Annex 2

Overview of Roadmap exercises from other organisations: European Commission, Eurelectric and Greenpeace

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This annex gives a short overview of selected Roadmap exercises commissioned by a range of different stakeholders from a public entity, business and NGO point of view. The objective of the annex is to provide a brief synopsis of the methodology used, and identify the key pathways and assumptions in these different Roadmap studies. The reader should note that the following overview is deliberately brief in nature. The reader should consult the examined studies for a more detailed understanding of the different reports. Any omission is solely due to the author.

I. European Commission's Roadmap for moving to a Low Carbon Economy in 2050 (2011)

- *Background information*

The European Commission's *Low Carbon Economy Roadmap* is a key part of the resource-efficiency flagship from the Europe 2020 Strategy. It does not provide concrete policy recommendations but rather in-depth analysis on trends of global climate action, energy and technology developments, which are to provide basis for sectoral policy proposals. The *Low Carbon Economy Roadmap* was published on the same day as the Energy Efficiency Plan and this might not be a coincidence – the Roadmap places an emphasis on the need for the EU to strengthen its efforts for achieving the 20% efficiency target. The Roadmap outlines milestones which would show whether the EU is on course for reaching its target, policy challenges, investment needs and opportunities in different sectors, bearing in mind that the 80 to 95% reduction objective in the EU will largely need to be met internally.

- *Modelling approach*

The methodology applied uses energy system modelling tools that project the evolution in supply and demand sectors in a coherent manner, without looking at any sector in isolation. This coherent modelling set also allows taking into account resulting changes in energy prices, an important driver for change in the energy system. The models used are POLES for the global energy system modelling and PRIMES for the EU energy system modelling. The Non CO_2 emissions from agriculture and industry are assessed with the GAINS model, with input from the CAPRI agricultural model to assess production from agriculture and subsequent emissions (e.g. livestock emissions, emissions from fertiliser use). The land use, land use change and forestry emissions and removals are assessed with the G4M and GLOBIOM.

- *Scenarios and key assumptions*

The *Low Carbon Economy Roadmap* aims to give insight on how the EU policy framework should develop in the next 10 years and beyond to (1) enable deep reductions of greenhouse gas emissions consistent with science while at the same time (2) reduce vulnerability to oil shocks and other energy security concerns, and (3) reap opportunities for sustainable growth and jobs. The impact assessment accompanying the Roadmap gives information on the overall and sectoral pathways, the underlying technological and structural changes required, the investment and cost patterns, and impacts on energy security that would need to be associated with a economy that decarbonises by 2050.

A set of possible future 'decarbonisation' scenarios is assessed and compared to a reference scenario that projects existing policies. The impact study does this at two levels, the global level, because climate change and energy security are to a great extent global problems and cannot be addressed by looking at the EU only, and, as primary focus of the analysis, at EU level, but consistent with the different global settings. The key scenarios analysed are *Global Climate Action* (-80% GHG in EU plus global climate action which reduces energy import prices) and *Fragmented Climate Action* (explores the important possible consequences if the world did not act in line with the 2ºC target, but the EU would maintain its policy of climate leadership and act consistently with available scientific evidence of what the required reduction effort should be) which are compared to a Reference scenario (current trends policies).

In the context of *Global Climate Action,* the model explores three key decarbonisation scenarios for the EU - *Effective and Widely Accepted Technology* (enabling framework for all technologies is ensured); *Delayed CCS* and *Delayed electrification*. Under *Fragmented Global Action* the model develops two scenarios - *High oil price and Oil shock* (oil shock occurring in 2030; structural increase of fossil fuel prices from 2030 onwards). The impact assessment also explores the effects of a *Delayed climate action (*studies the impacts of a 10-year delay to further climate action beyond the current Climate and Energy package) and *Specific measures for sectors exposed to global competition* (where carbon leakage concerns are addressed and society compensates additional costs for energy intensive industry).

In the *Reference* scenario international **fossil fuel price** assumptions follow global baseline projections: oil prices increase to 127 $(08)/barrel; gas prices reach 98 $(08)/boe whereas coal prices remain much lower at 30 $(08)/boe by 2050. In the context of *Global climate action*, international energy prices increase but not as rapidly as under *Reference* (for oil by 2050 prices go up to $70/barrel; for gas $43 boe, which represents a reduction of almost 50% on *Reference*).

Carbon prices in the *Reference scenario* are around 50 € per ton of $CO_{2\text{-eq.}}$ from 2030 onwards. For the Decarbonisation scenarios, the carbon price is projected to reach levels of above 100€ per ton of $CO_{2\text{-eq}}$ per 2050 (370€ under Global action and delayed CCS). Carbon prices increase if climate action is delayed.

The energy projections underpinning the *Global action* scenario project a 38% increase in **world primary energy demand** by 2050. But this increase is significantly smaller than in the baseline (149%). The *Fragmented action scenario* has a global energy demand increase of 124%, which is not very different from the baseline case.

In the EU, **energy demand** under both *Global Climate Action* and *Fragmented Action* returns to 1990 levels by 2020 and falls by 33-35% by 2050 compared to the base year. This corresponds to a 38-40% reduction with respect to baseline. For fossil fuels this translates in a reduction of -60% to -63% for oil, -31 to -41% for gas, -87% to -88% for coal. In a decarbonised EU, the **energy consumption** decreases across all scenarios going down to around 1650 Mtoe by 2030 (1720Mtoe under *Reference*). Decreases would be even steeper after 2030, resulting in a projected gross inland energy consumption of between 1300 and 1350 Mtoe by 2050.

Gross electricity consumption shows a different pattern to the described evolution of gross energy consumption. It is projected to continue to increase in all scenarios. In the reference scenario electricity consumption increases by 50% in 2050 compared to 2005. By 2050 in the decarbonisation scenarios, electricity consumption reaches around 5 - 5,5million GWh. In the decarbonisation scenarios, carbon pricing leads to higher incentives for electricity savings. However this electricity saving element is overcompensated by incentives to further electrify demand sectors to reach ambitious emission reductions and by the higher electricity use of some low carbon technologies (e.g. CCS)[1].

[1] For example, gross electricity consumption in 2050 in the Effective Technologies scenario is higher than in the Delayed Electrification scenario and is around 850 TWh higher than in the reference scenario. Plug-in hybrid cars, electric cars and greater use of heat pumps drive this increase in electricity demand. Delays in transport electrification would result in only moderate electricity demand increase over reference (about 150 TWh) in 2050. The Delayed CCS scenario requires in 2050 around 200 TWh less electricity than the Effective Technologies scenario that has more CCS.

In a decarbonised EU, total **energy imports** would more than halve compared to 2005 and be around 60% lower in 2050 than in the reference scenario (net oil imports ranging from 163-193Mtoe compared to 547Mtoe under Reference; net gas imports – 196-217Mtoe compared to 340Mtoe under Reference). This also implies cost savings of between 70-80% under the decarbonisation scenarios.

Cumulative investment into the grid from now until 2050 in the Reference scenario is projected to be €1.3 trillion and would need to increase to between €1.6 and 2 trillion in the decarbonisation scenarios. Delaying climate action causes **investment expenditure** to increase by around €100 billion per annum for the 20 year period from 2030 to 2050, without comparably decreasing the investment needs before 2030 (in the decarbonisation scenarios this additional increase is not detectable). An oil shock or high fossil fuel prices increase the required average investment expenditure after 2020 on average by about € 100 billion per year in case of no action on climate change, however in the decarbonisation scenarios this additional increase is not detectable.

- *Key findings*

Milestones of a cost effective path towards -80% by 2050 are emission reductions by around 25% in 2020, around 40% in 2030 and around 60% in 2040. Reaching these emission levels will require further action, given that our current policies are projected to reduce emissions to -20% in 2020, -30% in 2030 and around -40% in 2050. To increase reductions to -25% in 2020 additional energy efficiency policies are important.

The study shows that by 2050, a 80% EU internal reduction compared to 1990 is technically feasible with proven technologies if a sufficiently strong carbon price incentive is applied across all sectors. Despite significant variations in technological and fossil fuel price assumptions, results are quite robust in terms of the speed and magnitude of emission reductions over time.

All scenarios project that the **power sector** is able to cope with ambitious decarbonisation requirements even under conditions of increasing power demand. For the intermediate time horizon of 2030, this translates into reductions of more than 60% (except in the cases of oil shocks or high fossil fuel prices, resulting in reductions a bit above 50%)[2]. Under the current trends of the reference case, emissions in 2030 would decrease by less than 40%.

Near complete decarbonisation in power is mainly achieved by the combination of **RES, Nuclear and CCS equipped fossil fuel plants**, which mainly driven by increasing carbon prices together increase their share in total electricity production from around 45% in 2005 via 75 to 80% in 2030 to practically 100% in 2050 in all scenarios. Of these three technologies, **renewables** become the largest source of electricity, seeing its share increase from 15% of electricity production in 2005 to around 50 to 55% 2050, which represents an absolute growth of around 500% reaching 2.7 to 3.0 TWh by 2050.

Nuclear investment in the longer term is endogenous, but Member State restrictions are respected where applicable. National **nuclear policies** as of mid 2010 are assumed to continue. Member States that have no nuclear power production remain so, except for Italy and Poland where national plans envision nuclear use. Nuclear in Belgium and Germany is phased out according to legislation as of mid 2010. Sweden continues to use and invest in nuclear[3].

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[2] Emissions of power plants and district heating are down -64% compared to 1990 in the Effective Technology scenario and -68% lower in the case of delayed electrification due to lower electricity demand from transport and therefore higher emissions in that sector.

[3] Please note that the Low Carbon Economy Roadmap has been developed prior to the Fukoshima accident.

CCS penetration is determined on economic grounds and depend on ETS prices (apart from EU funding for demonstration plants). It is assumed that CCS infrastructure, regulation and legislation develops in all countries. Significant potential for technological progress is assumed, leading to capital cost reductions per kW by 40 to 50% until 2050, depending on the capture technology. Total EU potential storage capacity is roughly 250,000 million tCO_2. This compares to 190,000 million tCO_2 cumulative emissions until 2050 in the worst CO_2 projection.

Technological progress assumptions differ according to maturity, ranging between 10% (e.g. offshore wind, geothermal) and 70% (PV) capital cost reduction per KW between 2010 and 2050, It should be noted that these costs include standardized grid connection costs (including for example costs of DC links for offshore wind farms). Grid parity for PV is expected before 2030 in southern part of Europe[4].

In 2050, the **EU's total primary energy consumption** could be about 30% below 2005 levels. More domestic energy resources would be used, in particular renewables. Imports of oil and gas would decline by half compared to today, reducing the negative impacts of potential oil and gas price shocks significantly. Without action the oil and gas import bill could instead double compared to today, a difference of € 400 billion or more per annum by 2050, the equivalent of 3% of today's GDP[5]. With global action, energy import prices are lower and carbon prices need to be higher to achieve the required decarbonisation. The reverse is the case for fragmented action that requires more moderate carbon prices to decarbonise because of higher energy prices.

The analysis demonstrate that shifting towards a low carbon pathway leads to a massive **shift from fuel expenses to investment expenditure.** L**ow-carbon investment** to develop backbone technologies such as renewable energy, smart grids, passive housing, CCS, advanced industrial processes and the electrification of transport – an estimated expenditure of around EUR 270 billion p.a. will be needed over the next 40 years, which is equivalent to an additional 1.5% of the EU's GDP p.a[6]. Unlocking private investment and using private-public financing mechanisms is seen as crucial – innovative financing mechanisms such as revolving funds, preferential interest rates, guarantee schemes, risk-sharing facilities and blending mechanisms which can mobilise and steer the required private finance, including for SMEs and consumers are underlined[7].

Climate and energy policies in the coming decade will thus require a combination of smart pricing policies as well as instruments that can unlock private investment. This will involve improving the access to information for private investors on the real costs and benefits of the investments made on the longer term but also ensuring better access to financing itself. Member States have already introduced policies such as preferential loans schemes, grants that pay back part of a low-energy investment and tax rebates, with the aim to unlock private investment in low carbon technologies. These type of policies will need to continue and be expanded, according to the document.

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[4] Capital costs of already mature technologies decrease by 3% between 2010 and 2050, capital costs of new technologies decrease between 30% and 70% between 2010 and 2050 depending on technological potential and expected use.

[5] The level of reductions in the bill for fossil fuel imports depend on future fossil fuel price developments and diversification of supply sources.

[6] However, this figure needs to be put in a global context: the current EU investment level of 19% of GDP must be compared against 48% in China, 35% in India and 26% in Korea.

[7] Increasing domestic investments provide a major opportunity for increased productivity, added value and output from a wide range of EU manufacturing industries (e.g. automotive, power generation, industrial and grid equipment, energy–efficient building materials and the construction sector), which are key industries for the creation of future growth and jobs. The Commission also highlights the strong potential for job creation in renewables, green buildings and energy efficient equipment, which is also confirmed in the Energy Efficiency Plan. Average air pollution may be reduced by 65% by 2030 compared to 2005 levels, resulting in annual cost reductions of more than EUR 10 billion in health, plus another EUR 17 billion p.a. gained by 2030 due to reduced mortality.

- *Conclusions*

The Roadmap focuses on the need for clean technology investment and deployment of low-carbon technologies at an early stage. Full implementation of the Strategic Energy Technology Plan (SET Plan) is highlighted as one of the key EU instruments towards this goal. The Commission also recommends that Member States should actively explore using ETS auctioning revenues and cohesion funds to finance such efforts.

The Roadmap analysis demonstrate that the power sector can be completely decarbonised by 2050. Electricity demand increases but the overall energy consumption is not expected to increase beyond the historic growth rate due to the simultaneous efficiency gains on the demand side. The share of low carbon technologies (renewables, fossil with CCS and nuclear) is expected to increase from 45% today to nearly 100% by 2050. The currently agreed linear reduction of ETS caps is seen as insufficient to set strong price signals, and major investments in smart grids will be required at EU, national as well as local level. Investment in smart grids is seen as the key enabler for a low-carbon electricity system, notably facilitating demand-side efficiency, larger shares of renewables and distributed generation and enabling electrification of transport. Since grid investment accrue benefits for the society at large, the Roadmap suggests that future work should consider how the policy framework can foster these investments at EU, national and local level and incentivize demand-side management. For transport and mobility, improved fuel efficiency remains the major driver for climate protection until 2025. For the built environment, the Roadmap estimates a reduction potential of up to 90% by 2050, particularly through the improved energy performance of buildings. For the industrial sector, the Roadmap calculates a reduction potential of 83 to 87% by 2050. It is estimated that more advanced and efficient industrial processes and abatement technologies for non-CO2 emissions could reduce emissions in the energy intensive sectors by half or more. The Commission foresees that large-scale CCS deployment will be needed from 2035 onwards, which will require annual investments of more than EUR 10 billion. Carbon leakage remains a concern that will have to be continuously monitored, according to the Commission’s document.

II. European Commission Energy Roadmap 2050 (2012)

- *Background information*

The *Energy Roadmap 2050* explores the challenges posed by delivering the EU's decarbonisation objective while at the same time ensuring security of supply and competitiveness. The Roadmap is based on a relisation that in order to provide certainty to investors, governments and citizens, there is a need of adequate direction as to what should follow the 2020 agenda, because acting now can avoid costly changes in later decades and reduces lock-in effects.

- *Modelling approach*

The *Energy Roadmap 2050* explores routes towards decarbonisation of the energy system. It is based on the PRIMES energy model developed and run by E3MLab of the National Technical University of Athens. PRIMES has been under development since 1993. It simulates a market equilibrium solution for energy supply and demand within each of the 27 EU member states. Driven by engineering and economic principles, PRIMES determines the market equilibrium by finding the prices of each energy fuel that match the supply and demand of energy. PRIMES is structured around modules that represent different fuel supply (i.e. oil products, fossil gas, coal, electricity and heat production, the so-called 'sub-system'), energy conversion and end-use demand sectors: household, commercial, transport and (nine) industrial sectors. The technological component of the model is explicit and detailed for both the supply and demand sides and also for environmental abatement technologies.

- *Scenarios and key assumptions*

The Roadmap explores 7 key scenarios, two of them focus on the current trends (the *Reference* and the *Current Policy Initiatives* scenarios) and the rest analyse different decarbonisation pathways (*High Energy Efficiency, Diversified Supply Technologies, High RES, Delayed CCS, Low Nuclear*)[8].

For the *CPI* and *Reference Scenarios* **oil prices** are projected to reach $106/barrel in 2030 and $127/barrel in 2050. **Carbon price** under *CPI* is 51EUR/tCO_2 in 2050; the projections for *DSS* and *High RES* are 265EUR/tCO_2 and 285EUR/tCO_2 (for 2030, the carbon prices in EUR/tCO_2 are 32/CPI, 52/DSS and 35/High RES).

Under all scenarios average **electricity prices** rise up to 2030 and stabilise thereafter[9]. In the CPI scenario, electricity prices are slightly higher (1% in 2030 and 4% in 2050) reflecting the lower share of nuclear as well as higher lifetime extension costs post Fukushima and high investments for new electricity generation capacity, especially RES. **Average electricity price** is of 156.9EUR/MWh (compared to 110EUR/MWh at 2010) of which capital costs account for 54,6EUR/MWh. Under *DSS*, the average **electricity price** is 146,2EUR/Mhg (fixed and capital costs – 61.9; variable and fuel costs –

[8] Two of those scenarios deserve further attention, notably the *Diversified Supply Technologies* and the *High RES* scenarios. The former shows a decarbonisation pathway where all energy sources can compete on a market basis with no specific support measures for energy efficiency and renewables and assumes acceptance of nuclear and CCS as well as solution of the nuclear waste issue. It displays significant penetration of CCS and nuclear as they necessitate large scale investments and does not include additional targeted measures besides carbon prices. The latter *High RES* scenario aims at achieving a higher overall RES share and very high RES penetration in power generation, mainly relying on domestic supply.

[9] The price increase up to 2030 is due to three main elements: RES supporting policies, ETS carbon price and high fuel prices due to the world recovery after the economic crisis. Thereafter electricity prices remain stable because of the techno-economic improvements of various power generation technologies that limit the effects of higher input fuel prices and CO2 prices.

31.3; grid and sales costs – 29.1, ETS payments – 0,9). For *High RES*, it reaches a level of 198.9EUR/MWh, of which 101 for fixed and capital costs; 25 for variable and fuel costs,; 4 for ETS payments and 41 for grid and sales costs).

Total costs of energy (including capital costs, energy purchases and direct efficiency investment costs) are rising fast over the projection period. The average annual **total energy system costs** 2011-2050 are 2619bln/€(CPI), 2590bln/€(HIGH RES) and 2535bln/€(DSS). Capital cost represents 995 bln/€, 1089 bln/€ and 1100 bln/€ respectively. *Diversified supply technologies* and *Delayed CCS* scenarios have the lowest level of average annual energy system costs, representing even a cost saving of around 90bln€(08) compared to CPI (or around 50bln€ compared to the Reference scenario) mainly due to large fossil fuel **import savings**. Energy costs are rising faster than GDP. The faster rate of growth relative to GDP reflects significant investments needs in energy production, transmission and distribution as well as demand based energy efficiency measures.

The ratio of **energy system costs to GDP** is similar across the scenarios: ranging from around 14.1% to 14.6%, the costs of the *Diversified supply technologies* and *Delayed* CCS scenarios being at the lower end of the range. Exposure to **fossil fuel price** volatility would drop in decarbonisation scenarios as import dependency falls to 35-45% in 2050, compared to 58% under current policies. The decrease of the fuel bill from 2005 in the decarbonisation scenarios is smallest in the *Low nuclear scenario* at 31% and highest in the *High RES* scenario at 43% with RES replacing most fossil fuels. Savings in the external fuel bill are most striking in 2050. Compared with the CPI scenario, the EU economy could save in 2050 between 518 and 550 bln€ by taking this strong decarbonisation route under global climate action.

Infrastructure investment for the period 2011 – 2050 is 1357EUR bln under the *Current Policy Initiatives* Scenario, a number which dwarths in comparison to the projected infrastructure investment under the *DSS* and *High RES* scenario of respectively 1712EUR bln and 2195EUR bln.

Gross electricty generation reaches 4621TWh (CPI) in 2050. By 2050 renewables represent 48,8% of this total electricity generation, for DSS the level is 59.1% (of 4912TWh) and for High RES 83.1% (of 5141 TWh).

Primary energy consumption decreases as compared to the *Reference* scenario in all of the other projections, including CPI. By 2050, under CPI primary energy consumption reaches 1615Mtoe, which is a decrease of 8,4% as compared to Reference scenario (projected consumption for 2050 of 1763Mtoe). The decrease is even more striking under *DSS* and *High RES* of respectively 31% (1217Mtoe) and 35.7%(1134Mtoe).

While the Roadmap does not provide specific **electricity generation costs per technology**, capital expenditures per unit of capacity is given for several technlogies. For wind and solar PV relatively modest future cost reductions are assumed. For solar thermal on the other hand, costs are assumed to drop considerably until 2050. Interestingly, the Roadmap assumes a steady decrease in the capital expenditures for new nuclear power plants, decreasing from around 4380EUR/kW in 2010 to around 3600EUR/kW in 2050. Considerable cost reductions over time are also assumed for power plants equipped with CCS – e.g. a power plant with CCS reduces its capital expenditure from 3480 EUR/kW assumed today to around 2000 EUR/kW by 2040. The Roadmap also assumes only modest future cost reductions for the most important renewable technologies – this in combination with rather optimistic assumptions regarding the future cost reduction potential and technological viability of CCS technologies seems to lead to a relative disadvantage of renewable energy technologies in the electricity system in the PRIMES modelling[10].

[10] Technology parameters are exogenous in the PRIMES modelling and their values are based on current databases, various studies and expert judgement and are regularly compared to other leading institutions.

Very **significant energy savings** would need to be achieved in all decarbonisation scenarios. **Primary energy** demand drops in a range of 16% to 20% by 2030 and 32% to 41% by 2050 as compared to peaks in 2005-2006. The **final electricity energy demand** for 2050 reaches 3951TWh under CPI and 3618 under DSS. Under High RES, it is 3377 TWh. For comparison, under the Reference scenario the projected electricity demand is 4130TWh. According to the document, achieving significant energy savings will require a stronger decoupling of economic growth and energy consumption as well as strengthened measures in all Member States and in all economic sectors.

- *Key findings*

The Roadmap identifies key conclusions on no regrets options in the European energy system and seeks to develop a long-term European technology-neutral framework in which these policies will be more effective. It argues that a European approach to the energy challenge will increase security and solidarity and lower costs, compared to parallel national schemes, by providing a wider and flexible market for new products and services.

All decarbonisation scenarios show a transition from today's system, with high fuel and operational costs, to an energy system based on **higher capital expenditure and lower fuel costs.** The analysis shows that **cumulative grid investment costs** alone could be 1.5 to 2.2 trillion Euros between 2011 and 2050, with the higher range reflecting greater investment in support of renewable energy. The average **capital costs of the energy system** will increase significantly - investments in power plants and grids, in industrial energy equipment, heating and cooling systems, smart meters, insulation material, more efficient and low carbon vehicles, devices for exploiting local renewable energy sources, etc. All scenarios show **electricity will have to play a much greater role** than now (almost doubling its share in final energy demand to 36-39% in 2050) and will have to contribute to the decarbonisation of transport and heating/cooling. This will increase final electricity demand even in the *High energy efficiency* scenario. The power generation system, therefore, would have to undergo structural change and achieve a significant level of decarbonisation already in 2030 (57-65% in 2030 and 96-99% in 2050). This highlights the importance of starting the transition now and providing the signals necessary to minimise investments in carbon intensive assets in the next two decades.

Renewable energy technolgies are the most important supply-side element in the electricity sector for ambitious decarbonisation. At the same time significant energy efficiency improvements compared to reference development are needed to limit growth in electricity demand and to simultaneously enable considerable amount of electricity to be used in the transportation sector to help reduce CO_2 emissions in that sector. The scenarios also indicate that CCS can be an important mitigation technology within the European electricity system, but that its future availability and public acceptance is limited.

The **share of renewable energy (RES) rises substantially** in all scenarios, achieving at least 55% in gross final energy consumption in 2050, up 45 percentage points from today's level at around 10%. The share of RES in electricity consumption reaches 97% in a *High Renewables* Scenario. To handle the challenge of cost would require greater **convergence in support schemes** and greater responsibilities for system costs among producers, in addition to Transmission System Operators

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Technologies are assumed to develop over time and to follow learning curves which are exogenously adjusted to reflect the technology assumptions of a scenario. Overall, mature fossil fuel, nuclear as well as large hydroelectric technologies exhibit rather stable technology costs, except for innovative concepts such as 3rd generation nuclear power plants or carbon capture and storage (CCS), where costs decline with further RTD and more technology experience. Similar developments are assumed for new renewable technologies, such as off-shore wind and solar PV as has been witnessed in the past for most energy technologies (e.g. on-shore wind or more recently solar energy).

(TSO); improving **infrastructure** at distribution, interconnection and long-distance transmission is also essential – the analysis demonstrate that an overall increase of interconnection capacity by 40% up to 2020 will be needed**.** Also, analysis show that it is key to ensure policy developments in Member States do not create new barriers to electricity - or gas - market integration[11].

In all scenarios, including current trends, expenditure on energy and energy-related products is likely to become a more important element in **household expenditure**, rising to around 16% in 2030, and decreasing thereafter to above 15% in 2050. This trend would also be significant for small and medium-sized enterprises (SMEs).

Very **significant energy savings** would need to be achieved in all decarbonisation scenarios[12]. Achieving significant energy savings will require a stronger decoupling of economic growth and energy consumption as well as strengthened measures in all Member States and in all economic sectors.

As regards **security of supply**, all policy scenarios improve import dependency, the best being the *High RES* scenario with 35% import dependency in 2050 and the least effective the *Low nuclear* scenario with 45% in 2050 (as compared to 58% in the Reference scenario).

Most scenarios suggest that **electricity prices** will rise to 2030, but fall thereafter. The largest share of these increases is already happening in the *Reference* scenario, and is linked to the replacement in the next 20 years of old, already fully written-off generation capacity. The *High Energy Efficiency and the Diversified Supply Technology* scenarios have the lowest electricity prices while providing 60-65% of electricity consumption from RES, up from only 20% at present[13].

Carbon Capture and Storage (CCS), if commercialised, will have to contribute significantly in most scenarios with a particularly strong role of up to 32% in power generation in the case of *Constrained Nuclear Production* and shares between 19 to 24% in other scenarios with the exception of the *High RES* scenario. **Nuclear energy** will be needed to provide a significant contribution in the energy transformation process in those Member States where it is pursued. The highest penetration of nuclear comes in *Delayed CCS* and *Diversified supply* technologies scenarios (18 and 15% in primary energy respectively) which show the lowest total energy costs.

All of the scenarios show that centralized large-scale systems such as e.g. nuclear and gas power plants and decentralised systems will increasingly have to work together. A new configuration of decentralised and centralised large-scale systems needs to emerge and will depend on each other, for example, if local resources are not sufficient or are varying in time.

Gas will be critical for the transformation of the energy system. Substitution of coal (and oil) with gas in the short to medium term could help to reduce emissions with existing technologies until at least 2030/2035. In the *Diversified Supply Technologies* scenario for example, gas-fired power generation accounts for roughly 800 TWh in 2050, slightly higher than current levels. The text also specifies that greater flexibility in price formula, moving away from pure oil-indexation, will be needed if gas is to remain a competitive fuel for electricity generation.

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[11] Full market integration by 2014, as decided by the European Council on February 4th, 2011, supported by infrastructure developments and technical work on Framework Guidelines and Network Codes

[12] *Primary* energy demand drops in a range of 16% to 20% by 2030 and 32% to 41% by 2050 as compared to peaks in 2005-2006.

[13] In this context, it has to be noted also that price in some Member States are currently artificially low due to price regulations and subsidies.

Carbon pricing can provide an incentive for deployment of efficient, low-carbon technologies across Europe, and the scenarios show that carbon pricing can coexist with instruments designed to achieve particular energy policy objectives, notably research and innovation, promotion of energy efficiency and development of renewables[14]. More coherence and stability is however needed between EU and national policies for its price signal to function properly.

Energy subsidies could continue to be necessary beyond 2020 to ensure that the market encourages the development and deployment of new technologies and will need to be phased out as technologies and supply chains mature and market failures are resolved.

- *Conclusions*

The *Energy Roadmap 2050* shows that decarbonisation is feasible. Whichever scenario is chosen, a number of "no regret" options emerge which can bring down emissions effectively and in an economically viable way. Identical to other roadmaps, this one emphasises the need of 'a greater sense of urgency' and strengthened political ambition. A key conclusion which emerges from the Roadmap is that the overall system costs of transforming the energy system are similar in all scenarios and a common EU approach can help keep costs down. Moreover, exposure to fossil fuel price volatility would drop in decarbonisation scenarios as import dependency falls to 35-45% in 2050, compared to 58% under current policies. The clear message is that investments will pay off, in terms of growth, employment, greater energy security and lower fuel costs. The Roadmap prioritises the implementation of existing legislation and proposals currently in discussion (at the time of writing) – notably on energy efficiency, infrastructure, safety and internationa cooperation. Particular attention is paid to RES and the potential of EE. In order to speed up the commercialisation of low-carbon sources the rate of public and private investment in RES and technological innovation should be increased. Emphasis is placed also on the need for "energy prices need to better reflect costs", notably of the new investments needed throughout the energy system. The European Commission's Roadmap 2050 echoes previous roadmaps in the firm conclusions that the EU's energy system needs high levels of investment even in the absence of ambitious decarbonisation efforts.

[14] The CPI scenario results in a carbon value of some 50€ in 2050, the decarbonisation scenarios substantially more.

III. Eurelectric Power Choices - Pathways to carbon-neutral electricity in Europe by 2050 (2009)

- *Background information*

The *Power Choices - Pathways to carbon-neutral electricity in Europe by 2050* study was published in November 2009 by the Union of Electricity Industry (Eurelectric[15]). The *Power Choices* study examines how a "cost-effective and secure pathway to a carbon-neutral power supply by 2050" can be realised. One of the purposes of the study is to analyse the policy options that will be required to attain deep cuts in carbon emissions by 2050.

- *Modeling approach*

The PRIMES energy model developed and run by E3MLab of the National Technical University of Athens was used to examine this study's scenarios up to 2050. It simulates a market equilibrium solution for energy supply and demand within each of the 27 EU member states. Driven by engineering and economic principles, PRIMES determines the market equilibrium by finding the prices of each energy fuel that match the supply and demand of energy. PRIMES is structured around modules that represent different fuel supply (i.e. oil products, fossil gas, coal, electricity and heat production, the so-called 'sub-system'), energy conversion and end-use demand sectors: household, commercial, transport and (nine) industrial sectors. The technological component of the model is explicit and detailed for both the supply and demand sides and also for environmental abatement technologies.

- *Scenarios and key assumptions*

The central *Power Choices* scenario sets a **75% reduction target for greenhouse gases** across the entire EU economy until 2050 (compared to 1990 levels). It is assumed that **nuclear** power remains available and carbon capture and storage **(CCS)** technology is commercially available from 2025. Electricity becomes a major transport fuel, energy efficiency is pushed by specific policies and the price of CO_2 applies uniformly to all economic sectors, not just those within the ETS. Additionally no binding RES-targets are set after 2020; RES support mechanisms remain fully in place until 2020 and are gradually phased out during 2020-2030.

The robustness of the results of the this main scenario were tested by quantifying several sensitivity analyses: *CCS Delay* (the commercialization of CCS is delayed and becomes mature only from 2035 onwards, cumulative CO_2 emissions are 2.3% higher than in the main scenario), *Nuclear Facilitated* (abolishing the nuclear phase-out in Belgium and Germany, CO_2 emissions are 0.9% less than in the main scenario), *Less Onshore Wind* (difficulties arise for onshore wind development and it develops only at 1/3 of the development of the *Power Choices* scenario. CO_2 emissions are almost the same because the onshore reduction is partly offset by the development of additional offshore wind) and *No Efficiency Policies* (none of the policies such as penetration of technology advanced appliances or development of electrified road transportation take place, cumulative CO_2 emissions are 7.2% lower but the cumulative costs are 4.2% higher than in the main scenario. Due to the absence of the bottom-up policies and the electrification of road transportation, the carbon prices need to increase

[15] The Union of the Electricity Industry is the sector association which represents the interests of the electricity industry at pan-European level. Its mission is to contribute to the development and competitiveness of the electricity industry, to provide effective representation for the industry and to promote the role of low carbon electricity mix in the advancement of society. Eurelectric's main objectives are to deliver carbon-neutral electricity in Europe by 2050, ensure cost-efficient, reliable supply through an integrated market and develop energy efficiency and the electrification of the demand side to mitigate climate change.

over the entire period)[16].

In the study, world **fossil fuel prices** are projected using the Prometheus model (E3MLab) and by 2030 and beyond oil and gas reach $126/bbl and $16/MBtu respectively. The projections show coal prices between $135 and $150/t between 2020 and 2050. **Carbon price** for 2050 is assumed to 42EUR/tCO_2 (*Baseline*) and 103EUR/tCO_2 (*Power choices*).

The total **capacity of the transmission** lines is projected to increase from 179GW (2005) to 253GW (2030). In the period from 2030 to 2050 the transmission capacity remains stable. It is assumed that investments in advanced power grids, smart metering as well as control and communication systems will take place in a timely manner. In support of the electrification of road transport, it is assumed that grid extension (to enable charging of vehicles) will start by 2015.

Compared to a *Baseline* scenario (which assumes that all existing policies are pursued), the *Power Choices* demonstrates a **reduction of primary consumption** to 2050 falling from 1758Mtoe to 1408Mtoe (20% reduction on *Baselin*e); the reduction is even steeper for the **final energy demand** – with savings of 30% on *Baseline*. In *Power choices* electricity is projected to gain a share of 45% of **total final energy demand** in 2050, this leads to strong reduction in end-use of **gas and oil** – down from 52% of final energy demand under *Baseline* to only 34% under *Power choices*.

Total EU **net power generation** reaches 4,800TWh in 2050 (from 3,100TWh in 2005). 40% of this generation will be RES-induced (with onshore wind providing 35% and off-shore – 27%; hydropower – 23%, solar – 13%). **RES** accounts for 1,900TWh in 2050 (compared to just 15% in 2005; this represents an increase of 28% for 2050 as compared to *Baseline*). Gas-fired power accounts for 660TWh in 2050 (14% of EU electricity) and oil-fired plants have only a marginal role in 2050 (1% of power generation). **Nuclear** power generation increases somehow under *Power choices* from around 950TWh in 2005 to 1300TWh in 2050.

Under *Power Choices,* the **carbon intensity** of power generation falls by almost 95%, from roughly 360 kg/MWhin in 2005 to 26kg/MWh in 2050 (compared to 134kg/MWh in *Baseline*) and energy **imports** experience a reduction of 49% for the examined period.

Total **power generation investment** between 2011 and 2050 amounts to 1469GW (*Power Choices*). The projections show the commissioning of 821GW of new renewable plants[17], 442GW of new fossil fuels plants and 197GW of new nuclear plants. Total investment in CCS power plants amount to 191GW in *Power Choices* (compared to 61GW in *Baseline*).

In financial terms, **total energy system investment** amounts to 350EUR billion per year (*Baseline*

[16] Average electricity prices in the *Nuclear Facilitated* scenario are 3% lower than in *Power Choices*. In cumulative terms, over the period 2010-2050, the *Nuclear Facilitated* scenario implies savings of 360EUR on total energy system costs compared to *Power Choices*. The carbon price increase in the *CCS Delay* scenario and the total system costs in cumulative terms over the period 2010-2050 increase the *CCS Delay* scenario costs by 164EUR billion relative to *Power Choices*. In the *Lower Wind Onshore* scenario, the reduction in onshore wind development leads to an increase in total cumulative energy costs estimated at 119EUR billion relative to *Power Choices*. Average electricity prices are less affected. The *No Efficiency Policies* scenario implies 3552EUR billion of additional cumulative cost relative to the *Power Choices*, this represents 4.2% higher total cumulative energy costs. Carbon prices in this scenario rise to 146EUR/tCO_2 in 2030 and 195EUR/tCO_2 in 2050. Electricity prices are estimated to be between 3 and 5% higher than *Power Choices.*

[17] The total investment of 340GW in wind onshore will lead to total installed capacity of 257GW in 2050; for wind offshore – investment of 174GW will lead to an installed capacity of 125GW; solar electricity – investment of 199GW will lead to operating capacity of 140GW; biomass and waste energy will have installed capacity of 70GW.

implies 265EUR billion), **by 2050** it is estimated to reach 12,5EUR trillion (30% higher than *Baseline)*[18]. For the power sector specifically, the *Power choices* requires 25% higher annual investment amounts per year on average, relative to B*aseline and by* 2050, amount to 1,75EUR trillion, the biggest share of which would be spent for **investment for the power grids,** amounting to 1,5EUR trillion (35% up from *Baseline)*.

Overall **costs of energy** in the economy decreases in the long term – in 2050 cost of energy to GDP is about 10%[19] or just 0.3.% higher than the *Baseline* despite the more ambitious GHG reduction targets.

Import dependency decreases to a level of 46% in 2050 under *Power Choices*, the performance is due to increase energy efficiency leading to decrease in total primary energy requirements and to strong substitution of oil by electricity in transport, combined with increasing power generation from renewables.

- *Key findings*

The *Power Choices* roadmap requires a considerable **increase in investment** within all energy sectors (demand and supply), for energy savings and for developing a smarter and larger grid infrastructure. The high pace of energy investment needs to be sustained over a long period of time.

In terms of costs and prices, the study indicates that **high costs and prices are inevitable** given the adoption of the EU Directive introducing an ETS involving the auctioning of emission allowances and a continuously shrinking total amount of allowances.

The *Power Choices* scenario demonstrates that reducing carbon emissions provides savings on auctioning payments that are almost sufficient to finance the additional investment costs which enable achievement of the carbon-neutral goal. In addition, under the *Power Choices* assumptions, the additional capital intensive investment costs are partly offset by the savings resulting from a smoothed load curve, as cars are charged at off peak time, which further reduces auction payments and fuel costs.

The study demonstrates also that the **market design** need to address the challenges arising from progressive shrinking of the portion of the market exposed to competition and a corresponding progressive enlargement of the market portion under regulatory protection; the latter include the RES sectors, common infrastructure for the grid and carbon dioxide transportation and storage and the extensive ancillary services that will be required to accommodate high RES penetration levels.

*T*he cost-effective success of the *Power Choices* roadmap depends crucially on the removal of **long-term investment uncertainties**, on the provision of **sufficient price signals** through carbon pricing combined with wide- ranging **bottom-up policies**.

The extensive sensitivity analysis carried out has shown that all low-carbon options must be available and deployed according to their cost-effective potential. For example, **delays** in the commercialisation of CCS technology or barriers that prevent the deployment of some RES technologies (such as onshore wind) entail significant **additional costs** for meeting the emission reduction targets. On the other hand, the removal of the nuclear phase-out in some countries will induce a reduction in mitigation costs. The absence of bottom- up policies, including the possible

[18] 20% of total energy system investment costs in cumulative terms is investment in energy savings and energy efficiency.
[19] In cumulative terms, over the period 2010-2050 this implies a 300EUR billion incremental **energy system costs**.

failure to electrify the transport sector, implies dramatic **increases in mitigation costs**.

The analysis projects the **total cost of energy to increase** as percentage of GDP up to 2030 due to high capital outlay but progressively degreases afterwards to reach 10% in 2050. Power generation investments in the *Power Choices* case that contribute towards meeting the RES target and additional investments induced by carbon prices lead to a 21% increase in annual capital costs per MWh produced in 2020 relative to 2010. Grid costs also increase substantially in order to accommodate system operation with a high RES share: 35% up in 2020 from 2010 per MWh consumed. **Fuel costs** increase in 2020, relative to 2010, driven by rising world energy prices. However, in the *Power Choices* scenario fuel costs are lower than in the *Baseline* in 2020, since the former scenario involves restructuring away from fossil fuels. Summing up, the *Power Choices* scenario implies an increase of only 2% in average end-use electricity prices relative to the *Baseline* scenario.

- *Conclusions*

The study shows that carbon-neutral power in Europe is achievable by 2050. Political action is required to increase the degree of electrification of final energy usage and decarbonised power generation. According to the study, the following actions are required: investment in transmission and distribution lines; sectoral internalization of the GHG emissions costs; energy efficiency; public acceptance of modern energy infrastructure; road transport electrification. The major CO_2 reduction in the power sector occurs beyond 2020 because investment decisions taken today will result in lower carbon emissions over the next decade. A paradigm shift is needed on the demand side: intelligent electricity systems should replace direct use of fossil fuels, the document concludes.

IV. Eurelectric Power Choices Reloaded: Europe's Lost Decade? (2013)

- *Background*

The *Power Choices Reloaded* study revisits Eurelectric's 2009 model in light of changing political and economic assumptions (recession; slow progress in European market integration and infrastructure development; slow progress on the demonstration of CCS). It shows that sooner or later the 2050 goal will require a major reform of the entire European and national framework of low-carbon policies. But it also shows that until the current conflicting and contradictory signals are resolved, investors will avoid the European electricity market. Increasingly this problem is even seen in the supported renewables sector, the study suggests. Meanwhile, the delay while waiting for a policy signal poses a serious threat to security of supply and to the feasibility of meeting climate targets. Crucially it puts at risk the goal of affordable energy, the study concludes.

- *Modeling Approach*

The *Eurelectric* uses the PRIMES model developed and run by E3Mlab of the National Technical University of Athens under Professor Pantelis Capros. VGB PowerTech provided data on power technology and plants.

- *Scenarios and key assumptions*

Power Choices Reloaded updates the 2009 *Power Choices* study with a focus on the impact of recent regulatory and economic developments on the sector's path to decarbonisation and the raising awareness of the difficulties in investing and the crucial importance of enabling early investments. *Power Choices Reloaded* tests several scenarios and sensitivities demonstrating different possible EU policy approaches and regulatory measures. In order to explore the consequences of conflicting and contradictory policy signals and delayed investments, EURELECTRIC has modelled a *Lost Decade scenario* which postpones major abatement action beyond 2030. Having postponed action, an extremely steep abatement path becomes necessary to reach the 2050 goal, leading to bottlenecks in equipment supply, price effects due to overheated demand, and stranded assets because of exaggerated investments in redundant capacity.

The *Power Choices Reloaded* Scenario meets all the 2020 targets, although moderating the assumptions on achieving the 20% energy efficiency target by reaching this goal in 2025. This scenario also applies only an ETS carbon price in ETS sectors until 2020, but thereafter introduces a uniform CO_2 price signal in all sectors and all EU Member States. It also assumed that the key grid or storage infrastructure will be built as planned in line with the needs of the overall electricity system.

The *Lost Decade Scenario* explores consequences of delay in action caused by uncertainty in the policy framework due to conflicting and contradictory signals, which makes investment both more difficult and more costly. The scenario assumes slowed learning effects for offshore wind and CCS; implementation of the ENTSO-E plan taking 20 years instead of 10; delays in the deployment of recharging infrastructure for electric cars; delays in second generation biofuel supply; higher risk premiums on power sector capital investments; delays in energy efficiency in buildings; discontinuity in renewables incentives to 2020 and limited access to capital due to higher risk premiums for power sector investments.

The study makes the assumption that the CO_2 price signal is a very powerful tool for all sectors to efficiently drive low-carbon investment, but nevertheless this price signal needs to be complemented by bottom-up policies to drive large-scale investment in infrastructure, both for transport electrification and for grid intelligence, as well as to remove non-market barriers to energy efficiency.

The study defines some additional scenarios which are more or less a variation of the *Power Choices Reloaded* Scenario, which include *CO_2 price driven* scenario (marginal cost of abatement in the whole economy, but excludes support policies for RE and EE after 2020), a *Renewables push* scenario (30% EU RE target by 2030); *Barriers to energy efficiency* scenario (non-economic barriers are not overcome); a sensitivity which limits cross-border electricity trade, due to the assumption that the internal market does not fully develop; and a sensitivity which assumes that the current difficult financial conditions continue until 2030.

- *Key findings*

Power Choices Reloaded updates the 2009 *Power Choices* study with a focus on the impact of recent regulatory and economic developments on the sector's path to decarbonisation and the raising awareness of the difficulties in investing and the crucial importance of enabling early investments. The analysis give a stark conclusion: an early investment signal is vital in order for Europe to reach its whole-economy climate targets in an economically sustainable way. Postponing action would necessitate an extremely steep abatement path to reach the 2050 goal, leading to bottlenecks in equipment supply, price effects due to overheated demand, and stranded assets because of exaggerated investments in redundant capacity. During 2030-35 the percentage of carbon-free generation (renewables, nuclear and CCS) must increase from 60% to over 80% and the average rate use of thermal generation declines from over 35% to only just above 15%, at the same time the load factor of all power generation capacity decreases from over 40% to under 35%.

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The **power sector** contributes most abatement until 2050. Starting with emissions of 350g/kWh in 2010, the sector will deliver about 10g/kWh in 2050. This will happen through continuous investment. Reaching the whole-economy 2050 goal requires a significant share of final energy use to switch to electricity, notably in the transport sector, thus delivering emissions reductions and efficiency improvements.

The critical uncertainty is time: less ambitious climate goals will lead to much higher follow-up costs beyond 2030. By calculating energy system costs based on capital costs for investment, purchases of primary fuel, investment costs for direct efficiency measures and non-CO_2 costs, the study shows that overall energy system cost in the economy reaches a plateau and then decreases long term – except in the *Lost Decades* scenario where energy costs trend in only one direction – increasing **costs of energy**. The *Lost* Decade entails 5,5 billion EUR (2010) additional cumulative costs by 2050, which makes it 1.4% more expensive than the *Power Choices Reloaded* Scenario by 2050, reaching 16,7% of GDP – i.e. over 50% higher than in 2010. In short, the *Lost Decades scenario* is expensive in the beginning, and drastically more expensive in the end. In the Lost Decade scenario the major abatement has to be achieved between 2030 and 2040, reducing emissions from 3,987Mt to 1,519Mt (an annual abatement of 250Mt). However, average abatement over a ten year period in the EU-27 has been 51,7Mt p.a (1990 – 2000), 6.5 Mt p.a (1995-2005), and 31.1 Mt p.a. (2000-10). These figures demonstrate the scale of the challenge which would result from the *Lost Decade* scenario.

Specifically in the power sector, the *Power Choices Reloaded* Scenario shows that ETS can support renewables and energy efficiency development in combination with complementary policies to reduce market barriers for end-users, for grid development and for innovation. The major share of abatement stems from renewables (32%) and energy efficiency (21% policy-driven and 18% market-driven). A slight increase in gas firing is expected in the period 2030-35 (from 20.1% to 20.7%).

The *Lost Decade* scenario will require in the years after 2030 a radical surge in the growth of renewables and reduction in the share of coal-fired and gas-fired electricity (from 22.8% in 2030 to 14,5% in 2035).

- *Conclusions*

The results of the analysis undertaken by this report highlight the importance of robust grid development (in transmission capacity and distribution), technology improvements, and bringing renewables into the market. The contrast between the *Lost Decades* and the *Power Choices Reloaded* scenarios shows that while the former implies multiple revolutions, the latter can be managed as an evolution – enabling technology learning curves, supply chain build up and investor confidence and achieving an annual abatement of roughly 100Mt.

IV. Greenpeace: Energy [R]evolution – Towards a fully renewable energy supply in the EU-27 (2012)

- *Background information*

The study *Energy [r]evolution - Towards a Fully Renewable Energy Supply in the EU-27* (Greenpeace/EREC 2010) was published in July 2010 by Greenpeace International and the European Renewable Energy Council (EREC). The lead developer of the study's scenarios was the Institute of Technical Thermodynamics of the German Aerospace Centre. Some other institutes provided additional research on specific aspects of the scenarios; for example, the data on energy efficiency potential is based on work by Ecofys Netherlands. As the study's name suggests, the area under focus is the EU 27.

- *Modeling approach*

To model energy supply in the scenarios the technologically detailed bottom-up simulation model MESAP/PlaNet was used. The assumed growth rates of the various renewable energy technologies were important drivers of the model. These growth rates were determined, taking into account the natural potential of each renewable energy source and the expected economic improvements in each technology. The authors use the concept of learning curves to determine future technology costs. This means that based on empirical studies the typical cost reductions of a given technology for each doubling of its installed base is determined and extrapolated into the future. Energy demand in the two alternative scenarios is based on an Ecofys study of energy efficiency potential. For this latest energy [r]evolution study, the MESAP/PlaNet model has been extended and now also calculates the investment pathways and employment effects.

- *Scenarios and key assumptions*

The *energy [r]evolution* scenario study for the EU-27 consists of one reference scenario and two alternative scenarios for the period up to 2050. The *Reference* scenario is based on the reference scenario of the IEA's World Energy Outlook (WEO) 2009. It has been extended to 2050 since the WEO 2009 only covers the time horizon until 2030. In the reference scenario energy-related **CO_2 emissions** are only 16% lower in 2050 than in 1990. The share of **renewables in electricity generation** reaches 41% by the middle of the century.

One of the two alternative scenarios is called the *energy [r]evolution scenario*. Here it is assumed that **efficiency measures** are successfully enacted in all sectors of the economy, thereby exploiting to a large extent the significant energy efficiency potential identified. For instance, demand for heat is reduced by 23% in 2050 compared to the reference scenario through a significant increase in energy-related renovation of the existing stock of residential buildings, as well as the introduction of low and "passive house" energy standards for new buildings. EU 27's **CO_2 emissions** are 76% below 1990 emissions in 2050, while the share of **renewables in electricity** generation reaches 88% by this time.

The second alternative scenario is called *advanced energy [r]evolution scenario* and is even more ambitious. While technological advances in efficiency are assumed to be identical to the *energy [r]evolution scenario*, a speedier market uptake of many energy-efficient technologies (like efficient combustion vehicles, electric vehicles and CHP technology for industry) is assumed. In the electricity sector the maximum lifetime of coal-fired power plants is limited to 20 years and an assumed faster implementation of grid expansions and grid improvements allow for a higher share of fluctuating renewable electricity from wind and solar energy. A faster expansion of solar and geothermal heating systems is also assumed. By mid-century, energy-**related $C0_2$ emissions** in the EU-27 are 95% lower than in 1990 (around 4,000 Mt) compared to only 10% decrease under Reference and renewables have a 97% share in electricity generation.

Due to uncertainty about the future prospects of **CCS** as well as a generally sceptic view of this mitigation technology by the commissioning organisations, the use of CCS is not assumed in their scenarios. All alternative scenarios assume that **nuclear power** is phased out over the coming decades and will no longer contribute to electricity generation by the middle of the century.

The **CO_2 price** assumed under the E[R] is 20 $/t in 2020, up to 50 $/t in 2050. The **oil** price in the E[R] scenario reaches 150 $/bbl in 2030 and stays at this level until 2050, due to a decreased use of oil. For coal, the E[R] assumes the price of 143 $/t in 2030, going up to 172 $/t in 2050. For **gas**, the E[R] assumes for 2030 a price of 19 $/GJ, for 2050 the projections are for an increase up to 26 $/GJ.

World GDP is assumed to grow on average by 3.8% per year over the period 2009-2030, compared to 3.1% from 1971 to 2007, and on average by 3.1% per year over the entire modelling period (2009-2050). **GDP in Europe** (EU 27) is assumed to grow by on average 1.6% per year over the projection period.

- *Key findings:*

Under the *Energy [R]evolution* scenario, the increased deployment of renewable energy sources goes along with a strong **increase of investment costs** of EUR3,600 billion. But these are balanced by a strong **decrease in fossil fuel costs** of EUR3,300 billion. The **total costs** under the *Energy [R]evolution* scenario would be EUR6.9 trillion until 2050 - about 17% less than under the ECF 80% scenario[20]. Comparing the specific CAPEX for different renewable technologies shows that the ECF assumes photovoltaic prices to be about 40% higher than under the E[R] and 30%-50% higher for on-/offshore wind. Under *Energy [R]evolution* assumptions, costs for concentrated solar thermal power (CSP) and geothermal power plants are respectively 10%-30% and 50%-100% higher. These differences can be explained by different assumptions of learning rates, e.g. for photovoltaics: ECF: 15% price reduction, E[R]: 20% price reduction while doubling of the total installed capacity.

Because renewable energy has no fuel costs, the **fuel cost savings** in the *Energy [R]evolution* scenario reach a total of EUR3,010 billion up to 2050, or EUR75 billion per year. The total fuel cost savings based, on the assumed energy price path, would therefore cover the total additional investments compared to the Reference scenario twice over. These renewable energy sources would then go on to produce electricity without any further fuel costs beyond 2050, while the costs for coal and gas will continue to be a burden on national economies.

[20] ECF's 80% renewable energy scenario requires investment in power generation assets (CAPEX) of EUR2,620 billion in the 2011- 2050 period. Since those investments are partly used for fossil fuel power plants, fuel costs and thus operational costs (OPEX) remain on a very high level of EUR5,700 billion over the same period, causing total costs of EUR8.3 trillion.

Under the Reference scenario, the levels of investment in conventional power plants add up to almost 35% while approximately 65% would be invested in renewable energy and cogeneration until 2050. Under *the Energy [R]evolution* scenario, however, the EU 27 countries would shift almost 96% of their entire energy investment towards renewables and cogeneration. The average annual investment in the power sector under the *Energy [R]evolution* scenario between today and 2050 would be approximately EUR 99 billion.

To identify long-term cost developments, **learning curves** have been applied to the model calculations to reflect how the cost of a particular **technology** can change in relation to the cumulative production volumes. For many technologies, the learning factor (or progress ratio) is between 0.75 for less mature systems to 0.95 and higher for well-established technologies. A learning factor of 0.9 means that costs are expected to fall by 10% every time the cumulative output from the technology doubles. Empirical data shows, for example, that the learning factor for PV solar modules has been fairly constant at 0.8 over 30 years whilst that for wind energy varies from 0.75 in the UK to 0.94 in the more advanced German market. For PV, assuming a globally installed capacity of 1,500 GW by between 2030 and 2040 in the *Energy [R]evolution* scenario, and with an electricity output of 2,600 TWh/a, the study expects that generation costs of around 4-8 EURcents/kWh (depending on the region) will be achieved. The study assumes that investment costs for wind turbines will reduce by 25% for onshore and 50% for offshore installations up to 2050. The cost of energy from initial tidal and wave energy farms has been estimated to be in the range of 20-80 EURcents/kWh, and for initial tidal stream farms in the range of 11-22 EURcents/kWh. Generation costs of 7-8 EURcents/kWh are expected by 2030. According to the latest research findings, the learning factor is estimated to be 10-15% for offshore wave and 5-10% for tidal stream.

Under the E[R] - annual per capita emissions will drop from 7.1 tonnes to 3.5 tonnes in 2030 and 0.4 tonnes in 2050. Despite the phasing out of nuclear energy and increasing demand, CO_2 emissions will decrease in the electricity sector. With a share of 17% of CO_2 emissions in 2050, the power sector will drop below transport and other sectors as the largest sources of emissions.

Under the *Reference* scenario, **total primary energy demand** in EU 27 increases by 5% from the current 69,700 PJ/a to around 73,400 PJ/a in 2050 (including net electricity imports). The energy demand in 2050 in the Energy[R]evolution scenario decreases by 35% compared to current consumption and it is expected by 2050 to reach 45,500 PJ/a. The overall renewable primary energy share on 2030 is of 43% and of 85% in 2050.

Under the *Energy [R]evolution* scenario, **electricity demand** in the industry as well as in the residential and service sectors is expected to decrease after 2015. Because of the growing shares of electric vehicles, heat pumps and hydrogen generation however, electricity demand increases to 3,296 TWh/a in 2050, still 16% below the *Reference* case, where total electricity supply costs raise from EUR300 billion/year to more than EUR568 billion in 2050 (due to unchecked growth in demand, increase in fossil fuel prices and the cost of CO2 emissions).

By 2050, 96% of the electricity produced in EU 27 will come from renewable energy sources. ‘New’ renewables – mainly wind, solar thermal energy and PV – will contribute 75% of electricity generation. The *Energy [R]evolution* scenario projects an immediate market development with high annual growth rates achieving a **renewable electricity share** of 44% already by 2020 and 67% by 2030. The installed capacity of renewables will reach 989 GW in 2030 and 1,480 GW by 2050.

The introduction of renewable technologies under the *Energy [R]evolution* scenario slightly increases the **costs of electricity generation** in EU 27 compared to the Reference scenario. This difference will be less than 0.7 EURcents/kWh up to 2020, however. Because of the lower CO_2 intensity of electricity generation, electricity generation costs will become favourable under the *Energy [R]evolution* scenario and by 2050 costs will be 4.8 EURcents/kWh below those in the Reference version.

- *Conclusions:*

The authors place an emphasis on several key recommendations for energy policy changes which need to be implemented in order to be able to realise the sustainable pathways described in the *energy (R)evolution* scenarios. Developing a vision for a sustainable energy economy for 2050 is a key one, along with adopting and implementing ambitious and legally binding targets for emissions reductions, energy savings and renewable energy; removing barriers to a renewable and efficient energy system; implementing effective policies to promote a clean energy economy; and ensuring that the transition is financed.

Efficient large-scale super grids are said to be needed to link together a number of countries and connect areas with a large supply of renewable electricity to areas with large demand. At the same time local distribution network systems are said to become more important as large amounts of decentralised energy technologies in the alternative scenarios are connected to one another and to nearby consumers.

The authors of the study also stress that the electricity system needs to become more flexible so that it is able to deal with the fluctuations of variable renewable power, e.g. by adjusting demand via demand side management (DSM) or by deploying storage systems. Smart grid technology is also mentioned as an important instrument for this purpose.