PATHWAYS project
Exploring transition pathways to sustainable, low carbon societies
Grant Agreement number 603942

Deliverable D1.3
Improved set of scenarios based on interactions with other WPs

Andries F. Hof¹, Mariësse A. E. van Sluisveld¹, Samuel Carrara², Enrica DeCian², Jonathan Köhler³, Inês Martins⁴, Laetitia Navarro³, Philipp Oehler³, Henrique M. Pereira⁴, Benjamin Pfluger³, Isabel Rosa³, Georgia Savvidou⁵, Henk Westhoek¹, Detlef P. van Vuuren¹, Joyce Zwartkruis¹

¹ PBL Netherlands Environmental Assessment Agency, Bilthoven, Netherlands
² Fondazione Eni Enrico Mattei, Milan, Italy
³ ISI Fraunhofer Institute, Karlsruhe, Germany
⁴ German Centre for Integrative Biodiversity Research (iDiv), Germany
⁵ SEI, Stockholm, Sweden

August 2016
Executive summary

Introduction
This document is the outcome of the PATHWAYS project under Task 1.3, “Second set of refined scenarios accounting for feedback from WP2 and WP3”. It provides the results of revised model scenarios that meet a set of sustainable development targets for the domains electricity, transport, heating, agrifood, and land use & biodiversity. The scenarios have been developed based on insights from WP2 and WP3 analyses and discussions with socio-technical transition scientists about the initial set of scenarios that have been created at the beginning of the PATHWAYS project (see Deliverable D1.1).

Two distinct transition scenarios have been developed: The first one is a technical component substitution pathway (Pathway A). This pathways assumes that the objectives of EU sustainable development policies can be achieved by an adjustment of the existing regime without a full re-ordering of the existing societal structures (examples include for instance adding CCS to coal or gas-fired power plants or existing owners of the land broadening the services they provide). The second pathway is oriented at a broader regime transformation (pathway B). In contrast to Pathway A, this pathway entails a shift to a new socio-technical system by also including wider behavioural and cultural changes, new user practices and institutions. Both pathways are contrasted to a hypothetical baseline pathway (Pathway 0) in which no specific climate policies are assumed to be in place.

The description of the scenarios in this document focusses on the physical (mostly technological) quantitative aspects. In parallel, WP2 has created illustrative storylines for all domains and for each of the two pathways. These qualitative storylines focus on societal and behavioural aspects such as institutional change, different types of actors, their goals, strategies and resources, guided by socio-technical theories. These storylines are described in D2.5. The current report and D2.5 together provide a comprehensive picture of the two alternative sustainability pathways.

Several models have been used to develop the scenarios. Two Integrated Assessment Models (IAMs) with full coverage of all sectors and world regions have been used as boundary condition for less aggregated sectoral models, the latter of which provide detailed insights on a more fine geographical scale. This finer geographical scale is usually at country-level: for most domains, we have selected two countries to illustrate how country-specific circumstances could lead to differences in their sustainability pathways.

The analysis focuses on the development of the different domains over time until 2050. The main boundary condition for the domains electricity, transport, and heating was based on the EU target of a reduction in greenhouse gases (GHG) by 80% by 2050 relative to 1990. For agrifood and land use, a set of targets were assumed based on both this GHG target as well as the target to halt biodiversity loss.
Results
The IAM results show that (Figure S1) to bring about the changes needed to meet the abovementioned targets, changes – already in the short term – are required in all domains, especially in the power sector. The power sector is not only responsible for the highest share in CO2 emissions, but the potential for reducing emissions is also the highest in this sector: emissions are reduced much faster in the power sector than in the sectors transport, buildings, and industry.

![CO2 emissions graph](image)

**Figure S1: Sectoral EU-wide CO2 emission trajectories**

In Pathway A, the power sector reduces its CO2 emissions to zero by 2035-2040, after which it produces negative emissions via bioenergy and CO2 capture and storage (CCS). Under Pathway B, CCS, and therefore negative emissions, are not considered a viable option. Therefore, after a few decades, emissions from the power sector are higher than in Pathway A. The challenge to limit CO2 emissions within the required carbon budget for 2°C will therefore also be greater in Pathway B, especially beyond 2050.

The lack of CCS as a CO2 emission reduction option in Pathway B leads to a much higher share of renewable energy in this Pathway (Figure S2). By 2050, about 80% of EU power supply is generated by solar, wind, and bioenergy. In Pathway A, this share is about 60%.

![Share of Renewable Energy graph](image)

**Figure S2: Share of renewable energy sources (Solar, Wind and Bioenergy) in total power production**
In the transport domain there are also clear differences between Pathway A and Pathway B. One way to show this is by looking at the difference in the change in lifestyles between the pathways, as modelled by an agent-based model (Figure S3). In Pathway A, a lifestyle based on battery-electric vehicles becomes dominant in the next decades. For Pathway B, several alternatives might be envisioned. In a public transport pathway, lifestyles are changed towards less car ownership, more use of public transport and car sharing. In a slow modes pathway, walking and biking play a prominent role, which would require major changes in culture and policy, because this is a mobility lifestyle far removed from the present lifestyle for most consumers especially in the UK.

In the heating domain, differences between the pathways are less pronounced, but there are large differences between countries. This is illustrated in Figure S4, which shows heating energy demand for Sweden (top graphs) and Germany (bottom graphs) in the different pathways. The figure indicates that in Sweden, biomass, district heating and heat pumps will continue to dominate the heat energy domain until 2050. Both Pathway A and B indicate strong demand decrease and a phasing out of oil. Pathway B also indicates that solar heating will enter the market, but with a rather small share. In Germany, district heating, biomass and natural gas (although with a declining share) dominate the heat energy demand by 2050 in both pathways. As in Sweden, total energy demand is reduced drastically and oil is phased out. The reduction in demand is caused by energy savings from the combination of building refurbishments and increased use of efficient technologies (e.g. heat pumps).
The policy objectives (or ambitions) for the agro-food sector to contribute sustainable, resource efficient, low-carbon and climate-resilient and biodiversity rich societies are not very well stipulated. Based on existing documents on GHG emission ambitions for agriculture and biodiversity, we have assumed a i) 49% reduction of non-CO\textsubscript{2} GHG emissions by 2050 compared to 1990, ii) 15% reduction of agricultural land (both for arable land as well as for grasslands), in order to halt biodiversity loss, iii) a 30% reduction of the net import balance (in hectares) for the commodities soy beans, palm oil and cereals in 2050 compared to 2010.

The modelling results show that for Pathway A the goals for total arable land, grassland use, and import balance are met and the goal for GHG emissions is almost met (Figure S5). As the effect of carbon sequestration caused by land use changes is not factored in, in the end the GHG emission reduction goal will probably be met as well. For Pathway B most of the goals are not met, although the goals for GHG emissions and arable land use are almost met.

Most of the technological changes related to Pathway A require a strong involvement of farmers, of research and development (to stimulate innovations), as well as the input industry. In Pathway B the dependence on behaviour change is causing inertia in the system. It is hard to change behaviour, especially in governmental context in which consumers sovereignty is the prevailing paradigm: the idea is that consumers are free to choose what they would like to eat. However, a Pathway B approach asks for opportunities to encourage actors to change behaviour, for example via subsidies, taxes or encouraging civil society.

Figure S4: Heating energy demand in the different pathways, Sweden (top) and Germany (bottom)
Figure S5: Modelling results for the agrifood domain
The differences in agricultural land use between the pathways have consequences for biodiversity. Figure S6 shows that in both Pathway A and B, total species richness improves over Pathway 0. There are important differences between the pathways, however. In Pathway A, biodiversity is expected to decrease in intensive land-use areas due to the homogenization and intensification of the agricultural landscape. This decreases the mean richness of farmland species. Due to the projected increase in forest area, which will mainly occur in areas with lower human pressure, the mean richness of forest species is expected to increase. This is for instance the case for megafauna which will be favored by increased availability of habitat and connectivity. In Pathway B, extensive agricultural land use creates mosaic landscapes, with ecological reserves mixed with production areas. The increase of multifunctionality will lead to an increase in farmland species, as agricultural landscapes become more heterogeneous and consequently are able to support a wider range of species.

Figure S6: Maps of change in total species richness by 2050 in the Netherlands and Portugal
Contents

Executive summary ........................................................................................................................................... 2
List of figures ................................................................................................................................................ 10
List of tables .................................................................................................................................................. 11
1 Introduction ............................................................................................................................................. 12
2 Model and scenario descriptions ........................................................................................................... 14
2.1 Model descriptions ............................................................................................................................ 14
2.1.1 IMAGE ........................................................................................................................................... 14
2.1.2 WITCH ........................................................................................................................................... 14
2.1.3 PowerACE .................................................................................................................................... 15
2.1.4 MATISSE-KK .............................................................................................................................. 15
2.1.5 LEAP ............................................................................................................................................. 15
2.1.6 Agrifood ......................................................................................................................................... 16
2.1.7 Countryside SAR .......................................................................................................................... 16
2.2 Scenario assumptions ........................................................................................................................ 16
2.2.1 Pathway A .................................................................................................................................. 17
2.2.2 Pathway B ................................................................................................................................... 19
3 Overall EU emissions in the pathways................................................................................................. 22
4 Electricity ................................................................................................................................................ 24
4.1 EU-wide trends in electricity demand and generation ................................................................... 24
4.2 Detailed results for the EU as a whole .............................................................................................. 26
4.3 Results for the United Kingdom ........................................................................................................ 28
4.4 Results for Germany .......................................................................................................................... 29
5 Mobility .................................................................................................................................................. 31
5.1 EU-wide trends in mobility demand and emissions ...................................................................... 31
5.2 Detailed results for the EU as a whole .............................................................................................. 32
5.3 Results for the Netherlands ................................................................................................................ 33
5.4 Results for the UK ............................................................................................................................. 34
6 Heating ................................................................................................................................................... 35
6.1 Total EU household energy and heating demand ............................................................................ 35
6.2 Results for Sweden ............................................................................................................................ 36
6.3 Results for Germany .......................................................................................................................... 38
7 Agrifood and land use / biodiversity ...................................................................................................... 39
7.1 Targets for GHG emissions and biodiversity ................................................................. 39
7.2 Approach for the agrifood domain ................................................................................. 40
7.3 Results for agrifood ....................................................................................................... 41
7.4 Land use and biodiversity developments for the EU as a whole ............................... 43
7.5 Land use and biodiversity results for Portugal ............................................................. 43
7.5.1 Land use ..................................................................................................................... 43
7.5.2 Biodiversity ............................................................................................................... 45
7.6 Land use and biodiversity results for Netherlands ....................................................... 48
7.6.1 Land use ..................................................................................................................... 48
7.6.2 Biodiversity ............................................................................................................... 49
References .......................................................................................................................... 51
ANNEX I Inclusion of studied niche innovations in models .................................................. 54
ANNEX II Pathways implementation in models .................................................................... 57
ANNEX III Comparison of results for electricity between PowerACE, IMAGE, and WITCH ......................................................................................................................... 61
List of figures

Figure 1: Interaction between models and sociotechnical analysis
Figure 2: GHG emission pathways for the EU. The grey bar represents the EU 2050 target of reducing GHG emission levels by 80%-95% compared to 1990.
Figure 3: Cumulative global CO₂ emissions over time.
Figure 4: Comparison of emission developments in the different domains
Figure 5: Final energy demand for all demand sectors (IMAGE model results)
Figure 6: Share of renewable energy sources (Solar, Wind and Bioenergy) in total power production
Figure 7: Share of solar, wind, bioenergy, nuclear and hydro in total power production
Figure 8: Amount of carbon capture and storage over time
Figure 9: Share of energy carriers in total electricity production in the EU, UK, and Germany
Figure 10: Historical share of electricity production in the UK during the last two decades
Figure 11: Development of the spatial distribution of onshore wind turbines in the UK for Pathway B
Figure 12: Total passenger travel demand per mode
Figure 13: CO₂ emissions by type of transport category
Figure 14: Share of vehicle types within the total light-duty-vehicle fleet of the EU
Figure 15: Number of households with a certain mobility lifestyle in the Netherlands and the UK
Figure 16: Total energy use buildings (IMAGE results)
Figure 17: Heating energy demand (IMAGE results)
Figure 18: Heating technologies used (IMAGE results)
Figure 19: Heating energy demand in the different pathways, Sweden (LEAP)
Figure 20: Heating energy demand in the different pathways, Germany (LEAP)
Figure 21: The average probability of occurrence is negatively affected for most species.
Figure 22: Modelling results for the agrifood domain
Figure 23: Shares of different land use classes in Portugal by 2050 in each pathway
Figure 24: Land use maps in the different pathways in Portugal
Figure 25: Difference in the richness of different species groups between the pathways, Portugal
Figure 26: Maps of species richness in the pathways, Portugal
Figure 27: Map of difference in total species richness between Pathway A and Pathway B, Portugal
Figure 28: Shares of different land use classes in the Netherlands by 2050 in each pathway
Figure 29: Land use maps in the different pathways in the Netherlands
Figure 30: Difference in the richness of different species groups between the pathways, the Netherlands
Figure 31: Map of difference in total species richness between Pathway A and Pathway B, the Netherlands
Figure 32: Maps of species richness in the pathways, the Netherlands
Figure 33: Model comparison of total EU electricity demand by energy carrier
List of tables

Table 1: Niche innovations in electricity  54
Table 2: Niche innovations in mobility  55
Table 3: Niche innovations in heating  55
Table 4: Niche innovations in agrifood/land use  56
Table 5: Scenario interventions for electricity  57
Table 6: Scenario interventions for mobility  58
Table 7: Scenario interventions for heating  59
Table 8: Scenario interventions for land use/agrifood  60
1 Introduction

In order to prevent dangerous climate change and avoid further loss of biodiversity, the EU has set ambitious policies and strategies to move to sustainable, resource efficient, low-carbon, climate-resilient, and biodiversity rich societies. These policies and strategies are formulated, among others, in the EU’s Sustainable Development and Biodiversity Strategies, the Climate and Energy package (20/20/20 targets) and the Roadmaps for moving to a competitive, low carbon economy and resource efficient Europe (European Commission, 2011a, b, c; European Union, 2009). Related policies have been adopted at the level of individual member states. Achieving these sustainability goals will require fundamental societal transitions and coordinated policy action. Deepening (scientific) understanding of how to promote these fundamental and interrelated transitions is crucial for meeting sustainability goals.

Different scientific approaches offer insight into such transitions, including integrated assessment models (IAMs) (Moss et al., 2010), socio-technical transition studies (Geels, 2002; Smith et al., 2005) and participative action research (Checkland and Holwell, 1998; Chevalier and Buckles, 2013; Schon, 1983). While each of these approaches has its strengths, none alone can give a full picture. A strength of IAM is that they are able to link future goals to concrete implementation of technologies and related policies to achieve them. They also allow linking different policy issues, such as biodiversity protection and climate change, as these can be analyzed in one consistent model framework. However, the focus of modelling studies is often on least-cost pathways with little attention to institutional constraints and opportunities. This fragmentation of research weakens the understanding of transitions and thus limits the value of transition analysis to European, Member State and local policymakers.

The scenarios presented in this report have been developed based on insights from socio-technical transition analyses and participative action research. The scenarios meet a set of sustainable development targets for the domains electricity, transport, heating, agrifood, and land use & biodiversity. Several iterations of the scenarios have been run by the models since the development of the initial set of scenarios as provided by Deliverable 1.1. After each iteration, the results of the scenarios have been discussed with socio-technical transition scientists.

This report provides the physical, quantitative details of the final set of scenarios. In parallel, WP2 (the socio-technical transition science WP) has created illustrative storylines for all domains and for each of the two pathways. These qualitative storylines focus on societal and behavioural aspects such as institutional change, different types of actors, their goals, strategies and resources, guided by socio-technical theories. These storylines are described in D2.5. The current report and D2.5 together provide a comprehensive picture of the two alternative sustainability pathways.

Two distinct transition scenarios have been developed: The first one is a technical component substitution pathway (Pathway A). This pathway assumes that the objectives of EU sustainable development policies can be achieved by an adjustment of the existing regime without a full reordering of the existing societal structures (examples include for instance adding CCS to coal or gas-fired power plants or existing owners of the land
broadening the services they provide). The second pathway is oriented at a broader regime transformation (pathway B). In contrast to Pathway A, this pathway entails a shift to a new socio-technical system by also including wider behavioural and cultural changes, new user practices and institutions. Both pathways are contrasted to a hypothetical baseline pathway (Pathway 0) in which no specific climate policies are assumed to be in place.

Several models have been used to develop the scenarios. Two Integrated Assessment Models (IAMs) with full coverage of all sectors and world regions have been used as boundary condition for less aggregated sectoral models, the latter of which provide detailed insights on a more fine geographical scale (see Section 2 for more details). This finer geographical scale is usually at country-level: for most domains, we have selected two countries to illustrate how country-specific circumstances could lead to differences in their sustainability pathways.

The analysis focuses on the development of the different domains over time until 2050. The main boundary condition for the domains electricity, transport, and heating was based on the EU target of a reduction in greenhouse gases (GHG) by 80% by 2050 relative to 1990. For agrifood and land use, a set of targets were assumed based on both this GHG target as well as the target to halt biodiversity loss.

Section 2 provides the model and scenario descriptions used throughout the report, and explains how the models were linked with each other. Section 3 provides the overall EU trend in emissions in Pathway A and B. Finally, in Section 4-7 the results for each domain are discussed. The Annexes provide more detailed information about which niche-innovations studied in WP2 are explicitly modelled and which scenario interventions have been assumed in the two pathways.
2 Model and scenario descriptions

In the PATHWAYS project we employ two global Integrated Assessment Models (IAMs) – IMAGE and WITCH – and four domain-specific models with more regional detail (PowerACE for power supply, MATISSE-KK for mobility, LEAP for heating, and Countryide SAR for biodiversity) to develop scenarios in order to gain more insight into the required long-term changes. The two IAMs not only provide the picture for the EU as a whole, but also take into account linkages across domains (for instance, the effect of increased power demand by increased battery electric vehicle use in transport). Therefore, they are able to provide an overall consistent picture. The domain-specific models provide more sectoral and regional detail. The assumptions made in the domain-specific models have been made consistent with the assumptions made in the IAMs. Figure 1 summarizes the process of scenario development. Below, a short description of the individual models is given, followed by the scenario descriptions.

![Diagram of model interactions](image)

**Figure 1:** Interaction between models and sociotechnical analysis

2.1 Model descriptions

2.1.1 IMAGE

The IMAGE integrated assessment modelling framework (Bouwman et al., 2006; Stehfest et al., 2014) is based, at least to some degree, on a bottom-up approach and focuses on the chain of global environmental change for both climate and land use. Important inputs into the system are assumptions on population and economic development. The model describes the investments in and use of different types of energy options influenced by technology development (learning-by-doing) and resource depletion. Inputs to the model are macro-economic scenarios and assumptions on technology development, preference levels and restrictions to fuel trade. Emissions from land-use changes, natural ecosystems and agricultural production systems, and the exchange of carbon dioxide between terrestrial ecosystems and the atmosphere are also simulated.

2.1.2 WITCH

WITCH (Bosetti et al., 2006; de Cian et al., 2012; De Cian and Tavoni, 2012; Emmerling et al., 2016) is a hybrid optimal growth model. The economy is modelled through an inter-
temporal optimal growth model which captures the long term economic growth dynamics. A compact representation of the energy sector is fully integrated (hard-linked) with the rest of the economy so that energy investments and resources are chosen optimally, together with the other macroeconomic variables. Land use mitigation options are available through a soft link with a land use and forestry model (GLOBIOM). A climate model (MAGICC) is used to compute the future climate. Investments include investments in the aggregate capital that builds the stock of physical capital that enters the aggregate neoclassical production function, investments in power technologies, investments in light duty and road freight vehicles, and investments in R&D. Both innovation and diffusion processes are modelled. The model distinguishes dedicated R&D investments for enhancing energy efficiency from investments aimed at facilitating the competitiveness of innovative low carbon technologies (backstops) in both the electric and non-electric sectors. International spillovers of knowledge are accounted for to mimic the flow of ideas and knowledge across countries.

2.1.3 PowerACE

PowerACE is a detailed bottom-up electricity system/market model incorporating features of simulation and optimisation models. PowerACE has detailed technical representations of the underlying processes in the power sector. In the model, the behaviour of relevant market participants on both the demand and the supply side is modelled assuming their economic rationality. For long-term analyses up to 2050, the model endogenously determines the optimal investments into conventional and renewable electricity generation technologies. The mix of technologies is optimized for actual weather data per hour, including the interdependencies between technologies and meteorology.

2.1.4 MATISSE-KK

The MATISSE-KK model uses the concepts of transition theory as a framework for assessing possible pathways by which a transition to a sustainable mobility society might happen. The modelling approach combines agent-based modelling techniques with a system dynamics structure. There are a small number of complex agents representing the regime and niches, which have an internal structure and are therefore sub-systems within society, and a larger number of simple agents. The regime and niches rely on support for their strength; this comes from the support canvas, representing consumer/citizen support, implemented as supporters, which are simple agents. The (aggregate) agents and the supporters are set in a multi-dimensional practices space. Landscape pressure is implemented as external signals on the space, which can affect both agents and supporters. Based on UK and Swedish data, the results show that Fuel Cell Vehicles come to dominate, but only in the very long run (after 2030), while biofuels and ICE-electric hybrids are the main alternatives to the regime in the next 10-30 years, because a) they are already developed b) they fit better into current infrastructures.

2.1.5 LEAP

LEAP, the Long range Energy Alternatives Planning System, was used to develop a model of residential heating energy system for Sweden and Germany describing key drivers of change given specific objectives under the EU energy policy. LEAP is an integrated modeling tool that can be used to track energy consumption, production and resource extraction in all sectors
of an economy. It is not a model of a particular energy system, but rather a tool that can be used to create models of different energy systems, where each requires its own unique data structures. Key dynamic factors in the developed model are activity levels, energy intensities and technology change. It has a bottom-up end-use oriented tree structure that is used to calculate energy use for heating in residential buildings for the period until 2050. This structure is split into space and water heating; analysis of space heating is on a per m² basis while water heating is based on a “per dwelling” analysis. There is a distinction in types of buildings (single and multi-dwellings) as well as in existing and new building stock. In the model, policies may have an impact on the penetration of each technology. Factors such as efficiency and share of heating devices are influencing the evolution of heating demand. Changes in behavioural aspects and policies affecting building shell improvement such as lower indoor temperature and refurbishment measures respectively are affecting the useful energy intensity (heat) of the model.

2.1.6 Agrifood

The effects of the Pathways for the agrifood sector have been calculated by means of a customized, simple tool, which made it possible to quantify the effects of a combination of relevant interventions at EU level, being: dietary changes (esp. reduction of consumption of meat, dairy and eggs), reduction of food waste, increase in crop yields, changes in policies regarding Less Favoured Areas like the Common Agricultural Policy (CAP), changes in livestock efficiency (feed conversion) and certain technical measures to reduce GHG emissions from livestock operations. The tool quantifies the effects on: GHG from agriculture (excluding the effect of land use changes) and land use within Europe (cropland and pastures separately) and land use for feed production outside Europe (cropland; mainly soy bean cultivation). The tool basically interpolates the results of previous studies, notably Bryngelsson et al. (2016); Lesschen et al. (2011); Westhoek et al. (2014). The tool only provides a number of bio-physical data; economic effects have not been quantified.

2.1.7 Countryside SAR

Land use impact on biodiversity not only depends on the amount of land used, but also on the type of land use. Existing land use projections do not represent well the pathways storylines. Therefore, we used a simple approach to projected land use change in Portugal and the Netherlands by 2050, as a result of the assumptions of pathways A and B, and a business as usual scenario (BaU). Afterwards, the response of biodiversity to land-use change resulting from the three pathways was assessed using the countryside Species-Area Relationship (cSAR; Guilherme and Miguel Pereira, 2013; Martins et al., 2014; Pereira and Daily, 2006; Proença and Pereira, 2013). cSAR is a multihabitat SAR model that includes not only area but also habitat information, integrating the differential use of habitats by the different species. This allows the model to provide more fine-tuned analyses of species responses to habitat change as the classical SAR, leading to a better fit to empirical data (Pereira et al., 2014; Proença and Pereira, 2013).

2.2 Scenario assumptions

In the PATHWAYS project, we look at different ways to achieve long-term sustainable development targets. More specifically, two archetypical types of pathways were defined,
named Pathway A and Pathway B. Both pathways are consistent with an 80% reduction in GHG emissions in 2050 compared to 1990 levels in the European Union. In the IAMs IMAGE and WITCH, this target is met by introducing a price on carbon, next to the scenario interventions which were made to define the two pathways. In the rest of the world, a carbon price is implemented that so that the increase in global mean temperature in 2100 is less than 2°C relative to pre-industrial levels with a likely chance. In any case, we focus solely on the EU here.

Pathway A is defined as a pathway in which currently dominant actors, such as large power utilities and existing car companies, play a key role in the transition. This pathway assumes that the objectives of EU sustainable development policies can be achieved by adjusting the existing regime or adopting niche-innovations on a large scale (e.g. battery-electric vehicles, off-shore wind power), but without fully re-ordering the existing societal structures (examples include for instance adding CCS to coal or gas-fired power plants or existing owners of the land broadening the services they provide). Pathway A is interpreted as a technological transition that exploits substitution in technical components. While the technical components of the socio-technical regime change in this pathway, regulative, normative, and cognitive institutional elements (e.g. user practices, lifestyles, governance arrangements) remain close to the existing regime. This pathway tends to be advocated and enacted by incumbent, dominant actors.

Pathway B tries to mimic a broader regime transformation. This pathway entails a shift to a new socio-technical system, based on the breakthrough of radical niche-innovations that entails not only technical changes, but also wider behavioural and cultural changes, new user practices and institutions. Incumbent industry actors may be overthrown by new entrants (e.g. households supplying electricity), or enter into new alliances with them. New coalitions in land use occur between farmers, retailers and consumers. There is also a greater role for social movements, civil society actors, and multi-level governance.

The following sub-sections describe the different storylines in representing PATHWAY A and B in the different domains and models. The specific assumptions made for each domain are summarized in Annex II.

2.2.1 Pathway A

Regarding electricity, WP2 has classified offshore wind as a typical PATHWAY A technology with a relatively high momentum for further deployment, despite its need for substantial governmental support (as demonstrated by the UK case study). As this counteracts the cost-optimizing workings of the models, this requires stimulation in the form of a reduction in costs (this could be interpreted as a subsidy or a preference for offshore wind relative to onshore wind due to societal difficulties for the latter) or an improved learning rate. In the PowerACE model, offshore wind turbines are favoured by setting low interest rates thus lowering the effective costs approximately to the same level as onshore wind. Low interest rates and lower costs may be initialised by government support programmes. This might include special state-aided loans to encourage investment or feed-in-tariffs. Low interest can also be seen as a high acceptance among private investors, who lower their profit expectations in favour of investing in a new promising technology.
An important aspect is that in PowerACE, CCS and nuclear are exogenously defined in Pathway A from 2020 onwards, based on IMAGE results. Finally, in PowerACE the land availability for all photovoltaic technologies was lowered by one third of the standard value, and was raised for both on- and offshore wind by half of the standard value. Enlarging the available area for the specific technology leads to the effect that especially suitable areas can be used much more efficiently, and vice versa. The reasoning for this change is that WP2 case studies indicated that PV was found to be mainly a Pathway B technology, and by lowering the available land for PV, more differentiation between the scenarios was created. Table 5 summarizes the interventions for all models regarding electricity.

For transport, based on the analysis in WP2 alternative fuels and a switch from cars to (electricity-driven) trains have been identified as typical Pathway A in both the UK and the Netherlands. Momentum for electric cars was found to be relatively high, with technological solutions being developed by the global equipment manufacturers, driven by government support and environmental policy in California, Japan and the EU. In Pathway A, it is assumed that government support for low-carbon vehicles continues so that the cost difference relative to fossil fuels decreases and might even disappear over time. In IMAGE a subsidy reducing the purchasing price of electric, fuel cell and bio-fuelled vehicles by 25% has been assumed. In WITCH a 25%-increase in the learning rate of batteries (which are the key driver for the capital cost of electric vehicles) and a 50%-increase in the engines efficiency growth rate have been implemented. Similar assumptions are also adopted in the MATISSE-KK model: ICE cars become relatively more expensive compared to electric vehicles and biofuels. Furthermore, consumer preferences change to place more weight on CO₂ emissions reduction. Table 6 summarizes the interventions for all models regarding transport.

For heating, among the studied niche innovations, one clear Pathway A technology that has come forward is waste heat recovery with low to medium momentum. According to the Swedish heating domain report, Sweden is a world leading country for utilising industrial waste heat as an input source for its district heating systems, with a potential increase of 30-60% still being available. In order to represent this technology in IMAGE, a 45% efficiency increase is applied to secondary heat use.

On the national level, heat pumps, district heating and solar thermal were the technologies contributing to the main changes by 2050 in LEAP. In particular, in Sweden the use of direct electric heaters is faced out by an increasing use of heat pumps. In Germany, the penetration of coal and oil is diminished by 2050 and natural gas is significantly reduced. This is mostly replaced by the use of heat pumps in single dwellings and district heating in multi dwellings. In Germany, solar thermal use for domestic hot water is increased. Next to the changes in penetration of the different heating technologies, their efficiency is improved. Finally, under PATHWAY A, the refurbishment of building stock is contributing to around 50% energy demand reduction in both countries. Table 7 summarizes the interventions for all models regarding heating.

The agrifood domain in Pathway A is characterized by high-yield agriculture, separation of nature and agriculture, precision farming, genetically modified crops and livestock, and
enclosed environments for animal husbandry. A 10% reduction in the consumption of livestock products is assumed (by 2050 relative to Pathway 0), as socio-technical analysis revealed that reducing meat and dairy consumption can occur without conscious decisions of consumers, for example in the form of hybrid meat products, meat analogues etc. Also personal health considerations might lead to changes in consumption patterns. A 10% reduction in food waste is assumed by 2050, not as a result of behavioural change, but thanks to technological development in packaging technology. Crop yields increase by 15% in 2050 relative to 2010, based on both socio-technical analysis and on Bruinsma (2012); EC (2015). It should be noted that a 15% increase is ambitious, given the fact that the average crop yields in the EU are already high compared to other regions in the world. The freed-up agricultural land will be used for creating larger natural areas (rewilding). Finally, it is assumed that feed efficiency (the amount of feed needed per kg of meat or milk) increases by 7%. Bryngelsson et al. (2016) suggests that a 10% increase is possible (as an approximate average over the various livestock categories), but as socio-technical analysis revealed that within the livestock regime there is not much pressure to increase feed efficiency for of environmental reasons, we assumed a lower efficiency improvement.

GHG emissions from livestock operations (the largest source of agricultural GHG emissions in the EU) are being reduced by means of technical solutions in Pathway A. Bryngelsson et al. (2016) have made assumptions regarding technological options to reduce GHG from agriculture. They distinguish a Moderate and an Optimistic case for reductions of emission intensities in 2050. We have assumed a reduction of 75% of the Optimistic values (i.e. a 7.5% improvement in feed use per unit of meat/eggs/dairy, a 12% decrease in CH₄ emissions, and a 52.5% improvement in manure management), as socio-technical analysis has shown that although there is some pressure on the livestock sector to reduce GHG emissions, it cannot be expected that all possible technical measures will be implemented. Moreover, not all of the technologies assumed in Bryngelsson et al. (2016) are proven technologies. Table 8 summarizes the interventions for all models regarding agrifood.

The above developments of the agrifood domain have implications for land use and biodiversity. Better agricultural yields and the development of precision farming allow for the intensification of agriculture in productive areas. This leads to large areas of marginal land (with low crop yields / grassland production) being taken out of production, to be able to implement the separation of nature and agriculture. Natural areas are thus expected to increase due to natural succession on the abandoned lands, leading to an increase in forested areas in the later decades. In this scenario, multifunctional landscapes are projected to decrease in extent.

2.2.2 Pathway B
The storyline for Pathway B is based on transforming existing systems through the involvement of new actors, changing preferences and adopting different lifestyles. In the electricity domain, only solar PV has been classified as a typical component of this pathway in the WP2 case studies. In addition, the modelling protocol transcends the empirical assessment by making explicit choices for the future by excluding the use of the contested technologies CCS and nuclear, both of which are assumed to be more part of a ‘technological substitution’ narrative. Solar PV is assumed to be strong in Pathway B due to its modularity:
the governmental feed-in-tariff managed to reduce the price of the system triggering much interest from households, consumers and local communities. Moreover, there is greater enthusiasm for decentralized PV installation across a broad range of actors, leading to social learning. This greatly accelerated the uptake and diffusion of solar-PV. In order to emulate this increased interest for solar-PV systems the models introduced external (contextual) impulses to represent regulatory (e.g. subsidy) and technological changes (e.g. faster learning associated with social learning reinforcing technical learning) that modify the PV costs and thus the penetration and momentum of that technological option. In PowerACE, we raised the land availability for all photovoltaic technologies by one third of the standard value used in Pathway 0, and lowered it for both on- and offshore wind by a half of the standard value (see for explanation, Pathway A above).

For the transport domain, none of the studied niche innovations in WP2 that classify as typical Pathway B innovations are found to have significant momentum. In that sense it is more difficult to design a scenario that aligns itself to empirical findings. We implemented nevertheless several of the studied niche innovations in IMAGE assuming that the niches will pick-up momentum: e.g. car sharing is enforced by increasing the vehicle occupancy rate from 1.6 to 2.0. Furthermore, we have increased the preference for public transport. Affluent regions have the tendency to spend more of their travel budget on more expensive forms of traveling (faster modes, like air travel). We simulate a very radical reconfiguration by not allowing developed regions to spend more than 7% of their total income on travel (which is the share found in Japan during the 90s). The assumptions adopted in WITCH follow the same philosophy. As WITCH only models LDVs within passenger transport, a modal switch cannot be explicitly described. A slower increase in vehicle ownership and a decrease in travel demand, however, have been implemented in order to simulate the switch from private modes to public transport and a urban reconfiguration according to a compact city scheme. A strong diffusion of car sharing has been modelled as well, by considering an increase in the vehicle load factor (similar to IMAGE). In MATISSE-KK, a change to either car sharing, domination of a public transport based lifestyle or a mobility lifestyle based on cycling and walking requires not only a change in preferences towards CO₂ emissions reduction as in Pathway A, but also a change in consumer preferences towards mixed use urban structures and towards less private mechanized mobility. This is also a change in preferences away from private conventional car ownership.

For heating, the WP2 case studies have focussed on smart metering and passive-housing as a form of changing lifestyles. However, the typical Pathway B options are overall rated as having a “very low” to “low” momentum, resulting in limited quantitative material to underpin IAM scenario design, thus requiring the modellers’ own interpretation. There are several ways to implement behavioural change in a model focused on matching energy demand with energy production, utilizing the existing model-parameterisation. For example, several processes that are modelled include implicit assumptions for e.g. a representative household and representative user. By changing the parameterisation of the model, we implicitly also model (though exogenously and static) behavioural change which can be explained in the narrative of higher awareness by homeowners due to e.g. smart metering. A more in-depth discussion of the implementation and the initial parameterisation can be found in (van Sluisveld et al., 2016), but with parameterisation we manage to implement
heating demand reduction, lower size for dwellings, reduced rate for appliances, more efficient use of household appliances.

On the country level represented by LEAP, the introduction and increase of solar thermal is the main change with regard to technology penetration in both countries. Next to this, all newly built houses after 2020 comply with passive house standards and floor area is reduced by 10% by 2050 in comparison to the current levels. Lower indoor temperature is represented by 1 °C lower temperature setting for Germany and 3°C lower for Sweden, where according to WP2 there is a high potential for reduction.

In the agrifood domain, it is assumed that the consumption of livestock products (meat, dairy, eggs) is reduced by 30% (which is a downward revision of the original assumed 40% reduction, based on socio-technical analysis). The lower consumption of meat and dairy is mainly compensated by higher cereal use (Westhoek et al., 2014). This will require additional efforts, as it is not likely that this reduction will be reached spontaneously. Furthermore, it is assumed that the total amount of food waste is reduced by 50% by 2030 (and to remain constant after that). This is in line with the SDG target, which aims at a halving food waste.

The results of the two first runs (IAM assumptions and socio-technical analysis) showed that the target for land use was not reached. Therefore we assumed that actors in the crop regime receive some incentives to increase crop yields, leading to a 5% increase in yields. A relatively low 2% increase in feed efficiencies is assumed (animal welfare will increase in this pathway, leading to relatively low feed efficiencies). The 2% is a proxy for autonomous technological progress. N₂O emissions will be reduced as a consequence of lower input of nitrogen.

An important aspect for land use and biodiversity is that intensive agricultural land use will decrease by creating mosaic landscapes, with ecological reserves in high production areas. The increase of multifunctionality will lead to an increase in farmland species, as agricultural landscapes become more heterogeneous and consequently are able to support a wider range of species. The forest species are expected to increase in both richness and abundance, although at slower rate than projected in pathway A.
3 Overall EU emissions in the pathways

The strength of (integrated assessment) models is to show the effect of (policy) measures throughout the economy and over time. As each model has been set up to achieve the 2050 EU emission target of at least 80% GHG emission reductions, the GHG emission pathways are very similar across the two IAMs (Figure 2). The steep decrease in GHG emissions in the two mitigation pathways clearly show the mitigation challenge. In Pathway 0 (baseline), the models show more-or-less constant emission levels. Note that Pathway 0 is a hypothetical scenario used as counterfactual as no climate policies are assumed to be in place, which is not in line with reality.

![Figure 2: GHG emission pathways for the EU. The grey bar represents the EU 2050 target of reducing GHG emission levels by 80%-95% compared to 1990.](image)

In December 2015 at COP21, a long-term target of keeping temperature increase below 2°C has been adopted. As described in the IPCC AR5 WGIII report, this can be translated to not exceeding more than 1000 GtCO₂ between 2011 and 2100. As shown in Figure 3, this budget is more or less exhausted by 2050 in both Pathway A and Pathway B. This means that in both pathways, cumulative emissions in the period 2050-2100 need to be practically zero. This post-2050 challenge is larger in Pathway B than in Pathway A, as the possibility of negative emissions is largely excluded in Pathway B.

To bring about the changes needed to meet the abovementioned targets, changes – already in the short term – are required in all domains, especially in the power sector (see Figure 4). The figure not only shows that the power sector is responsible for the highest share in emissions, but also that the potential for reducing emissions is the highest in this sector: emissions are reduced much faster in the power sector than in sectors as transport, buildings, or industry.
In Pathway A, the participating models show that the power sector reduces its CO₂ emissions to zero by 2035-2040, after which it produces negative emissions via bioenergy and CO₂ capture and storage. Under Pathway B negative emissions are not considered a viable option. Initially, emissions are reduced faster than in Pathway A, but as negative emissions are not possible, power sector emissions are higher than in Pathway A after a few decades.

Due to lower mitigation potential in the power sector in Pathway B, the mitigation challenge is stronger in the demand sectors in this pathway, particularly in the buildings and transport domain. Without CCS, it will also be more problematic for the industry sector to reduce emissions.
4 Electricity

Currently responsible for the largest share of GHG emissions in the EU, the power sector plays a crucial role in a transition to a carbon-neutral economy. First, some overall EU trends of electricity generation in the mitigation scenarios will be discussed, after which more detail by illustration of the results of the UK and Germany will be provided.

4.1 EU-wide trends in electricity demand and generation

In general, energy demand is projected to be lower in Pathway A and B than in Pathway 0 due to increased energy efficiency (Figure 5). For electricity, the difference is smaller than for the other sectors, as a result of additional demand for electricity in the mitigation scenarios (for instance, demand from e-mobility and heat pumps). This implies that total electricity demand increases over time in the mitigation scenarios – although at a lower rate than in Pathway 0.

![Figure 5: Final energy demand for all demand sectors (IMAGE model results)](image)

By 2020, the share of non-hydro renewables (solar PV, CSP, wind (onshore and offshore) and bioenergy) is about 20% in both pathways. In Pathway A, the share increases to about 60% (55%-65%) by 2050 and in Pathway B it even increases to about 80% (Figure 6). The increase in Pathway B is higher as it is more difficult to reduce emission post-2050, due to the exclusion of CCS and nuclear. Therefore, emissions need to be cut faster in Pathway B to remain within the carbon budget (see Section 3).

The share of all “carbon free” energy sources (including hydro and nuclear) in electricity production is currently about 50%. In Pathway A this share increases substantially to 75-90% in 2050, and in Pathway B to 85-100% in 2050 (Figure 7).
In Pathway A, CCS technologies become part of the technology mix from 2020 onwards, and the combination of bioenergy and CCS some years later (Figure 8). The dependence on these technologies is very large especially in the second half of the century. The possible dominant role of this technology means that a prompt decision is necessary on the role of CCS in Europe’s decarbonisation strategy.
4.2 Detailed results for the EU as a whole

The results in this section are based on the PowerACE model; a comparison of EU results between the models PowerACE, IMAGE, and WITCH can be found in Annex III. The electricity demand is based on IMAGE output; it is broken down to national demands in PowerACE by assuming that the trend in demand is the same in each country.

The generation mix in Pathway A changes significantly compared to today. Both on- and offshore wind become important in this Pathway: around 40% of power is generated by on- and offshore wind in 2050 (Figure 9 top panel). In this scenario, offshore wind develops strongly due to the assumed lower investment costs (see also Section 2.2.1). The location of offshore turbines is spread across coastal European countries, though the diffusion is strongest in the attractive windy sites in Northern Europe. In Pathway B, onshore wind shows a much stronger development than offshore wind due to the lower costs of this technology.

The high CO₂ price towards 2050 significantly reduces the role of conventional coal in both Pathway A and B (the model already takes into account the expected high CO₂ prices in investment decisions). In Pathway A, lignite power plants are switched to CCS technology due to the lower electricity generation costs when taking carbon prices into account. In the PowerACE calculations, coal and natural gas CCS do not become competitive (this is in contrast with IMAGE and WITCH results; see Annex III). Bioenergy CCS (BECCS), however, is an important technology (for technical reasons, biomass and biomass CCS are cumulated in the energy generation plots). These BECCS plants would have to be rather large, centralised power plants, either dedicated biomass power plants or used for co-firing in fossil fuel-fired power plants. In Pathway B, CCS is not available and nuclear plants are phased out, therefore the model shows a much higher share of solar PV in electricity generation.
Figure 9: Share of energy carriers in total electricity production in the EU, UK, and Germany
Both in Pathway A and Pathway B natural gas is used as a flexibility option; natural gas plants mostly run to cover demand peaks or hours of low generation from renewable energy sources. In Pathway B, because of the higher share of the very variable PV technology, natural gas has a higher share. The vast majority of natural gas is used in highly efficient combined cycle natural gas plants which have low CO₂ emissions compared to other conventional plants. The (exogenously determined) biomass used in this scenario also acts as flexibility source. When considering the storyline of Pathway B, the biomass would in this scenario be used primarily in decentralised, smaller (possibly combined heat and power) plants.

4.3 Results for the United Kingdom

When looking at the changes in the historical electricity mix in the UK, the change from coal to natural gas is clearly visible. From 1995 to 2010, there has been a big boom of natural gas-fired plants especially in the United Kingdom (see Figure 10). By 2010, almost half of the energy produced in the UK came from natural gas fired stations. This has, however, since then changed dramatically.

![Figure 10: Historical share of electricity production in the UK during the last two decades](image)

The extraordinary wind potential also means that United Kingdom plays a crucial role in PATHWAY A and B. With carbon prices above 50 EUR/t, many wind site of the UK are the cheapest way of generating electricity in Europe at 5 €ct/kWh. However, the location of the UK makes it harder to balance fluctuations in renewable energy generation. Germany, for instance, has much more neighbouring regions with weather situations that deviate often.

In Pathway A, there is a decline of natural gas, although slower than in our baseline (Figure 9 middle panel). After 2030, natural gas serves as a flexibility option (back-up). The overall picture is that conventional plants are replaced by renewable technologies. The main technology in 2050 is offshore wind, which is highly favoured by the big incumbent actors, followed by onshore wind. Besides wind, there is a relatively high share of nuclear and
biomass (including biomass CCS). Biomass especially comes into play after 2030, when it replaces most of the natural gas fired plants.

In Pathway B, natural gas also declines, but it still accounts for 4.5 percent of supply in 2050. The decline and the phase-out of nuclear energy is covered mostly by onshore wind, which takes off much stronger than in Pathway A due to its profitability from the high acceptance, and becomes the central pillar of the electricity supply. In very windy hours, it becomes increasingly difficult to integrate wind energy into the grid. Therefore, PV becomes attractive towards mid-century. Biomass plays a smaller role in smaller distributed plants, which also act as a flexibility option.

The relative quality of renewable energy sites determines to a large degree how much a country imports or exports electricity in PATHWAY A and B; in our scenarios the comparatively good wind sites turn the UK into a significant exporter of energy from 2030 onwards. This is in contrast with current trends: in 2010, the import-export balance of the UK was close to zero; since then, the country has increased its imports, which exceeded 20 TWh in 2014.

As illustration, Figure 11 shows the development of onshore wind turbines over time. Each “tile” reflects an area of 7x7 km. The diffusion of onshore wind starts in the windiest, often coastal, areas of the UK. In the later decades, more and more inland sites are used – while keeping a certain distance to residential areas and nature protection areas. In 2050, a capacity of 77 GW is installed, equalling about 15,500 wind turbines of 5 MW each.

![Figure 11: Development of the spatial distribution of onshore wind turbines in the UK for Pathway B](image)

It is important to note that the high shares of wind in both Pathway A and B require a strong expansion of the grid. This is especially relevant for the interconnectors to other countries, which are needed to balance the generation from renewable energy sources between weather zones all over Europe. This requires acceptance for the construction of new overhead lines.

### 4.4 Results for Germany

The situation for Germany is quite different compared to the UK (Figure 9 bottom panel). Shares and growth rates of renewable technologies have been comparatively high during recent years due to the German Renewable Energy Act. Nevertheless, except for some good
sites in Northern Germany, wind power sites in Germany are only of average quality. For PV the quality is even poorer compared to southern European countries. Traditionally, the electricity supply in Germany was based on nuclear, coal and lignite. Additionally, natural gas plants and pumped storage plants in Southern Germany served as peak technology.

After the accident in Fukushima, Germany re-enacted its nuclear phase-out, so this technology is assumed not be available in either Pathway A or Pathway B after the decommissioning of the last reactor in 2022. In Pathway A, Germany shows developments that fit well into the overall storyline. Conventional lignite generation shifts towards lignite with CCS from 2030 onwards. By 2030, the major technology is offshore wind. The share of onshore wind remains more or less stable. Historically installed PV capacities are not renewed. High capacities of natural gas plants remain and act as flexibility providers, generating low amounts of the overall demand.

Compared to its electricity demand, Germany renewable energy potentials are below the European average. It is therefore more attractive to import a certain share of electricity from neighbouring countries than, for example, utilize mediocre wind sites in Southern Germany. In 2050, Germany imports approximately 20% of its electricity demand.

In Pathway B onshore wind becomes the leading technology in 2050, and PV also plays an important role. Another very important technology is natural gas power plants, covering around one third of the demand in 2050. These mostly are highly efficient combined cycle natural gas plants.

To understand high share of fossil fuels in Germany in this scenario, it is important to realize that the scenario assumes the existence of pan-European power market. This implies that in order to fulfill targets on a European level (like emissions), developments on a national level can deviate. In this case, some countries can contribute less to the overall target, while other countries fill this gap, evening out the targets on EU-level. Germany acts as a supplier of flexibility to the neighbouring countries, by concentrating natural gas power plants to Germany. The strong expansions to the transmission grid, mainly serve as enabler for the renewable energy integration. However, in times of low feed-in from renewable energy, the same lines are used to transport electricity from natural gas power plants, which are the cheapest, fully dispatchable electricity source in this Pathway.
5 Mobility

5.1 EU-wide trends in mobility demand and emissions

To meet the EU 80% climate target large changes are required in the transport sector, which is currently the second largest emitting sector (Figure 4). The figure shows transport CO₂ emissions are already projected to decrease in the baseline, due to increased efficiencies and a shift to battery electric vehicles. The decrease in the mitigation scenarios is much stronger, however. Total demand for travel increases much higher in Pathway A than in Pathway B, especially according to IMAGE for road transport (Figure 12). Partly, this is due to a shift from air travel to road, as air travel becomes relatively more expensive due to the price on carbon.

![Development of travel Demand](image)

Figure 12: Total passenger travel demand per mode
Note that WITCH only models road transport

The bulk of CO₂ emissions in transport is coming from road travel (Figure 13). However, further electrification of passenger travel (e.g. via PHEV and BEV vehicles) leads to a lower share of emissions from passenger travel over time. By 2050, the highest share of transport emissions in Pathway A and B come from heavy duty vehicles for freight transport, maritime freight transport, and aviation. In the rest of this section, our focus is on passenger travel.
5.2 Detailed results for the EU as a whole

The vehicle pool is projected to transform to a more electricity-driven fleet regardless of climate and energy policy at the European level (Figure 14). However, a price on carbon, subsidizing specific vehicle types, and stimulating learning for environmentally-friendly alternatives speed up the uptake in the market, which is clearly visible especially in Pathway A. Under stringent long-term climate policy the vehicle pool will transform to a largely electric one. In IMAGE, this happens before 2050, while in WITCH the transition starts in the first half of the century, but completes after 2050. In Pathway B the transition is somewhat slower as battery-electric vehicles are not subsidized.
5.3 Results for the Netherlands

The Netherlands is not typical of western European countries, because it has a very high proportion of trips undertaken by cycling and walking in the present society (Figure 15). This means that improved incentives for low carbon vehicles and the provision of charging infrastructure could relatively easily enable a widespread adoption of BEVs. Furthermore, as the Netherlands is a relatively small country, current BEV technology already would enable a large proportion of interurban trips to be undertaken without refuelling, as well as the shorter distance trips. Therefore, the Netherlands has an exceptionally favourable geographical environment for the widespread use of BEVs, which is clearly visible in Pathway A. BEVs compete with hybrids and win out in the longer run as BEVs’ range problems are solved by more infrastructure and user familiarity leading to higher perceived convenience.

For Pathway B, different configurations are possible, as illustrated by the two panels on the right side of Figure 15. New regimes could be formed around mass adoption of car sharing, the abandonment of motor cars for public/intermodal transport or the widespread adoption of cycling and walking for short distances, combined with public transport for longer distances. As an illustration, results of the MATISSE-KK model for configurations towards public transport (middle panel Figure 15) and slow modes (right panel of Figure 15) are shown.

In the Pathway B configuration “public transport”, there is an increased environmental awareness combined with a move away from individualised transport, such that car share competes with public transport. The storyline is that the Netherlands has so much slow mode trips, that after a while, further investment in public transport enables slow modes to
combine even better with public transport, such that mechanised individual vehicles are only used relatively infrequently. The high level of slow modes use in the Netherlands, enabled by the high quality cycling and pedestrian infrastructure, means that the Netherlands has the potential for a more rapid regime change in this direction than the UK. In the slow modes configuration, there is an initial adoption of electric hybrids and increased use of public transport for improved environmental performance. In the longer run, however, mobility lifestyles in the Netherlands change such that most people use slow modes for most local trips, while keeping hybrid cars for longer distance and using gasoline cars for more remote communication (the slow modes lifestyle does use public transport and car share for longer distances to a limited extent).

5.4 Results for the UK

In the UK, there is currently very little use of BEVs and only a moderate use of hybrids. In the Pathway A, the consumers place a very high weight on environmental performance, which makes hybrids less attractive than BEVs in the medium term. The potential of hydrogen is limited, because it is initially more expensive than BEVs, and a developed infrastructure is lacking. In order to make a PATHWAY A transition, quite a strong changes in infrastructure and technology choice is needed, which implies a strong policy support for BEVs. In such condition, however, a relatively rapid switch to alternative fuels is possible, with BEVs forming the new regime given the limitations of truly carbon-neutral biofuels supply.

In the public transport pathway B, there is a major programme of public transport improvement, including much higher convenience with new mobile/ICT systems. This combines with power for public transport from renewables and a continuing high level of urbanisation in the UK to make public transport with limited use of car sharing / car ownership the choice of the future.

In the slow modes pathway B, there is an increased emphasis on the environment and a loss of interest in owning a car. This leads to a strong uptake of car sharing, but in the longer run, slow modes are seen as the more desirable lifestyle (again, remember that the slow modes lifestyle does use public transport and car share for longer distances to a limited extent). A transition to a mobility society where urban mobility centred around cycling and walking will require major changes in culture and policy, because this is a mobility lifestyle far removed from the present lifestyle for most consumers in the UK. As can be seen by comparing the Netherlands results for this scenario to the UK results, given the same parameterization, the high level of slow modes use in the Netherlands, enabled by the high quality cycling and pedestrian infrastructure, means that the Netherlands have the potential for a more rapid regime change in this direction than the UK.
6 Heating

6.1 Total EU household energy and heating demand

Figure 16 shows the relative importance of the different energy services in the buildings domain. Currently, heating accounts for over 60% of total residential energy demand. This share is projected to remain fairly constant over time, although declining slightly as heating efficiency is assumed to increase faster than population growth. The share of appliance energy use, on the other hand, is projected to increase.

Without any further action in energy and climate mitigation we find that energy use for heating remains broadly constant over time, but needs to be drastically reduced by 2050 to stay in line with the EU2050 target (Figure 17). The energy demand decline is mainly driven by price-driven efficiency improvements in Pathway A. As similar autonomous and price driven efficiency improvements are subject in Pathway B as well, any further and more timely energy reductions are instigated by behavioural change—in particular changes in temperature setting which can find immediate implementation.

In the absence of negative emissions in the power sector, as prescribed in Pathway B, it requires the model to allocate more carbon neutral fuels to the demand sectors. Greater effort in fuel switching (less oil and gas, and more biofuels), in combination with the behavioural changes in Pathway B, thus leads to lower CO₂ emissions in Pathway B, as was shown in Figure 4.
A closer look at the heating technologies shows that currently the largest share of heating is provided (50%) by natural gas boilers in Europe. Over time the heating market shows to be rigid as the relative shares are not changing much for either pathway. Pathway A shows very similar developments over time as projected in Pathway 0. Only after 2050, heating technology use is diverging from Pathway 0 with most notably the switch to more modern biofuel boilers and heat pumps. In Pathway B, heat pumps and modern biofuel boilers enter the market earlier, reducing the share of natural gas boilers to less than 30% by 2050.

6.2 Results for Sweden

Figure 19 shows total, single dwelling, and multi-dwelling heating energy demand for the three pathways. The figure indicates that biomass, district heating and heat pumps will continue to dominate the heat energy domain until 2050. Both Pathway A and B indicate strong demand decrease and a phasing out of oil. Pathway B also indicates that solar heating will enter the market, but with a rather small share.
For single-dwellings, biomass and heat pumps are expected to be prominent, whilst direct electricity is projected to be phased out in both Pathway A and B. District heating energy demand is expected to stay constant in single-dwellings. It is interesting to note that Pathway A will lead to lower heat demand in single-dwellings than Pathway B. The main reason for this is that the energy savings from the combination of building refurbishments and increasing efficiency of technologies (e.g. heat pumps) in Pathway A is higher than the potential of Pathway B measures, including lower indoor temperature, lower floor space and passive standard for newly built houses in single-dwellings. With regards to multi-dwellings, district heating is expected to continue its domination in both Pathway A and B.

Pathway B will lead to a slightly lower total demand for heat than Pathway A. This is mainly because of the number of new, low-energy, multi dwellings is higher than new single dwellings. Another reason is that the main carrier in multi-dwellings is district heat, for which efficiency is kept at 100% while for example for heat pumps the efficiency increases by a factor 3-5.

Figure 19: Heating energy demand in the different pathways, Sweden (LEAP)
Left hand panels show pathway 0, middle panels Pathway A, right hand panels pathway B
6.3 Results for Germany

Figure 20 show total, single dwelling, and multi-dwelling heating energy demand for the three pathways. District heating, biomass and natural gas will dominate the heat energy domain in 2050. Both Pathway A and B are indicating a phasing out of oil, a reduction of natural gas use and an increase in solar thermal use in the market. In addition, both scenarios show a strong demand decrease, especially in Pathway A. The reason for this is that the energy savings from the combination of building refurbishments and increasing efficiency of technologies (e.g. heat pumps) in Pathway A is higher than the potential of Pathway B measures that include lower indoor temperature, lower floor area and passive standard for newly built houses.

For single-dwellings, natural gas, district heating, and biomass are projected to be prominent in 2050, whilst solar thermal is increasing in both Pathway A and B. The share of heat pumps in Pathway A is increasing, but so is their efficiency and therefore the increase in terms of energy use is not visible in the graph. With regards to multi-dwellings, district heating is expected to replace the natural gas domination in both Pathway A and B and especially in the latter. Solar thermal penetration increases noticeably.

Figure 20: Heating energy demand in the different pathways, Germany (LEAP)
Left hand panels show pathway 0, middle panels Pathway A, right hand panels pathway B
7 Agrifood and land use / biodiversity

7.1 Targets for GHG emissions and biodiversity

Other than for the energy & fossil fuel sectors, where at least the ambition regarding the reduction of GHG emissions is more or less clear, the policy objectives (or ambitions) for the agro-food sector to contribute sustainable, resource efficient, low-carbon and climate-resilient and biodiversity rich societies are not very well stipulated. The only thing which is stated in official EU documents is the need to reduce non-CO₂ emissions from agriculture by 42-49% compared to the 1990 level (EC, 2011b). As these emissions are not captured under the ETS-system, currently the Member states are responsible for reducing these emissions. For these sources, the Effort Sharing Decision establishes binding annual greenhouse gas emission targets for Member States for the period 2013–2020. Beyond 2020 no legislation is in force yet.

We assume that a 49% reduction in non-CO₂ GHG emissions is necessary by the year 2050 compared to the year 1990. As non-CO₂ GHG emissions already decreased by around 15% over the period 1990-2005, still a 30% reduction in GHG is needed between 2005-2050. As for CO₂ emissions, we assume that reducing land use by EU agriculture will guarantee a reduction of land use and land use change related emissions (or even will temporarily serve as a carbon sink). Due to methodological issues, we have not quantified the effects of land use change on CO₂ dynamics.

The EU Biodiversity Strategy aims to halt the loss of biodiversity and ecosystem services in the EU and help stop global biodiversity loss by 2020 (EC, 2011a). For the agricultural and forestry sectors the strategy states that by 2020, there must be a measurable improvement, compared to the EU2010 baseline, in the conservation of species and habitats depending on or affected by agriculture and forestry, and in the provision of their ecosystem services.

As for helping to stop the global biodiversity loss by 2020, target Action 14 of the Strategy says: “Reduce the impacts of EU consumption patterns on biodiversity and make sure that the EU initiative on resource efficiency, our trade negotiations and market signals all reflect this objective”. As biodiversity model results indicate that biodiversity loss is expected to continue (Figure 21), mainly as a result of climate change, it could be argued that, given its large land use in the EU, agriculture should provide literally room to compensate this loss, and to make connections between different nature areas possible. Also in intensive landscapes more natural elements are needed, partly because these have an important function in the provision of ecosystem goods and services, and partly because they can also serve as stepping stones between nature areas). For that reason, it is assumed that agricultural land use is reduced by 15% (both for arable land as well as for grasslands).

Moreover, Europe wants to reduce its impacts (largely related to the production of products as soy beans, palm oil, tropical fruits, coffee and cacao) outside Europe by limiting the import. However, the EU is currently already exporting cereals. Due to certain developments (such as: lower or higher meat production; substitution etc) this export might increase (or decease). It is assumed that the objective is that the net import balance (in hectares) for the commodities soy beans, palm oil and cereals is reduced by 30% in 2050 compared to 2010.
7.2 Approach for the agrifood domain

In contrast to the other domains, for the agriculture and food domain an EU-wide approach has been applied, rather than a country-specific approach. There are four main reasons for doing so:

1) The large intra EU-trade and interconnectedness of agricultural production. Due to the fact that the EU has one internal market, a large intra-EU trade exists for food and agricultural products. This trade is caused by factors as differences in geographic and climatic conditions, as well as differences in socio-economic conditions (such as differences in food consumption patterns, level of technology, prices of labour and land). This trade is not only in the form of final products, also products as feed and flour are traded in large quantities. For example, the Netherlands is a major exporter of meat (mainly pig and poultry), dairy and eggs, but a major importer of feed (mainly cereals from within the EU and soy beans from the Americas). Changes in consumption as well as in production patterns in one EU Member State might thus effect the agricultural production (as well as its environmental impacts) in other Member States (or even beyond the EU). Also some potential developments (as rewilding of marginal production areas) are not evenly distributed over the EU: while this discussion is hardly relevant in the Netherlands, it is very relevant in some other countries (such as Portugal and Spain).

2) The effects of changes in food consumption and agricultural production are not easy to catch in a single parameter. While in case of energy use and greenhouse gas emissions the allocation of environmental effects are relatively straightforward (even in case of transport from one country to another), these effects are less easy to quantify in case of food and agriculture. First of all, there is a multitude of effects, ranging from various forms of greenhouse gas emissions, direct and indirect impacts on biodiversity, nutrient losses and to water use. Secondly, it is difficult to directly link these impacts the food consumption; this has to be done in terms of complicated footprint analysis.

3) The EU Common Agriculture Policy is one of the main shaping factors for the agricultural sector. This policy is decided upon at the EU level, not at the national level. Member states can only decide for some aspects at the national level. This means that tensions in the current regimes and potential for change has to be evaluated at the EU level.
4) The lack of suitable models at the national level. There are (to our best knowledge) no national agri-food models. There is for example the EU-wide CAPRI-model, which operates at the national level for the Netherlands and Hungary, but using this model would have caused to issues as described under 1). Moreover, the CAPRI model is basically an agri-economic model, not a food model.

7.3 Results for agrifood

Before presenting the results, it is important to note that the agrifood domain differs from other domains for a number of reasons:

- The EU or national ambitions are less clear; and some of the goals might be even contradictory (see Section 7.1);
- The technical knowledge about the potential effects and costs of the various measures is less well established compared to the energy sectors;
- There are less or no integrated models which can assess the all relevant effects. Moreover, the models that are available are not goal oriented, with endogenously determined measures to reach certain goals.

The results show that for Pathway A the goals for total arable land, grassland use, and import balance are met and the goal for GHG emissions is almost met (Figure 22). As the effect of carbon sequestration caused by land use changes is not factored in, in the end the GHG emission reduction goal will probably be met as well. For Pathway B most of the goals are not met, although the goals for GHG emissions and arable land use are almost met. The gap for GHG emissions could potentially be met for a number of decades by carbon sequestration in soils.

In the agrifood domain change can be realised in different ways, often in indirect ways. Different actors can be addressed with policy changes. Nowadays the main changes in the sector are aiming at the production side (the farmers). However, other ways to influence the sector are via citizens or businesses.

Most of the technological changes related to Pathway A require a strong involvement of farmers, of research and development (to stimulate innovations), as well as the input industry. Under pathway A policy should motivate technological innovations by providing space to experiment with new technologies. This, however, requires different management practices as well. For example changes in manure management ask not only for technological innovations, but different ways to deal with manure.

In Pathway B the dependence on behaviour change is causing inertia in the system. It is hard to change behaviour, especially in governmental context in which consumers sovereignty is the prevailing paradigm: the idea is that consumers are free to choose what they would like to eat. However, a Pathway B approach asks for opportunities to encourage actors to change behaviour, for example via subsidies, taxes or encouraging civil society. Another route might be by changing the ‘food environment’ (being the physical and social surroundings that influence what people eat, especially relevant in urban areas) (Esnouf et al., 2013).
Figure 22: Modelling results for the agrifood domain

The reference scenario refers to Pathway 0, the revised scenario or Pathway A or B.
7.4 Land use and biodiversity developments for the EU as a whole

In Pathway 0, at the European scale an increase in forest is expected, resulting from the forest transition in which most countries already entered by the end of the 19th century (Meyfroidt and Lambin, 2011). This forest transition is also accompanied by farmland abandonment, particularly in remote areas and on less productive soils (Navarro and Pereira, 2012; Verburg and Overmars, 2009). As a result, natural succession will occur. Consequently, an increase of natural areas other than forest, is expected at least, in the years following farmland abandonment. For Pathway 0, it is projected that land-use trajectories which have been observed in the recent past are expected to continue.

In Pathway A better yields and the development of precision farming allow for the intensification of agriculture in productive areas, which leads to the abandonment of less productive and marginal farmland. These trends are expected to be stronger than in Pathway 0. Natural areas are thus expected to increase due to natural succession on the abandoned lands, leading to an increase in forested areas in the later decades. In this scenario, multifunctional landscapes are projected to decrease in extent. Both intensive agriculture and intensive forest are “locked” in this scenario and remain constant. The rate of loss of extensive agriculture is twice the rate of Pathway 0, resulting in larger areas being converted to extensive forest and other natural areas. The rate of natural succession is assumed to be lower than in Pathway 0 due to management practices that maintain early successional habitats (including rewilding).

In Pathway B, intensive agricultural areas are predicted to considerably decrease, being converted to extensive agricultural areas (intra-regime transition). This pathway leads to less farmland abandonment (i.e. less new available land for natural succession). As a result, the forest increase is more moderate than in Pathway A. The area of extensive forest lost to fire is reduced compared to Pathway 0 and Pathway A with the management resulting from the success of the “fire resilient forest” innovation niche.

7.5 Land use and biodiversity results for Portugal

7.5.1 Land use

Regarding the land use domain in Portugal, several land-use trajectories have been observed in the recent past, which are expected to continue in a Pathway 0. For instance, the north of the country has faced substantial permanent loss of cropland since the 1990s (Levers et al., 2015), which might either lead to an increase in forest, or in other natural areas depending on the fire regimes and projected changes in the climate (Batllori et al., 2013; Oliveira et al., 2012; Proença, 2010). Cropland was also lost in the south of the country, but in this case was mainly converted into extensive pastures (INE, 2011). At the same time, agriculture intensified, particularly in the centre of the country (Levers et al., 2015), a trend also expected to continue in a BaU scenario. The increase in extent of intensive forest (i.e. eucalyptus plantations) was, in the past 25 years, at the expense of extensive forest (90%) and other natural areas (10%), proportions that were kept for the BaU scenario (MAMAOT, 2013).
In 2010, Portugal’s territory (excluding urban areas) consisted of 8.6% intensive agriculture, 36.8% extensive agriculture, 29% extensive forest, 10% intensive forest and 15.5% other natural (Figure 23). By 2050, in BaU, we projected an increase in the area of intensive forest, a consequence of the expansion of eucalyptus plantations, and a loss of extensive forest, due to fire and conversion to intensive forest. The area devoted to agricultural production were projected to decrease as a result of land abandonment (conversion to other natural) and intensification of the agriculture processes (technological improvement lead to increasing yields, thus less area is needed to achieve the same production).

The projected land use for 2050 in pathways A and B differ as a result of the assumptions of the two pathways (Figure 24). Given the focus on technological improvements and the ‘land sparing’ vision of Pathway A we projected a significant reduction in the area devoted to agriculture in this pathway. From 45.4% in 2010, it reduces to 32.8% in 2050 as a result of land abandonment, better yields and improved technology that allow the production to rise in the remaining areas. In this pathway, there is no more conversion of extensive forest to eucalyptus plantations. Comparatively, in pathway B, the overall area of agriculture remains relatively stable compared to 2010 (44.5% in 2050 vs 45.4% in 2010). However, there is a significant decrease in the intensive use of the agricultural land (-50%), resulting in an increase in multifunctional areas (extensive agriculture), representing the ‘land sharing’ vision of pathway B. Moreover, we projected a significant increase in extensive forest and other natural areas, which together by 2050 would represent 57% of the non-urban area of the country, compared to 45.4% in pathway B. This represents the momentum gain of the rewilding niche in Pathway A.
7.5.2 Biodiversity

The response of biodiversity to land-use change resulting from the three pathways was assessed using the countryside species-area relationship (cSAR; Guilherme and Miguel Pereira, 2013; Martins et al., 2014; Pereira and Daily, 2006; Proença and Pereira, 2013; see also Section 2.1.6).

We projected that total levels of biodiversity will increase in all scenarios of land use change in Portugal (Figure 25 and Figure 26). While both Pathway 0 and Pathway B present a similar increase in the total richness of species (+0.35% and +0.39%, respectively) they show two distinct patterns. On the one hand, in pathway 0 there is a large variation across grid-cells, where species increase in the north-northeast and southeast of Portugal and decrease in the northwest, centre and southwest of the country. On the other hand, in Pathway B the increase (or decrease) in species richness is more moderate and is distributed across the entire country.
These changes in species richness follow the land use patterns. In Pathway 0, species richness declines in regions where intensive forest grows, whereas in Pathway B species richness increase in multifunctional areas. In Pathway A higher values of biodiversity are projected (+1.6%), as agricultural abandonment leads to an increase in natural habitat. Consequently, both the forest species richness and the richness of species associated with "other natural" habitats are projected to increase in Pathway A, while farmland species decrease below the values projected for Pathway 0. Farmland species only show a slight increase in their richness in Pathway B, as multifunctionality increases both the area and niches available to this species. Overall, Pathway A leads to 0.45% more species than Pathway B (Figure 27).

To summarize, biodiversity is expected to decrease in intensive land-use areas (i.e. loss of multifunctionality) due to the homogenization of the agricultural landscape, which will reduce the number of niches available in Pathway A (Guilherme and Pereira, 2013; Navarro et al., 2015; Proença and Pereira, 2013). This decreases the mean richness of farmland species although some species can increase in abundance if they have a high affinity for the resulting homogeneous landscape (Proença and Pereira, 2013). Due to the projected increase in forest area, which will mainly occur in areas with lower human pressure, the mean richness of forest species is expected to increase. This is for instance the case for megafauna which will be favored by increased availability of habitat and connectivity (Ceausu et al., 2015). In Pathway B, intensive agricultural land use creating mosaic landscapes, with ecological reserves in high production areas. The increase of multifunctionality will lead to an increase in farmland species, as agricultural landscapes become more heterogeneous and consequently are able to support a wider range of species.
The forest species are expected to increase in both richness and abundance, although at slower rate than projected in pathway A.

**Figure 26: Maps of species richness in the pathways, Portugal**
(a) Total species (b) forest species (c) farmland species (d) other natural species. From left to right: Pathway 0, Pathway A, and Pathway B.

**Figure 27: Map of difference in total species richness between Pathway A and Pathway B, Portugal**
Positive (yellow and green) values mean Pathway A > Pathway B.
7.6 Land use and biodiversity results for Netherlands

7.6.1 Land use

In 2012, the Dutch territory consisted of 53.4% intensive agriculture, 1.1% extensive agriculture, 8.3% forest, 3.5% other natural, 15.1% urban areas and 18.9% water (Figure 28). In pathway 0, we projected that by 2050, these shares will be 46% intensive agriculture, 3.6% extensive agriculture, 3.7% forest, 5% other natural, 21.7% urban areas and 20% water.

![Figure 28: Shares of different land use classes in the Netherlands by 2050 in each pathway](image)

Int. AG: intensive agriculture; Ext. AG: extensive agriculture; Oth. Nat: other natural; Urb.: Urban

The projected land use for 2050 in Pathways A and B differ as a result of the assumptions described in Section 7.4. Given the focus on technological improvements and the ‘land sparing’ vision of pathway A we projected a complete removal of extensive agriculture in this pathway. Comparatively, in Pathway B, there is a significant decrease in the intensive use of the agricultural land, resulting in an increase in multifunctional areas (extensive agriculture), representing the ‘land sharing’ vision of this pathway (Figure 29).

![Figure 29: Land use maps in the different pathways in the Netherlands](image)

(a) 2012  (b) Pathway 0 2050  (c) Pathway A 2050  (d) Pathway B 2050
7.6.2 Biodiversity

We projected that the total levels of biodiversity will increase in all scenarios of land use change (Figure 30 and Figure 31).

In Pathway 0, by 2050 there is a significant loss in biodiversity (-4% compared to 2012). In both Pathway A and B, the total levels of biodiversity increase relative to 2012 (by 0.4% and 0.7%, respectively). Forest species richness increase more in Pathway A, while other natural species increase more in Pathway B. Farmland species decrease in all scenarios, and in Pathway A the decrease is actually below the values predicted in Pathway 0. Multifunctionality will benefit other natural species over other species groups.

Figure 30: Difference in the richness of different species groups between the pathways, the Netherlands
(a) Total species (b) forest species (c) farmland species (d) other natural species

Figure 31: Map of difference in total species richness between Pathway A and Pathway B, the Netherlands
Positive (yellow and green) values mean Pathway A > Pathway B.
Figure 32: Maps of species richness in the pathways, the Netherlands
(a) Total species (b) forest species (c) farmland species (d) other natural species. From left to right: Pathway 0, Pathway A and Pathway B.
References


ANNEX I  Inclusion of studied niche innovations in models

Table 1: Niche innovations in electricity

<table>
<thead>
<tr>
<th>Niches</th>
<th>PowerACE</th>
<th>IMAGE</th>
<th>WITCH</th>
</tr>
</thead>
<tbody>
<tr>
<td>biogas</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>landfill gas</td>
<td>YES</td>
<td>NO</td>
<td>NO</td>
</tr>
<tr>
<td>biomass</td>
<td>YES</td>
<td>NO</td>
<td>NO</td>
</tr>
<tr>
<td>storage facility</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>power to gas</td>
<td>YES</td>
<td>NO</td>
<td>NO</td>
</tr>
<tr>
<td>batteries</td>
<td>YES</td>
<td>NO</td>
<td>NO</td>
</tr>
<tr>
<td>seasonal pump storage</td>
<td>YES</td>
<td>NO</td>
<td>NO</td>
</tr>
<tr>
<td>hydrogen</td>
<td>YES</td>
<td>NO</td>
<td>NO</td>
</tr>
<tr>
<td>AA-CAES</td>
<td>YES</td>
<td>NO</td>
<td>NO</td>
</tr>
<tr>
<td>fuel cells</td>
<td>YES</td>
<td>NO</td>
<td>NO</td>
</tr>
<tr>
<td>PV</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>rooftop</td>
<td>YES</td>
<td>NO</td>
<td>NO</td>
</tr>
<tr>
<td>field</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td>CSP</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>wind</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>onshore</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td>offshore</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td>small-scale wind</td>
<td>YES</td>
<td>NO</td>
<td>NO</td>
</tr>
<tr>
<td>CCS</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td>micro-generation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>micro-CHP</td>
<td>YES</td>
<td>NO</td>
<td>NO</td>
</tr>
<tr>
<td>virtual power plant</td>
<td>NO</td>
<td>NO</td>
<td>NO</td>
</tr>
<tr>
<td>geothermal</td>
<td>YES</td>
<td>YES</td>
<td>NO</td>
</tr>
<tr>
<td>wave/tidal power</td>
<td>YES</td>
<td>NO</td>
<td>NO</td>
</tr>
<tr>
<td>fusion</td>
<td>NO</td>
<td>NO</td>
<td>YES</td>
</tr>
<tr>
<td>small-scale hydro</td>
<td>YES</td>
<td>NO</td>
<td>NO</td>
</tr>
<tr>
<td>demand response / smart grid</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>smart homes (smart meter)</td>
<td>YES</td>
<td>INDIRECT</td>
<td>NO</td>
</tr>
<tr>
<td>heat pumps</td>
<td>YES</td>
<td>NO</td>
<td>NO</td>
</tr>
<tr>
<td>power to heat</td>
<td>YES</td>
<td>NO</td>
<td>NO</td>
</tr>
<tr>
<td>smart charging e-vehicles</td>
<td>YES</td>
<td>NO</td>
<td>NO</td>
</tr>
<tr>
<td>vehicle-to-grid (V2G)</td>
<td>YES</td>
<td>NO</td>
<td>INDIRECT</td>
</tr>
<tr>
<td>industry-specific</td>
<td>NO</td>
<td>NO</td>
<td>NO</td>
</tr>
<tr>
<td>CFL an LED lighting</td>
<td>YES</td>
<td>YES</td>
<td>NO</td>
</tr>
<tr>
<td>Grids</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DC transmission systems</td>
<td>NO</td>
<td>NO</td>
<td>NO</td>
</tr>
<tr>
<td>variable transformers</td>
<td>NO</td>
<td>NO</td>
<td>NO</td>
</tr>
<tr>
<td>underground cable</td>
<td>YES</td>
<td>NO</td>
<td>NO</td>
</tr>
</tbody>
</table>
Table 2: Niche innovations in mobility

<table>
<thead>
<tr>
<th>Niches</th>
<th>MATISSE_KK</th>
<th>IMAGE</th>
<th>WITCH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Battery electric vehicles</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td>Biofuels</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td>H2 fuel cell vehicles</td>
<td>YES</td>
<td>YES</td>
<td>NO</td>
</tr>
<tr>
<td>ICE/electric hybrid vehicles</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td>From ownership to mobility on demand</td>
<td>YES</td>
<td>INDIRECT</td>
<td>INDIRECT</td>
</tr>
<tr>
<td>(safe &amp; convenient) urban and peri-urban cycling</td>
<td>YES</td>
<td>NO</td>
<td>INDIRECT</td>
</tr>
<tr>
<td>Inter-modal transport</td>
<td>YES</td>
<td>NO</td>
<td>INDIRECT</td>
</tr>
<tr>
<td>Compact cities</td>
<td>YES</td>
<td>INDIRECT</td>
<td>INDIRECT</td>
</tr>
<tr>
<td>Remote working, shopping, etc</td>
<td>NO</td>
<td>INDIRECT</td>
<td>INDIRECT</td>
</tr>
</tbody>
</table>

Table 3: Niche innovations in heating

<table>
<thead>
<tr>
<th>Niches</th>
<th>LEAP</th>
<th>IMAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biogas Storage</td>
<td>biogas/biomethane injection</td>
<td>NO</td>
</tr>
<tr>
<td></td>
<td>power to gas/heat</td>
<td>NO</td>
</tr>
<tr>
<td>renewable heating</td>
<td>solar thermal heating (collectors)</td>
<td>YES</td>
</tr>
<tr>
<td></td>
<td>solar hot water heaters</td>
<td>YES</td>
</tr>
<tr>
<td></td>
<td>waste water heat recovery</td>
<td>NO</td>
</tr>
<tr>
<td></td>
<td>small biomass</td>
<td>YES</td>
</tr>
<tr>
<td></td>
<td>combined heating (cooling) and power (CH(C)P)</td>
<td>NO</td>
</tr>
<tr>
<td>heat generation</td>
<td>geothermal heating</td>
<td>NO</td>
</tr>
<tr>
<td></td>
<td>district heating</td>
<td>NO</td>
</tr>
<tr>
<td></td>
<td>virtual power plant</td>
<td>NO</td>
</tr>
<tr>
<td>Insulation</td>
<td>insulation of hot water pipes</td>
<td>INDIRECT</td>
</tr>
<tr>
<td></td>
<td>insulation of exterior walls, basement, roofs</td>
<td>YES</td>
</tr>
<tr>
<td></td>
<td>greening exteriors and roofs (also for cooling)</td>
<td>INDIRECT</td>
</tr>
<tr>
<td>ventilation</td>
<td>efficient mechanical HVAC systems</td>
<td>INDIRECT</td>
</tr>
<tr>
<td>energy efficiency</td>
<td>efficient, condensing boilers</td>
<td>YES</td>
</tr>
<tr>
<td></td>
<td>heating control systems (smart meters)</td>
<td>INDIRECT</td>
</tr>
<tr>
<td></td>
<td>heat pumps</td>
<td>YES</td>
</tr>
<tr>
<td>behavioral</td>
<td>lower indoor temperature</td>
<td>YES</td>
</tr>
<tr>
<td></td>
<td>lower size of dwelling per capita</td>
<td>YES</td>
</tr>
<tr>
<td></td>
<td>Behaviour change campaigns</td>
<td>INDIRECT</td>
</tr>
<tr>
<td>building standards</td>
<td>low-energy, zero/plus-houses</td>
<td>YES</td>
</tr>
</tbody>
</table>
Table 4: Niche innovations in agrifood/land use

<table>
<thead>
<tr>
<th>Niches</th>
<th>IMAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Precision farming in cereal production</td>
<td>NO</td>
</tr>
<tr>
<td>Reduction of GHG from dairy production: Sustainable dairy chain</td>
<td>YES</td>
</tr>
<tr>
<td>Reduction of food losses and waste</td>
<td>YES</td>
</tr>
<tr>
<td>Novel protein food / hybrid meat</td>
<td>YES</td>
</tr>
<tr>
<td>Algae production</td>
<td>NO</td>
</tr>
<tr>
<td>Shifts towards low meat and dairy diet</td>
<td>YES</td>
</tr>
<tr>
<td>Shifts towards local food</td>
<td>NO</td>
</tr>
<tr>
<td>Organic farming</td>
<td>NO</td>
</tr>
<tr>
<td>vegetarianism + eating less meat (e.g. once a week)</td>
<td>YES</td>
</tr>
<tr>
<td>hybrid meat</td>
<td>NO</td>
</tr>
<tr>
<td>‘artificial meat’ (created in lab or factory)</td>
<td>NO</td>
</tr>
<tr>
<td>soy milk (as alternative product for dairy)</td>
<td>NO</td>
</tr>
<tr>
<td>fish: aqua-culture (‘farmed fish’) to replace catching fish in oceans</td>
<td>NO</td>
</tr>
</tbody>
</table>
PATHWAYS Project 603942

Improved set of scenarios

ANNEX II  Pathways implementation in models

Table 5 - Table 8 show the implementation of the two pathways for each domain by the various models. The implementation of the pathways were done by either i) social and behavioural change, ii) regulatory change, iii) technical change, or iv) assuming shocks in the system. The colours in the table indicates the type of change assumed for the pathway.

Legend for Table 5 - Table 8

<table>
<thead>
<tr>
<th>Not modified relative to PATHWAY 0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Social and behavioural change (demand, preferences)</td>
</tr>
<tr>
<td>Regulatory change (intervention, governance)</td>
</tr>
<tr>
<td>Technical change (acceleration)</td>
</tr>
<tr>
<td>Shock (Shift away)</td>
</tr>
</tbody>
</table>

Table 5: Scenario interventions for electricity

<table>
<thead>
<tr>
<th>PATHWAY A</th>
<th>IMAGE</th>
<th>WITCH</th>
<th>PowerACE</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Onshore wind</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Offshore wind</td>
<td>Price same as onshore</td>
<td>Learning rate +50%, floor cost -20%</td>
<td>Price same as onshore; 1% interest rate</td>
</tr>
<tr>
<td>Bioenergy</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nuclear</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CCS</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>PATHWAY B</th>
<th>IMAGE</th>
<th>WITCH</th>
<th>PowerACE</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV price equal to overall electricity price</td>
<td>Learning rate +25%, floor cost -12.5%</td>
<td>Lower price Higher land availability</td>
<td></td>
</tr>
<tr>
<td>SSP1 assumptions: Higher resources at lower costs</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Exogenously set path</td>
<td>No new capacity after 2010</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Exogenously set path</td>
<td>Excluded</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### Table 6: Scenario interventions for mobility

<table>
<thead>
<tr>
<th>PATHWAY A</th>
<th>PATHWAY B</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>IMAGE</strong></td>
<td><strong>WITCH</strong></td>
</tr>
<tr>
<td><strong>Electric (both BEV and PHEV)</strong></td>
<td>25% purchasing price subsidy</td>
</tr>
<tr>
<td><strong>Bio</strong></td>
<td>25% purchasing price subsidy</td>
</tr>
<tr>
<td><strong>H2</strong></td>
<td>25% purchasing price subsidy</td>
</tr>
<tr>
<td><strong>Car sharing</strong></td>
<td>Increased vehicle occupancy</td>
</tr>
<tr>
<td><strong>Other</strong></td>
<td>Reducing available travel budget per person</td>
</tr>
<tr>
<td>Scenario Interventions for Heating</td>
<td>PATHWAY A</td>
</tr>
<tr>
<td>-----------------------------------</td>
<td>-----------</td>
</tr>
<tr>
<td>Heat pumps</td>
<td>IMAGE LEAP</td>
</tr>
<tr>
<td>Small-scale biomass heating systems</td>
<td>Change in penetration and efficiency of technologies</td>
</tr>
<tr>
<td>Solar Thermal installations</td>
<td>Change in penetration and efficiency of technologies</td>
</tr>
<tr>
<td>District heating</td>
<td>Change in penetration and efficiency of technologies</td>
</tr>
<tr>
<td>Waste heat recovery</td>
<td>Improved secondary heat efficiency (45%)</td>
</tr>
<tr>
<td>Low-energy housing</td>
<td>15% energy reduction due to improved insulation</td>
</tr>
</tbody>
</table>
| Behavioural change/ Smart metering| Change temperature setting by 1°C  
Switch off standby mode appliances  
No growth of appliance ownership after 2010  
No tumble dryer after 2010  
More efficient use of appliances  
Floor space is fixed to 2010 values (rural 50m²/cap and urban 40m²/cap) | Lower indoor temperature (1 °C lower for Germany and 3°C lower for Sweden)  
10% reduction in floor area |
| Lower size of dwelling            |           |           |
Table 8: Scenario interventions for land use/agrifood

<table>
<thead>
<tr>
<th>Scenario</th>
<th>PATHWAY A</th>
<th>PATHWAY B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reduction consumption animal products</td>
<td>10%</td>
<td>30%</td>
</tr>
<tr>
<td>Reduction of food waste</td>
<td>5%</td>
<td>20%</td>
</tr>
<tr>
<td>Crop yield increase 2015-50</td>
<td>15%</td>
<td>5%</td>
</tr>
<tr>
<td>Increase in livestock efficiency</td>
<td>7%</td>
<td>2%</td>
</tr>
</tbody>
</table>

Specific technical measures to reduce emissions:

- *Feed ruminants (CH4)*
  - PATHWAY A: 12%
  - PATHWAY B: 0%

- *Manure (CH4)*
  - PATHWAY A: 52.5%
  - PATHWAY B: 0%

- *Nitrification inhibitors (N2O)*
  - PATHWAY A: 28.5%
  - PATHWAY B: 0%

- *Manure (N2O)*
  - PATHWAY A: 52.5%
  - PATHWAY B: 19%

- *Cereal export (mkn tonnes)*
  - PATHWAY A: 60
  - PATHWAY B: 20
ANNEX III  Comparison of results for electricity between PowerACE, IMAGE, and WITCH

The trend in total electricity demand has been harmonized between the IAM IMAGE and the detailed sectoral electricity model PowerACE. Figure 33 shows how total energy production in IMAGE compares to WITCH and PowerACE, and compares the energy mix as well. WITCH shows a faster increase in electricity demand than IMAGE in all pathways. Furthermore, WITCH shows a higher share of nuclear and solar PV in Pathway A, and less offshore wind. In Pathway B, the energy mix is similar among the models, with dominant roles for onshore wind, solar PV, and hydropower.

Figure 33: Model comparison of total EU electricity demand by energy carrier