Challenges in achieving energy & climate goals from the EU Energy Roadmap 2050

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1. Introduction

Climate change is one of the biggest global challenges to date. The European Union (EU) has expressed the ambition to take the lead in combating climate change, by moving to a low carbon economy. This ambition resulted in the formulation of the 20/20/20 goals for 2020 (EC, 2008). These goals for 2020 include a 20% reduction in greenhouse gas (GHG) emissions compared to 1990[1], a 20% share of renewables in final energy consumption and 20% energy savings. These 2020 goals are a first step to realise the ambition formulated in the EU Energy Road map 2050 (EC, 2011a), to reduce the GHG emissions with 80-95% in 2050. The GHG target for 2020 is projected to be slightly overachieved (EC, 2013b), which can partially be explained by the recent economic crisis, as well as the increased share of renewables and energy savings. Although the GHG target for 2020 will be achieved, a 28% GHG reduction in 2020 would be required for the most cost-effective mitigation path towards an 80% GHG emission reduction in 2050 (Knopf *et al.,* 2013). Therefore, it is essential that an ambitious GHG target for 2030 will be set. This would also give a clear sign to businesses and the international community that Europe is serious about its decarbonisation ambitions, thereby reducing risks and uncertainty for companies investing in low carbon technologies.

Early 2014 the European Commission (EC) proposed the EU Energy and climate policy until 2030, which includes a GHG emission reduction target of 40% and an renewables target share of 27% (EC, 2014). A GHG cut of 40% is supported by almost all Member States (IBEC, 2013), but energy models suggest that a 47% emission reduction is required to reach the 2050 targets in the most cost effective way (Knopf *et al.,* 2013). An ambitious GHG target alone would be sufficient to drive innovation enough to achieve deep carbon emission reductions in a cost-effective manner. However, when the GHG

[1] 1990 is the standard base year, so the emission reductions mentioned hereafter are also relative to 1990, unless stated otherwise

target is not ambitious enough, like in the case of a 40% GHG reduction for 2030, there is the risk that only the cheapest abatement options will be implemented, inhibiting maturation of the abatement technologies needed to achieve deep GHG emission reductions in the long-term (PBL, 2013). As a consequence, GHG abatement beyond 2030 would become more expensive (*ibid.).* Therefore, to reduce costs of renewable energy technologies and energy efficient appliances sufficiently, an ambitious GHG abatement target is indispensible. Potentially, such a target could be complemented by financial support for R&D of low-carbon technologies.

The main objective of this study is to contribute to the discussion on the energy & climate targets and policies for beyond 2020. It attempts to answer the following research question: 'which are the biggest challenges to safeguard the achievement of a deep emission reduction in 2050, from a sectorial viewpoint?' In order to answer the research question, the following steps will be taken:

1. Decarbonisation in all sectors in the period 1990-2010 has been investigated to place the decarbonisation efforts in the 2013 Reference Scenario in the context of historical decarbonisation trends.
2. Decarbonisation efforts projected in the 2013 Reference Scenario between 2010 and 2020, have been compared with those projected for the period beyond 2020.
3. The change in GHG emissions from 2010 till 2050, included in the most recent EU 2013 Reference Scenario (Capros *et al.*, 2013) has been decomposed and investigated on a sectorial level
4. Decomposition of the difference in energy-related CO_2 emissions between the 2013 Reference Scenario and a deep emission scenario[2], to identify the additional efforts needed to move to an 80% emission reduction in 2050. Furthermore, sector-specific challenges to achieve deep GHG emission reduction will be discussed. Finally, the energy savings in the deep emission scenario will be compared to the maximum energy saving potentials.

[2] The average of the 5 deep emission scenarios in the Energy Roadmap, see section 2.4 for more information.

2. Data & Methods

In this chapter the research methods for each of the above mentioned steps are discussed. In this study the EU energy and Climate scenario: '*EU Energy, Transport and GHG Emissions Trends to 2050 – 2013 Reference Scenario*[3]*'* (Capros *et al*., 2013), has been used as baseline scenario for the evolution of the GHG emissions between 1990 and 2050. This scenario will be referred to in this study as the 2013 Reference Scenario. The geographical scope of this study is the EU27, which will be referred to hereafter as EU. Croatia was not included in this study, because it was not yet a EU Member State when the decarbonisation scenarios of the Energy Roadmap were made, making a fair comparison with the 2013 Reference Scenario impossible.

2.1 Step 1: Comparison of decarbonisation between 1990 and 2010 and decarbonisation in the 2013 Reference Scenario

To evaluate the ambition level of decarbonisation in the 2013 Reference Scenario is, the decarbonisation rate from 2010 till 2050 from the scenario has been compared to the rate of decarbonisation in the period 1990-2010. When looking at energy-related CO_2 emissions, decarbonisation can be described as a decline in the carbon intensity, which is the amount of CO_2 emissions per unit of activity[4]. The carbon intensity is composed of the energy intensity and the average emission factor, as described in equation 1.

(1) Carbon intensity = $\frac{CO_2}{activity} = \frac{CO_2}{FEC} \cdot \frac{FEC}{Activity}$

Where CO_2 denotes the absolute amount of CO_2 emissions (Mton) and FEC denotes the final energy consumption (Mtoe).

Historical levels of the carbon intensity were calculated using emission data, final energy consumption data and activity levels for all end-use sectors obtained from

[3] This scenario does not assume any new energy and climate policies beyond 2020. It only includes energy and climate policies that have been implemented as far as 2012 and continuation of the EU ETS is assumed, with a cap decreasing at a rate of 1.74%/yr. For more detailed information on the assumptions see Capros *et al.,* 2013.

[4] The term carbon intensity is also used to denote the amount of emissions per unit of energy input, which is the carbon intensity of energy (IEA, 2013b). In this paper the carbon intensity describes the amount of GHG emissions per unit of activity, usually kg CO_2-eq./€ value added. The amount of GHG emissions per unit of energy use will be referred to as the average emission factor in this study.

EUROSTAT. Carbon intensities from 1990-2010 were used to calculate the emission level in 2050 in case the 1990-2010 rate of decarbonisation would be sustained. This calculation has been done by linear extrapolation of the 1990-2010 carbon intensities till 2050 and subsequently the carbon intensity obtained for 2050 was multiplied with activity level projected in the 2013 Reference Scenario.

For the non energy related CO_2 emissions and non-CO_2 GHGs the relative decline of the absolute emission level between 1990 and 2010 has been extrapolated to yield the emission level for 2050, when the GHG abatement rate from 1990-2010 would be continued. This has also been done for the CO_2 emissions in the Energy Branch, since no activity indicators are available for this branche.

2.2 Step 2: Comparison of decarbonisation efforts in the 2013 Reference Scenario from 2010-2020 to those beyond 2020

Next to comparing the decarbonisation in the 2013 Reference Scenario with past decarbonisation trends, it is interesting to compare decarbonisation within the 2013 Reference Scenario in the periods 2010-2020 and 2020-2050 as well. This is an informative comparison, because decarbonisation in the period 2010-2020 is influenced by the 20/20/20 energy and climate package, whereas this influence is much less for the period beyond 2020. For this analysis, carbon intensities were used as decarbonisation indicator for the energy-related CO_2 emissions, except for the energy branch, as described in section 2.1. The decline in carbon intensity from 2010-2020 has been extrapolated linearly for 3 decades to calculate the emission level in 2050 in case that the 2010-2020 decarbonisation rate would be sustained. For the other non-energy related GHG emissions the relative decline in the absolute GHG emission level has been used for the extrapolation.

2.3 Step 3: Decomposition of CO_2 emission abatement in the 2013 Reference Scenario between 2010 and 2050

In this step the energy related CO_2 emissions, which are the largest source of GHG emissions in the EU are studied in more detail, to get a better understanding of the drivers underlying CO_2 abatement in the end use sectors and the power sector.

2.3.1 Decomposition of CO_2 abatement in the end-use sectors

Changes in the amount of energy related CO_2 emissions are influenced by three main drivers, namely the activity level, energy intensity and the average emission factor. The activity (A) level is the amount of economic output in a sector (in terms of value added or sector specific activity indicators). Since production of the economic output is often accompanied with energy use, changes in the activity level mostly lead to changes in CO_2 emissions as well. (EI) is the amount of energy needed to produce a certain amount of economic output (GJ/€ value added or sector-specific activity indicators). Changes in energy intensity can be caused by introduction of energy efficient equipment or structural change towards more energy intensive or energy-extensive processes. Finally, the 'emission factor effect' (EF) is the amount of CO_2 produced per unit of energy input. Changes in the average emission factor often result from changes in the fuel mix. Increasing the share of renewables in the fuel mix for example, leads to a drop in the average emission factor. The relation between A, EI and EF is described in equation 2.

Decomposition analysis has been used to divide the changes in energy related CO_2 emissions in the 2013 Reference Scenario between 2010 and 2050 into the aforementioned drivers. There is a variety of decomposition methods and the variant used in this paper is the Logarithmic Divisia index (LMDI) method (Ang, 2001). The advantage of this method is that it does not give an unexplained residual (interaction) term. Other methods such as the original Laspeyers index method do give a residual term, which makes the interpretation of the results difficult (Ang *et al.,* 1998, Ang *et al.,* 2003). However, it should be noted that although the LMDI method does not leave a residual term, it does not necessarily mean that the residue is distributed over the emission drivers in the right manner. Decomposition analysis has been used primarily to analyse changes in one country or region over time, but it has also been used to do cross-country comparisons (Ang & Zhang, 2000) and more recently to compare scenarios (IEA, 2012b). For an overview of the applications of decomposition analysis, see Ang & Zhang (2000).

(2)[5] $$\Delta CO_2 = A*EI*EF = (Activity) \cdot \left(\frac{FEC}{Activity}\right) \cdot \left(\frac{CO_2}{FEC}\right)$$

[5] NB This is the same as equation 1, but now the carbon intensity is multiplied with the activity level.

This three-factor decomposition has been done for industry, the tertiary sector, residential sector and transport. Below, the equations are given for emission driver.

$$(3) \quad \text{Activity effect (A)} = \left(\frac{(CO_2)_B-(CO_2)_A}{LN(CO_2)_B-LN(CO_2)_A}\right)\cdot LN\left(\frac{Activity_B}{Activity_A}\right)$$

Where CO_2 is the absolute level of CO_2 emissions (Mton). The activity is expressed in terms of value added for industry and the tertiary sector and in terms of household size for the residential sector[6]. For the transport sector activity of passenger and freight transport were summed, to yield activity in terms of Pkm+tkm. This was done because separate numbers for CO_2 emissions of passenger transport and freight transport are not publically available. However, adding the activity of passenger and freight transport can be done, because pkms and tkms have the same order of magnitude and are projected to increase in similar proportions. The subscript B denotes the situation in 2050 and the subscript A the situation in 2010 (this holds for equation 3-6).

$$(4) \quad \text{Energy intensity effect} = \left(\frac{(CO_2)_B-(CO_2)_A}{LN(CO_2)_B-LN(CO_2)_A}\right)\cdot LN\left(\frac{\left(\frac{FEC}{Activity}\right)_B}{\left(\frac{FEC}{Activity}\right)_A}\right)$$

Where $\frac{FEC}{Activity}$ is the energy intensity, in terms of final energy consumption (Mtoe) per unit of activity.

$$(5) \quad \text{Emission factor effect} = \left(\frac{(CO_2)_B-(CO_2)_A}{LN(CO_2)_B-LN(CO_2)_A}\right)\cdot LN\left(\frac{\left(\frac{CO_2}{FEC}\right)_B}{\left(\frac{CO_2}{FEC}\right)_A}\right)$$

Where $\frac{CO_2}{FEC}$ is the average emission factor, in terms of total absolute CO_2 emissions (Mton) per unit of final energy consumption (Mtoe).

2.3.2 Decomposition of CO_2 emissions in the power sector

For the power sector a four-factor decomposition has been done. In this decomposition all emissions were allocated to fossil power generation, since renewables and nuclear power generation are assumed to cause no direct CO_2 emissions in the 2013 Reference Scenario. The total amount of electricity generated was used as activity indicator. Structural change was introduced as fourth effect, which describes the change in share

[6] The number of people in a household and the number of households influence the energy use more directly than does household income.

of fossil power plants in electricity generation. A change in structure then reflects a shift from fossil power generation towards renewables and nuclear power generation. The equation describing this structure effect is given below:

(6) Structure effect = $\left(\frac{(CO_2)_B-(CO_2)_A}{LN\ (CO_2)_B-LN\ (CO_2)_A}\right)\cdot LN\left(\frac{\left(\frac{Electricity_{fossil}}{Electricity_{total}}\right)_B}{\left(\frac{Electricity_{fossil}}{Electricity_{total}}\right)_A}\right)$

The energy intensity effect then describes changes in the amount of fuel input needed per unit of fossil electricity generated(inverse of efficiency). Such changes are primarily caused by changes in the energy efficiency of power plants, but also thrugh implementation of carbon capture and storage (CCS) and to some extent by fuel switching as well[7]. Finally, changes in the emission factor now reflect fuel switching within fossil power generation as well as implementation of CCS. The effects of CCS and fossil fuel switching on the emission factor effect can also be separated. This separation is done by calculating the emissions resulting from the combustion of the fossil fuels, using fuel-specific emission factors[8]. The difference between the emissions given in the scenario and the emissions calculated is the amount of emissions that is captured by CCS (see equation 7). Subsequently, this amount of CO_2 captured can be subtracted from the CO_2 reduction from the emission factor effect, calculated using the decomposition.

(7) Emission factor effect – CO_2 captured with CCS = fossil fuel mix change effect

2.4 Step 4: Quantifying efforts required to move from baseline GHG abatement to an 80% GHG emission reduction

In the previous sections the decomposition of the change in energy-related CO_2 emissions in the 2013 Reference Scenario has been discussed. Similar decompositions have been done for the difference in energy related CO_2 emissions between the 2013 Reference Scenario and the case where an 80% GHG emission reduction is achieved.

[7] Switching from coal-fired power plants to combined cycle gas fired power plants for example leads to an increase in efficiency (IEA, 2012c)

[8] These emission factors were taken from the IPCC Guidelines for national greenhouse gas inventories (IPCC,2006). Since this report gives emission ranges, the emission factors were chosen so that these fit the emission data from the 2013 Reference Scenario. 2010 was used as base year to gauge the emission factors.

2.4.1 Decomposition of the additional CO_2 abatement in the deep emission reduction scenario compared to the 2013 Reference Scenario

In order to study deep emission reductions the deep emission scenarios from the Energy Roadmap 2050 Impact Analysis were used (EC, 2011b). This report includes five deep emission scenarios, which all reach an 80% GHG emission reduction in 2050, but differ in their assumptions about the implementation of energy savings, renewables, development of CCS and the role of nuclear energy. Despite of these different assumptions, the five scenarios are very similar in terms of sectorial emissions as well as final energy consumption[9]. To make a robust comparison between the 2013 Reference Scenario and the deep emission scenarios the outcomes of the average of the five scenarios was calculated to derive an average deep emission reduction scenario, which will be referred to as the DER scenario in the rest of this paper.

In order to analyse the additional efforts required to reach a CO_2 emission reduction of 80%, the difference in energy-related CO_2 emissions in 2050 between the 2013 Reference Scenario and the DER scenario is decomposed. Again, this has been done for both the end use sectors using formulas 2-6 and the power sector, using formulas 2-7. To show the impact of the decarbonisation strategy chosen for the power sector on the decomposition results, the difference in CO_2 emissions in 2050 between the 2013 Reference Scenario and the High RES scenario has been decomposed as well[10]. In contrast to the decomposition described in section 2.3.1, the subscript B is now the situation in the DER scenario, whereas A denotes the situation in the 2013 Reference Scenario. For this decomposition the same activity indicators were used as described in 2.1, except for the residential sector were household income has been used, because of lacking data regarding the number of households.

To give a complete picture of the decarbonisation in the DER scenario, the required abatement of non-energy related CO_2 emissions and non-CO_2 GHGs is shown as well. The abatement levels in these sectors in case of an 80% GHG emission reduction, were obtained from the '*Effective Technology scenario under global climate action (ET_GCA)'* (Capros *et al.,* 2012a), since emission levels for these sectors are not given in the

[9] Only the efficiency scenario differs substantially from the other four scenarios with respect to final energy consumption, but this will be discussed in section 3.3.3

[10] This scenario is one of the five deep emission reduction scenarios in from the energy Roadmap and this scenario assumes additional policies supporting renewables.

Energy Roadmap scenarios. The total CO_2 abatement in the ET_GCA scenario is virtually equal to that in the DER scenario, meaning that taking the non-energy related CO_2 emissions and non-CO_2 GHG levels for 2050 from this scenario probably does not lead to large errors.

2.4.2 Calculation of required acceleration in decarbonisation to mover from decarbonisation in the 2013 Reference Scenario to an 80% emission reduction

In order to clarify how much sectors have to accelerate decarbonisation efforts compared to the 2013 Reference Scenario, to reach an 80% emission reduction, carbon intensity improvement rates, energy intensity improvement rates and emission factor improvement rates from the DER scenario were divided by those from the 2013 Reference Scenario (see equation 8). Since energy and climate policies till 2020 are already relatively fixed and have been included in the 2013 Reference Scenario, the acceleration factor describes the required acceleration compared to the 2013 Reference scenario in the period 2020-2050.

(8) Acceleration factor = $\frac{Carbon\ intensity_{DER}}{Carbon\ intensity_{Ref}}$ or $\frac{Energy\ intensity_{DER}}{Energy\ intensity_{Ref}}$ or $\frac{emission\ factor_{DER}}{emission\ factor_{Ref}}$

2.4.3 Energy Savings

Energy savings in the 2013 Reference Scenario and the DER scenario were compared to the energy savings in the Energy Efficiency Scenario, to show the extent to which the importance of energy savings in the deep emission reduction scenarios from the Energy Roadmap can differ. Furthermore, the energy savings in the 2013 Reference Scenario and DER scenario were compared to the maximal energy savings potentials described in the Policy report '*Contribution of energy savings to climate protection within the European Union until 2050*' (Fraunhofer, 2012). From this policy report the maximal energy savings per sector were combined with the final energy use per sector in the Energy Roadmap Reference Scenario[11], to calculate the minimum final energy consumption for 2050 for all end-use sectors.

[11] This scenario was used as baseline scenario in the Energy savings potential study of the Fraunhofer institute (Fraunhofer, 2012)

3. Results

3.1 Decarbonisation between 1990 and 2010

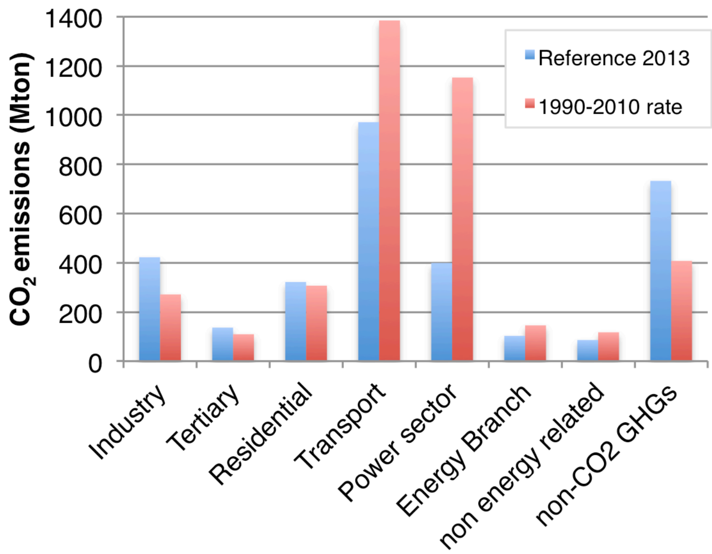

Figure 1. GHG emissions in 2050 for all sectors in the 2013 Reference Scenario (blue) compared to the extrapolation of the 1990-2010 trend (red).

In order to place decarbonisation rates in the 2013 Reference Scenario in the context of historical decarbonisation efforts, decarbonisation between 1990 and 2010 has been studied first. At the level of the entire economy, the carbon intensity [12] has been declining between 1990 and 2010 with 2.1% per year, compared to a projected annual drop of 2.6% between 2010 and 2050. The energy intensity is projected to drop with 1.7% annually from 2010 till 2050, while it declined 1.5% annually between 1990 and 2010. Finally, for the emission factor an annual drop of 0.9% is projected, compared to 0.6% between 1990 and 2010. The fact that the decarbonisation projected in the 2013 Reference Scenario between 2010 and 2050, is higher than the historical rate between 1990 and 2010 is largely explained by the acceleration of decarbonisation in the power sector. Figure 1 shows an extrapolation of the historical decline in carbon intensity for all sectors between 1990 and 2010 and compares it to decarbonisation in the 2013 Reference Scenario. From this figure it can be seen that the historical rates of decarbonisation are higher than in the 2013 Reference Scenario for all sectors except the transport sector and the power sector. This means that for most sectors, maintaining the decarbonisation level from 1990 till 2010 is enough to reach the emission levels projected in the 2013 Reference Scenario. For the transport sector and the power sector decarbonisation between 1990 and 2010 was very limited, so efforts have to accelerate in these sectors to achieve the emission level projected in the 2013 Reference Scenario.

[12] Here: the amount of energy-related CO_2 emissions per unit of GDP.

3.2 Comparison of decarbonisation rates from 2010-2020 and 2020-2050

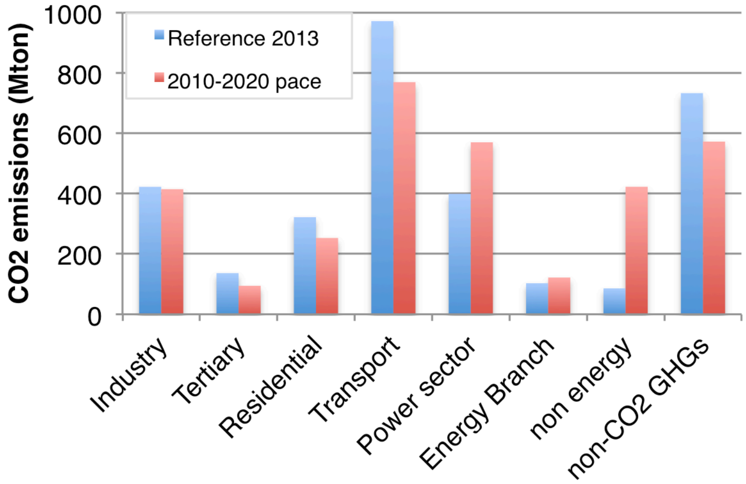

Figure 2. The level of GHG-emissions in the 2013 Reference Scenario (blue) and in case the decarbonisation rate from the period 2010-2020 would be sustained (red).

In the previous section the decarbonisation efforts from 1990 till 2010 have been compared to the rate of decarbonisation in the 2013 Reference Scenario. In this section the decarbonisation rates for different periods within the 2013 Reference Scenario are compared, namely for the period 2010-2020 and the period 2020 till 2050. Where GHG emissions declined with 12.8% between 1990 and 2010, the decline for the period 2010-2020 is projected to be 9.9%. Between 2020 and 2050 the GHG emissions are projected to drop with another 20%.

When looking at the entire economy, decarbonisation is projected to occur in about equal rates in the period 2010-2020 and 2020-2050. Figure 2 shows the level of GHG emissions in 2050 that would be achieved when the decarbonisation rate between 2010 and 2020 would be sustained till 2050. In industry, the tertiary sector and the residential sector a higher rate of decarbonisation is projected before 2020 than beyond 2020. However, for the power sector and the non-energy related CO_2 emissions this is the other way around.

3.3 GHG abatement in the 2013 Reference Scenario between 2010 and 2050

In the previous two sections the rates of decarbonisation in different periods have been compared, for all sectors, to get more insight into the evolution of decarbonisation efforts over time. Before moving to the question what is required to reach deep GHG emission reductions, it is important to study the evolution of GHG emissions till 2050 in the 2013 Reference Scenario. In this section the change in energy-related CO_2 emissions between 2010 and 2050 is decomposed into its underlying drivers. This is done for the end-use sectors as well as for the power sector.

3.3.1 Overview of the evolution of GHG emissions in the 2013 Reference Scenario

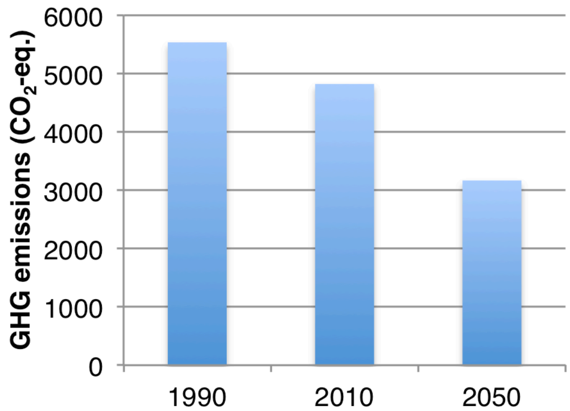

Figure 3. GHG-emissions in the EU27 in 1990, 2010 and the emissions projected for 2050 in the 2013 Reference Scenario.

In figure 3 the projected GHG emission level in the 2013 Reference Scenario for 2050 are shown and compared to the emission levels in 1990 and 2010. Between 2010 and 2050 the emissions are projected to be reduced by 34%. Table 1 shows to what extent the various sectors contribute to this emission reduction. The power sector is expected to make the largest contribution (57%) to the GHG abatement between 2010 and 2050. The remaining sectors contribute in about equal (absolute) quantities to the total emission reduction in 2050, although there are large differences in the relative emission reduction within the sectors (table 1).

Table 1. GHG abatement in the 2013 Reference Scenario between 2010 and 2050 for each sector. The first three columns indicate absolute emission levels and the absolute emission reduction. The 4th column shows the relative emission reduction within the sector compared to the 2010 emission level and the right column indicates to which extent each sector contributes to the total GHG abatement between 2010 and 2050.

	GHG emissions (Mton CO_2-eq)			Relative GHG abatement	
Sector	**2010**	**2050**	**Reduction**	**Within sector**	**Contribution to total abatement 2010-2050**
Power generation & District heating	1.337	402	935	70%	57%
Energy Branch	158	104	54	34%	3%
Industry	518	425	92	18%	6%
Residential	456	324	132	29%	8%
Tertiary	248	138	110	44%	7%
Transport	1.045	972	73	7%	4%
Non ER CO_2	234	86	147	63%	9%
Non-CO_2 GHGs	824	738	86	10%	5%

3.3.2. CO_2 abatement between 2010 and 2050 in the end use sectors

To gain more insight into the drivers of change in energy related CO_2 emissions between 2010 and 2050 in the 2013 Reference Scenario, the emissions were decomposed into an activity effect, energy intensity effect and emission factor effect, as shown in figure 4. It can be seen from this figure that all sectors show a significant activity effect, especially the transport sector. Nevertheless there is a net decline in CO_2 emissions, primarily due to declining energy intensity, explaining 69% of the decline in the end-use sectors. The remaining 31% is explained by a declining average emission factor.

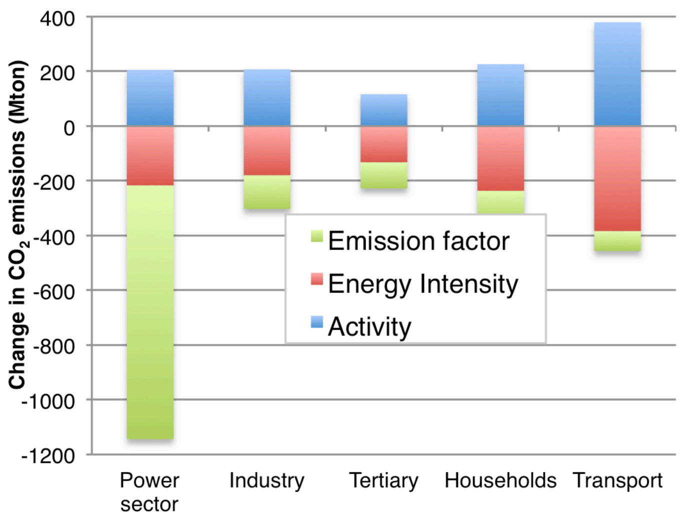

Figure 4. Decomposition of the change in energy-related CO_2 emissions in the 2013 Reference Scenario between 2010 and 2050 into activity, structure, energy intensity and emission factor effects.

The tertiary sector is the largest sector in the EU economy, contributing for 68% to the EU GDP in 2010. Nevertheless, the activity in this sector is projected to grow with 86% between 2010 and 2050, thereby being the fastest growing sector in the economy. At the same time the sector shows a 70% decline in its carbon intensity, which is the largest relative decline in carbon intensity of all end-use sectors.

In the transport sector the absolute CO_2 abatement till 2050 is only 77 Mt, because the activity in this sector is expected to grow significantly, with 41% for passenger transport and 57% for freight transport. In aviation, the activity is even projected to increase with over 132% between 2010 and 2050. Increasing emissions from increasing activity are counteracted by a drop in carbon intensity, which is projected to decline with 36% between 2010 and 2050. This decline in carbon intensity is primarily driven by energy intensity improvement. Energy intensity is projected to decline faster in passenger transport, with 1.1% per year, than in freight transport, where the annual decline is only 0.6%. The emission factor declines with only 10% in the 2013 Reference Scenario, because fuel switching from oil to biofuels and especially electricity is very limited in the 2013 Reference Scenario. In 2050 88% of the energy use in passenger transport is still supplied by fossil fuels, whereas biofuels and electricity only contribute for 9% and 3% respectively. In freight transport the emission factor is also lowered slightly, because of increased use of biofuels in road freight, contributing for 3.7% of the energy demand in freight transport, but also through further electrification of rail transport.

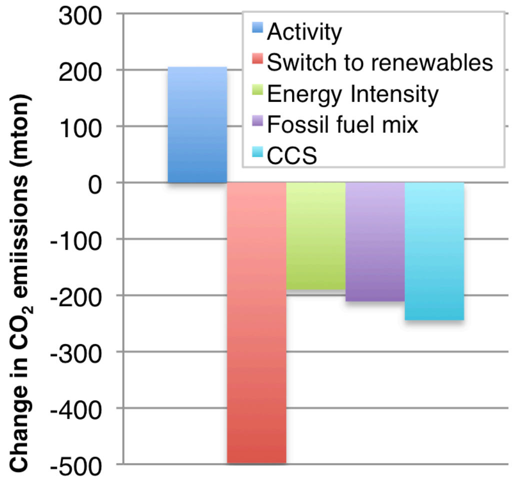

Figure 5 – Decomposition of the change in CO_2 emissions (Mton) in the power sector between 2010 and 2050 into an activity effect, power pant efficiency effect, switch to renewables, fuel switching between fossil fuels and CCS.

3.2.2 Decarbonisation of the power sector

As stated before the power sector contributes most strongly to decarbonisation in the 2013 Reference Scenario. At the same time the activity in the power sector increases, due to electrification of final energy demand, resulting in an increase of CO_2 emissions of about 200 Mton (fig.4.). However, this activity effect is more than compensated by the other effects, which lead to a total emission reduction of 1144Mton. Where emission reductions in the end-use sectors are primarily caused by a declining energy-intensity, the major source of decarbonisation in the power sector is a decline in the emission factor (figure 4), explaining 83% of the total emission reduction. Energy intensity improvement in fossil power generation explains the remaining 190 Mton (17%) of CO_2 abatement. The emission factor effect can be further decomposed into structural change towards more renewables, changes in the fossil fuel mix and implementation of CCS (figure 5). Replacement of fossil power generation by renewables explains the largest part of the emission factor effect, reducing emissions with 498Mton. CCS leads to another 245Mton of CO_2 abatement. Fuel switching between fossil fuels, primarily from coal to gas leads to 211Mton of CO_2 abatement.

In order to become the most important source of CO_2 abatement in the power sector, the share of renewables in electricity generation has to increase from 20.8% in 2010 to 51.5% in 2050, meaning an average annual growth of 3.0%. Wind energy is projected to be the largest source of renewable electricity, which is 48% of renewable electricity generation. To achieve this, the wind energy capacity has to increase from 84GW in 2010 to 421GW in 2050. This capacity also includes substantial deployment of offshore wind. However, where electricity generation from wind increases 7-fold from 2010 till 2050, solar electricity generation (PV and others) grows 15-fold. The cumulative installed capacity of PV is expected to grow from 30GW in 2010 to 110GW in 2020, which is in line with the BAU scenario from the European Photovoltaic Industry Association, which projects a cumulative installed capacity of 124GW (EPIA, 2013). In the 2013 Reference Scenario this capacity is projected to increase further to 230GW in 2050. Electricity generation from biomass is expected to double between 2010 and 2050 accounting for 15% of the renewable electricity generation in 2050. Geothermal electricity will increase five-fold, to contribute for 1.3% of the renewable electricity generation in 2050.

3.4 Quantifying efforts required to move from baseline GHG abatement to an 80% GHG emission reduction

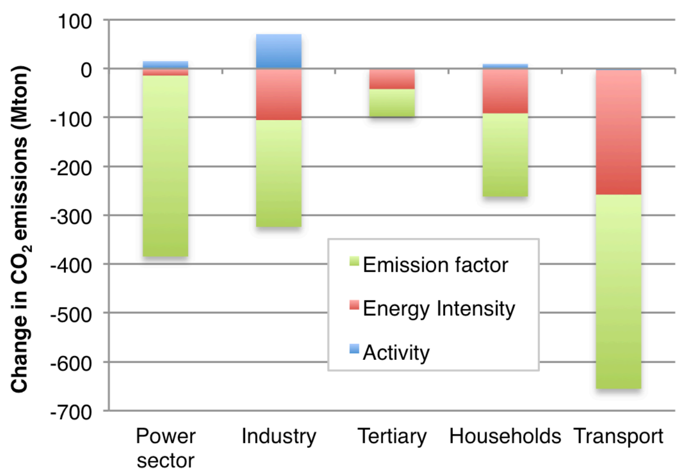

Figure 6. Decomposition of difference in energy-related CO_2 emissions between the 2013 Reference Scenario and the DER scenario in 2050 into activity, energy intensity and fuel mix effects.

Now the decarbonisation in the 2013 Reference Scenario and its underlying drivers have been discussed, the discussion turns to what is necessary to achieve a 80% GHG emission reduction. To this end the additional decarbonisation in the DER scenario, compared to the 2013 Reference Scenario are discussed in the following section.

3.4.1 Overview of additional decarbonisation efforts in the DER scenario

To achieve an emission reduction of 80% in 2050, the GHG emissions have to drop to one third of the 2050 emissions in the 2013 Reference Scenario, meaning an additional reduction of 2Gton CO_2-eq. The overall carbon intensity improvement has to speed up from 2.6% per year to 5.9% and the annual reduction in the absolute emissions has to speed up from 1.2% to 3.6%. In figure 6 the difference in energy-related CO_2 emissions between the DER scenario and the 2013 Reference Scenario is decomposed into a difference in sectorial activity, an energy intensity effect and an emission factor effect (figure 6). From this figure it can be seen that most of the sectors hardly show an activity effect, which means that the economic projections are quite comparable between both scenarios. Only industry shows a relatively large activity effect, of 72 Mton CO_2, meaning that growth projections for industrial activity have been adjusted a little bit downwards in the 2013 Reference Scenario. In contrast to CO_2 abatement in the 2013 Reference Scenario (fig 4), where energy intensity improvement is dominant in most sectors, the additional CO_2 abatement in the DER scenario is mainly achieved by lowering the emission factor.

3.4.2 Acceleration of sectorial decarbonisation rates

Although decarbonisation has to speed up in all sectors, the additional effort required is not equal for all sectors. Table 2 shows for each sector the factors by which the decline in carbon intensity, energy intensity and emission factor have to accelerate beyond 2020 (compared to the 2013 Reference Scenario) to reach an 80% emission reduction.

Although the carbon intensity improvement between the 2 scenarios in the transport sector does not have to accelerate more sharply than in other sectors, the absolute emission reduction has to accelerate 55-fold. This low level of absolute CO_2 abatement in transport can be explained by the large increase in transport activity.

Table 2. Decarbonisation efforts required in addition to those in the 2013 Reference Scenario, in order to reach a GHG emission reduction of 80% in 2050. This effort is expressed in terms how much the energy intensity improvement, decline of the emission factor and decline of the overall carbon intensity must be sped up.

		Factor by which processes should be accelerated after 2020		
Additional GHG emission reduction required (Mton)		**Energy intensity (EI)**	**Emission factor (EF)**	**Carbon intensity (EI)*(EF)**
Transport	655.1	1.5	1.9	2.9
Industry	246.1	1.3	1.8	2,4
Tertiary	97.1	1.6	2.1	3.4
Residential	247.7	1.6	2.7	4.3
Power sector	368.7	1.1	12.2	12.8
Energy branch	70.8	l.d.	l.d	l.d.

For the energy branch figures regarding the energy intensity and emission factor in are missing, due to a lack of data (l.d).

3.4.3 Decarbonisation of the power sector

The power sector is the sector for which the overall carbon intensity must be accelerated most sharply, which must come almost entirely from an additional decline in the emission factor (table 2). This is logical since the potential for energy efficiency improvement in thermal power plants is already utilized in the 2013 Reference Scenario.

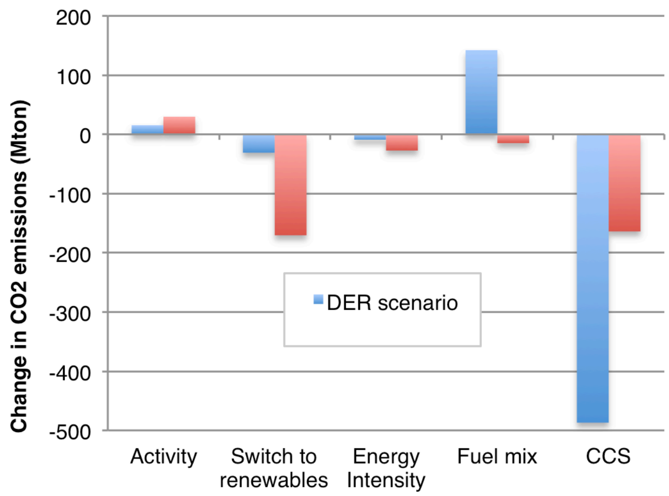

Figure 7. Decomposition of the additional CO_2 emission abatement in the power sector (Mton) compared to the 2013 Reference Scenario, for the DER scenario (blue) and the high renewables scenario (red).

To gain more insight the additional decarbonisation of the power sector in the DER scenario, the difference in CO_2 emissions of this sector between the 2013 Reference Scenario and the DER scenario was decomposed (blue bars fig. 7). From this figure it can be seen that additional electrification in the DER scenario leads to 15 Mton of additional CO_2 emissions. Interestingly, larger share of coal in the DER scenario than in the 2013 Reference Scenario leads to an increase in emissions of 142 Mton CO_2, explaining the positive fuel mix effect in figure 6. However, this additional CO_2 that is produced is hardly emitted into the air, since the importance of CCS increased a lot in the DER scenario. This can also be seen from figure 7, which shows a CO_2 abatement through CCS of 487 Mton (92% of the total emission reduction). Renewables and increased energy efficiency contribute for the remaining 31 Mton (6%) and 9 Mton (2%) of CO_2 abatement, respectively.

When looking at these results, one could get the impression that to fully decarbonise the power sector, CCS is indispensible, but this is only partly true. Full decarbonisation of the power sector can also be achieved by a stronger increase in the deployment of renewables, such as was done in the *high renewables scenario* from the Energy Roadmap (EC, 2011b). Therefore, the difference in CO_2 emissions between the *high renewables scenario* and the 2013 Reference Scenario has also been decomposed (red bars fig.6). As can be seen from figure 6, this scenario shows a completely different picture than the DER scenario. Renewables are far more important, being responsible for a CO_2 abatement of 170 Mton (45% of the total reduction). Due to the increased share of renewables the importance of CCS declines and is now responsible for a CO_2 abatement of 164 Mton (44% of total reduction). Because of the declined implementation of CCS, the share of coal is much lower (and gas higher) in the high renewables scenario, leading to an emission reduction of 15 Mton (4% of total) through fuel switching. The remaining abatement of 27 Mton (7%) is achieved by improved energy efficiency.

3.4.4 Final energy savings in the DER scenario

In the DER scenario the total final energy demand is reduced with 356 Mtoe (37.3%) compared to the 2013 Reference Scenario. The level of utilization of energy saving potentials differs between the deep emission scenarios from the Energy Roadmap, with the largest energy savings in the Efficiency scenario and a lower level of savings for the other four scenarios[13]. The Fraunhofer institute found that large potentials for final energy savings exist for all sectors (Fraunhofer ISI, 2012). In figure 8 the final energy consumption for the residential, industry, tertiary & transport sector in the 2013 Reference Scenario, the DER scenario, the Efficiency scenario and the minimum consumption level (maximal savings) found by the Fraunhofer institute are sown. From this figure it can be seen that the reduction in the energy consumption in the DER scenario compared to the 2013 Reference Scenario is much larger than the additional energy savings in the Efficiency scenario. A more important conclusion is that even in the Efficiency scenario the energy consumption levels are substantially higher than those in case of maximum energy savings. This is especially the case for the residential sector and industry (fig. 8).

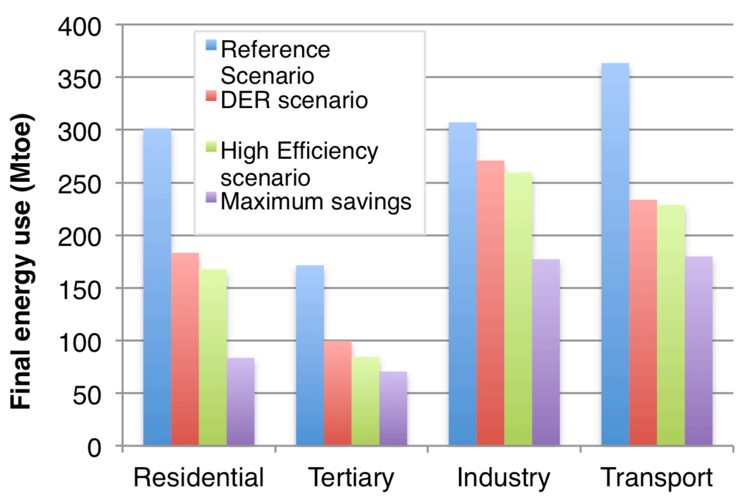

Figure 8. Final energy consumption levels (Mtoe) in 2050 per sector, in the 2013 Reference Scenario, the DER scenario, the Efficiency scenario and the consumption level in case of maximal energy savings.

[13] The sectorial final energy consumption does not differ much among these scenarios.

4. Discussion

4.1 Decarbonisation in the period 1990-2010

The decarbonisation developments in the end-use sectors assumed in the 2013 Reference Scenario are somewhat slower than the historical trend (figure 1), but this does not mean that no new policies will be required to maintain the historical rate of energy efficiency improvement and decarbonisation, since historical changes were also stimulated to some extent by policies. In the power sector and the transport sector a significant break in the trend is required to reach the emission levels projected in the 2013 Reference Scenario. However,

4.2 Developments between 2010 and 2020

Overall the decarbonisation rate between 2010 and 2020 is projected to be about equal to the rate beyond 2020, while decarbonisation in the end-use sectors and the non-CO_2 GHG sector are declining faster between 2010 and 2020 than beyond 2020. The slow down of abatement in the non-CO_2-GHG sector beyond 2020, reflects the fact that many cheap abatement options, such as the abolition of landfills, have been implemented before 2020. As a consequence, GHG abatement in this sector may slow down after 2020, because the marginal abatement costs for further abatement are much higher (Höglund-Isaksson *et al.,* 2010).

Furthermore, it is important to note that even in the 2013 Reference Scenario, decarbonisation in the power sector has to accelerate significantly beyond 2020. This might reflect the effect of the ETS on the power sector as well as decreasing costs of renewables.

The fact that all end-use sectors decarbonise faster in the period 2010-2020 than after 2020 suggests that the 20/20/20 policy package is successful in achieving GHG emission reductions (primarily through energy saving) beyond baseline improvement. The 20/20/20 package consists not only of its threefold target, but also contains a large package of European energy and climate policies such as the Ecodesign directive, the directive on the energy performance of buildings and the CO_2 performance standards for cars. In addition there are national policies supporting the energy and climate targets, such as the national renewable energy action plans. The policy package for 2030 will also require such specific policies.

In January 2014 the European Commission presented its energy & climate policy proposal for 2030, consisting of a 40% GHG emission reduction and a binding renewables share of 27% (EC, 2014). This started the discussion in Europe among policy-makers and scientist about what the most desirable climate and energy policy package for 2030 looks like. At the time of writing this article, the proposal of the Commission still had to be approved by the European Parliament and the European Council. The 40% GHG emission reduction target will probably be approved, since almost all Member States are in favour of such a target, but approval of a binding renewables target is unlikely, since a lot of Member States oppose such a target (IBEC, 2013). The main concern here is that countries wish to formulate the most cost effective way to reduce GHG emissions on their own (*ibid.*). The UK for example opposes a binding renewables target, while it is in favour of a 50% GHG emission target for 2030, in the light of future international climate negotiations (*ibid.*). Although a stringent GHG target might be sufficient to stimulate decarbonisation in all sectors, a 40% GHG emission reduction target might require additional policies to ensure sufficient innovation for cost-effective decarbonisation on the long-term (PBL, 2013). The next section will highlight some specific sectors and technologies these future policies have to focus on.

4.3 Decarbonisation in the 2013 Reference Scenario

After comparing the decarbonisation rates of different periods in the 2013 Reference Scenario, the challenges that must be taken to realise the decarbonisation efforts projected in the reference scenario will be discussed. This section will focus on the power sector and the transport sector. The power sector is important, because it is the sector for which the highest level of decarbonisation is projected in the Reference Scenario. The transport sector, is interesting to discuss, because emissions hardly decline in this sector, making a reflection on the underlying causes of this low level of CO_2 abatement useful.

4.3.1 Energy intensity improvement is dominant in the 2013 Reference Scenario

The dominance of energy intensity improvement is logical from an economic perspective, decreasing energy consumption leads to a decrease in energy expenses. Furthermore, a focus on energy intensity improvement is in accordance with scenarios from other models, which assume moderate (40%) GHG emission reductions (Knopf *et al.,* 2013).

To date a large part of the cost-effective energy savings potential remains untapped, due to the existence of a number of market failures and other barriers (Fleiter *et al.*, 2011). Therefore, commitment from EU policymakers is required to address these issues, in order to facilitate the energy savings projected in the 2013 Reference Scenario.

4.3.2 Decarbonisation of the power sector

In the 2013 Reference Scenario CO_2 emissions in the power sector drop with 70%, primarily because of increased deployment of renewables. For this to happen, electricity generation from wind has to grow with 5% per year. Although this growth is much slower, than the average 20% per year between 2000 and 2010 it might still be a challenging task, since future growth in wind capacity for example has to take place primarily at offshore locations (EWEA, 2011). In order to realize this offshore capacity, current institutional, legislative, technological and logistic problems with regarding offshore wind have to be addressed (Wieckzorek *et al.,* 2013).

PV capacity is projected to increase 7-fold, in spite of the relatively conservative assumptions regarding PV price developments. The price for large-scale PV was assumed to be around 1900€/kWp in 2015, while the price was already 1220€/kWp in 2013 (JRC EC, 2013). Further cost reductions are expected, primarily in the Balancing of Systems components Bazilian *et al.,* 2013). PV has already reached grid parity for the residential sector in some European countries such as Portugal, Spain and Denmark (Breyer & Gerlach, 2013). In 2020 grid parity will be reached for residential and industrial consumers for almost all over Europe, except the Scandinavian Member states (*Ibid*). These developments will make PV highly competitive with fossil fuels and could have tremendous effects on PV deployment. However, it is important to keep in mind that policies also heavily influence the deployment of PV. When policies such as feed-in tariffs and net metering are abolished, PV becomes less attractive for consumers and as a consequence PV deployment might become more dependent on utilities.

CCS contributes for only 6.9% to the electricity generation in 2050 in the 2013 Reference Scenario, which is relatively low. This is in line with the lagging deployment and development of CCS at the moment (IEA, 2013b).

4.3.3 Decarbonisation in the transport sector

For the transport sector, the baseline projections seem to be quite conservative. Firstly, autonomous decarbonisation in the 2013 Reference Scenario is slower than the historical trend (1990-2010), while there is no reason to assume that decarbonisation will slow down in this sector. Secondly, projections regarding the penetration of low-emission vehicles in passenger road transport are quite conservative. The penetration of electric vehicles in 2050 in the 2013 Reference Scenario is very low (3%). This is caused by assumptions about future developments in the battery prices and driving range of electric vehicles (EVs). The battery price is expected to remain around 600€/kWh from 2010 onwards (Capros *et al.,* 2012[B]) and to drop to a minimum of around 550€/kWh in 2050, while battery prices are already below 350€/kWh (IEA, 2013c). Since the battery price is one of the most important factors determining the purchasing cost of an EV (Van Vliet *et al.,* 2011), declining battery prices will heavily affect the purchasing price of the EVs as well. Another factor inhibiting EV penetration in the 2013 Reference Scenario is the limited driving range of EVs. The low range increases the perceived costs of these vehicles compared to conventional vehicles (Capros & Pelopidas, 2011), thereby inhibiting market penetration. However, there are already EVs on the market with a driving range of 350 km[14]. Since there is sufficient competition in the EV sector, spurring innovation as well as a very versatile group of actors is involved in EV development (dispersion) and a substantial number of new entrants in the sector, further development of the EV is expected to occur (Wesseling *et al.,* 2014). So EV penetration in 2050 might be much higher than projected in the 2013 Reference Scenario.

4.4 Efforts required to achieve a 80% GHG emission reduction in 2050

After looking at the decarbonisation efforts in the 2013 Reference Scenario and the efforts happening till 2020, the focus now turns to the long-term goal of reaching a GHG emission reduction of at least 80%.

[14] Tesla Model S Range and Charging: Some Clarifications - http://www.plugincars.com/tesla-model-s-range-and-charging-some-clarification-127409.html Retrieved on: 24 june 2014.

4.4.1 General comparison of 2013 Reference Scenario with DER scenario

The additional GHG abatement in the DER scenario compared to the 2013 Reference Scenario, is primarily caused by lowering the average emission factor. Although lowering the emission factor is always necessary to achieve a 80% GHG emission reduction, PRIMES like other energy system models prefers a focus on fuel switching over a stronger emphasis on energy savings, which is often the preferred option in General Computable Equilibrium models (Knopf *et al.,* 2013). Therefore, a critical look at the assumptions surrounding energy saving potentials in PRIMES[15] is desirable. In order to enable researches to reflect critically on this issue, the European commission should be more transparent about the assumptions underlying its energy and climate models.

4.4.2 Challenges to be overcome to fully decarbonise the power sector

As has been shown in sections 3.2 and 3.3 the power sector plays a pivotal role in the DER scenario and is almost completely decarbonised. To achieve this ambitious level of decarbonisation in the power sector successful deployment of renewables, potentially combined with CCS, is essential. Although deployment of renewables in Europe seems to be on track to achieve the 20% target in 2020 (Klessmann *et al.,* 2011), the share of renewables in primary energy consumption[16] must increase to 45-66% in 2050, meaning that an annual growth in renewable energy production of 4.6% is required. In electricity generation renewables have to grow annually with 3.9%, to reach a share 51-86% in 2050. Without such growth in the contribution of renewables to the total energy supply, an 80% GHG reduction is impossible (Knopf *et al.,* 2013). Wind energy is one of the most important renewables in electricity generation with a production of 122-216Mtoe in 2050, which means a 10 to15-fold increase compared to the amount of electricity generated in 2010, making PRIMES (the energy model used to generate the 2013 Reference Scenario) the most ambitious model in terms of wind energy deployment (Knopf *et al.,* 2013). However, to realise this tremendous growth sufficient cost reductions in offshore wind energy must be achieved and issues with regard to public acceptance of onshore wind must be resolved (IEA, 2013a). Furthermore, the high share of wind energy (and other intermittent renewables, such as PV) in the DER scenario will also require large adjustments to the grid and development of energy storage capacity

[16] Excluding non-energy use of fossil fuels

(Díaz-González *et al.,* 2012). In short, strong policies will be required to realise the ambitious installed capacities of renewables in 2050, while simultaneously ensuring grid stability and preventing oversupply. Some studies have suggested that there might be a synergy between intermittent renewables and large-scale deployment of EVs, as the latter could serve as energy storage (Richardson *et al.,* 2013). To ensure sufficient deployment of renewables, a combination of R&D funding to lower costs and ambitious targets is desirable. R&D should focus on development of immature technologies, such as CSP and wave energy. Technology-specific deployment targets might be desirable as well (PBL, 2013).

The deep emission scenarios differ quite sharply with regard to the importance of CCS in power generation, varying from 6.9% to 31.9%. As a result the contribution of CCS to the total CO_2 emission reduction can also vary a lot, as has been shown in figure 6. When deployment of renewables is strong enough, the importance of CCS is limited. CCS deployment increases if nuclear energy is phased out. Developments in CCS technology and implementation have been very limited in the last decade, R&D spending on CCS has been only 10% of the required amount to make CCS a technology significantly contributing to the decarbonisation of the power sector (IEA, 2013b). It is possible to supply electricity by renewables alone (Greenpeace, 2010, WWF, 2011), but this increases the total costs (EC, 2011b, Knopf *et al.,* 2013). However, when technological development of CCS keeps lagging, due to underinvestment and a lack of sufficient demonstration projects, CCS might mature too late to be a profitable option (WWF, 2011). Although an 80% emission reduction in 2050 is possible with a very limited role for CCS, negative emissions (net CO_2 uptake) may be required in the second half of this century in case of an emission overshoot or unexpectedly high climate sensitivity (Zickfeld *et al.,* 2009), which can be done by combining biomass with CCS. Furthermore, for some sectors, such as the cement industry CCS is the only possibility to reduce emissions. Therefore, large investments in R&D and financial support of demonstration projects will be required, to bring down the costs sufficiently. Furthermore, it has been suggested that a low-carbon technology target, instead of a strict renewables target might be beneficial for CCS implementation as well (PBL, 2013).

4.4.3 Strong policies for decarbonisation of the transport sector are indispensible

In all end-use sectors the carbon intensity improvement has to speed up with comparable factors. However, the transport sector should get high political priority, because this is a very important sector in terms of absolute emissions. The emission reduction required from the transport sector is as large as the additional emission reduction from industry, households, the tertiary sector and the energy branch together. This means that realising the required carbon intensity improvement in the transport sector is essential for the achievement of the 80% emission reduction target. The urgency of lowering the carbon intensity is that high, because of the strong increase in activity that is projected for this sector. In the 2013 Reference Scenario the activity is expected to increase in all countries, with a larger increase in the new Member States. The increase projected for the EU15 is also substantial, while the growth in transport demand is slowing down in many of these countries (Millard-Ball & Schipper, 2010). Since the emissions in the transport sector are strongly dependent on the activity level, it might be wise to focus policies not only on technological innovation, but also at reducing the growth of demand, especially in aviation. Especially in the short-term, modal shifts and other behavioural changes may be easier options to achieve emission reductions than technological developments (Chapman, 2006). However, the European Commission avoids such policies, because of the risk of harming economic growth (EC, 2011a).

The carbon intensity improvement for transport is achieved in the DER scenario primarily by electrification of passenger road transport and a switch to biofuels in the road freight, aviation and inland navigation sectors. The market share of EVs in 2050 increases from 3% in the 2013 Reference Scenario to 65% in the DER scenario. Although the assumptions about EV costs in the 2013 Reference Scenario are conservative (see sect. 3.1.4), a market share of 65% will still be very challenging and thus requires substantial policy support. Therefore, it has been suggested to set targets for the minimum amount of low-emission vehicles on the road in 2030 and 2050 (PBL, 2013). However, the disadvantage of such targets is that these are centred around personal car use, whereas modal shifts to more environmentally friendly transport modes might be desirable.

For CO_2 abatement in freight transport the development of second and third generation biofuels is indispensable (Geurs *et al.,* 2011). Since these technologies are still relatively expensive additional R&D support will be needed. Furthermore, it is important that the biomass used for biofuel production is sustainably sourced, so that emission reductions and avoidance of negative environmental impact are ensured (Markevičius *et al.,* 2010). In addition to fuel shifts some advances can be made by improving the weight and aerodynamics of trucks (Mattila & Antikainen, 2011) as well as by improving logistics (Geurs *et al.,* 2011). Therefore, EU policy on freight transport should cover both technological and organisational issues to foster all the potential emission abatement opportunities.

4.4.4 The importance of reducing non-CO_2 GHG emissions

Another sector that must receive extra attention is the non-CO_2 GHG sector. In the ET_GCA scenario the emission level of this sector drops to 539 Mton CO_2-eq in 2030, meaning an abatement of 285 Mton CO_2-eq. compared to 2010 (-34.6%). This is quite a challenging task, since this is more than the maximum abatement potential of about 260 Mton CO_2-eq. calculated by Höglund-Isaksson *et al.* (2010). Between 2030 and 2050 the emissions are projected even further to 469 Mton CO_2-eq in 2050 (-43.1%). Underdevelopment of non-CO2 GHG abatement technologies might be explained by the fact that abatement of these gases often has less co-benefits than abatement of energy-related GHG-emissions, since that often leads to cost reductions (through energy savings or decreased import costs). Investigation of this hypothesis could be a direction for future research. However, it is more important that future development of non-CO_2 GHG abatement technologies is stimulated, which emphasises the need for ambitious targets and policies for the non-ETS sectors for beyond 2020.

4.4.5 Importance of energy savings in the DER scenario

Although the final energy consumption in the DER scenario is significantly reduced compared to the 2013 Reference Scenario, there still seems to be room for additional energy savings. Especially, in industry where the final energy demand in the DER scenario is only slightly lower than in the 2013 Reference Scenario. However, it is difficult to determine whether a higher amount of energy savings would be desirable, since the difference in abatement costs of additional energy savings versus a further shift to low-carbon energy production are not given in the EU Energy scenarios. This lack of transparency about underlying assumptions, including those about abatement costs make scientific verification and improvement of the energy scenarios very difficult.

4.5 80% versus 95% emission reduction target

The ambition of the European Commission, stated in the Energy Roadmap is to reduce the GHG emissions with 80-95%. Interestingly, all DER scenarios assume an emission reduction of only 80%. This raises the question whether a more stringent emission target is feasible and in what way such a target could be achieved. An emission reduction of 95% will require the abatement of another 852 Mton CO_2-eq., which is comparable to the total emissions of Germany to date.

The dominant emitters in the DER scenario in 2050 are the transport sector (317 Mton CO_2-eq) and industry (176 Mton CO_2-eq) in the energy related CO_2 emissions and the non-energy related CO_2 emissions and Non-CO_2 GHGs (together responsible for about 495 Mton CO_2-eq.). It is questionable whether additional GHG emission reductions in the transport sector are feasible. Some studies suggest that the 60% GHG emission reduction that is stated in the Energy Roadmap is already very challenging technologically and maybe only possible when combined with behavioural change (Dray *et al.,* 2012). Other studies confirm that the transport sector is the most difficult sector to decarbonise and show that the PRIMES model is the most optimistic energy model with regard to transport sector decarbonisation (Knopf *et al.,* 2013). However, others suggest that there is room for additional GHG reductions, especially in freight transport (Mattila & Antikainen, 2011). In the DER scenario energy intensity improvement accelerates more in passenger transport (61%) than for freight transport (41%), while the energy intensity improvement for passenger transport was already much larger than for freight transport in the 2013 Reference Scenario. Since carbon intensity improvements in the DER scenario are mainly originating from passenger road transport, it makes sense to focus further GHG abatement in the transport sector on freight transport and aviation.

The tertiary sector and residential sectors are both already strongly decarbonised in 2050. However, there might be still some potential for additional energy savings, especially in the residential sector. Furthermore, because energy use in the tertiary and residential sectors is almost solely used for heating & cooling, electric appliances and lighting (Capros *et al.,* 2013), decreasing the emissions in these sectors to almost zero might be easier than realising extra emission reductions in industry, which also uses energy for high- temperature processes and other energy-intensive purposes. High-temperature heat cannot be supplied by all renewable energy technologies (Taibi *et al.,* 2012), which explains why natural gas keeps playing a relatively large role in final energy demand of industry in 2050. Biomass can supply the heat in the full temperature range (*ibid*), but it is questionable whether there is enough sustainable biomass supply to satisfy all the demand (Hoogwijk *et al.,* 2003). An alternative for biomass would be hydrogen, which can easily be used as fuel in a heater and can be produced with renewable electricity in times of oversupply (Gahleitner, 2013). However, to make production, storage and distribution of hydrogen feasible, large investments in R&D will be required to make such options cost-effective (Marban & Valdés-Solís, 2007, Bartels *et al.,* 2010). In some particular cases, such as in Southern Europe, concentrated solar power can be used for high temperature processes such as, aluminium or zinc production (Murray,1999, Epstein *et al.,* 2008). In addition to further fuel switching, there might be a remaining potential for energy savings in the DER scenario.

The non-CO_2 GHGs are still an important emission source in 2050 according to the ET_GCA scenario. For the achievement of additional emission abatement development of new technologies and practices (primarily in agriculture) are required.

4.7 Limitations of this research and further research

This study aimed at investigating the challenges at the sectorial level, which is quite useful to compare sectors to one another and to identify the sectors, which require the highest political priority. However, using energy and emission data on sector level also has a drawback, namely that it is hard to identify specific challenges such as technological problems within a sector. Therefore, this study should be used as an overview on what sectors need to do to achieve deep emission reductions and not as an in-depth description. Due to the sectorial level of aggregation, the decomposition effects should be seen as proxies of the changes taking place in the projections. Energy intensity (on value added) for example is a very rough indicator for energy efficiency, since it is not only influenced by the energy use during production of an asset, but also by its value. Therefore, the use of physical indicators of activity are preferable above monetary indicators, because these better reflect the relation with energy demand

(Worrel *et al.,* 1997). In this study, physical indicators were only used for the transport sector, due to a lack of sufficient physical indicators of other sectors. In this study emissions were decomposed into activity, energy intensity and emission factor. Some studies have suggested that OECD countries, including EU Members States face a shift away from industry to services (OECD, 2000). Therefore, some decomposition studies include a structure effect, measuring the relative change of the contribution that sectors make to the GDP. However, the meaning of such a structure effect can be questioned, since a difference in relative growth between sectors does not necessarily mean a shift in activity from one sector to another. Moreover, it has also been suggested that the relative decline of industry's share in the total GDP can be attributed to the sharp decline in production costs in industry, instead of declining production (Kander, 2005). When looking at physical production indicators, industrial production is actually only growing (*ibid*). However, next to structural change on sectorial level there can also be structural change at a sub-sectorial level. One of the critiques against the EU ETS as a unilateral carbon pricing mechanism is that it will force energy-intensive industries to leave Europe and move to areas without carbon pricing (Babiker, 2004), a process that has been named 'Carbon leakage'. This could lead to a structural change within industry, decreasing the share of energy-intensive industries. Although, investigation of carbon leakage is important, it was outside the scope of this study, primarily because of a lack of emission data on a sub-sectorial level in the Energy Roadmap decarbonisation scenarios.

Furthermore, the data for some sectors was relatively scarce, especially for the non-CO_2 GHGs and the non-energy related CO_2 emissions. With regard to non-CO_2 GHGs, future research should primarily focus on developing new technologies for mitigation, which can be implemented at lower costs. The non-energy related CO_2 emissions are a very versatile collection of emissions from unrelated processes (Patel *et al.,* 2005). Although studies have been done for abatement of these GHGs in specific sectors, such as the cement industry, an overview of the abatement potentials in this group of emissions is largely lacking in scientific literature about GHG abatement pathways. Because it is the remainder of emissions, which do not fall under other categories there is a great risk that policy-makers neglect this group of emissions. This could be a threat to the achievement of deep emission reductions, since this sector represents a substantial amount of emissions. To a certain extent, this risk of neglect also holds for non-CO_2 GHGs.

In this study it was also tried to give a critical review on the EU's 2013 Reference Scenario and the scenarios from the Energy Roadmap, by means of evaluating some important assumptions. However, just like those scenarios this study also has to deal with a high degree of uncertainty, regarding future technological developments. Some technologies may have developed faster in the last few years, than has been anticipated in the scenarios, but there is no guarantee that this pace will be sustained in the years to come. Furthermore, the analyses in this study are based on the data from the EU Energy scenarios, meaning that errors in these scenarios also affect the results of this study.

In this research the transport sector has been identified as an essential sector in the decarbonisation of the economy. In contrast to passenger road transport, road freight transport as well as aviation are very difficult to decarbonise. Therefore, these sectors require much attention in further research, so that new solutions for the decarbonisation of these sectors will be developed.

5. Conclusion

When the EU goes on with business as usual a GHG reduction of 44% in 2050 is projected, which will be mainly driven by the improvement of the energy intensity. However, the EU has the ambition to reduce its GHG emissions by 80-95% in 2050. Although the 20/20/20 energy and climate package is a first step in this direction, decarbonisation has to intensify after 2020, with a rate that is 3 times higher than in the period 2010-2020.

Almost full decarbonisation of the power sector is required for a deep emission reduction, meaning that successful development and deployment of renewables is essential. In case of a 40% GHG reduction target, a binding EU renewables target for 2030, or a low carbon technologies target (which also includes CCS) to ensure a sufficiently high level of innovation might is desired.

Although all end-use sectors have to accelerate their decarbonisation rates, extra attention should be paid to the transport sector, because it has a large share in the total GHG emissions in the EU and the activity of the transport sector is projected to grow steeply. Therefore, policies ensuring the effective decarbonisation of the transport sector are essential to reach deep emission reductions. Furthermore, policies supporting the development and deployment of low carbon freight transport technologies are required. Policies focused at reducing the activity growth in transport or promote modal shifts to towards lower emission transport modes should also be considered.

Energy savings might be underexposed in the deep emission scenarios from the Energy Roadmap, since the energy savings potential might not be exploited to the full, especially in industry an the residential sector. This may make the achievement of the deep emission reduction goals more difficult.

An emission reduction of 95% is extremely difficult with the present state of technology. Especially because remaining emissions from freight transport, aviation and some non-CO_2 GHGs are very hard to abate.

Finally, it is important to keep in mind that EU climate policies will only be beneficial for the climate and for the EU itself, if the international community also undertakes action to combat climate change. Therefore, the outcome of future international climate agreements will heavily affect the success of EU Energy & Climate policy, but more importantly the protection of our planet and its people.

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