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MEDEAS

MODELING THE RENEWABLE ENERGY TRANSITION IN EUROPE

Project Nr: 691287

Guiding European Policy toward a low-carbon economy. Modelling sustainable Energy system Development under Environmental And Socioeconomic constraints

Deliverable 3.1 (D9) Transition Scenarios 1

Due date of deliverable: 31/10/2016

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Document info sheet

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MEDEAS
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Scope of document

This deliverable is structured in two parts. **Part A** is devoted to the time-series of data on transition scenarios and pathways. This part is a description of IPCCs' Shared Socioeconomic Pathways (SSP) data for MEDEAS scenarios/pathways analysis. **Part B** outlines the final scenario for 2050, using GHG emissions regulations by the EC together with the different energy plans in EU for a transition to a low carbon energy system within a decarbonised economy.

We must emphasize that this deliverable is an evolving document and it pretends to be an starting point at this stage. The ideas here written (especially in the part B) will evolve with the different contributions of the MEDEAS consortium and future research. In this vein, this document aims to help to construct the most suitable scenarios/pathways for the MEDEAS model implementation, motivating the share of ideas and points of view between MEDEAS partners

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Part A: Shared Socioeconomic Pathways at the global, regional and country level

Description

This deliverable intends to provide time-series data on transition scenarios (1), with an emphasis on compatibility with the IPCC's implementations of the Shared Socioeconomic Pathways (SSPs), at the global, regional, and country level.

The Fifth Assessment of Intergovernmental Panel on Climate Change (IPCC) adopted a "parallel process" to develop new scenarios for future climate change and for the integrated analysis of future climate impacts, vulnerabilities, adaptation, and mitigation. This process includes the Representative Concentration Pathways (RCPs), which cover the climate forcing dimension of different possible futures and serve as the basis for the development of new climate change projections; the storylines (narratives) of SSPs (see, Appendix A-1), which serve as the starting point for the development of the quantitative SSP elements; an implementation framework which combines SSPs and the RCPs (and other climate scenarios) in a Scenario Matrix Architecture; and the marker quantification of the SSPs using a range of integrated assessment models, which translate the narrative of a specific SSP-RCP combination into the quantitative scenario for the evolution of the future global economy, energy and land system in a world of this SSP-RCP combination.

The marker implementations of SSPs have been more or less completed by September 2016, based on the collective efforts of the climate research community. These marker implementations provide the most up-to-date and widely accepted quantitative scenarios for the evolution of the global economy, energy and land system in the future SSP worlds. Therefore, they should be used to define and constrain values for key Partially Aggregated Variables (PAVs) in MEDEAS project, and to design boundary conditions for the energy and input-output models of MEDEAS. On the other hand, the resolution of such SSP implementations is typically coarse in terms of socioeconomic sectors, geographic jurisdictions, and technical transformation pathways. This leaves broad rooms for MEDEAS model to explore (e.g., plausible technological breakthroughs in a specific sector).

This time-series dataset contains the following three excel files.

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(I). The first excel file (12Mb) of this dataset, "SSP scenarios (pop gdp urbanization)", contains SSP scenarios on population, GDP (under PPP), and urbanization share. For each SSP, a single population and urbanization scenario was developed by IIASA and the National Center for Atmospheric Research (NCAR). Scenarios on population include total population and population by sex, age cohort (5-years), and level of education for the world and for 5 and 32 macro regions (see Appendix A-2 for the definition of SSP regions), respectively, over the period of 2010-2100 in five-year time steps.

The GDP projections, over the period of 2010-2100 in five-year time steps, are based on harmonized assumptions for the interpretation of the SSP storylines in terms of the main drivers of economic growth. Three alternative interpretations of the SSPs by the teams from the OECD, IIASA and the Potsdam Institute for Climate Impact Research (PIK) are included in this dataset.

These population and GDP scenarios will provide the (exogenous) bases for MEDEAS' System-Dynamic (SD) models, Input-Output (IO) models and the integration of SD and IO models at global, EU, and case-study country levels

(II). The second excel file (497Kb) of this dataset, "SSP2_MESSAGE-GLOBIOM_Aug 2016", contains the SSP2 implementation outcomes/scenarios of IIASA's Integrated Assessment Modelling Framework on energy use and supply, land-use, emissions, climate change and policy-costs. This implementation was completed in August 2016. In the quantitative elaboration of the mitigation scenarios, three of the four RCPs forcing targets were used if applicable (6.0, 4.5, 2.6 W/m2). In addition, an intermediate forcing target of 3.4 W/m2 was applied to explore implications of climate policies between 4.5 and 2.6 W/m2. SSP2 represents a "middle-of-the-road" scenario for the 21st century and therefore, it is a very relevant reference to MEDEAS SD-IO models.

(III). The third excel file (786Kb) of this dataset, "SSP1and3_MESSAGE-GLOBIOM_Sep 2016", contains the SSP1 and SSP3 implementation outcomes/scenarios of IIASA's Integrated Assessment Modelling Framework on energy use and supply, land-use, emissions, climate change and policy-costs. This implementation was completed in September 2016. RCPs 6.0, 4.5, 2.6, and 3.4 were used in the implementation. SSP1 represents a "taking-the-green-road" scenario and therefore it is mostly in line with the "low carbon economy" goal of MEDEAS project, whereas SSP3 represents a "regional-rivalry" rocky road scenario and thus may form the toughest challenges to pathway finding, in MEDEAS modelling simulation or in practical mitigation and adaptation.

Please note that the second and third excel files cannot be shared to anybody outside the consortium.

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Appendix

Appendix 1: Summary of SSP narratives (Riahi, et al. 2016)

SSP1 Sustainability – Taking the Green Road (Low challenges to mitigation and adaptation)

The world shifts gradually, but pervasively, toward a more sustainable path, emphasizing more inclusive development that respects perceived environmental boundaries. Management of the global commons slowly improves, educational and health investments accelerate the demographic transition, and the emphasis on economic growth shifts toward a broader emphasis on human well-being. Driven by an increasing commitment to achieving development goals, inequality is reduced both across and within countries. Consumption is oriented toward low material growth and lower resource and energy intensity.

SSP2 Middle of the Road (Medium challenges to mitigation and adaptation)

The world follows a path in which social, economic, and technological trends do not shift markedly from historical patterns. Development and income growth proceeds unevenly, with some countries making relatively good progress while others fall short of expectations. Global and national institutions work toward but make slow progress in achieving sustainable development goals. Environmental systems experience degradation, although there are some improvements and overall the intensity of resource and energy use declines. Global population growth is moderate and levels off in the second half of the century. Income inequality persists or improves only slowly and challenges to reducing vulnerability to societal and environmental changes remain.

SSP3 Regional Rivalry – A Rocky Road (High challenges to mitigation and adaptation)

A resurgent nationalism, concerns about competitiveness and security, and regional conflicts push countries to increasingly focus on domestic or, at most, regional issues. Policies shift over time to become increasingly oriented toward national and regional security issues. Countries focus on achieving energy and food security goals within their own regions at the expense of broader-based

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development. Investments in education and technological development decline. Economic development is slow, consumption is material-intensive, and inequalities persist or worsen over time. Population growth is low in industrialized and high in developing countries. A low international priority for addressing environmental concerns leads to strong environmental degradation in some regions.

SSP4 Inequality – A Road Divided (Low challenges to mitigation, high challenges to adaptation)

Highly unequal investments in human capital, combined with increasing disparities in economic opportunity and political power, lead to increasing inequalities and stratification both across and within countries. Over time, a gap widens between an internationally-connected society that contributes to knowledge- and capital-intensive sectors of the global economy, and a fragmented collection of lower-income, poorly educated societies that work in a labor intensive, low-tech economy. Social cohesion degrades and conflict and unrest become increasingly common. Technology development is high in the high-tech economy and sectors. The globally connected energy sector diversifies, with investments in both carbon-intensive fuels like coal and unconventional oil, but also low-carbon energy sources. Environmental policies focus on local issues around middle and high income areas.

SSP5 Fossil-fueled Development – Taking the Highway (High challenges to mitigation, low challenges to adaptation)

This world places increasing faith in competitive markets, innovation and participatory societies to produce rapid technological progress and development of human capital as the path to sustainable development. Global markets are increasingly integrated. There are also strong investments in health, education, and institutions to enhance human and social capital. At the same time, the push for economic and social development is coupled with the exploitation of abundant fossil fuel resources and the adoption of resource and energy intensive lifestyles around the world. All these factors lead to rapid growth of the global economy, while global population peaks and declines in the 21st century. Local environmental problems like air pollution are successfully managed. There is faith in the ability to effectively manage social and ecological systems, including by geo-engineering if necessary.

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Appendix 2: Definition of SSP Regions

5 Regions

R5OECD Includes the OECD (1990) and EU member states and candidates:

Albania, Australia, Austria, Belgium, Bosnia and Herzegovina, Bulgaria, Canada, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Guam, Hungary, Iceland, Ireland, Italy, Japan, Latvia, Lithuania, Luxembourg, Malta, Montenegro, Netherlands, New Zealand, Norway, Poland, Portugal, Puerto Rico, Romania, Serbia, Slovakia, Slovenia, Spain, Sweden, Switzerland, The former Yugoslav Republic of Macedonia, Turkey, United Kingdom, United States of America.

R5REF = Countries from the Reforming Economies of Eastern Europe and the Former Soviet Union:

Armenia, Azerbaijan, Belarus, Georgia, Kazakhstan, Kyrgyzstan, Republic of Moldova, Russian Federation, Tajikistan, Turkmenistan, Ukraine, Uzbekistan.

R5ASIA includes most Asian countries with the exception of the Middle East, Japan and Former Soviet Union states:

Afghanistan, Bangladesh, Bhutan, Brunei Darussalam, Cambodia, China (incl. Hong Kong and Macao, excl. Taiwan) Democratic People's Republic of Korea, Fiji, French Polynesia, India, Indonesia, Lao People's Democratic Republic, Malaysia, Maldives, Micronesia (Fed. States of), Mongolia, Myanmar, Nepal, New Caledonia, Pakistan, Papua New Guinea, Philippines, Republic of Korea, Samoa, Singapore, Solomon Islands, Sri Lanka, Taiwan, Thailand, Timor-Leste, Vanuatu, Viet Nam.

R5MAF includes the countries of the Middle East and Africa:

Algeria, Angola, Bahrain, Benin, Botswana, Burkina Faso, Burundi, Cameroon, Cape Verde, Central African Republic, Chad, Comoros, Congo, Côte d`Ivoire, Democratic Republic of the Congo, Djibouti, Egypt, Equatorial Guinea, Eritrea, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Iran (Islamic Republic of), Iraq, Israel, Jordan, Kenya, Kuwait, Lebanon, Lesotho, Liberia, Libyan Arab Jamahiriya, Madagascar, Malawi, Mali, Mauritania, Mauritius, Mayotte, Morocco, Mozambique, Namibia, Niger, Nigeria, Occupied Palestinian Territory, Oman, Qatar, Rwanda,

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Réunion, Saudi Arabia, Senegal, Sierra Leone, Somalia, South Africa, South Sudan, Sudan, Swaziland, Syrian Arab Republic, Togo, Tunisia, Uganda, United Arab Emirates, United Republic of Tanzania, Western Sahara, Yemen, Zambia, Zimbabwe.

R5LAM includes the countries of Latin America and the Caribbean:

Argentina, Aruba, Bahamas, Barbados, Belize, Bolivia (Plurinational State of), Brazil, Chile, Colombia, Costa Rica, Cuba, Dominican Republic, Ecuador, El Salvador, French Guiana, Grenada, Guadeloupe, Guatemala, Guyana, Haiti, Honduras, Jamaica, Martinique, Mexico, Nicaragua, Panama, Paraguay, Peru, Suriname, Trinidad and Tobago, United States Virgin Islands, Uruguay, Venezuela (Bolivarian Republic of).

32 Regions

R32ANUZ includes Australia and New Zealand.

R32BRA = Brazil.

R32CAN = Canada.

R32CAS includes the countries of Central Asia:

Armenia, Azerbaijan, Georgia, Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, Uzbekistan

R32CHN = China (Mainland, Hongkong, Macao; excl. Taiwan).

R32EEU = Eastern Europe (excl. former Soviet Union and EU member states):

Albania, Bosnia and Herzegovina, Croatia, Montenegro, Serbia, The former Yugoslav Republic of Macedonia

R32EEU-FSU = Eastern Europe, former Soviet Union (excl. Russia and EU members).

Belarus, Republic of Moldova, Ukraine

R32EFTA includes Iceland, Norway, Switzerland.

R32EU12-H = New EU member states that joined as of 2004 - high income.

Cyprus, Czech Republic, Estonia, Hungary, Malta, Poland, Slovakia, Slovenia

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R32EU12-M = New EU member states that joined as of 2004 - medium income.

Bulgaria, Latvia, Lithuania, Romania

R32EU15 includes European Union member states that joined prior to 2004.

Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, Netherlands, Portugal, Spain, Sweden, United Kingdom.

R32IDN = Indonesia.

R32IND = India.

R32JPN = Japan.

R32KOR = Republic of Korea.

R32LAM-L includes the countries of Latin America (excl. Brazil, Mexico) - low income.

Belize, Guatemala, Haiti, Honduras, Nicaragua.

R32LAM-M includes the countries of Latin America (excl. Brazil, Mexico) - medium and high income.

Antigua and Barbuda, Argentina, Bahamas, Barbados, Bermuda, Bolivia (Plurinational State of), Chile, Colombia, Costa Rica, Cuba, Dominica, Dominican Republic, Ecuador, El Salvador, French Guiana, Grenada, Guadeloupe, Guyana, Jamaica, Martinique, Netherlands Antilles, Panama, Paraguay, Peru, Saint Kitts and Nevis, Saint Lucia, Saint Vincent and the Grenadines, Suriname, Trinidad and Tobago, Uruguay, Venezuela (Bolivarian Republic of)

R32MEA-H includes the countries of Middle East Asia - high income.

Bahrain, Israel, Kuwait, Oman, Qatar, Saudi Arabia, United Arab Emirates

R32MEA-M includes the countries of Middle East Asia - low and medium income.

Iran (Islamic Republic of), Iraq, Jordan, Lebanon, Occupied Palestinian Territory, Syrian Arab Republic, Yemen

R32MEX = Mexico

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R32NAF = This region includes the countries of North Africa.

Algeria, Egypt, Libyan Arab Jamahiriya, Morocco, Tunisia, Western Sahara

R32OAS-CPA includes the countries of Other Asia - former Centrally Planned Asia.

Cambodia, Lao People's Democratic Republic, Mongolia, Viet Nam

R32OAS-L includes the countries of Other Asia - low income.

Bangladesh, Democratic People's Republic of Korea, Fiji, Micronesia (Fed. States of), Myanmar, Nepal, Papua New Guinea, Philippines, Samoa, Solomon Islands, Timor-Leste, Tonga, Vanuatu

R32OAS-M includes the countries of Other Asia - medium and high income.

Bhutan, Brunei Darussalam, French Polynesia, Guam, Malaysia, Maldives, New Caledonia, Singapore, Sri Lanka, Thailand.

R32PAK region includes Pakistan and Afghanistan.

R32RUS = Russian Federation.

R32SAF = South Africa.

R32SSA-L region includes the countries of Subsahara Africa (excl. South Africa) - low income.

Benin, Burkina Faso, Burundi, Cameroon, Cape Verde, Central African Republic, Chad, Comoros, Congo, Côte d`Ivoire, Democratic Republic of the Congo, Djibouti, Eritrea, Ethiopia, Gambia, Ghana, Guinea, Guinea-Bissau, Kenya, Lesotho, Liberia, Madagascar, Malawi, Mali, Mauritania, Mozambique, Niger, Nigeria, Rwanda, Sao Tome and Principe, Senegal, Sierra Leone, Somalia, South Sudan, Sudan, Swaziland, Togo, Uganda, United Republic of Tanzania, Zambia, Zimbabwe

R32SSA-M region includes the countries of Subsahara Africa (excl. South Africa) - medium and high income.

Angola, Botswana, Equatorial Guinea, Gabon, Mauritius, Mayotte, Namibia, Réunion, Seychelles

R32TUR = Turkey.

R32TWN = Taiwan.

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R32USA = United States of America. Includes:

Puerto Rico, United States Virgin Islands, United States of America

In the regional grouping by income, high income countries are based on the World Bank classification of countries (http://data.worldbank.org/about/countryclassifications; for 2010, the threshold for the high income group is 12,275 USD/capita). Middle income countries combine all World Bank upper-middle income countries, and those lower-middle income countries that have (i) at least 2,500 USD/cap income in 2010 (excluding the poorest countries in this group), plus (ii) at least 2% growth projected for 2010-2015 (excluding stagnant countries), and (iii) income above 4,000 USD/cap or growth above 4% (i.e. identify the high achievers in the group in terms of either income or growth). Low income countries are all other lower-middle income countries plus all low income countries from the World Bank classification. This classification on countries, and especially the thresholds for the middle income country group, is chosen to highlight the elements in the SSP storylines that differentiate between developing countries that have good opportunities to catch up to higher income countries, and countries that are in a more challenging situation.

COUNTRY LEVEL DATA

Please note that country level data are denoted by ISO 3166-1 alpha3 three-letter country codes (see, https://en.wikipedia.org/wiki/ISO_3166-1_alpha-3).

Reference:

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Part B: Initial scenarios characterization for the year 2050

1 Introduction

This part of the deliverable was prepared by Anglia Ruskin University as part of Work Package 3 (Scenarios and pathways) of the MEDEAS project. The aim of this task was to develop a robust qualitative scenario (with supporting quantitative evidence) detailing what a decarbonised EU energy system would look like in 2050, by defining and constraining values for key Partially Aggregated Variables (PAVs).

The scenario presented here will constitute the goal (or end-point) of the MEDEAS model which will be achieved through the design and implementation of different policies and supporting recommendations (representing different pathways) to be tested by the MEDEAS model. The scenario presented here directly aligns with the aims of the European Commission, which has previously committed to reducing greenhouse gas (GHG) emissions by 80-95% by 2050 compared with 1990 levels (EC, 2010).

Initially, PAVs (derived from Work Package 2 - Deliverable D2.1) were compiled and analysed for their suitability in line with the aim of this task. Additionally, the list of current PAVs was reviewed as part of a gap-analysis to identify any missing variables (and/or variables which needed to be disaggregated) in order to define and achieve a 'fully decarbonised' European energy system by 2050. This exercise identified key gaps in the current list of PAVs and the results are described in Section 4 and summarised in the spreadsheet 'Additional PAVs 2050.xlsx' attached to this report. This exercise highlighted the need to include additional targeted PAVs (as well as further disaggregation) related to different priority areas:

1. GHG emissions from different sectors (e.g. GHG emissions from agriculture sector, Mtcoe)
2. Biofuels (e.g. World use of crops for biofuels, ktoe)
3. Thermal generation (e.g. Capacity factor non-RES, %)
4. EU Emission Trading System (EU ETS) (e.g. number of permits allocated)
5. Import/export of energy (e.g. international oil price, $/barrel)
6. Social issues, (e.g. Energy subsidies, €)
7. Economic issues (e.g. social and behavioural discount rates, %)

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A number of methodological challenges were encountered when attempting to define values for various PAVs required to achieve a reduction in GHG emissions of at least 80% (EC, 2010). In particular, the interconnected nature and complexity of the EU energy system required a number of decisions to be made with respect to the detail of targets defined by the MEDEAS 2050 scenario. For instance, the exact nature of the final energy mix, defined here as the proportion of energy generation from different sources, has direct implications for GHG emissions from each sector, but also indirect implications on Energy Returned on Energy Invested (EROEI), level of technology, capacity factor, investments and power density for different energy sources. Therefore, the scenario presented here only constrains the emissions target for 2050, recognising that this will directly and indirectly modify other sectors as well as enable and encourage the design of flexible and adaptable policies.

Additionally, in order to avoid duplication of efforts and to provide the necessary foundations to permit the comparison of the MEDEAS model and project with other studies funded by the European Commission, the decision was taken to incorporate existing knowledge and assumptions from past studies, focussing in particular on the EU 2050 High Renewable Energy Sources (High-RES) scenario from 2011 (EC 2011a).

For the above reasons the decision was taken to develop one 2050 scenario for MEDEAS, contrasting this and the MEDEAS model with EU High-RES to support cross-validation of results. Thus, the remainder of this report is separated into two sections:

1. **Scenario development:** This section describes the scenario underpinning MEDEAS model which only constrains GHG emissions in 2050, providing estimates for sectorial GHG emissions reductions based on a set of assumptions outlined in this document.
2. **Scenario cross-validation:** This section contrasts the MEDEAS scenario with the EU 2050 High-RES scenario and develops a set of PAVs to support cross-validation of the MEDEAS model.

The EU 2050 High-RES scenario (EC, 2011a) was previously commissioned by the European Commission and in principal had a similar aim as the MEDEAS project, namely to explore different pathways to achieve an 80% reduction in GHG emissions by 2050 across the EU energy system. A number of different scenarios were originally developed (see Section 3), however the most relevant from the perspective of the MEDEAS project is the High-RES scenario. This scenario “aims at achieving very high overall RES share and very high RES penetration in power generation (around 90% share and close to 100% related to final consumption)” (EC, 2011c, p. 6).

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The GHG emissions reductions resulting from this scenario are primarily achieved through the adoption of Renewable Energy Sources (RES), with limited reliance on technologies such as Carbon Capture and Storage (CCS) and nuclear power. Currently, these two technologies are highly contested within Europe and are therefore unlikely to make a significant impact on emissions reductions unless there is a systemic shift in public opinion and political will over the next few years. This is because nuclear plants are characterised by long development stages (Thurner, et al., 2014) and CCS plants are yet to become commercially viable. Finally, neither of these are currently promoted by national governments (see for example House of Commons Energy and Climate Change Committee on the UK government cancellation of plans to provide funding for the commercialisation of CCS in the UK[1] and the decision of several EU countries such as Austria[2] and Italy[3] to phase out nuclear). Therefore, given that neither of these technologies are currently undergoing significant development, it is highly unlikely that they can contribute to significant emissions reductions by 2050. However this does not prohibit significant advancements beyond this timeframe.

[1] House of Commons Energy and Climate Change Committee (HCECCC) 2016. Future of carbon capture and storage in the UK. Second Report of Session 2015–16, HC 692. Available at: http://www.publications.parliament.uk/pa/cm201516/cmselect/cmenergy/692/692.pdf.
[2] http://www.bbc.co.uk/news/mobile/world-europe-16359991
[3] http://www.bbc.co.uk/news/world-europe-13764550

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2 MEDEAS 2050 final scenario with emissions constraints

The only EU policy targets of direct relevance to MEDEAS are related to GHG emissions (EC, 2010) and the share of renewable energy (EC, 2009). However, the policies currently in place at the European level aim to a share of renewable energy of 20% of energy consumed by 2020 and no longer term target currently exist. The GHG emission reduction target is currently set at 80-95% below 1990 levels by 2050 (EC, 2010). As this is the only recognisable and accepted constraint, the scenario development in MEDEAS ensured all other PAVs were set as unconstrained to allow different pathways that achieve the emission reduction target to be explored.

It is important to note at this stage that the EU commitments refer to the reduction of several GHGs, not just carbon dioxide (CO_2). For this reason, the calculations presented here include all GHGs as opposed to just CO_2 emissions. Additionally, while the total European GHG emissions in 1990 (EEA, 2016) are quoted without international aviation and maritime, a recent agreement (ICAO, 2016) to manage these emissions is likely to be implemented at least alongside, if not fully incorporated, into international climate deals between now and 2050. Therefore, we include international aviation and maritime emissions in the targets for 2050 within MEDEAS.

Although MEDEAS aims to investigate different possible pathways to achieve the stated GHG emissions reduction target, the only PAV currently included that explicitly measures several GHGs (and not just CO_2 emissions) is related to transport. For this reason, the authors strongly advocate the inclusion of a number of additional GHG-related PAVs listed below:

1. Agriculture GHG emissions (million tonnes - Tg)
2. Aviation and maritime GHG emissions (million tonnes - Tg)
3. Industry GHG emissions (million tonnes - Tg)
4. Residential GHG emissions (million tonnes - Tg)
5. Transport sector GHG emissions (million tonnes - Tg)
6. Other sectors GHG emissions (including energy generation) (million tonnes - Tg)

These sectors are explicitly referenced with respect to the 2050 scenario presented here.

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2.1 Summary for the sectorial GHG emissions reductions for scenario development

Scenario development initially focussed on defining GHG emissions levels for 2050 and evaluating emission reductions from all key sectors. To achieve this, sectors where full decarbonisation is anticipated to be highly problematic and not particularly realistic (and where further emission reduction may not be entirely possible) were initially identified, calculating the residual emissions allowance (i.e. all sectors emission allowance - problematic sectors emission allowance) across those sectors where emissions reductions may be easier to achieve. The problematic sectors which have been identified as facing particular challenges between now and 2050 are defined here as (1) Agriculture, (2) Aviation and Maritime, (3) Industry and (4) Residential. Other sectors will likely encounter challenges in the pursuit of full decarbonisation, but these were recognised to be less significant and thus feasible. These sectors were subsequently excluded from the analysis.

Below is a brief summary of the final 2050 values for the initial scenario development, including the percentages of total 1990 GHG emissions for each sector in 2050 (a more comprehensive explanation is provided in section 2.3):

1. **Agriculture sector – 7.4%.** This translates in maximum GHG emissions of 435 MTcoe allowed from the agriculture sector in 2050. Note that this value does not include Land Use, Land-Use Change and Forestry (LULUCF) reductions.
2. **Aviation and maritime – 7.3%.** This amounts to total GHG emissions 429 MTcoe from the bunkers total, aviation and maritime sector in 2050.
3. **Industry sector – 1.9%.** This amounts to total GHG emissions of 109 MTcoe from the industry sector in 2050.
4. **Residential sector – 1.3%.** This amounts to total GHG emissions of 78 MTcoe from the residential sector in 2050.
5. **Transport (all other means of transport) – 0%**
6. **Other sectors (including energy generation) – 0%.**

Therefore, the total emissions from these sectors in 2050 account for 18.0% of 1990 GHG emissions (see Figure 2.1 and Table 2.1). To achieve at least an 80% emission reduction from a 1990 baseline by 2050 means the total emissions from all sectors should be a maximum of 20% of 1990 GHG emissions. This means by 2050 only 2.0% of 1990 emissions remains for all other sectors to meet the European target of an 80% reduction. Given that this target is a minimum, and the reductions assumed in these four sectors rely on technological improvements and uptake, we propose taking a precautionary approach. The authors have therefore set all GHG emissions from other sectors at 0% representing the full decarbonisation of these sectors.

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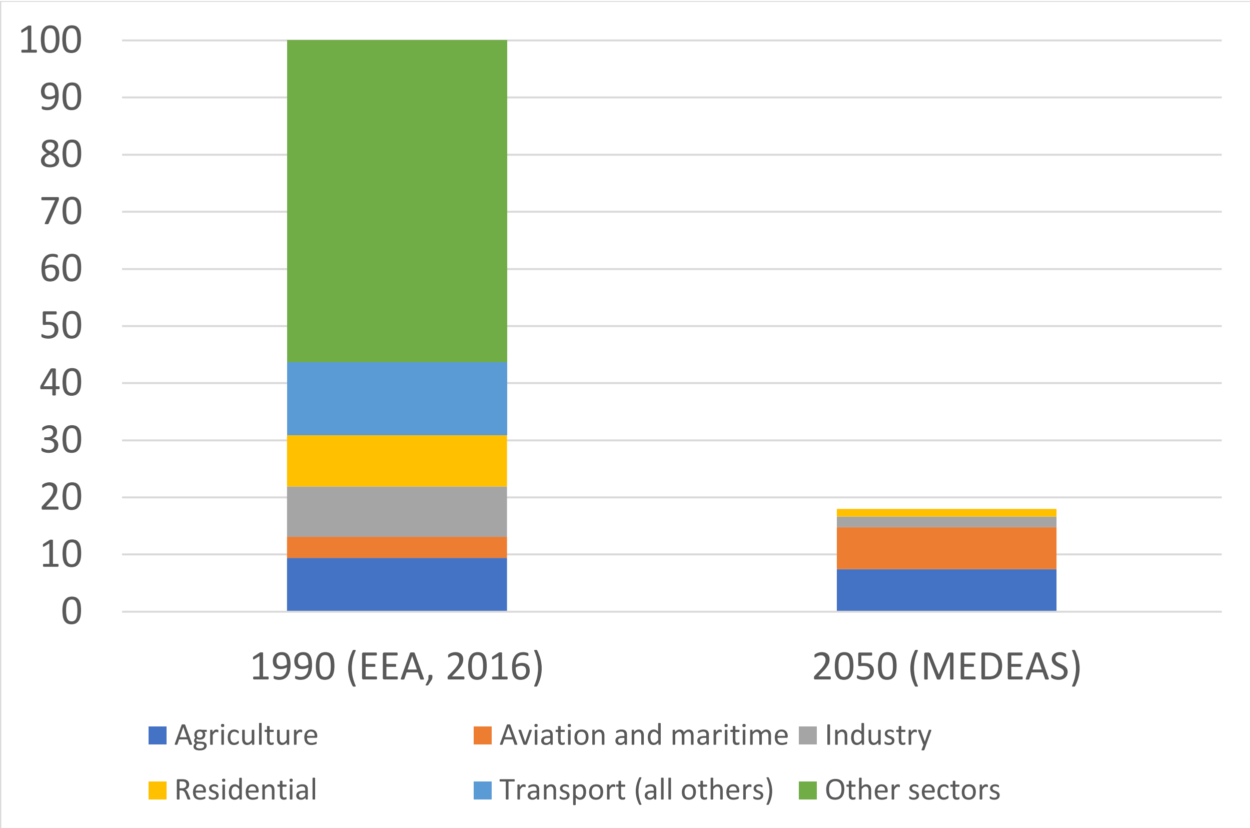

Figure 1 – Emissions from sectors in 1990 and 2050 as a percentage of total emissions in 1990 (note that the EEA original sectors have been re-aggregated to match those proposed here to produce this figure).

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Table 1 – Emissions from sectors in 2050 according to MEDEAS scenario and comparison with emissions in 1990.

Sector	GHG emissions per sector in 1990 (EEA, 2016)	Sectorial emissions in 2050 (MTcoe)	% of total emissions in 2050 as compared to 1990
Agriculture sector	**549**	**435**	**7.4%**
Aviation and Maritime	218	429	7.3%
Industry sector	514	109	1.9%
Residential sector	523	78	1.3%
Transport (all other)	745	0	0%
Other sectors (including energy gen.)	3295	0	0%
Total	5844	1051	18.0%

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2.2 Rationale for constraints applied to initial scenario development

As discussed above, the constraints applied to initial scenario development mainly relate to GHG emissions from specific sectors. The rationale behind this decision is directly aligned with the aims of the European Commission, which intends to curb the emissions of GHGs. The authors acknowledge that this (based on the analysis presented here) may entail full decarbonisation of individual sectors. This is reflected in the EU commitments for 2050: "The EU is committed to achieve the EU agreed objective to reduce emissions by 80-95%, as part of the developed countries' contribution to reducing global emissions by at least 50% below 1990 levels in 2050" (EC, 2010, p.8). In terms of initial scenario development, the pathway to achieve this reduction is largely the discretion of the MEDEAS model and derived/inferred policies, since few policies extending into the future considered by MEDEAS currently exist. However, these policies are likely to include the pursuit of different combinations of energy mixes that can lead to those reductions, potentially based on different technology, infrastructure and behavioural priorities. It is recognised that the definition of specific constraints for different energy mixes is unnecessary at this early stage of the project and would place unnecessary constraints on the development of possible policies that could achieve the planned reductions.

Most of the PAVs that were constrained in this scenario are currently missing from the list of PAVs included in Deliverable D2.1. The authors thus strongly advocate their inclusion in the MEDEAS model. It is important to consider additional sectors when constraining emissions in 2050 as the European Commission targets refer to total emission reduction and are not sector specific.

In particular, we highlight four sectors where absolute decarbonisation, or any significant reduction in emissions, will be very difficult between now and 2050; agriculture, aviation and maritime, industry and residential sectors. For instance, it is highly unlikely that the agriculture sector will be able to achieve full decarbonisation by 2050 due to the fossil fuel inputs for several activities utilised in this sector as well as direct emissions. The production of fertilizers is a clear example, as their production is predominantly reliant on fossil fuels. Furthermore, their use is projected to increase in the future due to the need to feed an increasingly larger population that is consuming more. In addition, the projected increase in the demand for biofuels will result in an increase in the cultivation of these crops that will likely translate in more emissions from the agriculture sector. Finally, livestock and waste management are sources of large quantities of methane. Although steps towards the development of measures that can meet these needs sustainably (sustainable intensification) have been made (Pretty and Bharucha, 2014), several

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authors highlight a close link between intensification and GHG emissions (e.g. van Beek, et al., 2010).

The same can be argued for the industrial sector and, to a lesser extent, the residential sector. Although a reduction of GHG emissions can be achieved through the substitution of more polluting coal and oil with RES and natural gas, certain processes such as chemical reactions in industry (e.g. the manufacturing of cement) inevitably emit GHGs. New technologies including carbon capture and storage are not commercially viable at present with little evidence that this will change in the next few years. Coupled with projections of economic growth, the scale of potential emission reduction from industry needs to be considered carefully. As for residential activities, although the largest part of GHG emissions from this sector are due to fuel combustion for heating/cooking, and can be hence avoided or heavily reduced through the implementation of RES technologies, it is highly unlikely that the entire residential sector across Europe will be retrofitted with zero carbon technology over the next three decades. An example of this are emissions from garden machinery and fluorinated gases released from aerosols/metered dose inhalers (DECC, 2015). The share of GHG emissions allowed for each of these sectors as defined in this initial scenario reflects the different challenges faced by each of them as well as the projected growth expected.

The unconstrained PAVs are equally important for the achievement of the EU objective of at least -80% total GHG emissions by 2050, however it is argued here that these play an important role in achieving the emission targets rather than representing targets in themselves. PAVs related to different technologies such as their capacity factor, EROI, investments, costs, lifetime, efficiency, but also variables concerning production and consumption of each resource, socio-economic variables, and energy transformation are all important components of the complex system that the MEDEAS model is set to simulate and represent a set of different possible transition pathways. These variables are all highly interconnected and the GHG emissions from each sector are an output of the dynamics of these interactions. For example, the type of energy used will depend on the EROI of the different energies, which in turn will depend on investments in that particular energy source, which in turn will partly depend on costs and prices. All these variables affect (and are affected by) the efficiency of the energy source, its power density and finally its production. Similar behaviours are present in the other sectors as well.

By setting targets for emissions from each sector, the authors anticipate the final version of the MEDEAS model to be able to accurately simulate this system, its components and

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interconnections and the values for these variables to be an outcome of the model. In addition, these will likely vary according to the different policies implemented in the model. As a result, PAVs for the following categories for each energy source (either RES or non-renewable): capacity factor, EROI, investments, costs, lifetime, efficiency production, consumption, but also socio-economic variables, and PAVs related to energy transformation, were not constrained.

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2.3 Assumptions for sector specific GHG emission reductions

To maintain compatibility with EU policy frameworks, we used a total GHG emissions for 1990 (the total without LULUCF and with indirect CO_2 emissions and international bunkers) of 5,844 MTcoe. An 80% reduction in GHG emissions by 2050 would reduce this value to 1,169 MTcoe. This figure was used to calculate the values for the different sectors listed below and included in the files 'Additional PAVs.xlsx'. The calculations performed in this first exercise used data for GHG emissions reported by the European Energy Agency and available online (EEA, 2016).

For some of the assumptions underpinning this scenario the authors partly relied on the EU 2050 High-RES scenario (EC, 2011c). In particular, some of the calculations presented here required the definition of two parameters: the increase in efficiency of sectors and the growth in demand for the services provided.

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2.3.1 Agriculture sector

A close inspection of the GHG emissions trend for this sector 1990 – 2014 showed a 20% decrease in emissions from 1990 until around 2000s and then a plateau (see Figure 2).

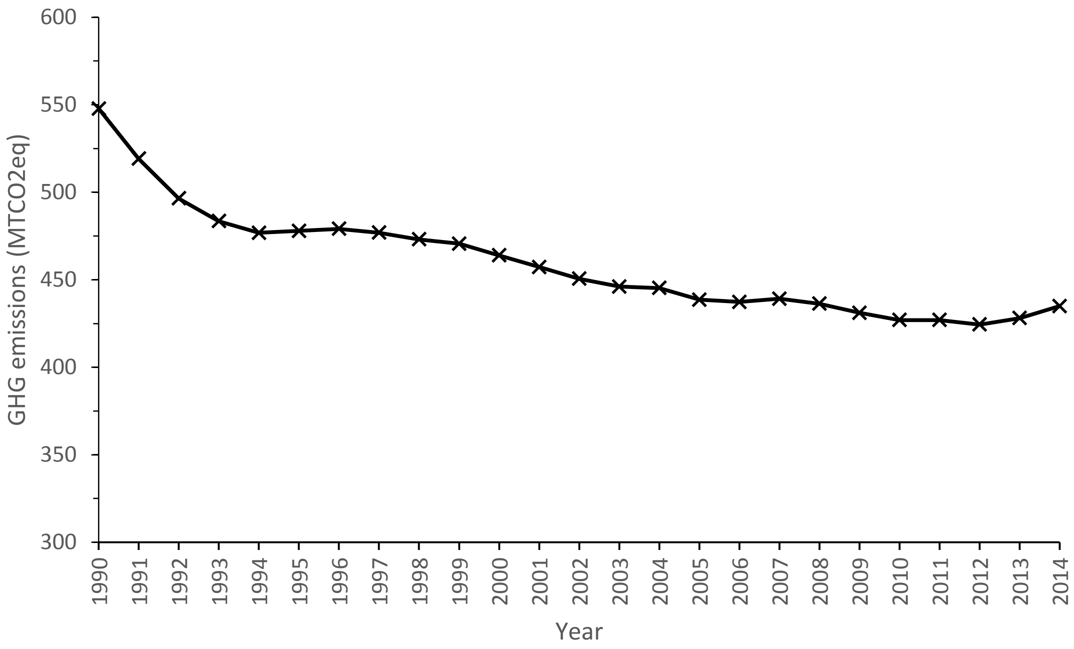

Figure 2 – Time-series of GHG emissions from Agriculture for EU 28. Modified from EEA (2016).

It is increasingly recognised that agriculture is one of the sectors that presents challenges for achieving significant reductions. This is supported by academic research (e.g. Moran, et al., 2011; Bennetzen, et al., 2016). For instance, Moran et al. (2011) undertook a study aimed at identifying measures that can promote the decarbonisation of the agriculture sector in the UK. The authors conclude that all abatement measures, regardless of cost, would reduce UK emissions from agriculture by just 22%. Bennetzen et al. (2016) provide a more detailed picture: their analysis of global emissions from the agriculture sector per unit crop between 1970 and 2007 yielded estimates that varied widely regionally, from -94% in Oceania to +4% in North America. Although some of these countries reduced their per unit crop emissions, their crop production doubled during the same period, which, coupled with an almost threefold increase in livestock production from these countries, resulted in an increase in the emissions from these countries of 34% (Bennetzen, et al., 2016). These figures once again show that the potential for reduction of the GHG emissions from this sector exists, however it has been proven difficult to harness during the past 30 years, at least in some regions of the world, mainly due to the increase in production.

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Given that the EU has already witnessed a 20% reduction in emissions from agriculture over 1990 levels (Figure 2.1) which have since plateaued we assume that modest growth and efficiency gains will balance between now and 2020. Therefore, the value for the 2014 GHG emissions from agriculture (last year available) was extrapolated as unchanged until 2050. Therefore, to calculate the portion of emissions from the agricultural sector in 2050 with respect to the 1990 GHG emissions value following Equation 1.

$$\frac{2050\ GHG\ emissions\ from\ Agriculture\ (equiv.\ 2014)}{1990\ Total\ GHG\ emissions} * 100 = 7.4\%$$

Equation 1 – Calculation of the GHG emission share of the agriculture sector in 2050 as a percentage of 1990 emissions.

The GHG emissions from the Agriculture sector in 2014 amounted to 435 MTcoe according to EEA (2016). According to the same source, the 1990 Total GHG emissions were 5,844 MTcoe. The result from the calculation is 7.4%, which amounts to 435.21 MTcoe from the Agriculture sector. Note that this value does not include LULUCF reductions. This represents a 20% reduction in emissions from agriculture over the 1990 level.

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2.3.2 Aviation and Maritime

This sector is usually represented in a variable measuring fuel use (bunkers) and includes national and international aviation and maritime, which in the EU accounts are usually reported as part of the energy sector. However, we believe that this sector has a number of challenges, which means it is likely to maintain a large portion of the GHG emissions in 2050. For instance, although emissions for flights to, from and within the European Economic Area are included in the EU ETS (EU, 2016), this policy has not provided any additional incentives to the aviation industry as the carbon price remains only a small portion of total fuel use costs. In addition, although an international agreement to cut emissions from the aviation sector has recently been signed (Milman, 2016), it only includes cargo shipments and will entail the offsetting of emissions for the sector. Therefore, this is unlikely to produce any large impact in emissions reductions from these sectors before 2050 above and beyond those that are already envisioned. *With regards to the maritime sector, Europe is committed to reduce emissions from this sector by at least 40 % by 2050 (EC, 2013). However, this does not include international shipping. In addition, and importantly, both of these sectors are projected to grow significantly between now and 2050. Therefore, it is likely that the emissions from this sector will remain high in 2050.* For these reasons, the authors decided to keep these two sectors separate from the other variables in the transport sector.

The forecast of the GHG emissions from these sectors in 2050 required the definition of two parameters: the efficiency increase of these means of transport and the growth in demand. For these, we relied on the assumptions made by the EU 2050 High-RES scenario. For simplicity the authors have decided to use the growth and efficiency projections in aviation as a projection for the whole sector as aviation makes up the vast bulk of emissions.

The EU 2050 High-RES scenario projects the aviation sector to grow 3.8 times between 1990 and 2050 (EC, 2011c) as measured by person kilometres. This significant growth in aviation underpins some of the projected economic growth for the EU over this period. This growth projection was subsequently utilised in the absence of further detailed studies that explore lower growth or decouple economic activity from increased transport requirements. Despite this growth, the aviation industry are investing significant research and development effort in improving the efficiency of the sector (Lee, et al., 2009). The projected increase in fuel use in the EU 2050 High-RES scenario is only a doubling which, when compared with the passenger-kilometre growth, implies an efficiency gain of approximately 50%. Therefore, for the MEDEAS scenario, the authors assume a similar technology innovation and growth rate for the aviation and maritime sector (note, this parameter is implicitly calculated in Equation 2.).

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The value for this PAV was derived using Equation 2.

$$(1990\ sector\ emissions) * \frac{2050\ fuel\ use\ aviation / 1990\ fuel\ use\ aviation}{1990\ Total\ GHG\ emissions} * 100 = 7.3\%$$

Equation 2 – Calculation of the GHG emission share of aviation and maritime (including bunkers) sectors in 2050 as a percentage of 1990 emissions.

According to EEA (2016), the emissions from aviation, domestic navigation and international bunkers in 1990 accounted for 14.47, 24.68 and 178.93 Tgcoe (million tonnes) respectively. The 2050 and 1990 fuel use aviation was sourced from EC (2011c, p. 73), which accounted for 57377 ktoe and 29038 ktoe, respectively. Finally, the 1990 Total GHG emissions were 5,844 MTcoe according to EEA (2016). The result from the calculation is 7.3%, which amounts to total GHG emissions 429.17 MTcoe from the aviation and maritime sectors in 2050.

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2.3.3 Industry sector

The industry sector, defined as the emissions from industrial and chemical processes, is one of the largest contributors to GHG emissions for Europe (EEA, 2016). It is noted that the emissions from energy use of the industry sector are not included here but are instead included in the energy generation sector.

Although measures and policies have been developed and implemented to reduce the emissions from this sector, these have not always been successful and while improvements have been made, it is unlikely to completely decarbonise by 2050. This is confirmed by the projections from the EU 2050 High-RES scenario, which forecasts 166 $MTCO_2$ in 2050 still being emitted from this sector (EC, 2011c, p. 72). For this sector we used the prediction of the increase in efficiency and demand growth from the EU 2050 High-RES scenario. The final 2050 value was calculated following Equation 3.

$$\frac{\frac{2050\ CO2\ emissions\ from\ industry}{1990\ CO2\ emissions\ from\ industry} * 1990\ GHG\ emissions\ from\ industry}{Total\ 1990\ GHG\ emissions} * 100 = 1.9\%$$

Equation 3 – Calculation for the share of industry sector in 2050 as a percentage of 1990 emissions.

Data for the CO_2 emissions in 2050 and 1990 from the industry sector was sourced from the EU 2050 High-RES scenario to derive the increase in efficiency and demand growth as explained above. Here we assume that the efficiency improvement in all GHG emissions tracks the improvement in CO_2 emissions. These values were 165.7 $MTCO_2$ and 781.4 $MTCO_2$, respectively (EC, 2011c, p. 72). The 1990 total level of GHG emissions and those from the industry sector were alternatively sourced from EEA (2016), which accounted for 5,844 MTcoe and 513.68 MTcoe, respectively. The final share of GHG emissions in 2050 from the industry sector is forecast at 1.9% of 1990 emissions. This accounts for total GHG emissions of 108.93 MTcoe from the industry sector in 2050. Compared to the 1990 emissions this represents an almost 80% reduction in emissions over this period in line with the overall European target.

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2.3.4 Residential sector

Similarly to the industry sector, the residential sector is unlikely to be able to reach full decarbonisation by 2050. This is confirmed by the projections from the EU 2050 High-RES scenario, which forecasts 66.6 $MTCO_2$ in 2050 still being emitted from this sector (EC, 2011c, p. 72)[4]. The final value for the 2050 GHG emissions from this sector was calculated using Equation 4.

$$\frac{\frac{2050\ CO2\ emissions\ from\ residential}{1990\ CO2\ emissions\ from\ residential} * 1990\ GHG\ emissions\ from\ residential}{Total\ 1990\ GHG\ emissions} * 100 = 1.3\%$$

Equation 4 – Calculation of the GHG emission share of residential sector in 2050 as a percentage of 1990 emissions.

Similarly to the calculation for the industry sector, data for the CO_2 emissions in 2050 and 1990 from the residential sector was sourced from the EU 2050 High-RES scenario. These values were 66.6 $MTCO_2$ and 449.4 $MTCO_2$, respectively (EC, 2011c, p. 72). The 1990 total level of GHG emissions and those from the residential sector were alternatively sourced from EEA (2016), which accounted for 5,844 MTcoe and 523.37 MTcoe, respectively. The final share of GHG emissions in 2050 from the residential sector is forecast at 1.3% of total 1990 emissions. This amounts to total GHG emissions of 77.56 MTcoe from the residential sector in 2050. Compared to the 1990 emissions this represents an 85% reduction in emissions over this period, which is higher than the overall European target.

[4] The assumptions on which the scenario relies are listed in Section 3 of this report.

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2.3.5 Ground transport and energy producing sectors

The total emissions from agriculture, aviation and maritime, industry and residential in 2050 as a percentage of 1990 emissions is therefore:

$$7.4\% \ + 7.3\% + 1.9\% + 1.3\% = 18.0\%$$

Equation 5 – Calculation for the share of agriculture, aviation and maritime, industry and residential sectors in 2050 as a percentage of 1990 emissions.

The European Commission aims to achieve an overall GHG emission reduction of at least 80% by 2050 over a 1990 baseline (EC, 2010). Therefore, all sectors present in 2050 can, at maximum, contribute 20% of 1990 emissions. Given these four sectors contribute 18.0%, or 1051 MTcoe, this leaves 2.0% of 1990 emissions or 117 MTcoe. For MEDEAS, the authors advocate the precautionary approach and assume that any of these four sectors may not achieve the significant technological innovation required to meet their emissions reduction targets alongside their growth. Furthermore, if the Commission opts at any point to increase its emission reduction target from 80% the authors note that these four sectors will have to increase their contribution. Therefore, the authors assume that the remaining 117 MTcoe is allowed space for missed targets and all other sectors should completely decarbonise – that is achieve 0% of 1990 emissions by 2050.

For transport, the GHG emissions from this sector, (i.e. private and public transport excluding maritime and aviation) are assumed to be 0% (0 MTcoe) in 2050. This may be possible through the exponential increase in uptake of electric vehicles in both the private and public transport sector.

All energy producing sectors not listed above should be fully decarbonised with 0% (0 MTcoe) emissions. Electricity generation is assumed to be fully decarbonised (zero emissions) by 2050. It is noted that there will be a larger number of sectors requiring electricity in 2050, for example ground transport for electric cars, although the overall demand will depend on efficiency gains between now and then.

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2.3.6 Fossil fuel production constraints

An additional constraint that was introduced in this scenario was the production from the most polluting fossil fuels, i.e. oil and coal, will be terminated before 2050, both in their conventional and unconventional forms. This is reflected in the 0 value associated to all the PAVs that related to the production and use of these energy sources, in particular PAVs 81, 82 and 85 (conventional oil production, unconventional oil production and coal production, respectively) from the final list of PAVs attached to Deliverable D2.1. In line with this rationale, the PAV relating to the capturing of CO_2 emissions from electricity (PAV 29) was also set to 0 kgCO_2/kWh, assuming the complete substitution of fossil fuels with RES in this sector.

Coal remains a dominant fossil fuel with a high EROI (Hall, et al., 2014). However, it is also widely acknowledged that coal is the most polluting fossil fuel. Its demand has been rising during the past few years, especially in developing countries in Asia to meet their economic growth, which has demanded an increasing input of cheap energy. However, this trend is forecast to change. IEA (2015) projections for the future of this fossil fuel anticipate a significant decrease in its use, primarily attributed to implementation of international policies to tackle climate change. IEA (2015) adds that the continued use of coal will only be possible if other technologies to tackle its emissions will be implemented, such as CCS. On the basis of these assumptions (recognising that MEDEAS considers CCS as a possible technological wildcard rather than a secure technology), it is argued here that the EU should aim for the complete phasing out of coal by 2050.

Oil is the second most polluting fossil fuel after coal and the most widely used source of energy. Although reserves for this fossil fuel are still plentiful, global peak-oil is generally believed to have taken place during the first decade of the 21st century, with some experts arguing that this already occurred in 2005 or 2006 (Bardi, 2009). Hall, et al. (2009) estimated that the EROI for basic functions of society is 3:1, arguing that this estimate would allow for conventional oil to be utilised as part of the energy mix only until 2030 at the current rate of production. For all these reasons, we find it reasonable to argue that the EU should aim for a complete phasing out of oil by 2050.

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2.3.7 Conclusions

The total amount of GHG emissions from the four sectors (Agriculture, Industry, Residential and Aviation and Maritime) underpinning the scenario presented here contribute 18.0% of 1990 GHG levels emissions. The emissions from all other sectors are assumed to be zero. Therefore, this represents an emissions reduction of 82% over 1990 emissions by 2050. This figure is also within the target reduction of 80-95% set by the European Commission. Furthermore, it is slightly higher than the 80% minimum target, hence implying a stricter target and higher reductions in EU GHG emissions for 2050. However, within each of these four sectors, the emission levels will only be achieved if new technology or processes can be adopted with sufficient sector penetration that allows much higher efficiency gains. For example, within aviation it is highly unlikely that the entire European fleet of planes (including commercial and private) will be able to achieve a 50% efficiency gain or that the residential sector will achieve 85% emissions reductions including fully retrofitting all homes over the next three decades.

Alternatively, any sector could experience a period of de-growth or much slower growth than projected or a technology revolution in a particular sector may occur. Currently, 94% of the total allowed emissions in 2050 are already accounted for by four sectors shown here (Agriculture, Industry, Residential and Aviation and Maritime). Recognising this, combined with expectation the level of ambition is likely to increase over time (leading to a higher target than 80%), the authors have deliberately set the emission expectation from all other sectors to zero. That is a complete decarbonisation of all sectors outside of residential, industry, aviation/maritime and agriculture. The emission headroom (representing 2% of 1990 emissions or 117 MTcoe) provides some flexibility in terms of additional growth or lower efficiency in the four sectors as well as some margin of error. If the EU wishes to adopt a higher than 80% target then each of these 4 sectors will need to grow more slowly, de-grow or find a technology revolution.

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3 MEDEAS 2050 cross validation - EU 2050 High RES

The EU 2050 scenario (EC, 2011a) is part of a set of plans set up from the European Union to deliver on its commitment of transitioning to a decarbonised European energy system by 2050. This scenario was commissioned by the European Commission in 2011 with the aim of developing a set of scenarios that could deliver an (at least) 80% reduction in the GHG emissions from the European energy system by 2050. Seven different scenarios were developed as part of this exercise, divided into current trend scenarios (1 and 2), and decarbonisation scenarios (3 – 7):

1. Reference (REF)
2. Current Policy Initiatives (CPI)
3. High Energy Efficiency (HEE)
4. Diversified Supply Technologies (DST)
5. High Renewable energy sources (RES)
6. Delayed CCS (DEL)
7. Low nuclear (NUC)

The REF scenario '*includes current trends and long-term projections on economic development (gross domestic product (GDP) growth 1.7% pa). The scenario includes policies adopted by March 2010, including the 2020 targets for RES share and GHG reductions as well as the Emissions Trading Scheme (ETS) Directive. For the analysis, several sensitivities with lower and higher GDP growth rates and lower and higher energy import prices were analysed.*' (EC, 2011a, p.3).

The CPI scenario '*updates measures adopted, e.g. after the Fukushima events following the natural disasters in Japan, and being proposed as in the Energy 2020 strategy; the scenario also includes proposed actions concerning the "Energy Efficiency Plan" and the new "Energy Taxation Directive".*' (EC, 2011a, p.3).

The HEE scenario assumes '*political commitment to very-high energy savings; it includes e.g. more stringent minimum requirements for appliances and new buildings; high renovation rates of existing buildings; establishment of energy savings obligations on energy utilities. This leads to a decrease in energy demand of 41% by 2050 as compared to the peaks in 2005-2006.*' (EC, 2011a, p.3).

The DST scenario assumes that '*no technology is preferred; all energy sources can compete on a market basis with no specific support measures. Decarbonisation is driven by carbon pricing assuming public acceptance of both nuclear and Carbon Capture & Storage (CCS).*' (EC, 2011a, p.3).

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The High-RES scenario' assumes '*strong support measures for RES leading to a very high share of RES in gross final energy consumption (75% in 2050) and a share of RES in electricity consumption reaching 97%.*' (EC, 2011a, p.3).

The DEL scenario is '*similar to Diversified supply technologies scenario but assuming that CCS is delayed, leading to higher shares for nuclear energy with decarbonisation driven by carbon prices rather than technology push.*' (EC, 2011a, p.3).

The NUC scenario is '*similar to Diversified supply technologies scenario but assuming that no new nuclear (besides reactors currently under construction) is being built resulting in a higher penetration of CCS (around 32% in power generation).*' (EC, 2011a, p.3).

The different scenarios are presented and analysed in depth (EC, 2011b,c) and the results were obtained by introducing these scenarios in the PRIMES model (EC, 2011b). However, the main difference between the decarbonisation scenarios listed above are the policy assumptions as well as their implementation, which may result in different final energy mixes and the promotion of certain energy sources above others. For instance, the DST and DEL scenarios assume high penetration of nuclear in the European energy system, resulting in a high share of this technology in the final energy mixes (EC, 2011c). These two scenarios and the NUC scenario also assume similar penetration of CCS, which again results in a rather high use of this technology to abate emissions deriving from high use of fossil fuels.

The only two scenarios which were compatible for the MEDEAS comparison were the HEE and High-RES scenarios. Although the rationale behind both scenarios made them equally suitable, the High-RES scenario was preferred due to the greater emphasis placed on and facilitation of renewable resources, which is more in line with the rationale behind MEDEAS. The energy mixes resulting from this scenario were thus used to constrain the 2050 values for some of the key PAVs used in the MEDEAS model cross validation purposes. The next section will introduce the main assumptions and findings from the RES scenario. For a more in-depth explanation of the assumptions underlying each EU 2050 scenario and their results we refer to EC (2011b,c), and particularly EC (2011c) for a focus on the decarbonisation scenarios and with particular attention on the High-RES.

All the decarbonisation scenarios achieve a reduction of 80% in the GHG emissions and around 85% in the CO_2 emissions from the energy sector by 2050 as compared to 1990 levels. The scenarios share most of their assumptions with the reference and current Policies scenarios (for further details see Table 1). All scenarios assume a GDP growth rate of 1.7 % per annum on

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average for 2010-2050. In contrast with the Current Trend scenarios, the decarbonisation scenarios ‘have lower fossil fuel prices as a result of lower global demand for fossil fuels reflecting worldwide carbon policies (oil price is 84 USD'08 per barrel in 2020; 79 in 2030 and 70 in 2050).’ (EC, 2011b, p. 25). The policies assumed by all the decarbonisation scenarios are listed in Table 2, and those additionally implemented in the High-RES scenario are listed in Table 3.

GDP growth rate: 1.7 % pa on average for 2010-2050

Oil price: 106 $/barrel in 2030 and 127 $/barrel in 2050 (in year 2008 dollars)[37]

Main policies included (Reference scenario): Eco-design and Labelling directives adopted by March 2010; Recast of the Energy Performance of Buildings Directive, EU ETS directive; RES directive (20% target); Effort Sharing Decision (non-ETS part of the 20% GHG target); Regulation on CO2 from cars and vans.

Main policies included (Current Policy Initiatives scenario) in addition to those already included in the Reference scenario 2050: Energy efficiency Plan; facilitation policies for infrastructure and updated investments plans based on ENTSO-e Ten Year Network Development Plan; Nuclear Safety Directive; Waste management Directive; revised Energy Taxation Directive

Consequences of the Japanese nuclear accident leading to abandon of nuclear programme in Italy, nuclear phase-out in Germany and in case of nuclear lifetime extension up to 20% higher generation costs reflecting higher safety requirements as well as introduction of a risk premium for new nuclear power plants; revisiting of progress on CCS in demonstration projects and policies and initiatives leading to slightly higher uptake of electric vehicles.

Costs for technologies: 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. 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).

Drivers: Within these framework conditions market forces drive energy and emission developments. Economic actors optimise their supply and demand behaviour while the simulation of energy markets in the model derives energy prices, which in turn influence the behaviour of energy actors (power generators, various industrial and service consumers, households, transport, etc). The Reference and CPI scenarios do not assume any additional policies. The model provides a simulation of what the interplay of market forces in the current economic, world energy, policy and technology framework would bring about if no new policies would be put in place.

All scenarios are built on assumptions of perfect foresight and "representative" consumer leading to a very high certainty on regulatory framework for investors and rather optimistic deployment of technologies by households and services that will be challenging to ensure in practice.

Figure 3 – Main assumptions of the Current Trend scenarios (EC, 2011b, p.14).

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4	Guarantee funds for all low carbon generation technologies	The model reflects support to early demonstration and first of a kind commercial plants for all innovative low-carbon technologies in the energy sector (nuclear, RES and their infrastructure needs, CCS, etc.).
5	Storage and interconnections	Higher penetration of variable generation leading occasionally to excess electricity is dealt with by increased pump storage and more interconnection capacity. Moreover, large parts of such excess electricity generation from variable sources is transformed into hydrogen, which is fed, up to a certain degree, into the natural gas grid, thereby providing a means for (indirect) storage of electricity and reducing the carbon content of gas delivered to final consumers enabling deeper emission cuts. Where for technical or economic reasons, simulated in the model, feeding into the natural gas grid is not feasible, excess electricity (mainly from RES) is stored in form of hydrogen at times of excess supply and transformed back into electricity when demand exceeds supply. (Hydrogen storage is used to a different degree in various decarbonisation scenarios, see also measures under Scenario 4).

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Figure 4 – Measures implemented in all the EU 2050 decarbonisation scenarios (EC, 2011c, p.3).

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	Measure	How it is reflected in the model
1	Facilitation and enabling policies (permitting, preferential access to the grid)	Represented by significantly higher RES-values in the model than in other decarbonisation scenarios; these RES facilitating policies include for example lower lead times in construction, and involve greater progress on learning curves (e.g. small scale PV and wind) based on higher production.
2	Market integration allowing for more RES trade	Use of cooperation mechanisms or convergent support schemes coupled with declining costs/support result in optimal allocation of RES development, depending also on adequate and timely expansion of interconnection capacity (point 4);
3	Stronger policy measures in the power generation, heating and transport sectors in order to achieve high share of RES in overall energy consumption in particular in household micro power generation and increased power production at the distribution level.	Higher use of heat pumps, significant penetration of passive houses with integrated RES reflected through faster learning rates (cost reductions), higher penetration rates (e.g. due to RES building/refurbishing requirements)
4	Infrastructure, back-up, storage and demand side management	Substantial increase in interconnectors and higher net transfer capacities including DC lines from North Sea to the centre of Europe. Back-up functions done by biomass and gas fired plants. Sufficient storage capacity is provided (pumped storage, CSP, hydrogen). Smart metering allows time and supply situation dependent electricity use (peak/off-peak) reducing needs for storing variable RES electricity. All these measures allow for exploiting greater potentials for off-shore wind in the North Sea.

Figure 5 - Measures specifically implemented in the High-RES scenario (EC, 2011c, p.6).

As a result of the measures listed above, the results from the High-RES scenario show 38% in energy consumption saving in 2050 over 1990 levels. In addition, the energy and carbon intensity resulting from the High-RES scenario show a decrease of almost 75% as compared to 1990 levels. In this scenario the RES share in gross final energy consumption reaches 75% in 2050, which constitutes a 65% increase from current levels.

The RES share in transport increases to 73% and the RES share in power generation reaches 86%. The share of RES in electricity consumption amounts to 97%. In this scenario, RES capacity in 2050 reaches over 1900 Gigawatts (GW), which is more than 8 times the current RES capacity and also more than twice today's total generation capacity (including nuclear, all fossil fuels and RES). The high share of RES in the final energy mix leaves little room for nuclear, which only supplies 4% of primary energy. Similarly, due to the almost complete reliance on RES for electricity generation, the CCS contribution would be small, amounting to a 7% share in gross electricity generation in 2050.

Tables 4, 5, 6, 7a and 7b report some of the final energy mixes and key indicators resulting from the High-RES scenario. These tables were the main source used to develop the constraints listed in the excel spreadsheet attached to this deliverable 'PAVs 2050 DN – EU 2050 scenario

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constraints.xlsx'. This scenario also included assumptions on the phasing out of coal and oil by 2050.

	2005	2050		
		Reference	Scenario 1bis	Scenario 2
Final energy demand (in TWH)	2762	4130	3951	3203
Industry	1134	1504	1426	1109
Households	795	1343	1230	913
Tertiary	759	1184	1041	518
Transport	74	100	255	663
	2050			
	Scenario 3	Scenario 4	Scenario 5	Scenario 6
Final energy demand (in TWh)	3618	3377	3585	3552
Industry	1211	1169	1201	1191
Households	1026	938	1019	1013
Tertiary	707	605	696	677
Transport	675	664	669	671

Figure 6 - Final energy demand in TWh from the EU 2050 High-RES scenario (EC, 2011c, p. 21).

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ktoe	2005	Reference scenario		Current policy Initiatives	
		2030	2050	2030	2050
Total domestic biomass	86285	179649	185863	175987	188914
of which biofuels	*3129*	*35255*	*36957*	*34295*	*38912*
Biofuels in bunkers	0	0	0	133	2325
Total use of biomass	86285	179649	185863	176120	191239
		Energy efficiency		Diversified supply technologies	
		2030	2050	2030	2050
Total domestic biomass		162716	241476	172145	253209
of which biofuels		*25033*	*68393*	*26174*	*71047*
Biofuels in bunkers		553	18062	553	17995
Total use of biomass		163268	259538	172698	271204
		High RES		Delayed CCS	
		2030	2050	2030	2050
Total domestic biomass		188675	301805	172953	252893
of which biofuels		*26296*	*72453*	*26112*	*69370*
Biofuels in bunkers		553	18060	552	17523
Total use of biomass		189227	319865	173505	270415
		Low nuclear			
		2030	2050		
Total domestic biomass		175360	257226		
of which biofuels		*26135*	*70794*		
Biofuels in bunkers		553	17981		
Total use of biomass		175913	275206		

Figure 7 - Use of biomass and biofuels for each EU 2050 scenario (EC, 2011c, p. 39).

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		2005	2050		
			Reference	Scenario 1bis	Scenario 2
Electricity generation	TWh	**3274**	**4931**	**4620**	**4281**
Nuclear energy	Shares (%)	30.5	26.4	20.6	14.2
Renewables		14.3	40.3	48.8	64.2
Hydro		*9.4*	*7.6*	*8.5*	*9.2*
Wind		*2.2*	*20.1*	*24.7*	*33.2*
Solar, tidal etc.		*0.0*	*5.1*	*7.0*	*10.6*
Biomass & waste		*2.6*	*7.3*	*8.4*	*10.9*
Geothermal heat		*0.2*	*0.2*	*0.2*	*0.3*
Fossil fuels		55.2	33.3	30.6	21.6
Coal and lignite		*30.0*	*15.2*	*11.1*	*4.8*
Petroleum products		*4.1*	*2.2*	*2.1*	*0.0*
Natural gas		*20.3*	*15.1*	*16.7*	*16.7*
Coke & blast-furnace gasses		*0.9*	*0.7*	*0.7*	*0.0*
Other fuels (hydrogen, methanol)		0.0	0.0	0.0	0.0
		2050			
		Scenario 3	Scenario 4	Scenario 5	Scenario 6
Electricity generation	TWh	**4912**	**5141**	**4872**	**4853**
Nuclear energy	Shares (%)	16.1	3.5	19.2	2.5
Renewables		59.1	83.1	60.7	64.8
Hydro		*8.0*	*7.7*	*8.1*	*8.1*
Wind		*31.6*	*48.7*	*32.4*	*35.6*
Solar, tidal etc.		*9.9*	*16.4*	*9.9*	*10.8*
Biomass & waste		*9.3*	*9.6*	*9.9*	*9.8*
Geothermal heat		*0.3*	*0.6*	*0.4*	*0.4*
Fossil fuels		24.8	9.6	20.1	32.7
Coal and lignite		*8.1*	*2.1*	*5.1*	*13.1*
Petroleum products		*0.0*	*0.0*	*0.0*	*0.1*
Natural gas		*16.6*	*7.5*	*14.9*	*19.5*
Coke & blast-furnace gasses		*0.0*	*0.0*	*0.0*	*0.0*
Other fuels (hydrogen, methanol)		0.0	3.9	0.0	0.0

Figure 8 - Summary of energy mixes for electricity generation from different scenarios. In this table Scenario 1 is Reference scenario, Scenario 1b is CPI scenario, Scenario 2 is HEE scenario, Scenario 3 is DST scenario, Scenario 4 is High-RES scenario, Scenario 5 is DEL scenario and Scenario 6 is NUC scenario (EC, 2011c, p.22).

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EU27: High RES scenario														SUMMARY ENERGY BALANCE AND INDICATORS (A)					
ktoe	1990	1995	2000	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050	'90-'00	'00-'10	'10-'20	'20-'30	'30-'40	'40-'50
														Annual % Change					
Production	936047	950181	941860	900326	833310	806698	779610	742056	698518	699081	731599	752101	764124	0,1	-1,2	-0,7	-1,1	0,5	0,4
Solids	366477	277810	213423	196277	177924	167143	130847	105741	70120	50626	42866	34971	29452	-5,3	-1,8	-3,0	-6,0	-4,8	-3,7
Oil	129551	171052	173006	134290	104398	73819	46224	35904	31670	23560	14980	7066	2278	2,9	-4,9	-7,8	-3,7	-7,2	-17,2
Natural gas	162447	188965	207559	188677	164866	129037	110518	89489	71627	58053	44334	29044	19735	2,5	-2,3	-3,9	-4,2	-4,7	-7,8
Nuclear	202589	223028	243761	257360	235016	237344	229652	213206	145795	112636	85647	64628	43640	1,9	-0,4	-0,2	-4,4	-5,2	-6,5
Renewable energy sources	74984	89326	104111	123722	151107	199354	262370	297715	379306	454205	543773	616393	669019	3,3	3,8	5,7	3,8	3,7	2,1
Hydro	25101	28054	30374	26395	30008	30294	30817	31604	32220	32722	33245	33693	34059	1,9	-0,1	0,3	0,4	0,3	0,2
Biomass & Waste	46473	57201	67982	85129	98472	122897	149005	159999	180886	218149	253415	282753	294621	3,9	3,8	4,2	2,0	3,4	1,5
Wind	67	350	1913	6061	12781	28465	52714	67465	103030	125049	161406	189752	215507	39,8	20,9	15,2	6,9	4,6	2,9
Solar and others	153	274	421	807	3446	9395	19017	26413	40371	52058	67572	79864	90649	10,7	23,4	18,6	7,8	5,3	3,0
Geothermal	3190	3447	3421	5331	6400	8305	10817	12234	22800	26227	28134	30331	34182	0,7	6,5	5,4	7,7	2,1	2,0
Net Imports	756079	738600	826299	986048	969129	1046554	952439	911227	863234	767139	631727	510481	413127	0,9	1,6	-0,2	-1,0	-3,1	-4,2
Solids	81846	79338	98645	126639	102268	112548	86128	69892	38524	19365	7407	-6329	-6046	1,9	0,4	-1,7	-7,7	-15,2	
Oil	535645	512185	533039	599851	580795	609089	582627	557236	533764	460454	364573	263832	198402	0,0	0,9	0,0	-0,9	-3,7	-5,9
- Crude oil and Feedstocks	508460	494000	513725	581995	578276	603822	577997	556269	534989	464675	373779	285995	221344	0,1	1,2	0,0	-0,8	-3,5	-5,1
- Oil products	27185	18185	19314	17856	2519	5267	4630	967	-1225	-4221	-9206	-22163	-22942	-3,4	-18,4	6,3			
Natural gas	135121	145288	192531	257366	278450	317916	271631	276670	282045	273453	241524	227188	190699	3,6	3,8	-0,2	0,4	-1,5	-2,3
Electricity	3323	1508	1686	971	696	-634	-2118	-1959	558	1723	3146	4397	4829	-6,6	-8,5			18,9	4,4
Renewable energy forms	144	279	397	1222	6921	7636	14171	9388	8342	12143	15077	21393	25243	10,7	33,1	7,4	-5,2	6,1	5,3
Gross Inland Consumption	1660159	1662517	1723099	1825989	1752388	1801136	1679135	1600572	1509860	1417185	1316560	1217955	1134336	0,4	0,2	-0,4	-1,1	-1,4	-1,5
Solids	452940	364248	321007	319922	280191	279691	216975	175633	108644	69991	50272	28642	23406	-3,4	-1,4	-2,5	-6,7	-7,4	-7,4
Oil	631058	650858	658727	676859	635141	630791	575936	540429	514095	438052	340749	240880	175825	0,4	-0,4	-1,0	-1,1	-4,0	-6,4
Natural gas	294905	333268	393417	445998	443315	446953	382149	366159	353672	331506	285858	256232	210434	2,9	1,2	-1,5	-0,8	-2,1	-3,0
Nuclear	202589	223028	243761	257360	235016	237344	229652	213206	145795	112636	85647	64628	43640	1,9	-0,4	-0,2	-4,4	-5,2	-6,5
Electricity	3323	1508	1686	971	696	-634	-2118	-1959	558	1723	3146	4397	4829	-6,6	-8,5			18,9	4,4
Renewable energy forms	75343	89606	104501	124880	158028	206990	276541	307103	387095	463277	550887	623177	676202	3,3	4,2	5,8	3,4	3,6	2,1
as % in Gross Inland Consumption																			
Solids	27,3	21,9	18,6	17,5	16,0	15,5	12,9	11,0	7,2	4,9	3,8	2,4	2,1						
Oil	38,0	39,1	38,2	37,1	36,2	35,0	34,3	33,8	34,0	30,9	25,9	19,8	15,5						
Natural gas	17,8	20,0	22,8	24,4	25,3	24,8	22,8	22,9	23,4	23,4	21,7	21,0	18,6						
Nuclear	12,2	13,4	14,1	14,1	13,4	13,2	13,7	13,3	9,7	7,9	6,5	5,3	3,8						
Renewable energy forms	4,5	5,4	6,1	6,8	9,0	11,5	16,5	19,2	25,6	32,7	41,8	51,2	59,6						
Gross Electricity Generation in GWh,	2562823	2712209	2991720	3274121	3310017	3609375	3665380	3751472	3666305	3879733	4357597	4726244	5140565	1,6	1,0	1,0	0,0	1,7	1,7
Nuclear	794718	881662	944823	997519	911418	920951	894470	840519	578404	449157	344218	260161	179105	1,7	-0,4	-0,2	-4,3	-5,1	-6,3
Hydro & wind	292648	330306	375545	378836	514979	716559	1046829	1280628	1838420	2222236	2819421	3298070	3744893	2,5	3,2	7,4	5,8	4,4	2,9
Thermal (incl. biomass)	1475456	1500241	1671352	1897765	1883620	1971864	1724081	1630325	1249481	1208340	1193958	1168013	1216567	1,3	1,2	-0,9	-3,2	-0,5	0,2
Fuel Inputs for Thermal Power Generation	383492	362334	382613	424208	410954	424609	371495	346950	280705	264227	256594	249960	264725	0,0	0,7	-1,0	-2,8	-0,9	0,3
Solids	263837	230040	223012	229245	208905	209783	153229	116717	53950	29831	22172	15880	17556	-1,7	-0,7	-3,1	-9,9	-8,5	-2,3
Oil (including refinery gas)	54404	51463	39294	29780	15595	14589	8560	10199	9028	8466	6629	2096	246	-3,2	-8,8	-5,8	0,5	-3,0	-28,0
Gas	56754	67806	102408	134637	145869	141081	124787	126024	110577	110044	85265	66166	55752	6,1	3,6	-1,5	-1,2	-2,6	-4,2
Biomass & Waste	5724	10033	14960	25901	35185	52352	76511	84921	88926	94230	107154	111032	109233	10,1	8,9	8,1	1,5	1,9	0,2
Geothermal heat	2774	2992	2939	4645	5400	6804	8409	9089	18156	20713	22294	23895	26799	0,6	6,3	4,5	8,0	2,1	1,9
Hydrogen - Methanol	0	0	0	0	0	0	0	0	69	942	13079	30891	55138					69,0	15,5
Fuel Input in other transformation proc.	839073	814654	827098	842975	793843	795868	744588	709740	683212	609457	525856	442356	399684	-0,1	-0,4	-0,6	-0,9	-2,6	-2,7
Refineries	679426	705954	735244	758152	718104	712903	658842	625630	598726	518600	415000	307676	230223	0,8	-0,2	-0,9	-1,0	-3,6	-5,7
Biofuels and hydrogen production	2	202	610	3129	12208	19510	26833	25850	25967	44429	77991	116325	158393	79,6	34,9	8,2	-0,3	11,6	7,3
District heating	32960	23240	19323	16212	15983	15699	13874	13522	13912	11437	8920	6722	5813	-5,2	-1,9	-1,4	0,0	-4,3	-4,2
Others	126685	85258	71921	65482	47547	47757	45039	44738	44607	34990	23945	11634	5255	-5,5	-4,1	-0,5	-0,1	-6,0	-14,1
Energy Branch Consumption	82379	88696	88176	96033	90926	90041	83106	77580	70485	63523	56656	52976	48370	0,7	0,3	-0,9	-1,6	-2,2	-1,6
Non-Energy Uses	97931	110541	112495	117477	111488	115324	118124	119728	121483	120976	120110	112142	105116	1,4	-0,1	0,6	0,3	-0,1	-1,3
Final Energy Demand	1068710	1069989	1112989	1173676	1160711	1214573	1145345	1103544	1093422	1039229	965315	885616	804231	0,4	0,4	-0,1	-0,5	-1,2	-1,8
by sector																			
Industry	365650	328513	326949	326308	310794	322842	317478	316730	319583	314659	311272	291614	275822	-1,1	-0,5	0,2	0,1	-0,3	-1,2
- energy intensive industries	234722	214526	213112	210991	192050	196819	190503	188016	187697	180244	173169	157044	142999	-1,0	-1,0	-0,1	-0,1	-0,8	-1,9
- other industrial sectors	130928	113987	113837	115317	118743	126023	126975	128714	131887	134414	138104	134570	132823	-1,4	0,4	0,7	0,4	0,5	-0,4
Residential	264307	280418	286784	308104	306349	320875	289859	273993	273054	260550	240796	220031	190190	0,8	0,7	-0,6	-0,6	-1,2	-2,3
Tertiary	158484	160442	159866	176859	173601	183698	167475	154457	151363	140799	126815	114332	100614	0,1	0,8	-0,4	-1,0	-1,8	-2,3
Transport	280269	300617	339389	362405	369967	387158	370533	358363	349421	323222	286432	259639	237605	1,9	0,9	0,0	-0,6	-2,0	-1,9
by fuel																			
Solids	125031	84977	61454	54486	47220	44757	39481	33969	29050	19765	14092	5914	2458	-6,9	-2,6	-1,8	-3,0	-7,0	-16,0
Oil	444429	456959	478882	495857	477402	476889	433240	403337	382481	317430	235116	166879	120383	0,7	0,0	-1,0	-1,2	-4,7	-6,5
Gas	227902	245996	265552	283524	268457	275889	227971	209061	212137	193706	165069	137402	95510	1,5	0,1	-1,6	-0,7	-2,5	-5,3
Electricity	184145	193367	216403	237537	241593	264268	269375	277243	277332	290261	301824	296091	290419	1,6	1,1	1,1	0,3	0,8	-0,4
Heat (from CHP and District Heating) [A]	48610	44616	40061	44441	57920	71519	78393	82568	78039	71951	69538	61492	53924	-1,9	3,8	3,1	0,0	-1,1	-2,5
Other	38592	44073	50640	57832	68119	81250	96886	97365	114383	146118	179676	217838	241538	2,8	3,0	3,6	1,7	4,6	3,0
CO_2 Emissions (Mt of CO_2 - sec approach)	4030,6	3800,1	3810,6	3946,6	3687,8	3672,9	3087,1	2776,2	2394,9	1964,4	1454,9	986,9	670,0	-0,6	-0,3	-1,8	-2,5	-4,9	-7,5
Power generation/District heating	1484,3	1321,2	1320,8	1381,1	1271,6	1261,5	957,9	817,6	523,3	403,4	250,3	103,5	52,5	-1,2	-0,4	-2,8	-5,9	-7,1	-14,5
Energy Branch	152,2	171,0	170,2	181,6	156,5	146,2	127,7	112,0	97,6	65,1	48,0	33,0	21,1	1,1	-0,8	-2,0	-2,7	-6,8	-7,9
Industry	781,4	678,1	623,0	581,9	498,3	480,6	434,7	412,7	407,6	363,6	314,0	238,3	165,7	-2,2	-2,2	-1,4	-0,6	-2,6	-6,2
Residential	499,4	481,6	466,2	486,7	466,9	466,9	384,3	329,2	318,5	260,1	186,8	125,4	66,6	-0,7	0,0	-1,9	-1,9	-5,2	-9,8
Tertiary	300,5	275,3	242,0	262,2	246,3	240,1	189,7	166,1	162,3	138,4	102,2	70,7	41,0	-2,1	0,2	-2,6	-1,5	-4,5	-8,7
Transport	812,7	872,9	988,5	1053,1	1048,2	1077,6	992,9	938,6	885,6	733,8	553,5	416,0	323,1	2,0	0,6	-0,5	-1,1	-4,6	-5,2
CO_2 Emissions Index (1990=100)	100,0	94,3	94,5	97,9	91,5	91,1	76,6	68,9	59,4	48,7	36,1	24,5	16,6						
CO_2 Emissions (Mt of CO_2 - ref approach)	4172,0	3950,7	3922,7	4087,6	3755,2	3740,5	3154,9	2843,0	2463,7	2028,4	1522,0	1075,6	775,5	-0,6	-0,4	-1,7	-2,4	-4,7	-6,5

Figure 9 - Summary of energy balance and indicators for High-RES scenario (EC, 2011c, p.72).

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EU27: High RES scenario														SUMMARY ENERGY BALANCE AND INDICATORS (B)					
	1990	1995	2000	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050	'90-'00	'00-'10	'10-'20	'20-'30	'30-'40	'40-'50
														Annual % Change					
Main Energy System Indicators																			
Population (Million)	470,388	477,010	481,072	489,211	499,389	507,727	513,838	517,811	519,942	520,654	520,103	518,362	515,303	0,2	0,4	0,3	0,1	0,0	-0,1
GDP (in 000 MEuro'05)	8142,7	8748,4	10107,2	11063,1	11385,6	12750,3	14164,0	15503,7	16824,7	18157,1	19527,9	21002,9	22560,0	2,2	1,2	2,2	1,7	1,5	1,5
Gross Inl. Cons./GDP (toe/MEuro'05)	203,9	190,0	170,5	165,1	153,9	141,3	118,5	103,2	89,7	78,1	67,4	58,0	50,3	-1,8	-1,0	-2,6	-2,7	-2,8	-2,9
Gross Inl. Cons./Capita (toe/inhabitant)	3,53	3,49	3,58	3,73	3,51	3,55	3,27	3,09	2,90	2,72	2,53	2,35	2,20	0,1	-0,2	-0,7	-1,2	-1,4	-1,4
Electricity Generated/Capita (kWh gross/inhabitant)	5448	5686	6219	6693	6628	7109	7133	7245	7051	7452	8378	9118	9976	1,3	0,6	0,7	-0,1	1,7	1,8
Carbon intensity (t of CO_2/toe of GIC)	2,43	2,29	2,21	2,16	2,10	2,04	1,84	1,73	1,59	1,39	1,11	0,81	0,59	-0,9	-0,5	-1,3	-1,5	-3,5	-6,1
CO_2 Emissions/Capita (t of CO_2/inhabitant)	8,57	7,97	7,92	8,07	7,38	7,23	6,01	5,36	4,61	3,77	2,80	1,90	1,30	-0,8	-0,7	-2,0	-2,6	-4,9	-7,4
CO2 Emissions to GDP (t of CO2/MEuro'05)	495,0	434,4	377,0	356,7	323,9	288,1	218,0	179,1	142,3	108,2	74,5	47,0	29,7	-2,7	-1,5	-3,9	-4,2	-6,3	-8,8
Import Dependency %	44,6	43,5	46,8	52,5	53,8	56,5	55,0	55,1	55,3	52,3	46,3	40,4	35,1						
Energy intensity indicators (2000=100)																			
Industry (Energy on Value added)	130,3	115,2	100,0	95,1	89,8	84,6	75,3	69,1	64,8	59,4	54,9	48,1	42,6	-2,6	-1,1	-1,7	-1,5	-1,6	-2,5
Residential (Energy on Private Income)	114,4	113,2	100,0	97,5	96,3	89,6	73,3	63,9	59,1	51,8	44,6	37,6	30,5	-1,3	-0,4	-2,7	-2,1	-2,8	-3,7
Tertiary (Energy on Value added)	126,5	117,0	100,0	99,4	93,9	87,9	71,9	60,3	54,2	46,6	38,9	32,5	26,5	-2,3	-0,6	-2,6	-2,8	-3,3	-3,8
Transport (Energy on GDP)	102,5	102,3	100,0	97,6	96,8	90,4	77,9	68,8	61,8	53,0	43,7	36,8	31,4	-0,2	-0,3	-2,1	-2,3	-3,4	-3,3
Carbon Intensity indicators																			
Electricity and Steam production (t of CO_2/MWh)	0,46	0,40	0,37	0,35	0,31	0,27	0,20	0,17	0,11	0,08	0,05	0,02	0,01	-2,1	-2,0	-4,2	-5,8	-8,1	
Final energy demand (t of CO_2/toe)	2,24	2,16	2,08	2,03	1,95	1,87	1,75	1,67	1,62	1,44	1,20	0,96	0,74	-0,7	-0,7	-1,1	-0,7	-3,0	-4,7
Industry	2,14	2,06	1,91	1,78	1,60	1,49	1,37	1,30	1,28	1,16	1,01	0,82	0,60	-1,1	-1,7	-1,6	-0,7	-2,3	-5,0
Residential	1,89	1,72	1,63	1,58	1,52	1,45	1,33	1,20	1,17	1,00	0,78	0,57	0,35	-1,5	-0,6	-1,4	-1,3	-4,0	-7,6
Tertiary	1,90	1,72	1,51	1,48	1,42	1,31	1,13	1,08	1,07	0,98	0,81	0,62	0,41	-2,2	-0,6	-2,2	-0,5	-2,8	-6,6
Transport	2,90	2,90	2,91	2,91	2,83	2,78	2,68	2,62	2,53	2,27	1,93	1,60	1,36	0,0	-0,3	-0,6	-0,6	-2,7	-3,5
Electricity and steam generation																			
Net Generation Capacity in MW_e			654168	715466	821393	925364	1028870	1093152	1323971	1473174	1763357	2002770	2219028		2,3	2,3	2,6	2,9	2,3
Nuclear energy			133966	134452	131393	125743	124752	106542	89509	74531	70208	59974	40649		-0,2	-0,5	-3,3	-2,4	-5,3
Renewable energy			112878	147262	206776	284863	421571	520864	790367	975140	1266151	1510674	1748963		6,2	7,4	6,5	4,8	3,3
Hydro (pumping excluded)			99714	104505	107315	111624	114963	117041	120084	124646	127086	129206	131439		0,7	0,7	0,4	0,6	0,3
Wind			12793	40584	83905	144765	247477	308743	469770	567394	734513	865683	984455		20,7	11,4	6,6	4,6	3,0
Solar			371	2172	15307	27898	57398	92099	195255	272546	385411	491250	602883		45,1	14,1	13,0	7,0	4,6
Other renewables (tidal etc.)			0	1	249	575	1732	2981	5259	10554	19140	24534	30187			21,4	11,7	13,8	4,7
Thermal power			407324	433752	483224	514758	482548	465746	444095	423503	426999	432122	429416		1,7	0,0	-0,8	-0,4	0,1
of which cogeneration units			76247	85453	97871	118960	124171	132317	135857	154830	170519	176464	178477		2,5	2,4	0,9	2,3	0,5
of which CCS units			0	0	0	0	2711	2711	2711	6268	22077	42460	52528				0,0	23,3	9,1
Solids fired			194165	186620	183457	182723	154491	129046	107532	83960	73806	67977	62189		-0,6	-1,7	-3,6	-3,7	-1,7
Gas fired			129444	166863	218569	241148	231203	231452	227152	215553	204223	193967	181585		5,4	0,6	-0,2	-1,1	-1,2
Oil fired			71058	62082	55901	45785	34998	33937	29321	24824	20949	20026	18956		-2,4	-4,6	-1,8	-3,3	-1,0
Biomass-waste fired			12051	17502	24569	44194	60735	70101	77673	96413	125058	146976	163125		7,4	9,5	2,5	4,9	2,7
Hydrogen plants			0	0	0	0	0	0	0	0	0	0	0						
Geothermal heat			605	686	727	908	1121	1211	2418	2754	2964	3176	3562		1,9	4,4	8,0	2,1	1,9
Load factor for net electric capacities (%)			49,1	49,1	43,8	42,5	39,0	37,7	30,7	29,3	27,0	25,5	24,8						
Indicators for gross electricity production																			
Efficiency for thermal electricity production (%)			37,6	38,5	39,4	39,9	39,9	40,4	38,3	39,3	40,0	40,2	39,5						
CHP indicator (% of electricity from CHP)			11,4	11,7	14,8	18,8	20,2	21,1	18,5	17,5	15,2	13,0	10,5						
CCS indicator (% of electricity from CCS)			0,0	0,0	0,0	0,0	0,6	0,6	0,6	0,9	3,3	6,0	6,9						
Non fossil fuels in electricity generation (%)			45,8	44,8	47,3	50,9	61,0	65,6	75,6	79,2	84,8	88,5	90,0						
- nuclear			31,6	30,5	27,5	25,5	24,4	22,4	15,8	11,6	8,0	5,7	3,6						
- renewable energy forms and industrial waste			14,2	14,3	19,8	25,4	36,6	43,2	59,8	67,6	76,8	82,9	86,4						
Indicators for renewables (excluding industrial waste) (%) [(*)]																			
RES in gross final energy demand (%)			7,6	8,6	11,4	14,8	21,3	24,6	31,2	39,1	50,6	63,0	75,2						
RES in transport (%)			0,5	1,4	4,3	6,6	10,9	13,9	20,0	33,3	50,2	63,2	73,5						
Transport sector																			
Passenger transport activity (Gpkm)	4880,7	5307,7	5892,2	6240,3	6511,3	7133,0	7480,3	7921,8	8379,5	8681,7	8912,2	9140,9	9287,2	1,9	1,0	1,4	1,1	0,6	0,4
Public road transport	544,0	504,0	517,6	526,0	545,0	573,7	639,6	675,1	721,1	766,5	806,9	846,2	887,8	-0,5	0,5	1,6	1,2	1,1	1,0
Private cars and motorcycles	3501,1	3986,3	4428,1	4686,5	4866,0	5288,2	5414,1	5655,3	5908,7	6030,5	6111,5	6174,0	6179,1	2,4	0,9	1,1	0,9	0,3	0,1
Rail	472,5	421,7	447,9	461,0	482,5	525,9	607,7	646,0	703,3	761,5	813,5	878,4	953,4	-0,5	0,7	2,3	1,5	1,5	1,6
Aviation	317,3	351,3	456,9	527,3	576,9	702,8	775,7	900,3	999,1	1073,6	1128,9	1189,1	1212,4	3,7	2,4	3,0	2,6	1,2	0,7
Inland navigation	45,8	44,4	41,7	39,5	40,8	42,5	43,1	45,0	47,4	49,6	51,5	53,2	54,5	-0,9	-0,2	0,6	1,0	0,8	0,6
Travel per person (km per capita)	10376	11127	12248	12756	13038	14049	14558	15299	16116	16675	17135	17634	18023	1,7	0,6	1,1	1,0	0,6	0,5
Freight transport activity (Gtkm)	1848,4	1942,4	2195,7	2494,6	2662,6	2952,6	3058,2	3216,8	3387,8	3499,1	3597,1	3654,0	3646,6	1,7	1,9	1,4	1,0	0,6	0,1
Trucks	1060,4	1288,7	1518,7	1800,3	1940,3	2164,3	2155,1	2259,0	2362,1	2400,8	2427,4	2419,1	2347,9	3,7	2,5	1,1	0,9	0,3	-0,3
Rail	526,3	386,1	403,7	414,1	440,5	489,3	575,3	608,5	657,5	710,6	766,1	816,4	868,7	-2,6	0,9	2,7	1,3	1,5	1,3
Inland navigation	261,6	267,6	273,3	280,2	281,9	299,0	327,8	349,2	368,2	387,8	403,6	418,4	430,0	0,4	0,3	1,5	1,2	0,9	0,6
Freight activity per unit of GDP (tkm/000 Euro'05)	227	222	217	225	234	232	216	207	201	193	184	174	162	-0,4	0,7	-0,8	-0,7	-0,9	-1,3
Energy demand in transport (ktoe)	280269	300617	339389	362405	369967	387158	370533	358363	349421	323222	286432	259639	237605	1,9	0,9	0,0	-0,6	-2,0	-1,9
Public road transport	5197	4732	4914	5039	5182	5315	5423	5239	4928	4673	3910	3474	3317	-0,6	0,5	0,5	-1,0	-2,3	-1,6
Private cars and motorcycles	154395	166321	182974	187736	186407	184712	167417	148591	139470	120494	97075	85366	75653	1,7	0,2	-1,1	-1,8	-3,6	-2,5
Trucks	74969	79037	90951	105104	111606	123126	119059	121710	122731	116740	107691	95806	86075	2,0	2,1	0,6	0,3	-1,3	-2,2
Rail	9560	9452	9600	9436	9597	10166	11035	10609	9631	9491	9275	8779	8356	0,0	0,0	1,4	-1,4	-0,4	-1,0
Aviation	29038	34112	45395	49703	51709	58141	61530	65826	65945	64896	61450	59255	57377	4,6	1,3	1,8	0,7	-0,7	-0,7
Inland navigation	7110	6963	5555	5386	5466	5699	6070	6389	6715	6929	7030	6958	6827	-2,4	-0,2	1,1	1,0	0,5	-0,3
Efficiency indicator (activity related)																			
Passenger transport (toe/Mpkm)	39,6	39,5	40,3	39,5	38,0	35,4	31,9	28,3	25,6	22,4	18,7	16,7	15,1	0,2	-0,6	-1,7	-2,2	-3,1	-2,1
Freight transport (toe/Mtkm)	47,1	46,8	46,3	46,5	46,1	45,7	43,2	41,8	39,8	36,8	33,3	29,4	26,6	-0,2	-0,1	-0,6	-0,8	-1,8	-2,2

Figure 10 - Summary of energy balance and indicators for High-RES scenario (EC, 2011c, p.73).

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The following categories of PAVs (column 'fields' in the spreadsheet) were constrained using data from the High-RES scenario:

A. Electricity transformation
B. Electricity generation from RES
C. Electricity generation from non-RES
D. Thermal transformation for RES
E. Transport
F. Industrial energy consumption
G. Residential energy consumption
H. Other sector energy consumption
I. Energy transformation

In particular, the results reported in Table 4 were used to define constraints for electricity consumption from the industrial, residential and other sectors (PAVS 71c, 73c and 76c). Values from Table 5 were used to define constraints for the production of biofuels (PAV 97). Results from Table 6 were used to define electricity generation from RES (PAVs 37a-e) and non-RES (PAVs 44, 45, 47 and 49). Finally, the results and indicators reported in Table 7 were used to define constraints for thermal transformation for RES (PAVs 54b,c).

Due to methodological issues, the values resulting from this scenario could not be fully implemented within the MEDEAS 2050 cross-validation scenario. Despite the detailed information on the High-RES scenario provided by its impact assessment in EC (2011c), the information was not sufficient to find a perfect correlation with the list of PAVs included in the MEDEAS model. For instance, the High-RES scenario includes in the energy mix for electricity generation hydrogen and methanol as energy sources (see Table 6). Although data from Table 6 was utilised to define the constraints for this comparison scenario, this discrepancy prevented the full implementation of the High-RES scenario.

Despite this methodological challenge, we believe that the assumptions and results from the High-RES will prove to be an invaluable term of comparison with MEDEAS. Indeed, the assumptions implemented in the MEDEAS model for technology, investments and productivity could be parameterised using the High-RES scenario to ascertain whether these are sufficient for the mainstream diffusion of RES technologies. Finally, the comparison of the results between the MEDEAS model and the High-RES scenario could potentially be used to validate the model through cross-validation.

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4 Additional proposed PAVs

This part of the report is divided in four sections: sub-section (i) introduces various PAVs for GHG emissions specific to each sector; (ii) introduces biofuels and how they are addressed in the model and monitored; (iii) describes a list of additional PAVs (excluding emissions and biofuels) which will be equally critical for the project, alongside the rationale for their inclusion; (iv) discusses the inclusion of potential technology wildcards, some examples of which are provided. The authors note that these variables do not all necessarily need to be defined to develop the reference 2050 scenario. For example, the authors propose that technology wildcards should not be included in the main MEDEAS scenario, however it is still useful to capture these, at least in narrative, to ensure that if a particular technology does appear to be more viable in future it can be incorporated in the MEDEAS model. Finally, the authors would also recommend changing the unit of PAV 3 ‘Green GDP’ from $ to €.

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4.1 PAVs for sectorial CO_2 emissions

Variables

- Agriculture GHG emissions (MTcoe)
- Industry GHG emissions (MTcoe)
- Residential GHG emissions (MTcoe)
- Aviation and maritime GHG emissions (MTcoe)
- Other sectors GHG emissions (including energy generation) (MTcoe)

Rationale

As explained in the main text of the report, after a careful consideration of the different options available to shape the future of the European energy system, the decision was taken to only constrain the GHG emissions relating to certain sectors. Once again, the authors believe that it is of critical importance to capitalise on previously commissioned work from the European Commission, hence why some of the values and assumptions from the EU 2050 High-RES scenario (EC, 2011c) were utilised to define the GHG reduction targets reported in the spreadsheet attached (file: Additional PAVs 2050.xlsx).

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4.2 Biofuels

Variables

- World use of crops for biofuels (ktoe)
- Average crop prices for biofuels production (€/ktoe)
- Biofuels use ratio for agricultural commodity demand/production

Rationale

The process of phasing out fossil fuels could possibly result in the increase in consumption and production of biofuels to reduce the reliance of sectors on oil, especially the transport sector. The use of biofuels increased steadily in this sector, reaching a 3% share of the global road transport fuels in 2010 (IEA, 2011) and is projected to supply 8% of road energy transport by 2035 (IEA, 2013). However, the increased production of biofuels will result in competing demands for agricultural land, which can have negative consequences for food security, biodiversity and land availability. This is also acknowledged in Deliverable D2.1 (p.216). In addition, WRI (2013) argues that the conversion from food to fuel of biofuels crops is highly inefficient.

The effects of policies to promote biofuels on food security have been studied in depth. In particular, Lagi et al. (2015) found that the underlying upward trend in international food prices of the last decade can be explained by the increasing demand of biofuels on its own. In return, high international food prices have clear negative effects in terms of food security and political fragility (e.g. Natalini, et al., 2015). Finally, it is important to note that an increased demand of biofuels, if met by unsustainable practices (e.g. deforestation), can result in a net increase of GHG emissions. The final list of PAVs included in the MEDEAS model does not currently include variables that would allow the capture of these important dynamics and the added pressure on food and, more generally, the social system from the increased production of biofuels.

Deliverable D2.1 (p.193) already had important variables capturing these dynamics, as shown in Table 4.1. These variables should not be aggregated, but rather kept as they are, in particular the variables ‘World use of crops for biofuels (2005, 2030, 2050)’, ‘Average crop prices for biofuels production (2024)’ and ‘Biofuels use ratio for agricultural commodity demand/production’. These have been aggregated in PAV 97 ‘Biofuels production’. Maintaining the disaggregation of these PAVs would allow some of the dynamics described above to be captured, in particular the pressure of biofuel production on food security and the consequences for prices.

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D2.1 Results	PAV	PAV description
Evolution of world biofuels production in the period 1995-2013	97	Biofuels production
Evolution of world biofuels consumption for transport in the period 1995-2013	69	Biofuel share in transport fuels
Biofuel share in transport consumption in 2050	69	Biofuel share in transport fuels
Biofuels consumption in road transport (2011, 2035)	69	Biofuel share in transport fuels
World use of crops for biofuels (2005, 2030, 2050)	97	Biofuels production
Average crop prices for biofuels production (2024)	97	Biofuels production
Biofuel use ratio for agricultural commodity demand/production (2004-2013)	97	Biofuels production
Corn ethanol GHG produced or absorbed	68	GHG evolution of light duty vehicles

Figure 11 - PAVs for biofuels from Deliverable D2.1, p. 193.

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4.3 Further proposed PAVs

4.3.1 Thermal transformation for non-RES

At the moment there are no PAVs that capture the non-RES contribution to thermal generation. Although oil and coal will likely be phased out by the end of 2050, natural gas will likely still be part of the energy mix. We therefore recommend the inclusion the same PAVs for non-RES as for the sector (already included) 'Thermal transformation for RES'.

A. Capacity factor non-RES (%)
B. Investment cost non-RES (c€/kW)
C. Thermal energy cost from non-RES (c€/kWh)
D. Non-RES production for thermal applications (TWh/yr)
E. Non-RES power density from technology point of view (kW/m2)
F. Non-RES power density from resource point of view (ha/MWh*yr)
G. Non-RES lifetime for thermal applications (yr)
H. Non-RES EROI (from cradle to grave) (dimensionless)

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4.3.2 EU Emissions Trade Scheme (EU ETS)

A. Price (€/unit) – the price of the permits under the EU ETS will partly define the emissions reductions as the higher the price, the more emissions will have to be reduced. It is hence important to capture this variable, as the price of the permits is a key factor in the EU policies. We expect this to be different from PAV 25 'CO_2 certification prices', which is currently included in the list of PAVs.

B. Size

   I. **Number of permits auctioned each year -** the number of permits available on the market is currently one of EU's policies to fight CO_2 emissions, and it is likely to become more important in the future

   II. **Number of permits freely allocated each year –** a certain number of permits will still be freely allocated until the end of the third phase of the EU ETS (2013 – 2020). This has implications for the price of the permits

   III. **Percentage of total emissions covered under the EU ETS (%)** – this again will be part of the EU policy towards a decarbonised energy system and it will also be an important indicator for what other policies (and which sectors) need further policy implementation.

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4.3.3 International prices

A. **Oil ($/barrel)-** The reason for including the international price of oil is that in modelling the cost benefit analysis of different energy sources as well as projected investment returns will be heavily dependent on the price of energy and in particular oil prices
B. **Food (FAO FPI, index) –** International price of food is also suggested as an additional PAV due to the high and increasing correlation between the international price of fuel and food and to monitor the effect on prices of competing demands for agricultural products and land (e.g. biofuels production), which are expected to increase due to future energy policies.

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4.3.4 Exchange rates (US $ and Euro €)

Similarly to the variables above, it will be important to evaluate the contribution of imports and exports of energy (from EU to the rest of the world and vice versa) to EU's GDP and GVA, whether negative or positive.

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4.3.5 Import/Export of energy

A. **Emissions related to imported energy (MTcoe)** – In order to prevent the possible situation where EU countries start importing 'dirty energy' from developing countries with old technologies for the production of energy, we recommend the inclusion of a PAV that could capture the emissions related to the use of imported energy. For instance, this variable could capture the emissions related to the use of 1ktoe of imported coal from China

B. **Energy Exports (TW/h)** – Due to the increased investments in RES capacity, EU countries are expected to exponentially increase their energy production from RES, potentially beyond their energy needs. In case this were true, and in case the energy grid or other storage technologies allowed for the export of energy to non-EU countries, it will be important to capture the energy exports and their contribution to GDP and GVA

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4.3.6 Access to energy resources

In the current list of PAVs there does not seem to be a good representation of consumers' access to basic services such as electricity and heating. The PAVs already include median income and cost/price of energy. It is hence possible to develop indicators such as 'fuel poverty' or use existing definitions such as the Fuel Poverty Indicator of the UK Sustainable Development Indicators (DEFRA, 2013). Such measures will help to define any feedback constraints on uptake of new technology, use of energy at certain prices or other socio-economic impacts on energy usage.

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4.3.7 Energy subsidies (€)

it is widely known that countries heavily subsidise the price of energy and food resources to make them affordable (IMF, 2008). The transition to a decarbonised energy system for Europe will result in higher energy prices due to the more expensive energy sources used, i.e. RES and governments will need to be ready to protect the most vulnerable sectors of the population by increasing subsidies (EC, 2011c). In particular, it is possible to foresee an increase in subsidies for RES prices and a decrease of subsidies for fossil fuels. It is important for MEDEAS to capture these dynamics.

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4.3.8 Discount rate (%)

The decarbonisation of the EU energy system will mainly be driven by larger investments on RES. An effective way to define and capture this dynamic is to introduce in the model the discount rate applied to capital, which defines the disposition of different sectors to invest in energy efficiency. In energy modelling two types of discount rates are generally employed (Cambridge Econometrics, 2015):

A. **Behavioural (or first-stage)** discount rate – 'to model the decision-making behaviour of economic agents and to determine which projects and/or technologies would attract private investment' (Cambridge Econometrics, 2015, p. 2)
B. **Social (or second-stage)** discount rate – to convert investments into yearly instalments, in order to compare the value of the total costs and benefits of policies or investment programmes (Cambridge Econometrics, 2015, p. 2).

Fossil-fuel-based technologies usually require a low initial capital, but have higher maintenance costs, as opposed to renewable technologies which normally require a larger investment upfront, but whose benefits are delivered in the long-term through lower maintenance costs and carbon emissions reductions. Table 4.2 below is from a report from Cambridge Econometrics (2015) who evaluated the discount rates applied in the model PRIMES, which is widely used at the EU level to inform policy making and that also constituted the basis for the EU 2050 scenario (EC, 2011). The table compares the discount rates assumed for the different sectors in the model with those implemented in different models and reports.

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		Discount factor (weight attached to future costs/benefits)		
Model	**Discount rate**	in 10 years	in 20 years	in 30 years
PRIMES	17.5% (Households) 12% (Large industry) 9% (Utilities)	20% 32% 46%	4% 10% 22%	1% 3% 10%
TIMES	typically 4%	68%	46%	31%
MESSAGE	typically 10%[9] 5% sensitivity	39% 61%	15% 38%	6% 23%
UK MARKAL	typically 10% 3.5% sensitivity	39% 71%	15% 50%	6% 36%
PAGE (Stern)	1.4%	87%	76%	66%
DICE-2007 (Nordhaus)	5.5%	59%	34%	20%
EC IA guidelines	4%	68%	46%	31%
UK Green Book	3.5% (declining rates are used for valuation in the very long term[10])	71%	50%	36%

Sources: Duerinck (2012), Norvaisa et al. (2007) Kannan et al. (2007), Stern (2006), Nordhaus (2007), European Commission (2009), HM Treasury (2011).

Figure 12 - The weight attached to future costs and benefits in different energy system models, integrated assessment models and national governments (Cambridge Econometrics, 2015).

The discount ratios for the PRIMES model are in line with those reported by the EC (2011b) for the reference (BAU) scenario (see table below), although the report states ‘The PRIMES model is based on individual decision making of agents demanding or supplying energy and on price-driven interactions in markets. The modelling approach is not taking the perspective of a social planner and does not follow an overall least cost optimization of the energy system. Therefore, social discount rates play no role in determining model solutions. However, social discount rates can be used for ex post cost evaluations’ (EC, 2011b, p. 73). This seems to imply that no discount rates were used in the models, although these were assumed to allow for the evaluation of the model’s results. In any case, the only values useful to us would be the discount rates applied to the ‘High RES Scenario (Scenario 4), which unfortunately are not reported.

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Discount rates	
Industry	12%
Private individuals	17.5%
Tertiary	12%
Public transport	8%
Power generation sector	9%

Figure 13 – Discount rates for the different actors (EC, 2011b).

For MEDEAS the authors suggest a social discount rate of 0% and a behavioural discount rate that can be varied according to the transition scenario under investigation (with different rates applied to different technologies over time if needed).

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4.3.9 Geopolitics of the energy transition (e.g. national exports of energy as a percentage of global energy produced, %)

Aa key variable that is currently missing from the model is the distribution of current energy sources and the future energy potential brought by the increasing use of RES. Indeed, it is possible to forecast a power shift from countries previously fundamental to the world's fossil fuel supply chain (e.g. Iraq and Saudi Arabia), being overtaken by countries with large potential production of RES. Capturing this power shift in the MEDEAS model would add to the novelty and comprehensiveness of the project.

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4.4 Technology wildcards

Within the scope of the MEDEAS model technology innovation and uptake is accounted for by modelling existing technology and improvements to its efficiency and emissions footprint. However, most models do not account for possible technological breakthrough that can change the way energy is produced and consumed. To account for potential revolutions in technology, we recommend the inclusion of one or two 'technology wildcards' to ensure that at least the possibility has been explored. Below are two possible options:

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4.4.1 Carbon Capture and Storage (CCS)

A. *CCS is mentioned as a 'critical instrument' in the whole 2050 EU strategy towards a decarbonised energy system (e.g. EC, 2011) and should therefore be included in the MEDEAS model as either aid for the transition, or as a longer-term instrument to reduce carbon emissions*
B. Investments (€)
C. Rate of Abatement (%)
D. Energy required (TW/h)
E. Carbon emissions successfully stored (Mtcoe)
F. Potential energy output (TW/h)
G. Number of jobs created and average annual salary including stdev. (€)

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4.4.2 Nuclear fusion

Nuclear fusion experiments are currently being undertaken to test the potential of this energy source (e.g. ITER). The timeline for nuclear fusion plants to come online goes beyond the end of this project. However, it is to be expected that an increasing amount of investments will be directed to their development, which will need to be captured by the MEDEAS model.

A. Investments (€)
B. Rate of Abatement (%)
C. Energy required (TW/h)
D. Carbon emissions successfully stored (Mtcoe)
E. Potential energy output (TW/h)
F. Number of jobs created and average annual salary including stdev. (€)

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MEDEAS
MODELING THE RENEWABLE ENERGY TRANSITION IN EUROPE

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