sources, whilst fuel costs are often most significant for fossil fuel generators (both unabated and with CCS). The carbon price, which is set at €162/tCO_2 (as average value of a linearly increasing price between €75/tCO_2 in 2030 and €250/tCO_2 in 2050), presents a significant cost to unabated gas and (particularly) coal. As a carbon price is technologically agnostic, and as in a market-based approach this is the only driver for decarbonisation in the power sector, it would be expected that generation technologies with the lowest LCOE would come to dominate. The projections in Figure 16 suggest that although coal is the most expensive option on a LCOE basis (aside from Biomass with CCS), no renewable technology will be cheaper than unabated gas, and nuclear is the lowest-cost option. Such values would therefore suggest, upon initial inspection, that whilst the prevention of new coal capacity construction is achieved, nuclear and gas with CCS would dominate, with renewables remaining priced out of the mix. As such, the power sector requirements outlined in Section 2.1 would not be achieved.

However, various issues complicate this. For example, project lead times[60] vary significantly. Whilst the average lead time for a renewable installation in the EU is around 30 months (PwC, 2010), nuclear plants may have a lead time exceeding a decade (with conventional coal and gas plants experiencing lead times of around 5 years) (DECC, 2013). As such, even if it is assumed the required carbon price is achieved and maintained in any given year, it must be predictable a number of years in advance (also to ensure generation from such plants may be sold on the market, as discussed below). Therefore, if investment in new power capacity is to shift significantly to renewables by 2030, and existing nuclear capacity is to be maintained, the carbon price level for 2030 and beyond must be clear (within a relatively small margin of unpredictability), by 2025 at the very latest (and likely before).

However, even if this is assumed, the remaining components of the LCOE calculation presented in Figure 16 are uncertain and subject to variation. Capital cost developments (particularly for renewable technologies, but also for CCS technologies[61]), and fossil fuel prices, are difficult to predict. Whilst renewable capital costs can only decrease, fossil fuel prices are highly volatile and may increase or decrease substantially over relatively short periods of time. They may also vary between Member States, not least due to the impact of local producer subsidies (e.g. lignite production in Germany). Additionally, the values in Figure 16 assume capacity factors specific to the UK. Capacity factors, particularly for solar and wind technologies, are likely to vary substantially across the continent, possibly altering the magnitude of the denominator in the LCOE calculation significantly (e.g. a higher capacity value would be expected in Member States with high solar irradiation, *ceteris paribus*, reducing the final LCOE value, and vice versa), and possibly to levels below that of other generation sources. Indeed, in 2013, grid parity was achieved for commercial-scale solar PV in Germany, Italy and Spain (Eclareon, 2014). A single EU-wide carbon price delivered by the EU

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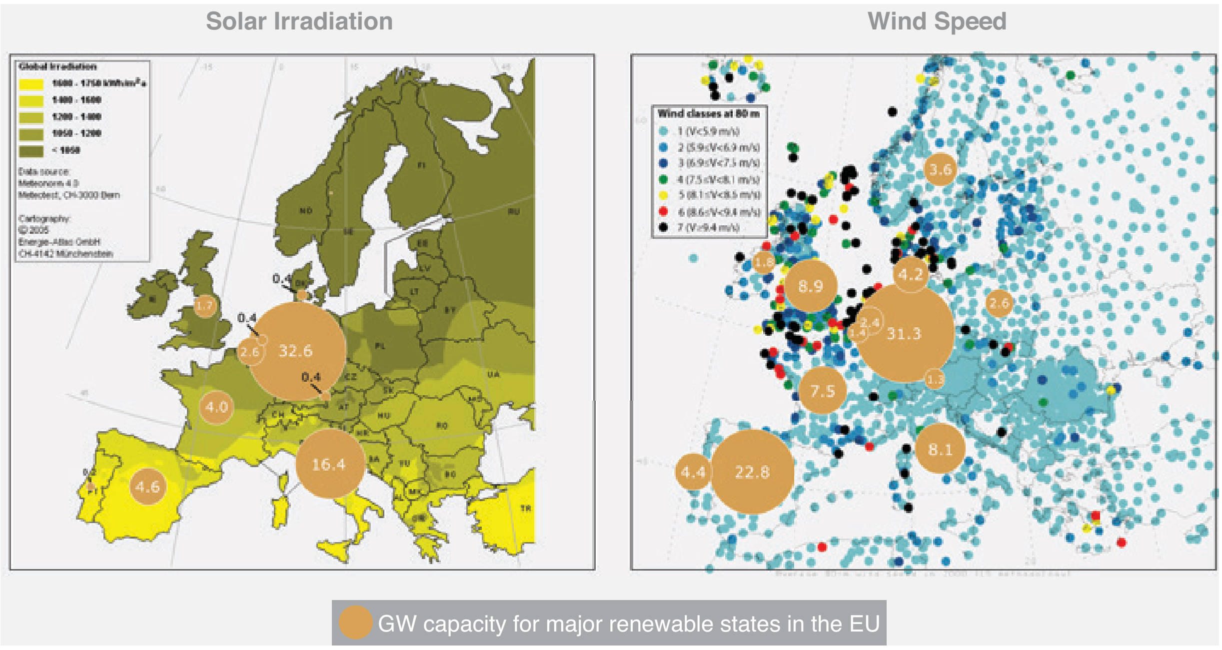
[60] The time taken between project initiation to grid connection (including planning stages and construction).
[61] It is assumed that CCS technologies will be proven and available for use when they are required.

ETS, coupled with a European supergrid and single electricity market and in the absence of flanking measures, would be expected to produce deployment of generation capacity in the EU where the LCOE is least (although whether such deployment is sufficient to meet the requirements outlined in Section 2.1 is dependent on the factors outlined above, and discussed below). As described, for wind and solar technologies, this is likely to be where the resource is strongest. Almost all RES-E deployment in the EU achieved thus far is a result of dedicated support mechanisms rather than the EU ETS (Agnolucci & Drummond, 2014), designed and implemented at Member State level. As such, deployment has been achieved where the most lucrative support mechanisms (and other enabling measures, discussed in Section 3.5) are situated, rather than where LCOE is least at an EU-level. Figure 17 illustrates the existing disparity between renewable resource and capacity deployment.

Figure 17 - Wind and Solar Generation Capacity against Wind Speed and Solar Irradiation Values in the EU (Source: WEF, 2015)



However, other issues remain that may prevent an appropriate deployment profile of generation technologies in the presence of a carbon price. The most prominent is electricity market design. Currently, electricity in European markets is dispatched according to the 'merit order', which is set by the marginal generation costs of each generator. For fossil fuel generators the marginal cost represents fuel costs and the carbon price, whilst for renewable generators, this cost is zero (or near zero). As such, renewables enter first in the merit order and are (generally) dispatched first, with the increasingly expensive generators (first nuclear, and then fossil fuel plants), dispatched according to demand. The wholesale electricity price is set by the marginal costs of the marginal generator, meaning that at times of high demand prices are higher, with generators lower in the merit order receiving increasing revenue (at the differential between their marginal costs, and the wholesale price). With increasing penetration of renewables (and also nuclear), fossil fuel plants are increasingly displaced, and lower average wholesale prices are produced (with increasing carbon prices offset by reduced fossil fuel generation). This means that fossil fuel plants are increasingly unable to generate and thus do not generate sufficient revenue (a 'missing money' problem), regardless of LCOE values. However, this issue also reduces revenue to renewable generators, and in the absence of dedicated support mechanisms (such as feed-in tariffs), renders them also unable to generate sufficient revenue to cover non-marginal, fixed costs. As such, existing electricity market arrangements must be redesigned – options for which are discussed under Section 3.5.

A carbon price as a lone instrument, along with the specific future design of the electricity market, may impact the distribution of renewable generation between centralised and decentralised installations, and the cost and availability of finance. For decentralised electricity (particularly for autoproduction) to be an economically attractive option, the LCOE must be less than the retail price of the equivalent electricity generated by other (centralised) entities. However, this also includes, for example, the cost of installation, planning and other permit applications, and building retrofitting (generally, whilst these costs are also present for large, centralised installations (of all types), they experience economies of scale are reduced as a proportion of total costs). Such costs are present regardless of the policy instrument pathway adopted. Whilst such costs are largely known *ex ante* for any given installation, the retail price may vary over time (the frequency, direction and magnitude of which depends on electricity market design), producing a level of uncertainty. Energy consumption subsidies, such as reduced rates of VAT applied to domestic energy in the UK (5% rather than the standard rate of 20%), will also impact price signals across Member States.

Firms, communities and individuals are typically unable to finance capital investments through their own savings, and thus require access to external finance. This may come principally through bank lending, or in the case of larger firms, market debt (by issuing debt instruments, such as 'green bonds'[62]), or market equity (either through private investment or the purchase of shares of publicly listed companies). Due to the capital-intensive nature of renewable (and nuclear) investments, they experience proportionally higher financing costs than fossil fuel installations (Campiglio, 2014). Financing costs add further to relative LCOE values (between conventional, nuclear and renewable, but also between centralised and decentralised renewables). For decentralised installations, potential uncertainty in the retail price (and therefore return on investment) may increase financing costs further (or reduce its availability altogether), which in itself adds to the cost base. However, low- or zero-interest financing instruments, such as that discussed under the 'buildings' sector below (Section 3.2.3).

Some issues remain with the deployment of decentralised generation from which large scale, centralised installations do not suffer (or suffer to a significant lesser degree). The first is information failure. Households, communities and small organisations may not be fully aware of the existing and likely future cost of their electricity consumption, the availability, cost and

[62] 'Green bonds' are bonds that earmark proceeds for climate or environmental projects.

processes surrounding the establishment of a decentralised installation, or how the two components may relate to each other. Such information may also be difficult to obtain or calculate (although, the increasing rollout of smart meters will likely reduce this issue). Additionally, individuals (in particular) tend to discount the value of future savings or expenditures, meaning that if a large up-front expenditure is required to accrue savings over time, particularly if such savings are relatively small (and as above, possibly uncertain or unpredictable), the investment is less likely to be made (even if other barriers have been overcome) (Kaenzig & Wustenhagen, 2010). A significant 'hassle factor', either real or perceived, may also be present at all stages of an installation (from information gathering to ensuring maintenance). However, even if such above issues are alleviated, barriers such as the 'landlord-tenant' dilemma are likely to remain, possibly preventing the installation of decentralised units in cities, regions or Member States with high proportions of rented properties (private or social), or with, for example, high-rise residential blocks.

Linked to this is the issue of spatial planning and other authorisation procedures, which have proven particular constraints to the deployment of RES-E in the EU, particularly (onshore) wind and solar (both centralised and decentralised) (Agnolucci & Drummond, 2014). Spatial planning and other authorisation processes are an issue for the power sector, and other sectors, regardless of the policy paradigm assessed. This issue is discussed in Section 3.5.

3.2.2 Industry

Table 3 presents a brief summary of the policy instruments proposed for the 'Industry' sector under the 'market-based' policy pathway. The EU ETS is the key instrument in this sector, coupled with a re-aligned Energy Taxation Directive (ETD). **Energy Audits** for large companies, required every 4 years by Article 8 of the EED and discussed under the behaviour-based policy pathway (Section 3.4.2), remain as currently mandated.

Table 2 – Market-Based Policy Pathway - Industry

Policy Instrument	Description
Energy Taxation Directive (ETD)	The ETD is reformed and is composed on an 'energy' and 'CO_2' component, with the latter imposing a CO_2 price on (non-industrial) heating fuels equalised to the EU ETS price. Motor fuels and Industrial consumption is subject to the 'energy' component only, with CO_2 emissions covered by the EU ETS.
EU ETS	The EU ETS is substantially reformed to produce a robust, increasing price over time, along with scope increasing to the road transport sector.

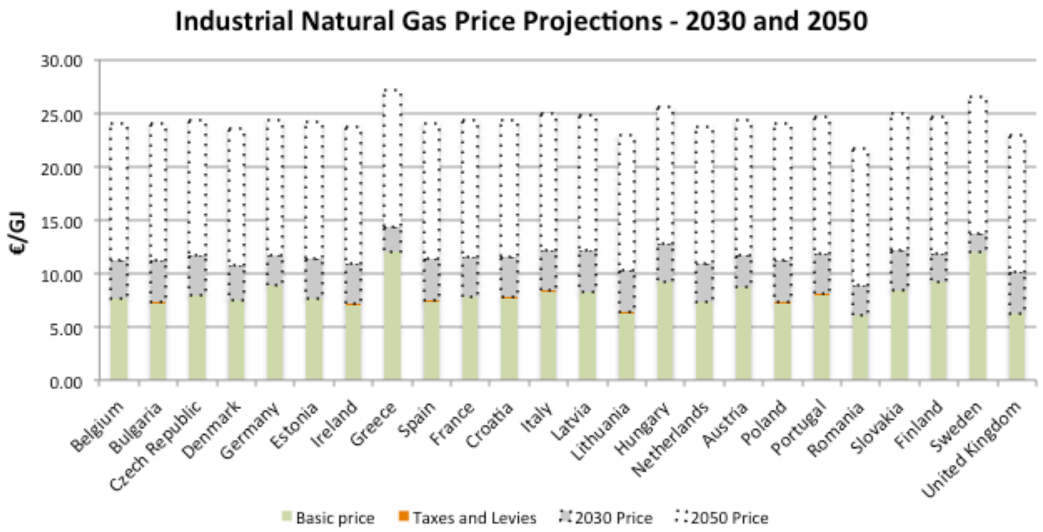
Energy Taxation Directive

The ETD, along with proposed reforms under this policy pathway, is described below (Section 3.2.3). Exemptions for energy-intensive industry are removed, with a minimum €0.15/GJ imposed on all energy products. Energy-intensive industry is exempt from the 'carbon' component of the revised ETD, as it is subject to the EU ETS. The combined impact of this reform with the EU ETS is discussed below.

EU ETS

The EU ETS, along with the majority of proposed reforms under this policy pathway, including carbon price objectives, is described above (Section 3.2.1). At present, the majority of industrial (manufacturing) sectors are subject to 'benchmarking', in which the most efficient installations manufacturing each product in principal review 100% free allocation, with less efficient plants receiving less in proportion to their performance against each product-specific benchmark (calculated as the average performance of the best 10% of installations in

Figure 18 - Industrial Natural Gas Price Projections - 2030 and 2050 (Data Source: Eurostat and Author's Calculations)



GHG intensity). In 2013, such industries received 80% free allocation, decreasing to 30% by 2020. Industries considered at risk of carbon leakage (defined as 'energy-intensive, trade-exposed' (EITE) currently receive 100% free allocation. By 2021 (the start of Phase 4), free allocation to all installations is fully removed under this policy pathway. However, EITE sectors will require an alterative mechanism to prevent carbon leakage. Whilst various options exist to achieve this (and a discussion of such options is beyond the scope of this report), under this policy pathway a Border Carbon Adjustment (BCA) is assumed, to ensure the carbon price is able to maximise its potential to incentivise decarbonisation.

Figure 18 illustrates the combined impact of the new ETD minimum rate and the carbon prices described in Section 3.2.1 by 2030 and 2050 on natural gas prices. Basic prices are averaged over a seven-year period (2007-2013). 'Taxes and Levies' are those additional to the average of those imposed over this same timeframe, from the imposition of a mandatory €0.15/GJ minimum rate. '2030 Price' and '2050 Price' indicate the carbon price burden in addition to current prices (i.e. considering Member States where existing taxes and levies are in excess of €0.15/GJ)[63]. It is clear that under these assumptions gas prices would be

[63] Data for Cyprus, Luxembourg and Malta was not available. A CO_2 intensity value of 0.051tCO_2/GJ for natural gas was applied. Data for Band I5 (1,000,000GJ – 4,000,000GJ were used. For Taxes and Levies, only non-recoverable values are used. Similarly, as many firms are able to recover their VAT on energy consumption, VAT is not presented.

expected to double by 2050, although it would likely become the least-cost fossil fuel by this time (with coal, for example, reaching around €35/GJ under current prices). Changes in electricity prices would depend on the electricity market design, discussed in Section 3.5.

As energy consumption is already a substantial cost to energy-intensive industry, much of the existing energy efficiency potential has already been exploited. However, a further increase in costs should allow for additional cost-effective efficiency opportunities, such as the use of electric-arc furnaces in steel production (a 60-70% reduction in energy consumption compared to blast furnaces), with electricity also replacing fossil fuel as an energy source, and the use of dry-rotary kilns rather than wet-process clinker kilns in cement production, also cutting both energy consumption and CO_2 emissions (Grubb, 2014). Such options are likely to cost-effective before well before 2030 at the carbon prices projected in Figure 18 (Fischedick *et al*, 2014) particularly as the EU ETS covers both energy and process emissions from these sources.

However, for smaller, less energy-intensive manufacturing industries, the evidence suggests that relatively substantial energy efficiency opportunities exist at current prices that have not been exploited. For example, a cost-effective potential energy saving of 15-25% is likely available from the use of the most efficient motor drives (with a potential saving of 100MtCO_2/year in the EU). Such potential is often not taken up due to a lack of awareness, which energy audits required by the EED may help to alleviate. However, a lack of capital, organisational inertia, and other behavioural issues are more prevalent in industries where energy costs are not necessarily paramount, and present further barriers to uptake (Grubb, 2014). However, across the industry sector (including the most energy-intensive), substantial efficiencies may be gained from the recovery of waste heat from one process to allow it to be fed into another. In the UK for example, the potential for such recovery equals around 2.4% of existing industrial heat use (and 4% in the most energy-intensive) (DECC, 2014b). Issues in physical siting of industrial plants and market structures to enable such transfer when technically possible are the key barriers to such potential being utilised, rather than pricing incentives (DECC, 2014b; Grubb, 2014).

It is possible that a level of fuel switching (from coal and oil to electricity, gas and biomass) may be experienced for both heat generation processes and in production processes (e.g. coke derived from biomass rather than fossil fuels in steel production) as a result of the price developments discussed above, although as described in Section 2.2, such an effect are likely to be relatively minor. Estimates of the required carbon price to allow the cost effective uptake of CCS in the industrial sector vary significantly, both overall and between sub-industries. The IEA (2012) present a range of estimates of around €55-140/tCO_2 for CCS in iron and steel, and between around €50-185/tCO_2 for the cement sector. Such ranges suggest that CCS may enter into use sometime between around 2025 and 2040. This serves to highlight the deep uncertainty that remains around this key technology for industry sector CO_2 abatement.

Additionally, as with other sectors, it is unclear how basic fuel prices and the cost of efficient and low-carbon technologies may develop. However, differently from other sectors, the basic price component of the energy price in 2050 (in particular) is likely to be smaller than the carbon price liability, rendering significant overall price fluctuations less likely. Another confounding factor may be the effect of the particular design of the mechanism designed to prevent carbon leakage. Although a BCA is assumed here, other mechanisms may act to prevent industrial installations from experiencing the full effect of the carbon price produced by the EU ETS (e.g. output-based allocation), reducing the low-carbon incentive. As such, despite encouraging the correct price incentives, the extent to which the combined effort of the reformed ETD and EU ETS would have on the industrial sector by 2030 and 2050, and whether it would achieve the requirements laid out in Section 2.2, particularly surrounding the use of CCS, is highly uncertain.

3.2.3 Buildings

Table 3 presents a brief summary of the policy instruments proposed for the 'buildings' sector under the 'market-based' policy pathway. The primary focus is on heating fuels, with a carbon price imposed and equalised to the EU ETS, through a revision to the Energy Taxation Directive (ETD). **Building Energy Performance Standards** remain, as do existing **Energy Efficiency Obligations** and **Technology Performance Standards** (all of which are discussed under Section 3.3.3), along with **Energy-Related Product Labelling** and **Building Energy Performance Certification** (both of which are discussed under Section 3.4.3) however such instruments are not actively continued or expanded beyond existing definitions and time limits.

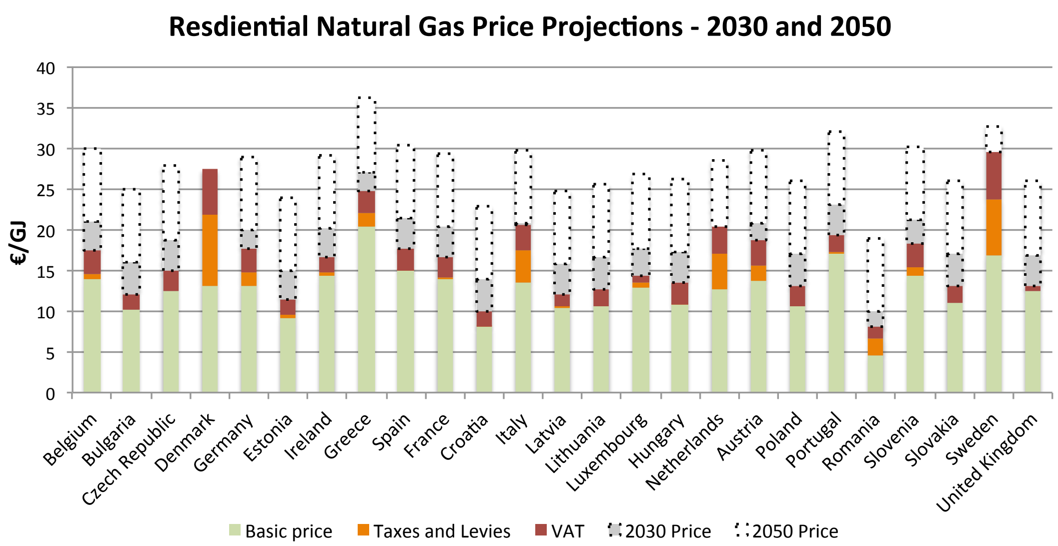
Table 3 - Market-Based Policy Pathway - Buildings

Policy Instrument	Description
Energy Taxation Directive (ETD)	The ETD is reformed and is composed on an 'energy' and 'CO_2' component, with the latter imposing a CO_2 price on (non-industrial) heating fuels equalised to the EU ETS price. Motor fuels and Industrial consumption is subject to the 'energy' component only, with CO_2 emissions covered by the EU ETS.
Tax Incentives for High-Efficiency/Low-Carbon Products	Tax incentives are introduced, in various potential forms, to encourage the purchase of high-efficiency, low-carbon products – especially heating systems.
Stimulation of ESCo Market	The market conditions to allow the spread of Energy Saving Companies (ESCos) are established
Voluntary 'Pay as you Save' Finance Instrument	A PAYS instrument is introduced to reduce issues of access to finance for energy efficiency and renewable installations, along the lines of the UK's 'Green Deal'

Energy Taxation Directive (ETD)

The ETD imposes minimum taxation rates on electricity, heating and motor fuels across the EU, with different minima for consumption for commercial and domestic purposes (see Drummond (2013) for a full discussion of the particular design of the ETD, and inherent issues this produces). Under this policy pathway, reforms largely as proposed by the European Commission in 2011 (European Commission, 2011c), are implemented. Minimum rates are recast to include an 'energy' component and a 'carbon' component. The 'energy' component would be set as a flat rate for electricity and heating fuels on an energy content basis (proposed at €0.15/GJ, the existing minimum rate for natural gas and electricity), with a separate rate for motor fuels (discussed below, under Section 3.2.4). Possible exemptions for energy-intensive industry (as discussed under Section 3.2.2, above), and for domestic heating would be removed. Industry and transport would be exempt from the 'carbon' component, as CO_2 from these sectors is priced under the EU ETS. Similarly, electricity consumption by all end users is exempt from this component, as CO_2 is priced by the EU ETS upstream. For the residential and commercial sectors a fixed minimum value, aligned to EU ETS values (a minimum of €75/tCO_2 in 2030 and €250/tCO_2 in 2050), is imposed, in addition to the 'energy' component. Figure 19 and Figure 20 illustrate the potential effect on gas prices in the residential and commercial sectors (which for the purposes of this discussion, may also be considered to encompass the public sector), across the EU from the imposition of such reforms.

Figure 19 - Residential Natural Gas Price Projections - 2030 and 2050 (Data Source: Eurostat and Author's calculations)



In these figures, the values for basic prices, taxes and levies and VAT are averaged over a seven-year period (2007-2013). To calculate the projected impact of the revised ETD in 2030 and 2050, indicated by the labels '2030 Price' and '2050 Price', it is assumed that 'taxes and levies' in each Member State represented is set at €0.15, regardless of existing values. As such, these projected values represent total additional cost, *ceteris paribus*, rather than the absolute value of the 'carbon' component of the revised ETD structure[64].

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[64] For both figures, data for Cyprus, Malta and Finland was not available. A CO_2 intensity value of 0.051tCO_2/GJ for natural gas was applied. For Figure 19, data for Band D2 (20GJ to 200GJ) were used. For **Error! Reference source not found.**, data for Band I3 (10,000GJ to 100,000GJ were used. The cost imposed by VAT would also change as a result of carbon prices/tax effects (with the equivalent sign), however this change is not calculated. For Taxes and Levies, only non-recoverable values are used. Similarly, as many firms are able to recover their VAT on energy consumption, VAT is not presented.

[65] TCO represents the lifetime cost of owning and operating a technology or product including original purchase

Figure 20 - Commercial Natural Gas Price Projections - 2030 and 2050 (Data Source: Eurostat and Author's calculations)

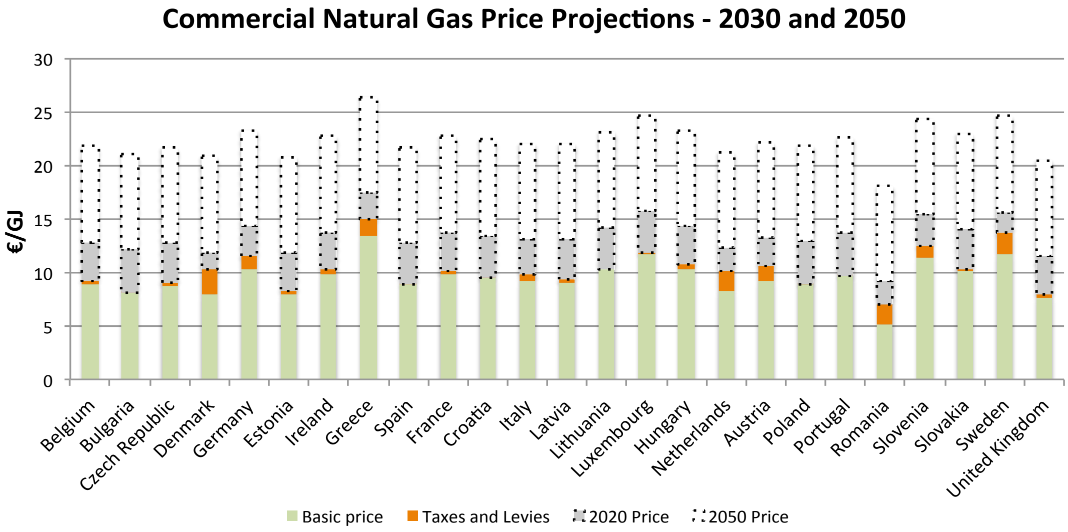

Figure 19 clearly illustrates the difference in residential gas prices present across different Member States, driven by basic prices (varied due to regional markets), taxes and levies (whilst some Member States implement the exemption permitted for the taxation of residential heating fuels, such as the Bulgaria and Lithuania, in other Member States, such as Denmark and Sweden, they are a significant proportion of the final price), and differences in VAT. Average prices vary from €8/GJ in Romania, to €30/GJ in Sweden. In 2030, the imposed carbon price increases total prices by an average of around €2.5/GJ, or 13% (assuming taxes and levies are set at €0.15/GJ, whilst all else remains equal), although there is significant range, with the Netherlands, Italy, Sweden and Denmark experiencing a decrease (with the latter producing a 32% reduction on current levels). In 2050, the carbon price, under the conditions highlighted above, produced an average €11.2/GJ increase (or 77%) from current levels, again with significant range. Whilst Romania experiences a 133% increase, prices in Denmark remain approximately current levels (a 2% decrease). As illustrated by Figure 20, the variation in existing gas prices in the commercial sector is much less between Member States than residential prices, and are mainly driven by basic prices (although taxes and levies are imposed, their magnitude per unit of energy is much less than the residential sector, with the highest value, imposed in Denmark, of around €2.5/GJ). Average prices vary from around €7/GJ also in Romania, to around €15/GJ in Greece. In 2030, the imposed carbon price (and €0.15 tax minima) increases prices by an average of around €3.3/GJ, or 34%, with little variation between Member States (due to the existing broad lack of taxation and VAT). The carbon price in 2050 produces an average increase of around €12/GJ (or 124%), again with relatively little variation.

To determine the impact such changes may have in encouraging the extent and rate of deployment of low-carbon heating technologies and efficiency measures, in particular, the relative total costs of ownership (TCO)[65] of different technologies and measures must be examined. For residential properties in the UK at present, the annual TCO for a new gas

[65] TCO represents the lifetime cost of owning and operating a technology or product including original purchase price, maintenance costs, fuel costs and any taxes and fees.

condensing boiler is around €1,300 (broadly the lowest for any technology) (DELTA, 2012). Assuming an increase in prices at the EU average rates highlighted above (for residential supply), the annual TCO, *ceteris paribus*, increases to around €1,450 in 2030, and around €2,200 in 2050. For air source heat pumps (ASHPs) the current TCO is around €1,650, with ground source heat pumps (GSHPs) around €2,050[66] (DELTA, 2012). All else equal, this would suggest that gas remains the least-cost option by 2030 for the residential sector, whilst heat pumps (particularly ASHP) become more cost-effective by 2050. Such a trajectory is likely to be present for commercial systems.

However, this conclusion is subject to significant uncertainty, for numerous reasons. Firstly, fuel prices may be volatile and unpredictable, and are likely to continue to vary between Member States. Basic gas prices on average have varied by around €8.6/GJ between 2007 and 2013 for residential consumers, and around €6.8/GJ for commercial consumers. In both cases, the magnitude of this variation is more than double that of the projected 2030 increase in total average prices from the carbon price burden, and around two-thirds and a half of the projected average increase in 2050 in the residential and commercial sectors, respectively. As such, the carbon price signal may be significantly dulled or even entirely counteracted by underlying price fluctuations. However, these calculations assume taxes and levies to be set at the revised minimum of €0.15/GJ in all Member States, whereas in reality Member States may impose levies at any rates above this, as many currently do. Additionally, VAT rates may alter from present levels. The development of each of these components is likely to vary by Member State, although developments such as the evolution of the proposed internal gas market (similar to the single EU electricity market), the potential for a single EU purchaser for gas[67], or increasing federalisation of the EU allowing for more centralised and co-ordinated taxation regimes, may reduce such disparity. Other confounding factors remain. Firstly, developments in electricity prices, which further alter cost-benefit calculations and TCO values, will depend on electricity market design (discussed under Section 3.5). Secondly, regardless of fuel price developments, differences in total demand for heating (and therefore the influence of fuel price in TCO calculations), due to climate, building size and efficiency levels, are likely to remain between Member States – particularly in the residential sector. Thirdly, capital costs, particularly for heat pumps and other low-carbon heating options, are likely to reduce substantially over time. This may be driven by underlying cost reductions, but also through the use of policy measures such as tax incentives, discussed below. The combination of these various potential developments and differences makes the calculation of the influence of carbon pricing on relative TCO values in the future complex and highly uncertain.

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[66] The price of a residential condensing gas boiler is around €3,500 (£2,500). Assuming an average 15 year lifetime, total operating costs (based on existing gas prices) are around €16,000 (£12,000). Capital costs for air source heat pumps (ASHPs) are approximately €11,000 (£8,000), with ground source heat pumps (GSHPs) approximately double this. Assuming a 20 year lifespan for these technologies, operating costs (at current electricity prices) for both are around €25,000 (£18,000). Maintenance costs are not included.

[67] Proposed as an option under the recently-proposed Energy Union package.

However, even if the economic evaluation comes to favour low-carbon heating systems on a TCO, in either the short- or long-term, other barriers to rapid deployment remain. In existing, particularly residential buildings, such an evaluation is only likely to take place when a previous heating system requires replacement. In rented properties, capital costs are likely to be the overriding factor in an investment decision, as the investor (the landlord) is not liable for fuel cost (making the imposition of carbon pricing on such investments redundant). Such an issue may also be present for new buildings, between the property developer and buyer. However, both regulatory and commercial competitive pressures may constrain this. For existing buildings, additional restraints may be present, such as capital costs and availability (which may be tackled by financing arrangements and mechanisms, discussed below), the technical ability to retrofit, spatial planning regulations, and 'soft' issues, such as hassle factor, the discounting of future costs and savings, and information asymmetry (although, the smart meter rollout will reduce this). Such issues also heavily restrict the voluntary deployment of cost-effective energy efficiency measures.

Tax Incentives for High-Efficiency/Low-Carbon Products

Tax incentives for the purchase of high-efficiency/low-carbon (HELC) products (such as heating equipment, lighting, white goods and other appliances) can take the form of direct tax reductions or the provision of tax credits based on the capital costs of such products possibly coupled with an increase for low-efficiency/high-carbon products (in a 'feebate'/'bonus-malus' system), or they may take the form of a reduction in indirect taxes, such as council taxes. Tax incentives have been shown to be an effective means of reducing the capital costs of energy efficient building-related equipment and appliances (Gold and Nadel, 2011), which as discussed above, is a key component of TCO calculations, and a frequent barrier to investment due to discounting and capital availability. However, the extent to which tax incentives are successful in overcoming such barriers as to stimulate additional deployment of HELC goods is a much under-researched area in energy and climate policy - primarily due to methodological challenges (Warren, 2015), and depends on the particular design of the instrument (including the magnitude of the change to capital costs), the products targeted (heating products, electricity-using appliances, domestic or commercial products, etc.), the presence and combination of non-capital cost barriers (such as those highlighted above), and the effect of flanking instruments such as carbon pricing (both direct, as discussed above, and upstream, such as on the generation of electricity and subsequent cost pass-through).

In colder European climates, such as northern Europe, energy-efficient and low carbon heating systems have potentially larger impacts on energy and CO_2 savings than focussing tax incentives on other consumption areas (such as high-efficiency lighting). For warmer European climates, such as countries in the Mediterranean region, energy efficiency cooling systems, such as high-efficiency HVAC units, should be the focus of tax incentives. Some studies have shown that tax incentives are often more effective than subsidies in encouraging the consumer uptake of high-efficiency products (Markandya *et al*, 2009; Warren, 2015), however regulatory, market and social differences between Member States are an important determining factor. For example, Markandya *et al* (2009) found that tax credits for high-efficiency boilers were effective in Denmark and Italy, but subsidies (especially for Compact Fluorescent Lighting (CFLs)) were more effective in France and Poland.

Stimulation of Energy Saving Company (ESCo) Market

Energy Saving Companies (ESCos) engage in developing, installing and financing comprehensive, performance-based projects that improve the energy efficiency or load reduction of facilities owned or operated by customers (in the industrial, commercial, public or residential sectors) (Vine, 2005). ESCOs focus on the demand for energy services (such as heating, cooling, lighting, comfort, and refrigeration), rather than the demand for energy itself (Boait, 2009). They act as intermediaries between consumers and building refurbishment providers, financial service providers, or energy suppliers (THINK, 2012), and often provide (or arrange) finance for energy saving projects and/or energy management activities (such as audits and training). Remuneration is directly tied to the energy savings achieved (i.e. their business models are based on receiving a proportion of the financial savings from energy saving activities), with energy savings usually guaranteed through 'performance contracts' (Bertoldi *et al*, 2006), which are ensured by monitoring performance (Boait, 2009), and installing proven measures that recoup their costs through the savings that are produced over their lifetimes (ICF International, 2007). An alternative to energy performance contracting is 'chauffage contracting', where the fee for services is calculated based on the client's existing energy bill minus a certain level of financial savings with service guarantees. This is the most common approach taken in the EU (Bertoldi *et al*, 2014).

ESCos are well established in the USA. Goldman *et al*. (2003) calculated that industry investment was US $2 billion in 2000, with typical projects saving 150-200 MJ/m^2/year. These projects produced median cost-benefit ratios of 1.6:2.1 and had median payback times of seven years. The study found that the use of efficient lighting measures and comfort conditioning through HVAC (heating, ventilation and air conditioning systems) were the most common projects (82% and 68% of the study sample respectively), followed by the installation of efficient motors/drives (23% of the study sample). Thus, the installation of energy efficient products, rather than 'soft' measures such as energy management and training, were the primary method of achieving savings.

In the EU, the Member States that have experienced the most growth in their ESCo markets are Sweden, Italy, Spain, and Denmark (Bertoldi *et al*, 2014). In Sweden, the target market has primarily been municipal buildings such as schools, hospitals, and administrative buildings. In Italy, the target market has principally been the public sector, such as healthcare facilities, where more profitable larger projects can be undertaken. In Spain, the target market has mainly been the public sector, particularly public lighting (representing 90% of all public sector projects), municipal offices and healthcare facilities. Although public sector activities dominate, there has been some activity in hotels, corporate buildings, sports facilities, and heating systems in apartment buildings. In Denmark, the ESCo market first developed in the industrial sector, but since 2008 the public sector has become a strong target market.

As is clear, existing ESCos primarily focus on existing buildings in the commercial and public sectors, with little activity in the residential sector (particularly individual dwellings). Whilst the introduction of equalised carbon pricing on electricity and heating fuels coupled with tax incentives for high-efficiency, low-carbon energy-using products is likely to further establish the economic opportunity for ESCos to develop in both the commercial/public and residential sectors, framework and regulatory barriers remain that in part prevent the widespread development of ESCos. Under this market-based policy pathway, actions are taken to remove these barriers to allow the ESCo market to develop. Such barriers, and associated measures to address them, include (Bertoldi *et al*, 2014):

- **Introduction of standardised certification schemes and standards**. In many countries it is the company itself that decides whether to brand itself as an ESCo (as in the Netherlands, France, Croatia and other West Balkan countries). This, along with a lack of accreditation or guidelines for what an ESCo should offer and provide, creates confusion and a lack of trust among potential clients.
- **Introduction of standardised measurement and verification practices**. Without a standardised, comparable methodology to prove energy savings, the outcome of a service provided by an ESCo may be disputed. This has lead to court cases (e.g. Latvia) and failed projects (e.g. Sweden). Robust measurement of results is also a common precondition for projects where public budget is involved (either in publicly-owned operations, or where grants to the private sector are provided).
- **Amendment of public procurement regulation**. In many Member States, the ESCo that carries out a feasibility study (baseline audit) cannot participate in the competitive process to receive the contract to provide ESCo services. This produces disincentives to undertake feasibility studies for public sector opportunities, or leads to the creation of 'grey' solutions (such as the establishment of a 'vehicle' company for this phase).

The first and third of these proposals are to some extent already mandated by the Energy Efficiency Directive (2012/27/EU), particularly Article 16 (certification schemes) and Article 18 (encourage the development of quality labels, and support the public sector to use ESCos). Whether these requirements are implemented and developed individually by Member States (as foreseen under existing proposals), creating varied but perhaps Member State-appropriate designs, or whether a single EU-wise approach to the above measures is taken, will likely depend on whether the EU policy making becomes increasingly centralised, or if the status quo is maintained.

Although these measures tackle particular 'framework' barriers that act to inhibit the growth of the ESCos market, it does not necessarily follow that the market will grow to such an extent as to drive significant increases in energy efficiency in the buildings stock across the EU. Although significant carbon pricing and tax incentives for high-efficiency products increase the market potential for ESCOs in all sectors, it is likely that the most attractive markets will remain relatively large-scale commercial and public sector projects, with small scale (particularly individual households) providing small returns. However, 'pooling' (or 'bundling'), in which several buildings enter into an ESCo contract as a single entity, may reduce this issue to some extent[68]. An issue preventing the growth of economies of scale is the heterogeneity of the building stock type, ownership, age and usage across sectors and Member States, requiring the use of tailored measures and making the development of standardised practices difficult. Additionally, split incentives between landlord and tenant, as with previous instruments, may prevent 'deep' renovation (such as building fabric measures (e.g. insulation) or efficient heating systems) in the rented sector (both residential and commercial), whilst technical and spatial planning constraints may present further roadblocks. Although the introduction of certification schemes and standardised measurement and verification practices reduces transaction costs for ESCo customers (as less time may be spent in sourcing and comparing ESCos and their offers), they are likely to remain high for small energy consumers (residential and commercial) in relation to returns (including 'hassle factor') – particularly if they must seek out and form a 'pool' in order to attract interest.

Although around 90% of ESCo contracts require no external finance (EEVS, 2013), overcoming issues of access to capital, the remaining 10% may still experience such issues. The European finance sector has shown very limited interest in the energy efficiency of buildings to date, for various reasons. For example, the returns from investing in energy efficiency are uncertain and are perceived across the financial sector as higher risk than other investments, and there is a lack of awareness and established methods for assessing the value of investments (ACE, 2013). Banks currently have low awareness of ESCo products, and those that do see them as 'irregular' and therefore inherently 'risky', and as such few offer suitable financial products. Those that do often see significant underutilisation due to high interest rates and administrative processes that do not match with the ESCo process (Bertoldi *et al*, 2014). Other issues present themselves from the client (loan recipient) side. Public, commercial and private sector actors are often reluctant to take on debt to finance energy efficiency measures for various reasons. Uncertainty on the return on the investment, and the time over which it may occur (payback period), is a key issue. Additionally, in the private residential sector, interviews conducted across ten EU Member States found that homeowners were reluctant to invest in measures that did not add financial value to their property. In the public sector, many municipalities and other authorities are prohibited by their national governments to take loans for ESCo projects, as they are often considered as adding to the value of government debts[69], often a politically difficult approach. Whilst there is no clear solution for this issue, some Member States do not consider ESCO finance as loans (e.g. Denmark), or do not clearly take a stand either way (e.g. Spain) (Bertoldi *et al*, 2014).

Yet further - non-financial - barriers remain, particularly in the small commercial and residential sectors. In addition to high transaction costs, a basic lack of awareness of energy efficiency issues and of ESCo may severely inhibit their growth. Risk perceptions surrounding, for example, privacy and a lack of control over energy management that may compromise

[68] Such a practice in increasing in popularity in Austria, Germany, Luxembourg and Denmark – with the latter holding an average of 60 buildings in a single 'pool' (Bertoldi *et al*, 2014).

[69] Under the EUROSTAT methodology ESA 95 (European System of Integrated Economic Accounts)

core business activities, along with financial risks discussed above, many also present significant barriers to growth.

‘Pay as you Save’ Finance Mechanism

‘Pay-as-you-save’ (PAYS) mechanisms provide access to finance to cover upfront costs of energy efficiency investments with repayments made as financial savings from reduced energy consumption are achieved, with an objective that the loan recipient (which may be residential, commercial or public sector) therefore experiences little or no additional cost burden. Such an instrument may also be available for investment in renewable energy installations. PAYS mechanisms are usually ‘soft loans’, in which a government entity, donor agency, utility or other third party funds are used to create dedicated credit lines or risk-sharing facilities that reduce interest rates for consumers below commercial market rates. Repayments may be linked to the entity receiving the loan, or as proposed and examined here, linked to the property in which efficiency measures are being installed, and recovered through energy bills or local authority service charges (known as ‘on-bill’ recovery) (Rosenow and Eyre, 2012).

On-bill recovery for energy efficiency soft loans, despite being a relatively new instrument, has been implemented by a number of countries. A prominent example is the UK’s ‘Green Deal’, which applies to both the domestic and non-domestic market. Analysis of the impact of the Green Deal in the domestic market in its first seven months of operation since its official launch in January 2013 found that it had generally raised awareness of energy efficiency across households planning to renovate their homes, whether or not they were originally intending for energy efficiency to be included in their renovations (Pettifor *et al*, 2015). By being tenure-neutral, on-bill recovery is in theory able to overcome issues of split incentives, although early evidence from the Green Deal found it may be more appealing to owner-occupiers (Hope and Booth, 2014), with 75% of recipients in owner-occupied housing, 13% in privately rented, and 12% in socially rented properties, in a country where the residential stock is split between these three categories by a ratio of roughly 65:18:17 (DECC, 2014a). ACE (2013) also finds that PAYS on-bill recovery instruments may in practice favour owner-occupiers. Overall, the rate of uptake of the domestic Green Deal mechanism has significantly been below expectations (reaching around 9,500 ‘deals’ by the end of January 2015 (DECC, 2015), with 10,000 initially expected to be reached by the end of 2013), despite significant numbers of ‘Green Deal Assessments’ (audits). However, the low conversion rate may be due to a high proportion of those receiving such assessments self-funding the improvements suggested, indicating a role in reducing information failures. UK Parliament (2014) identified three types of barriers that are likely to have significantly contributed to this low level of uptake. The first are financial barriers, particularly surrounding interest rates and the ‘Golden Rule’. Green Deal loans exhibit Interest rates of 7% and above – higher than commercial unsecured loans at around 6-7%, and significantly higher than secured loans (mortgages) at around 3.5% (Rosenow *et al*, 2013). Research indicates that in the UK, homeowners are significantly more likely to take on Green Deal loans at interest rates of below just 3% (Ipsos MORI, 2011). The length and total loan value is determined by the ‘Golden Rule’, which states that loan repayments (including interest payments, plus an initial £63 fee and a £20 annual fee) should not exceed the value of monthly energy cost reductions (as described, the central pillar of a PAYS instrument). The calculated energy and costs savings induced by the introduction of approved efficiency measures are based on a 'typical' household (UK Parliament, 2014), which may thus, and coupled with uncertainties in energy prices, over- or under-estimate savings to meet the golden rule for any individual building, and thus the measures and loan value available. This also applied to the provision of a PAYS instrument used to provide capital costs for renewable installations. However, it is reasonable to suggest that a PAYS instrument would be much less successful in deploying renewables under a 'Golden Rule' proviso, particularly in the absence of dedicated support mechanisms.

The second set of barriers surrounds communication and trust issues. Principally, it appears that there is confusion surrounding how the mechanism itself operates, including what benefit the Green Deal offers, and how it is linked to the property and dependant on future fuel prices. ACE (2013) found this to be a common issue with PAYS instruments. Misrepresentation of the potential costs and benefits of the loan, particularly surrounding the Golden Rule[70] coupled with miss-selling by 'rogue traders' has been relatively significant – both of which led to negative press coverage, further reducing clarity and trust in the instrument (UK Parliament, 2014).

The third set of barriers is behavioural, and linked to those discussed previously. For example the 'hassle factor' appears prominent, along with the discounting of future benefits, and loan aversion - linked with the 'alien' concept of linking a loan to a property rather than an individual or company. Additionally, this was viewed as having a detrimental impact on the ability to sell or rent property (as discussed above, homeowners are likely only to implement measures if they believe it will have a positive impact on property value) (UK Parliament, 2014). Although this assessment of the Green Deal applies to the residential sector, the lessons are likely to be largely applicable to the commercial and public sector building stock; although there are likely to be some relatively minor differences (for example, research suggests that the commercial sector would find a slightly higher interest rate of 5% or below an attractive proposition for a PAYS loan) (Rosenow *et al*, 2013).

Additionally, it is likely that these lessons will remain broadly applicable across Member States. However, some differences between Member States may produce differences in potential effectiveness of a PAYS instrument. On the 'supply' side, it is likely that due to split incentives between energy suppliers and customers and the below-market interest rates, utilities and private sector funders will not be a significant source of funding. Therefore, it is likely to be the public sector that provides finance, with associated budgetary issues. This may limit loans available, for example per building (as with a limit on £10,000 per household under the UK's Green Deal), preventing investment in potentially cost-effective measures with high capital cost, such as solid wall insulation. This may be at least partially solved in a

[70] A DECC Spokesperson was quoted that 'no one can borrow more than they will pay back in energy savings, so no one will lose money by taking out a Green Deal loan'. However, this is not guaranteed (UK Parliament, 2014).

scenario where the EU becomes increasingly centralised, where new or existing funds may be employed (structural and investment funds, for example, or EU ETS revenues) in a centralised instrument operated at an EU level, or used to fund regional or Member State level instruments. On the 'demand' side, whilst the introduction of an increasingly high carbon price (which is likely to increase heating fuel and electricity prices substantially in most Member States overtime), coupled with tax incentives for HELC products, is likely to improve the economics for many efficiency measures an efficient products over time from a PAYS perspective, there is significant difference in energy efficiency potential between Member States across all sectors, with different measures appropriate to realise that potential (e.g. increasing insulation and heating system efficiency in colder climes, and air conditioning in warmer climes). Therefore, loans made against pre-approved technologies and measures must be appropriate to the Member State, region and sector in question. This requires frequent review as costs and technological characteristics of 'approved' technologies change over time, and as new technologies become available. Whilst the rollout of smart meters and smart grids may help reduce the magnitude of over- and under-estimated efficiency potential and loan repayments, energy price uncertainty and building stock heterogeneity will mean this remains a persistent phenomenon, allowing for under-realised efficiency gains on one side, and dissuading clients from taking part in a PAYS instrument on the other.

The public sector, as discussed above, must have the ability to receive a loan. In the private sector, application and assessment procedures must be simple enough to not constitute a barrier for households and (particularly small) commercial enterprises. Additionally, the loan recipient must be credit-worthy. This may prevent low-income households (particularly in the rented sector), for example, from participating.

Yet further differences and potential barriers remain. As with other instruments, spatial planning restrictions may prevent deep renovation from occurring in some jurisdictions or types of building stock. Substantial alterations may be required to utility or other tax collection or billing systems, tax codes and energy-related legal structures. The knowledge and capacity of the local supply chain, including the building trade, may place a bottleneck on the ability and speed at which measures may be installed, and the quality of installation.

3.2.4 Transport

Table 4 presents a brief summary of the policy instruments proposed for the 'transport' sector under the 'market-based' policy pathway. The EU ETS is expanded to cover road transport fuels. Other pricing instruments are introduced and amended to alter the economics of purchasing and operating high- and low-carbon vehicles. Existing **CO_2 Intensity Regulations** for passenger cars and LGVs remain (discussed under Section 3.3.4), as does **CO_2 Labelling** of passenger cars (discussed under Section 3.4.4)

Table 4 - Market-Based Policy Pathway - Transport

Policy Instrument	Description
EU ETS	The EU ETS is substantially reformed to produce a robust, increasing price over time, along with scope increasing to the road transport sector. The 'energy' component of the revised ETD is also applicable.

'Feebate' Registration Tax	A registration tax system in which vehicles of high-CO_2 intensity must pay a fee, and low-CO_2 intensity vehicles receive a rebate. Applicable to all road vehicle types.
CO_2-Graded Circulation Tax	Circulation/ownership taxes are introduced for all vehicles, based on CO_2 intensity
Reform of Company Car Taxation Rules	Company Car taxation rules are amended to ensure current distortions are reduced and incentives for AFVs over conventional vehicles are heightened for both organisations and employees.
Urban Low CO_2-Emission Zone Charging	A CO_2-intensity based charge is applicable to all vehicles entering designated large urban areas

EU ETS

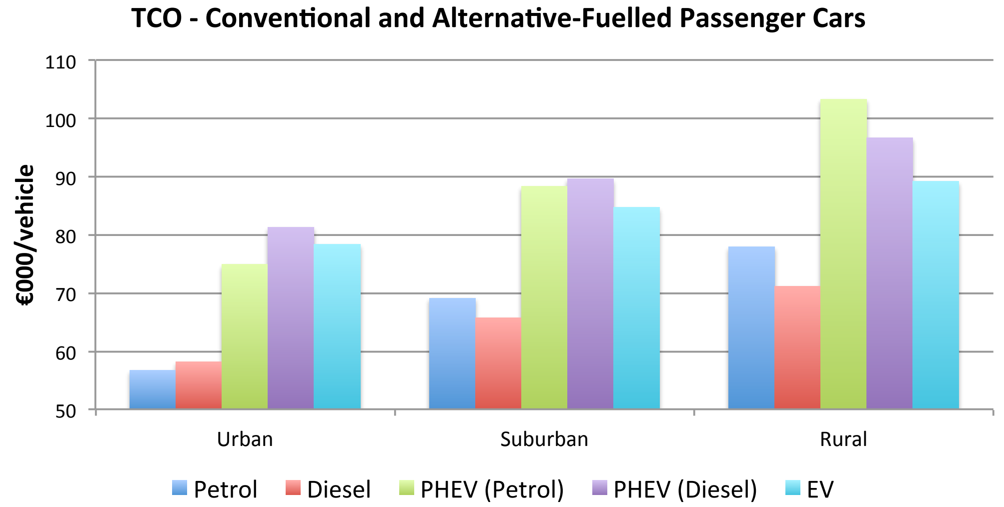
The inclusion of road transport CO_2 emissions into the EU ETS would expand EU ETS coverage to around 70% of EU emissions released in 2012. The point of obligation could be with the fuel supplier, which would be required to surrender allowances corresponding to the volume of fuel sold and the resulting CO_2 emissions from combustion of that fuel by the end user (equally, the point of obligation could also be further upstream, at the point of production or import). Under this pathway, it is assumed that such a sector expansion could occur at the beginning of the EU ETS Phase 4 (2021). Appropriate reforms to the EU ETS under this policy pathway, along with appropriate carbon price levels (and issues with achieving, maintaining and predicting this), are discussed under the power sector, above (Section 3.2.1).

In order to determine how effectively inclusion under the ETS can drive decarbonisation in the road transport sector, the project change in fuel price as a result of the projected minimum carbon price requirements (discussed under the power sector) must be determined. At a carbon price of €75/tCO_2 in 2030, the cost of supplying diesel and petrol in the EU, and if 100% pass-through is assumed, the price of purchasing diesel and petrol increases by €0.20/l and €0.17/l, respectively. In 2050, at a carbon price of €250/tCO_2, this increases to €0.67/l and €0.58/l, respectively[71]. The weighted average EU diesel and petrol prices between January 2005 and January 2015 were €1.24/l and €1.37/l. As such, if this average value were to be maintained to 2050 (in real terms), prices in 2030 for diesel and petrol would increase by 16% and 12% respectively, and in 2050 by 54% and 42%, respectively.

As with previous sectors, an initial requirement for the penetration of low-carbon infrastructure under a market-based paradigm is positive economic benefit to the actor in question. Figure 21 illustrates the estimated EU-average total cost of ownership (TCO) of conventional and alternative-fuelled vehicles (AFVs) medium-sized passenger cars used in urban, suburban and rural locations[72].

[71] Assuming CO_2 intensity values of 2.68kgCO_2/l (diesel) and 2.31kgCO_2/l (petrol).
[72] With mileage assumptions of 8,000km/year (urban), 15,000km/year (suburban) and 15,000km/year (rural).

Figure 21 - Total Cost of Ownership - Conventional and Alternative-Fuelled Passenger Vehicles (Source: Maca *et al*, 2013)



As illustrated in Figure 21, under the existing policy landscape and with certain assumptions[73], conventional petrol and diesel vehicles hold the lowest lifetime cost in all situations (with diesel lower for suburban and rural use, due to higher fuel efficiency negating the slightly higher fuel price discussed above[74]) EVs are the lowest cost on a TCO basis of the AFVs in all situations, with PHEVs (both petrol and diesel the highest cost in all scenarios (except PHEVs in an urban setting, with a lower TCO than EVs). An additional carbon price burden of €250/tCO_2, *ceteris paribus*, means an increase in TCO for both petrol and diesel vehicles of around 10% in urban areas, 15% in suburban areas, and around 20% in rural areas. The change in TCO for EVs due to 'fuel' price changes depends on the design of the electricity market (and pass-through of the equalised carbon price applied to the power sectors), whilst changes to the TCO of PHEVs (both petrol and diesel) depends on both on electricity retail prices and the division of labour between the combustion engine and electric drivetrain. However, as discussed under Section 3.5, it is likely that electricity retail prices will increase. One effect of a fuel price increase is a reduction in transport demand. Whilst such an impact is not the focus of this report[75], it serves to reduce relative TCO values – with vehicle types with fuel costs as a higher proportion of TCO (such as conventionally fuelled vehicles) generally experiencing a larger effect. This means that the application of a carbon price of €250/tCO_2 to transport fuels, *ceteris paribus*, is unlikely to increase TCO for conventionally fuelled passenger cars above that of AFVs, and thus not encourage a significant shift.

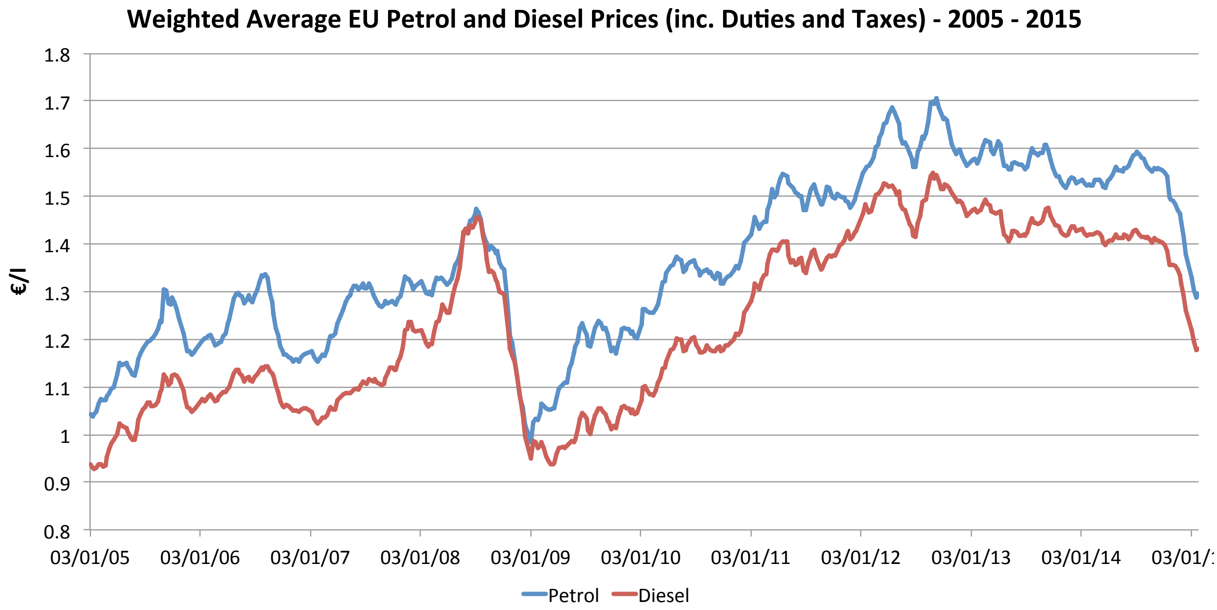
Whilst the above discussion concerns passenger vehicles, similar conclusions are likely to apply to LGVs and HGVs. However, fuel costs are likely to represent a higher proportion of the TCO for such vehicles, with elasticity of demand (by the nature of their use) likely to be

[73] In addition to those highlighted in Footnotes 72 and 74, key assumptions include a 14 year vehicle lifespan, no residual value, and a 3% discount rate. See Maca *et al* (2013) for more information.
[74] 96l/1000km for petrol, and 67l/1000km for diesel (Maca *et al*, 2013).
[75] See Maca *et al* (2013) for a review of elasticities for private transport.

lower[76], meaning a greater relative reduction in TCO between conventionally fuelled vehicles and AFVs than passenger vehicles.

Two key issues may further reduce the significance of the carbon price signal implicit in diesel and petrol prices, to operators of all vehicle types. The first is fuel price volatility. Figure 22 illustrates the range of weighted average petrol and diesel prices in the EU between 2005 and 2015.

Figure 22 - Weighted Average EU Petrol and Diesel Prices (Inc. Duties and Taxes - 2005 - 2015 (Source: European Commission, 2015c)



It is clear there has been significant volatility in weighted average prices over the last decade, largely driven by trends in oil prices, with the differential between peak and trough prices at €0.62/l for diesel, and €0.72/l for petrol. These ranges are of the same magnitude or larger than the additional cost of carbon pricing in 2030 (in particular) and 2050, meaning that it is possible that the impact of even substantial carbon pricing may be negated entirely by the underlying volatility in oil prices. However, petrol and diesel prices are also heavily dictated by taxes and duties levied. Figure 23 and Figure 24 illustrate petrol and diesel prices across the EU28 in January 2015, and the contribution by taxes and levies to these values.

[76] Although, very little literature has been produced on elasticities of the commercial road freight sector (Goodwin *et al*, 2004).

Figure 23 - Petrol Prices in the EU - January 2015 (Source: European Commission, 2015c)

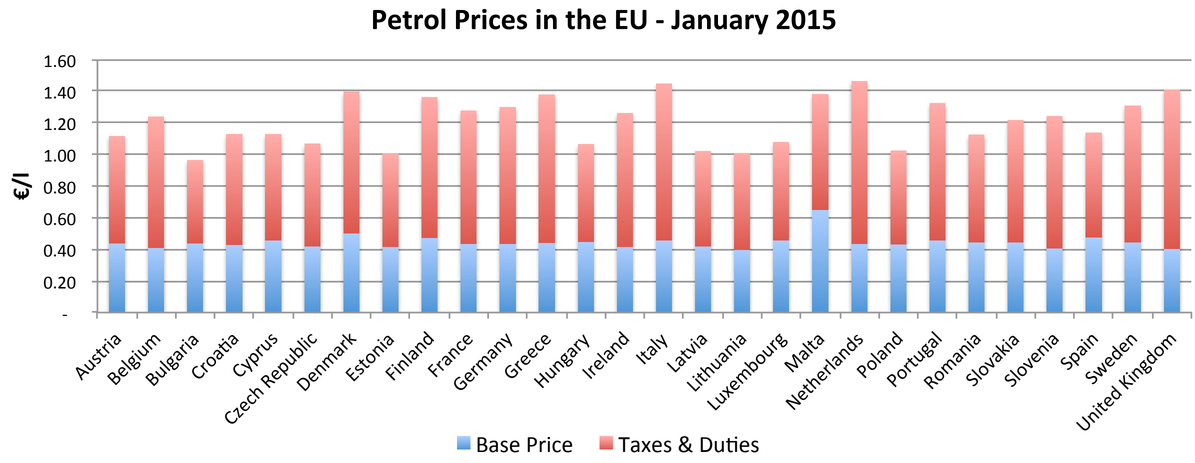
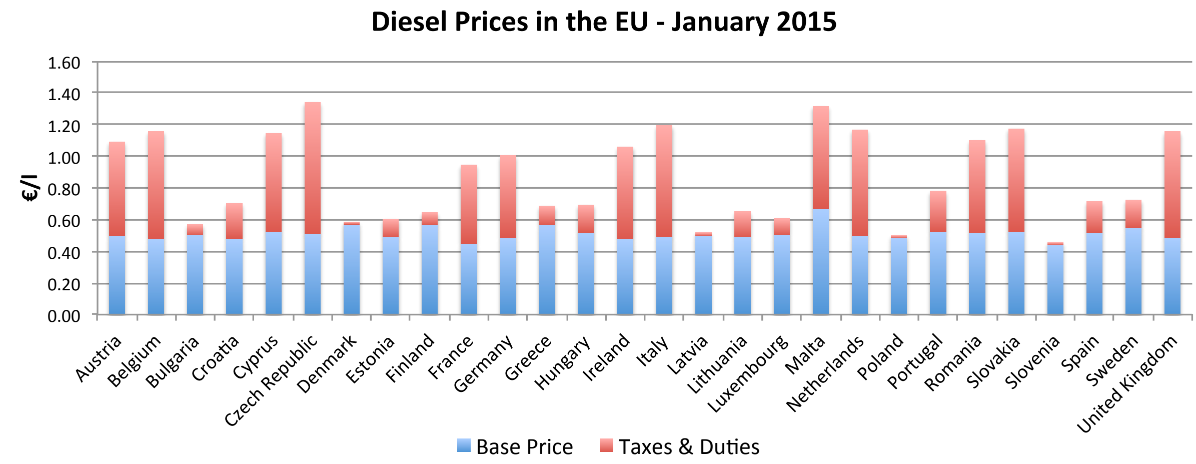
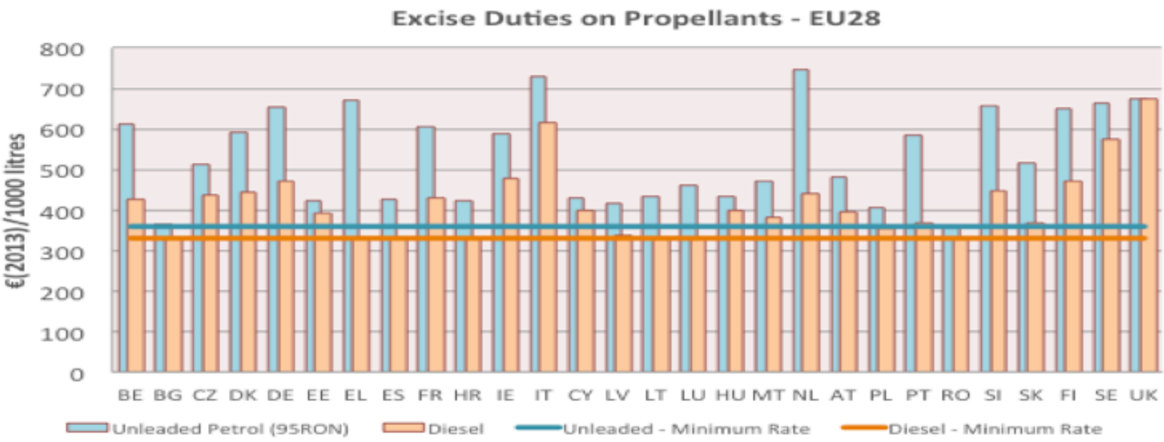


Figure 24 – Diesel Prices in the EU – January 2015 (Source: European Commission, 2015c)



In January 2015, the taxes accounted for between 53% (Malta) and 71% (UK) of total petrol prices, and between 3% (Denmark) and 62% (Czech Republic) for diesel. This may produce the second issue; whilst such taxies and levies are not the key driver for the price volatility indicated in Figure 22, each Member State may compensate for the additional carbon price burden by reducing taxes and duties. Although, as illustrated by Figure 25, the potential for levy reduction depends on the extent to which each Member State levies of taxes and duties above minimum mandatory requirements for transport fuels. Under this pathway, it is assumed that the 'energy' component of the revised ETD (described in Section 3.2.3) is applicable to road transport fuels, but set at the current minima, as illustrated in Figure 25.

Figure 25 - Excise Rates on Petrol and Diesel in the EU28 (Source: DG TAXUD, via Maca *et al*, 2013)



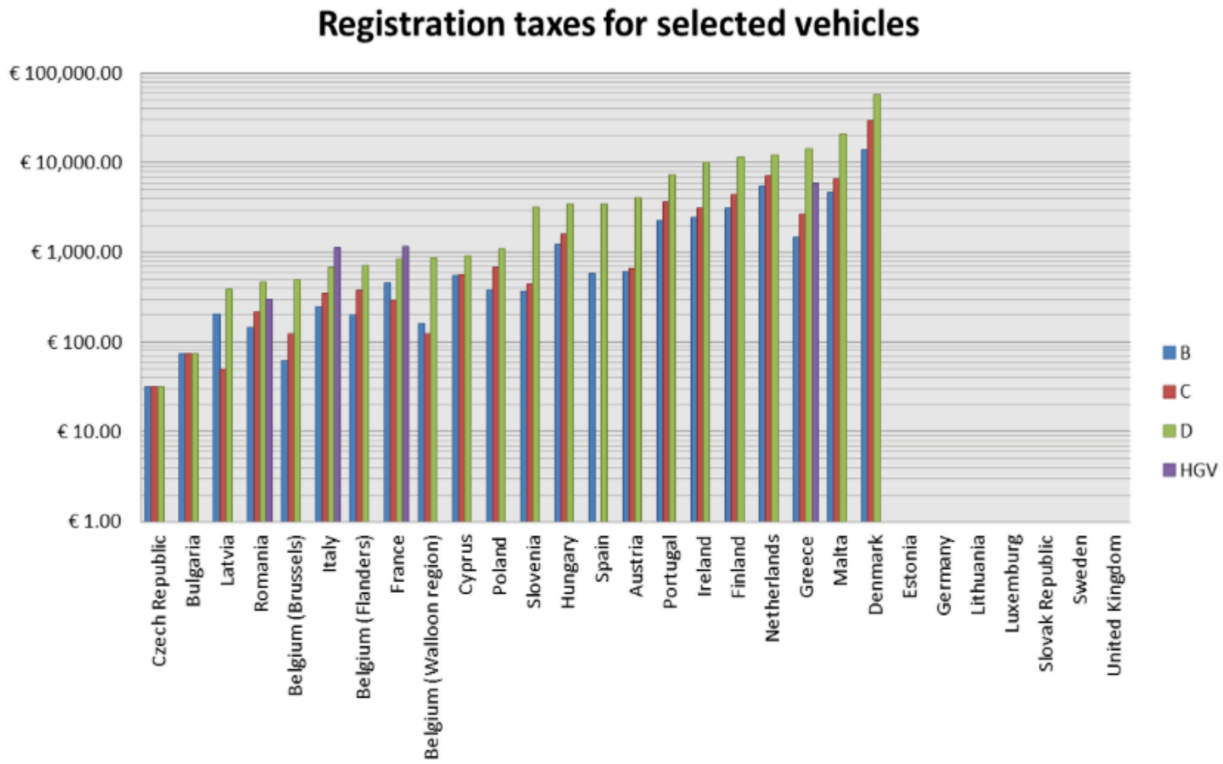
If price differentials remained in place between Member States, incidences of arbitrage (fuel tourism), in which actors seek to minimise costs by purchasing fuel in Member States where it is cheapest (i.e. the lowest taxes and duties), would remain. Whilst most related literature addresses the occurrence of fuel tourism with international commuters, transit traffic and individuals living close to international borders (a small proportion of total EU passenger transport), it is likely that international commercial freight (HGVs), which is likely to account for a significant proportion of the total EU HGV fleet, also plan refuelling stops to take advantage of price differentials (Maca *et al*, 2013). This acts to further reduce the carbon price signal.

As with other sectors, other variables and complications remain. Whilst flanking instruments such as those discussed below may influence the status and development of other components of the TCO components, other components, such as capital costs, may alter independently of any direct policy-related guidance. Such developments may alter the TCO calculation in a relatively unpredictable manner over time. However, issues outside the TCO calculation may remain. For example, the availability of finance to cover capital costs, which are higher for AFVs than conventional vehicles (and are likely to remain so for the foreseeable future), may also present a barrier to uptake. The presence of enabling infrastructure (such as electric charging) is likely to vary been urban and rural areas (as discussed in Section 2.5), influencing suitability of non-conventional vehicles (and particularly passenger EVs), in different areas. For all AFVs (but for passenger vehicles in particular), issues such as technological acceptance and range anxiety may also present barriers. Such issues are likely to vary by regions and by Member States.

'Feebate' Registration Tax

Registration tax is an upfront tax levied on a vehicle when it is first purchased and registered. Registration taxation systems across the EU are heterogeneous, with different Member States determining the value levied based typically on a single or combination of vehicle characteristics such as fuel type, engine size, weight, power, age, value, or environmental characteristics such as CO_2 and other pollutant emissions (Hermsen *et al*, 2003**). Figure 26** illustrates registration taxes applicable across the EU for passenger cars and HGVs (on a logarithmic scale).

Figure 26 - Comparison of registration taxes in EU Member States for selected vehicles (for 2012); B=Small cars, C=Medium cars, D=Large cars, HGV= Heavy Goods Vehicles (Source: van Essen *et al*, 2012)



As illustrated in Figure 26, 20 of the EU27 Member States apply a registration tax (or variant thereof) to at least some proportion of the road vehicle fleet[77], albeit with very significant variation in value. Registration tax mostly applicable for passenger vehicles only, with commercial freight vehicles (HGVs) only subject to registration tax in 6 Member States (Denmark, France, Greece, Italy, Malta and Romania), and even then exemptions or reductions often apply[78]. In France, Italy and Romania, the tax is based primarily on engine power, while in Greece is based solely on the vehicle's value. 14 Member States consider CO_2 emissions in their levy on passenger vehicles, with 6 holding CO_2 as one of two parameters (with the other often vehicle value). None of the 6 Member States that apply a levy to HGVs considers CO_2 emissions as a parameter.

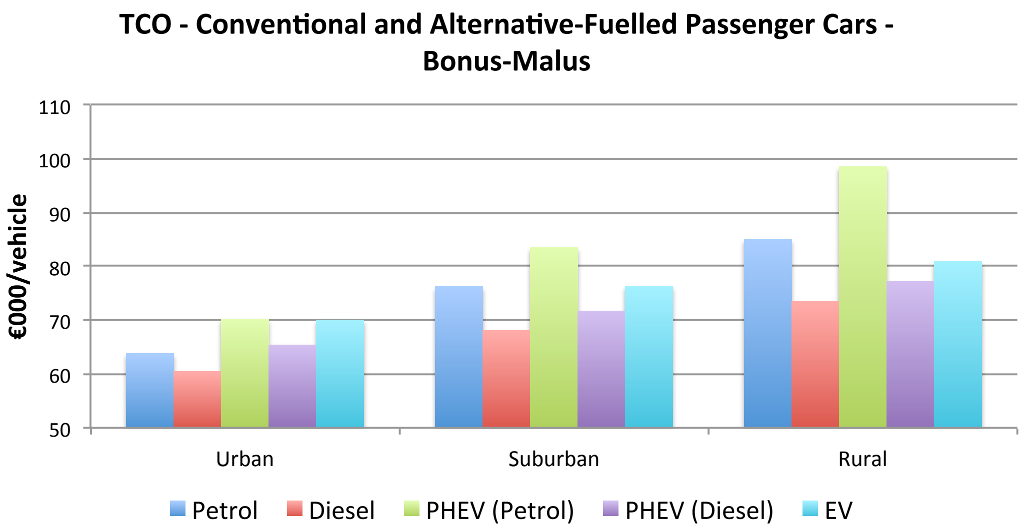
Under this policy pathway, a 'feebate' system, centred on CO_2 emissions, is introduced across Member States and all vehicle types (both private and commercial). A feebate, a combination of and contraction of the words 'fee' and 'rebate', offers a rebate to purchasers of low-emission vehicles but levy a fee on purchasers of high-emission vehicles (Adamou *et al*,

[77] At the time of the survey in 2012, Croatia was not an EU Member State. Additionally, the UK now levies a flat rate of £55 per vehicle upon registration.

[78] e.g. Denmark (exemption for freight vehicles with GVW over 4,000 kg, and buses) and Malta (tax level for class N3 vehicles of one of the two most recent EURO classes equal to zero) (DG MOVE, 2012)

2014). Figure 27 illustrates the impact on passenger car average TCO under the French 'Bonus-Malus' feebate system[79]

Figure 27 - Total Cost of Ownership - Conventional and AFV Passenger Cars - Bonus-Malus (Source: Maca *et al*, 2013)



Compared with Figure 21, it is clear that the TCO of (medium-sized) conventionally fuelled vehicles increase, whilst AFVs (partcularly EVs), decrease, as would be expected, across all usage categories. Whilst the differential between the TCOs of different vehicle types decreases substatially compared to those illustrated in Figure 21, the relationship between them remains largely static within and across usage types. The only significant difference is with diesel PHEVs, which reduces in TCO second only to conventional diesel vehicles in rural and suburban areas, and experiencing the lowest TCO of any AFV in an urban setting. EVs also achieve a TCO below petrol vehicles (both conventional and PHEV) in a rural and suburban setting. The trends illustrated in Figure 27 also largley hold for small and large passenger cars (Maca *et al*, 2013). A combination of a feebate instrument aligned with the French system (pre-2014) with the a successully applied EU ETS in the transport sector would likely mean that, *ceteris pariubs*, EVs exhibit the lowest average TCO across all three usage types, certainly by 2050 (at a price of €250 /tCO_2), and possibly by 2030 (at a price of €75/tCO_2). However, this depends significantly on the level of the fee and rebate applied (and the access criteria for vehicles), the carbon price being achieved and being additional (with uncertainties discussed above), and the evolution of other cost components of a TCO calculation (particualrly underlying captial costs). Again, although this analysis concerns passenger cars only, similar dynamics are likely to be present for LGVs and HGVs in the presence of both carbon pricing and a feebate scheme. However, the extent to which relative TCOs of different propellant technolgoies alter in the presence of these instruments are not further examined here for these vehicles.

[79] Pre-2014 values, which range from a €7,000 rebate to a €6,000 fee. All other assumptions as given in the commentary around Figure 21 remain.

Member States may design the feebate to be revenue neutral, either entirely (such as in Member States that currently levy no registration tax), or compared to non-zero rates (in Member States that rely on the income generated from existing registration levies) (Gallagher and Muehlegger, 2011). Similarly, the specific design (e.g. vehicle classfications, fee/rebate banding), may vary between Member States, altering specific TCO values and producing uneven incentives across the EU. A centralised system, permitted by a more federalised EU, may overcome this issue.

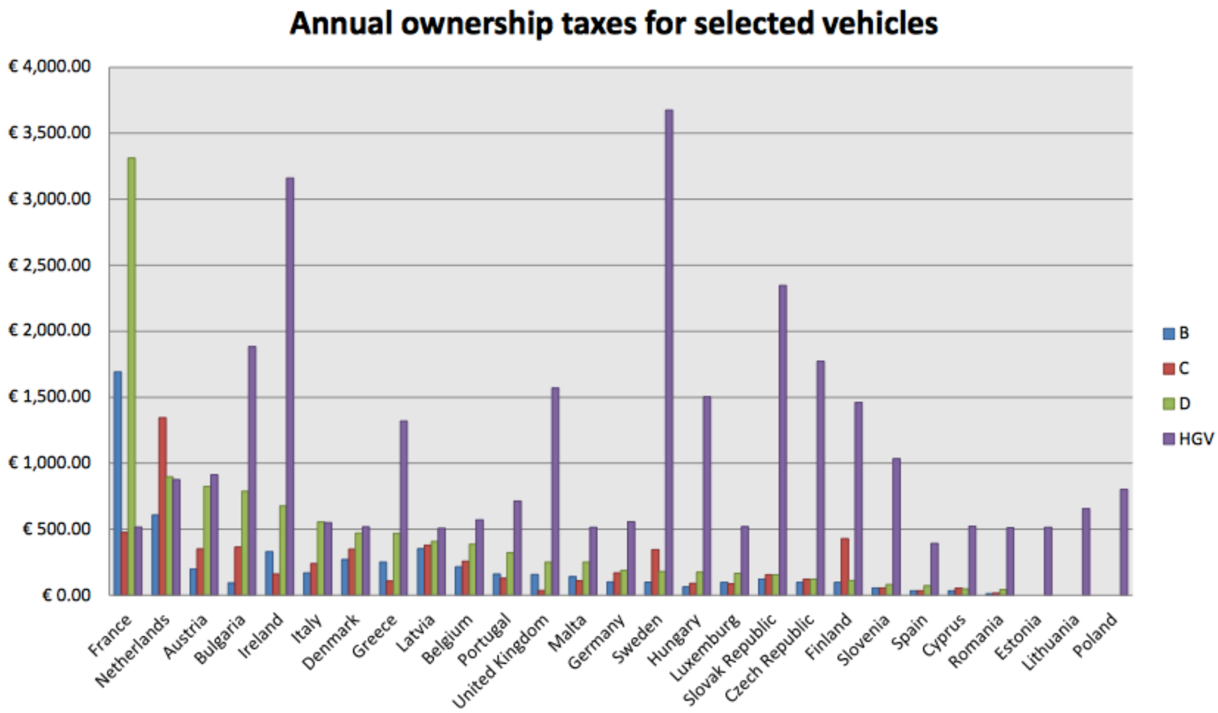
As a feebate system addresses captial cost issues, it reduces associated barriers (such as discounting and availability of finanace), that instruments acting on fuel price and other long-run costs address less adequately (however, the feebate may still have relatively little impact on total captial costs of a vehicle, depending on design, and thus these issues may still be significant). By targeting the instrument directly at the consumer rather than the producer, the behavioral response is likely to be stronger, as information asymetteries are also reduced (Busse *et al*, 2006). These characteristics make a feebate system a potentially highly effective instrument in decarbonising the road transport sector in the long run (Maca *et* al, 2013). Indeed, the French bonus-malus system induced a significant shift in the sales profile of passenger cars to low-emission vehicles, despite it consitituting only a moderate proportion of vehicle list prices. However, it also acted to increase total vehicle sales by around 13% (with total vehicle stock increasing) therefore potentially having realtively little impact on total emissions (and potentaially negative) (D'Haultfoeuille *et al*, 2013). Whilst an increasing carbon price on transport fuel coupled with other flanking instruments (discussed below) may dampen this phenomenon in a market-based policy pathway, it remains a potential side-effect.

Additionally, this instrument may be applied to new vehicles only, and is unlikely to have a significant impact on the second-hand market in the short term. However, as the entire passenger car fleet is replaced approximately every 15 years, over this time the fee or rebate will increasinly feed through to vehicle reasale values, influencing second hand vehicle choices. Based on the existing prevelance of the second hand market in overall vehicle sales in different Member States, the effect is likely to be felt more rapdily in Western Europe (Maca *et al*, 2013). Again, flanking measures (including carbon pricing and other pricing measures, discussed below), are likely to speed up this process in all regions. However, again, this instrument does little to overcome non-cost barriers to AFV uptake (range anxiety, etc.)

CO_2-Based Circulation Tax

A circulation (or ownership) tax is a levy incurred by the owner to allow the use of a vehicle on public roads, the frequency of which (quarterly/biannual/annual) varies by Member State. All Member States levy one or more forms of periodic circulation tax, although contrary to registration taxes, HGVs are subject to this form of taxation in nearly all Member States, and to significantly higher levels. Figure 28 illustrates circulation taxes as currently applied across the EU.

Figure 28: Comparison of ownership taxes in EU Member States for selected vehicles (for 2012) B=Small cars, C=Medium cars, D=Large cars, HGV= Heavy Goods Vehicles (Source: van Essen et al., 2012)



Circulation taxes are most often levied based on engine size/power and CO_2 emissions for passenger cars (12 Member States), with 6 Member States considering CO_2 emissions as the only parameter. For HGVs, GVW (Gross Vehicle Weight), in many cases combined with the vehicle's axle configuration and suspension type, is considered. Currently, no Member State considers CO_2 emissions in circulation tax rates for HGVs. Vehicle value is not applied for circulation taxation. Under this policy pathway, circulation taxes are applied across all Member States based on (direct) CO_2 emissions as the primary (or sole) factor, to all vehicle types (both private and commercial).

As with the EU ETS on transport fuels and a feebate registration tax, a circulation tax framed against CO_2 emissions will positively alter the relative TCO of conventional and alternative vehicles. As with a feebate system, although the impact on TCO depends on the specific design of the tax (band definitions, taxation levels and differentials between them) (UK DfT, 2003), and in opposition to the carbon price experienced, it is a fixed cost with little future uncertainty against which decisions may be made. However, like fuel costs but unlike a feebate system, it produces costs or savings over time, meaning it is subject to discounting and thus of reduced importance compared to an instrument that influences upfront costs and tackling issues of access to finance. However, as a circulation tax applies to all vehicles, the existing fleet and the second-hand market is influenced directly. As such, it may act to prevent the delay in the price signal generated by the feebate from reaching the second-hand market, and curb the potential for an increase in overall vehicle sales as experienced in France (discussed above). Therefore, although the influence of a CO_2 graded circulation tax is likely to be relatively minor compared to a feebate instrument, it is likely to be a useful complementary instrument. Although, other existing barriers, discussed above, remain.

Reform of Company Car Taxation Rules

Whilst the rules surrounding the taxation of company cars varies by Member State, they often act to dull the influence of market-based instruments acting on passenger cars. In all Member States, a company car is bought by the employer for use by the employee, who declares the vehicle as an in-kind benefit as part of taxable income. How the value of this in-kind benefit value differs (e.g. a proportion of catalogue price, assumed split between business and personal use, or another standard rate). Costs related to insurance, maintenance, repair and other taxes are covered by the employer, but typically not factored in to the calculation of the taxable in-kind benefit. Fuel costs are also commonly covered by the employer, which is often, alongside the costs of maintenance, insurance and other taxes, plus the purchase price of the vehicle itself, VAT deductible. Additionally, as the employee receives the vehicle as an in-kind benefit substituting for a proportion of forgone salary, social security and other related taxes levied on income, which are paid by both the employer and employee, are not due (Maca *et al*, 2013).

As such, the purchase of a company car is financially beneficial to both the employer and employee; with the incentives each is faced with distorted. For example, the employee has no need to consider the fuel efficiency of the vehicle they are receiving, as they are not bearing the cost of the fuel (which also reduces incentives to reduce vehicle use). Whilst the employer has an incentive to reduce fuel costs (via a more efficient vehicle), it is also incentivised to choose a vehicle with high capital costs, to maximise the benefit of reduced taxation. These incentives are evident in the size and make up of the company car fleet. Around half of all new car purchases in the EU are company cars (Copenhagen Economics, 2010), and higher in some Member States (e.g. 70% in Germany (Federal Motor Transport Authority, 2013)). The market is also heavily skewed towards larger, more powerful and even luxury vehicles. For example in Germany, over 85% of 'high-end' vehicles are sold as company cars, with some luxury models exclusively registered as company vehicles (Federal Motor Transport Authority, 2013). Consequently, CO_2 intensity is, on average, higher than for private vehicles (Maca *et al*, 2013).

In this policy pathway, company car rules across the EU are amended along the lines of the reforms implemented by the UK and Belgium. In both cases, the taxable proportion of the in-kind benefit is related to the CO_2 intensity of the vehicle (e.g. the higher the CO_2 intensity, the higher the rate of tax levied), and at least part of the fuel received must be declared as taxable income. As such, the employee bears increasing costs for more CO_2 intensive vehicles, reducing their attractiveness as an in-kind benefit (and impacting incentives for vehicle use once purchased) (Copenhagen Economics, 2010). The change in incentives depends on the specific configuration of this reform, as it likely to be different between Member States.

Evidence from the UK suggests that such reforms are effective in reducing CO_2 intensity of company cars, where average CO_2 intensity decreased quicker than passenger cars bought for private use after reforms were introduced (Veitch and Underdown, 2007). It also suggests that the company car market may respond to market conditions faster than the private car market (Maca *et al*, 2013). As these reforms also allow the price signals generated by the other instruments discussed in this policy pathway to operate on all, rather than only the private, share of the EU's passenger car market.

Low CO_2 Emission Zones

Low Emissions Zones (LEZs) are designated areas in which vehicles are required to pay a charge to enter, based on emission intensity of a given pollutant (often local air pollutants). Under this policy pathway, large urban areas across the EU introduce LEZs applicable to both private and commercial vehicles (passenger cars, LGVs and HGVs), with the fee payable based on CO_2 intensity.

Li and Hensher (2012) describe the effects on car use and profile resulting from four existing congestion-charging schemes in London, Stockholm, Milan and Singapore. Whilst congestion charges often aim to internalise non-CO_2 related externalities (such as congestion and local air pollution, with CO_2 abatement as a secondary benefit), the mechanism itself is comparable (with the London congestion charge, for example, providing a charge exemption for cars or vans with a CO_2 intensity of 75gCO_2/km or below), and thus able to provide broad lessons for a CO_2-focussed instrument. It is clear that the most significant impact of the instruments reviewed is a reduction in the number of vehicles (passenger cars, in this analysis) entering the affected zone coupled with a broad modal shift to public transport (Li and Hensher, 2012), rather than a broad shift in average emission intensities (in systems that differentiate by pollutant intensity)[80]. However, Borjesson (2012) found that the exemption experienced by alternative-fuelled vehicles from the Stockholm congestion charge led to a substantial increase in the sales of AFVs.

The cost imposed is clearly most linked to the TCO of urban-use passenger cars illustrated in Figure 21 and Figure 27. Although such road pricing mechanisms appear to influence vehicle use more than vehicle choice, the specific effect will vary across each instrument depending on particular design details (including cost, band differentiation, time of application, whether the charge is proportional to time or a flat daily rate, etc.), and contextual issues, such as the availability of alternative transport (i.e. public transport) and the elasticity of travel demand to and within the urban area concerned. Overall, the impact on driving a shift in passenger cars from conventional to AFVs is likely to be marginal when employed in parallel to the instruments described above, particularly for passenger cars for rural and suburban use, but also largely to urban use vehicles.

Due to the relatively inflexible nature of goods transport (goods must still reach their final destination, with limited alternative transport options in urban areas), it is likely that operators of LGVs and HGVs would be subject to an increased incentive to reduce the CO_2 intensity of their fleet from the introduction of an LEZ mechanism. However, again, the extent to which this is the case depends on specific design of the instrument (for example,

[80] The evidence is mixed on whether traffic is to some extent displaced to outside of the affected zone (Li and Hensher, 2012).

the incentive is greatly reduced if the instrument does not apply at night, to which goods transport may often be shifted to some degree, to avoid additional cost).

3.2.5 Summary of the Market-Based Policy Pathway

This pathway principally employs equalised carbon pricing applied across all sectors and fuels through the EU ETS and ETD in order to drive investments in low-carbon infrastructure, flanked by other economic instruments designed to correct or improve otherwise unfavourable market conditions. Similar dynamics and issues appear across the sectors in this pathway. Even if the desired carbon prices are produced by the EU ETS (in particular) and the ETD, significant uncertainty surrounds their likely effect. This is a result of two factors. The first is the influence, primarily, of underlying fossil fuel prices, which may significantly or even entirely negate the influence of a carbon pricing instrument at both 2030 and 2050 levels (€75/tCO_2 and €250/tCO_2, respectively). Existing taxes and levies, along with inefficient energy production and consumption subsidies, may either be maintained or altered to either enhance or reduce costs. This produces significant uncertainty regarding total price signals and their development over time. The second factor is broader uncertainty surrounding relative costs between alternative options, driven in part by the issue above, but also by, for example, capital costs and developments in electricity prices (dependent on electricity market design). Combined, these factors broadly render the relative economics of different infrastructure options, and achievement of the infrastructure requirements established in Chapter 2, highly uncertain. Issues such as information failures, discounting of future costs and benefits and spatial planning and other authorisation procedures are likely to present further issues.

However, some differences are present themselves at the sector level. In the power sector, it is possible that a carbon price produced by the EU ETS may alone produce profile required by 2030 and 2050, however this is highly uncertain (due to the above-mentioned issues), with significant variation possible in terms of the types of capacity development, capacity distribution between Member States, and the development of centralised and decentralised installations. Similarly, the deployment of CCS in the industry sector is likely to be highly uncertain, along with the ability to produce significant gains in energy efficiency.

In this pathway, both the building sector and the transport sector remain subject to existing legislation (instruments that are the focus of and often strengthened in other policy pathways), that are likely to have an impact to which the instruments discussed in this pathway are additional. In the buildings sector, these are Building Energy Performance Standards, Energy Efficiency Obligations, Technology Performance Standards (all discussed under Section 3.3.3), Energy-Related Product Labelling and Building Energy Performance Certification (both of which are discussed under Section 3.4.3).

Although a revised ETD produces a substantial effective carbon price on heating fuels improves the economic conditions for substantial uptake and effectiveness of the to which the four primary instruments proposed under this policy pathway (see Table 3) (assuming a substantial effective carbon price is indeed produced), It is relatively unclear the extent they will produce additional progress toward the minimum infrastructure requirements for the building sector by 2030 and 2050. It is uncertain whether ESCos, even with improved operating conditions, will prove attractive to consumers. If they are, it is likely that their focus will be on the large commercial sector, with barriers such as high transaction costs, split incentives, 'hassle factor' and arrangements in public finances preventing a significant role in the public, residential and small commercial sectors. A PAYS instrument may complement an ESCo by providing finance for the 10% of projects that requires external finance, and by addressing these remaining sectors. However the alien concept of attaching a loan to a property rather than a (natural or legal) person, along with a wider loan aversion and credit-worthiness to receive it, and the apparent negative impact on building value (amongst others), may limit uptake. However, the initial assessments that both instruments require are essentially energy efficiency audits, as described in Section 3.4.3. As such, these instruments may act to reduce information failures and stimulate private investment in efficiency measures, outside of the intended financing mechanism, increasing their overall effectiveness. The rollout of smart meters is also likely to reduce information issues. Tax incentives for high efficiency, low carbon products will further alter the relative attractiveness of such products, and also further address upfront cost barriers. However, the extent to which this instrument is of consequence depends on the specific products addressed, and the level of incentive provided.

In the transport sector, it is likely that pre-existing CO_2 Intensity Regulations applicable to passenger cars and LGVs will meet the minimum requirements for both modes well in advance of 2050 (as discussed under Section 3.3.4). As such, it should be considered whether the instruments proposed under this policy pathway might allow for overachievement of these requirements. The use of a feebate registration tax (at a design similar to the French instrument) applied EU wide would likely have a significant impact of the relative TCOs between conventional and alternative vehicles, and as upfront costs are impacted, issues of access to finance and a psychological discounting of future savings are directly tackled. This, in combination with a CO_2-intenity graded circulation tax, would likely make AFVs (particularly diesel hybrids) more cost-effective than conventional vehicles (particularly petrol), relatively rapidly – particularly with decreasing AFV capital costs. As discussed, an effective carbon price at the levels discussed would further this cause, and make AFVs cost-effective in all regions of all Member States (rural, urban and suburban), and likely for all vehicle types (although such a conclusion is less certain for LGVs and HGVs). The reduction of market distortions caused by existing company car taxation rules would allow these price signals (particularly the carbon price) to feed through to all passenger car owners and operators, reducing the current attractiveness of 'luxury', high-CO_2 intensity models for use as company cars. Indeed, the removal of this market distortion would likely have this effect at existing fuel prices. As such, it is likely that the instruments proposed under this pathway would have an impact additional to the CO_2 intensity targets, and therefore exceed the minimum requirements for the road transport sector (particularly for passenger cars, but also for LGVs and HGVs). However, the use of these instruments in parallel to CO_2 intensity regulations employing a 'fleet average' approach may reduce the overall effectiveness of instruments individually. For example, the parallel use of other instruments simply allows manufacturers to reduce efficiency improvements to conventional vehicles, as progress towards the CO_2 intensity targets is made via indirect means (Anderson *et al*, 2011; McConnell and Turrentine, 2010).

3.3 Technology-Based Policy Pathway

3.3.1 Power Generation Infrastructure

Table 5 presents a brief summary of the policy instruments proposed for the 'power generation' sector under the 'technology-based' policy pathway. The EU ETS remains as the main economic instrument but it is complemented with CO_2 intensity standards for fossil fuel power plants and to continuation of renewable support mechanisms.

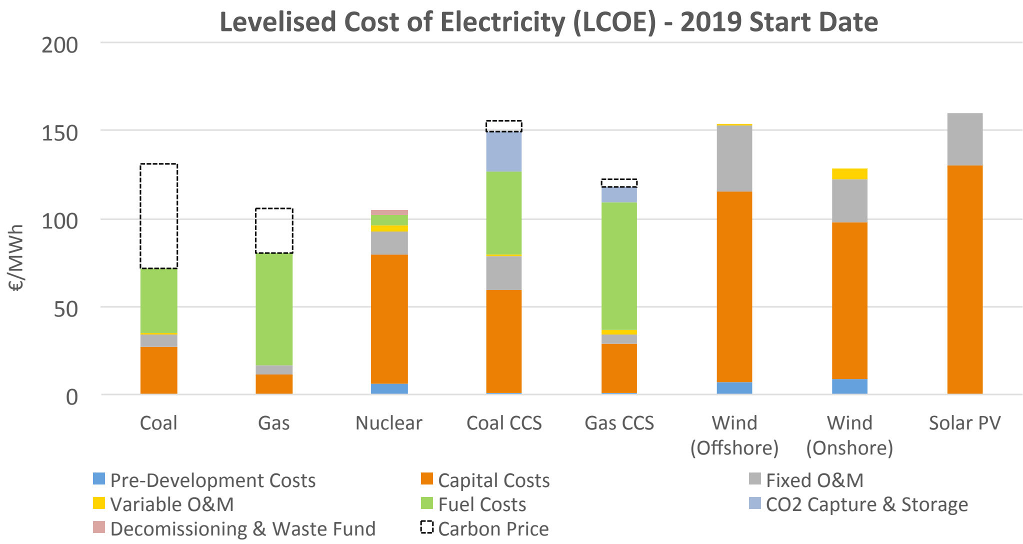
Table 5 - Technology-Based Policy Pathway - Power Generation

Policy Instrument	Description
EU ETS	The EU ETS is substantially reformed to produce a robust, increasing price over time (but less than the Market-Based Policy Pathway).
CO_2 Emission Intensity Standard	CO2 Emission Intensity Standards are applied to all new fossil fuel generation plants.
RES-E Support Mechanism	Dedicated RES-E support mechanisms are maintained

EU ETS

Under this technology-based policy pathway, the EU ETS remains a key cornerstone of low-carbon policy. Existing GHG and sectoral coverage is maintained to 2050, with only the Market Stability Reserve and Linear Reduction Factor achieved by way of reform (see Section 3.2.1 for a description of the EU ETS, its effects, and these reform proposals. However, under this pathway, the effects of parallel instruments must be considered when setting the details of such reforms). Whilst the EU ETS is strengthened compared to contemporary circumstances, its role is diminished compared to the market-based policy pathway. The combination of relatively minimal reforms and an increase in focus on non-market based mechanisms in EU ETS sectors (power and industry) is assumed to produce explicit carbon prices at around half those delivered by the market-based policy pathway, rising to a minimum of around €35/tCO_2 in 2030 and €125/tCO_2 in 2050. Figure 29 presents a revised version of Figure 16, with a carbon price set at €80/tCO_2 (an average value of a linear increase between 2030 and 2050 values).

Figure 29 - Levelised Cost of Electricity (Technology-Based Policy Pathway) - 2019 Start Date (Source: DECC, 2013; DECC, 2012b)



With the carbon price burden on fossil fuel generating plants approximately halved in magnitude compared to the values illustrated in Figure 13, relative LCO values alter relatively substantially. Unabated coal is now cheaper than solar PV (now the highest-cost option) and offshore wind (and approximately level with onshore wind), whilst gas CCS LCOE remains below renewable technologies. Nuclear is joined by unabated gas as the overall equal-least-cost options. As such, the carbon price produced under this pathway would not be sufficient to drive investment away from unabated fossil generation and towards renewable sources, either independently or above the requirements set by other instruments in this policy pathway[81]. However, all aspects of uncertainty and dependency discussed under Section 3.2.1 concerning carbon price predictability and exogenous developments (and the interaction with lead times), cost components and their developments and electricity market design (and associated impact on the development of centralised and decentralised generation), and differences between Member States, remain.

CO_2 Emission Intensity Standard

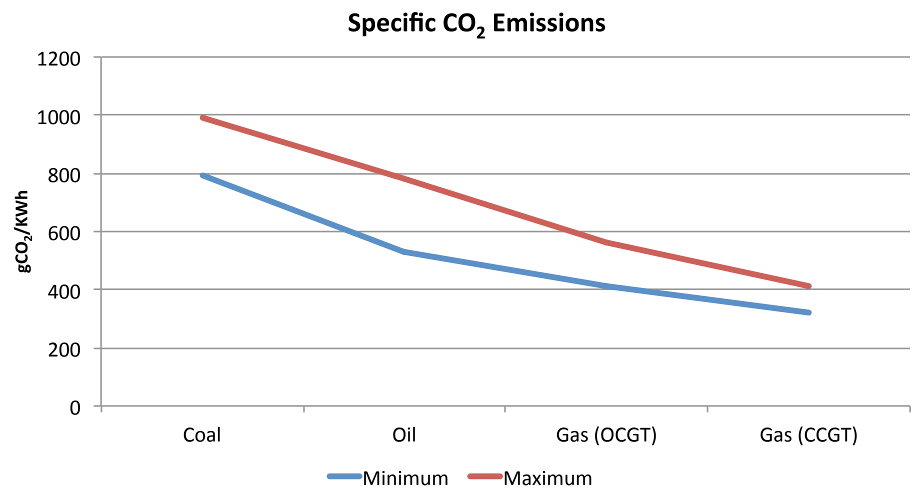
Emission intensity standards (EIS) may be applicable in the power sector to either new or existing generation, as a value of total emissions against total generation. Under this policy pathway, EIS on new generation capacity are introduced and applied at the plant level, modelled on the Emission Performance Standard (EPS) in the UK[82]. As described in Section 2.1, unabated coal should be entirely removed from the electricity generation mix by 2050, and constitute a minor proportion of generation by 2030. As such, given the average lifespan of a coal-fired plant is around 40 years, it would seem reasonable that an EIS should initially

[81] Fuel switching between fossil fuel capacities would likely be achieved, although this is not further examined.

[82] Introduced under the UK's Energy Act 2013, the EPS places a statutory limit of 450 gCO_2/kWh on new fossil generating stations in the UK.

be set, at a minimum, to prevent the construction of new unabated coal-fired installations. Figure 30 illustrates the minimum and maximum specific CO_2 emissions for different fossil-generating plants in the EU found in the literature.

Figure 30 - Specific CO_2 Emissions of Power Generation Technologies (Source: Steen, 2001)



According to the values presented in Figure 30, an EIS value of at least 600gCO_2/KWh (as an upper value) would be suitable in order to prevent the construction of new coal-fired installations. Both open cycle gas turbines (OCGT) and closed cycle gas turbines (CCGT), along with high efficiency oil installations, would be permitted. A decrease to a value of at least (maximum) 400gCO_2/KWh by 2030, which would prevent the construction of all but CCGT installations (which maintain a small but important share of the electricity mix, as discussed in Section 2.1) would also be appropriate. However, in practice, this reduction is likely to prove redundant. Only CCGT gas-fired installations are likely to remain a viable option for new non-coal fossil fuel construction (as OCGT LCOE values are around double that on CCGT (DECC, 2013), and oil-fired power plants, particularly with a carbon price such as that discussed above, have an extremely high LCOE compared to other options - in addition to other restrictions, such as air quality regulation). Whether an EIS is set at the EU level and applied equally across Member States, or whether Member states implement and determine appropriate levels, potentially depends on the level of policy centralisation.

However, even if an EIS (any level of stringency) is implemented immediately for new plants, it is possible that, in the absence of other influences, a high proportion of existing coal installations will still be online 2030, and a not-insignificant proportion may be present in 2050 (particularly those constructed within the last few years). Additionally, aside from effectively banning certain types of generation, an EIS does little to influence the profile of the capacity that is installed. For example, based on the LCOE values illustrated in Figure 29, coal and nuclear would remain the generation technologies of choice (*ceteris paribus*), over renewables and CCS technologies. An EIS also does not influence the generation profile from use of these new and existing installations - this remains determined by marginal generation costs, influenced by the EU ETS (and underlying fuel costs) – with total CO_2 emissions remaining under the EU ETS cap. Therefore, a EIS serves largely as a 'backstop' to the EU ETS (Bloomberg NEF, 2011), preventing additional lock-in of the highest-carbon power generation technologies, but not contributing to additional CO_2 abatement or significantly towards the power sector requirements outlined in Section 2.1.

RES-E Support Mechanism

RES-E Support mechanisms are instruments that act to alter the economics of renewable electricity technologies to attract investment and achieve deployment, by providing (or allowing for) returns that cover LCOE vales for the technology (or technologies) in question. Various support mechanisms have been, or are currently, in use across the EU. These generally fall into two categories; instruments that directly subsidise capital costs (such as direct grants, low interest loans and tax reductions or exemptions), or those that subsidise generation (such as quota obligations (often coupled with green certificates), tenders, contracts-for-difference, feed-in tariffs or premium tariffs). See Agnolucci and Drummond (2014) for a full description of each of these instruments[83]. All EU Member States (aside from Latvia) currently employ at least one form of support mechanism; with feed-in tariffs (FiTs) the most commonly employed primary mechanism (Agnolucci and Drummond, 2014).

Under this policy pathway, active support mechanisms are maintained. Whilst such mechanisms are responsible for the vast majority of RES-E deployment across the EU (Agnolucci and Drummond, 2014), the level of success each Member State has seen resulting from such support has been highly varied. This has been a function of the design of support mechanisms themselves, but also wider issues (discussed below).

Quota instruments and tenders, by their nature, determine the level of renewable electricity generation required over a given time period (usually as a mandated proportion of total supply, rather than absolute generation). Whilst this does not directly determine deployment, it requires suitable deployment to meet the level of generation required. Whilst FiTs and other price-based (rather than quantity-based) incentives do not directly determine deployment levels, they may include mechanisms that use market forces to heavily influence it (such as growth corridors[84]). Similarly, both instrument types may substantially influence the profile of this deployment. Quota and tendering systems may directly mandate the profile required (or influence it through market mechanisms such as green certificates[85]), whilst FiTs and other price-based instruments may set technology-specific rates (for which control mechanism, such as growth corridors, might be individually set). However, for either

[83] Except contracts-for-difference (CfDs). CfDs stabilise returns for generators at a fixed level known as the strike price. Generators receive revenue from selling their electricity into the market as usual. In addition, when the market price is below the strike price they also receive a top-up payment from suppliers for the additional amount. Conversely if the market price is above the strike price, the generator must pay back the difference (DECC, 2012c).

[84] Growth corridors involve defining the level of capacity a Member State would like to see installed over a given timeframe. If growth is in line with expectations, the normal tariff degression would apply. If capacity growth is lower than expected, the degression is reduced. If growth is higher than expected, tariff degression is increased (Agnolucci and Drummond, 2014).

[85] Certain technologies may qualify for different numbers of certificates.

approach, a significant determinant of success has consistently been policy stability (Agnolucci and Drummond, 2014).

Support mechanisms and their design provide different incentives and likelihood of encouraging centralised and decentralised installations. For example, FiTs are more likely to encourage the development of decentralised capacity (along with centralised), than quota mechanisms. They require no element of competition that would otherwise favour large, centralised installations, which (due to economies of scale, etc.) experience reduced LCOE (and are thus able to place lower supply bids in a quota system). Transaction costs are reduced, and relative certainty on returns is provided (which in turn allows for reduced cost of capital) (Butler and Neuhoff, 2008).

The appropriate form for the development of support mechanisms in the future depends on parallel developments, firstly in the level of centralisation of EU policy making. In a more federalised union, a single, centrally operated instrument (or combination of instruments) may be applied with equal terms across Member States. Broadly, and under a well-designed instrument (discussed below), this would allow RES-E installations to develop across the EU where renewable resources are most favourable. Under existing (or even more fragmented) conditions, where Member States provide varied levels of support through individual support mechanisms, deployment is unlikely to be achieved in the most suitable locations (and therefore increase total costs), as illustrated by Figure 17. The second depends on how the design of the electricity market develops. An increasingly centralised, interconnected and liberalised electricity market would require a single, co-ordinated support mechanism to avoid further distortions to the market.

As under the market-based policy pathway, success may be permitted, or significant stumbling blocks reduced, depending on the renewable installation application and planning procedure (discussed under Section 3.5), availability of finance, grid connection rates, hassle factors and other similar issues discussed previously.

3.3.2 Industry

Table 6 presents a brief summary of the policy instruments proposed for the 'Industry' sector under the 'technology-based' policy pathway. Technology standards are the key instrument, coupled with the EU ETS. **Energy Audits** for large companies, required every 4 years by Article 8 of the EED and discussed under the behaviour-based policy pathway (Section 3.4.2), remain as currently mandated.

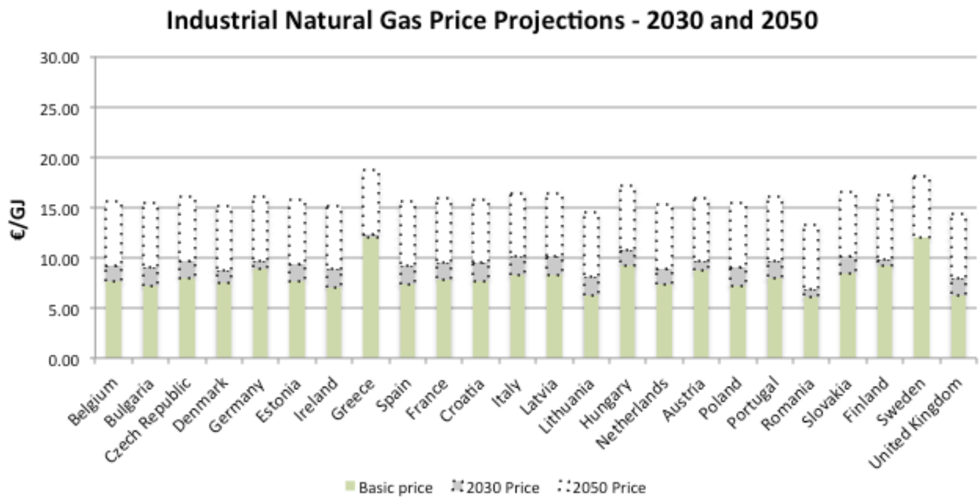
Table 6 - Technology-Based Policy Pathway - Industry

Policy Instrument	Description
EU ETS	The EU ETS is substantially reformed to produce a robust, increasing price over time (but less than the Market-Based Policy Pathway).
CO_2 Emission Standards	The Industrial Emissions Directive is expanded to include CO_2 emissions from industrial installations

EU ETS

The development of the EU ETS under this policy pathway is described above (Section 3.3.1). Full auctioning and measures to guard against carbon leakage are introduced, as under the market-based policy pathway (Section 3.2.2). Figure 31 presents a revised version of Figure 18, and illustrates the impact of industrial natural gas prices of the EU ETS under this policy pathway.

Figure 31 - Industrial Natural Gas Price Projections - 2030 and 2050 (Source: Eurostat and Author's Calculations)



As under this policy pathway it is assumed that possible exemptions for industrial energy consumption remain, taxes and levies are not present in Figure 31. Although around double contemporary prices, compared to the market-based policy pathway, prices for 2050 are projected at around €10/GJ lower (~40%) across Member States. This reduces the potential for certain technologies to become cost-effective in the long run, along with a reduced incentive for fuel switching. Additionally, according to the estimates described in Section 3.2.2, CCS for industrial applications may not become cost-effective before 2050. Uncertainty surrounding this would also likely increase, as basic energy prices form a larger part of the total price, increasing the potential for volatility compared with the market-based pathway.

CO_2 Emission Standards

The Industrial Emissions Directive (IED) (2010/75/EU) establishes requirements for the control of pollution arising from industrial activities, and replaces seven previous Directives (including the Large Combustion Plant Directive from 2016). It requires operational permits to be based on Best Available Technologies (BAT) concerning various polluting activities. At present it does not require limits on GHGs from installations subject to the EU ETS. Under this policy pathway, this exemption is removed, and BAT with regards to CO_2 emissions must be a condition of an operation permit being granted.

Such an instrument would remove reliance on the uncertain and variable price incentive produced by the EU ETS, and reduce organisational inertia and other such behavioural issues that may prevent the adaption of more efficient, low-carbon technologies even in the presence of suitable price incentives. This also applies to CCS, if and when it becomes an available option. However, the carbon price produced by the EU ETS remains an incentive for efficient use of such technologies and reduces the possibility of rebound effects. Such influences would likely be particularly important in 'smaller' energy-intensive (manufacturing) industries, where such issues are more prevalent.

At present, the Article 15 of the IED contains a provision that allows Member States to reduce the stringency of its requirements if it would produce 'disproportionately higher costs compared to environmental benefits'. It is not clear to what extent this provision has been applied and the practical impact it has had on the installation of BAT technologies for non-CO_2 pollutants. However, it is possible that this provision may be applied in future under this pathway such that the EU ETS price remains the decisive factor for the installation of low-carbon and energy efficient technologies in the industry sector (along with basic fuel and technology costs, discussed above). Indeed, it is likely that for EITE industries, some form of additional mechanism to prevent carbon leakage would be required (e.g. a subsidy).

3.3.3 Buildings

Table 7 presents a brief summary of the policy instruments proposed for the 'buildings' sector under the 'technology-driven' policy pathway. New buildings are constructed according to stringent standards and codes, whilst refurbishment requirements are implemented for existing buildings. Energy-related products are subject to increasing efficiency standards, whilst low-carbon heating and cooling technologies are subsidised. **Building Energy Performance Certification** and **Energy-Related Product Labelling** also remain as currently configured.

Table 7 - Technology-Based Policy Pathway - Buildings

Policy Instrument	Description
Building Energy Performance Standards	The current 'near-zero' energy requirement for new buildings in 2020 becomes a 'net-zero' energy requirement.
Energy Efficiency Obligation Scheme	Article 7 of the EED is expanded to require average annual energy savings achieved each year to 2050.
Technology Performance Standards	The existing Ecodesign Directive is amended to follow the Japanese 'Top-Runner' approach.
Renewable Heating/Cooling Subsidy	Support mechanisms, similar to that provided for renewable electricity, is made available for renewable heating and cooling installations.

Building Energy Performance Standards

Building Performance Standards are building codes that set minimum performance standards (MEPS) for new buildings (or those that undergo extensive renovation), which the building and construction industry are required to meet. The Energy Performance of Buildings (EPBD) Directive (2010/31/EC) requires that by 31st December 2020, all new buildings must be classified as 'nearly zero-energy buildings' (NZEBs), with a deadline of 31st December 2018 for buildings owned and occupied by public authorities. An NZEB is defined as a building with a very high energy performance, with the remaining low energy demand covered very significantly by renewable energy. Each Member State is required to submit their own interpretation of this definition considering national, regional and local conditions, reflected by a numerical indicator of primary energy consumption (measured in kWh/m^2 per year, and including electricity from the grid with a primary energy conversion factor applied), which may be varied by different categories of building (Drummond, 2013). It is clear that the in-practice definition of an NZEB varies significantly across Member States, from energy-positive (in Denmark and France), up to 270 $kWh/m^2/y$ (approximately the average energy intensity of the existing non-commercial building stock - see Figure 6). Requirements for new residential buildings vary between 33 $kWh/m^2/y$ (Croatia) and 95 $kWh/m^2/y$ (Latvia), with the majority setting definitions at 45 $kWh/m^2/y$ or 50 $kWh/m^2/y$. The highest values are largely assigned to hospitals or other special non-residential buildings. Few Member States explicitly require that any proportion of the remaining energy consumption must be supplied by renewable sources (Ecofys, 2014a).

Under this policy pathway, the near-zero energy building requirement is tightened to become a 'net-zero' energy building requirement – all new buildings in the EU must be a (minimum) net-zero consumer of energy produced outside the system boundary[86] (based on delivered rather than primary energy) meaning that each building must be able to generate and export as much energy as it consumes from delivered sources, annually (producing zero direct CO_2 emissions). This requirement may be met through a combination of increasing building efficiency (both envelope efficiency and in energy-using products) and distributed renewable deployment. Although whether or not each building may generate enough energy for export to compensate for imports over a given time period is a result of actual energy consumption and variable generation potential (both between Member States and time), standard assumed rates may be applied for each renewable technology regarding generation potential and the split between autoproduction and export, and the volume of delivered energy (at a Member State or regional level). Such an approach incentivises the installation of the least-cost combination of efficiency and renewable measures available (based on capital costs), to achieve net-zero energy consumption. This means, for example, that building developers in southern Member States may deploy solar PV to a higher degree than northern Member States in order to meet these requirements. As such, whilst net-zero energy consumption is maintained in new buildings in all Member States, gross energy consumption may vary. However, it is likely that building envelope efficiency would be responsible for the majority of the net-zero requirement, with space and water heating largely electrified (with renewable fuels such as biomass also featuring, where viable).

If all new buildings are constructed to net-zero energy standards, and assuming the average energy intensity of the existing building stock remains at current levels (see Figure 6), average energy intensity of the residential and commercial (including public) building stock decreases to around 144 $kWh/m^2/y$ and 207 $kWh/m^2/y$ by 2050, respectively; failing to reach the minimum requirements for building stock energy intensity as laid out in Section 2.3 (115 $kWh/m^2/y$ and 170 $kWh/m^2/y$ for residential and commercial, respectively). Reductions in CO_2 emissions intensity also remain significantly above minimum requirements of 10

[86] The site of the building. This definition also includes appliances, which are not mandatory for inclusion under the NZEB requirement.

$KgCO_2/m^2/y$ and 12 $KgCO_2/m^2/y$ for the residential and commercial stock, respectively (reaching 18.2 $KgCO_2/m^2/y$ and 24.6 $KgCO_2/m^2/y$, respectively)[87].

However, there are issues with assuming that each new building will achieve regulated net-zero delivered energy consumption. As discussed above, assumptions on the level of electricity consumed from the grid, auto-produced or exported to the grid depend on variables such as generation potential, occupant behaviour and the use and energy efficiency of appliances – none of which are within the control of the building developer. As such, buildings are likely in practice to be either net energy producers or consumers, within a certain margin around net-zero. Even if such issues are accepted and this margin is small and accepted, enforcement of these standards may prove difficult. Existing standards in many Member States are already poorly enforced, with compliance often found to be relatively low (Hong, 2009; Pan and Garmiston, 2012). As such, enforcement and penalty mechanisms require strengthening, under each policy paradigm, to ensure the requirements set for new buildings are achieved.

Energy Efficiency Obligation Schemes

Energy Efficiency Obligations Schemes (EEOS) mandate energy suppliers or distributors (or in other cases, public entities, building owners, or users) to achieve certain energy or carbon savings over a given timeframe amongst their end users (THINK, 2012). Article 7 of the Energy Efficiency Directive (EED) (2012/27/EU) requires that all Member States implement an EEOS, in which energy suppliers must achieve the equivalent of average annual cumulative savings of 1.5% of total sales, by volume, based on average total sales of the industry across the three-year period leading up to the 1st January 2013[88]. The obligation period is from 1st January 2014 until 31st December 2020, and Member States have flexibility as to how and when the required savings are implemented over this period. Alternative measures may be implemented in place of an EEOS (including an 'Energy Efficiency National Fund' to support energy efficiency initiatives), as long as such instruments achieve equivalent energy savings (Drummond, 2013). At present, 17 Member States have, or plan to implement, an EEOS (often in combination with other instruments), with analysis suggesting around 40% of the required 2020 target to be achieved by such instruments (Rosenow *et al*, 2015). Under this policy paradigm, EEOS become fully mandatory across Member States (with no possibility for alternative measures), are applicable only to the residential and commercial building stock[89], and are extended from 2020 to 2050. The obligated parties may be energy suppliers or distributors.

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[87] For comparison, assuming all new buildings (residential, commercial and public) achieve an energy intensity of 45 kWh/m^2 year – as per the residential target commonly set for new residential stock (as discussed above), total average energy intensity of around 154 $kWh/m^2/y$ and 220 154 $kWh/m^2/y$ is reached for residential and commercial, respectively, and a total average CO_2 intensity of 19.3 $KgCO_2/m^2/y$ and 26.1 $KgCO_2/m^2/y$ is achieved.

[88] Sales volumes to installations covered by the EU ETS may be discounted from this requirement. Energy consumption in transport may also be excluded.

[89] Although this is already largely the case, some Member States intend to achieve a proportion of their EED obligations in the transport and industrial sectors (Rosenow *et al*, 2015).

The energy saving target should be set so that savings are achieved from existing buildings only (with new buildings and those undergoing major renovations covered by Building Energy Performance Standards, discussed above), and be sufficient to reach the energy intensity requirements described above, and in Section 2.3. As such, an annual energy consumption reduction target of at least 0.6% and 0.4% (of current levels) between 2015 and 2050 for the total residential and commercial stock, respectively, would be required[90]. Whilst these values are below existing requirements, they extend past existing obligations to 2050, producing absolute energy savings of around 21% and 15% from existing residential and commercial energy consumption. Energy suppliers would be able to 'bank' annual overachievement for future compliance (but not 'borrow' future from future years for earlier compliance). A white certificate system may also be employed.

Obligated entities (as currently) would be free to choose measures to implement in order to achieve these savings. However, sub-targets may be implemented, such as requiring certain measures in certain households or commercial properties of a given demographic or sub-sector, may be implemented to tackle issues such as fuel poverty (as with the UK's Energy Company Obligation[91]). Measure 'standardisation' (i.e. a standard level of energy saving expected) may be required for administrative feasibility and compliance purposes, as used in PAYS mechanisms described under the market-based policy pathway (Section 3.2.3). However, issues of over/underestimation of the level of expected energy savings achieved, as discussed under the Market-based policy pathway, would remain.

Obligations may be satisfied either by the installation of 'shallow' retrofits (such as insulation) across a large number of properties, 'deep' retrofits (such as replacing heating or ventilation systems) across a smaller number of properties, or a combination of both, as dictated by the approximate least-cost (including transaction costs). The approach taken may vary significantly between Member States, and would have consequences for the range of energy intensities experienced out to 2050 (although, this may be constrained by the use of sub-targets). However, the imposition of a clear, long-term obligation coupled with the ability to bank overachievement mat encourage 'deep' retrofits to a greater extent than short-term instruments where overachievement is not incentivised, as such an approach may be least-cost over the timeframe and achieve the level of energy savings required. Additionally, if the energy reduction target is based on delivered energy, it may also encourage the installation of renewable technologies (which the existing formulation does not incentivise).

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[90] The existing requirement for a 3% rate of renovation for central government floor space laid down by Article 4 of the EED is maintained, and expanded to buildings owned and occupied by regional governments. The renovation requirements must still meet Building Energy Performance Standards in the EPBD, now tightened to net-zero energy as above.

[91] The Energy Company Obligation 1 (ECO), which runs from 2013-2015, includes three sub-targets. These are a *Carbon Emissions Reduction Obligation,* focussing on domestic solid wall insulation and hard-to-treat cavity wall insulation, a C*arbon Saving Community Obligation,* focussing on providing insulation measures and connections to domestic district heating systems supplying low-income households (15% must be achieved in vulnerable households in rural areas), and a *Home Heating Cost Reduction Obligation,* focussing on low-income and vulnerable households.

However, even if such minimum requirements for energy intensity retrofits are achieved, it does not necessarily follow that CO_2 intensity requirements are also met (as described in Section 2.3). Even if it is assumed that all energy consumption savings in existing buildings are achieved through reductions in fuel oil use as a result of this instrument (in both residential and commercial sectors), total average CO_2 intensities reduce by around 8.3 $KgCO_2/m^2/y$ and 11 $KgCO_2/m^2/y$ in the residential and commercial sectors by 2050, respectively. Coupled with net-zero energy requirements for new buildings (producing zero direct CO_2 emissions, and assuming such requirements are achieved), this produces final average CO_2 intensities of around 11 $KgCO_2/m^2/y$ and 14.9 $KgCO_2/m^2/y$ in the residential and commercial sectors in 2050, respectively. Whilst these values represent significant improvements on existing values, they do not achieve respective minimum requirements (maximum levels) of 10 $KgCO_2/m^2/y$ and 12 $KgCO_2/m^2/y$. However, these values are subject to significant uncertainty. First, it is highly unlikely that 100% of the required energy savings will be achieved through a reduction in fuel oil consumption (whilst it may count for a significant proportion of savings in some Member States, in others it is likely to be through reducing natural gas or electricity use for example - with a lower and zero direct CO_2 emissions intensity, respectively). Secondly, the target given for an absolute reduction in energy consumption from existing levels assumes energy consumption and intensity remains static in the counterfactual. As such, it does not prevent increasing energy consumption (and therefore energy intensity) overall (amongst existing buildings). However, equally, counterfactual energy consumption and intensity in existing buildings may reduce over time, producing additional savings. Thirdly, once measures have been installed (and thus accounted as having produced savings), in addition to variations in occupant behaviour and the potential for the rebound effect (discussed above), the obligated entity cannot ensure that these measures are not later replaced with less efficient or more CO_2 intensive technologies – particularly at a given measure's end-of-life (although, this is less applicable to measures such as insulation). Additionally, building owners and occupiers must be willing to accept the installation of measures in the first place. Finally, a lack of instrument robustness in practice, along with monitoring and enforcement, may hamper effectiveness. Rosenow *et al* (2015) find that of the 17 Member States that have or are implementing ESOS for EED Article 7 compliance, 8 have major credibility issues, 6 have minor credibility issues, and only 2 have no issues[92]. As energy suppliers are obligated to reduce demand for their product, they have a clear disincentive to ensure its achievement (and certainly overachievement). Strong monitoring regimes, which are likely to face different challenge in different Member States, and significant penalties for non-compliance would be required to increase the likelihood of success. Little information is available on the monitoring and enforcement regimes of (largely proposed) ESOS instruments across Member States for Article 7 compliance, however

[92] The final Member State, Portugal, has an existing ESOS instrument in place but has not notified the Commission of their intention to use this for Article 7 compliance, and thus instrument credibility was not assessed by this study.

Rosenow *et al* (2015) find that most monitoring, verification, control and compliance regimes are likely to be inadequate.

Technology Performance Standards

Technology Performance Standards refer to minimum energy performance standards for building-related energy-using products, such as heating and lighting systems, white goods and electrical equipment, and/or energy-related products; products that have an indirect impact on energy consumption, such as water-using devices, insulation materials and windows. At present, the Ecodesign Directive (2009/125/EC) implements minimum performance standards on a range of energy-using and energy-related products, and has been effective in driving (often substantial) efficiency improvements (see Drummond (2013) for a full description of the Directive and coverage).

Under this policy pathway, the Ecodesign Directive is strengthened to operate in line with the Japanese 'Top Runner' approach – a shift in philosophy from 'eliminating the worst' to 'aiming for the best' (Siderius and Nakagami, 2007). In Top Runner, the highest energy efficiency currently available on the market is set as the minimum standard all manufacturers must meet for the weighted average of all their products available on the market by a certain target year (Siderius and Nakagami, 2007). In some cases, the standards are set above the most efficient products on the market to take into account the potential for energy efficiency improvement in the future (Kimura, 2010). Between 1998-2009, 21 technology groups were included across building-related technologies and transport[93]. The scope of measures is reviewed every 2-3 years (Kimura, 2010). The instrument has required average energy efficiency improvement rates ranging from 16% to 80%, each of which have been achieved, often relatively easily and with significant overachievement (Kimura, 2010; Siderius and Nakagami, 2007).

By focussing requirements on disseminating the most efficient products rather than on removing the least efficient products, it is likely that a Top Runner approach would be more effective in shifting the market for regulated products to higher average energy efficiency level. However, this is likely to vary significantly by product. For example, the average market energy intensity of a product under the existing Ecodesign approach may reach the same 'fleet-average' approach as under a Top Runner Approach. Equally, a 'fleet-average' Top Runner approach still permits the sale of low-performing products that might otherwise be banned under an Ecodesign absolute minimum standard. Additionally, under either approach, such regulations tackle the energy efficiency of a product, but do not directly tackle absolute energy consumption resulting from the number of (energy-using, rather than energy-related) products in use, changing usage patterns, or continued used of less efficient products. Changes to such trends may in part be induced by the regulation itself, via the rebound effect (assumed at 10% for electricity and 30% for heating technologies (Ecofys, 2012)). The rate at which more efficient products are likely to enter use (and thus generate any savings against the counterfactual, regardless of whether or not rebound effects occur) is

[93] In this pathway, the proposed approach would focus on building-related products only.

also likely to depend on the product. For example, building heating systems have a significantly longer average lifetime than, for example, a television. As a result, technology performance standards are more effective at improving the rapid uptake of products that have relatively short lifetimes (and thus faster replacement rates).

Evidence suggests an existing Ecodesign Directive non-compliance rate of around 10-20%, largely due to under-resourced monitoring and enforcement procedures (Drummond, 2013). Due to the increased monitoring burden and complexity of an average-sales based approach, the potential for increased non-compliance. Additionally, there are documented differences in efficiency levels between products subject to test procedures, and those operating in the real world. For example, even the industry itself recognises that an artificial efficiency improvement of 30% results from the design of the test procedure, compared to real world operation (Toulouse, 2014).

Renewable Heating/Cooling Support Mechanism

Under this policy pathway, support mechanisms for renewable electricity are joined by support mechanisms for renewable (non-industrial) heating and cooling. Support mechanisms may be in the form of capital subsidies, feed-in or generation tariffs, or through low- or zero-interest loans, serving the same function as support mechanisms for RES-E technologies, and suffering similar opportunities, barriers and design considerations.

In the UK, the Renewable Heat Incentive (RHI) policy utilises a generation tariff to encourage the uptake of renewable heating technologies (with tariffs differentiated by technology). The policy was introduced in 2011 for the commercial and public sectors and in 2014 for the domestic sector. The RHI has been relatively successful in incentivising deployment of renewable heating in both the commercial sector (success of the domestic scheme is too early to determine) (Donaldson and Lord, 2014), however the design of the instrument may mean it is not reaching its potential. For example, planning permission for some technologies must be sought before the RHI is applied for, placing risk on the installation owner, as there is no guarantee their installation will qualify even after the costly planning application is submitted. Additionally, small installations (<200kW) must be in place before the RHI may be applied for (Donaldson and Lord, 2014) – a clear risk and disincentive to install such technologies. Such issues would have to be taken into account for future instrument.

3.3.4 Transport

Table 8 presents a brief summary of the policy instruments proposed for the ‘transport’ sector under the ‘technology-based’ policy pathway. A CO_2 emission standard for new vehicles is the key instrument in this sector, with the banning of conventionally fuelled cars in urban areas and the public procurement of low-carbon vehicles as key flanking instruments. Existing requirements for the **CO_2 Labelling** of passenger cars remains (discussed under Section 3.4.4)

Table 8 - Technology-Based Policy Pathway - Transport

Policy Instrument	Description

CO_2 Emission Standards	Fleet-average CO_2 emission intensity standards remain for passenger cars and LGVs, and are extended to HGVs.
Banning of Conventionally Fuelled Cars in Urban Areas	Conventionally fuelled passenger cars are banned from entering large urban areas by 2050.
Green Public Procurement of Vehicles	All publicly-owned institutions purchase low-CO_2 intensity vehicles

CO_2 Emission Intensity Standards

Regulation 443/2009, introduced in 2009, sets fleet-average CO_2 emission performance standards for new cars registered in the EU, for each manufacturer. It mandates a fleet-average limit of 130 gCO_2/km be achieved by 2015, and 95 gCO_2/km be achieved by 2021. In 2014, Regulation 253/2014 was introduced to impose similar standards for LGVs, set at a fleet-average value of 175 gCO_2/km by 2017 and 147 gCO_2/km by 2020. HGVs are not currently subject to such regulation[94].

Regulation 443/2009 has proven effective in reducing the CO_2 intensity of passenger cars; average new-car CO_2 emissions fell from 170 gCO_2/km in 2001 to 127 gCO_2/km in 2013, a 25% reduction in 12 years. The annual rate of improvement in CO_2 intensity increased from around 1% in the years leading up to 2007 (before the regulation), to around 4% after, meaning that the 2015 emission target of 130 g CO_2/km was met two years in advance with the reduction attributable in large part to the regulation (Drummond, 2013; Maca *et al*, 2013). It takes around 10 to 15 years to replace the full stock of passenger cars. As such, the average CO_2 intensity of the full passenger car fleet should reach 130 g CO2/km by around 2030. Similarly, if the 2021 target of 95 gCO_2/km for new cars is achieved, the full passenger car fleet should meet this value by around 2036. As such the minimum requirement for average passenger car CO_2 intensity of 100 gCO_2/km by 2050, as stated in Section 2.3, is achieved under existing legislation.

However, there are potential issues with this assessment. Most prominently, there is a recognised (and increasing) gap in fuel consumption and CO_2 emissions between the real-world performance of vehicles and laboratory tests upon which regulatory compliance is based. While in 2001 the discrepancy was around 8%, by 2013 it had increased to around 31% for private cars, and as much as 45% for company cars (ICCT, 2014).

Vehicle performance is tested using the New European Driving Cycle (NEDC), which does not take into account various factors that affect CO_2 emissions. Principal amongst these is vehicle weight, which increased by around 10% between 2001 and 2011 (ICCT, 2014), with Nijland *et al* (2012) calculating a resulting increase of around 8.4% in CO_2 emissions not registered by the NEDC methodology. As such, it is possible that the 2015 target of 130 gCO_2/km has not yet actually been met in practice. However, the EU plans to adopt the new Worldwide Harmonized Light Vehicles Test Procedure (WLTP), with its more dynamic test cycle and tightened test procedure, to reduce the differential between laboratory and real-world

[94] However the EU's HGV Strategy adopted in May 2014, envisages legislation to be proposed in 2015 which would require CO_2 emissions from new HGVs to be certified, reported and monitored.

performance. Whilst this will tighten compliance with the 2021 target (95 gCO_2/km) some differential will likely remain, meaning that in practice, whilst the limit may be officially met on time, real-world compliance may be met a few years later. Consequently, total fleet average CO_2 intensity may achieve this level more towards 2040 than 2035. Regardless, the minimum 100 gCO_2/km is still likely to be met under existing legislation. The proposed (but not yet adopted) target of 68-78 g CO_2/km for 2025 would certainly achieve this target.

However, these limits are technology-neutral, and thus do not necessarily produce a substantial shift to, for example, electric vehicles. Simply increasing vehicle engine efficiency, or reducing weight, may alone achieve significant gains – particularly with a fleet-average approach, and 'super credits' for electric cars[95]. Additionally, as the instrument focuses on CO_2 intensity only, absolute emissions may not reduce proportionally. This will depend on the number of vehicles on the road and distance driven, but also the distribution between ownership types. Without revision to company car taxation rules (as proposed under the market-based policy pathway, discussed under Section 3.2.4), larger, more CO_2-intensive cars are likely to be highly represented in the company car fleet, and are likely to be more intensively driven then private vehicles – with clear consequences for absolute CO_2 emission reductions resulting from this instrument.

Although it is too soon to determine the impact of the LGV-related regulation, if the new fleet-average limit highlighted above is achieved, the slightly reduced vehicle turnover rate compared to passenger cars would mean LGVs in the EU would exhibit an average CO_2 intensity of 147 gCO_2/km by around 2040. This significantly exceeds minimum requirements projected by the ETM-UCL model (illustrated in Figure 6), although the above caveats relating to technological shift and absolute emissions (except for company car taxation impacts) remain.

As such, no changes to the regulations for passenger cars or LGVs are proposed in this (or any) policy pathway. However, for HGVs, similar fleet-average CO_2 intensity regulations are applied. The average lifespan of an HGV is around 16 years (European Commission, 2006), meaning that new fleet-average intensity limits of around 500 gCO_2/km should be introduced in around 2019 to reach this total average value by 2035, and 200 gCO_2/km by 2034, to meet this total average value by 2050 (as illustrated in Figure 8). However, again, the above caveats apply.

Banning Conventionally Fuelled Cars in Urban Areas

The EU's 2011 'Roadmap to a Single European Transport Area' states that Member States should, amongst other things, attempt to 'halve the use of 'conventionally fuelled' cars in

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[95] To incentivise the development of cars with ultra-low CO_2 emissions, each vehicle sold with emissions below 50 gCO_2/km (including electric vehicles) counted as equivalent to 3.5 cars sold in 2012 and 2013, 2.5 in 2014 and 1.5 in 2015. These are termed 'super credits' (Drummond, 2013). Between 2016 and 2019 these vehicles will receive no preference. However, super-credits will apply from 2020 to 2023, where each low-emitting car will be counted as equivalent to 2 car sold in 2020, 1.67 in 2021, 1.33 in 2022 and 1 from 2023. For this second phase there will be a cap on the scheme's contribution to the target of 7.5 gCO_2/km per manufacturer over the three years.

urban transport by 2030, and phase them out in cities by 2050' (European Commission, 2011d). Under this policy pathway, this ban is fully implemented by 2050, and includes any passenger car propelled by conventional fuels (including hybrid vehicles). This may be phased in over time, based on vehicle CO_2 intensity limits, or by expanding spatial coverage, for example.

Although without reliance on price-based incentives alone, such an instrument is similar to the Low Emission Zones proposed under the market-based policy pathway (see Section 3.2.4), with induced effects likely to vary by Member State, region and individual urban areas based on local circumstances (such as concentration, availability and cost of alternative vehicles and modes, electric vehicle charging infrastructure, etc.).

Green Public Procurement of Vehicles

Public authorities require vehicles for a range of activities; from ordinary passenger cars to small vans and LGVs, buses and waste disposal trucks. The total annual purchase of vehicles by public authorities is estimated to be in the order of 110,000 passenger cars, 110,000 LGVs, 35,000 HGVs and 17,000 buses for the EU-25. The corresponding shares of public procurement of all sales in the EU-25 are slightly below 1% for cars, around 6% for LGVs and HGVs, and around 30% for buses (BRE, 2011). The Clean Vehicles Directive (2009/33/EC) requires that energy consumption, fuel type, CO_2 and other emissions be taken into account in the public procurement of road vehicles, using a standard methodology for the calculation of operational lifetime costs. Under this policy pathway, Member States tighten their requirements along the lines of the Japanese Top Runner approach, described above in application to energy-related products for buildings (Section 3.3.3). Whether this is mandated by an amendment to the Clean Vehicles Directive, or simply permitted by an amendment and introduced by individual Member States, will depend on the development of policy competence between the EU and consistent Member States.

Such public procurement requirements would contribute to the faster penetration of low emission vehicles, although due to the relatively low proportion of publicly procured vehicles in relation to overall fleet numbers (particularly for cars), this contribution would likely be limited. However, such public procurement programme may also promote the adoption of AFVs by private consumers due to network effects - by creating a signalling effect as lead users, governments can create or expand the network required for early adopters, subsequently normalising their presence and demonstrating their viability (performance, reliability, etc.), reducing psychological barriers and information asymmetries, encouraging uptake in private firms and consumers.

3.3.5 Summary of the Technology-Based Policy Pathway

This pathway principally employs regulatory instruments across the economy to drive investments in low-carbon infrastructure, with economic instruments playing a largely secondary role. However, a common issue amongst most sectors and many instruments is that of appropriate levels of monitoring and enforcement. A number of existing regulatory requirements experience either relatively substantial levels of outright non-compliance, whilst others achieve high levels of compliance but significant insufficiencies in monitoring regimes, meaning that achievement in practice may be called into question. As under this policy pathway a number of such regulatory requirements are tightened, it is reasonable to suggest that resistance to improvement monitoring and enforcement mechanisms would be strong, meaning that mitigating these issues to any meaningful level is likely to be difficult, reducing overall effectiveness of these instruments in both the short- and long-term.

However, again, there are sector-specific variations in likely effectiveness of instruments (individually and in combination) in achieving the requirements laid out in Chapter 2. The EU ETS remains the central instrument in the power sector, and assuming carbon prices in 2030 and 2050 at approximately half the levels experienced in the market-based pathway are achieved, new coal and (particularly) gas installations are likely to remain relatively economically competitive with other generation from a LCOE perspective (although as discussed, the merit-order effect is likely to prevent actual generation from these installations at all but times of particularly high demand and/or low supply). However, regardless of the economics, the proposed EIS would prevent the construction of new coal and inefficient gas installations. Dedicated RES-E support mechanisms would further improve the economics of renewable installations (both centralised and decentralised), although whether efficient deployment throughout the EU would be achieved depends on the level of co-ordination between Member State-level instruments, or the introduction of a single mechanism across Member States if policy making centralisation over time permits such an approach. Instruments in the building and industry sectors, particularly Building Energy Performance Standards and Energy Efficiency Obligation Schemes, are also likely to encourage the growth of decentralised generation. Overall, these instruments in combination (assuming appropriate design) are likely to achieve the requirements for the power sector as laid out in Section 2.1, along with relatively significant control over the profile of technologies deployed. However, an appropriate electricity market design (discussed under Section 3.5) is a key requirement. The success of the combination of the EU ETS with CO_2 standards in the industry sector would depend largely on the extent to which 'excessive cost' provisions are and would be employed, reducing requirements (in addition to assumed availability of key technologies – particularly CCS).

The combination of net-zero new buildings with energy efficiency obligations for existing buildings would likely achieve substantial improvements to both energy and CO_2 intensities of buildings – assuming high quality implementation and suitable enforcement, both of which are often lacking at present. However, even if this is achieved, it remains unlikely that these instruments alone would be sufficient to reach the requirements (particularly average CO_2 intensities) laid out in Section 2.3. The introduction of a more ambitious technology standards, and to a lesser extent the availability of renewable heating and cooling support mechanisms, would likely add to the savings achieved by these two instruments (particularly for existing buildings) – however numerous variables makes such a conclusion highly uncertain.

As discussed above, and under the summary of the market-based policy pathway (Section 3.2.5), although CO_2 Emissions Standards would likely to achieve the minimum requirements for the transport sector alone, instruments applied in parallel to CO_2 Emission Standards in the may simply act to reduce the effort required under this instrument, rather than producing additional savings. The continued presence of company car taxation rules would likely underscore this position. However, it given the proportion of journeys undertaken in urban areas, a ban on conventional vehicles in such areas would indeed be expected to produce additional CO_2 savings – in both absolute and intensity terms.

3.4 Behaviour-Based Policy Pathway

3.4.1 Power Generation Infrastructure

Table 9 presents a brief summary of the policy instruments proposed for the 'power generation' sector under the 'behaviour-based' policy pathway. The EU ETS remains and is reformed along the lines discussed under the technology-based policy pathway, flanked by dedicated RES-E support mechanisms.

Table 9 - Behaviour-Based Policy Pathway - Power Generation

Policy Instrument	Description
EU ETS	The EU ETS is substantially reformed to produce a robust, increasing price over time (but less than the Market-Based Policy Pathway).
RES-E Support Mechanism	Dedicated RES-E support mechanisms are maintained.

The **EU ETS** and **RES-E Support Mechanisms** remains and are developed along the lines described under the technology-based policy pathway (Section 3.3.1), with impacts, limitations and uncertainties largely remaining the same. However, in this policy pathway, psychological and certain behavioural barriers may be reduced through increasing awareness driven by instruments with a focus on other sectors (such as those discussed under the Buildings sector, below). However, it is likely that cost-benefit will remain the key driver, permitting or preventing the development of low-carbon power generation. This would likely be particularly the case for decentralised installations, but cultural developments arising from increasing awareness, such as the reputational or conspicuous consumption value of installing solar PV panels, or the 'inconspicuous' consumption exhibited through the use of 'green' tariffs offered by energy suppliers, may encourage both centralised and decentralised generation (depending on transmission and distribution infrastructure development, spatial planning laws, etc., and other similar items discussed in the previous two policy pathways).

3.4.2 Industry

Table 10 presents a brief summary of the policy instruments proposed for the 'industry' sector under the 'behaviour-based' policy pathway. The EU ETS remains, but voluntary agreements between the government and particular industrial sectors are the key instrument in this policy pathway. The use of Energy Management Systems become mandatory.

Table 10 - Behaviour-Based Policy Pathway - Industry

Policy Instrument	Description
EU ETS	The EU ETS is substantially reformed to produce a robust, increasing price over time (but less than the Market-Based Policy Pathway).
Voluntary Agreements	Fully voluntary agreements between government and industrial sectors are introduced.
Mandatory Energy Management System (EMS)	Article 8 of the EED is amended to require non-SMEs to implement an EMS.

Voluntary Agreements

Voluntary Agreements (VA) for energy efficiency and/or CO_2 reduction between government and energy- and CO_2-intensive industrial sectors are the primary policy instrument under this policy pathway for this sector. VAs may be designed in various ways to achieve the requirements outlined in Section 2.2 (e.g. they may focus on energy or CO_2 (or both), have targets or other requirements set on an annual basis or cover several years, etc.). Such instruments already exist in a number of Member States (e.g. Germany, Belgium, Netherlands), in addition to mandatory instruments. However, under this policy pathway, VAs are fully voluntary, with no monetary or regulatory incentives or penalties in addition to the other instruments discussed.

The evidence suggests highly varied levels of effectiveness across the world for VAs focussing on energy and CO_2 abatement, although those that are completely voluntary exhibit low participation rates and weaker results (Price, 2005). Although they do not provide a direct incentive to participate, the price burden delivered by the EU ETS (as with the power sector, the impact on industry would be expected to be similar to that discussed under the technology-based pathway (Section 3.3.2)), and the potential for increased competitive pressure produced by the awareness-raising instruments discussed below, may be expected to increase participation rates beyond what might otherwise be expected. However, if the targets and requirements of the VA were significantly in excess of those produced by other incentives, participation rates would likely remain low. As such, it is doubtful whether a fully voluntary VA would produce significantly additional CO_2 or energy savings.

Mandatory Energy Management System

Article 8 of the EED requires that all large companies (not defined as SMEs[96]) must be subject to an energy audit carried out every four years from the end of 2015. However, firms subject to an Energy Management System (EMS), certified by an independent body according to the relevant EU or international standards (e.g. ISO 50001), are exempt from this requirement. Under this policy pathway, this requirement changes to mandate that all such organisations must implement an independently certified EMS.

[96] Enterprises which employ fewer than 250 persons and which have an annual turnover not exceeding €50 million euro, and/or an annual balance sheet total not exceeding €43 million.

The objective behind such a requirement would be to improve knowledge of energy consumption within such firms, and to encourage increased energy efficiency where options are cost-effective. However, much of the existing evidence suggests that the introduction of EMS, either voluntary or mandatory, often fails to produce substantial energy (and CO_2) savings. For example, in Japan, where an EMS is mandatory for around 12,000 firms (along with the use of qualified energy managers the development of long-term energy efficiency investment plans, and the achievement of an annual 1% improvement in energy intensity), it is often not effective at promoting tangible energy efficiency activities (Kimura and Noda, 2014). Various reasons for this are suggested in the literature, including a lack of capacity to interpret and act upon the information provided by an EMS, poor data quality upon which to base decisions, a lack of integration of such data and interpretations into the wider decision-making process, organisational inertia, hassle factor, other investment priorities, and a lack of access to capital (Kimura and Noda, 2014; Melville and Whisnat, 2014; Thollander and Ottosson, 2008). As such, it is unlikely that such a mandatory requirement would deliver significant additional energy or CO_2 savings beyond existing EED requirements, or the incentives delivered by other instruments employed in this policy pathway.

3.4.3 Buildings

Table 11 presents a brief summary of the policy instruments proposed for the 'buildings' sector under the 'behaviour-based' policy pathway. Labelling and other information programs are the primary instruments in this pathway, along with 'nudging' approaches to further encourage behaviour change. Existing **Building Energy Performance Standards**, **Technology Performance Standards** and **Energy Efficiency Obligation Schemes (**discussed under Section 3.3.3), remain in place. In addition, **Voluntary 'Pay As You Save' Instruments** are introduced (as discussed under Section 3.2.3).

Table 11 - Behaviour-Based Policy Pathway - Buildings

Policy Instrument	Description
Building Energy Performance Certification	Certification requirements remain as currently designed, when sold and entering a new tenancy.
Free Residential and SME Energy Audit	Residential and commercial buildings may receive free energy audits to identify cost-effective efficiency measures
Energy-Related Product Labelling	The Energy Labelling Directive is reformed to have A-G classes only.
Residential Behavioural 'Nudges'	'Nudges' on energy bills become mandatory in all cases.
Voluntary 'Pay as you Save' Finance Instrument	A PAYS instrument is introduced to reduce issues of access to finance for energy efficiency and renewable installations, along the lines of the UK's 'Green Deal'

Building Energy Performance Certification

The EPBD, in addition to minimum energy performance standards, requires that any private new building, or any private building that is sold or rented to a new tenant must issue an Energy Performance Certificate (EPC), containing information on the energy performance of the building, reference values (such as minimum requirements), recommendations for the cost-effective improvement of energy performance, and indications of where the owner or tenant may find more information to implement these recommendations. In addition, Display Energy Certificates must be clearly visible in any public building with over 250m^2 floor space and that is frequently visited by the public (Drummond, 2013). There are no clear pathways to extending existing certification requirements (in combination with other instruments proposed in this policy pathway). As such, existing requirements remain (in all three policy pathways).

Several studies suggest that EPCs have not produced the energy reductions expected by *ex-ante* projections. This is due to several reasons, of which a number surround implementation. Whilst all Member States have a functioning EPC scheme, their design and structure differ somewhat, often resulting from a slow and partial implementation of the EPBD (Economidou *et al*, 2011; Ekins and Lees, 2008). Firstly, not all Member States require EPCs for public, domestic and commercial buildings. Other differences across Member States arise from the use of independently constructed calculation methodologies, which are not uniformly robust. Rates of monitoring have also been low across all Member States, casting doubt on the level of compliance. However, Member States are now required to have independent control systems for EPC with requirements to check quality through random sampling and produce inspection reports annually, which may reduce this impact to some degree[97] (Economidou *et al*, 2011; Kaderják, 2012). As the EPC, even if fully implemented, is only applicable to buildings when constructed, sold or at the start of a new tenancy, many buildings are not assessed for their energy performance (particularly buildings under long-term owner-occupancy). As such, the proportion of buildings with an EPC currently ranges between less than 1% to just above 24% across Member States (Economidou *et al*, 2011). However, over time these values will increase, and additionally under this pathway, flanking instruments (discussed below) may plug this gap.

The purpose of such an instrument is to overcome information failures to stimulate cost-effective efficiency measures through commercial pressure. However, studies suggest that whilst energy efficiency of a property is important, numerous other factors take precedence in the decision to purchase or rent a property. For example, Mudgal *et al* (2013) finds that in France, it ranks sixth in importance. Murphy (2014) finds similar results in the Netherlands. The introduction of the requirement to provide suggestions of cost-efficient improvement options, and where to find information on implementing these options (if implemented in practice by Member States), may over time increase the impact of EPCs, along with the increasing roll-out of smart meters and behavioural nudges (discussed below), however issues of split incentives for tenants, for example, may remain prominent, along with potential rebound effects.

Free Residential and SME Energy Audit

Article 8 of the EED also requires Member States to 'develop programmes to encourage SMEs to undergo energy audits', and 'develop programmes to raise awareness among households

[97] The expected savings from this amendment is 21 Mtoe/a by 2020 according to modelling in the proposal for the recast (Economidou *et al*, 2011).

about the benefits of such audits'. Under this policy pathway, such requirements are supplemented with the guaranteed provision of free energy audits for SMEs and households, upon request. This allows the building stock that does not receive EPCs (or are not covered by EED Article 7 energy audit requirements), to receive information to allow them to implement cost-effective efficiency measures. Indeed, 'in the information tools family it is custom-made audits that are viewed as holding the most potential in stimulating the installation of energy efficiency measures' (Murphy, 2014). However, various factors influence how effective such an instrument may be in delivering reductions in energy consumption.

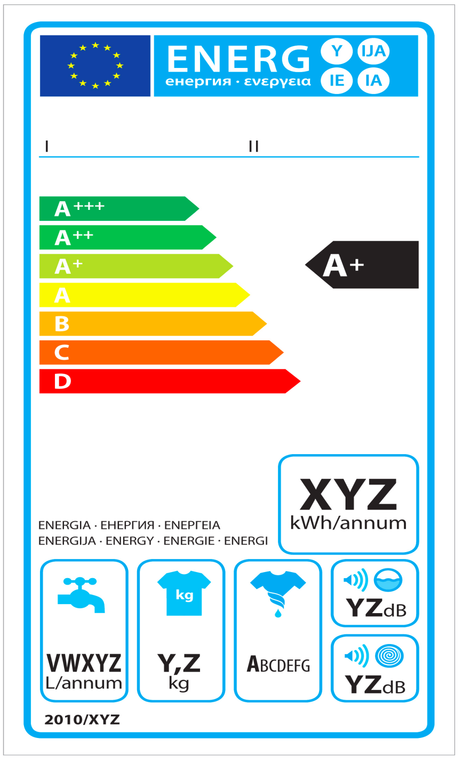
Firstly, as this instrument relies on the recipient to request an audit, households and SMEs must first be aware of their existence, and be motivated to request it. Whilst the roll-out of smart meters and the use of behavioural nudges (discussed below) may increase such motivation, rates of uptake would be highly uncertain, and likely to vary substantially between Member States and socio-economic groups (in the residential sector). A number of studies have shown that age, housing type and income are strongly associated with more sustainable energy use, while a study on energy efficiency renovation in Germany found that this was carried out by people over 50 with higher education and income than average (Murphy, 2014) Secondly, the potential for energy efficiency improvement will vary significantly across the building stock. Older buildings are likely to have far greater potential for improvement, with significant variation across Member States. This is related to the first issue of audit uptake. Additionally, what may be considered a cost-effective option depends on the cost of energy consumption, and the cost of installing efficiency measures. Such costs will vary over time, and are influenced by other policy instruments (such as energy taxation and product energy efficiency standards, which in this policy pathway, largely retain the status quo). Regardless of the potential magnitude of cost-effective improvements, there is not necessarily a proportional link between these measures and CO_2 emissions (if, for example, suggested efficiency measures are largely centred around reducing electricity consumption).

A third key issue is whether, once an audit has been taken and cost-effective measures identified, this advice is acted upon. The empirical evidence suggests relatively low proportions of audit recipients fully act on the advice provided. For example, a study in the USA found that only 40-50% of audit recipients invested in energy efficiency measures, which was only slightly higher than non-recipients (Frondel and Vance, 2013). Examining the role of audits in the Netherlands, Murphy (2014) found that a high percentage of audit recommendations were ignored by audit recipients. A key reason behind this may be that audit recipients simply do not agree with the results of an audit (NHER ad The National Energy Foundation, 2009). Another significant factor is that of high capital costs and discounted future savings (Frondel and Vance, 2013). Indeed, where measures were implemented, the installation of just one or two measures in tandem was considered the norm, although the use of a PAYS mechanism may overcome issues of access to capital to some extent (see Section 3.2.3 for a discussion of this instrument). Despite this, the above-mentioned issues, plus those of split-incentives and potential rebound effects further limiting the ability to implement measures and savings from them, mean that this instrument would likely achieve relatively minor reductions in commercial and residential energy consumption and direct CO_2 emissions.

Energy-Related Product Labelling

Energy-related product labelling schemes are also designed to overcome the information deficit which constrains the uptake of energy efficient products (Economidou *et al*, 2011). The Energy Labelling Directive (2010/30/EC) requires suppliers placing on the market or putting into service any energy-related product subject to an implementing measure[98] to supply a label and a fiche (table of information) with the product containing information relating to energy consumption and other resources, where relevant (Drummond, 2013). Products must be labelled on a relative scale ranging from A+++ to D for most products[99], as per the example illustrated in Figure 32.

Figure 32 - Energy Labelling Directive - Label Example (Source: European Commission, 2010)



Wiel and McMahon (2003) argue that regulatory labelling schemes that are well implemented and audited can produce very large energy savings, which are comparatively simply to quantify and readily verified. However, whilst assessment of the effectiveness of the Energy Labelling Directive are difficult to separate from that of parallel measures (particularly the Ecodesign Directive), it is unlikely that it has had any significant impact on

[98] Products covered thus far are residential ventilation units, domestic ovens and range hoods, vacuum cleaners, space heaters, water heaters, electric lamps and luminaires, household tumble driers, air conditioners, household washing machines, televisions, household refrigerating appliances, household dishwashers, household electric ovens, household combined washer driers.

[99] A+ to A+++ ratings were introduced in the 2010 recast of the Directive. Prior to this, ratings were between A and G.

overall market sizes, structure or product choices amongst consumers for the products covered (Ecofys, 2014b).

A range of factors influences the effectiveness of labelling schemes. First, effectiveness is substantially dictated by the format of the label, and how information is communicated to the consumer. The introduction of A 'plus' labels appears to have introduced confusion and a feeling of diminishing returns amongst consumers, reducing its efficacy compared to the simpler A-G scale (LE and Ipsos, 2014; Heinzle and Wüstenhagen, 2012). Additionally, around 90% of appliances covered by implementing measures fall into the 'A' category (Heinzle & Wüstenhagen, 2012). As such, under this policy pathway, the energy labels are reformed to be dynamic, with A-G classess only (with colour-coding re assigned), in order to ensure future-proofing and re-establish clarity, in line with recommendations produced by an evaluation of the existing Directive (Ecofys, 2014b).

However, other issues would remain. Sales of appliances and other energy-using products (in particular) are increasingly sold online (or over the telephone), where consumers may not be shown a label, or only told which category it falls in but not whether this is a green, yellow or red category (however, this would be partially solved by a standardised A-G ranking). Even if consumers are aware of and presented with the label, the information communicated is only effective in impacting product choice if the consumer considers it important. Waide and Watson (2013) found that almost half of their multi-country respondents considered energy efficiency a key aspect in purchase decisions for products with energy labels, with Mills and Schleich (2010) finding that a socio-economic circumstance of a household produces little difference to this effect – an opposing result to that for energy efficiency building renovation measures. However, other factors such as capital cost and product features are likely to be highly (if not more) important. Energy efficiency ratings are graded based on an assumed operating conditions of a given product (for example, a washing machine is graded according to it's energy consumption when undergoing a cotton cycle at 60°C, with a 6kg load and a supply of cold water at 15°C. Actual energy consumption reductions will depend significantly on the distribution of in-use product application around these assumptions, which ay vary significantly by demography and Member States, along with levels of potential rebound effects.

As with a number of other instrument, deficiencies in monitoring and enforcement may further reduce potential effectiveness. There is general agreement that the level of market surveillance is low, with only five members are considered to have an active surveillance policy, six countries report no activity, and the rest reporting ´moderate to low´ level of market surveillance activity. Although 15 Member States actively check compliance with the correct display of labels on products, some 20% of products are estimated to be offered for sale without the energy labels properly displayed, with 15% of products are estimated to have the label displayed in an insufficient way (e.g. wrong placement, retailer made label, label hidden or covered, etc.) (Ecofys, 2014b).

Residential Behavioural 'Nudges'

'Nudge theory' is a strain of behavioural science that looks at how the target can be encouraged to implicitly comply with policy objectives. It focuses on non-price interventions that can be just as powerful as prices in changing consumer choices, and energy policy has been shown to be an area which can benefit from 'nudging' people in the right direction (Allcott and Mullainathan, 2010), helping to overcome behavioural barriers to energy efficiency in particular. There are number of ways that insights from behavioural science can be used by policy makers to target energy demand. A key example is peer comparison. The EED currently requires energy suppliers to publish on residential consumer bills the average energy consumption for households of a similar profile, along with information on how to receive a free energy audit (discussed above), but only when 'possible and useful'. In this policy pathway, such a requirement becomes fully mandatory.

The theory behind such an instrument indicates that individuals attempt to conform to a social norm. By providing average energy consumption as 'social norm information', households with higher than average energy consumption will reduce their consumption to comply with the social norm. However, theory would also suggest a 'boomerang effect' in that those households consuming less than the average may then increasing their consumption for the same reason (Clee and Wicklund, 1980).

Various trials have been conducted to determine the potential effect of such an instrument in practice. A series of trials conducted in the USA covering nearly 600,000 households in treatment and control groups show that over 17 experiments, average energy consumption reductions of 1.4% to 3.3% were achieved, with these gains persisting over time (due to the repeated intervention at the time of each energy bill). Effects varied across households with different pre-trial energy consumption levels, with the highest-consuming decile reducing consumption by around 6%, and the lowest-consuming decile close to no change. As such, boomerang effects were not experienced (Alcott, 2011). However, Costa and Kahn [2010] found statistically significant boomerang effects in the lowest 30% of consumers (pre-trial), and also discovered that this kind of normative nudge might backfire with political conservatives, who may actually increase their electricity consumption in reactance to it. Another US-based trial generated reductions of between 1.2% to 2.1% which were sustained over time (Ayres *et al*, 2012). A similar in the London Borough of Camden, which covered 600 homes, found that the instrument induced a reduction in gas demand of 6% over a 15 month period Dolan and Metcalfe, 2013) Other trials also confirm that energy consumption reduces after the introduction of such an instrument (Allcott and Mullainathan, 2010).

However, whilst the evidence is strong that such an instrument produces energy savings on average, such an effect is relatively minor. Whilst such studies do not indicate the methods by which these savings are achieved, it is likely that, in the short run at least, they are produced by reduced demand for space heating and non-useful use of lighting and other appliances (i.e. switching off lights in rooms not occupied, or turning off electronics rather than leaving them on standby). Whilst consumers are guided on how to receive a free energy audit, and thus information on cost-effective measures to introduce, the effectiveness of such audits in driving (particularly deep) efficiency measures is questionable (as discussed above, and if, indeed, an audit is requested in the first place as a result of such advertising). The positive feedback loop produced by increasing average efficiency, which is then reported as the new norm and (theoretically) subsequently acted upon again, may produce longer-term benefits than relatively short trials have been able to produce. However, either way, any improvements over time will be limited by cost-effectiveness, and the relationship between initial capital costs and discounted savings over time.

3.4.4 Transport

Table 12 presents a brief summary of the policy instruments proposed for the 'transport' sector under the 'behaviour-based' policy pathway. **CO_2 Emission Standards** for passenger cars remain the core instrument, whilst CO_2 labelling of vehicles are reformed and expanded to LGVs and HGVs. Personalised transport planning is introduced, to encourage improved transport decision making.

Table 12 - Behaviour-Based Policy Pathway - Transport

Policy Instrument	Description
CO_2 labelling of Vehicles	The Directive on CO_2 labelling of cars is reformed to cover LGVs and HGVs, whilst labels across the EU are harmonised.
Personalised Travel Planning	Instruments are introduced in all large urban areas and commuter belts in the EU to provide information, incentives and motivation to individuals to optimise their travel habits and modes.

CO_2 labelling of Vehicles

As with other labelling and information instruments, Directive 1999/94/EC on the CO_2 labelling of cars attempts to provide consumers with information on the fuel economy and CO_2 intensity of vehicles to allow them to make more informed purchase decisions. Member States must ensure that a label is attached to each new passenger car at point of sale (or lease), or displayed nearby. Labels must conform to Member States-specific label formats; at a minimum they must contain the numerical value of the official fuel consumption of the car to which the label is attached (expressed in litres per 100km (l/100km), or variations of magnitude), and the specific emissions of CO_2 (expressed in grams per kilometre (gCO_2/km)). Several countries take a similar approach to that of the Energy Labelling Directive (discussed above), but slightly varied approach. For example, bands may be set relative to specific emissions of cars of the same type (e.g. Germany and Spain), whilst others set an 'absolute' banding, comparing a specific vehicle's emissions against all other cars on the market (e.g. UK, France, Denmark) (Drummond, 2013). Under this policy pathway, labelling formats are harmonised across Member States (along the lines of the Energy Labelling Directive formatting), must include information on running costs, and are expanded to LGVs and HGVs. These proposals were put forward by the Commission in 2007 (Drummond, 2013).

Various studies have concluded that these car labelling requirements have had no noticeable effect on consumer purchasing decisions (Gartner, 2005; AEA, 2011; Codagnone *et al*, 2013). This largely results from the relatively low importance placed on environmental concerns by the general populous when making a car purchase decision; in a survey conducted by

Codagnone *et al* (2013), it ranked eleventh, after aspects including price, safety and performance. Consumers generally first select a class of vehicle, and only may consider environmental performance when selecting a specific model. This lack of priority is compounded by a lack of awareness of the labels, and even when this exists, a lack of understanding is also evident. For example, the above-mentioned survey found that many respondents confused the label as symbolising reliability. Additionally, as the majority of Member States do not require these labels for the sale of second-hand vehicles, the instrument does not cover a significant proportion of the passenger car market (with significant variations across Member States). In contrast to many other similar instruments discussed in this report, it appears that levels of non-compliance are relatively low (Gartner, 2005), and thus not likely to be a significant driver behind the apparent ineffectiveness of this instrument.

As such, it is not clear to what extent implementing the reforms proposed above what increase the effectiveness of this instrument. Codagnone *et al* (2013) tested various labelling designs/structures, and concluded that labels are more effective when running costs and savings are presented. Requiring a standardised EU-wide format along the lines used for energy-related products under the Energy Labelling Directive may also improve understanding. However, both reforms rely on awareness of the labels in the first place. Other items discussed above are also likely to remain of a higher importance – particularly that of capital cost which, as previously discussed, are of a higher significance than savings achieved over time, due to the discounting of such items. Additionally, the continued presence of company car tax distortions (discussed under Section 3.2.4), render any fuel savings achieved through the purchase of more efficient vehicles, redundant to these consumers. The effect expansion of labelling requirements to LGVs and HGVs would have is also unclear. However, issues of fuel efficiency (for HGVs in particular) are paramount for these industries, and thus the provision of information in a different (albeit more available format) is not likely to produce significant changes over time, above that resulting from other influences (such as fuel prices and efficiency regulation).

Personalised Travel Planning

'Soft' transport policy measures aim to directly influence decision making by altering perceptions of the objective environment, by altering judgements of the consequences associated with different travel alternatives, and by motivating and empowering individuals to switch to alternative travel options (Bamberg *et al*, 2011). Many instruments and initiatives may fall under this definition. Under this policy pathway, 'Personalised Travel Planning' (PTP) instruments are introduced by Member States across all large urban areas and commuter belts. PTP provides information, incentives and motivation tailored to the individual, rather than through general mass marketing methods (Ker, 2003).

PTP instruments have been extensively trialled across the world. A review of PTPs in several cities across the world calculated that these instruments produced a reduction in car use of between 2% and 15% (DETRA, 2004). In London, four PTP pilots reduced car usage by 5%-11% (Transport for London, 2004). A meta-analysis of the effectiveness of 10 PTP instrument across four cities in Japan determined that a total of an 18% reduction in car use was produced, along with a 50% increase in public transport, producing a 19% reduction in CO_2 emissions (Fujii and Taniguchi, 2006). Based on a review of 32 PTP programs in Sweden Friman *et al* (2013) conclude that positive effects are on a par with the results observed in other countries. In 7 of these programs, which focussed on car users, the reduction in the number of car trips is 22%. The majority of programs aimed at promoting the use of public busses over private cars. On average, these programs led to an increase in the number of bus trips by 36% (ranging between 2% and 93%). Two programs that aimed at increasing bicycle use report an average increase of 43 % in bicycle trips.

According to Cairns *et al* (2004) PTP instrument are amongst those that promise the largest potential to reduce car travel. However, it appears individual policy design is significant in determining the magnitude and type of impact[100]. The primary aim of many PTP instruments is to encourage mode shifting away from private cars to other means. The mode to which travel demand is shifted depends on the design and purpose of the instrument, and the options available (e.g. whether public transport options, or cycle routes, are available). However, there is little evidence to suggest that PTP instruments influence the purchase of low carbon private cars. Regarding long-term impacts, the evidence is generally positive that the effects generated are maintained – although longer term studies will be required to produce evidence for truly long-term impacts (Maca *et al*, 2013).

Richter *et al* (2009) highlight that PTP and other soft transport policy measures have different impacts on different target groups. For example, people with strong habitual car use seem to be less likely to participate in soft policy measures, underscoring the importance of personal characteristics and attitudes. They underline that although some results indicate that soft policy measures are more effective in promoting public transport to non-frequent public-transport users than to frequent public-transport users (Fujii and Taniguchi, 2006), the latter are more likely to participate in the first place (Seethaler and Rose, 2005). Additionally, a PTP instrument does influence LGV and HGV operators, and due to the lack of economic incentives for a reduction in travel demand or mode shift, drivers of company car drivers are unlikely to be substantially impacted.

3.4.5 Summary of the Behaviour-Based Policy Pathway

This pathway principally employs instruments designed to influence and modify behaviour, to produce a preference for low-carbon technologies and behaviours, and to tackle behavioural barriers to the uptake of technologies that would otherwise be selected. However, a common issue across sectors in this pathway is the apparent lack of substantive effect that evidence suggests such instruments often have. Pricing and regulatory instruments still underpin whether or not technological change is likely to be delivered at anywhere near the appropriate scale. In the industry sector, for example, organisational inertia, capacity and

[100] A discussion of specific design aspects and their impacts may be found in Maca *et al* (2013).

structural issues are likely to remain barriers for uptake of additional, cost-effective energy efficiency and low-carbon options, particularly in smaller industrial sectors, preventing informational instruments from producing any substantive impact. The EU ETS is likely to remain the driving force.

In the buildings and transport sectors, existing regulatory and pricing instruments are also likely to be by far the most significant drivers and barriers to a technological shift. Building energy performance standards and energy efficiency obligation schemes in the former, for example, and CO_2 intensity regulations in the latter (with uncorrected company car taxation rules perpetuating existing distortions). In both sectors, the evidence suggests that labelling and other information measures have likely been ineffective thus far, as energy or CO_2 emissions are not a significant concern to consumers, or information is simply not believed. However, with more ambitious scope and level of implementation, along with amendments to potential drawbacks in instrument design, it is possible that long-term cultural changes may see increasing impact from these instruments (and perhaps partially induced by them).

3.5 Energy and CO_2 Transmission & Distribution Networks

Electricity Transmission, Distribution and Management Infrastructure

Barriers to deployment of the required electricity transmission and distribution networks (including interconnections), as discussed in Section 2.5, may be split into four broad categories. The first is technical. For example, technologies produced by different vendors must be interoperable, and able to safely and effectively connect to other components of the network. Three of the ten 'network codes' (set of rules governing various aspects of the electricity network), namely the three 'connection' codes currently being developed under Regulation 714/2009 (discussed further below), addresses such issues. Figure 33, below, illustrates the status of these three codes (RFG, DCC and HVDC). As each of the codes are not yet in force, it is not clear to what extent (non-market) technical issues will be resolved by these instruments, however it is unlikely that they will leave technical issues unaddressed that would be prohibitive for the development of the required infrastructure.

The second category surrounds authorisation, planning and procedural issues. In 2006 the European Network of Transmission Service Operators - Electricity (ENTSO-E) analysed the legal and administrative procedures for constructing 110-400 kV overhead lines in the EU. The results showed that legal structures are comparable and largely conducive to development in all Member States, but planning, authorisation and implementation processes varied significantly, and often constitute a substantial barrier (Battaglini *et al*, 2012). Such issues are discussed below.

The third category concerns finance. Particularly, how new transmission and distribution assets are paid for, and who bears the cost. Within a Member State, Transmission System Operators (TSOs), the organisations that own and in most cases operate the grid, finance investments in new infrastructure through debt and equity, and receive revenue though tariffs regulated by national regulatory agencies that generally define a revenue cap intended to reflect capital costs, depreciation and operation costs of an efficient TSO (ENTSOE, 2014b).

However, such tariffs and revenue caps are set based on realised costs of past years. This allowed suitable returns and allowed for reinvestments when requirements were largely stable. However, the rapid increase in transmission and distribution infrastructure required will need substantial increases in investment finance, rendering the existing approach unsustainable. Various methods are available to do this, including altering the tariff and revenue cap calculation, equity injections, dividend reductions and project bonds (ENTSOE, 2014). However, an arguably more difficult issue to solve is financing from cross-border interconnectors. Interconnection infrastructure in Europe is generally built on the basis of 'user commitments', following agreement between TSOs and regulators in each jurisdiction. Usually, countries that are net importers ultimately pay those that are net exporters via a centrally administered fund, with costs recovered from consumers via tariffs descried above. However, producing such agreements becomes increasingly difficult as the benefits of interconnectors possibly become more regional than national, where a link between two countries primarily benefits a third country, or where projects are very risky. The ability to finance International transmission lines through the 'merchant interconnector' model, in which operators may profit from the difference in electricity prices between countries, will also reduce over time as the single electricity market becomes established, producing price convergence (UK Parliament, 2011). A key solution to this is likely to be the use of centralised European funds, such the general Structural and Investment Funds, or the more specific packages such as the Connecting Europe Facility (CEF). The CEF provides funding for Projects of Common Interest (PCIs) across transport, telecommunications and energy, with €5.35 billion dedicated to the latter (around 3% of total investment requirements to 2020 (European Commission, 2015)). Although these funds can leverage other finance, a substantial increase is likely needed. Additionally, the access criteria may be extended beyond PICs to sub-national projects, helping to circumvent issues of funding such projects, as discussed above. However, increasing centralisation of EU policy making would likely be required to achieve this.

The final category of barriers, linked to the above issues, is political. For example, Member States are unlikely to be willing to invest in new infrastructure, politically interconnectors, if the beneficiaries lay primarily within another Member State. Interconnections between France and Spain have been reportedly delayed due to fears that low marginal cost renewable generation from Spain would undermine nuclear generators in France – a highly political issue. Such an issue is difficult to overcome with policy instruments. Public opposition (discussed further below), for both inter- and intra-Member State infrastructure may also dictate national political stances.

As described in Section 2.5, the Third Energy Package requires smart meters be deployed to at least 80% of electricity consumers in the EU by 2020. At present, penetration is at around 20%. Deployment levels in each Member State may be conditional on a positive cost-benefit analysis, with the 80% target then applicable to only positively assessed cases. CBA assessments proved positive to around two-thirds of electricity consumers. As such (European Commission, 2014b)

- **16 Member States** (Austria, Denmark, Estonia, Finland, France, Greece, Ireland, Italy, Luxemburg, Malta, Netherlands, Poland, Romania, Spain, Sweden and the UK) will proceed with large-scale roll-out of smart meters by 2020 or earlier, or have already done so. In two of them, namely in Poland and Romania, the CBAs yielded positive results but official decisions on roll-out are still pending;
- In **7 Member States** (Belgium, the Czech Republic, Germany, Latvia, Lithuania, Portugal, and Slovakia), the CBAs for large-scale roll-out by 2020 were negative or inconclusive, but in Germany, Latvia and Slovakia smart metering was found to be economically justified for particular groups of customers;
- For **4 Member States** (Bulgaria, Cyprus, Hungary and Slovenia), the CBAs or rollout plans were not available at the time of writing; and
- Legislation for electricity smart meters is in place in the majority of Member States, providing for a legal framework for deployment and/or regulating specific matters such as timeline of the roll-out, or setting technical specifications for the meters, etc. Only five Member States (Belgium, Bulgaria, Hungary, Latvia and Lithuania) have no such legislation in place.

The European Commission (2014b) estimate that the above commitments will deliver around 200 million smart meters by 2020, representing 72% of all European electricity consumers. However, only eight of the 16 Member States proceeding with a large scale rollout require functionalities in line with Recommendation 2012/148/EU (described under Section 2.5). Of the remaining 8, 7 do not comply with the functionality to deliver frequently updated consumption data delivered to the consumer, to enable consumers to make informed choices on their consumption patterns and facilitate the development of new retail services and products (European Commission, 2014b). As such, whilst it appears the target of 80% rollout will be largely achieved by existing regulations (particularly as positive CBA evaluations are likely to increase over time), interoperability and functionality issues may remain if the minimum requirements suggested by Recommendation 2012/148/EU are not made mandatory, along with an under-realised potential of the awareness-raising aspect of smart meters.

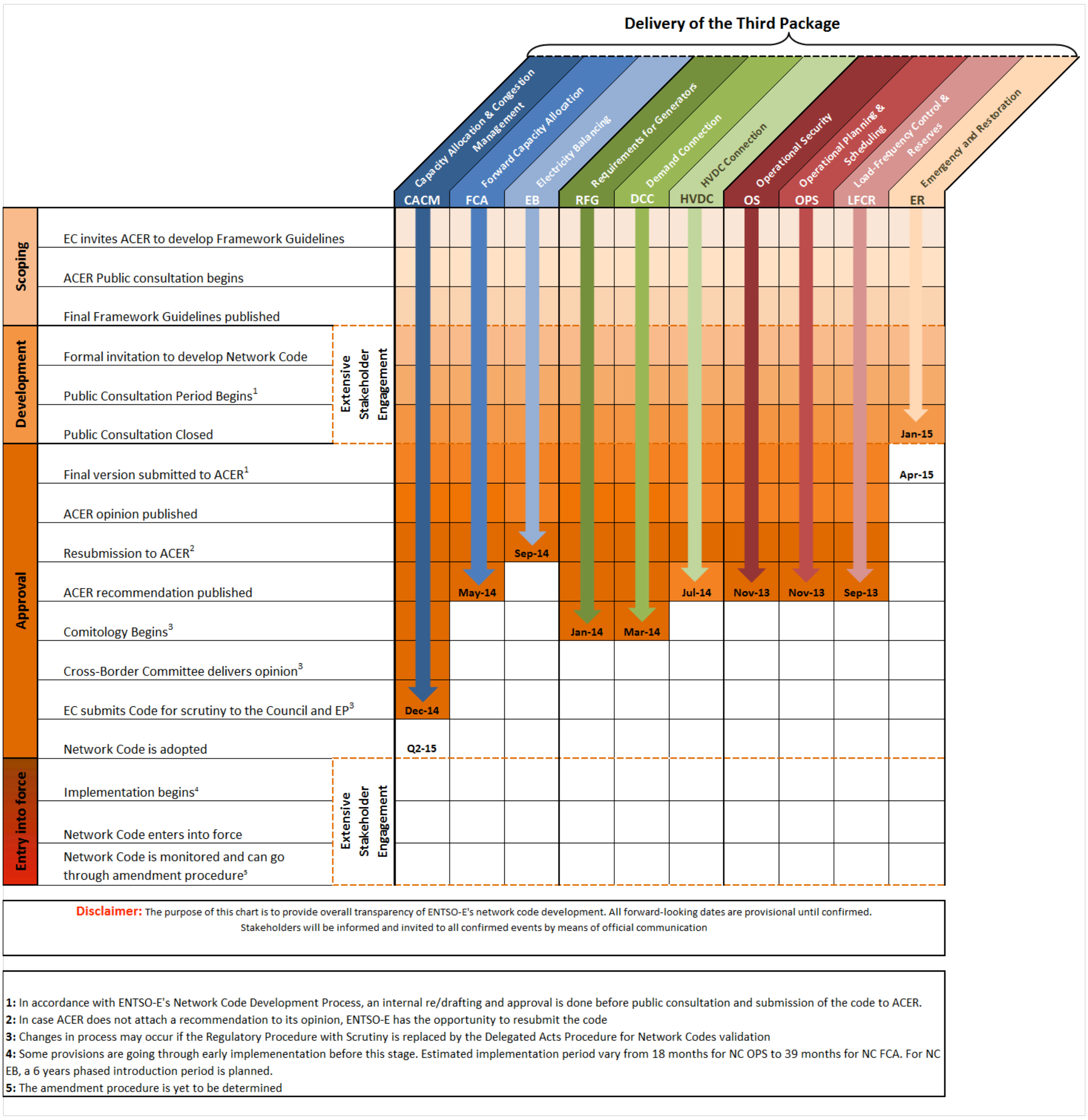
Electricity Market Design

There are two key issues that must be addressed to ensure that a single electricity market with a significant penetration of renewable power functions as required. The first is ensuring that all Member States and other actors in the system operate in a compatible manner.

The Third Energy Package is the main legislative instrument for achieving such compatibility (see Footnote 47). Key provisions have been largely achieved (e.g. 96 of the approximately 100 TSOs are compliant with the 'unbundling' requirements), although full implantation is still required across all Member States (European Commission, 2014d). The Third Energy Package also envisages the introduction of a harmonised legal framework for the operation of the single electricity market through the implementation of 10 'network codes' (set of rules governing various aspects of the electricity network), made operational under Regulation 714/2009. These may be categorised broadly into **Connection Codes** (including

Requirements for Generators, *Demand Connection and HVDC Connections*), **Operational Codes** (including *Operational Security, Operational Planning and Scheduling,* and *Load Frequency Control and Reserves*), and **Market Codes** (*Capacity Allocation and Congestion Management*, *Forward Capacity Allocation* and *Electricity Balancing*). A final 'stand-alone' code concerns *Emergency and Restoration*[101]. Figure 33 illustrates the level of implementation for each network code.

Figure 33 - Network Codes Implementation Status (Source: ENTSOE, 2015)



As is clear, no network code has yet entered into legal force. As such, it is not clear how long it will be, and to what extent Member States and regulatory authorities will adopt these codes, and thus reduce barriers to the operation of an effective single market.

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[101] See http://networkcodes.entsoe.eu/ for more information regarding each of the codes.

Once a harmonised framework of operation is in place across Member States, the second issue yet remains. As discussed in Section 3.2.1, the current structure of the electricity market is not suited to the increasing penetration of renewable electricity. The 'missing money' problem prevents investment in new capacity of any kind (particularly conventional generation, required for back-up against intermittent renewable generation), whilst differentiated support mechanisms for renewables produce market distortions.

Various options exist to reform the electricity market to guard against such issues. The first would be to harmonise the structure, although not necessarily the level, of national RES-E support mechanisms (Buchan, 2012). However, such an approach may require increased centralisation of EU policy making.

As discussed in Section 2.5, a fully integrated supergrid with a single market substantially contributes to the levelling of electricity supply and demand within a single Member State or region, reducing the need for investment in back-up, non-intermittent capacity. However, as discussed in Section 2.1, such capacity (largely nuclear and gas) will still be required to some degree. A key option for maintaining such capacity that would no longer receive requisite revenue from the market is the introduction of 'capacity mechanisms', which may be of various design, but all provide payments to generators in return for bringing a certain level of capacity online when required. Around half of all Member States have introduced, or have proposed the introduction of, capacity mechanisms to ensure presence of and investment in adequate back-up supply (Platts, 2015). However, as with renewable subsidies, misalignment of capacity mechanisms may cause market distortions, which would require alignment, or the introduction of an EU-wide mechanism, to resolve. The network codes (particularly on Forward Capacity Allocation) will go some way to addressing this. Capacity mechanisms may also employ demand side dynamics. For example, in a mechanism that secures capacity via auction, large industrial consumers may bid to reduce their demand by a level equivalent to the additional capacity level required at the time requested, thereby offsetting the need for additional capacity and generation in the first place. As discussed under Section 2.5, the deployment of smart meters and the use of dynamic pricing, particularly coupled with smart appliances, furthers the ability for dynamic demand response to reduce the need for additional capacity (overall, and backup), and capacity mechanisms to deliver it.

Although the increasing penetration of RES-E has the effect of reducing wholesale electricity prices, even with full single market implementation, total electricity retail prices are likely to increase to the medium term, at least. This is a result of increasing total subsidy costs for this RES-E deployment, the EU ETS on fossil fuel generation, capacity mechanism payments (which the European Commission (2013) estimates will add 10%-20% on wholesale prices), and potential increased tariffs to allow investment in new transmission infrastructure. However, to what extent this occurs against the counterfactual depends on the interplay between these factors, the specific design of these instrument (e.g. whether any are contributed to or covered by general taxation), and infrastructure cost (including RES-E technologies) and fossil fuel price developments.

Low-Carbon Vehicle Energy Supply Infrastructure

In September 2014, the EU adopted Directive 2014/94/EU, on the deployment of alternative fuels infrastructure. The Directive holds three broad objectives and requirements. The first is to require Member States to develop national policy frameworks for the market development of alternative fuels and their infrastructure. Each Member State must ensure that the requisite number of publicly available electric recharging points is in place by 31st December 2020 to ensure that electric vehicles are able to circulate at least in urban and suburban agglomerations and other densely populated areas. Of Member States that choose to adopt hydrogen and fuel cell vehicles, an appropriate number of refuelling points must be available to ensure circulation of such vehicles within nationally determined networks (including cross-border links), by 31st December 2025. The second requirement is the standardised design of such charging and refuelling points as detailed in Annex II of the Directive (for AC electric charging points, Type 2 must become the standard), implemented by November 2017. The third requirement is the provision of appropriate consumer information on alternative fuels, including a clear and sound price comparison methodology.

Member States have until September 2016 to transpose these requirements into national law. It is difficult to determine the extent to which these requirements will be implemented and complied with, and whether the mandated timeframes will be met. However, if all requirements are met, it would seem that electric charging infrastructure would reach suitable levels (and interoperability) to enable a broad shift to such vehicles as detailed in Section 2.4. However, as the uptake of hydrogen infrastructure is voluntary and co-ordinated at the Member State level, it would seem that existing policy facilitates, but does not yet encourage widespread development of hydrogen infrastructure for HGVs. Over time, as hydrogen vehicles and fuel cell technologies become more cost-effective, it may be beneficial for requirements to facilitate long-distance HGV travel across the EU to be implemented.

CO_2 Transportation and Storage

The CCS Directive (2009/31/EC) establishes a legal framework for the environmentally safe geological storage of CO_2 captured by CCS technology (Drummond, 2013[102]). Transportation infrastructure are largely addressed by other Directives, such as the Environmental Impact Assessment Directive (2014/52/EU) (European Commission, 2015e), However, CO_2 transportation-specific issues are not fully addressed, such as CO_2 stream composition standards. Such items may be considered for inclusion under the CCS Directive in the longer term, under the next review of the Directive (Morbee *et al*, 2010).

Spatial Planning and Authorisation

Spatial planning and other authorisation procedures have proven a hindrance to the deployment of various types of infrastructure. Permission processes to construct long-distance, cross border interconnectors may take up to 20 years in some cases. Battaglini *et al* (2012) concluded that the main reason for this is the complexity and unpredictability of procedures and decision making at local authority level, several jurisdictions of which such

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[102] Refer to this reference for a full description of the CCS Directive.

projects must often pass. Such unpredictability derives from various sources. Firstly, the strong interrelation between goals related to energy system, spatial planning and other environmental objectives, and the potential trade-offs between them. Secondly, the high number of stakeholders involved in such processes, both within and across jurisdictions. Alongside transmission and distribution system operators, environmental authorities, national and regional authorities, administrative bodies, NGOs and regional citizens' organisations interact with the planning process and may naturally delay the process significantly, particularly if opposing views are held. Indeed, public resistance driven by fear of negative health impacts and a general reduction of well-being and quality of life, concerns of negative economic impacts to the local area and environmental concerns, are common reasons for delays to and even prevention of the development of new transmission and distribution infrastructure projects (Boie *et al*, 2014).

Member States and European institutions must work to overcome such barriers to enable the required development of the grid. Requirements to do so are already present in various forms. For example, Community guidelines for Trans-European Energy Networks (TEN-E) stress the importance of facilitating and speeding up the completion of PCIs, and Member States must take all measures necessary to minimise administrative delays. The guidelines also establish a framework for closer cooperation between Member States, providing for an exchange of information and active communication to reduce barriers to the construction of interconnectors (European Commission, 2007). One of the five main objectives of the Priority Interconnection Plan (PIP), which proposes actions to ensure a stable environment favourable to investments in interconnectors, is to 'accelerate planning and authorisation procedures by encouraging their simplification and harmonization, and obliging the Member States to establish national procedures to ensure that planning and approval for projects of European interest are completed within a maximum five-year period' (European Commission, 2008).

However, despite this, Zane *et al* (2012) find that most Member States do not have regulatory and management environments that contribute positively to the development of the grid to the level required to facilitate extensive RES-E deployment. However, some Member States have made progress to overcoming such issues. For example, in light of the slow construction of power lines, Germany reformed its authorisation and planning procedures. In 2011, Germany adopted the Grid Acceleration Law, which included new rules for public participation, a shift of authorisation competences from the regional (Lander) to the federal level, and stricter deadlines and instruments to force grid operators not to delay the procedure. Also, in 2013 another law required the construction of 2800 km new power lines by 2022 and introduced the use of HVDC power lines and extended the usage of underground cables. Uniformity of rules and administrative practices through a national, single authority could facilitate the procedure and reduce bureaucracy for such sub-national and inter-state infrastructure that are otherwise subject to procedures in several jurisdictions, across all Member States (Steinbach, 2013).

Complex and opaque planning and permission processes are also prevalent for the installation of RES-E capacity. The Renewable Energy Directive requires Member States to set rules regarding authorisation, certification and licencing of renewable installations to be objective, transparent and streamlined, to reduce the barrier such issues currently present. However, most Member States still require multiple permissions and permits to be granted, with only Greece, Portugal, Denmark, Italy and the Netherlands operating a nationwide 'one stop shop' or single permit approach (although some states, such as Germany and Sweden, have such processes in place for certain technologies or at a sub-national level). Enforcement of the RED on this issue will therefore contribute to reducing these barriers. Planning consent for installations remains a significant issue in some Member States. This is often linked to the public (and therefore political) acceptability and attitude towards such installations. Although the majority of EU citizens are pro-renewables (71% 'very positive' about the use of wind energy in their country, for example), this varies by Member State, and often comes in the form of local opposition, or 'NIMBYism' (Not In My Back Yard). Indeed, this is often a key factor impeding the granting of planning permission for wind installations (often the target of the most severe opposition – particularly onshore) (del Rio and Tarancon, 2012). This is particularly the case for the UK, in which it is often cited as the largest barrier to additional RES-E capacity (Butler and Neuhoff, 2008), but also France (del Rio and Tarancon, 2012). Public acceptance of RES-E technologies in Germany is very high, and although there is evidence to show that a very high proportion of the projects that do not go ahead in Germany are a result of a refusal of planning permission, this is much less of an issue than the UK, for example (Butler and Neuhoff, 2008). As with grid-related planning reforms, improved stakeholder engagement may help overcome some such barriers, however ingrained norms and cultural values are often a significant influence, and thus difficult to overcome with policy measures in the short term.

4 Discussion and Conclusions

It is clear that a substantial shift in the physical characteristics of the EU's energy system is required to achieve an 80% reduction in CO_2 emissions by 2050 (from 1990 levels), with various interdependencies presenting themselves. Principal among these is the decarbonisation of electricity generation, to allow for increased electrification of key demand sectors (buildings and transport, in particular). In addition, the minimum requirements for each sector highlighted in Chapter 2 must be recognised as such. It is likely that an effort more than the sum of these minima must be reached, meaning that some (if not all) sectors must decarbonise yet further to achieve the summary target.

Three stylised policy pathways have been presented; a 'market-based' pathway, a 'technology-based' pathway, and a 'behaviour-based' pathway, broadly based on each of the three 'pillars of policy' proposed by Grubb (2014), and developed for the purposes of this report by Rey *et al* (2014). The market-based policy pathway principally employs carbon pricing and other pricing mechanisms to drive decarbonisation. It is likely that such a pathway has a substantial chance of achieving many of the requirements discussed in Chapter 2, however the potential for price instability, and unknown technological cost development produces a great deal of uncertainty. Principal-agent issues, along with information asymmetries and behaviour and psychological issues (at both the individual and organisation level) present other barriers to technological shifts. The technology-based policy pathway focuses on the use of direct regulatory instruments. As with the market-based policy pathway, upon initial inspection it would appear this option also holds a reasonable chance of achieving the required objectives. However, whilst issues of uncertainty and principal-agent problems, for example, are reduced compared to the market-based pathway, issues of monitoring and enforcement of regulations may become prominent, calling this conclusion into question. Technological change in the behaviour-based policy pathway is likely to be driven primarily by remaining pricing and regulatory instruments, rather than information and other behavioural instruments. The evidence suggests that information and other instruments designed to modify and overcome barriers to behaviour change have thus far proven largely ineffective – although this may change over time with awareness, culture, and improved scope and instrument design.

It is evident that any effective policy mix for decarbonisation of the EUs energy system must include components from all three approaches, to counter the drawbacks inherent in focussing on a single paradigm, and to produce synergies that would otherwise not arise. For example, in the residential buildings sector, Warren (2015) highlights that utility obligations work well when combined with minimum energy performance standards, labelling, and tax incentives or subsidies. Similarly, in the transport sector, the EEA (2010) conclude that instruments targeted at altering specific behaviours, whilst simultaneously using existing technological and economic instruments, will increase the likelihood of sustaining long-lasting emissions reductions. Such a combined approach is in fact central to the three 'pillars of policy' approach proposed by Grubb (2014). However, the particular configuration of policy instruments must consider issues other than simple 'effectiveness', as employed in this report. Issues of cost-efficiency, both static and dynamic, must be considered. In the longer term, dynamic incentives for innovation are particularly important in order to deliver some of the key technologies (e.g. CCS), and produce cost reductions (e.g. renewable and low-carbon vehicle technologies), discussed above. Additionally, of course, policy instruments and instrument mixes must be feasibly introduced and complied with. This includes the interrelated issues of public and political acceptability, legal compatibility and administrative ability. Such aspects are the focus of other reports under the CECILIA research project.

Some aspects may be summarised from this report that may be classified as key 'bottlenecks'; issues for which if progress if not made or solutions not found within the near future, they may act as significant hurdles or even barriers to achieving the CO_2 emissions reductions sought in the required timeframe. Below are listed the most prominent of such bottlenecks:

- **Electricity grid expansion and interconnection**. As discussed in Section 2.5, an annual increase of around 1% in electricity transmission network length is likely required between now and 2030, along with substantial investment to upgrade existing transmission and distribution infrastructure, to enable an approximate doubling of (largely renewable) electricity capacity to come online (both centralised and decentralised). This includes an on average doubling in interconnector capacity between Member States. Such objectives must be achieved to enable rapid, cost-efficient decarbonisation of the electricity generation, whilst maintaining electricity security. This includes consideration of methods of financing and authorisation procedures, discussed below.
- **Electricity market design**. The existing EU electricity markets, with increasing renewable electricity capacity, are expected to produce an inherent 'missing money' problem, where renewable, nuclear and fossil fuel generators alike cannot generate sufficient revenue from the market to cover their levelised costs. This prevents investment in any installation that does not receive enough external subsidy to substitute for this (particularly fossil fuels), risking security of supply issues. Electricity market designs, either a single EU integrated market or aligned national markets, must be reformulated or complemented (e.g. with capacity markets) in the near future to account for this.
- **Streamlined, integrated and permissive administration and authorisation procedures.** Authorisation and planning procedures have proven to be significant barriers to the development of low-carbon or enabling infrastructure – particularly transmission infrastructure and renewable electricity installations. Such barriers must be removed to permit the development of such essential infrastructure.
- **Incentives to transition to low-carbon electricity generation and capacity profile.** Although an expanded, interconnected grid and suitable electricity market design allows for the development of a low-carbon power sector, it will not (necessarily) drive it. Other incentives will be required, which will likely include reforms to the EU ETS to produce a higher, more predictable carbon price, and depending on the specific design of a future electricity market, the presence of some form of renewable electricity support mechanism (either centralised at the EU level, or more likely harmonised to a substantial degree across Member States). It is unlikely that decarbonisation of the power sector would be successfully delivered without such instruments working in tandem, particularly in the short term. Although which of these, or any other instruments, is the driving force, may vary depending on the particular policy mix employed.
- **Decarbonisation of the existing residential building stock.** Over 80% of the residential building stock expected to be present in 2050 in the EU is already in existence. Energy consumption by these buildings must reduce by at least 0.6% per year between 2015 and 2050. Whilst the EED currently requires energy savings of 1.5% per year (across both residential and commercial consumers), this requirement ends in 2020, and evidence suggests that of the 17 Member States that have chosen to implement EEOS mechanisms to fulfil this obligation, 14 have credibility concerns. Issues such as appropriate financial incentives, the landlord-tenant dilemma, access to and cost of capital, the 'hassle factor',

discounting of costs and benefits and other behavioural issues are persistent problems that often prevent the voluntary installation and introduction of energy efficient and low-carbon technologies and behaviours. At present, the EU policy mix does not sufficiently tackle these issues in order to produce conditions conducive to long-term reductions in energy consumption and CO_2 emissions from this sector. In order to achieve the average annual reduction outlined above over the coming 35 years, and given the long life of such infrastructure and investments, this should be addressed as a matter of urgency.

For the (road) transport and industrial sectors, no particular issues were identified that constitute urgent bottlenecks of a similar nature to those outlined above (in terms of instrument 'effectiveness', as used in this paper, at least). For example, the passenger car stock is fully replaced approximately every 15 years, meaning that substantial decarbonisation under an effective policy mix results may be delivered relatively quickly. Additionally, requirements are already in place to ensure electric vehicle charging networks are established to allow circulation of such vehicles in urban and suburban conglomerations by 2020. In the industrial sector, as energy is a major cost liability for the most energy- and CO_2-intensive sectors, the reform of the EU ETS may produce relatively rapid increases in efficiency and low-carbon measures. However, one such measure is the widespread introduction of CCS on industrial processes. This is heavily dependent on the availability and associated cost of such technology. Whilst this paper assumes it will be commercially available when it is required, efforts are needed to ensure that this will indeed be the case, along with technological availability and cost reductions in other sectors, although such issues are outside the scope of this report. However, substantial action is still required in order to meet and exceed the minimum requirements outlined for all sectors discussed, driven by improvements and changes that will be required to the existing climate policy mix, over the short-, medium- and long-term.

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