Integrated Impact Report: synthesis of REEEM

D1.2b

July 2019

About this report

This report aims to synthesise the work carried out in REEEM, to extract the main messages from the project activities and to highlight the main impacts. It reports on the main objective of the project, which is to provide a **comprehensive understanding of the system-wide implications of energy strategies** in support of transitions to a competitive low-carbon EU energy society. This report constitutes an updated version of the midterm report D1.2a – First Integrated Impact Report. It reflects methodological discussions extensively taken under D1.1 - Report on pathway definition, and it summarises the findings of the studies presented in all other project deliverables (Case study reports, Focus reports and sectoral Policy Briefs).

Section 1 sets the background: it focuses on the EU's strategic priorities for the energy system, identifies the challenges related to such priorities and summarises the contributions of key EU-funded actions to informing such challenges. Such funded actions represent past or present efforts which the project partners have collaborated with. The aim of the REEEM Consortium in this respect has been to leverage on and complement the findings of such actions. Section 2 describes the design of the REEEM pathways: a set of scenarios specifically co-designed with stakeholders, to explore the above challenges and provide insights complementing those of other research. Section 3 describes the key messages obtained through the integrated modelling framework, providing policy relevant insights into the challenges and opportunities of decarbonisation across economic

REEEM partners

About REEEM

REEEM aims to gain a clear and comprehensive understanding of the system-wide implications of energy strategies in support of transitions to a competitive low-carbon EU energy society. This project is developed to address four main objectives: (1) to develop an integrated assessment framework (2) to define pathways towards a low-carbon society and assess their potential implications (3) to bridge the science-policy gap through a clear communication using decision support tools and (4) to ensure transparency in the process.

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sectors, wider society and the environment. Section 4 synthesises the messages from Section 3 into 7 consistent, integrated messages which summarise the findings of the REEEM project. Those integrated messages are:

1. Impacts of the transition to a low carbon EU energy system are multi-dimensional and spatially varied
2. Broader engagement is imperative for deep decarbonisation
3. The EU low-carbon transition is strongly linked to non-EU drivers
4. There are non-trivial multidimensional path dependencies that cannot be ignored
5. Among the technology trends, energy efficiency and electrification of transportation are consistently confirmed as potential enablers of the decarbonisation
6. Focusing on direct mitigation misses important leakage effects
7. New energy security paradigms

Moreover, Section 4 describes the different tools and activities developed under the scope of REEEM, aiming at communicating the findings and promoting engagement. Finally, Section 5 presents how the messages may be relevant for and communicated to various stakeholders of the transition, while suggestions on how to build on the current research and make further progress are made.

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Table of Contents

List of Figures

List of Tables

List of acronyms

CECILIA	Choosing Efficient Combinations of Policy Instruments for Low-carbon development and Innovation to Achieve Europe's 2050 climate targets
CL	Coalitions for a Low-carbon path
CCS	Carbon Capture Storage
DALY	Disability Adjusted Life Years
DH	District Heating
EMP-E	Energy Modelling Platform for Europe
EFS	Effort Sharing Decision
ETS	Emission Trading Scheme
EU Calc	EU Calculator
EC	European Commission
EU	European Union
GDP	Gross Domestic Product
GHG	Greenhouse Gas
HHI	Herfindahl-Hirschman Index
GVA	Gross Value Added
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
IRL	Innovation Readiness Level
LCA	Life Cycle Assessment
LNG	Liquified Natural Gas
LS	Local Solutions
MS	Member States
OEP	OpenEnergyPlatform
OSeMBE	Open Source energy Model Base for the European Union
OSeMOSYS	Open Source energy MOdelling SYStem
PA	Paris Agreement
PA-EU	Paris Agreement – EU
RCP	Representative Concentration Pathway
RF	Reference
SET Plan	Strategic Energy Technology Plan
TIMES BGS	TIMES Baltic Gas Security
TRL	Technology Readiness Level
UK	United Kingdom
US	United States
2DS	2 Degree Scenario

1. Background

1.1. The EU's strategic priorities for the energy system

In 2011, the European Commission (EC) published the Energy Roadmap 2050 [1]. The Roadmap sets the **path to decarbonisation** of the European energy system, with the objective to keep climate change below 2°C. It features several decarbonisation pathways, all compatible with an 80% greenhouse gas (GHG) reduction target (and 85% energy-related emissions), relative to 1990 levels. A model-based analysis of these pathways established the following key conclusions: firstly, such level of decarbonisation *is possible*. The highest decarbonisation is expected to occur in the power sector (nearly 100% in 2050) and in industry (83-87% compared to 1990); the most difficult sectors to decarbonise are expected to be agriculture (42-49% in 2050, compared to 1990; those emissions come from livestock) and transportation (54-67%). Secondly, *decarbonisation is expected to rely on increased electrification and penetration of variable renewables*. The share of electricity in the final energy consumption will double to 36-39% by 2050. The share of renewables in the gross, final energy consumption will rise to 55% in 2050. This, in turn, is expected to impact the energy generation mix (which will likely require diversification of supply options), on the structure of energy generation costs (which will shift from fuel costs to capital expenditures) and on the energy prices (with an expected increase of electricity prices until 2030 and consequent increase of household expenditure on energy).

It becomes clear that such a process of deep decarbonisation entails the restructuring of economies in the European Union (EU) and is likely to deeply impact various sectors of its society. In view of this, the European Commission published the Energy Union package in 2015 [2]. This intended to establish that the roadmap to decarbonisation must put citizens at the core and focus on supplying **secure, sustainable, competitive and affordable energy** for all Europeans. Means to achieving such an objective also include the strengthening of the internal energy market, investment in energy efficiency, and investments in Research and Innovation. Moreover, the Energy Union package increases the decarbonisation ambition.

The Energy Union established a **legally binding framework** for all Member States (MS), within which 2030 targets have been updated. The Governance Framework included in the Energy Union [3] provided the basis for MS to elaborate their new National Energy and Climate Plans [4], to be submitted to the European Commission by end of 2019.

The Clean energy for all Europeans strategy, issued in 2016, [5] and the Clean Planet for all strategy, issued in 2018 [6], support the implementation of the Energy Union and further increase the ambition. The latter comes almost in parallel with the IPCC Special Report on the impacts of global warming of 1.5°C [7] and confirms Europe's commitment to lead in climate action and achieve **net zero GHGs emissions** by 2050. The strategy shows that, as the ambition increases, **the scale of the problem and its complexity increase**. It calls for radical transformation of the energy, agriculture, industry and transportation. It imposes changes from transnational, to national and local scale and it affects several dimensions of European societies. The analysis of the strategy unveils a number of key-issues which are described in the subsequent paragraphs.

As industry is expected to play a key role in decarbonisation, the strategy stresses that the impacts on competitiveness must be assessed. Heavy industry relies on fossil fuels and currently available low-carbon technologies are not able to supply energy with the needed intensity. Deep transformation of the whole value chains will be needed, implying among others electrification of the energy supply, sustainable supply of role materials and circular economy, energy efficiency and large-scale demonstration of breakthrough technologies. Consequently, job losses are expected in sectors which are due to decline (e.g. coal mining, extraction of oil and gas, related services), especially in regions currently more heavily relying on them (e.g. Eastern Europe). This is at the centre of debate among Member States, with mitigation options such as those supporting the creation of 'green skills' for vulnerable industries needing to be assessed. Completely new skills may also be needed in other sectors such as the building and mobility sectors.

Meeting energy efficiency and decarbonisation targets will also require strong action in the residential sector. Here, however, effective changes may rely more on consumers' habits and choices. While awareness raising may help change behaviours, affordability of energy and of new technologies may be the strongest driver of consumers' choices. Moreover, the civil society is ultimately expected to be impacted the most by changes in the energy sector, not only in terms of affordability – as already highlighted in previous strategies – but also in terms of **climatic changes (and related energy demands) and health**.

Changes may be facilitated by a number of enabling factors, residing in finance (private investments are expected to take on great share of the investment needs), research and innovation (which will have to focus on developing a wide portfolio of low-carbon alternatives, including zero-carbon power, circular economy, hydrogen technology, electrification of sectors and bioeconomy), transnational cooperation (including aspects of security of energy supply, raw and rare material supply, interconnections and infrastructure investment) and trade (while the EU aims at becoming leader in renewables, it faces competition from China, United States (US) and India, which also benefit from high economies of scale).

1.2. Challenges

Emerging from the above discussion, the Clean Planet for all strategy underlines the complexity of the changes entailed by a high decarbonisation ambition. Here we synthesise the challenges that in our view emerge from the strategy. Some of them may be identified as between scales, others as across scales (or pervasive).

The challenges between scales may be synthesized as:

- *Transnational*: decisions at a European level or in specific EU countries in terms of climate and energy policy and in terms of infrastructure investments may affect others. Conflicting approaches may arise where national priorities are not aligned between Member States and with the European Union as a whole. Member States may have different priorities. Economies relying on mining will have a set of skills and related labour force which make it difficult to transition quickly away from fossil fuels. Again, national strategies in favour of large penetration of renewables may neglect the potential benefits of regional cooperation in the management of primary energy sources and energy infrastructure. Furthermore, national strategies in favour of use of particular energy sources may not see local impacts, such as on ecosystem services.
- *Temporal*: while the long-term vision is clear and the mid-term objectives are set, the potential investments pathways for infrastructure, technology and innovation on the way to 2050 are numerous and highly uncertain. Many combinations of energy resources and technologies to reach 2050-and-beyond decarbonisation targets are possible. They are specific to Member States and local constraints

and they are bound by resource availability, structures of economies and societies, and learning processes. In some cases, technological solutions may rely more on cooperation, in others more on independence; on centralised supply or local solutions. No solution fits all.

- *Sectoral*: the Clean Planet for all strategy draws attention on the global and multi-faceted dimension of the challenges ahead. Sectors of the economy and ecosystems are interlinked. Actions in one will impact others, either positively, or negatively. For instance, investments in renewable generation to decarbonise economies may bear strongly positive impacts for mitigation. However, expansion of hydro power could affect life in rivers and use of fresh water for agriculture. Extensive use of biomass could affect land use, with rebound effects on climate in the long term. The trade-offs and synergies between systems need to be evaluated in the framework provided by the Sustainable Development Goals and policies need to be elaborated not in silos.

In addition to 'between scale' issues, pervasive challenges across scales could also impact the transition to low-carbon EU economies across all scales. Key ones emerging from the Commission's analyses are in our view:

- *Technology innovation*: it is clear that technology innovation is needed in all sectors and a large spectrum of innovative options will speed up the transition. However, there is large uncertainty as to what the barriers and enablers of innovation in each sector are, how much innovation can and should be pursued in each sector and how big impact it may bear on the transition.
- *Behaviour*: the transition is not a mechanical process. It relies heavily on the individual choices of large and small consumers, with those choices often made under incomplete information and uncertainty. If consumers fail to engage, decarbonisation targets may not be reached or the pace of the transition may diverge considerably from what expected. Research findings on the challenges and opportunities of decarbonisation pathways need to be communicated at different levels of the energy decision chains, and tools for formulating science-based evidence on this need to be developed and used in a transparent manner.
- *Resource availability*: the resource base for changing energy systems has not been assessed in a comprehensive way. For instance, the technically exploitable potentials of biomass need to be updated taking into account the effects of climate change, water uses in other sectors and potential effects on ecosystems. The same may be said about land resources. Furthermore, the life cycle impacts of resource use need to be estimated taking into account the global scale of trade. I.e. clear understanding is needed on where impacts are placed and what they are caused by. Finally, critical materials may be crucial in enabling the transition (e.g. cobalt and lithium for batteries for large storage options, rare earths for second generation solar panels, etc.). Global boundaries in the use of scarce materials and the impacts of circular economy need to be assessed.
- *Global economy*: the transition needed of the EU is deep and is expected to bear impacts on GDP and job markets. Competition by other world regions is strong. The objectives of guaranteeing secure, competitive and affordable energy can be met only if distributional and competitiveness impacts are assessed jointly and along with environmental impacts.

In order to facilitate the transition to deeply decarbonised economies, a comprehensive analysis of the impact of decarbonisation pathways across all of these areas is needed.

1.3. Scenario analyses to inform decarbonisation strategies

The EU strategies for decarbonisation have been informed by impact assessments since the beginning. These assessments are based on scenario analysis practices widely consolidated globally, both in businesses (e.g. Shell [8]) and research institutions (e.g. the World Energy Council [9], the Intergovernmental Panel on Climate Change (IPCC) [7] and the Integrated Assessment Modelling Consortium [10]). There exist two key components to these scenario analyses: model-based assessments and stakeholder engagement.

1.3.1. Model-based assessments

The Commission's strategies have been supported by model-based analyses carried out with a suite of tools including PRIMES, PROMETHEUS, GAINS, GLOBIOM and GEM-E3. In the Energy Roadmap 2050, for a number of decarbonisation scenarios, this suite of models was used to provide quantitative analysis on the evolution of the energy sector and its impacts on climate and air quality (in terms of CO_2 and non-CO_2 emissions), economy (impacts on GDP and job market), society (especially households expenditure) and resource use (land and water). In the Clean Planet for all strategy, a similar impact assessment was carried out for a set of scenarios with higher decarbonisation targets.

These analyses do address questions of economic and distributional impacts, changes in industrial production and overall resource balances. However, they fail to capture spatially-resolved dynamics related to the **impacts of and on societies** of the transition (such as consumers' behaviour and health impacts), which the Clean Planet for all considers key in impacting the pace of the transition. They also fail to represent some of the **dynamics happening between spatial and temporal scales** (such as reliability of supply issues, local impacts on environment and ecosystems, technology diffusion etc.).

Funded actions within the Framework Programme 7 and Horizon 2020 have also provided model-based assessments of the impacts of decarbonisation pathways. CECILIA (*Choosing Efficient Combinations of Policy Instruments for Low-carbon development and Innovation to Achieve Europe's 2050 climate targets*) provided model-based insights on the potential success and impacts of decarbonisation policies [11]. It measures their effects on equity, competitiveness and innovation. The assessment complements and validates the one run for the Commission's Energy Roadmap 2050, with a different set of modelling tools (including a European energy model based on TIMES, the environment-economy model GINFORS and the Input-Output model EXIOBASE). The main insights into the energy system transformation highlight that an 80% cut in emissions does not appear to be feasible without negative emissions from biomass carbon capture storage (CCS), given hard to decarbonise sectors such as industry. However, the analysis is limited to assessing policies and their socio-economic implications, but does not elaborate on the **use of resources and behaviour,** two issues listed in Section 1.2. Additionally, the scope is wide and the modelling presents challenges, as to what assumptions are made about future developments (e.g. gross domestic product (GDP), energy prices, population) across all modelling tools.

Another tool to explore decarbonisation pathways is the ongoing EU Calculator project (EU Calc), oriented to policy makers to provide an accessible and user-friendly platform to quantify and visualise impacts of distinctive pathways. The platform is based on a simulation model, which represents links between economy, energy and resource systems and dynamics of final consumption. The model is simple enough to allow users to modify a large number of decision levers related to lifestyle, technologies and biophysical systems and evaluate the impacts of these decisions. It fulfils the essential purpose of scrutinising the dynamics of the transition, but it **does not necessarily embed the complexity of impacts between and across all scales**.

Another group of projects initiated in 2016 and funded under the same Low-Carbon Energy call 21 (LCE21-2015) as REEEM include MEDEAS, REflex, and SET-Nav. These projects aim at modelling and analysing the energy system, its transformation and impacts, as per the call's terms of reference. Their approaches are complementary. MEDEAS focuses on the construction of a new open source modelling framework to analyse transitions to a 100% renewable EU energy system, including Input-Output modules to account for environmental, social and economic impacts. REflex combines several modelling tools to study the role of flexibility options and technological progress in the transition to low-carbon systems. The models range from bottom-up tools to elaborate demand projections, to tools to specifically analyse flexibility options in electricity, heat and mobility, tools for modelling policy measures and, to some extent, tools to analyse impacts on environment and society (Life Cycle consumption of resources and health impacts). SET-Nav uses a modelling framework consisting of five models and sets of indicators to inform the Strategic Energy Technology Plan (SET Plan) on the potential role of technological innovations. The three actions deliver a wide array of insights on multi-sectoral impacts of the decarbonisation of the EU energy system. However, some of the dynamics occurring between scales are missing (e.g. different behavioural patterns in different EU regions and local impacts on environment and ecosystems) and the use of resources is assessed partially in each action (use of critical materials and land and water across different climate scenarios).

Besides the differences in the types of modelling tools and the specific focus of the different analyses, they have all contributed to a large body of knowledge on the potential impacts of decarbonisation. A range of potential pathways to achieve decarbonisation of the EU economy have been identified, as have some consistent trends e.g. the challenges in the industrial sector and segments of transportation, the need for electrification, the potential role of nuclear and CCS. Silo-thinking has been left behind, and multi-sectoral impact assessments have become established practice, in line with the spirit of the Clean Planet for all strategy. An increasing push for open data and their structuring into accessible databases has emerged, with the four LCE21-2015 projects marking a step change in tendencies. Yet, limitations emerge in the scenario practices:

- Analyses are often **one dimensional**. The set of models employed for the analyses is limited and mostly relying on one central modelling framework which takes inputs from others. The use of rigid modelling frameworks with specific tools interlinked with each other has shortcomings. It prevents the use of flexible impact assessment approaches, where the chosen modelling framework depends on the type of question and the scale that need to be addressed (and not vice versa). Such approaches may be unusable and cumbersome for certain type of sector-specific or region-specific analyses. They are also difficult to communicate to the broader community, which may perceive the efforts as not very transparent.
- In a few cases, specific sets of data are employed but **not all the modelling assumptions are entirely traceable**. This prevents scenarios being fully reproduced, by the numerous other tools now existing in Europe. As a result, modelling efforts are potentially duplicated, comparability is hindered and potential synergies between different analyses are not fully exploited.

1.3.2. Stakeholder engagement practice

All of the above actions have relied to a greater or lesser extent on stakeholder consultation, in different ways. For the Energy Roadmap 2050 and the Clean Planet for all strategy, stakeholder consultations mostly occurred before and after the scenario formulation. The former were aimed at collecting views on the needs for a strategy and the focus of the strategy. The latter were aimed at reviewing relevant scenario exercises and comparing them to the effort undertaken for the two strategies. The EU Calculator project engaged with stakeholders in a new way: it created a transparent and user-friendly online tool which stakeholders can access to facilitate understanding of the different pathways. This is in line with the increasing agreement on the need to bridge the gap between scientists, policy makers and the civil society, through open science and transparency.

The MEDEAS, REflex and SET-Nav projects have all invested a great part of their efforts on stakeholder engagement. Besides involving stakeholders in the co-design of scenarios, they aimed at making their tools accessible. Thereby the commitment to using open source tools, data and databases as far as feasible.

Yet, an approach combining all these aspects was missing, namely:

- **Co-designing** scenarios covering several sectors, to be analysed through large and complex modelling frameworks;
- **Documenting** research methodologies through open source tools and data structures;
- **Simplifying** the picture into serious games accessible by non-experts;
- **Sharing** findings with the research community and communicating them to policy-makers through international fora.

1.4. Role and objectives of REEEM

The REEEM project aims to address some of the challenges outlined in Section 1.2, and enhance the practice of decarbonisation modelling, providing new insights and complementing the analyses reported in Section 1.3.

Exploring possible deep decarbonisation pathways, the REEEM analysis gains and communicates a **comprehensive understanding of the system-wide implications of energy strategies** in support of transitions to a competitive low-carbon EU energy society. It does this by recognising the strength of energy systems modelling combined with wider economic analysis, but also the many impacts associated with a low-carbon transition, for the environment and wider society. This means the need to establish a modelling framework that is integrated around and linked to the core energy-economy components, shown in Figure 1.

In addition to the common elements of energy-economy-environment analyses pointed out in Section 1.3, it assesses economy-wide impacts along with distributional impacts within societies in the EU. It assesses the potential implications of **behaviour and consumer's choices** on the pace of the decarbonisation. It devotes great effort to assessing the **use of resources** under different pathways and climate change scenarios. The expression 'use of resources' acquires in REEEM a more comprehensive meaning than in previous efforts and joins impacts on land use, water use, use of critical materials and life cycle assessments and interactions with the ecosystems. It looks at the role of technologies in the transition no longer through the lens of the Technology Readiness Level (TRL) metric, but through the lens of the Innovation Readiness Level (IRL): this **combines 5 key dimensions affecting the diffusion of technologie**s, namely technology readiness (TRL), freedom to operate, market readiness, consumers behaviour and society readiness. In an attempt to shed light on local impacts of the energy transition, five sub-national case studies have been also considered. The messages which are derived from the latter can, to some extent, be transferred to other regions. Although the sub-national case studies are not part of the integrated framework to analyse impacts on a Pan-European level, they have been considered in the data harmonisation process. Between all the aforementioned activities there is exchange of data. The data exchange can fall under the following 4 categories:

1. Two activities have some common input and thus, they align the relevant values.
2. One activity takes some input data which is an output of another.
3. One activity takes some input data which is an output of another, but the latter also takes some input data which is an output of the former.
4. Same as in case 3, but for a number of iterations until the 2 activities reach convergence in certain values.

The following diagram depicts the exchange of data between all the aforementioned activities, while the exact data exchanges are described in the subsequent sub-sections.

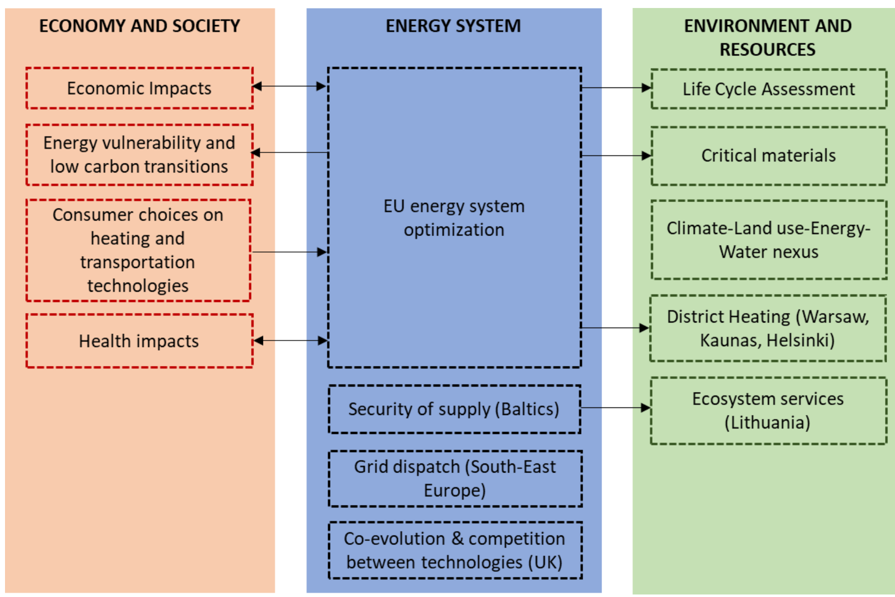


Figure 1. REEEM modelling framework.

The modelling presented in this report cuts **across scales and across sectors**: it analyses medium- and long-term investment needs in Member States to comply with more and less ambitious decarbonisation targets under several scenarios of higher or lower cooperation; it estimates the costs and benefits of the transition across sectors and at a European, regional and local scale; it zooms into regional and local aspects of the transition, e.g. in terms of electricity dispatch, energy supply security, impact on ecosystems and use of resources, without losing connection with the European picture. In brief, the modelling scope is tailored to investigating those challenges outlined in the Clean Strategy for all not yet comprehensively analysed in previous efforts.

The modelling approach is flexible, to avoid lock in into a pre-defined modelling framework, not suitable for the scope of the analysis and for the questions brought up by stakeholders. The modelling framework has been gradually built during the project, starting from the large set of tools available to the Consortium. The data structures have been updated consequently, with the data collection process being transparent and documented.

This allows for input from stakeholders and experts to be incorporated during the modelling process (**co-designing**) and for all the steps of the analysis to be documented and version-controlled (**documenting**). The complex and deep models are then 'translated' using open and accessible tools, so that the insights may be effectively communicated and transferred (**simplifying**): the suite of open source tools and web platforms includes an open source stakeholder engagement model; a business game; and a pathway diagnostics tool. Finally, with inputs from the European Commission's Directorate Generals Energy, Research and Innovation and Joint Research Centre, a European modelling platform has been established, where this modelling effort and others can be presented, with sharing of insights and experiences. This approach should ensure the longevity and continued development of this suite of tools, ensuring consolidation of knowledge and expertise (**sharing**).

The following sections explain how the modelling approach was developed and describe the resulting insights.

2. REEEM pathways

While the development of the REEEM integrated analysis framework and resulting insights are the key novel contributions of this research, another key component has been the scenario pathway design. This section describes the objectives and steps of the process and the resulting REEEM pathways.

This section builds on the earlier deliverable D1.1 – Report on pathway definition [12], which set out the methodology and the key aspects of the pathway design process in the early phases of the project. This has been revisited here in light of further development of the process.

2.1. Objective of the pathways

The REEEM pathways describe three alternative energy system decarbonisation futures. They were designed in the early phases of the project (and subsequently revised) to provide a basis for:

- Investigating key challenges related to the deep decarbonisation of the EU energy system outlined in the Energy Union package and the Clean Planet for all strategy, with a focus on the role and impact of technologies;
- Coordinating the analyses carried out by the modelling groups within the REEEM Consortium on different sectors and scales;
- Allowing stakeholders to provide inputs on the key issues of the decarbonisation.

In line with these objectives, the REEEM pathways do not necessarily represent likely or unlikely futures, nor any best – middle of the road – worst cases, nor any specific sets of policy decisions. Rather they attempt to analyse the effects of potential main dynamics which could occur in a deep decarbonisation transition, namely:

- The decarbonisation effort is mostly undertaken by decarbonisation of the energy supply (mainly decentralised);
- Consumers take on an active role in the decarbonisation;
- Ambitions are raised and all sectors of the economy must act together to achieve the targets.

The following sub-sections describe why the above three themes were chosen and how the pathways were conceived and designed.

2.2. Key features

The REEEM pathways consist of storylines, supported by numbers drawn from model analyses. They all start from the same point in time, where the status quo is represented, in terms of environment, global setting, EU policies, economy, society, technology development. Then, each pathway narrates one way the energy system could transition (in terms of technology investments and use of resources) and what impacts the change could bear on the economy, society and environment.

To fulfil the aims of REEEM expressed in Section 1.4, the REEEM pathways are designed to bear three main characteristics. Firstly, they facilitate the **development of the analytic framework**. To this end, the following practices are carried out prior to the design of the three REEEM pathways:

- The pathways are not established a priori, with a pre-concept of what needs to be analysed. The analysis instead starts with setting up a **pilot case**. The pilot is a simple, yet informative first-attempt analysis of potential trade-offs between opposite energy policy decisions. It is used to coordinate the rolling out of modelling activities by various group within the Consortium. It is set up by providing all modelling teams with a storyline, including one key assumption (e.g. a decarbonisation target). Each team turns the storyline in modelling assumptions according to the structure of their models, without harmonising all assumptions with other teams. While lacking the coherency of a well-calibrated approach, this method is useful as a starting point for modelling activities, as:

  - It gives one first picture of the case that needs investigation in the project and it exposes strengths and weaknesses of the modelling tools available to the Consortium;
  - Consequently, it provides understanding of which tools may be used and at which stage of the modelling process (in REEEM, one tool initially proposed was replaced and others were scheduled for use at a later stage);
  - It serves as a discussion ground for 1) calibration of the large modelling effort to be undertaken in the rest of the project and 2) mapping of the most relevant links between models to be established;
  - Overall, it helps expose that upfront rigidity / hard integration between tools would have narrowed the scope of analysis and potentially prevented its success;

- After the pilot phase identifies the modelling needs and potential steps to address them, the core pathway assessment starts, focusing on few representative pathways, narrating clearly different futures.
- Each pathway is summarised using simple but comprehensive storylines as in the approaches by Shell, and the IAM Consortium.

Secondly, the REEEM pathways are **co-designed** with stakeholders, to collect experiences from sector experts, technology experts, industry and start-ups, civil society and policy makers about the pervasive issues and to turn them in key numerical assumptions. The stakeholders are involved in two stages:

1. They are first asked to highlight 'what matters' in the transition to a low-carbon EU energy system and needs to be considered. They decide key inputs and direction of the analysis, feeding directly into the choice of the overall topics of the pathways.
2. Afterwards, they are called to provide specific inputs and assumptions required for the modelling activities.

Finally, the REEEM pathways are **comprehensive and coherent**. They are comprehensive as they analyse the implications of decarbonisation across several sectors and they represent cause-effect relationships between aspects of the global and European geopolitical setting, the economy, the society, the environment and technology. However, as they cover such a broad range of issues, they are at risk of inconsistency: it is not uncommon that a picture of how the future may play out is inconsistent in the assumption of how different sectors may develop, e.g.: the growth of energy demand may not be consistent with the projected GDP growth; the favourite technology deployment pathways may not be consistent with the consumers' preferences; the planned use of resources on a national scale may conflict with local constraints. The risk of inconsistencies is even higher, considering that stakeholders are involved in the pathway design process. Stakeholders could include in the pathways elements and assumptions related to their own experiences and not necessarily consistent with other stakeholders' assumptions. Internal coherence is ensured by making use of the **morphological approach** [13] from the earliest phases of the pathway design: in stakeholder workshops dedicated to defining the overall theme of the pathways, the future is imagined as divided into six 'dimensions', Global setting, Policy, Economy, Environment, Society and Technology. For each of these dimensions, several potential changes are assumed separately, based on inputs from stakeholders. After all assumptions are collected for each dimension, only combinations of assumptions across the dimensions which are not mutually exclusive are considered and internally coherent storylines derived from them.

Coherency is also checked at later stages of the analysis*, for example during the collection of numerical assumptions for the models, and after model results have been obtained* (the consistency of the results with the overall assumptions on how the global end European geopolitical setting, economy, society, environment and technology may evolve is checked).

2.3. Process of pathway construction

The steps of the process are shown in Figure 2 and described below. Under each step, indication is given about which of the above characteristics it mostly contributes to, highlighted in brackets and bold characters. Step 3 includes a large number of activities, which are subsequently described in detail in Section 3.

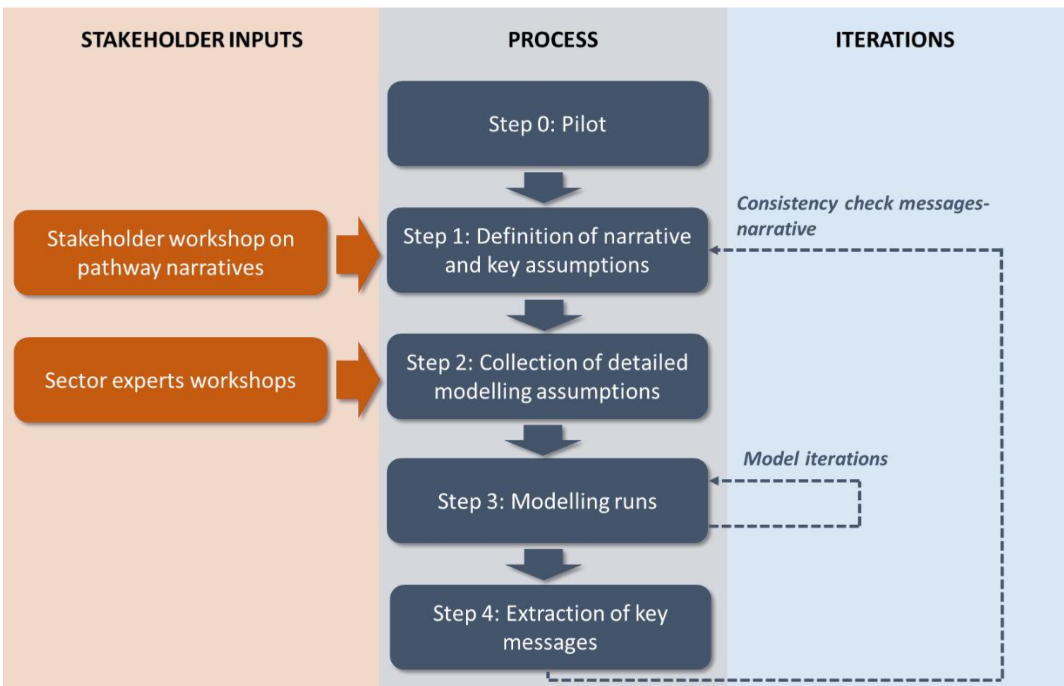


Figure 2. Pathway construction process in REEEM.

- **Step 0: Pilot:** This is a simple, yet informative first-attempt analysis on the trade-offs between opposite energy policy decisions (centralized vs national) leading to the same reduction in GHG emissions. Two cases were analysed in this experiment:
  - Pilot 1 – The EU acts as an Energy Union, where one unique target of 80% GHG emission reduction in 2050 compared to 1990 is imposed and this is shared by the Member States;
  - Pilot 2 – Each Member State imposes its own 80% GHG emission reduction target in 2050 compared to 1990 independently.

Only a limited number of the REEEM modelling tools were used to analyse these two cases. They were calibrated with input data available to modelling teams prior to the project and not necessarily harmonised between teams. The modelling results highlight the cost effectiveness of centralised decisions (i.e. at EU level), with burden sharing based on the marginal abatement costs of Member States. In addition, the pilot allowed the consortium to identify 1) what aspects of the transition may need more investigation among the many aspects that could be undertaken within the scope of the project, 2) which models to use for which part of the assessment, 3) how to link them and 4) according to which time plan. **[Development of the analytic framework]**

- **Step 1: Definition of narrative and key assumptions**: This relies on stakeholder inputs on what matters in the energy transition and what questions need investigating. For this reason, a mixed group of stakeholders were invited to a workshop, including representatives from industry, research institutions and policy makers. The outcome was two storylines and a collection of key assumptions for each, representing the first draft of the pathways *Coalitions for a Low-carbon path* and *Local Solutions*. **[Co-designed, comprehensive and coherent]**
- **Step 2: Collection of detailed modelling assumptions**: The key assumptions defined in the previous step provide a general direction for the analysis, but they are not enough for setting up runs of all the REEEM models. The knowledge of modellers is imperative, as they have to turn the story defined in the previous step into consistent detailed numerical figures. In addition, another round of involvement of sector experts and stakeholders is needed to help define specific numerical inputs. Several stakeholder workshops and interviews of experts were carried out to collect such inputs for models performing different sectoral and regional analyses. **[Co-designed, comprehensive and coherent]**
- **Step 3: Modelling runs**: These are carried out with the modelling tools and according to the methodologies described in Section 3. At this step, comparison between energy and economic models happen, to ensure they use consistent inputs and provide consistent outputs to enable integration. **[Coherent]**
- **Step 4: Extraction of key messages**: From the outputs of all the model runs in the previous step, key messages are extracted on the impacts of transitions to a low-carbon EU energy system and the role of technologies. Though consistency in the model inputs was ensured in the previous steps, the models still have a large solution space and the indicators they provide as output may not be completely in line with the storyline assumed in Step 1. If this is the case, the process is iterated: the narrative and the key assumptions are adjusted (Step 1) and all the following steps are carried out consequently. If for instance, the storyline foresees a certain share of EVs which does not materialise in the first run, the model is calibrated accordingly (using a number of assumptions) in order to achieve this share. **[Coherent]**

2.4. Pathway narratives

At the end of the above process, three comprehensive and coherent REEEM pathways were obtained. As previously mentioned, the three pathways narrate divergent stories revolving around main trends which could emerge in the transition towards a low-carbon EU society:

- **Coalitions for a Low-carbon path (CL)**: *energy carrier suppliers take on the highest burden in the decarbonisation of the EU energy system, with consumers observing this transition in mostly a passive way and being reactive to policies as they emerge.*
- **Local Solutions (LS)**: *consumers (especially households) engage more proactively in the transition, through choices on end use appliances, energy efficiency measures and transportation technologies.*
- **Paris Agreement (PA)**: *the EU undertakes an ambitious decarbonisation effort, with a target of 95% reduction of CO_2 emissions by 2050. This overshoots the Paris Agreement pledges. Both energy carrier suppliers and consumers engage in the challenge.*

The pathways are described in the following sections. The key assumptions are listed in greater detail in Appendix A, whereas all the numerical inputs of all models (where not covered by copyright) are available in the REEEM Database and on REEEMPathways.org.

2.4.1. Coalitions for a Low-carbon path

Economic growth in the EU restarts after the financial crisis, but at different speeds across Member States. Affinity on trade, labour, defence and energy security policy arises between groups of countries, depending on their geographic location, economy and domestic availability of resources. Under a general political recognition of the impacts of climate change, the EU sets itself on a high decarbonisation path. The emission targets for sectors included in the Emission Trading Scheme (ETS) are complied with and overshot in some instances, leading to 83% cut in energy-related CO_2 emissions by 2050 compared to 1990. On the contrary, sectors not regulated by the ETS rely more on consumers' choices and reduce emissions to a lesser extent. Additionally, despite the common general ambition to fulfil the Energy Union Strategy and the Paris Agreement, coalitions of more and less willing Member States emerge, setting more and less ambitious decarbonisation targets for non-ETS sectors.

A similar coalitional pattern emerges outside Europe, where countries being most affected by climate change extremes and/or having the means take on more climate change mitigation actions than others.

Energy carrier suppliers and large industrial users subject to ETS targets take up large part of the decarbonisation effort. On the contrary, even though the effects of climate change are observed in Europe (especially with Southern regions becoming on average warmer and drier), not all consumers across the EU perceive it as likely to affect their lives significantly. Therefore, they tend to hold on to their current consumption behaviours and transition more slowly to energy efficient end-use appliances, unless pushed otherwise by top-down policies. This ultimately causes the levels of ambition for sectors not included in the ETS (such as residential and transportation) to be generally lower and to vary between Member States.

Under the pressure of policy targets, utilities undertake large investments in centralised renewable energy supply options. In the electricity sector, solar photovoltaic fields and wind farms (both onshore and offshore) dominate. Innovation in offshore wind by breakthrough of floating platforms contributes to the penetration of the technology in the market. Biomass-fired power plants and, to a minor extent, Carbon Capture Storage (CCS), gain a small share. Decarbonisation measures in end use sectors remain more limited. The rate of renovation of residential buildings increases considerably compared to the current rate, but not enough to guarantee complete renovation of the stock by 2050. Technologies such as heat pumps and solar thermal are not cost competitive enough to gain a share in the energy mix.

This pathway was agreed upon as a useful base case for REEEM by the participants of the First Stakeholder Workshop held on October 6th 2017 in Brussels. It resembles characteristics of two of the five scenarios described in the 'White paper on the future of Europe' discussed by President Jean-Claude Juncker at the State of the Union 2017: 'Carrying on' and 'Those who want more do more'.

2.4.2. Local Solutions

The transition to a low-carbon EU energy system is accelerated by communities and households proactively making choices that are low-carbon, such as on household energy provision (i.e., stronger efforts to retrofit homes, purchasing of energy efficient (and smart) appliances, replacement of heating systems).

This moderately stronger societal push is underpinned by a *recognition* of the increasing and stronger climate signals, both within and outside of Europe (i.e. more pronounced and frequent flooding events in Europe, particularly in the winter, and longer and more extreme hot spells during the summer months, leading to wild fires, water shortages and heat-related health impacts).

The pace of change in the demand for low-carbon goods initially leaves decision makers in the EU lagging behind in their policy efforts to drive the transition. This lag is particularly evident out to 2030 due to the initial rapid rate of change.

Meanwhile, Member States are set on course to 80% reduction in energy-related GHG emissions by 2050 as compared to 1990. However, coalitions of more and less willing countries set different targets for sectors not covered by the Emission Trading Scheme, depending on their geographic location, economy and domestic availability of resources. A coalitional pattern similar to the one within the EU is identifiable outside Europe. These aspects are similar to the Coalitions for a Low-carbon path.

This pathway was suggested by participants at a scenario workshop in Brussels on October 6th 2017 as an interesting scenario narrative to explore in the context of the REEEM project.

2.4.3. Paris Agreement

After the release of the IPCC Special Report on Global Warming of 1.5C, the effects of climate change obtain increasing media coverage. Climate strikes start worldwide and put pressure on Governments and public opinion. Awareness of the effects of climate change increases globally, both on the side of Governments and on the one of citizens.

In the EU, green parties increase their representation in the Parliament. At the same time, the EU emerges stronger from the Brexit negotiations and the financial crisis. This leads to growing alignment between Member States on environment and climate matters, as envisaged by President Juncker in two scenarios of the 'White Paper on the future of Europe'. The EU makes a political commitment to taking the world lead in fulfilling the Paris Agreement and sets a target of at least 95% reduction of GHGs emissions by 2050 compared to 1990 levels.

On the other side, the increased awareness by citizens results in behavioural shifts and green choices. These come especially when replacing household heating appliances and cars which reached end of life or when offered the chance to renovate old, inefficient buildings.

Stringent policies provide the incentives and the policy certainty for large consumers and energy carrier suppliers to also shift towards low-carbon options. Industrial consumers replace fossil fuels in their primary energy supply for heating with biomass and electricity. As Carbon Capture and Sequestration technologies become commercial, they are applied to different power generation units. Energy carrier suppliers also invest significantly in renewable options, particularly for large-scale centralised electricity generation. Overall, increased electrification of the energy supply is observed.

The decarbonisation effort undertaken in the EU demonstrates the feasibility of a low-carbon economy and opens market opportunities for other economies, where parts of the value chains of low-carbon technologies are located. In these economies, investments in the production of low-carbon technologies increase quickly and policies are put in place to support these investments. The United States and China take advantage from large economies of scale and solid market shares in the production of low-carbon technologies. This soon gives them a competitive edge and the two economies are set on a path towards decreasing GHGs emissions to Paris Agreement levels. Other world economies follow the same path.

In the beginning, the shift from the technologically mature and short-term secure fossil fuel supply and the large infrastructure investments put a burden on European economies. GDP growth across Member States is slowed, hindering the competitiveness of the EU versus China and the United States. However, the rate of growth increases closer to 2050. Furthermore, the projected economic benefits from avoided externalities are important.

This pathway was first discussed at the REEEM General Assembly in Zagreb 14-15 May 2018 as an important future to explore in the context of the REEEM project.

2.4.4. Summary of the pathways

The key characteristics of the storylines underpinning each pathway and the relative main assumptions are summarised in Table 1 below. Where the numerical assumptions include several items or historical series, more information may be found in Appendix A and in the REEEM Database.

Table 1. Summary of key assumptions of the REEEM pathways.

	Coalitions for a Low-carbon path	*Local Solutions*	*Paris Agreement*
Economy	***Growth at different speeds*** *Population and GDP growth from The 2015 Ageing Report* [14] *and EU Reference Scenario 2016* [15]		***Competitiveness of the EU potentially affected by rapid shift to low-carbon economy*** *Population and GDP growth from The 2015 Ageing Report* [14] *and EU Reference Scenario 2016* [15]
Policy	***Stronger decision making / policy parallels within clusters of Member States*** *Binding decarbonisation targets set by the EU 2020 Climate and Energy Package and the 2030 Climate and Energy Framework*	***Pace of local solutions leaves policy making lagging behind in the near to medium term*** *Binding decarbonisation targets set by the EU 2020 Climate and Energy Package and the 2030 Climate and Energy Framework; 83% decarbonisation target for the ETS sectors in the EU as a*	***The EU takes the lead in fulfilling its obligations under the Paris Agreement*** *Binding decarbonisation targets set by the EU 2020 Climate and Energy Package and the 2030 Climate and Energy Framework*

	83% decarbonisation target for the ETS sectors in the EU as a whole in 2050, compared to 2005 levels; *Ambitions on non-ETS sectors different by clusters of Member States*	*whole in 2050, compared to 2005 levels;* *Ambitions on non-ETS sectors different by clusters of Member States*	*by 2050, 95% decarbonisation target for the ETS sectors in the EU as a whole, compared to 2005 levels*
Society	***Passive society in the transition***	***Change of EU citizens' perception towards climate change and resulting behavioural shifts***	
Global setting	***Global push to climate change mitigation driven by some regions / countries*** *Emission trajectories for regions outside the EU aligned with Reference Technology Scenario (RTS) of International Energy Agency (IEA) Energy Technology Perspectives 2017* [16]		***Global R&D push to climate change mitigation*** *Emission trajectories for regions outside the EU aligned with 2 Degree Scenario (2DS) of IEA Energy Technology Perspectives 2017* [16]
Environment	***EU's general recognition of the impacts of climate change*** *Changes in heating and cooling degree days computed assuming (Representative Concentration Pathway) RCP4.5*	***Citizens' recognition of the impacts of climate change.*** *Changes in heating and cooling degree days computed assuming RCP4.5*	***General strong recognition of the impacts of climate change*** *Changes in heating and cooling degree days computed assuming RCP2.6*
Technology	***Large penetration of centralised renewable energy supply options*** *Limited penetration of solar heat pumps and renovation rate of buildings in residential sector;* *Higher push to decarbonisation of industrial processes;* *Breakthrough of floating platforms for offshore wind*	***Accelerated renovation of residential buildings and uptake of low-carbon technologies in households and road transport*** *Limited penetration of nuclear and CCS;* *Higher renovation rate of buildings in residential sector;* *Higher decarbonisation of transportation and residential sectors;* *Breakthrough of Building-Integrated PV;* *Breakthrough of Li Ion-Air batteries*	***Large penetration of low-carbon energy technologies both in centralised supply and at end-use level*** *Investments in biomass-CCS allowed;* *Higher renovation rate of buildings in residential sector;* *Breakthrough of floating platforms for offshore wind* *Breakthrough of building-integrated PV;* *Breakthrough of Li Ion-Air batteries*

2.5. Case studies: zooming into regional and sectoral challenges

The pathways described in the previous subsections are analysed with a suite of tools capable of investigating the economic, environmental and social impacts of decarbonisation in the EU and in each Member State, the insights from which are described in Section 3. However, EU-wide and national scale analyses may not capture challenges and opportunities experienced in the decarbonisation process within specific localities or regions. For this reason, the set of pathways defined above are also applied in five sector- and region-specific case studies.

These REEEM case studies analyse impacts of deep decarbonisation pathways in selected geographical areas and with focus on specific challenges. All of the case studies have either national (single Member State), trans-national (several Member States) or sub-national focus, but address issues that have broader relevance and are applicable outside of their geographical scope. In other words, they provide important insights into issues that are worth examining in the whole EU. The areas of interest of the five case studies are:

- Ecosystem services (Lithuania);
- Coevolution and competition of technologies in a low-carbon system (United Kingdom);
- District heating (Helsinki, Warsaw and Kaunas);
- Regional energy security (Baltic region and Finland);
- Grid and dispatch (South-Eastern Europe).

Given their specific focus, the input assumptions of the case studies need to be much more spatially resolved than those of the Pan European studies described so far. To give an example, in TIMES PanEU assumptions are made about policies and technology options for the decarbonisation of Poland, Finland and Lithuania on a ***national scale***. However, no information is given on policies and availability of technologies ***on a city scale***. The range of policy options and available technologies for cities which may comply with the national plans represented in TIMES PanEU is very large. Therefore, further assumptions are needed in the case study analysing district heating options in Helsinki, Warsaw and Kaunas, which cannot be taken from TIMES PanEU. Such assumptions are made by modellers in the REEEM Consortium based in the analysed areas, with inputs from sector/local experts through dedicated workshops. The process happens in parallel with the one of definition of the three REEEM pathways, as depicted in Figure 3.

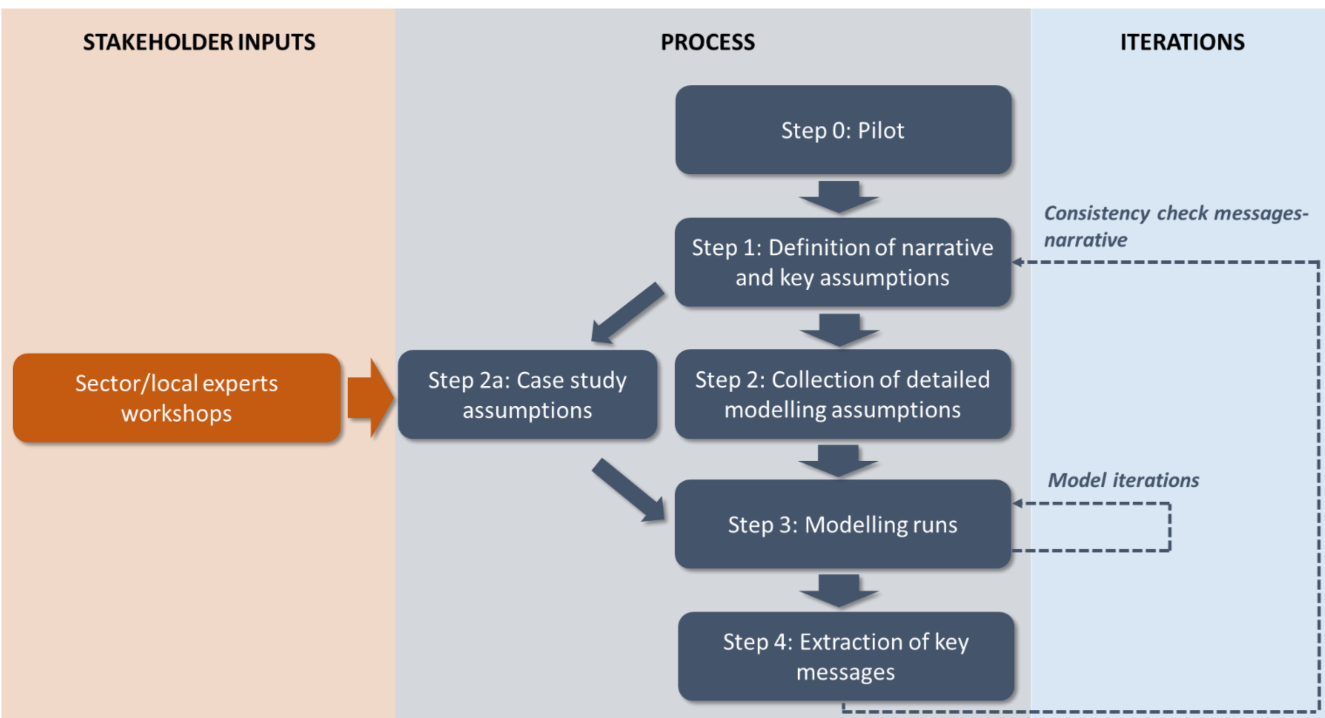


Figure 3. Process of case study definition.

Consistency with the assumptions of the PanEU studies presented in the previous sections is ensured by carrying out a process of harmonisation between TIMES PanEU and the models used for the case studies for all input assumptions which are common. All the other assumptions made by the modellers and by the experts are made so as to comply with the qualitative EU-scale narrative presented in Section 2.4. Therefore, each case study analyses a ***wide range of sensitivities*** around the main trends depicted in the three REEEM pathways. The choice of such sensitivities depends on the specific challenges analysed in each case study. The sensitivities are named differently in each case study.

2.6 Technology innovation and behavioural analysis

In order to provide the above described comprehensive assessment and fill gaps in previous analyses, deep assessments of technology innovation and behaviour were carried out in REEEM. Those contributed to the formulation of pathways and, hence, are described below. However, as they also deliver insights which may lead to policy messages, the latter are given in Section 3.

2.6.1 Technology innovation in the pathways

A large set of energy supply and end use technologies is available and new ones may be available in the future, to meet energy needs and decarbonisation targets, as highlighted by the Strategic Energy Technology (SET) plan [17]. The pace of this transition to a low-carbon energy system may be affected incrementally or from breakthrough innovation in these technologies, co-development or competition between them, economies of scale, market barriers, regulatory and behavioural barriers and other elements. In order to understand how the decarbonisation may happen, it is necessary to assess the role of technologies in the process, how they may impact the decarbonisation and enablers/barriers to their adoption. The results of the modelling activities highlight the pervasive challenges and opportunities related to different technologies and their impacts on investment needs and operational profiles (energy systems optimisation), related emissions (health and environmental impacts), final energy prices (energy vulnerability), Life Cycle use of resources and critical materials, use of land and water.

The study of enablers and barriers is part of the pathway design process, instead, as it helps understand which technologies may play a role and what can be expected in terms of their future developments. This analysis was led in REEEM by EIT InnoEnergy, with inputs from experts and a large network of stakeholders and industrial partners. Three technology groups were analysed: selected **renewable energy technologies**, expected to play a fundamental role in the decarbonisation process; selected **storage technologies**, representing one of the potential flexibility options to back up the variability of wind and solar (alongside smart appliances, smart grids, extension of interconnections, system integration options and fast-ramping generation) and presenting high innovation potential; **energy efficiency in buildings**, potentially one of the low-hanging fruits of decarbonisation. The product of the analysis consisted in three **Technology and Innovation Roadmaps** and three related **Innovation Readiness Level assessments**, one for each of the technology groups analysed. The findings of these studies are included in the pathway narratives and are turned into numerical modelling assumptions where applicable.

The Technology and Innovation Roadmap focusing on renewable energy analyses three groups of technologies, each having different potentials in accessing the European energy market. These technology groups are wind power (onshore and offshore), solar PV and ocean power (tidal and wave). For each technology group, several technological innovations and improvement opportunities have been listed in order to support the development and deployment of these technologies in the European electricity market. The outcomes shed light on possible technological innovation and market solutions that can facilitate attaining the European targets for 2030 and

2050. Stakeholder inputs for this roadmap were collected during a workshop held at InnoEnergy premises in Brussels on May 19th, 2017. The roadmap is available here. Findings on potential breakthroughs in wind offshore, in the use of floating platforms are considered in the Coalitions for a Low-carbon and Paris Agreement pathways and on Building-Integrated PV in the Local Solutions and Paris Agreement pathway. The former fits the narrative of strong changes on the side of energy supply carriers, whereas the second fits the case of deep changes towards the end uses.

The Technology and Innovation Roadmap on storage delineates into 5 different applications of storage technologies namely, grid-scale, behind-the-meter, off-grid, mobility and thermal storage applications. The essential requirements and technical characteristics of each application are discussed and highlighted. Several recommendations and actions are listed in accordance on how to increase the role and potential of energy storage technologies in the European energy market. Stakeholder inputs for this roadmap were collected during a workshop held at InnoEnergy premises in Brussels on April 17th, 2018. The roadmap is available here. Findings on potential breakthrough in Li-air batteries are considered in the Local solutions and Paris Agreement pathway, where the large penetration of technologies making use of batteries (such as electric vehicles) may push their deployment.

The Technology and Innovation Roadmap on energy efficiency in buildings focuses on technologies and market solutions that enable enhancing energy efficiency. Buildings contribute to 40% of the overall CO_2 emission in Europe and accordingly, improving their energy efficiency has a high potential to reduce European emission base, especially where changes in heating and cooling demands are expected as a result of climatic changes. The roadmap sheds lights on three categories of technologies including buildings facades, heating and cooling technologies and household appliances. Based on the findings of this roadmap, a number of policy and market recommendations are listed on how to further improve the development and deployment of the markets and technologies for buildings' energy efficiency in Europe. Stakeholder inputs for this roadmap were collected during a workshop held at InnoEnergy premises in Brussels on March 19th, 2019. The roadmap is available here. Findings on potential rates and depth of renovation of buildings as a result of a mix of measures are included in all REEEM pathways. From Coalitions for a Low-carbon path, through to Local Solutions and Paris Agreement, increasing rate and depth of renovation are considered.

In parallel with the technology roadmaps, three Innovation Readiness Level (IRL) assessments are carried out and relative reports issued. The IRL is a new metric introduced by InnoEnergy for measuring the innovation and diffusion potential of technologies. It includes, but expands the Technology Readiness Level (TRL) concept. The IRL combines five indicators of maturity:

- Technology Readiness Level (TRL);
- Freedom to operate (IPRL);
- Market Readiness Level (MRL);
- Consumer behaviour (CRL);
- Society (SRL).

As such, the IRL explains that technology innovation could be not the only reason explaining the success or failures of innovative technologies in accessing the markets. The IRL reports explore factors and processes that are prerequisites for successful technology development and access to a market along the five dimensions.

Similar to the roadmaps, the developed IRL reports focus on three groups of energy technologies, identical to the ones of the roadmaps. The first IRL reports focus on storage technologies, in particular, Li-ion, flow batteries, supercapacitors, compressed air energy storage and hydrogen technologies. The second IRL report focuses on renewable energy technologies and assesses IRL of onshore and offshore wind energy, solar PV and tidal and wave energy. The final IRL reports are dedicated to buildings' energy efficiency technologies and evaluate solar tiles (as a type of smart roofs), heat pumps and wood fibre insulation materials. The findings of IRL reports highlight points in innovation processes of each of the studied technologies which can positively influence their success in accessing the markets.

For the storage technologies, a literature review was conducted to collect right techno-economic data for the REEEM models. These cost projections then have been consolidated with experts and put into the right formats in order to be integrated into the REEEM models (in particular in TIMES PanEU). The cost projections for renewable energy technologies, studied in the second roadmap, were conducted using DELPHOSTM®. DELPHOSTM® is a tool developed by InnoEnergy which studies the impact of innovation on the levelised cost of energy technologies. The results, again, have been consolidated with experts for validation and improvement. In the final roadmap on energy efficiency in buildings includes two heat saving models to provide cost projections for the energy efficiency technologies in buildings. The first model is dedicated to the energy efficiency of technologies utilised in buildings for heating and cooling by 2050 and second model focuses on heat saving potential in relation to cost as a step function.

2.6.2 Behavioural analysis

Models built for strategic European energy policy assessments often make compromises in terms of how they represent human behaviour and decision making, which is a design choice that is usually forced on model designers by a lack of data availability on consumer preferences. As a result, it is often difficult for energy models to depict uptake levels and technology diffusion rates for new consumer technologies in households that are in line with real world observations. As part of the REEEM project, a multinational research team from the United Kingdom (UK), Finland and Croatia took steps to address this critical shortcoming in energy models by carrying out detailed surveys on 3000 European households in their respective countries, and using these to build databases of attitudes, preferences, and lifestyles. Discrete choice modelling, a technique used to understand which factors drive decision making, was used to identify the critical determinants of consumer purchases in domestic heating and privately-owned vehicles. It was found that costs are usually an influential factor when it comes to technology choice, but also that there are a range of other considerations that exert a powerful influence on decision-making.

3. Messages from the modelling framework

This section gives a brief description of the modelling activities and other types of analysis that contributed to the impact assessment, investigating the REEEM pathways described in Section 2. Moreover, it is explained how those activities link to each other in order to create the REEEM integrated framework. Each description is followed by the main messages that emerge from the relevant activity, accompanied by supporting graphs and charts that point out the indicators selected. The modelling activities are split into the following thematic categories.

Energy System and Technology

- Energy system optimisation (EU);
- Technology innovation in the pathways;
- Case study on grid and dispatch in South Eastern Europe;
- Regional energy security case study of the Baltic region and Finland;
- Coevolution and competition of technologies in a low-carbon system: a UK case study.

Economy and Society

- Economic impacts (EU);
- Health and Environmental impacts (EU);
- Energy vulnerability and low-carbon transitions (EU);
- Behavioural analysis (EU – described in Section 2).

Environment and resources

- Life Cycle Assessment (LCA) (EU);
- Critical materials (EU);
- Water-Climate-Energy-Land use nexus (EU);
- Ecosystem services case study;
- Case study on district heating.

3.1. Energy System and Technology

3.1.1. *Energy system optimisation*

The energy system optimisation in REEEM is carried out based on the Pan-European TIMES energy system model (TIMES PanEU). The latter is built with the TIMES model generator, developed and maintained within the Energy Technology System Analyses Program (ETSAP) of the International Energy Agency (IEA) to carry on policy and scenario analysis based on technical-economic energy system models [18]. TIMES PanEU is a bottom-up linear partial equilibrium model with the complete European energy system for the time horizon from 2010 up to 2050. The model minimises the energy system cost according to given energy demands, energy technologies and policy requirements. All costs are discounted to the reference year which is used to calibrate the energy balances and technology stocks based on statistical data. TIMES PanEU covers all European Union Member States as well as Norway and Switzerland. Each country is modelled as a single region with implemented trading mechanisms enabling exchanges and interactions between these. The model horizon is divided in five-year intervals, with one year comprising twelve time slices (four seasonal and three day levels). The reference energy system of the model represents all energy and material flows across the entire energy system, starting from the supply of resources and ending with fulling different energy demand services. It is split into seven main sectors (supply, electricity and heat production, industry, commercial, residential, agriculture and transport) representing different demand structures and transformation steps. All sectors can interact with each other and different indicators (e.g. energy use) are calculated through each step in the reference system. To analyse environmental policies, GHG (CO_2, CH_4, N_2O) and local air pollutants ($PM_{2.5}$, PM_{10}, NO_X, SO_2, NH_3, NMVOC, CO) are included in the model.

The TIMES PanEU energy system model sits at the core of the integrated framework, and is linked to other modelling and analytical activities (further described in the next sub-sections).

It has undergone some development in this project to ensure robust integration with other modelling and analytical tools. The main steps of the development are here summarised:

1. *Technology innovation outlooks* developed in Technology Innovation Roadmaps are integrated, with focus on storage options, renewable energy technologies and heat savings in residential buildings. Those roadmaps provide certain techno-economic figures which are used as input parameters in TIMES PanEU.
2. An assessment of the *health impacts of emissions* by the energy sector is carried out. For this purpose, a soft-link is established between TIMES PanEU and EcoSense, where the former takes figures from the latter and uses those as externalities.
3. A step is to improve representation of some key *regional and local specificities of the energy system development* of selected EU countries. This part builds on a harmonisation process between TIMES PanEU and case study models focusing on energy supply security and grid and dispatch with the help of the experts in the case study regions, existing base year capacities and electricity trade flow between the regions are improved and the planned capacities from ENTSO-E [19] are incorporated into the model as well.
4. A further step is the inclusion of *impacts of consumers' technology choices*. The main drivers of consumers' choices regarding heating and transportation are drawn from surveys through a novel discrete choice model. Selected insights are included in TIMES PanEU. The methodology is explained in deliverable D6.1 – Integrated Energy System Model, available here.
5. The *effect of climate changes on heating and cooling demand* across the EU is evaluated starting from climate databases. In turn, the effect of these changes on the energy demand-supply balance and investment requirements is assessed through TIMES PanEU.

Finally, economic impacts of the energy transition are integrated to TIMES PanEU with a soft-link with NEWAGE. In this case, **the two models have been coupled**, with certain data flows related with the electricity generation back to NEWAGE und in return GDP and industrial developments incorporated into TIMES PanEU to update the end-user and industrial demand figures until the models reached convergence. The detailed information for the process is given in deliverable D6.1 – Integrated Energy System Model, available here.

The complete model structure, as well as the advancements carried out for the REEEM project are described in deliverable D6.1 – Integrated Energy System Model, available here.

3.1.1.1. Main insights

Message 1: Breakthroughs in RES technologies could determine the direction of the energy transition

Innovation in RES technologies could play a key role in the direction of the energy transition. Selected breakthroughs in solar and wind technologies, judged likely by experts within the industrial stakeholder's network of InnoEnergy, are analysed in deliverable D2.1b - REEEM Innovation and Technology Roadmap: Renewable Energy Integration. One of the breakthrough scenarios is expected in the solar PV industry with the Building Integrated Solar PV technology. Based on the pathway definitions, this breakthrough scenario is applied in the Local Solutions (LS) and Paris Agreement (PA) pathways (see assumptions in Appendix A). The effect of such a breakthrough is seen in the installed capacity deployment in the electricity sector in Figure 4.

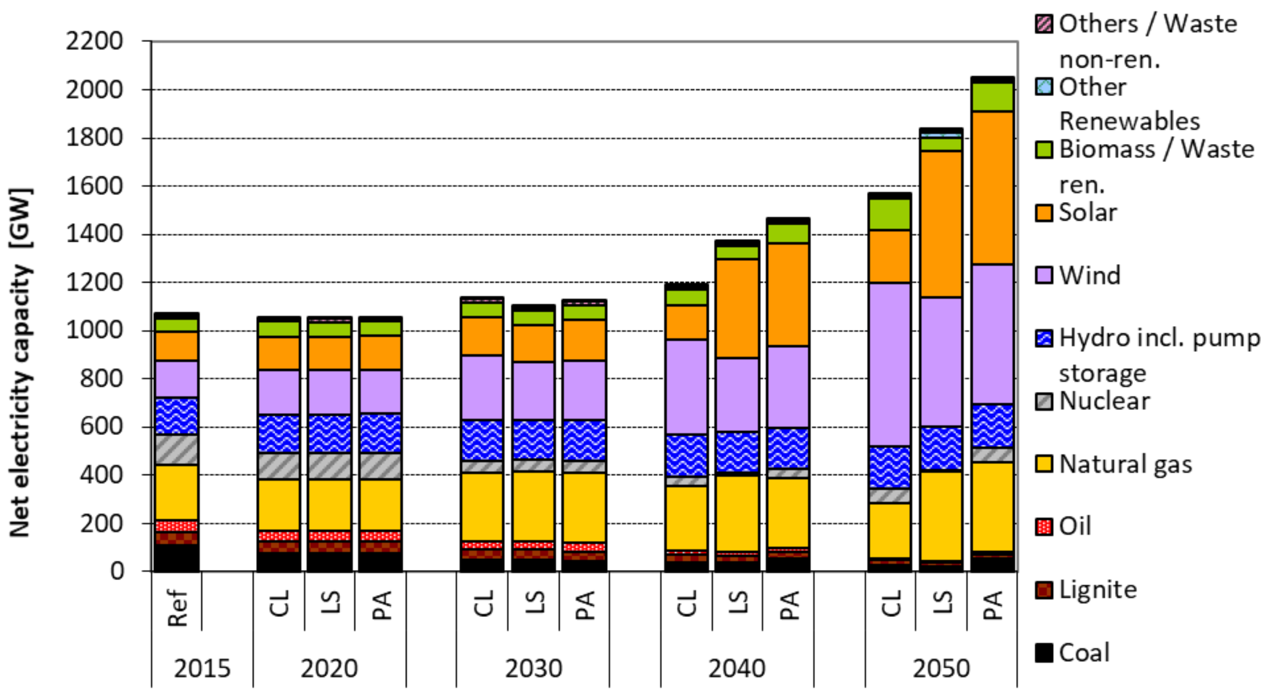


Figure 4. Net electricity generation capacity in the EU28 [GW].

Another key breakthrough may be in wind offshore, with the diffusion of floating platforms for wind turbines. This is assumed in the CL and PA pathways. According to these figures in deliverable D2.1b - REEEM Innovation and Technology Roadmap: Renewable Energy Integration, offshore wind becomes quite competitive with onshore wind and even with Solar PV. Additionally, the availability factor is higher, due to the higher availability of the resource off the coast. With this competitive advantage, offshore wind has relatively high potential and it is chosen over onshore wind and solar technologies especially after 2030 as a generation technology. Another advantage of offshore wind over onshore is the fact that it does not compete with other sectors for land which - especially in the more densely populated countries- can be an issue. This aspect, however, is not captured in this modelling activity. The technological advancements in certain mitigation technologies may have a significant impact on the direction of the energy transition. Nevertheless, it is important to stress that the high variability of most renewable energy technologies needs a more refined temporal resolution in order to capture their dispatch ability. The grid and dispatch case study sheds light on whether the suggested capacity expansion can be dispatched in certain South-Eastern European countries. Given the significant effect that such breakthroughs could have, the establishment of supporting mechanisms to expedite their occurrence could be a way for the transition to materialize sooner and at a lower cost.

Variations by pathway

It is clear that the consideration of breakthroughs in the modelling leads to a higher share in the final capacity mix which also determines the direction of the transition. In CL, where breakthrough is not considered for solar, the solar capacity in 2050 is less than three times compared to LS and PA pathways results. In general, the share in those pathways is almost similar which is indication that solar could play a major in a deep decarbonisation scenario. On the other hand, as the offshore wind breakthrough scenario is applied in CL and PA pathways, the higher deployment of this technology is observed in both of the pathways. The deployment is higher in the CL pathway compared to PA as this technology is applied as only breakthrough scenario. In the PA, both of the breakthroughs show their effects along with the higher reduction target.

Message 2: Power generation expected to rise

In all three pathways, the total capacity of the power system and the generation are expected to rise. This can be attributed to the fact that decarbonisation leads to higher demand for renewable electricity. The power generation capacity expansion will cause changes to the system. Those changes could be of either operational or economic nature. From an operational point of view, the higher share of renewables will make the system more susceptible to variability which needs addressing from an institutional point of view (e.g. integration of smart grids). For this reason, the model suggests that a certain capacity of natural gas will remain in the system even in 2050, to be used as a backup option, with much reduced full-load hours compared to today. From an economic point of view, this transition will cause the system to shift its cost from operational to capital. This requires a shift in the financing schemes and whether the consumer funds the investment directly or indirectly, depends on the level of system decentralisation. Figure 5 shows the energy mix in terms power generation for the three pathways.

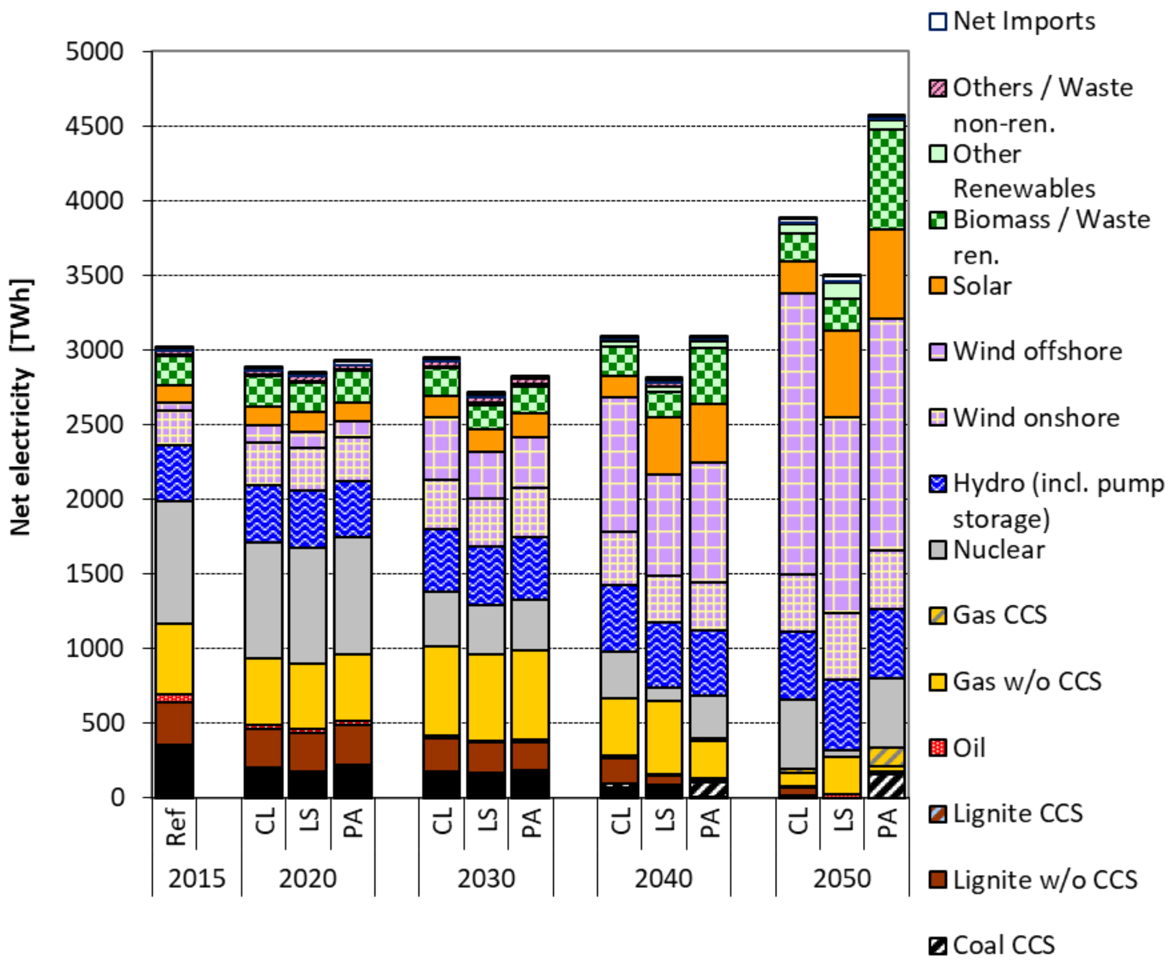


Figure 5. Net electricity generation in the EU28 [TWh].

Variations by pathway

In the LS pathway, the centralised technologies are limited to support the motivation of the pathway. This means that the nuclear power plant deployment, together with the CCS power plant options are not allowed except for the already planned capacities as there are some pilot projects scheduled in Netherlands, Germany, Spain and Poland. Therefore, the system is forced to move towards decentralised generation options, like Building Integrated Solar PV, which leads to higher power generation capacity compared to the CL pathway; although, these two pathways have the same reduction targets at the EU level overall. However, because of the full load hours of the decentralised technologies which means lower capacity factors compared to conventional technologies, lower electricity generation is observed in the LS compared to the CL pathway. In the PA pathway, the overall power generation is higher comparable to the other two pathways. This would probably mean that an ambitious decarbonisation target such as that proposed in the PA would require coordinated effort by different institutes as, for example, the electrification of industry could rely more on self-funding by the industries themselves rather than the government.

Message 3: Biomass appears to have a significant share in the energy generation – Implications must be examined

Biomass and the energy carriers based on biomass can be defined as mitigation options in different parts of the energy system. However, the exploitable potential of biomass depends on a plethora of local constraints which are not necessarily captured at a national level. One of these factors relates to the intensity of biomass use. Trade-offs with other sectors in which the use of biomass is imperative need be examined as part of energy planning. The REEEM case study on ecosystem services reveals such trade-offs and suggests different mix for the allocation of forestry resources.

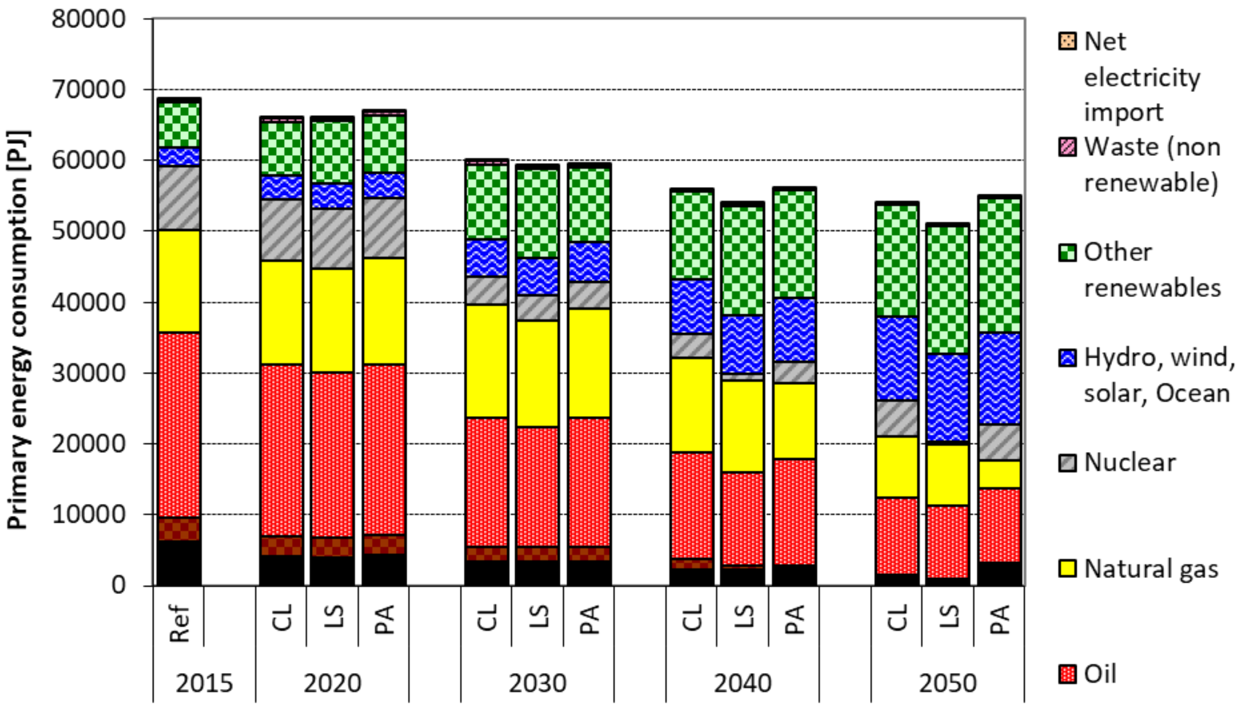


Figure 6. Primary Energy Consumption [PJ].

Variations by pathway

The utilisation of biomass seems to be consistently cost-competitive across decarbonisation pathways. The balance of use across sectors varies according to the pathway narrative and the economically optimal allocation of bioenergy given its high system value. In the CL pathway, it is mainly utilised in the industry sector, as shown in Figure 7, while in LS the priority is given to the transport sector to meet the pathway's sector-specific targets (Figure 8). On the other hand, in the PA pathway, priority is given to the electricity sector due to biomass CCS availability as a mitigation option. Biomass will be a limited resource and the specific targets will largely determine where it will be most valuable to use it.

The 80% share of renewables in the gross final energy consumption is achieved only in the PA pathway. With potential reduction in the amount of biomass that can be considered as exploitable (when trade-offs with other sectors are better examined), the achievement of the renewable energy target will become even more infeasible.

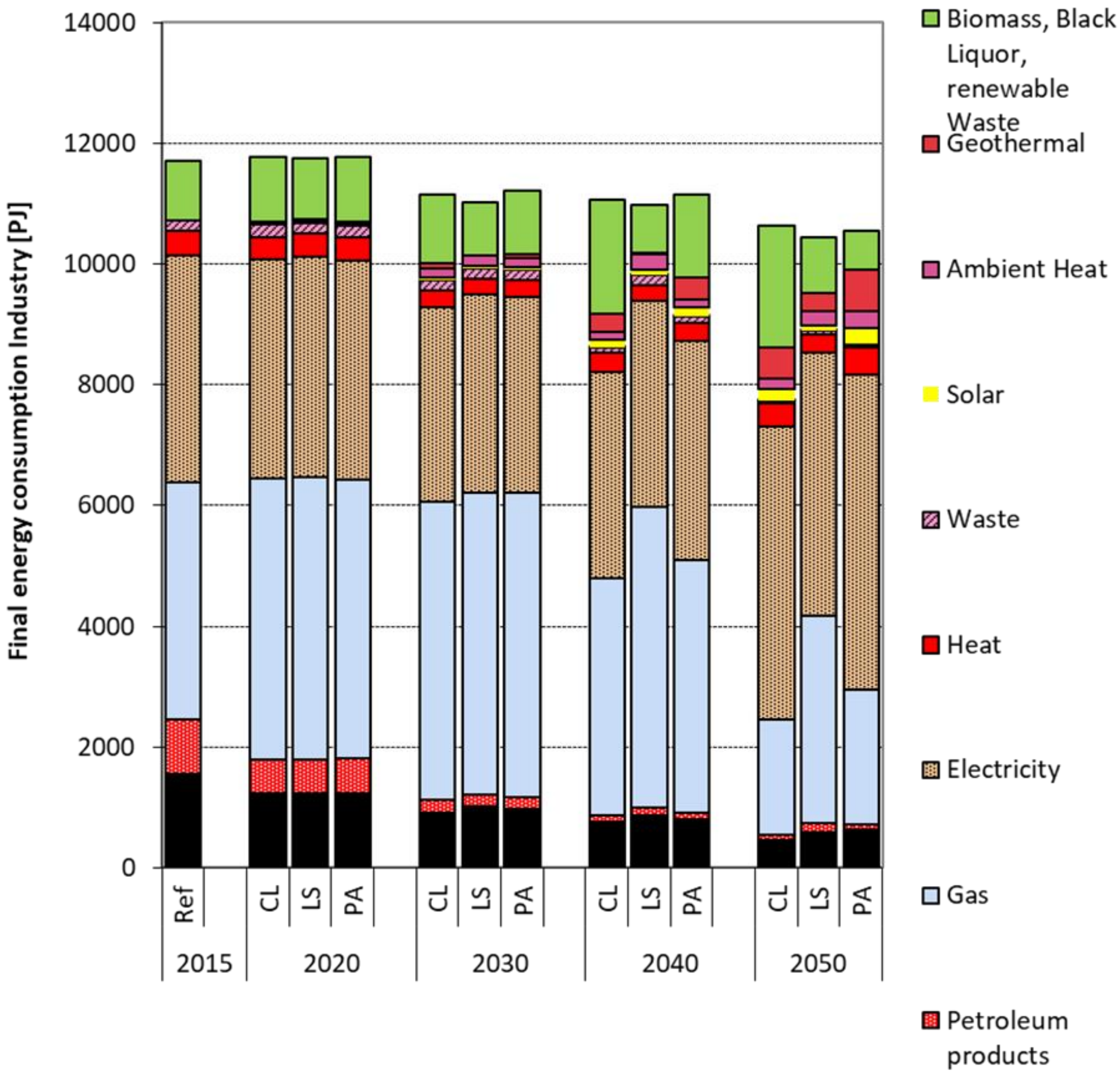


Figure 7. Final energy consumption by industry [PJ].

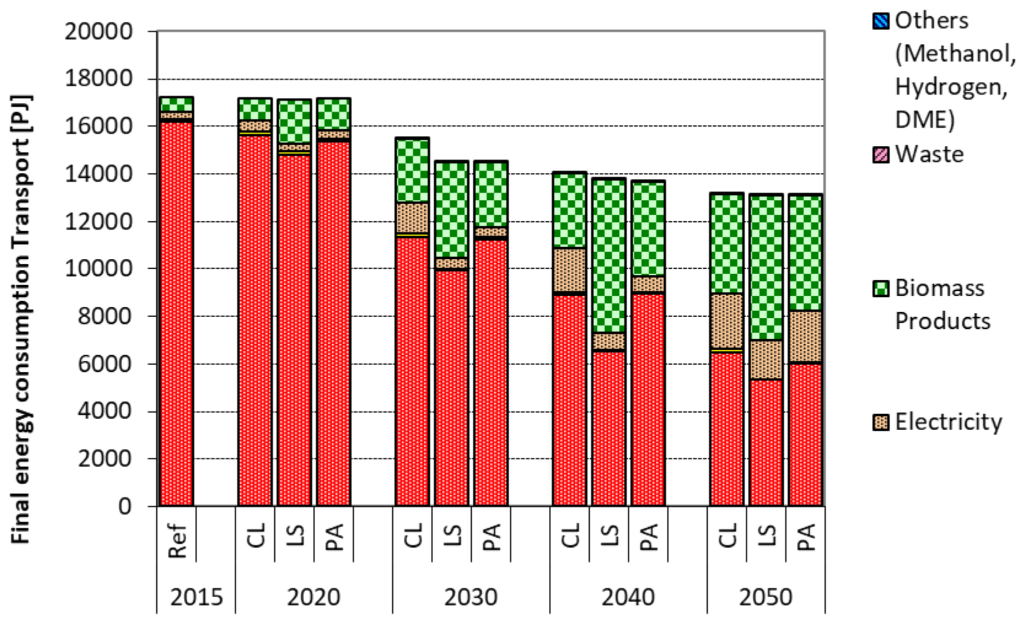


Figure 8: Final Energy Consumption by Transport [PJ].

Message 4: Beyond 80% reduction such as 95% is feasible in the energy system.

In PA pathway, the reduction target 95% is feasible by allowing the biomass CCS option which means that to produce negative emissions through a technology. In the other pathways, given targets are also fulfilled additional to the ETS and NON-ETS targets.

Variations by pathway

Due to different sectoral targets in the CL and LS pathways defined in the narrative of the pathways, decarbonisation is prioritised in industry in the CL pathway and in the residential and transport sector in the LS pathway. The other sectors which are not part of the specific targets have the opportunity to decarbonise less and thus, they benefit from additional reductions in those sectors which have the additional targets. For example, In LS agriculture does not need to decarbonise as much as in CL. As agriculture, residential, transport and commercial share the NON-ETS targets together, with the additional reduction in transport and residential it can reduce less in LS pathway. These benefits are visible in the sectoral CO_2 emission levels.

As shown in Figure 9, the emissions by industry are quite similar in the CL and PA pathways, indicating that industry has maximised reductions in CL, as no further reductions emerge under PA. These graph shows the emissions before they captured. Therefore, PA numbers shows the values before they are captured biomass CCS. Conversely, the LS pathway sees less decarbonisation in industry due to the additional targets and therefore effort in the residential and transport sectors.

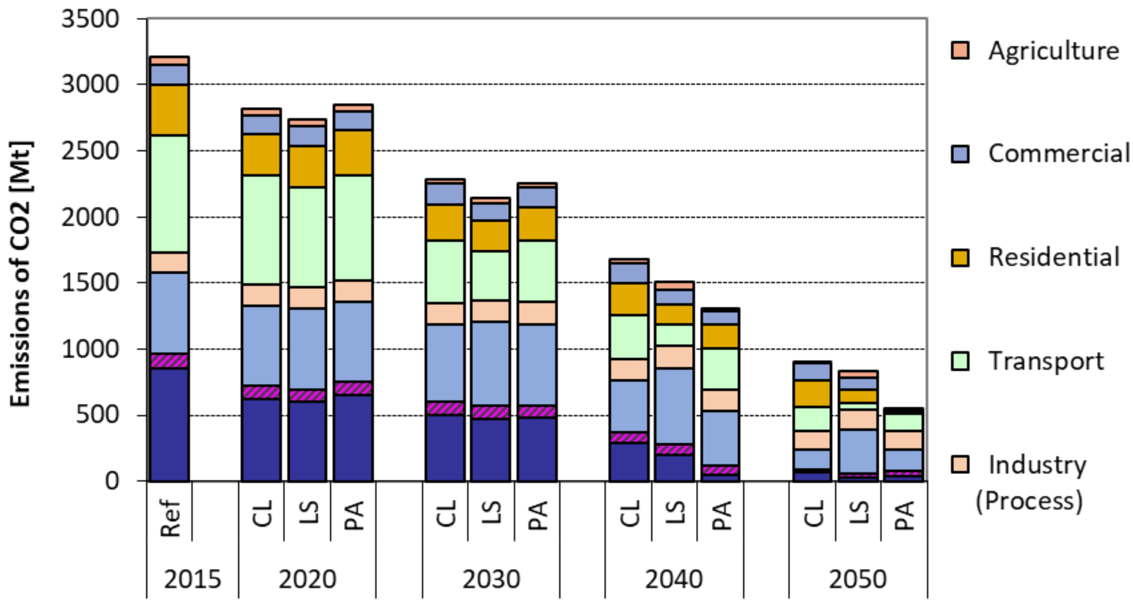


Figure 9. CO_2 emissions in the EU28 [Mton].

Message 5: The way the society responds to the transition will have an impact on the energy mix

In the CL and LS pathways, the push for the decarbonisation comes from the different actors in the energy system. The share of the electricity and emissions-free energy carriers across sectors differ.

Variations by pathway

Higher level of electrification is observed in the CL in industry compared to LS (Figure 7). On the other hand, electrification is higher in the residential and commercial sectors in LS compared to CL (Figure 10). Additionally, the highest electrification is observed in all the sectors in the PA pathway due to the need for more mitigation, as shown in Figure 11.

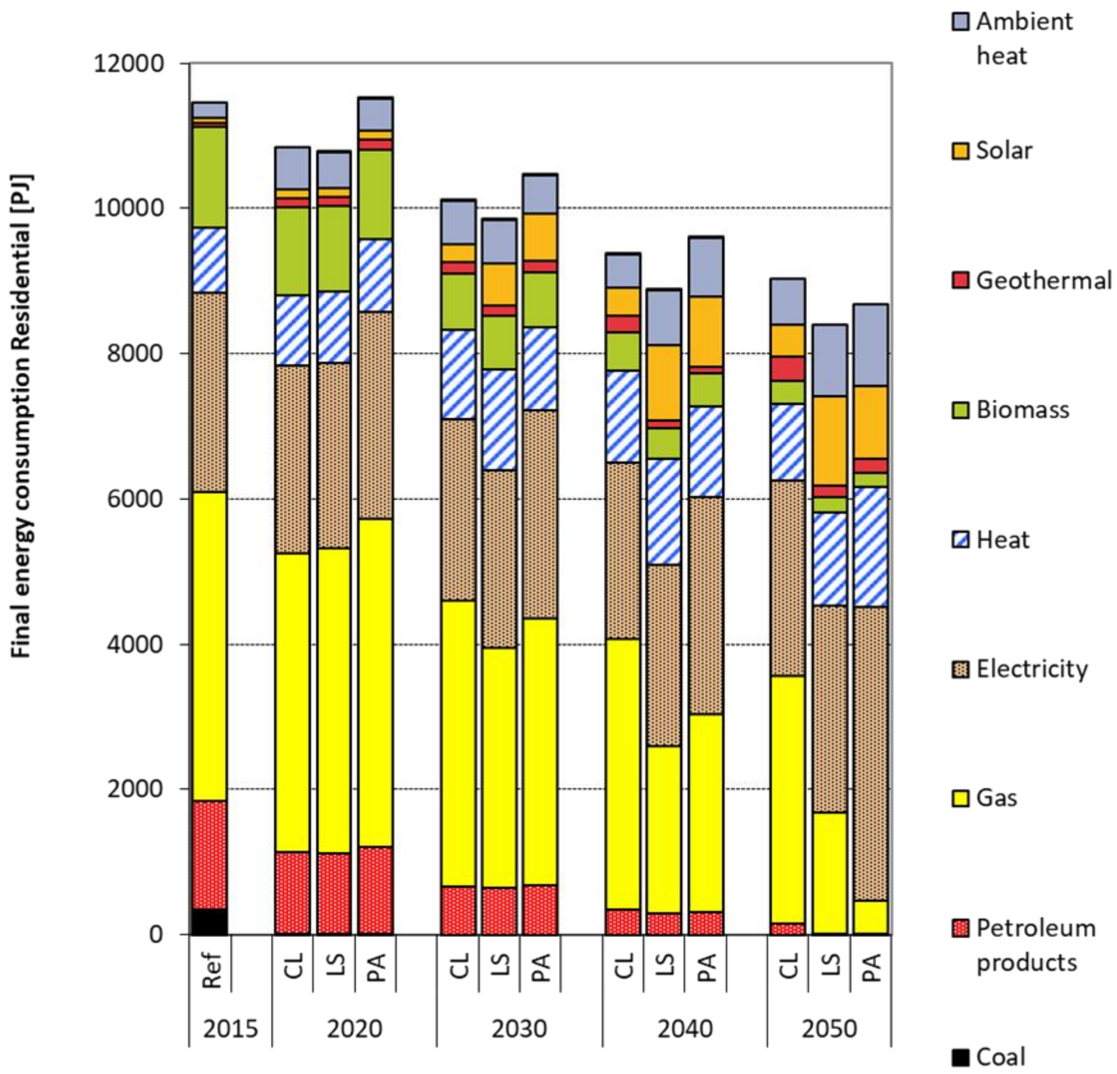


Figure 10. Final energy consumption in the residential sector [PJ].

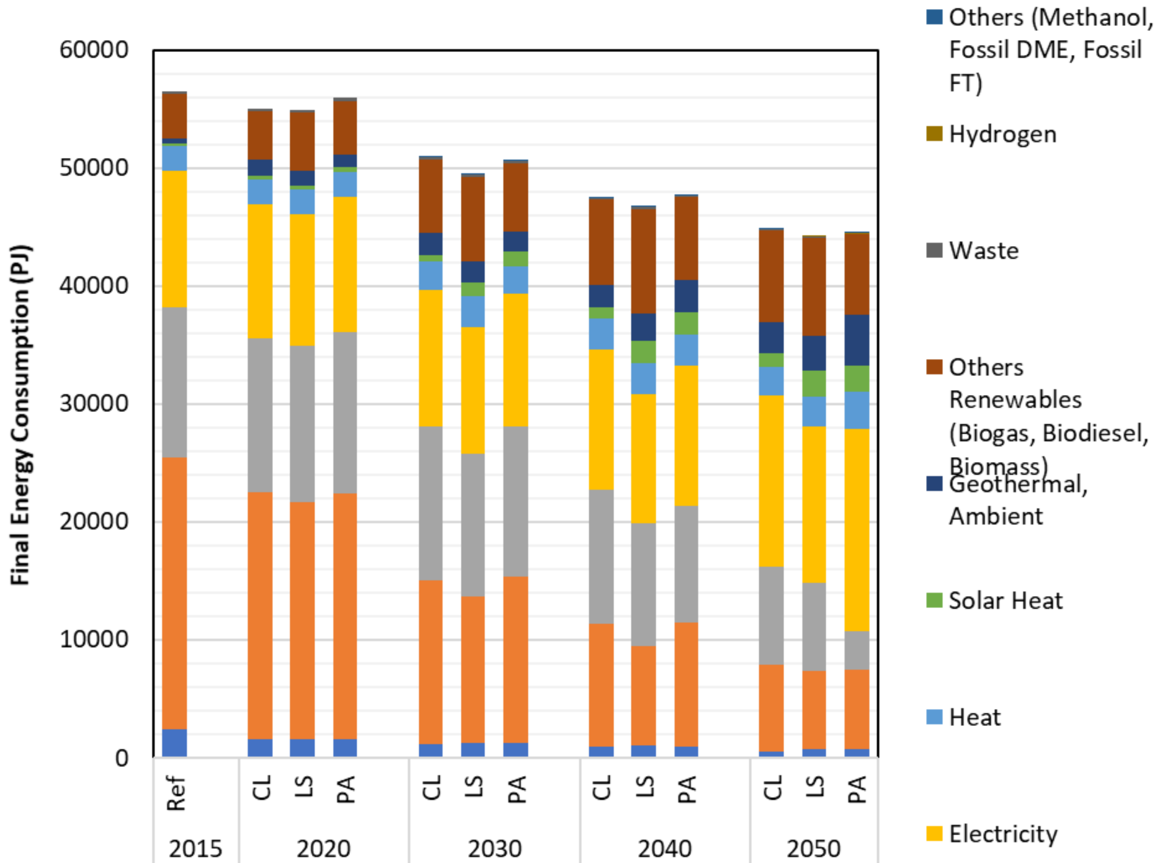


Figure 11. Total Final Energy Consumption [PJ].

Additionally, environmental heat and especially solar thermal grow rapidly in the LS pathway to fulfil the decarbonisation targets in the residential segment. This proves that the aforementioned technologies could have an even higher contribution to the total energy generation according to given decarbonisation targets.

3.1.2. Technology innovation in the pathways

The main insights derived from the technology innovation analysis described in Section 2 are given below.

3.1.2.1. Main insights

Message 6: Different types of barriers may hinder the development of the market

The technology innovation analysis identified several barriers and challenges and opportunities in the deployment of the analysed technologies as enablers of the decarbonisation in Europe. The barriers could be summarised and categorised into five main groups, namely: regulatory and institutional, awareness and skills, access to finance, technological and others. Below each of these groups is explained, followed by proposed actions to overcome those barriers.

- Regulatory and institutional barriers: In many cases, the set targets might be unambitious or the legislation might be characterised by a high level of bureaucracy. Also, EU and national targets and regulations might not be in line (e.g. renewable energy targets). Policies need to become more targeted and designed more from the perspective of the consumer and producer and keep the level of complexity to the minimum.

- Lack of public awareness: Often, consumers are not aware of certain technologies and their benefits. This might hinder significantly market development. Therefore, to achieve energy transition, campaigns and educational programs must be launched in order for consumers to become more engaged and contribute actively to the transformation of the system.
- Access to finance: Despite the need and the long-term benefits that energy storage, renewables and energy efficiency can bring, the higher investment cost that they have compared to conventional technologies can be a significant restraining factor. Therefore, the right supporting funding mechanisms must be established, making sure that those technologies find their way into the market but without creating unsustainable growth.
- Technological barriers: Government support itself is not sufficient to overcome fundamental weaknesses that those technologies might have. Further technological development is needed in order to make them more cost effective, lighter (in the case of batteries), produce them at larger quantities etc. This can be achieved through R&D investments undertaken by both the public and the private sector.
- Other barriers: This category encompasses any sort of barrier that cannot be classified under any of the aforementioned cases. This can be for example, cultural barriers such as the conservativeness of construction companies, lack of reliable data about innovative technologies and their actual performance or lack of interests in small-scale projects. All these examples add to the slow development of those key technologies and can be overcome through strategic actions that aim to restructure the market holistically.

Despite the barriers, consistent findings of the stakeholder workshops point at the opportunities offered by:

- The exploitation of synergies between value chains. For instance, the processes of installation of offshore wind turbines and ocean energy technologies may mutually benefit from sharing infrastructure.
- New business models around low-carbon technologies, which can increase the set of technological options available, foster dynamism in the market and accelerate the emergence of new, yet market-ready technologies.

3.1.3. Regional energy security case study of the Baltic region and Finland (D6.2)

The case study analysed energy security in the Baltic region (Estonia, Latvia, and Lithuania) and Finland in the context of the energy transition. The analysis included modelling various possible disruptions to assess the resistance of the planned energy system to possible threats.

3.1.3.1. Main insights

Message 7: It is crucial for the interconnectors capacity between Baltic countries to be maintained or even extended

The Baltic States have powerful electrical connections in terms of their capacities and their load (see Figure 12) with neighbouring power systems. The capacity of a separate power line may exceed 30-50% of the country's total power demand. A disruption of the operation of such a line may cause a major disturbance on the entire power system, especially in the case where throughput capacity of interconnectors is reduced. The results of the case study suggest that the number of interconnectors and their throughput capacities, used for electricity trade between countries as well as for providing balancing and reservation services, should be maintained or even extended. This observation could be useful and should be studied further in other Member States as it could, potentially, lead to the expansion of the interconnectors capacity, resulting into overall lower system cost and higher energy security at the same time.

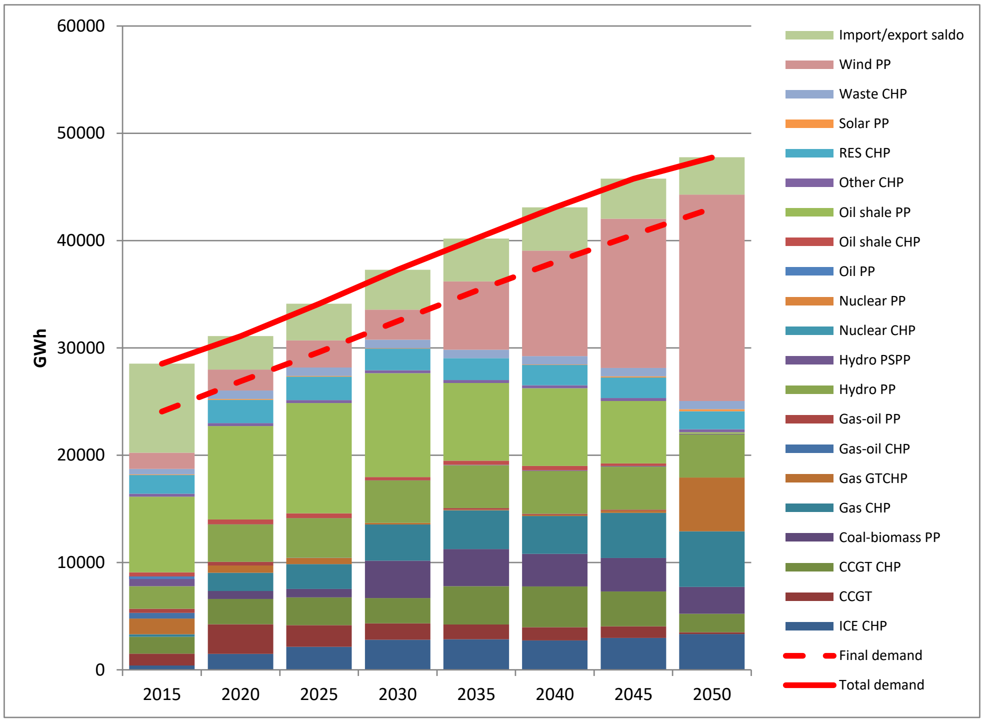


Figure 12. Electricity production by technology type in Baltic States in the case of Base (equivalent to Coalitions for Low-carbon path) scenario.

3.1.4. Case study on grid and dispatch in South Eastern Europe (D6.3)

The case study focused on verifying the feasibility of dispatch for the least-cost electricity generation mix calculated on a EU scale with TIMES, and analysed the influence of short-term variability on long-term investments and system configurations. TIMES PanEU operates with 12 time slices in a year and a modelling horizon between 2015 and 2050, divided into 5-year intervals. Such a coarse time resolution may seem too coarse when modelling significant system changes involving variable renewables. A model of power systems in five EU Member States (Bulgaria, Croatia, Hungary, Romania and Slovenia) in PLEXOS operating on hourly level was used to verify feasibility of dispatch in 2030 for a power system obtained with TIMES PanEU. For the study, the least-cost electricity mix computed by TIMES PanEU for the Coalitions for a Low-carbon path pathway was analysed.

3.1.4.1. Main insights

Message 8: Feasibility of dispatch for the power system of Southeast Europe obtained in TIMES PanEU is verified for 2030.

It was confirmed that hourly balancing of variable renewable energy sources is possible with projected generation capacities in Southeast Europe obtained in TIMES PanEU for 2030. Figure 13 illustrates a close match between PLEXOS and TIMES for electricity generation in 2030 for the Coalitions for a Low-carbon path pathway. A similar analysis could be useful for other Member States and for different years, especially when high variability in the demand for and, more importantly, the supply of electricity is recorded. This could shed light on the selection of technologies and additional measure such as increased storage or higher base-load capacity could be considered. Demand side management measures might be also particularly useful as they could help the demand curve get closer to the supply curve.

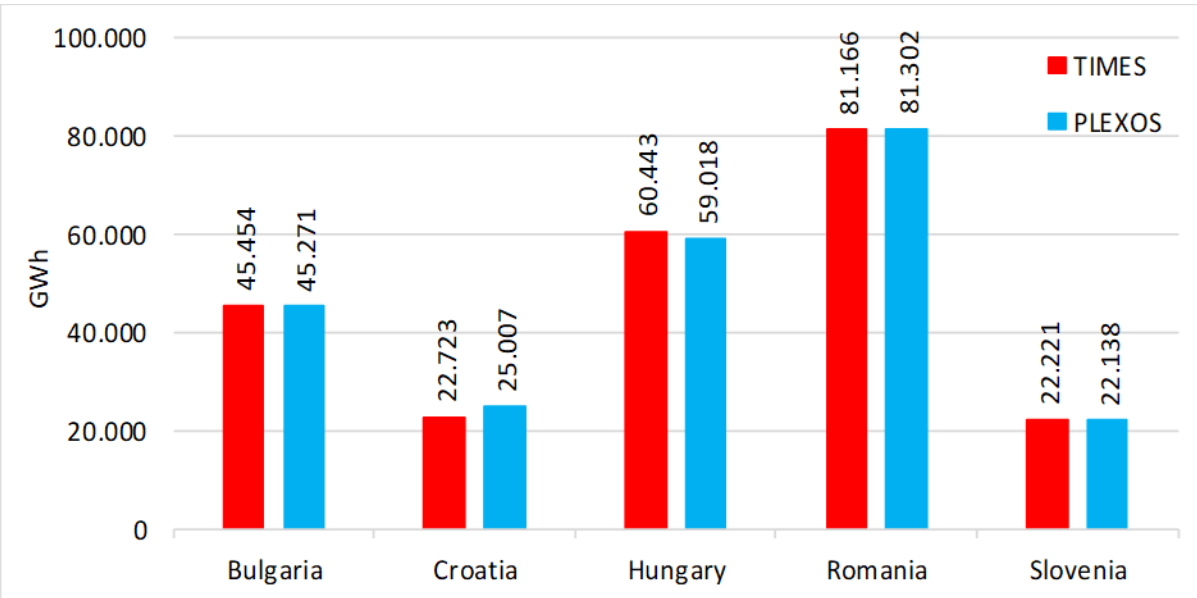


Figure 13. Electricity generation in 2030 for the Coalitions for a Low-carbon path pathway.

3.1.5. Coevolution and competition of technologies in a low-carbon system: a UK case study (D2.4)

The case study explored a range of uncertainties around future technology cost, performance, deployment and socio-political feasibility to better understand how different technologies are impacted both by the deployment of other technologies, and key system wide factors such as carbon price signal, resource availability etc.

3.1.5.1. Main insights

Message 9: CCS and bioenergy are expected to play a key role in the evolution of the energy system

The large scale deployment of CCS drives down the costs of mitigation, both highlighting it as an option that requires much more consideration in policy. However, its effect on costs also means that it strongly shapes the take-up of options across the wider system. There is a danger that this influence is hidden in many analyses and that resulting strategies are not robust to the failure of this technology. Its dominance also precludes alternatives from receiving the necessary focus, and allows for 'buying time' to make the necessary investment to effect the longer term transition.

Under ambitious climate policy, the value of bioenergy increases. Whilst this usefully identifies the important role bioenergy can play, there are critical uncertainties concerning future availability, the sustainability of its use, its impact on ecosystem services and concerns of wider environmental impacts e.g. air quality. A final crucial insight is that a number of options are more robust to uncertainty in that they typically deploy at scale under a range of conditions, including offshore wind in the power system, and increased electrification both in the transport and building sectors. Other technologies remain much more contingent on other factors such as resource availability (bioenergy, influencing hydrogen use in transport) or technology costs (nuclear deployment where cost-effective alternatives may not be available).

Such insights, which are applicable to other Member States not just the UK, can help shape future strategy direction. However, they also give rise to further questions given the inherent uncertainty and the issues that fall outside of the model boundary e.g. broader sustainability concerns of bioenergy, legal and social acceptability of negative emissions. What is key is that firm insights can start to shape action now while issues of greater uncertainty are considered further and subjected to further research.

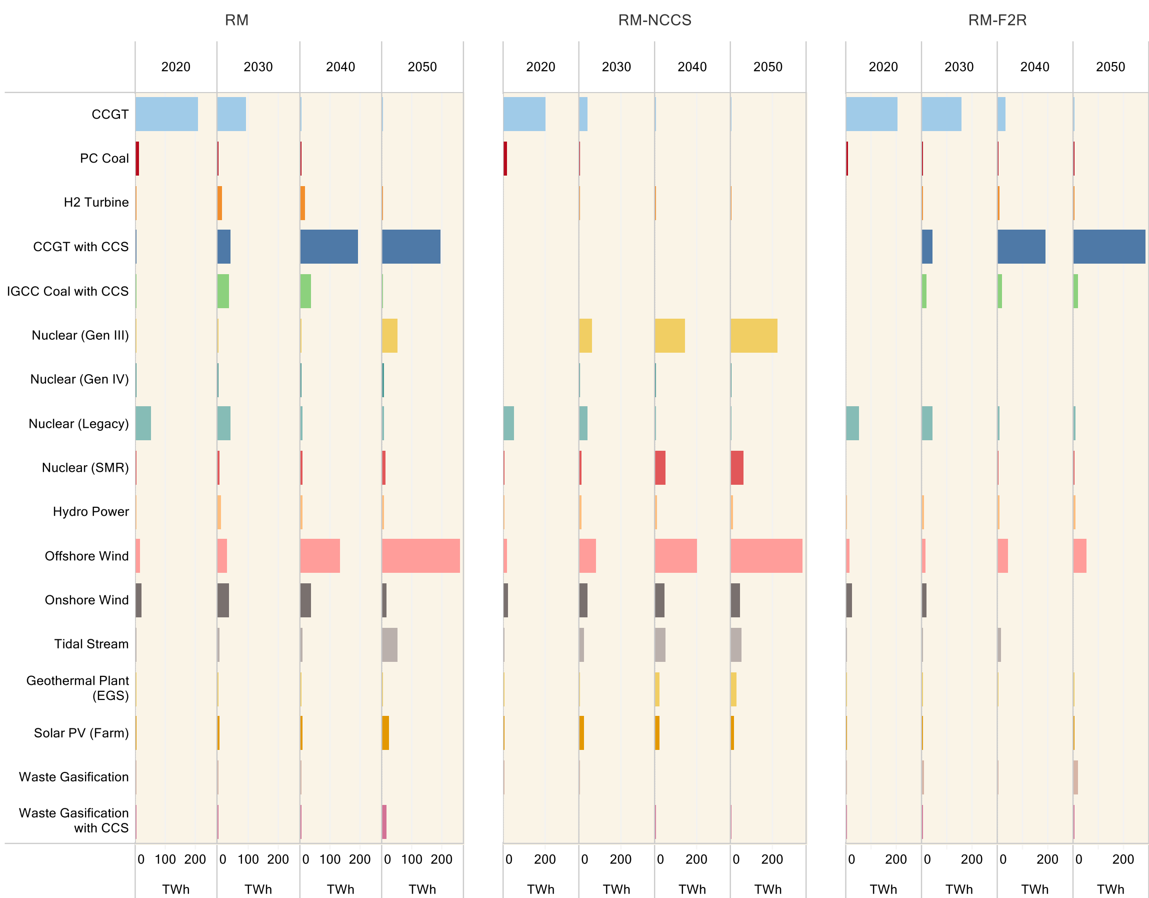


Figure 14. Median generation levels across power sector technologies between 2020 and 2050.

3.1.6. Behavioural analysis

The main insights derived from the behavioural analysis described in Section 2 are given below.

3.1.6.1. Main insights

Message 10: While consumers' choices for energy technologies are affected by costs, they are not the only, or even the main driver of decisions

The survey data and modelling showed that a range of different factors affect the stated technology choice of individuals (see Table 2 and Table 3). Perhaps most importantly, while costs are often found to be a significant factor, this is not always the case. This demonstrates that policies only providing economic incentives may not always be effective and further underlines the dangers in considering end users as economically optimising agents in models describing an energy system transition.

Message 11: Consumers have a strong preference for the technologies they are familiar with

One factor that was found to be especially influential in determining the technology choices of the respondents was the current ownership of a specific technology. This was often found to be more important than costs of the different alternatives. This suggests that there is significant inertia and "stickiness" in people's preferences, which makes it more difficult for policy makers to influence their technology choices, especially with economic incentives.

Message 12: While many factors affecting choices are shared across the three countries, there are also clear differences

As Table 2 demonstrates, decisions of the respondents in the three countries are often influenced by similar factors. With that said, there are also a number of decision drivers that are more important in specific countries. For example, decisions are less often based on costs in the UK than in the other two countries. Similarly, respondents in Finland are less concerned about their own control of the heating system than those in the UK and Croatia. Differences like these underline the importance of designing policies for the local circumstances – as the determinants of decisions differ, the required incentives are likely to do so as well.

Message 13. Many factors that may affect decisions in one sector, may not do so in another

The survey focused on assessing stated preferences for two investments: Heating technologies and automobiles. Some factors affecting decisions were linked to the specific use case (e.g. driving frequency), but many were more general socio-demographic elements. These, however, did not necessarily have a similar impact when decisions about automobiles on the one hand and heating technologies on the other were considered. For example, gender affected decisions for heating technology, but not for cars in Finland. Age of the respondent played a role for heating choice in all countries, but in the UK it didn't do so for the car choice. This finding further emphasises the previous point about the importance of tailored, rather than blanket, policies.

Table 2. Factors affecting consumers' heating technology choices in the three countries.

Category		UK	Finland	Croatia
Socio-demographic	Age	●	●	●
	Gender		●	●
	Area	●	●	
	Region		●	●
	Household income	●	●	●
	Education level	●	●	

	Number of children	●	●	●
	Number of residents	●		
	Work status	●	●	●
Dwelling	Type	●	◐	○
	Age	●	◐	○
	Number of bedrooms			●
Economic	Capital cost	○	●	●
	Annual cost	○	●	●
	Heating bill		●	
Environmental	GHG emissions	●	●	◐
Technological	Ease of use	○	●	◐
	Heating hours per day	●	●	●
	Experience (e.g. used to install a particular system)	○	●	○
Ownership of heating system	Existing systems	●	●	●
Knowledge of heating system	Familiarity with heating systems	●	◐	○
	Easy-of-use	◐	◐	●
	Costs	○	●	◐
	Reliability		○	◐
	Climate change impact		○	◐
	Local pollution impact	○	●	●
	Space requirements	○	○	
	Impacts on the resale value of homes	◐	●	◐
	Environmental credentials	◐	○	○
Psychological	Environmental friendliness	○	○	○
	Access to information	◐	○	○
	Personal innovativeness	◐	◐	○
	Importance of advice	●	●	●
	User control	●	●	
	Maintenance costs	●		
	Installation costs	●		
	Typical reasons and rationale for heating system replacement	◐	◐	◐

Note: ●: most of the relevant factors are influential; ◐: some of the relevant factors are influential; ○: limited number of the relevant factors are influential.

Table 3. Factors affecting consumers' vehicle technology choices in the three countries.

Category		UK	Finland	Croatia
Socio-demographic	Age		●	●
	Gender	●		●
	Area	○	○	○
	Region		◐	◐
	Household income	●		●
	Housing tenure	●		●
	Education level	○	○	◐
	Number of children		●	

	Work status	●	◉	●
Dwelling	Type	●	◉	
	Age	●	●	◉
	Number of bedrooms		●	
Economic	Capital cost	●	●	●
	Annual cost	●	●	●
Environmental	GHG emissions	◉	○	◉
Technological	Driving range	○	◉	○
Ownership of heating system	Number of cars owned		●	
	Car type	●	◉	◉
Knowledge of vehicles	Familiarity with car technologies	●	●	●
	Driving range			○
	Easiness of use	○		○
	Costs	○		
	Safety	○		
Transport behaviour	Ownership of driver license	●	●	●
	Ownership of private parking space	●		
	Main reason(s) for using a car	◉	◉	◉
	Frequency of various driving ranges	◉	○	○
	Frequency of various travel modes	●	●	○
Psychological	Environmental friendliness	○	◉	◉
	Access to information	○	◉	◉
	Personal innovativeness	◉	◉	◉
	Brand	●	●	●
	Model		●	●
	Costs	●	●	●
	Noise	●	●	
	GHG emissions	●	●	●
	Performance	●	●	
	Reliability	●	●	
	Safety	●		●
	Style	●		

Note: ●: most of the relevant factors are influential; ◉: some of the relevant factors are influential; ○: limited number of the relevant factors are influential.

3.2. Economy and Society

3.2.1. Economic impacts

The main tool to analyse the economic impacts of the transition to a low-carbon energy system was NEWAGE (National European World Applied General Equilibrium). NEWAGE is a Computable General Equilibrium (CGE) model that divides the World in 18 regions, being 9 of them inside the EU, 18 production sectors and 4 production factors. The model presents a disaggregated electricity generation sector, with 18 different technologies.

Being a macroeconomic model enables NEWAGE to capture the interaction between different sectors of the economy. One of the main outputs, for example, is how a carbon tax can influence sectoral production by increased energy costs, or how consumers react to price changes of energy goods. Ultimately, NEWAGE is capable of indicating how the Gross Domestic Product (GDP) of a country or region is likely to increase or decrease for a given policy.

Under the scope of the REEEM integrated framework, the main modelling activities performed were the ***coupling of NEWAGE with TIMES-PanEU*** and the ***disaggregation of the households' sectors*** in NEWAGE into 5 representative household groups. For the former, the main steps were:

1. Calibration of NEWAGE over a Reference pathway;
2. Definition of parameters to be transferred from TIMES Pan-EU to NEWAGE and vice-versa:
    a. From TIMES-PanEU to NEWAGE:
        i. Sectoral emissions (calibration)
        ii. Electricity generation by technology (coupling process)
    b. From NEWAGE to TIMES-PanEU:
        i. Sectoral production (coupling process)
        ii. GDP (coupling process)
3. Interface for data transferring between the two models;
4. Iterative coupling between the two models.

Although not in the scope of the REEEM project, the Reference pathway (RF) was added to the coupling process between NEWAGE and TIME-PanEU for a couple of reasons. First, NEWAGE does not produce predictions, but does pathway analysis, so the Reference pathway is used as a starting point, from which the counterfactual pathways (three REEEM pathways and one extra, PA-EU) are compared to. In order to create this pathway, we chose the EU Reference Scenario 2016, which contained GDP, emissions and population projections until 2050 and calibrated NEWAGE to be able to generate similar results when running under the Reference pathway configuration. Additionally, in the framework of the model coupling, TIMES-PanEU was also calibrated according to the Reference pathway in order to ensure that both models had compatible assumptions regarding technology development and ensured the convergence between them.

With the coupling, two objectives were reached. First, NEWAGE was made capable of assimilating the detailed technology information contained in TIMES-PanEU and, second, TIMES-PanEU was able to respond to energy demand shifts caused by changes on sectoral production levels.

The households' disaggregation had the objective of gaining deeper understanding on the impacts of carbon taxation on groups of different incomes, shedding light on potential ***winners and losers of the energy transition***. Important results from this analysis are the share of income dedicated to energy goods per household group and its effects on energy poverty.

The analysis of economic impacts covers the CL, LS and PA pathways. A sensitivity was also created, assuming fulfilment of the Paris Agreement merely by the EU and not the rest of the world (PA-EU). A summary of the key characteristics of the analysed pathways is given in Table 4. For the analysis, the qualitative assumptions on global effort towards decarbonisation reported in the description of the pathways (Section 2.4) are turned into quantitative inputs for NEWAGE. In the CA and LS pathways it is assumed that the EU28 has a target to decrease its CO_2 emissions by 80% until 2050, compared to 1990 levels, while the global push to climate change mitigation is assumed to be ***driven by some regions/countries***. In the PA pathway, the EU28 has a target to decrease its CO_2

emissions by 95% until 2050, compared to 1990 levels, where an ***indistinct global push*** is assumed instead. For the special case of PA-EU pathway, the 95% target is kept, but the rest of the world follows the same emission targets as in Coalitions for a low carbon path and Local solutions. Further information on the economic impacts derived from the REEEM analysis can be found in deliverable D3.3a – Focus report on economic impacts and D3.3b – Policy brief. More details on the assumptions regarding emission trajectories outside the EU are given in Appendix A.

Table 4. Key pathway assumptions for the economic impacts analysis.

	Reference Pathway (RF)	Coalitions for a low carbon path (CL)	Local Solutions (LS)	Paris Agreement – EU (PA-EU)	Paris Agreement (PA)
ETS sectors	62% reduction in 2050[1]	83% reduction in 2050[1]	83% reduction in 2050[1]	95% reduction in 2050 compared to 1990 levels	95% reduction in 2050 compared to 1990 levels
non-ETS sectors	no targets	50 to 80% reduction in 2050[1] Extra European targets: Industry	50 to 80% reduction in 2050[1] on the national level Extra European targets: Residential Transport Services		
Remaining regions	no targets	Regional Push	Regional Push	Regional Push	Global push

Table 5. Country index for the current study.

NEWAGE Region	**NEWAGE Code**	**Countries**
Germany	DEU	Germany
Italy	ITA	Italy
Poland	POL	Poland
France	FRA	France
UK	UKI	UK
Spain + Portugal	ESP	Portugal, Spain
Benelux	BNL	Belgium, Luxembourg, Netherlands
Northern EU	EUN	Denmark, Estonia, Finland, Ireland, Latvia, Lithuania, Sweden

[1] Compared to 2005 levels

Central and South-Eastern EU	EUS	Austria, Bulgaria, Croatia, Cyprus, Czech Rep., Greece, Hungary, Malta, Romania, Slovakia, Slovenia

3.2.1.1. Main insights

Message 14: Robust GDP growth is expected to continue under stringent decarbonisation objectives, although at slightly lower rates

On a broader level (i.e. without looking into winners and losers), the EU economy will continue to grow under the transition to a low carbon pattern. As illustrated in Figure 15a, GDP rises at a steady pace very decade, reaching a total of 55-72% in 2050 compared to 2011 levels. However, economic growth could be slowed in the cases where the highest decarbonisation effort is pursued, as shown in Figure 15b.

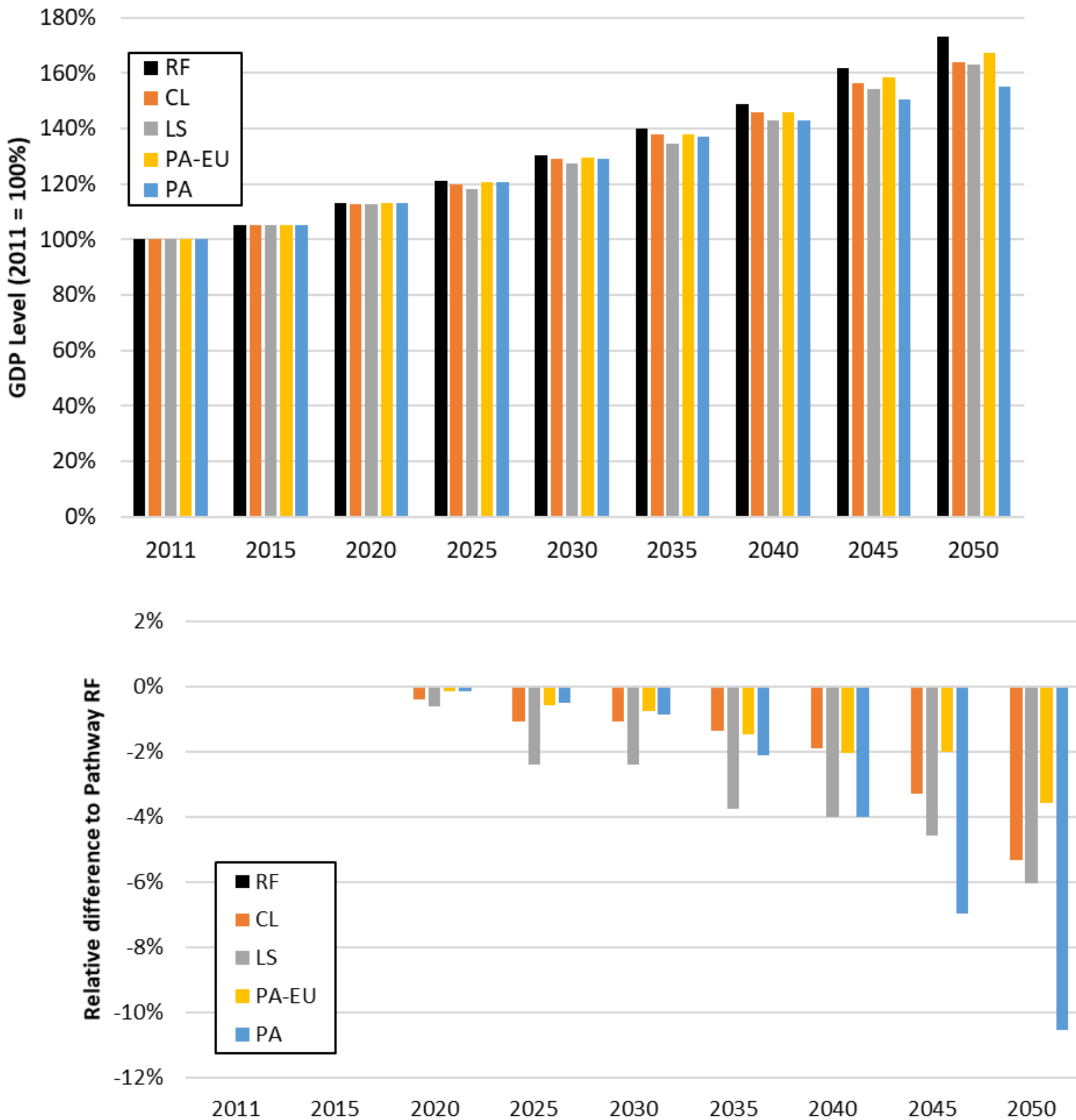


Figure 15. a) Relative growth compared to 2011; b) Difference to Reference Pathway.

Compared to 2011, on a European level, the LS pathway delivered lower GDP growth by the year 2040 in comparison to other pathways, indicating that taxing consumers, transportation and services is the least efficient of the presented strategies. The cause relies in that services comprehend more than 70% of European economic activity [20] and the European consumers are the main target of goods produced within the EU. Consequently, an uneven carbon taxation policy, as in the LS pathway where a few sectors have to undergo a higher emission reduction, decreases European GDP growth by imposing a high burden on consumers and, thus, decreasing their consumption of locally produced goods. However, in the last 10 years of the analysis, the lowest GDP growth is recorded in the PA pathway. This can be attributed to the more ambitious targets set, which require more drastic measures that appear to have a negative impact on the economy. Nevertheless, even when examining the worst case, the maximum relative difference to the CL pathway is around 6%, which is not dramatic considering the fact that there is a global action towards the Paris Agreement's goal and, thus, other regions will also experience lower GDP growth[2]. Finally, it is important to keep in mind that factors such as technology or demography which, so far in the future as 2050, are governed by a high level of uncertainty, could potentially have an even greater impact on the economy than decarbonisation.

PA-EU and PA have similar GDP development until 2035. However, in years 2045 and 2050 PA-EU has much higher GDP development than PA. This is due to the fact that under the PA pathway it is expected that there will be lower economic activity in the other regions of the world due to higher expenditure on climate protection. Furthermore, GDP development under the PA-EU, despite having a higher decrease of European CO_2 emissions than the CL and LS pathways, still has a higher development than these pathways because of its carbon taxation scheme, as described in Table 4, which shares the burden more evenly among the players of the economy. Although these results might seem negative for the PA pathway, it is important to remember that until 2040, the PA pathway had GDP development very similar to the other pathways and only diverged on the last two-time steps. Considering that these time steps are over 25 years in the future, there is enough time to prepare and adapt for this pathway.

Message 15: Different sectors may grow at a different pace

The analysis shows that the contribution of every sector to the economic growth will increase. In other words, as shown in Figure 16, the Gross Value Added (GVA) of every sector is expected to increase, though at different rates. The chemical industry for example, seems to record the lowest growth potential. The reason is that industries like this and the non-ferrous metals are sectors focused on the European market. Thus, they grow according to the EU's own economic growth and, in addition, the European chemical sector has been stagnant for the last 10 years, so a 20% growth can be still considered positive. Since those sectors are oriented towards the internal EU market, we can expect that their growth trend follows that of the EU, considering that they keep their market share. However, with new competition entering the EU, it is plausible that they record relative losses. In other words, their growth is expected to be hindered by foreign competition. On the other hand, sectors that are more export oriented, such as that of non-metallic minerals are expected to record higher economic growth due to the higher economic growth potential outside the EU.

[2] Important to note that in its actual stage, NEWAGE is not capable of accounting for damage costs avoided by environmental policies.

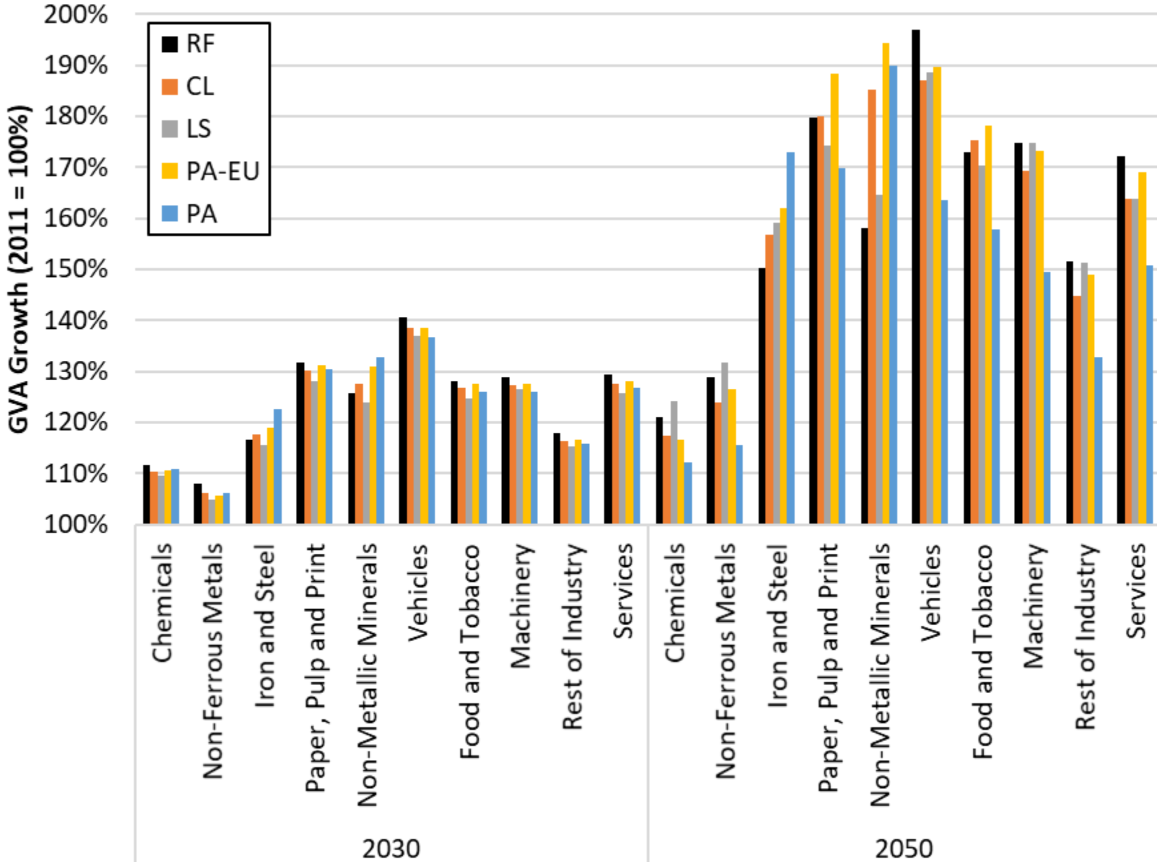


Figure 16. Competitiveness index (GVA) development.

Variations by pathway

When looking into industrial production in the EU, the results indicate that for the PA pathway, sectors which are strongly oriented to exports, such as vehicles and machinery, have a lower GVA in 2050 compared to the other pathways, due to lower economic activity in the rest of the world.

In some sectors, the Reference pathway shows lower growth compared to the other pathways (e.g. iron and steel), while in others higher growth. This can be attributed to the fact that since they are export oriented, the higher the (relative to the EU) economic growth outside the EU, the more they benefit.

Vehicle, machinery and rest of industry are sectors that are not energy intensive. Therefore, they do not suffer in the CL, LS and PA-EU pathway, but are quite export oriented, so they are negatively affected in the PA pathway, because economic activity in other regions decreases. As for chemicals, non-ferrous metals and the paper sector which are energy intensive and more oriented for internal consumption, they follow the overall European economic tendency.

Message 16: Uneven GDP growth occurs across Member States

With very few exceptions, every other country/region will see a lower rate of economic growth in a decarbonisation pathway compared to the Reference pathway, although strong overall growth. Figure 17 shows that the economy of Germany and Northern Europe will be affected the least from decarbonisation, compared to all other regions. This can be explained by the fact that those countries currently record a relatively low per capita emission rate and have already decarbonised their systems significantly compared to 1990. Therefore, the remaining burden for them is consequently lower.

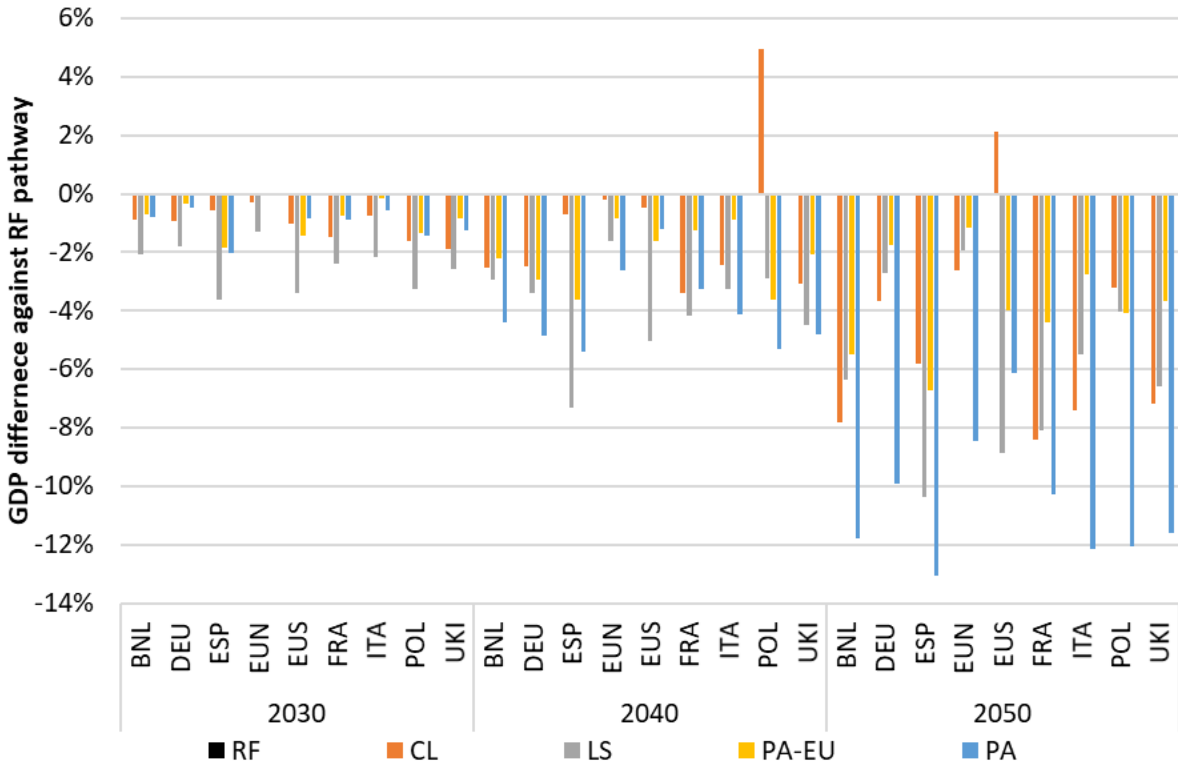


Figure 17. GDP difference relative to RF pathway for the European Regions in NEWAGE.

Variations by pathway

In the CL pathway where decarbonisation targets are lower in particular regions, Poland and the South and Eastern European countries are affected less than the rest in terms of economic growth. On the other hand, the fulfilment of the Paris Agreement will have more severe effects on almost every region, with Italy, Poland, Spain and Portugal impacted the most. In the case of Italy, its economy is still recovering from the last crisis and is vulnerable against such policies, while Poland is economic dependent of its coal reserves and Portugal and Spain have both increased their emissions compared to 1990 levels, meaning they have to undertake higher emission reduction than the other western European countries.

Message 17: Effects on different income groups

From the analysis on distinct income groups, as shown in Figure 18, results demonstrate that the richest 20% of population in the EU will be able to afford a higher share of their total consumption of energy goods on carbon tax and, thus, consume a higher share of fossil fuels. In this case we consider energy goods not only as electricity, gas, coal and oil products, but also as the corresponding carbon taxation of each pathway, represented by the dotted columns. Additionally, while columns "PA taxation" and "LS taxation" are straight forward regarding the pathway they represent, column "ESD" represents the taxation for the Effort Sharing Decision [21] which has a price in this case because it was modelled as a cap-and-trade policy with national targets.

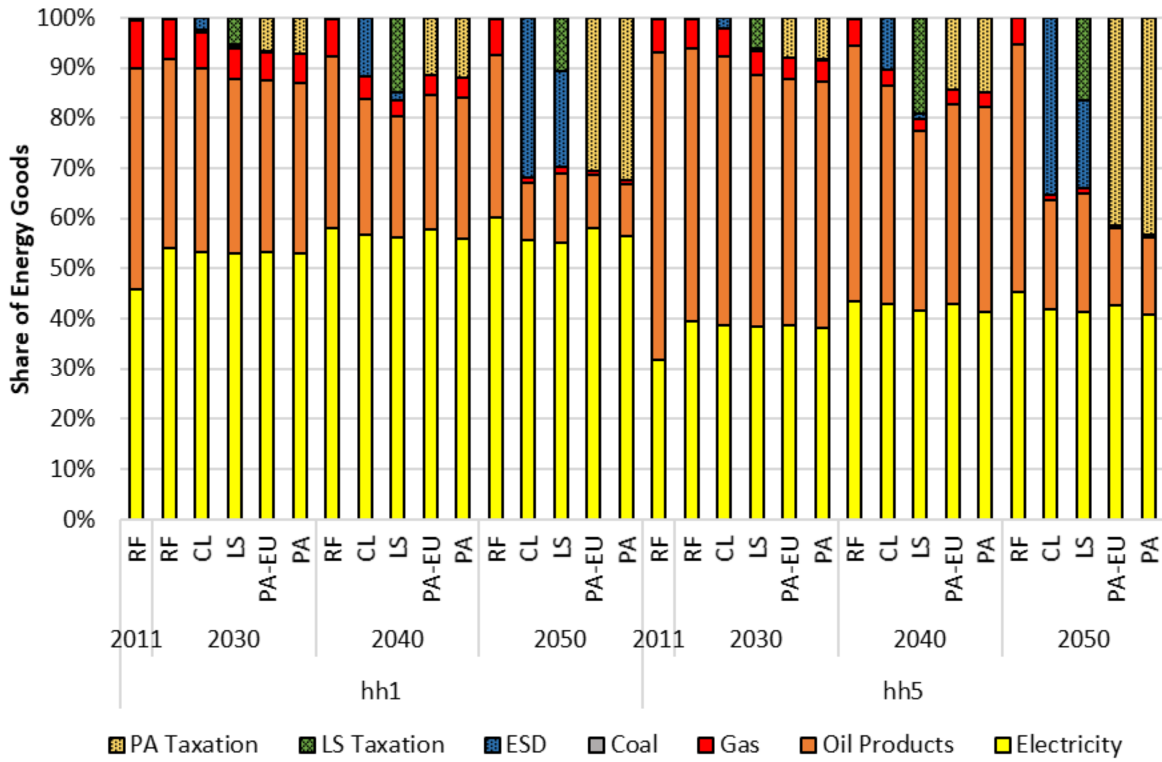


Figure 18: Consumption of specific EG in the EU-28 according to income level (hh1 are the 20% poorest households and hh5 are the 20% richest households). Source: Authors.

The results on income development among different income groups were also analysed in order to find effects on income inequality as a response to environmental policies. Assuming that revenues from CO_2 certificates are payed back to households in the same proportion as government payments are made today among quintiles, there is a potential that they can be used as a tool to decrease income inequalities, as gross income grows more for lowest income quintile than highest in 2050, the year when carbon price reaches its peak, especially for pathways PA-EU and PA, while in the RF pathway the opposite is true for all years analysed.

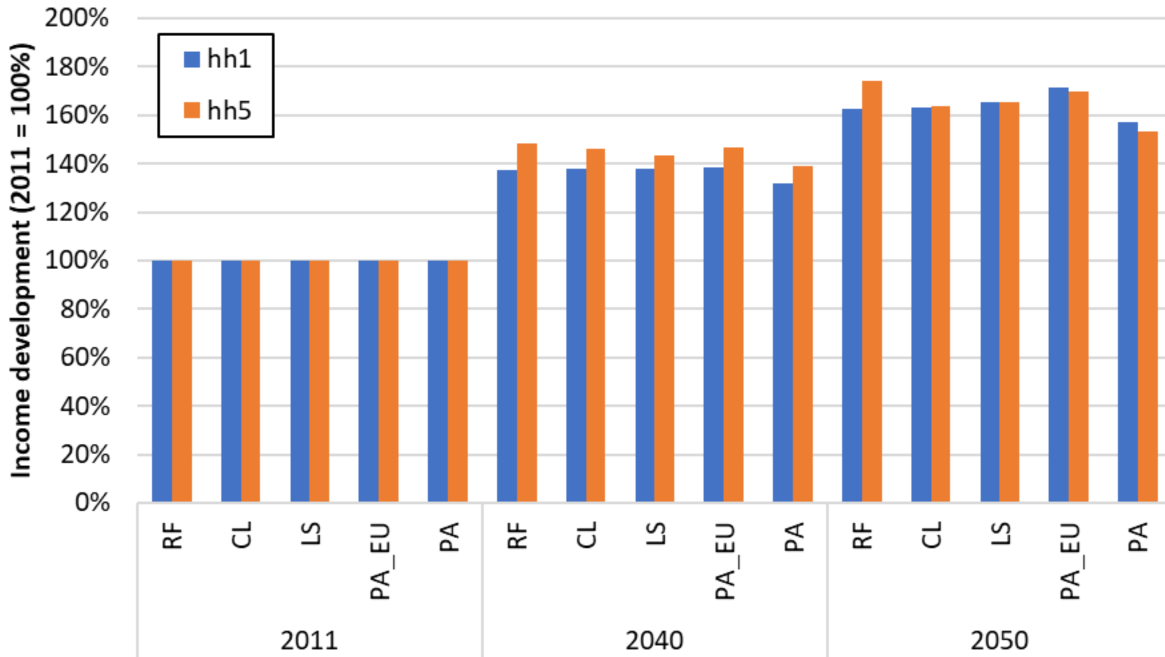


Figure 19: Development of gross income for the 20% poorest households (hh1) and 20% richest households (hh5). Source: Authors.

3.2.2. Health and Environmental impacts

Health and environmental impacts are accounted for using *EcoSense.* The latter is an integrated impact assessment model following the *Impact Pathway Approach* to estimate health impacts caused by different air pollutants [22], [23], which is primarily designed to support and inform assessments of different air pollution mitigation strategies and related cost-benefit analyses. The *Impact Pathway Approach* is a bottom-up method to estimate environmental benefits and costs by following the complete impact chain from source emissions to physical impacts, which can be monetised in a final step.

First, changes in anthropogenic emissions are translated into changes in air pollutant concentration levels by using dispersion and air quality models. Air pollutants are transported and transformed over long distances; a change in emissions in one country may lead to a change in concentration levels in a different country. Additionally, some pollutants may react chemically with each other, leading to secondary pollutants such as secondary aerosols or ozone. To account for these complex, partially non-linear chemical transformation processes, a chemistry-transport model (CTM) can be applied. CTMs are full atmospheric dispersion models to estimate concentration and deposition levels of air pollutants by taking into account meteorology and chemical transformation schemes, reflecting the complex mechanisms in the atmosphere. Due to the inherited complexity and non-linearity, these models are computationally expensive. Particularly in policy assessment, where often many different scenarios need to be analysed, computer time and power are, however, critical resources. To reduce computation time, *EcoSense* implements a parameterised atmospheric dispersion model in form of country-to-grid source receptor matrices based on the EMEP/MSC-W[3] CTM, linking a specific change in emissions

[3] http://emep.int/mscw/index_mscw.html (last checked: 14-12-2018).

in the source region to a change in concentration at the receptor grid. The source-receptor matrices allocate changes in emissions of SO_2, NO_X, non-methane volatile organic compounds (NMVOC), NH_3 and primary particles ($PM_{2.5}$ and PM_{10}) in a given country to changes in concentration levels of ozone, NO_2 and particulate matter (separated in P $PM_{2.5}$ and PM_{10}) across Europe and neighbouring regions in Asia and Africa with a spatial resolution of 0.5° × 0.25°. The source-receptor matrices in *EcoSense* are based on 2020 emission projections, which makes them suitable for estimating future emission reduction impacts. For these future estimates, source-receptor matrixes are averaged over four meteorological years (2006-2010) to account for meteorological variabilities.

To estimate the change in future exposure, detailed population data is needed which is combined with the spatially resolved changes in concentration levels. For this purpose, a high-resolution population density grid has been combined with UN population data to include country-specific age structures and population projections. This means that *EcoSense* considers demographic change for future years, yet internal migration effects, such as urbanisation, are not included. While the age structure may change over time, the spatial distribution is always taken from the original dataset. The final dataset in *EcoSense* thus includes spatially resolved population data and projections with 5-year age-bands and a final resolution of 2.5' × 2.5'.

By applying concentration-response functions (CRFs), the marginal physical impacts, i.e. the effects on human health caused by an increase or decrease of 10 µg/m³ in concentration levels, are assessed and multiplied with the respective change in concentration levels. CRFs combine information about the change in risk due to a specific change in ambient concentration levels (relative risk) with background rates of certain health outcomes. Relative risks are derived based on epidemiological studies and are provided for each pollutant-outcome pair. Physical impacts comprise both mortality and morbidity. As mortality due to air pollution is mainly caused by long-term exposure (chronic mortality), it is estimated as average loss in life expectancy based on life table calculations, which results in “Years of Life Lost” (YOLL). Intermediate results in terms of individual health outcomes such as increased chronic mortality, hospital admissions or restricted activity days are aggregated to two common metrics: monetary values and ‘Disability Adjusted Life Years’ (DALY). DALY reflect the impact of a specific health outcome on both the quality and quantity of a life lived by providing scores for each health outcome according to its severity between 1 (death) and 0 (perfect health). When this is combined with the typical duration of an illness, it is possible to calculate a weighted sum of mortality (one YOLL equals one DALY) and morbidity as a combined indicator for health impacts due to air pollution.

Similarly, *EcoSense* estimates effects on ecosystems as biodiversity losses in terms of fractions lost due to deposition of NO_X and SO_2 (measured in potentially disappeared fraction). These biodiversity losses are monetized by applying restoration costs, i.e. the costs to restore a specific land use type with fewer species to one with more species. A more detailed description can be found in deliverable D5.2 – Focus report on environmental impacts.

EcoSense is used to estimate health impacts and associated external costs (including biodiversity losses) due to air pollution for different transformation pathways. It is also applied to estimate unit cost factors that can be used in energy system models to estimate the impact of air pollution control on the energy system transformation.

It is important to note that besides the three REEEM pathways, one more namely “Reference” has been considered in this case. This is the same as the CL pathway, except for it does not consider the damage cost caused by air pollution. The purpose of analysing this pathway is get to insightful conclusions with regards to how much air pollution control can impact the overall health and cost as well as GHG reductions when taken into consideration.

For all the aforementioned estimates, the key data from TIMES PanEU is the emissions of air pollutants ($PM_{2.5}$, PM_{10}, NO_X, SO_2, NMVOC, NH_3).

3.2.2.1. Main insights

Message 18: Air quality benefits from clean energy transition and vice versa

Ambitious GHG-mitigation targets seem to be a driving force in reducing air pollution, already achieving reduction levels between 30 % and 55 % in 2050 compared to 2015 for most air pollutants in the EU28 (Figure 20, Reference case). By including health related costs of air pollution in the decision making process (CL pathway), emission reductions are visibly higher in early years (2020), resulting in additional reductions in 2050 of up to 15 %. This additional effort in reducing air pollution also leads to lower GHG emissions in 2050 as well as lower CO_2-prices for ETS emissions in all years except 2050. On average, these prices are 44 % lower in the CL pathway compared to the Reference pathway. The other two pathways show similar reduction patterns. The more ambitious, cross-sectoral targets in the PA pathway push emission reductions further, resulting in the lowest emission levels in 2050 across all considered pathways. This indicates that integrated climate change mitigation and air pollution control policies are favourable with air pollution control positively affecting decarbonisation particularly in the near future. These findings also support the idea of an integrated approach to meet all energy-related UN Sustainable Development Goals, which has also been pointed out to be beneficial on world level by IEA's Sustainable Development Scenario[4].

Variations by pathway

The most striking difference between the four pathways is the sharp increase of SO_2 in the Reference pathway between 2030 and 2045. This is mainly caused by conversion processes such as gasification and synthetic fuel production using sulphur-heavy fuels like refinery oil and coal. These processes are not utilized if health costs of air pollution are considered. We also see a sharper initial decrease of air pollutants - especially of particulate matter and SO_2 - in the CL pathway in 2020 as a result from banning coal in the residential sector and replacing fuel oil in maritime transport with diesel.

Without considering health costs in the decision making, a high share of biomass in the Reference pathway leads to an increase of $PM_{2.5}$ emissions from industry, agriculture and the commercial sector (Figure 21). For industry, $PM_{2.5}$ emissions even increase in all other pathways, indicating that a reduction below 2015 levels is infeasible without additional technical measures due to a high share of process emissions and increasing demand. As shown in Figure 21, introducing air pollution control costs in form of costs of related health impacts, mainly results in reductions in air pollutants in the commercial sector, agriculture, conversion and public electricity and heat production. Increasing demand and process emissions of particulate matter (abrasion and tyre wear) limit the reduction potential in the transport sector without introducing additional technical measures. The potential for

[4] https://www.iea.org/weo/weomodel/sds/ (last checked: 15-07-2019).

electrification in road transport seems to be limited with the PA and the CL pathway showing similar shares of electric vehicles in 2050. Compared to electric technologies in other sectors (e.g. heat pumps in residential), electric vehicles are also not necessarily favourable with regard to air pollution. They may have no exhaust emissions, but they still do emit particulate matter through road abrasion, tyres and break wear, giving them no specific advantage over conventional cars following the new low emission standards as long as there is enough biofuel potential to reduce CO_2. This results in almost stagnating emissions of particulate matter from 2040 on (Figure 20).

Compared to the CL pathways, the LS pathway results in better air quality by further reducing NMVOC, NH_3 and particulate matter. The active role of consumers to mitigate climate change in combination with a breakthrough in Building Integrated Solar PV in the LS pathway leads to a higher deployment of solar technologies (see also message 1) in the residential and commercial sector, with electricity mainly replacing biomass and natural gas. Similarly, the additional targets for transport push the utilization of biofuels in road transport (see also message 3). This results in less biomass utilization in most other demand sectors as well as lower evaporation of NMVOC from gasoline and ethanol cars in road transport, effectively reducing particulate matter, NH_3 and NMVOCs further. Additional reductions of GHG, NO_X and SO_2 from the residential, commercial and transport sector are counterbalanced by lower reductions in industry and even increasing emissions from agriculture, resulting in effectively the same reduction levels in 2050 as in the CL pathway. Especially agriculture seems to be “free riding” as it does not change its final energy consumption pattern much in 2050 compared to 2015. Since agriculture is the only sector without specific targets in this pathway, it directly profits from any additional ambition in the other sectors. The increase in GHG emissions in agriculture is also dominated by increasing N_2O emissions; both CO_2 and CH_4 are stagnating at their 2015 levels (-4 %).

This situation is different in the PA pathway, which does not only have more ambitious GHG reduction targets, but also aiming at cross-sectoral reductions, taking into account all emissions from all sectors on an equal footing. Although the option and utilisation of biomass CCS (see also message 3) also results in higher emissions (particularly NO_X and particulate matter, Figure 21) from public electricity and heat production, the subsequent increased electrification cleans up industry, agriculture and the residential and commercial sector to a sufficient degree to still achieve additional reductions in total emissions between 3 % (SO_2) and 14 % (NH_3) compared to the CL pathway. GHG are reduced by an additional 12 %. Overall, air quality clearly benefits from ambitious, cross-sectoral GHG reduction targets in this case and further reductions of air pollution seem to be mainly limited by process emissions from industry and road transport (SO_2 and particulate matter).

To sum up, taking into account air pollution control and its implications on human health in the decision making leads to higher reductions in emissions of air pollutants and GHG and thus additional benefits for the society. As both climate change and air pollution mostly relate to the same emission sources, climate change mitigation and air pollution control policies should be developed and assessed in an integrated manner to benefit from each other.

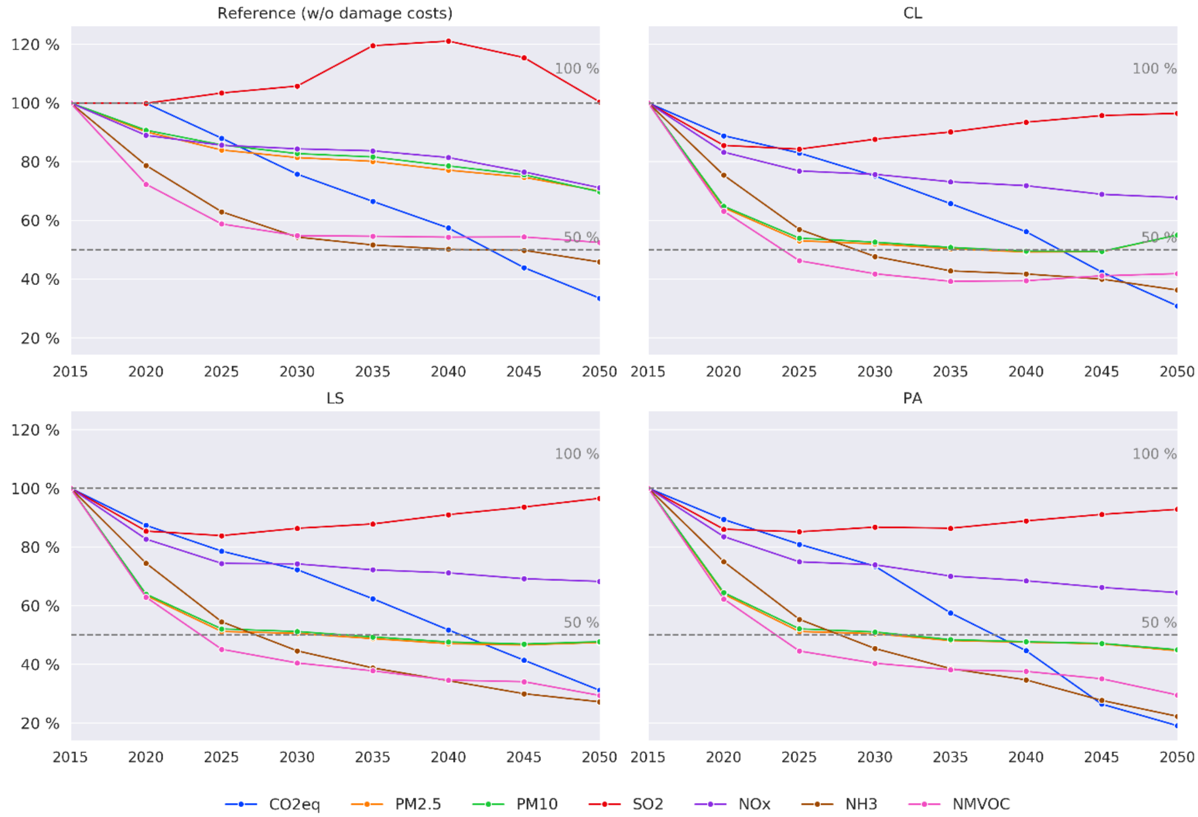


Figure 20. Changes in emissions of air pollutants and GHG relative to 2015 levels.

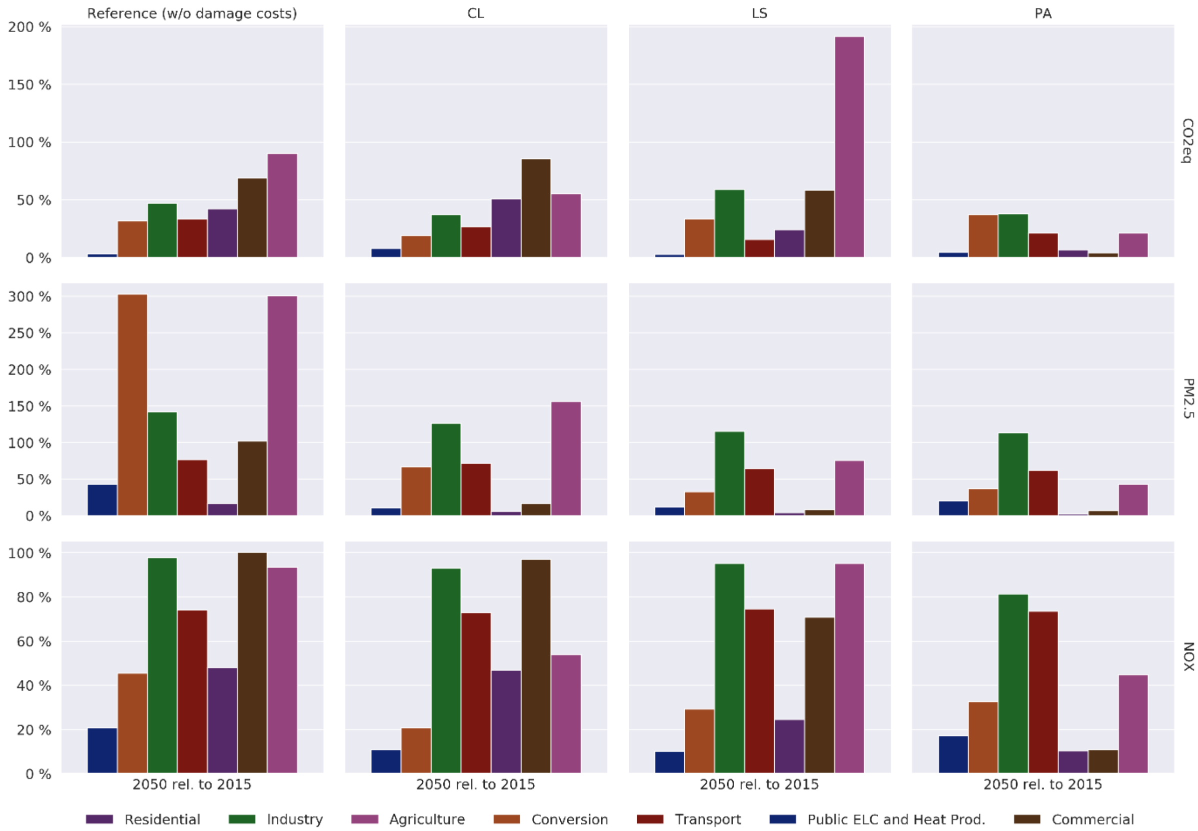


Figure 21. Sector-specific levels of emissions of CO_2-eq. and $PM_{2.5}$ in 2050 relative to 2015.

Message 19: Low-carbon transition brings about health benefits

The emission reductions and associated improvements in air quality lead to health benefits in all four pathways, especially in 2050. This is visible in both health impacts given as "Disability Adjusted Life Years" per country representing the exposed population and associated health costs following the "Polluter Pays" principle. Across the EU28, GHG mitigation targets lower associated costs of air pollution in 2050 by 21 % (relative to 2015) resulting in a welfare benefit of 54 bn. € in the Reference case; in the CL pathways these savings are increased to 76 bn. € (Figure 22). The additional ambition to reduce cross-sectoral GHG emissions in the PA pathway leads to additional health benefits in most countries across the EU. On average and compared to the CL pathway, further reductions in air pollution lead to additional savings in annual health costs of 8 bn. € from 2030 onwards; for the LS pathway these savings are 4 bn. €, so only about half as much. This also indicates that more ambitious climate mitigation targets are further leading to additional co-benefits which may outbalance the cost of extra effort. In order to quantify this, a detailed cost-benefit-analysis should be carried out, which also comprises additional impact categories not part of this study such as comfort losses and life-cycle implications.

Variations by pathway

The push from active consumers in the LS pathway seems to result in a more favourable situation in 2020 and 2030 with most countries showing lower or similar impacts as in the PA pathway (Figure 23). With its higher ambitions for GHG reductions in 2050, the latter still leads to the lowest impacts across Europe in the years after

2030, resulting in overall lowest associated costs over the years. Overall, additional benefits in the form of reduced health impacts and additional costs seem to depend mainly on air quality improvements with regard to particles. All three pathways (CL, LS and PA) show similar levels of emissions of primary particles and precursors of secondary particles up until 2030 (see also message 8). The additional health benefits in the LS pathway are a result of reduced primary particles and NH_3 due to a higher share of solar and ambient heat and lower utilization of biomass in the residential and commercial sector. In the PA, these emissions are even further reduced as the commercial and residential sector as well as industry are highly electrified as a result of utilizing biomass CCS in the power supply sector. These results highlight the critical role of biomass and its utilization not only in terms of climate change mitigation but also with regard to air quality. Depending on the sector and the respective technology used, biomass utilization can affect air quality positively or negatively. Sector integration and cross-sectoral mitigation targets are an important pillow to achieve additional co-benefits of air pollution control and ambitious GHG mitigation, which may outbalance the extra effort needed.

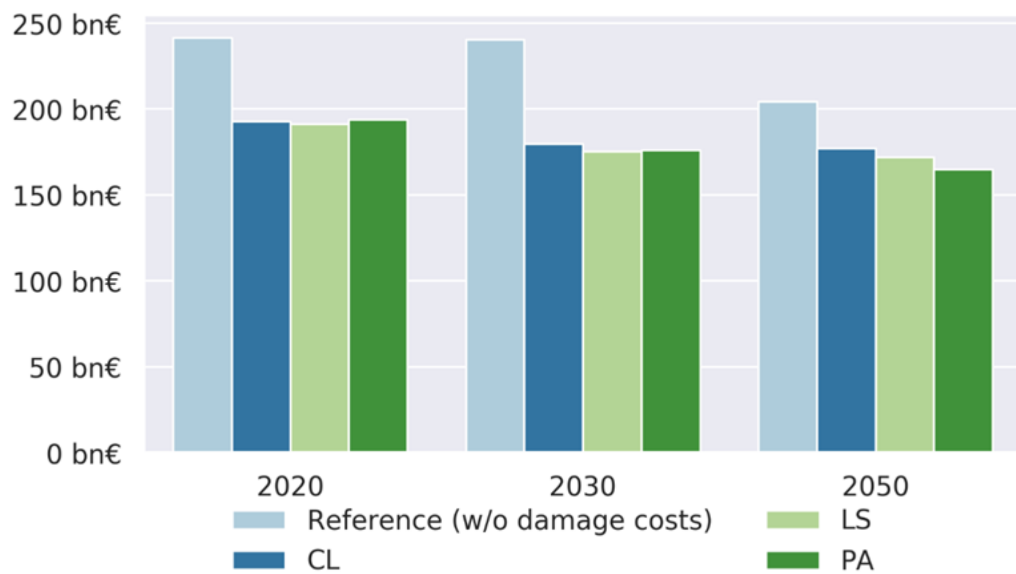


Figure 22. Health costs associated with air pollution on EU28 level for all pathways in the years 2020, 2030 and 2050.

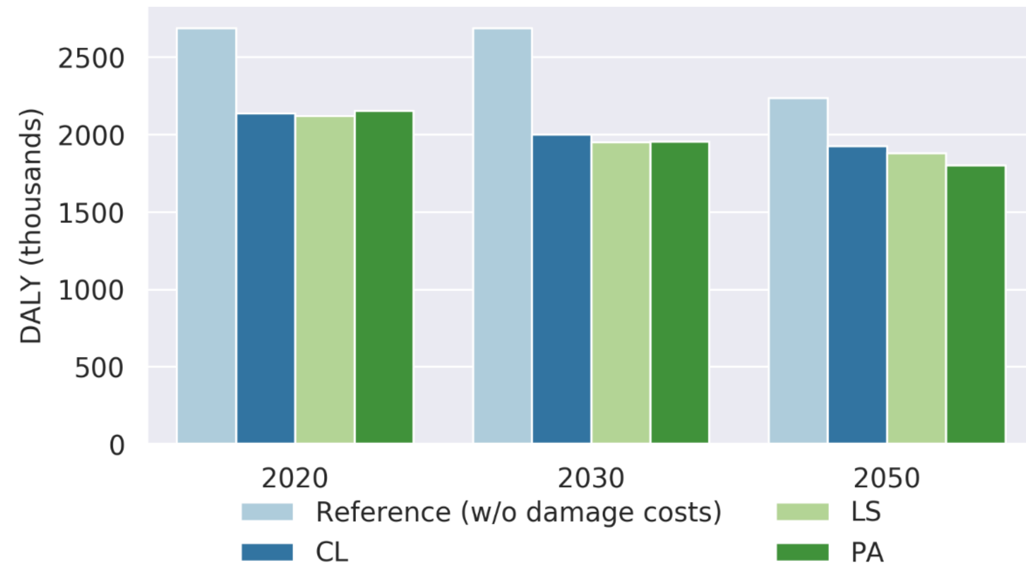


Figure 23. DALYs on EU28 level for all pathways in the years 2020, 2030 and 2050.

Message 20: Central European countries profit the most from better air quality and health

When analysing the distribution of health impacts caused by air pollution from the EU28, CH and NO, not all countries profit from a cleaner energy system in this aspect. The principle of burden sharing in GHG reductions in combination with national targets seems to result in a re-distribution of emissions of air pollutants and thus related health impacts and associated costs from central Europe to south-eastern Europe, with Greece showing an increase of impacts over time, even if health costs of air pollution are considered in the decision making of a low-carbon pathway (Figure 24, CL pathway vs. Reference pathway). Central European countries such as Germany and Poland seem to profit the most, cutting their health impacts and also associated costs at least in half in 2050 compared to 2015. This spatial pattern is also noticeable for the other two pathways.

Variations by pathway

With the principle of burden sharing in GHG reductions in combination with national targets, not all countries profit from better air quality and health due to emission reductions. While some countries, such as Germany and Poland, show high reductions in exposure and attributable external costs - clearly identifying them as beneficiaries of climate change mitigation efforts within the European energy system - exposure to air pollution, related health impacts and attributable costs actually increase for other countries (Figure 24 and Figure 25). Note that associated costs in Figure 25 are allocated following the "Polluter Pays" principle including health costs in neighbouring countries whereas health impacts in Figure 24 only relate to their own exposed population. This includes exposure to emissions coming from neighbouring countries. In the Netherlands, health impacts only seem to increase in the middle years in the Reference pathway due to an increase in fuel oil consumption in navigation which is later replaced by diesel, still resulting in an actual reduction of health impacts and associated costs in 2050 compared to 2015. With the health costs considered in the CL pathway, diesel is used to meet the increasing demand in navigation from early years on, preventing increasing fuel oil use and thus health impacts. For other countries like Greece and Ireland, health impacts increase. Both countries also show increasing attributional costs, indicating that their own emissions of air pollutants increase as well. Similarly, Bulgaria and Slovakia are characterised by increased attributional costs in both pathways.

Additionally, countries like Germany, Poland and France can reduce their attributable costs due to health impacts across Europe more than health impacts among their own population. Because of their geographic location they seem to only have limited control over reducing actual health impacts in their own territories since these are affected greatly by emissions from neighbouring countries and long-range transport of air pollution. The large decrease of attributable cost in these counties in combination with the increase of these costs in Greece, Bulgaria and Slovakia also suggest that emissions of air pollutants are re-distributed. With a mix of burden sharing and national GHG reduction targets, reductions in emissions of air pollutants in central Europe seem to be at least partly achieved by shifting activities and related emissions to south-eastern Europe. Considering costs of health impacts in the optimising, leads to an even more decisive decrease in health impacts as well as attributable costs in Germany and Poland in the CL pathway, triggering additional reductions of air pollution and related impacts in these countries. This also means that most of the potential cost savings can be attributed to reducing health impacts in only few countries.

Similarly, not all countries seem to benefit equally from cleaner air in the LS and PA pathway (Figure 24 and Figure 25). In comparison to the CL pathway, most countries show similar levels of health impacts and associated costs up until 2030. From 2030 on, all countries except for the Netherlands and Spain seem to profit from additional improvements in air quality. In both the LS and the PA pathway, the Netherlands show higher emissions of particulate matter from transport (incl. navigation) and Spain has higher NO_X emissions in industry leading to worse air quality. The biggest profiteers from better air quality in these two pathways are distributed across Europe with Belgium, Germany, France, Greece, Italy and Poland all showing lower health impacts in 2050 than in the CL pathway. These countries are also showing the biggest annual savings in associated costs, which are allocated according to the “Polluter Pays” principle. This means that the additional benefits from better air quality in both the LS and the PA pathway are only attributable to few EU Member States who are able to further reduce their emissions. Note that Greece still shows higher impacts and associated costs in 2050 than in 2015; the increase is just not as high as in the CL pathway.

The uneven distribution of health benefits across countries, with some countries even showing higher exposure in 2050 compared to 2015, may lead to conflicts between pan-European climate mitigation policy and national or even local air quality plans. Additionally, the role of trans-national impacts, i.e. impacts occurring in one country caused by emissions of another country, should not be underestimated. This highlights the necessity for a pan-European strategy to address climate change and air pollution simultaneously. With burden-sharing schemes and national targets aiming to achieve a common target across the EU, integrated policies are even more important.

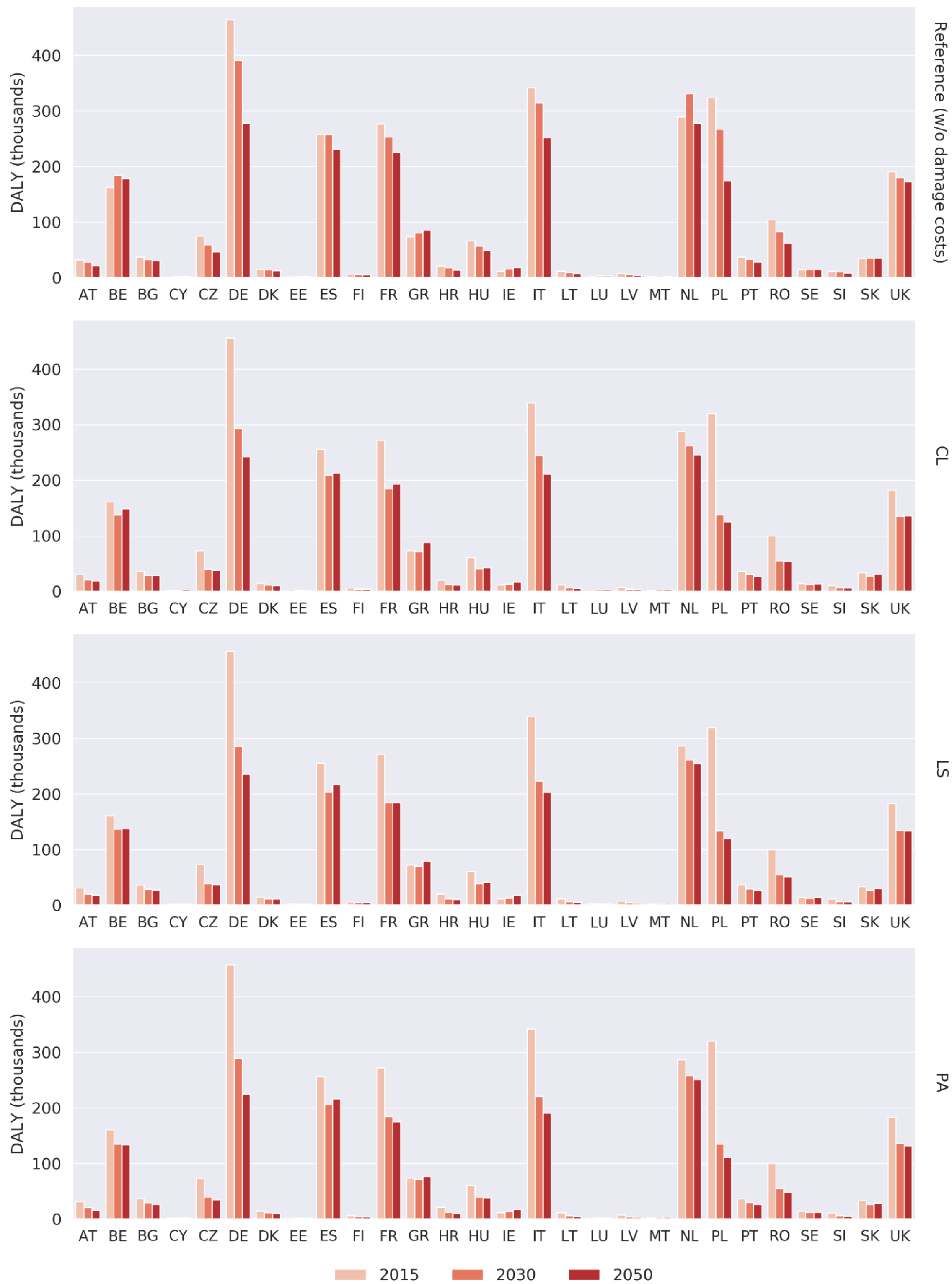


Figure 24. Country-specific health impacts in DALY attributable to air pollution from the EU28, CH and NO for selected years.

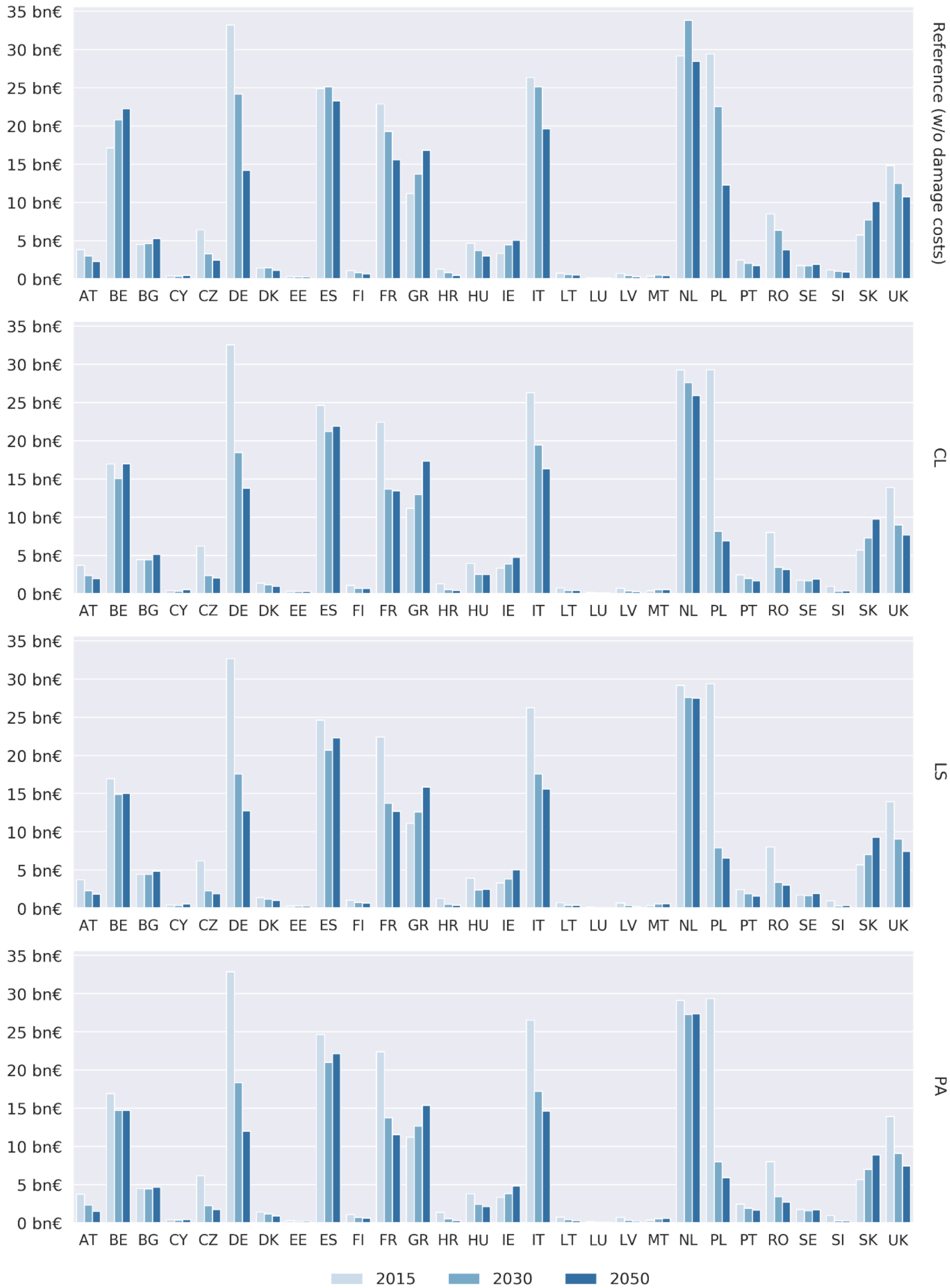


Figure 25. Country-specific costs of air pollution due to health impacts following the "polluter pays" principle for 2015, 2030 and 2050.

3.2.3. *Energy vulnerability and low-carbon transitions*

The low carbon transition envisioned for Europe is set to bring substantial benefits, from an increase in employment across specific sectors developing low carbon technology, to less reliance on fossil fuels and the associated price volatility, reduced levels of air pollution, and opportunities for lower energy costs through measures improving household insulation. However, it is inevitable that some households and industries more vulnerable to the changes that a rapid and large-scale transition brings could lose out, particularly if adequate mitigating measures are not put in place.

Recognising that the impacts of the large-scale structural shift towards a low carbon energy system will be distributed differently across sectors and different regions of the EU is important for three reasons; firstly, there is a moral imperative to ensure that the transition is fair and does not disproportionately impact those less able to make necessary change. Secondly, the transition will need broader stakeholder buy-in and engagement, which will be challenging to achieve if the low carbon transition is perceived as unfair. Finally, the transition provides a huge opportunity to address underlying structural problems across communities and industry, such as under-investment in inefficient buildings and the need for efficiency improvements to industrial processes.

At the EU and Member State level, the distributional impacts of climate and energy policy are not well recognised, nor are the data and tools for effective assessment. Impact assessments seldom undertake rigorous assessments that consider regional differences in household or industry sector impacts [24], with the process focused on economic efficiency.

The lack of recognition of this issue in part reflects the use of scenario analyses that consider aggregate spatial scales only and work with coarse sector resolution. Furthermore, economics framing focuses assessment on what is cost-effective and cost–optimal. In addition, distributional analyses require disaggregated data, whether that be spatial, sectoral, or by socio-economic groupings. However, these are not reasons for maintaining the status quo.

This research is motivated by the absence of a recognition of distributional impacts but also an acknowledgement that scenario analyses that use a techno-economic framing are widespread and have considerable benefits. This reflects the REEEM approach that has techno-economic pathways at its core around which it builds complimentary, linked analyses. We propose a complimentary approach to exploring the implications of different low carbon pathways for vulnerable regions, known as InVEST, or *Indicators of Vulnerability in Energy System Transitions*. This seeks to address the question of how we ensure that insights from modelled pathways used in strategy development take account of distributional impacts, and recognises vulnerable households and industries.

Crucially, key concepts that provide policy traction for energy vulnerability are recognised by the Commission, including just transitions and energy poverty, both of which were reflected in the recent Clean Planet for all strategy [6]. Just transitions relates to protection of workers in industries that may be more vulnerable to sustainable development policies. Driven by the trade union movement, the principles of just transitions are captured by guidelines provided by the International Labour Organisation [25]. Energy poverty is a situation where households are unable to adequately meet their energy needs at an affordable cost. It is caused by a combination of inter-related factors including low income, high energy prices, poorly insulated buildings, inefficient technologies and sometimes limited access to clean and affordable energy sources [26].

The InVEST approach first maps out different subnational regions across Europe that may be more vulnerable to impacts arising from the proposed low carbon energy transitions, based on a set of indicators. The indicator set captures energy vulnerable households, and industry sectors that are energy-intensive, both of which may struggle with increased costs, and sectors that are carbon-exposed, such as the coal sector. Based on the regional picture of vulnerability, the next step is then to consider how different pathways may impact such regions and communities in the future, if such vulnerabilities were to persist. We refer to regional vulnerability indicators as sensitivity metrics, and pathway impacts as exposure metrics, as per the vulnerability framing used in the climate impacts and adaptation field [27]. The basic concept is illustrated in Figure 26.

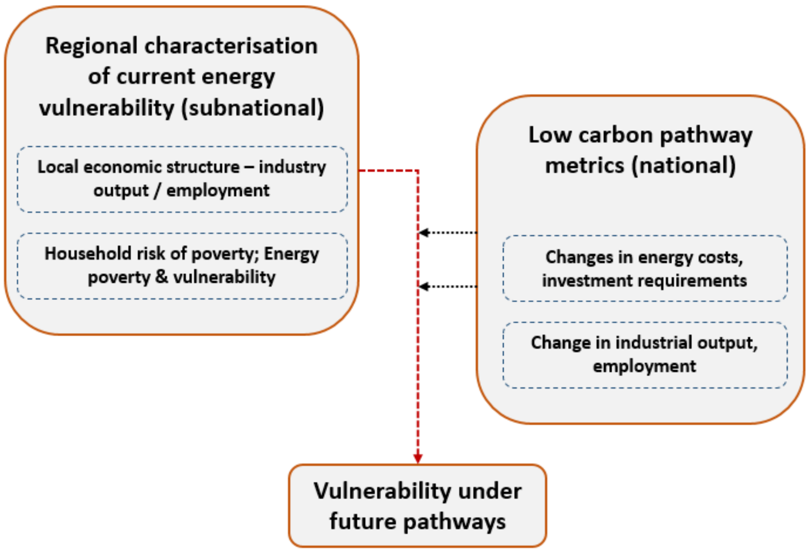


Figure 26. Concept of combining low carbon scenario metrics with proxy energy vulnerability datasets.

For households, sensitivity metrics (identifying vulnerable regions) include:

- Energy affordability, based on household budget surveys and other surveys focused on living conditions;
- Household income.

For industry, metrics include:

- Employment in fossil fuel-based industries;
- Employment in sectors defined as energy-intensive;
- Long term unemployment.

An example of one of the above sensitivity metrics – share of households unable to keep adequately warm - is shown in Figure 27 below.

Once mapped, the implications of the REEEM low carbon pathways across the different regions were considered. This was done by overlaying scenario metrics of relevance to regional vulnerability mapping. For example, coal production under the low carbon scenarios was compared to the employment levels in regions in different Member States. For households, scenario metrics such as energy costs and investment levels across Member

States were compared to regions in those same Member States identified as vulnerable. The complete findings of the analysis can be found in deliverable D4.1b – [Focus report on behavioural effects and distributional impacts](#).

3.2.3.1. Main insights

Message 21. Specific regions of Europe are more vulnerable to the impacts of low carbon transitions than others

The low carbon transition will have multiple impacts that are likely to affect different regions of the EU, but to differing extents. To explore these distributional impacts, selected indicators of vulnerability across industry and household sectors have been selected, based on sensitivity to energy cost increases or exposure to reducing demand for goods (in industry).

We find that specific regions of Europe are potentially more likely to be sensitive to low carbon transitions. For households vulnerable to change, it is the regions of eastern and southern Europe where issues of affordability and energy adequacy are most prominent. One of the six indicators used to measure this is provided in Figure 27, showing the spatial distribution of households who self-report that they are unable to adequately heat their homes.

Factors giving rise to this vulnerability include insufficiency of heating systems during colder periods of the year (notably in Southern Europe), while in Eastern Europe factors may relate to a range of issues from poor building fabric to inefficient energy systems. Affordability is also a key factor in these regions, where incomes are typically lower than in other EU countries. While there are differences, most of the other metrics used show a similar trend.

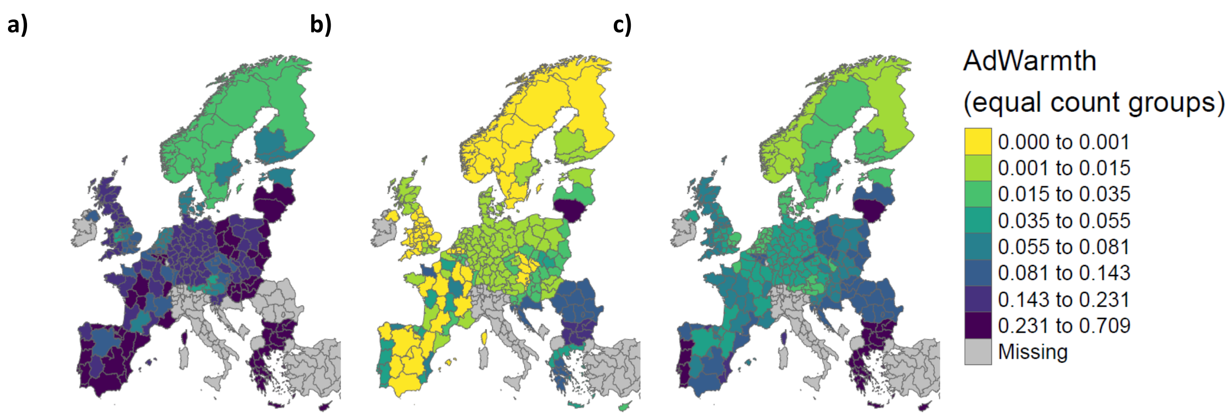


Figure 27. Share of a) decile 1, b) decile 10 and c) average households by NUTS1 regions who report that they are unable to adequately heat their homes.

On industry, the selected vulnerability indicators relate to the number of employees in the coal sector, and share of manufacturing employment in energy-intensive sectors. Coal production and generation jobs are highly concentrated, based on regions with large resources, notably Poland and Germany (Figure 28). Śląskie in Poland (situated in the Silesian basin) is by far the region most dependent on coal mining, accounting for over a quarter of the total sector employees across Europe (which total 400,000). These regions need to be considered; previous transitions suggest that coal phase out could lead to detrimental employment and societal impacts if not managed.

There are also specific regions of Europe with higher shares of employees in energy intensive industries, which could be subject to higher energy cost pressures, and in some case, competitive pressures from the globalised nature of the sector. Regions include those located in Eastern Europe, BENELUX, and parts of Scandinavia, where key sectors include primary metals, non-metallic minerals, paper and pulp, and to a lesser extent, chemicals. These sectors account for some 3 million employees.

a) b)

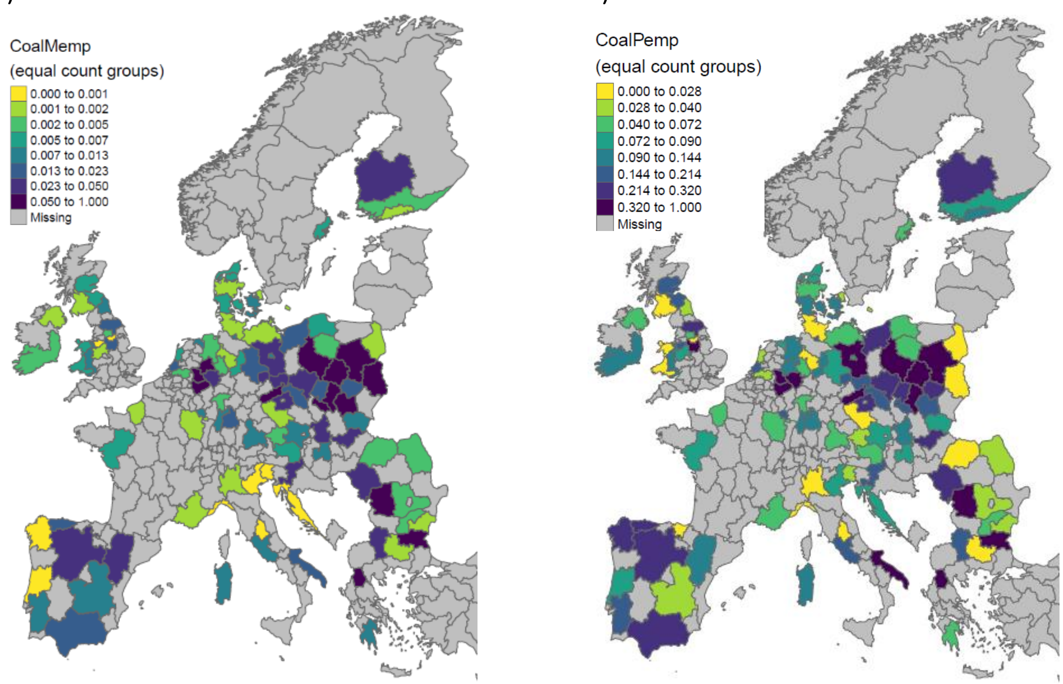


Figure 28. Distribution of coal sector employees across EU. a) Employees in coal mining (direct & indirect), normalised to 1 by highest region (1 = 114,000 in Śląskie, Poland); and b) Direct employees in coal generation, normalised to 1 by highest region (1 = 2910 in Śląskie, Poland).

There is limited geographical overlap between residential and industry metrics of vulnerability, although some regions do have multiple vulnerabilities. Some coal regions also see higher household energy vulnerability, such as Yugoiztochen (BG), Severozápad (CZ), Śląskie (PL), and Sud-Vest Oltenia (RO). Regions which have both high employment in energy intensive industry sectors and household energy vulnerability include cases in Slovenia, Hungary, Lithuania and Estonia. From a policy perspective, these overlaps are interesting to identify where sensitivities exist across multiple sectors to possible impacts of transitions. Regions in Spain and Italy are also identified due to their relatively lower disposable incomes and higher levels of unemployment; recognising specific issues around capacity to respond to the low carbon transition (as indicated by these indicators) is important for designing policy and targeting resources.

Message 22. The ability of households to respond to changes is likely to vary significantly within regions, not only between regions

This analysis highlights that it is not only the distributional impacts between regions that are important but also those within regions. This is highlighted in Figure 27, which shows that for the metric in question, vulnerability is much higher for income decile 1 (lowest) compared to decile 10 (highest). Taking the example of Greece, decile 10 has an average share of households unable to keep warm at 5%, while the decile 1 has a share of 55%, a very large difference. This pattern is replicated across other Member States – and across the most of the household vulnerability metrics. This within-regional variation arises from differences in local economies, incomes, and other factors (local energy systems, building stock, access to services etc.).

While not investigated in this research, the same is probably true of different industries, which are often highly heterogeneous within a region, with some more prepared for shifting to low carbon production than others. The lack of data at the EU level means that this is challenging to determine.

Message 23. The REEEM pathways highlight that energy vulnerable regions may also incur higher energy costs but also the prospects of large investment required to deliver the transition.

There are no significant differences between pathways so the CL pathway is used here as representative of all three pathways.

Regions in the red boxed areas of Figure 29 highlight that those most vulnerable (primarily in countries in eastern and southern Europe) also incur the higher investment levels. This increased investment highlights the opportunity that the transition brings to resolving some of the underlying structural problems inherent in driving household energy vulnerability (poor building stock, insufficient heating provision). It is likely that some of these regions see higher investment due to the need for improved efficiency and associated infrastructure. Policy therefore needs to manage the short-term risks of increasing cost, which could impact negatively on affordability, while incentivising and supporting the large-scale investment that is necessary.

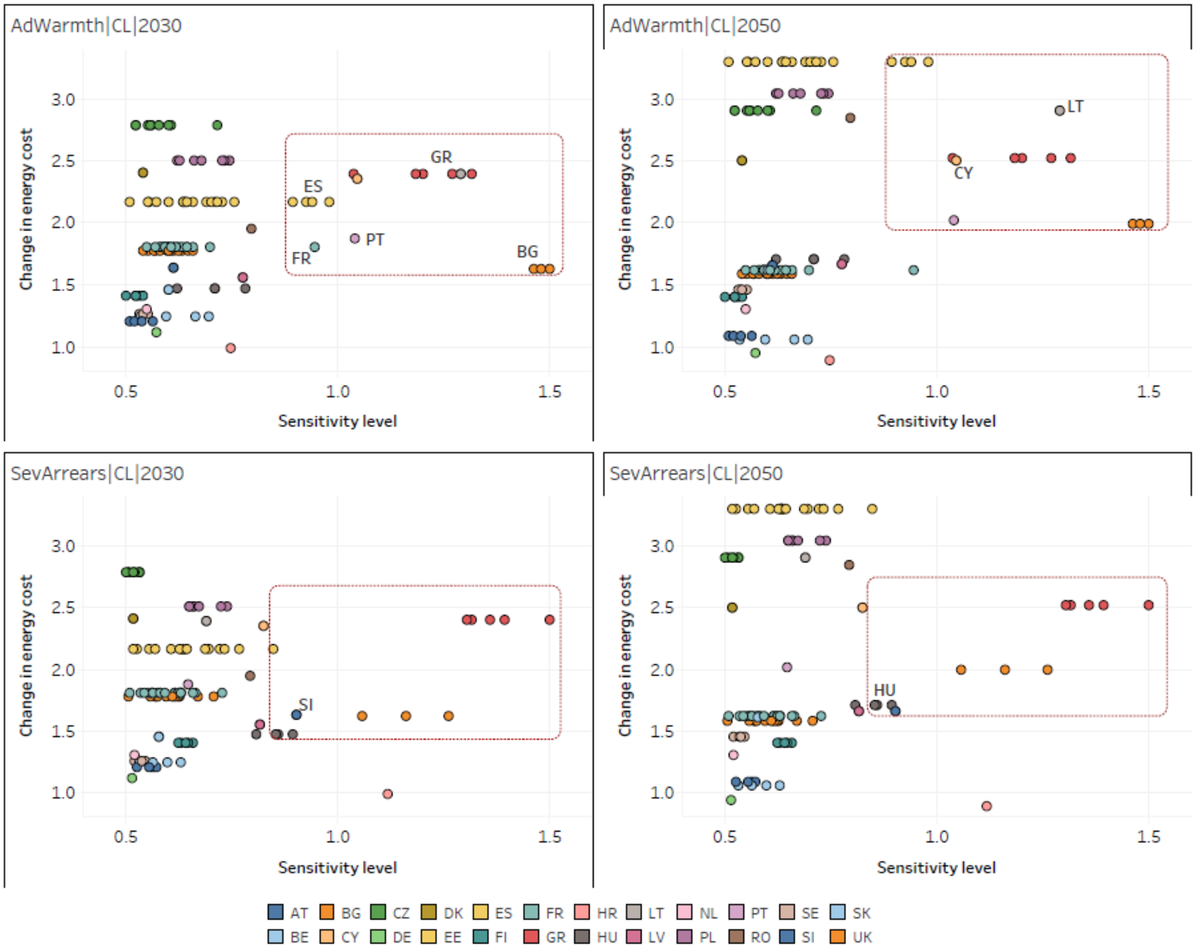


Figure 29. Change in investment level in 2030/50 (indexed relative to 2015, vertical axis) under the CL pathway versus current household vulnerability (horizontal axis) as measured by consensual indicators, AdWarmth and SevArrears. Red boxes highlight those regions who are both vulnerable to impacts and see high levels of investment.

The REEEM pathways do not indicate an increase in energy cost specifically for regions with high employment dependency on energy intensive industries. However, the general trend of the pathways is to show increasing energy costs and the need for large investments to be made in these industries if they are to remain competitive in a low carbon world, and ensuring that Europe retains its heavy industrial base. Unlike the coal sector, the vulnerability of employment in these regions can be reduced through investment, but which will need to be incentivised through policies, including measures that recognise and reward the low carbon provenance of goods.

Message 24. For coal dependent regions, all pathways show rapid decline in both coal production and generation. Just Transition planning is therefore vital for the affected regions.

The pathways see a post-2030 decline that is rapid, with very low or zero output by 2050, meaning that effective planning focused on new opportunity for workers needs to be put in place over the next decade. Unlike other industries, there appear to be no real prospects for keeping these extractive industries in business. While the PA shows some increase in CCS application for coal, it is questionable whether such a prospect is realistic in a net-zero emission world.

Message 25. Recognition that regions differ significantly in terms of vulnerability and capacity to respond, both between and within regions, should be mainstreamed into the policy process.

A range of policy insights and recommendations emerge from this research. Crucially, recognising vulnerability and the potential for distributional impacts across Europe is a first step to then shaping policy to mitigate negative impacts whilst reinforcing and maximising the positive ones. This means mainstreaming this type of analysis into the impact assessment process; the ESPON developed Territorial Impact Assessment (TIA) approach would be an excellent starting point.

In addition to adopting a TIA-type approach, the EU could also play a key role in facilitating the gathering of necessary data to better understand regional differences, and the specific factors that make certain regions more or less resilient to change. An excellent1 initiative on energy poverty has been the establishment of an observatory. Such an initiative could be replicated to further explore industry sector vulnerability, the data needed to measure this, and measures to ensure Just Transitions.

With an enhanced understanding of distributional impacts, an informed policy response can be developed, building on current policy to ensure the necessary support for vulnerable regions. This will be relevant for EU policy but also for Member States policy, including that focused and implemented at the regional level.

3.3. Environment and resources

3.3.1. Life Cycle Assessment

Energy system investment decisions can significantly impact the environment and the transition to a more environmentally sustainable society. Environment here should be understood in a broad sense, not just addressing climate change impacts from greenhouse gases (which can be reflected by the change in radiative forcing – expressed in kg-CO_2eq – or by metrics that model further the cause-effect chain and capture the potential damages to human health and ecosystems)) but other types of environmental problems like chemical pollution, resource depletion, etc. To ensure environmental sustainability, it is important to quantify to what extent the anticipated pathways towards a low-carbon EU society contribute to all those environmental problems, and whether they lead to actual impact reductions.

To conduct such quantification, life cycle assessment (LCA) can be conducted. LCA is an ISO-standardised methodology that enables us to quantify a large variety of environmental impacts in a life cycle perspective, i.e. from extraction of raw materials, through production and use, up to end-of-life and potential recycling or disposal [28]. Thanks to its holistic nature, LCA is widely used to address eco-efficiency questions in comparative studies; for example addressing whether a specific technology is better than another, providing the same service. The inclusion of the full life cycle perspective and the broad variety of environmental problems is essential to identify potential hotspots, which are places in the energy system life cycle that are associated with large environment impacts, and potential burden-shifting across life cycle stages or environmental problems. An example of environmental burden-shifting could occur if a particular strategy leads to decreasing of some environmental impacts (e.g. climate change impacts from greenhouse gases, which can be reflected by the change in radiative forcing (expressed in kg-CO_2eq) or by metrics that model further the cause-effect chain and capture the potential damages to human health and ecosystems) while increasing others at the same time (e.g. chemical pollution) [29].

Here, an LCA model has thus been developed to enable the assessment of the entire energy systems of EU with a full life cycle coverage and with a coverage of several environmental impact categories. Three pathways are considered in REEEM: "Coalitions for a Low-carbon path", "Local Solutions", and "Paris Agreement". The first, in this report referred to as the CL pathway, achieves an 80% reduction in energy-related emissions by 2050 as compared to 1990 levels. The second also achieves an 80% reduction, but with a significant fraction of the climate mitigation efforts driven by communities and individuals. The third achieves a 95% reduction corresponding to the obligations agreed upon in the Paris Agreement. It is important to stress that this activity has not considered the Local Solutions pathway, only the CL and PA pathways.

TIMES is an energy system model generator using a bottom-up linear optimisation model, and its outputs are used as inputs for constructing the LCA model that strongly relies on life cycle inventories – see Figure 30. Life cycle inventories (LCI) are building bricks for the model that compiles all inputs (energy, intermediate materials or products, resources) and outputs (energy, waste, emissions, intermediate products) of a given process or activity (e.g. rolled steel production, high-voltage electricity from a specific technology of coal-fired power plant in a given country, etc.). Using the ecoinvent database (v3.3 [30]), which is currently the largest LCI database with more than 20,000 process LCIs, as starting point, the LCA model was built with the addition of 7,275 created or edited processes, which were parameterized and linked to an Excel interface allowing for differentiating between technologies, time and countries, and allow for assessing different pathways (connection via 33,112 links between the LCI processes and the Excel interface).

The LCA model was applied to all energy systems. Only assessment at full EU28 scale was assessed since the TIMES PanEU model in REEEM was developed to fit EU-wide narratives and it therefore does not bring full consistency at national level. For example, some national energy policies are not factored in the TIMES PanEU model, meaning that potential important discrepancies exist between national pathways framed in existing and planned policies and national trends resulting from the TIMES PanEU model.

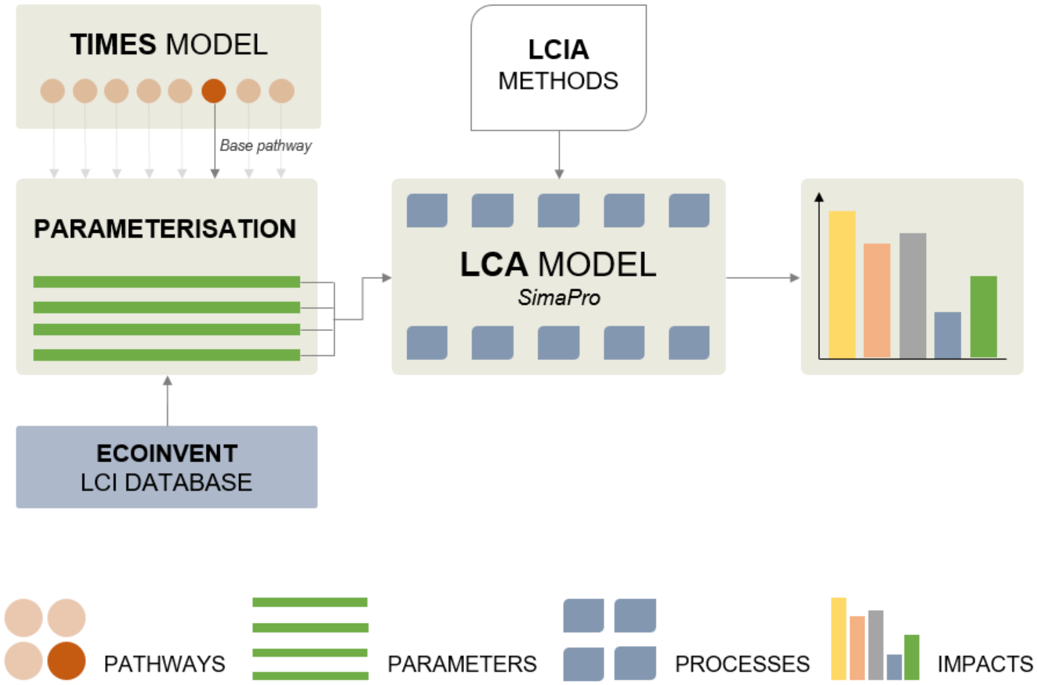


Figure 30. Illustration of the model structure around the LCA model.

3.3.1.1. Main insights

Message 26. Reductions of life cycle impacts on climate change are not aligned with the reduction of GHG emissions from the pathway modelling

Reductions of climate change impacts (expressed as change in radiative forcing, in kg-CO_2 equivalent) of 32% and 49% between 2015 and 2050 are obtained for the CL and PA pathways, respectively (see Figure 31), based on the LCA approach. These decreases are much lower than the reduction of GHG emissions. For example, in the Paris Agreement pathway, a reduction of 95% GHG emissions in 2050 compared to 1990 level is modelled in TIMES PanEU model, which roughly corresponds to a decrease of 93% between 2015 and 2050. This is different from the decrease of 49% obtained with the LCA model. An explanation for such differences may stem from the inclusion of the full life cycle in the LCA study, as opposed to the main focus on greenhouse gas emissions occurring within the EU28 geographical boundaries in the TIMES PanEU model. The climate change impacts of fossil fuel-based energy technologies are driven by the combustion processes, while those of renewables sources like wind turbines or photovoltaics are stemming from their production stage. As a consequence, the switch from fossil fuels to renewables tend to shift the climate change impacts outside the EU28, if renewable energy technologies are produced outside Europe and imported thereafter. This may therefore limit the actual decrease in anticipated greenhouse gas emissions. On the other hand it should be noted that potential reductions of GHG emissions in regions outside Europe are not considered in the LCA model, which may then tend to overestimate the GHG emissions in these regions (because of no time differentiation factoring in the decreases in emission intensities), and lead to underestimate the overall decrease in the global GHG emissions associated with the two pathways. In the PA pathway, decarbonisation in regions outside EU is indeed modelled. An estimate of the true decrease in GHG emissions should therefore be expected to range between the reduction values used in the pathway modelling (in the TIMES PanEU model) and the reduction values reported above.

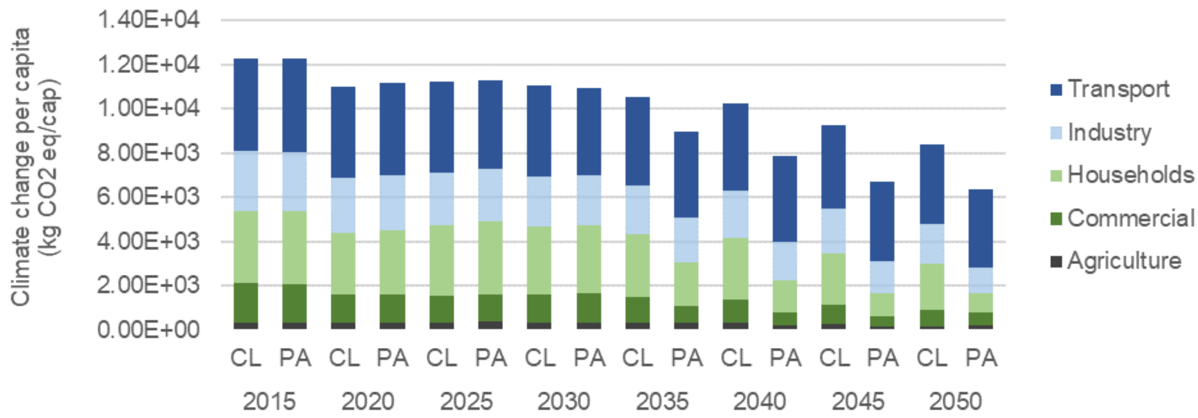


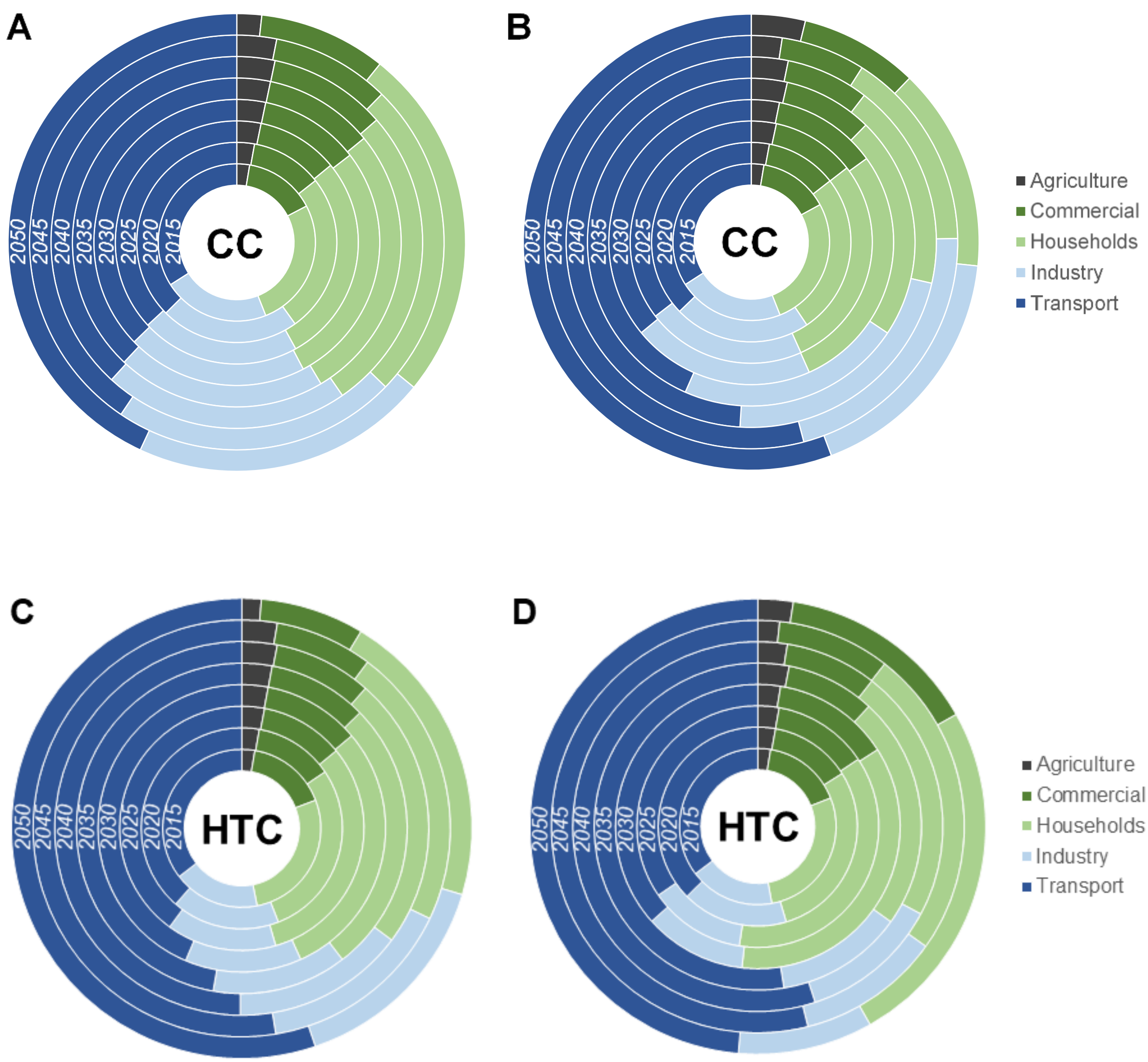
Figure 31. Trends for climate change impacts (per capita) in the EU28 between 2015 and 2050 for both CL and PA pathways.

Message 27. The transport sector is increasingly driving environmental impacts in the EU28 between 2015 and 2050.

As illustrated in Figure 32A-F, the transport sector tends to become increasingly dominant in the different environmental impacts between 2015 and 2050 for both CL and PA pathways (in 2050: near or above 50% of climate change impacts, toxicity impacts from released chemical compounds, and health damages from particulate matter). This is a result of the reduction of environmental impacts in the electricity and heating systems (incl. cooling), which transitions to renewables-based energy sources between 2015 and 2050, while transport systems in the CL and PA pathways continue to mainly rely on internal combustion engines with fuels based on biomass and natural gas. However, it should be noted that several road transport processes were created with major assumptions due to lack of data for modelling their emissions; in those cases, conventional technologies were used, which might lead to overestimate the actual emissions from road transportation, and hence tend to amplify the contribution of the transport sectors in the total environmental burden of energy systems.

Yet, the results of this assessment suggest the need for energy policy-makers to focus on this component of the energy systems and ensure transitions to more environmentally-sustainable transport systems. When doing so, a full life cycle perspective and a broad coverage of environmental problems should be included in the assessment to provide reliable support for decision-making. In addition the refining of the modelling to better capture emissions from new technologies for road transportation should be investigated and factored in.

CL **PA**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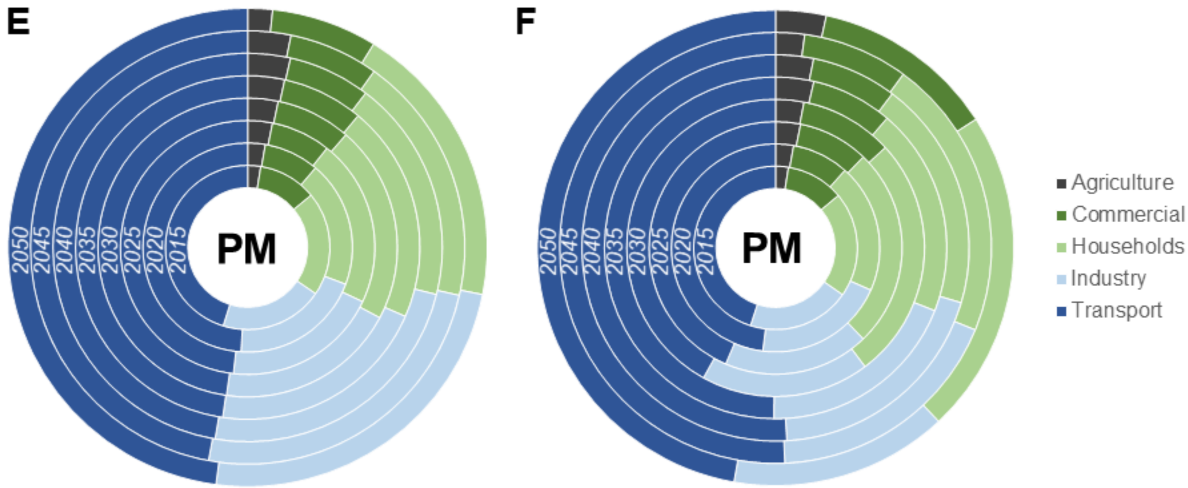

Figure 32. Sector distribution for climate change (CC, Figure 32A-B), human toxicity cancer-effects (HTC, Figure 32C-D) and particulate matter (PM, Figure 32E-F)) for the CL pathway and Paris Agreement pathway. Figures on the left refer to Coalitions for a Low-carbon path, figures on the right refer to Paris Agreement.

Message 28. Human health damages caused globally by energy systems in the EU28 primarily stem from particulate matter formation, climate change and toxic impacts from releases of chemicals

When assessing the total human health damages, neither the PA nor the CL pathway seem to perform better than the other – see Figure 33. Results show that both pathways lead to the same level of decrease between 2015 and 2050 (i.e. decrease of ca. 30%). However, it must be noted that environmental trade-offs occur, with some environmental impact categories tending to decrease more in one pathway over another, e.g. climate change decreasing more in PA than in CL pathway, and vice versa, e.g. cancer effects from released chemicals aka "human toxicity, cancer effects (HH canc)" (Figure 33). Particulate matter formation, climate change and toxicity of chemical releases are found to be the three main contributors to human health damages from energy systems in the EU28. These impacts are caused by emissions of particulate matter (and its precursors, like SO_x, NO_x, NH_3), greenhouse gases and metal and organic substances.

It can be observed that the total damages from the LCA study are equivalent to approx. 17 million DALYs in 2015 and decrease to 12 million DALYs in 2050 for both CL and PA pathways (Figure 33), although as noted in the previous messages, overestimations are expected in these estimates, particularly in future years due to the modelling of regions outside Europe using the same technology efficiencies – and hence emission intensities – as today (no time differentiation). Yet, factoring in this overestimation, the obtained results would still remain higher than the results reported when using the EcoSense model, where approximately 2.8, 2.0 and 1.9 million DALY were found to stem from the energy systems in the EU28 in 2015 for both pathways, in 2050 for the CL and in 2050 for the PA pathway.

The different scoping between the two assessments explain part of this difference since the EcoSense model focuses on the emissions during the operation stage of the energy system, while the LCA study includes the entire life cycle of the energy systems, from extraction of raw materials through production and installation and operations up to end-of-life. For example, the impacts associated with production of goods in China which are then imported to Europe will be captured. The difference in impact contributors to the total human health damages is another cause for the difference. The assessment from the EcoSense model considers emissions of few air pollutants, while the LCA study encompasses all environmental stressors contributing to human health damages, hence including contributions from climate change, water stress and carcinogenic and non-carcinogenic effects induced by chemical releases like metals and organic substances.

These findings demonstrate that, in addition to a systemic and holistic perspective, including all life cycle stages (and not just the operations within the EU), a broad spectrum of environmental problems, covering all relevant impacts of energy systems, must be included in environmental sustainability assessments. Only such broad and all-encompassing scoping can provide a complete overview of which environmental problems are predominant in the total environmental burden, where potential environmental trade-offs occur, where burden shifting from one life cycle stage to another or from one impact to another arise, and what to prioritize in decision-making processes.

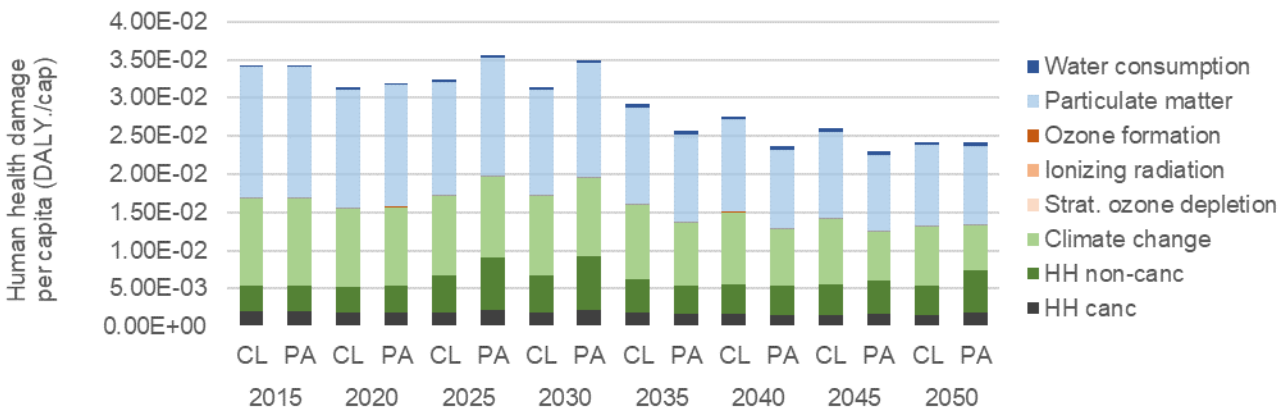

Figure 33. Total human health damage assessment results in the EU28 over 2015-2050 for both Coalitions for a Low-carbon path and Paris Agreement pathways, with contribution of different environmental impact categories.

3.3.2. Critical materials

The critical materials assessment component of Task 5.3 in REEEM covers 14 raw materials and 7 energy technologies that require these materials, exploring how European energy technology related demands for these materials might change between the three different pathways explored in REEEM under Work Package 1. Moreover, the risk of supply bottlenecks that might impede these technological transitions in future are also assessed. Table 6 and Table 7 below show the materials and the energy technologies considered in this activity.

Table 6. Materials considered in this report.

Material	**Chemical Symbol**
Cobalt	Co
Dysprosium	Dy
Europium	Eu

Gallium	Ga
Indium	In
Hafnium	Hf
Lanthanum	La
Lithium	Li
Neodymium	Nd
Platinum	Pt
Praseodymium	Pr
Tellurium	Te
Terbium	Tb
Yttrium	Y

Table 7. Clean energy technologies considered in this report.

Energy Technology	**Notes**
Lighting	We consider both: - *energy efficient fluorescent lamps* - *lamps based on light emitting diode (LED) technology*
Electric Vehicles	We consider a range of body styles – *small/medium/large passenger cars, light duty vehicles, heavy duty vehicles, buses*; and also capture multiple automotive drivetrain types, including: - *hybrid electric vehicles* i.e. where the battery is used only for storing energy from regenerative braking and is not charged directly from mains power - *battery electric vehicles* i.e. where a rechargeable battery provides the main motive power source - *plug-in hybrid electric vehicles* i.e. where electrical energy from a rechargeable battery is combined with at least one other stored fuel source for motive power (fuels include gasoline, diesel, ammonia, methane, biofuels and hydrogen from various production paths)
Wind Turbines	We assume a mix of permanent magnet and electromagnet *wind generators*, as well as a blend between geared and gearless transmissions for both *onshore* and *offshore* installations
Photovoltaics	We assume a mixture of *crystalline* and *thin-film* photovoltaic technologies
Nuclear Reactors	We assume that new nuclear power deployments take the form of conventional *pressurised water reactors (PWRs)*
Fuel Cells	We consider both: *Solid oxide fuel cells* for stationary applications *Proton exchange membrane (PEM) fuel cells* found in vehicles
Electricity Storage Batteries	We consider: *Electrical storage batteries* for stationary applications *Electrical storage batteries* found in vehicles

3.3.2.1. Main insights

Message 29. Material demands are dominated by vehicle technologies

Figure 34 illustrates a breakdown of material demand for each pathway by energy technology. From this chart the major drivers behind the demand for materials can be seen clearly. In all three pathways, electric vehicles and plug-in hybrid electric vehicles are the major sources of material demand. This renders the automobile sector (which is expected to play an important role in the transition) susceptible to various types of risk which need to be taken into account when designing a strategy.

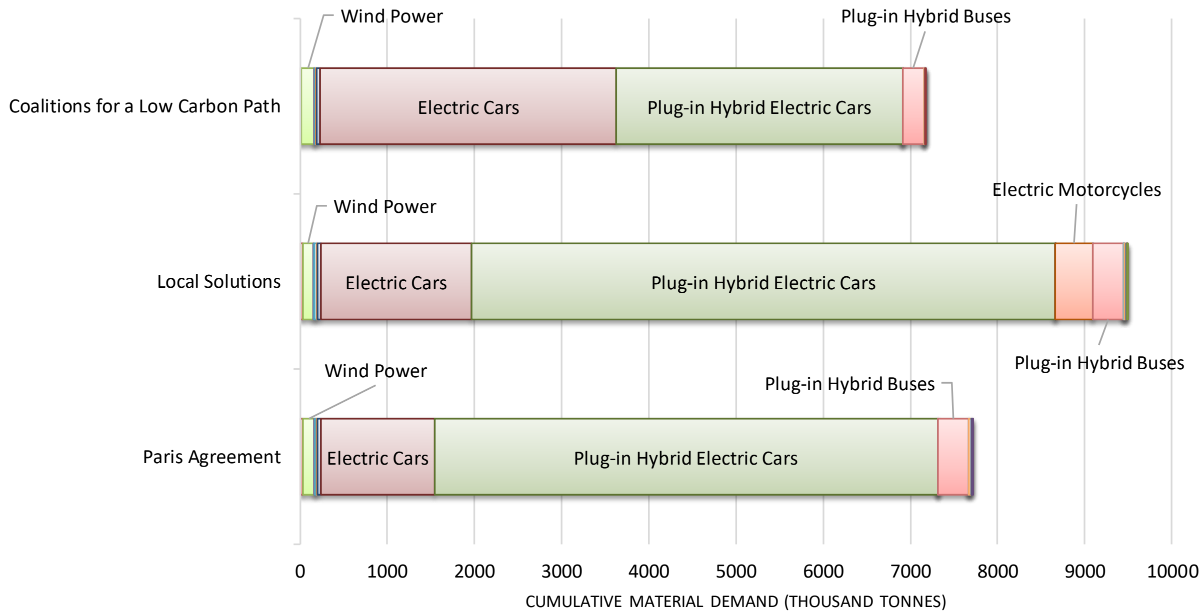

Figure 34. Cumulative material demand by technology.

Variations by pathway

LS and PA feature a significantly higher share of demand attributed to hybrid electric cars than the CL pathway (where shares are almost equal). Overall, the demand for critical materials by the vehicle sector is increased in the LS pathway compared to the other two.

Message 30. A number of potential supply bottlenecks exist across the geological, economic and geopolitical dimensions. The most at risk materials appear to be cobalt and tellurium, with a second grouping being platinum, rare earths (particularly dysprosium and neodymium), gallium, and indium.

Table 8 summarises the supply risks for each of the selected materials. Cobalt and tellurium appear to be at risk across all three assessed dimensions. Platinum and the rare earths are not at risk from a geological perspective but are exposed to economic risks due to rapid demand growth and geopolitical risks as a result of high supply concentrations in single countries. Gallium and indium are also clearly exposed to economic and geopolitical risks but the overall geological risk level could not be determined due to a lack of quantitative data on reserves. Lithium is at risk from the economic dimension but is not likely to be affected by geological constraints or geopolitical crises. Finally, hafnium does not appear to be at risk in any of the assessed dimensions.

Table 8. Overview of Supply Risks for Selected Materials.

Material	Risk		
	Geological	Economic	Geopolitical
Cobalt (Co)	Yes	Yes	Yes
Gallium (Ga)	-	Yes	Yes
Indium (In)	-	Yes	Yes
Hafnium (Hf)	No	No	No
Lithium (Li)	No	Yes	No
Platinum (Pt)	No	Yes	Yes
Rare Earths	No	Yes	Yes
Tellurium (Te)	Yes	Yes	Yes

Variations by pathway

Figure 35 illustrates results for each of the REEEM pathways, both the shares of cumulative material demand across the modelled time horizon and the detailed of how material demand changes over time for individual elements. Both the CL and the PA pathways represent similar levels of material demand at 7169 kt and 7710 kt respectively. The LS pathway has the highest material demand of all at 9483 kt, likely owing to the significantly larger role that a transition to low-carbon end-use demand technologies has in this case.

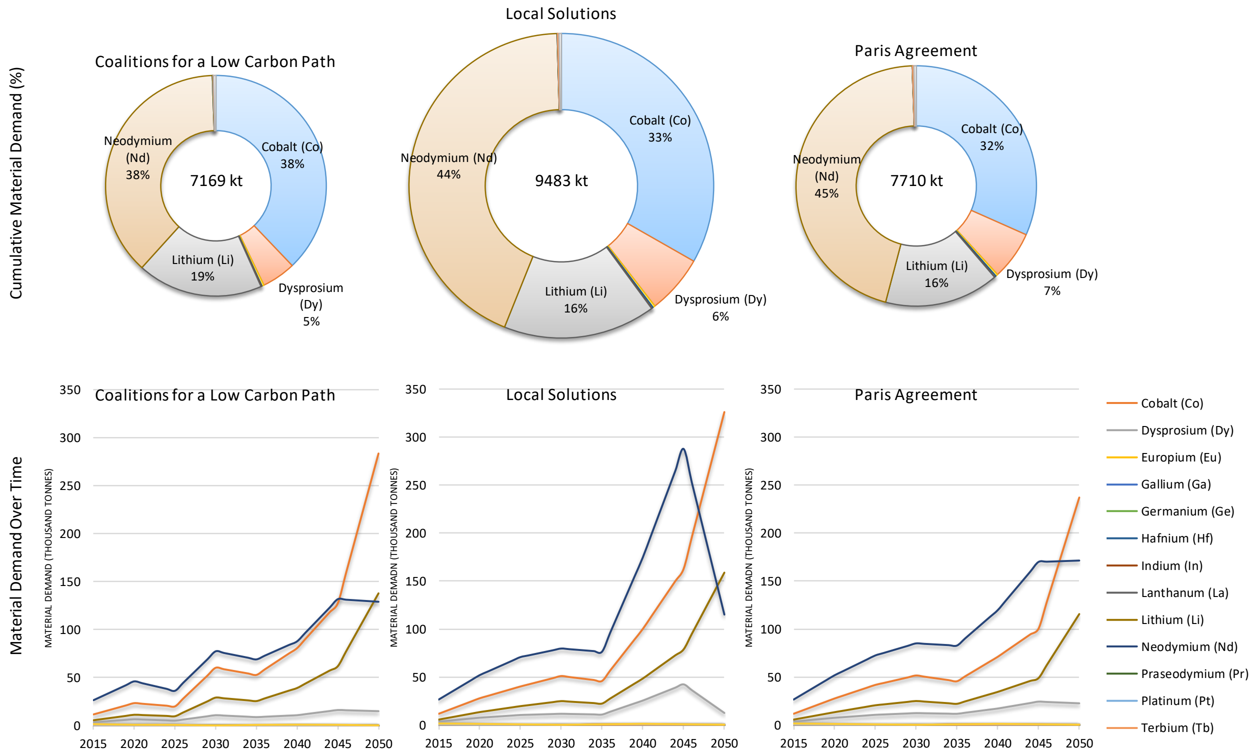

Figure 35. Material Demand for Each REEEM pathway.

Message 31. Key mitigation options for the EU are material efficiency, recycling and substitution[5], which should be considered as policy imperatives

A large fraction of the critical material demand assessed in this report arises from the transition to electro-mobility, so per unit estimates of material demand for vehicles are a key driver of the report findings. It is worth reflecting that research into material efficiency and component substation has found that rare earth content in vehicle magnets could be reduced through efficient design by up to 40% and that options for electric motors are under development that are free of rare earths entirely. This is a pathway independent message.

3.3.3. Climate-Land use-Energy-Water nexus

Deep changes in the way energy is supplied and consumed, as those advised in the Clean Planet for all strategy and in SDG7, combined with climate changes, are likely to affect and be affected by changes in other related systems. Two of these are water and land resources. Part of the integrated assessment of REEEM focused on analysing selected interactions between the energy, water, land and climate sector (with a so-called Nexus approach) under the transformations assumed in the REEEM pathways. For this task, REEEM employed a vast

[5] It is often possible to substitute materials from a similar group (albeit with often reduced or altered performance characteristics). An example from the platinum group metals (PGM) would be replacing platinum with palladium, while from rare earths an example would be substituting samarium for dysprosium.

range of existing external data sources, which have been processed, or modelled. To complete the modelling, part of the input data was taken from the output data-set of TIMES PanEU. The data exchange pertains mainly to energy generation and capacity of relevant units across the EU. The selected interactions REEEM analysed within the scope of this part of the assessment are:

- Water Use in Electricity Generation for Water-Energy Nexus Analyses;
- Future changes in heating and cooling demands over Europe as the effect of a changing climate;
- Land use changes in relation to changes in the energy system.

The rationale for the linkage between water and energy is the tight link between these two components: a substantial share of the global water usage is due to the energy sector, with high impact on water resources. In REEEM we address the current basis for a performing quantitative analyses on the water-energy nexus also with regards to data availability and quality. We then address and validate the quality of literature estimates on water factors (water used per energy unit produced) on historical timescales as well as projecting these for the future using under the REEEM pathways. Further, we address the impact of increasing temperatures under climate change scenarios on energy demands in the EU, by calculating the future changes in heating and cooling demands. This study is meant to highlight the importance – especially under climate change - of environmental drivers of energy demand, besides economic and demographic drivers. Finally, we calculate the interlinkages between changes in land use and changes in the energy system especially with regards to the use of biomass for energy supply. As the decarbonisation may require more biomass in industry and power generation (as resulting from the energy system optimisation study), its impacts on EU, national and sub-national scale need to be assessed.

The activities to study the aforementioned interactions can be categorised into the following five components:

1. Water Use in Electricity Generation for Water-Energy Nexus Analyses: The European Case

This study assesses the historical water usage (withdrawals and consumption) of all major relevant electricity generation sources and sub-technologies based on an extensive literature review and validates its results against available country-level data on actual withdrawals [31].

2. Future risks of water shortage at the European scale: Energy sector water usage and projected scarcities

This study employs the methodology developed in [32] paper on water usage factors (water volume per. Electricity unit generated) in conjunction with all three REEEM pathways to estimate the future electricity generation water usage (until 2050). These estimates are then analysed in conjunction with data on future precipitation, net precipitation (precipitation minus actual evapotranspiration) and temperature to address ***areas of potential scarcities*** and competing demands. Since the study employs every available modelling output (up to approx. 18 models per RCP scenario) from the high-resolution (12.5km) CORDEX database [33], estimates on the robustness and variability is also incorporated.

3. Future changes in heating and cooling demands over Europe

This study assesses the future heating and cooling demand based on a degree-day methodology and state-of-the-art CORDEX regional climate model ensemble data from the RCP scenarios 2.6 (for the Paris Agreement pathway) and 4.5 (for the Coalitions for a Low-carbon path and Local Solutions pathway) up until 2050.

4. Challenges of Data Availability: Analysing the Water-Energy Nexus in Electricity Generation

This study aims to discuss and demonstrate the challenges of data availability and quality in the assessment of research questions within the water-energy nexus. A broad range of datasets are presented from the water, climate and energy communities respectively and examples on the usage of these datasets are further highlighted.

5. Land use changes in relation to REEEM energy pathways

The REEEM pathways are used to show the necessary changes in land use as mainly related to biofuels.

The complete description and the output of the aforementioned activities can be found in deliverable D5.1 - Focus Report on climate impacts on the Energy-Food-Water nexus.

3.3.3.1. Main insights

Message 32: More ambitious decarbonisation targets can lead to higher water consumption

Energy system is a major consumer of water as mostly used in the cooling of thermal power plants, but also other uses such as cleaning. Energy system transitions will influence water usage levels, while climate change will have an influence on its availability. The assessment of water consumption until 2050 shows decreasing water consumption mostly resulting from phasing out of fossil fuel thermal plants (*Figure 36*). At the same time, higher utilisation of geothermal (along with the high water intensity of this technology) in response to more ambitious decarbonisation targets leads to an increase in water consumption.

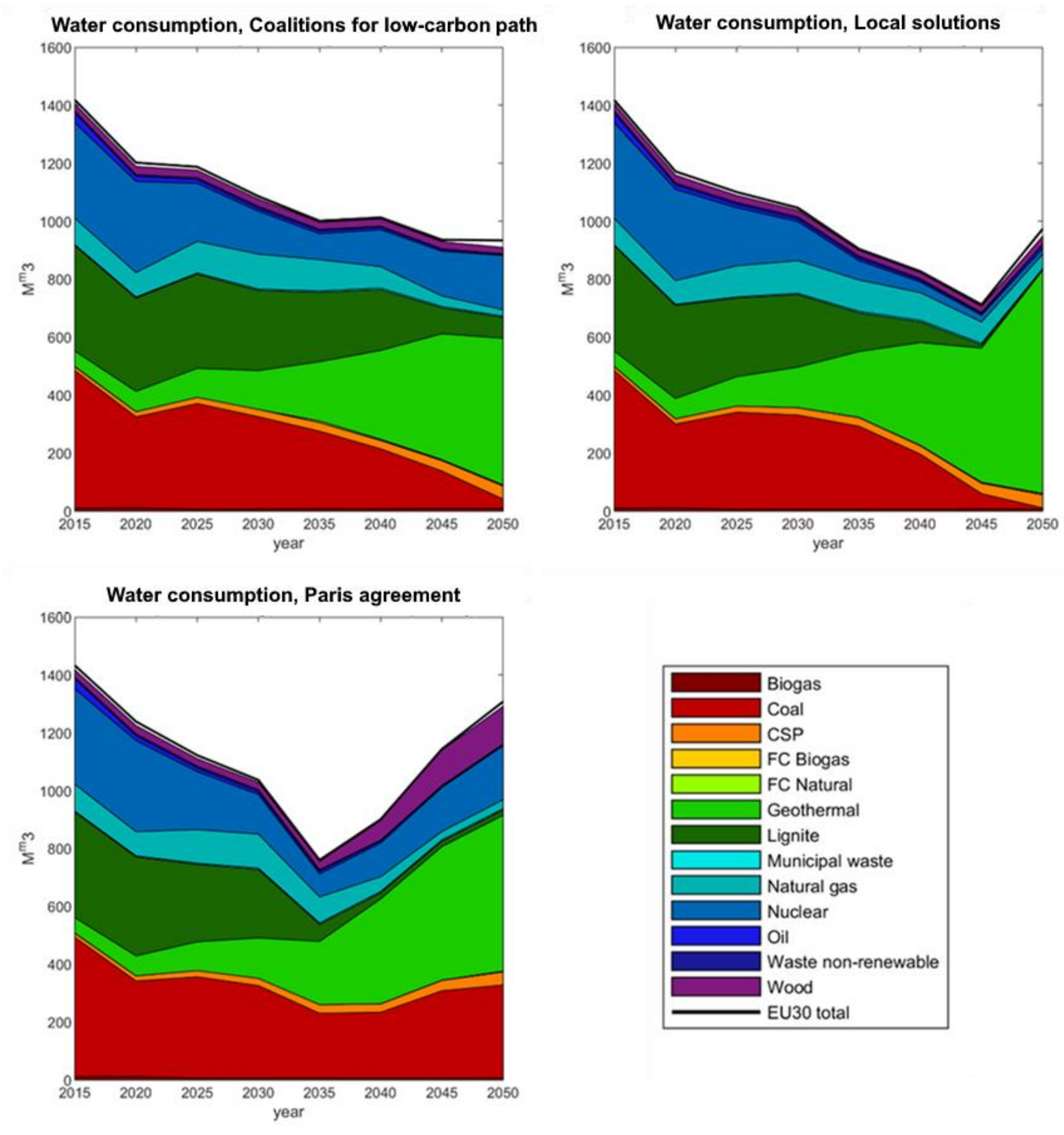

Figure 36. Water consumption for electricity generation in CL, LS, and PA pathways for the EU28 (all energy sources) and EU30 (total).

Variation by pathway

On a EU28+2 level, the total water consumption from electricity generation (*Figure 36*) is decreasing from 2015 towards 2050 for the CL pathway and to some extent the LS pathway, whereas in the PA pathway it decreases towards 2035 where after an increase to approximately 2015 levels is seen in 2050. The main sources for the decreasing levels is seen for the traditional non-renewable energy sources such as coal, lignite, natural gas and to some extent nuclear. The main water consuming energy sources after the implementation of renewables is geothermal energy – for all pathways a vast increase in geothermal water consumption is seen, especially for LS.

The main reason for the increase in total water consumption in the PA pathway is a smaller reduction in coal-, and to some extent nuclear-, water consumption as compared to the CL and LS pathways.

Message 33: To unlock the full potential of using biomass for energy production, further development and exploitation of second or higher generation biofuels are key. Continued harvesting of biomass from vegetable oils, starch and sugar crops may be necessary along the way.

Biomass is projected to play an important role in an energy system with an increasing share of renewables. While often assumed to be carbon neutral, some forms of biomass production for energy purposes may arguably be associated with substantial emissions, including the growing of wood crops. For example first generation biofuels produced from food crops such as wheat and maize or from vegetable oils extracted from, e.g., rape seed or soy beans, may incur considerable associated emissions and lead to increased water stresses locally. In contrast, second or higher generation biofuels based on crop or wood residues will optimize the potential of introducing biomass into the energy system in terms of both climate change mitigation and water usage.

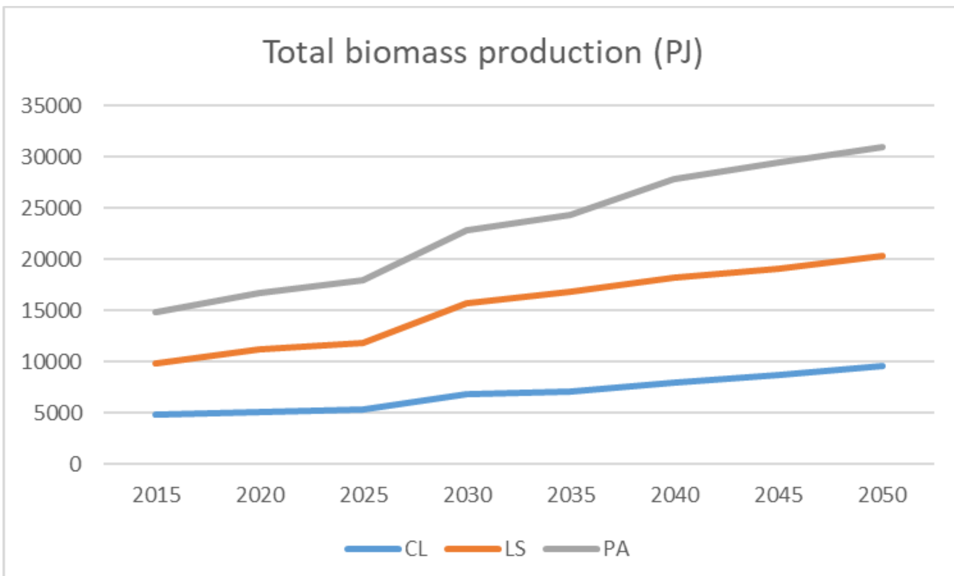

Figure 37. Projected biomass production [PJ] by pathway and the associated land use change emissions and water usage. In the case of biomass-induced GHG emissions due to land use change, full lines indicate a median estimate whereas (LO, HI) indicates estimates calculated using conversion factors corresponding to the 25th and 75th percentiles, i.e., providing an estimate of the uncertainty. For total water usage the corresponding values correspond to the mean estimate and (-/+) one standard deviation.

Variations by pathway

In the LS pathway, bioenergy (Figure 37, top panel) is initially harvested mainly from vegetable oil (rape seed) and other potential sources like residues that are converted into second- or higher generation biofuels; the role of starch crops and woody crops is small. Until 2030, the use of rape seed and other bioenergy sources is growing dramatically, leading to increased emissions (Figure 37, middle panel) and water usage (Figure 37, bottom panel); after that the use of oils declines slightly, while the exploitation of the latter continues to climb. The contribution of starch crops decline further, whereas the role of woody crops increases moderately, leading to sustained high water usage and land use change emissions; however, they play only smaller roles compared to the other two. The high water usage of woody crops though is mainly associated with “green water” and not in terms of actual irrigation.

In the CL and PA pathways, which emerges as the more sustainable ones, considering water usage and emissions induced by biomass production, the role of advanced biofuels are projected in a similar way and the use of woody crops is more significant, in particular in PA. As in the LS pathway, rape seed is initially an increasingly important component of the energy mix, but here it is quickly phased out of the system after 2030.

Dashed and dotted lines indicate a low, respectively, high estimate of the biomass-induced GHG emissions due to land use change and total water usage and shows the abovementioned results to be robust.

Message 34: Heating demands decrease throughout EU - the opposite is seen for cooling demands

In T5.1, the effects of future temperature changes on space heating and cooling demands in European buildings were analysed. The analysis was performed for two low-to-medium GHG emission climate scenarios and eight regional climate models. By utilising minimum, maximum and mean daily temperatures in five-year steps between 2010 and 2050 to calculate heating and cooling degree days (HDDs and CDDs), both absolute and relative climate changes were explicitly accounted for. HDDs and CDDs were subsequently utilised to scale up/down the projected space heating and cooling demands in buildings, while population density was employed as proxy for the spatial distribution of the demands to obtain the national space heating and cooling demands.

Figure 38 presents the country-level relative changes in HDDs and CDDs for scenarios RCP2.6 and RCP4.5 between the years 2010 to 2050. Heating demand generally decreases throughout the EU. Almost all countries in northern and western Europe have a higher decrease in HDD for RCP4.5 (>10% decrease) than for RCP2.6 (5-10% decrease). Also, Greece and Bulgaria experience only a <3% decrease in RCP4.5 compared 7-10% decrease levels for RCP2.6. For cooling demand, the opposite is true – it increases throughout the EU. The largest increase in cooling demand is seen for RCP4.5 especially for the Northern parts of Europe including UK, Germany and the Baltic countries (>100%).

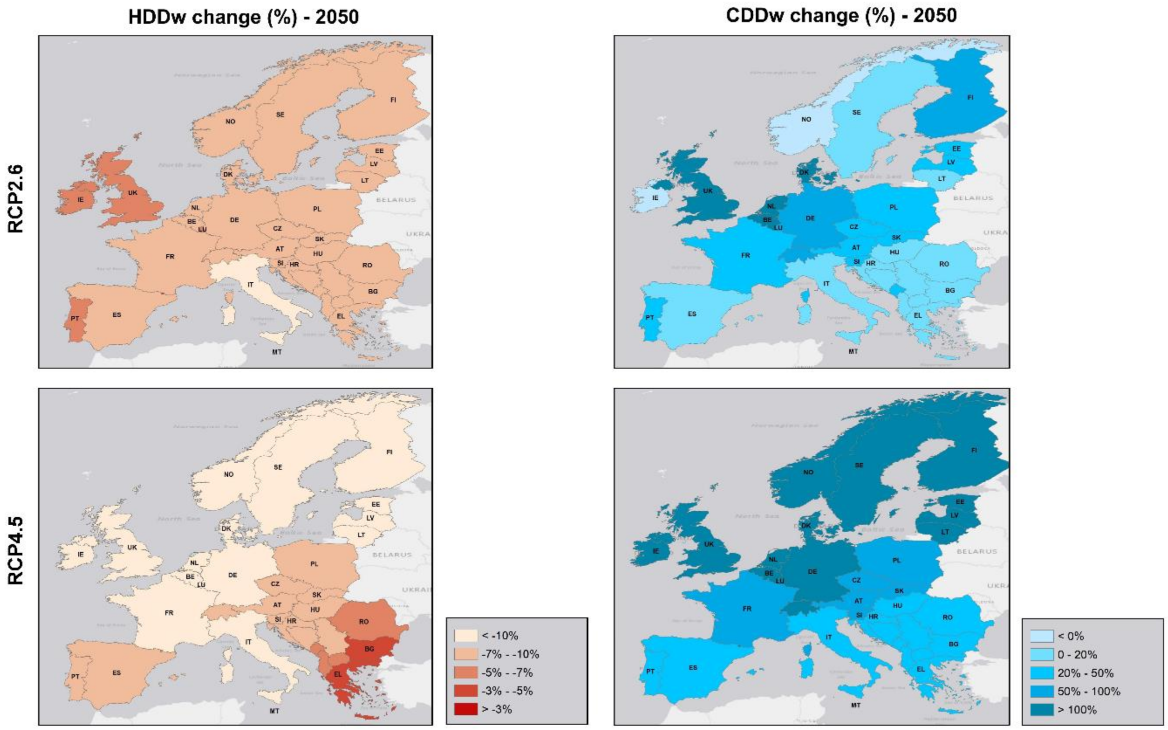

Figure 38. Country level relative changes in weighted heating and cooling degree days (HDDw and CDDw) from 2010 to 2050 for the RCP2.6 and RCP4.5 climate scenarios respectively.

3.3.4. Ecosystem services case study (D5.4)

Focused on Lithuania, it assessed impacts of alternative forest management strategies on multiple ecosystem services (i.e. industrial wood, bioenergy, carbon storage, recreation and habitat). The case study also developed and discussed linking between an ecosystem service assessment tool (LEcA tool) and an energy systems model (MESSAGE) in order to integrate ecosystem services in sustainability assessment of energy policy and related forest bioenergy options.

3.3.4.1. Main insights

Message 35: Forest management strategies could ensure desired level of ecosystem services while supporting fulfilment of national decarbonisation targets

Substantial focus should be given to developing management strategies that keep the desired level of ecosystem services while supporting fulfilment of national decarbonisation targets. The same level of biomass supply can often be obtained using a multitude of different forest management configurations, both with regards to the character of activities and their geographic allocation. Figure 39 illustrates that when increasing the yields above a certain threshold, the resources may be exhausted in the long run. At the same time, ecosystem services such as carbon storage, recreation and habitat supporting biodiversity may also be affected. Forest management strategy is a crucial linkage between forest biomass extraction and other ecosystem services. This could be particularly useful, as the energy systems optimisation in REEEM suggests that a significant share of biomass will be included in the energy mix. Thus, before allocating resources for bioenergy, judicious planning is critical in order to ensure the well-being of other services.

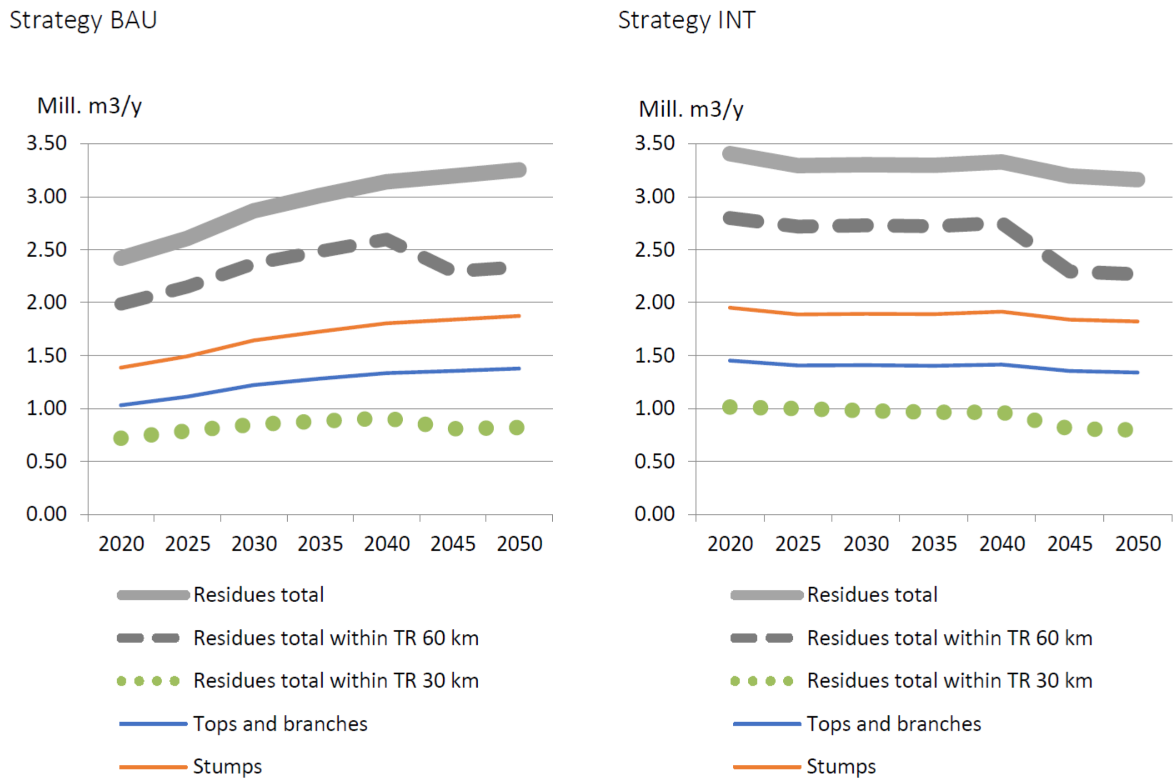

Figure 39. The extraction of logging residues with and without transport restrictions, for the forest management strategies BAU and INT.

3.3.5. Case study on district heating (D4.2)

The case study analysed the possibilities of three city regions (Helsinki, Warsaw, and Kaunas) to transform their district heating (DH) systems to achieve carbon neutrality, thereby supporting national strategies towards deep decarbonisation. It employed the energy system modelling tools EnergyPLAN and MESSAGE and scenario analysis combined with interaction with national and city-level stakeholders.

3.3.5.1. Main insights

Message 36: Biomass could have a key role in decarbonising DH in cities.

The analysis in the case study on district heating showed that in order to reduce emissions, rather large changes are needed in the DH systems. These changes include especially increased use of biomass, waste, heat storages and heat pumps. In addition, the use of CCS technologies could be considered and energy efficiency improved. According to the results of the analysis, heat production in Kaunas could be based solely on wood chips and waste in 2050 (Figure 40). In Warsaw, biomass, waste and electricity could be the main fuels for DH production (Figure 41). The results suggest that in Helsinki region heat and electricity production could mostly be based on wood pellet and waste in 2050 (Figure 42). Increased use of wood, biomass and waste as well as diminished dependence on fossil fuels also contribute to the energy security goals. However, the low availability of these fuels may limit the possibilities to increase their utilisation in DH production in the future. In addition, their price may increase due to the increased demand. This, in combination with the insights from the ecosystems services, as well as the coevolution of technologies case study, is a clear indication that important decisions with regards to the share of biomass in the final energy mix, as well as the use of CCS must be made. On the one hand, those sources/technologies have a significant potential to help decarbonise the system, but at the same time, they are governed by controversy over their deployment and the trade-offs with other sectors.

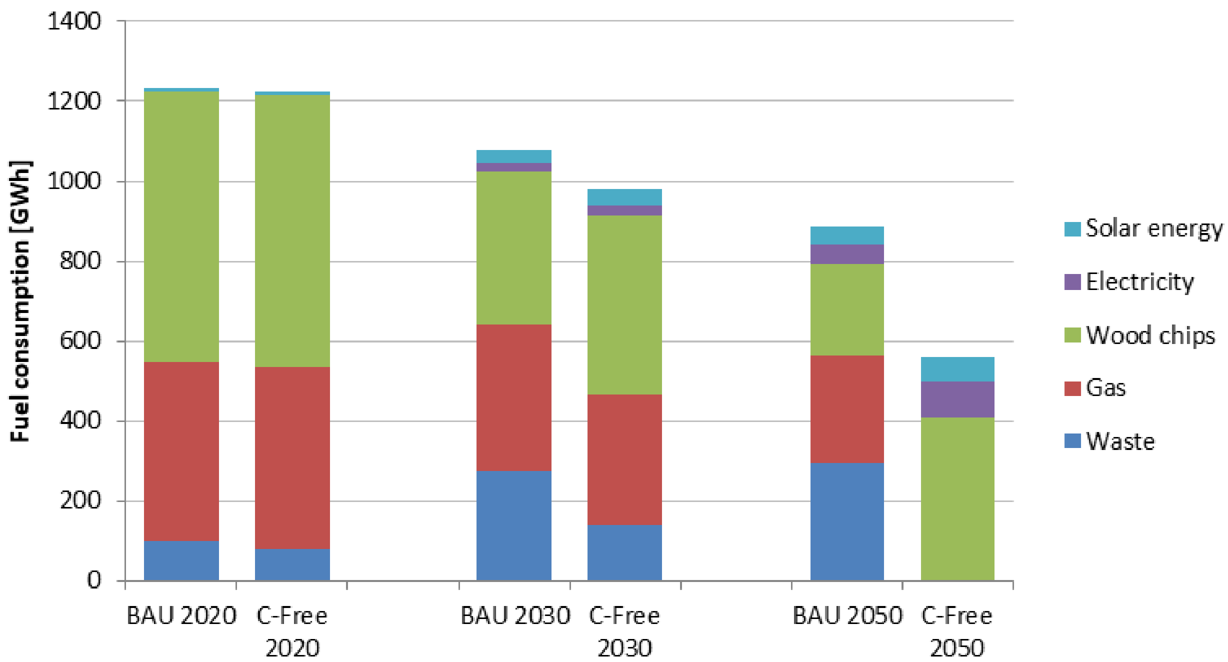

Figure 40. Fuel consumption in Kaunas DH system in different pathways.

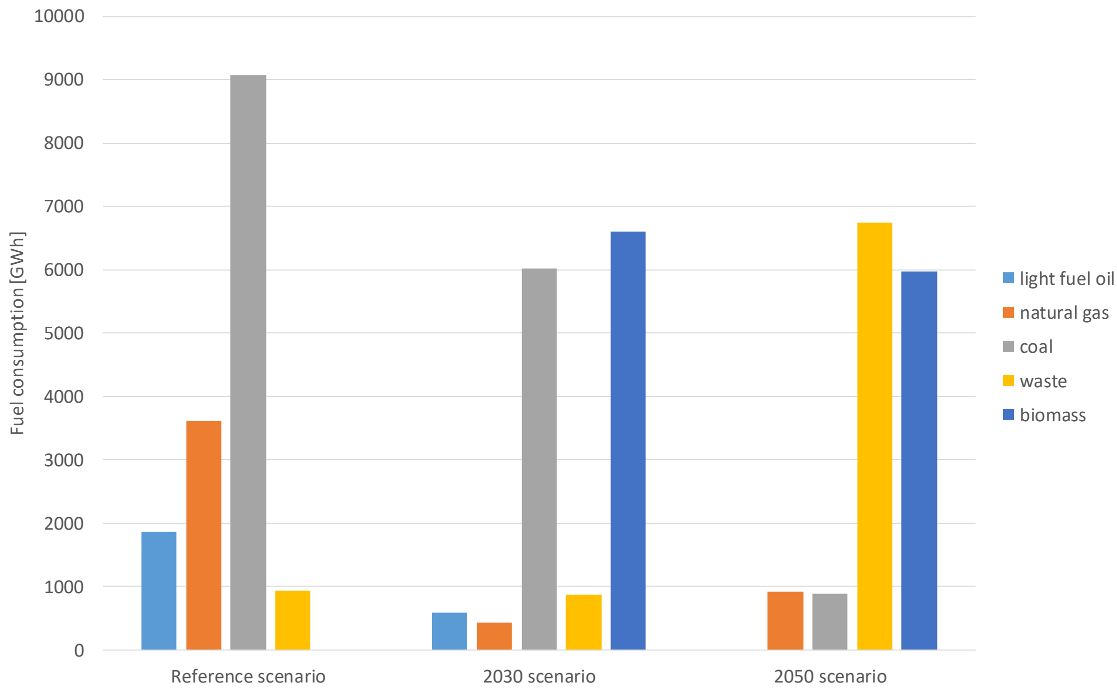

Figure 41. Fuel consumption in Warsaw DH system in different pathways.

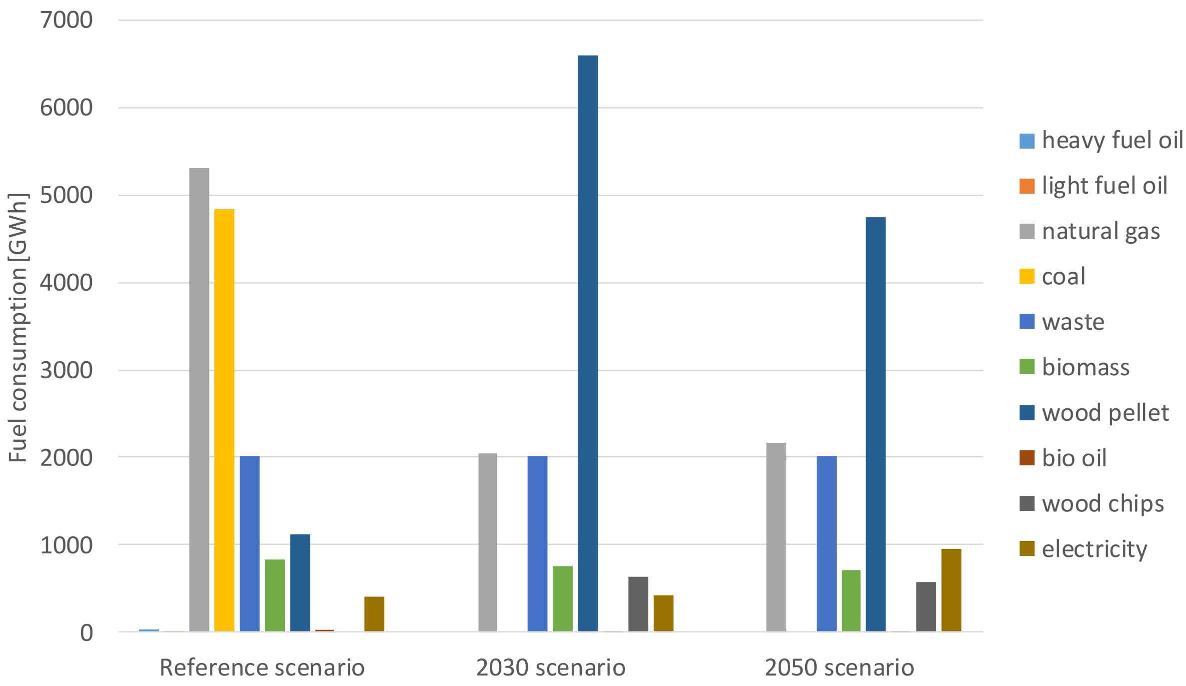

Figure 42. Fuel and electricity consumption in the DH system of Helsinki region in different åathways.

4. Synthesis and outreach

Section 3 revealed a number of messages emerging from the various types of analysis carried out in REEEM. Although those messages can be relevant for both the scientific community and policy-makers, further actions must be taken in order to integrate and communicate. The objectives of the synthesis and outreach process are:

- Elicit integrated (i.e. cross-sectoral) messages that can help define the direction of policy making from a broader perspective.
- Communicate all messages (and the supporting material such as data and background information) in a way that promotes transparency, reproducibility, wide engagement and educational aspects.
- Be easily absorbed by future projects and processes, so that work undertaken here need not be repeated.

To fulfil the above objectives, the outcome of REEEM is shaped into the following products:

- **Synthesis of messages:** An attempt to draw broader messages, emerging from the co-analysis of the messages presented in Section 3 for the EU as a whole and for the case studies. This action helps fulfil the first objective of the synthesis and outreach process.
- **REEEM Database:** An open source database to store all the modelling outputs relevant to the integrated impact assessment and the underlying input data (as far as openly available). This product, as well as all the following ones, aim at fulfilling the second and the third objective of the process.
- **OSeMBE:** The Open Source energy Model Base for the EU is an open-source, low-threshold model of the energy system of the EU28 + Norway and Switzerland built in the open source modelling framework OSeMOSYS [34]. It is used as stakeholder engagement model.
- **REEEMgame:** A business game aimed at interactively taking experts and non-experts through key dynamics of transitions to a low-carbon energy system.
- **REEEMpathways:** An online free and open platform showcasing the three REEEM pathways and the related messages defined in Section 3 and 4.1 with databased information - available in a digestible format.
- **Energy Modelling Platform for Europe (EMP-E):** It is a platform consisting of a website, special issues of a leading journal and annual meeting was created by REEEM with inputs by DG R&I, DG Ener and DG JRC. Its aim is to provide a digest of energy models and insights for researchers and policy makers. It culminates in an annual event where energy modellers and policy-makers exchange ideas trough plenary discussions, workshops and poster sessions.

These products draw from what is called the REEEM "Integrated Framework". That (described earlier) is a method derived to maximise the coherency and integration of a set of different tools and approaches calibrated to various levels by common pathway assumptions.

Figure 43 below depicts how the aforementioned products are linked. The data used and produced in the REEEM Integrated Framework is fed into the database. OSeMBE also takes data from and harmonises assumptions with the Integrated Framework. The data produced for and by OSeMBE (as well as the other models) is then also fed into the database. OSeMBE data is used in the development of the REEEMgame. Data and insights from all the models are used in the REEEMpathways tool. All the aforementioned tools and insights are then discussed, and data disseminated, at the EMP-E and particular ideas discussed there may then lead to their improvement.

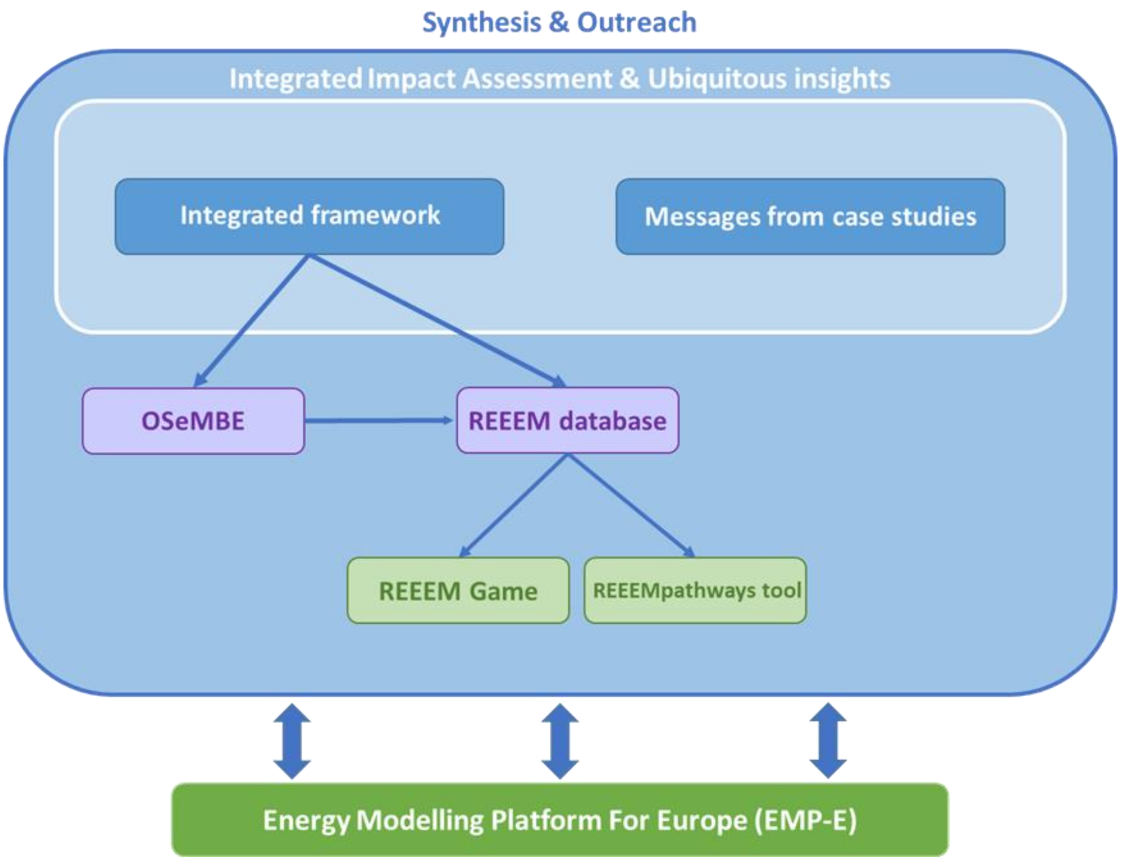

Figure 43. Synthesis & outreach framework of the REEEM project.

4.1 Synthesis of messages

This sub-section describes the integrated messages emerging from the synthesis of the insights given in Section 3.

Integrated message 1: The impacts of the transition to a low carbon EU energy system are multi-dimensional and spatially varied

The high decarbonisation targets set by the European Union will have impacts on the development of the energy sector, and as a result on the environment, economies and societies in which that system operates. Those impacts though, are not expected to be distributed uniformly. They differ by Member State, sector of the economy and even regions within a country. Under possible future pathways, some groups will benefit while others may see detrimental effects. Firstly, in all pathways, economic growth (measured by GDP) is expected to be uneven across Member States, without necessarily being skewed towards a particular geographic area/group of countries. At the same time, when examining health impacts, central European countries such as Germany and Poland seem to benefit the most from the transition, as they see their Disability-Adjusted Life Year (DALY) losses decrease the most.

Similarly, affordability (defined as the capacity of households to bear the energy expenditure to heat their properties) is another attribute that differs by Member State. The discrepancies in terms of affordability, as well as unemployment rate, may be even more pronounced when one looks at different regions within a country. The same may be said in terms of unintended environmental impacts. The study on the impact of high decarbonisation strategies on local ecosystems for Lithuania provides a clear case: strategies aiming at high shares of biomass in primary energy supply to curb GHGs emissions potentially open the path for intensive uses of such source. That results in intense mono-culture plantations reducing biodiversity. These in turn may cause irreversible damage to the ecosystem and, ultimately, to the economy of local communities. Part of that bio-diversity includes wild berries and mushrooms, that are prize pickings for locals. Their removal might result in strong opposition to low-carbon national strategies. The latter is a clear indication that national strategies and targets may have important effects if they are designed top-down without accounting for regional impacts. Moreover, even when GDP shows a considerable growth in a particular country, not every sector follows the same trajectory. Both in terms of gross added value to the national economy, as well as in terms of employment rate. Some sectors are expected to thrive (e.g. non-metallic minerals and vehicles), while industries such as coal will be negatively affected. Therefore, in order for a strategy to be thoroughly evaluated to explore differences in costs and benefits, impacts need to be assessed at different spatial and sectoral levels, with consideration given to a multi-criteria decisional approach.

The expected diverse impacts between and within Member States indicate risks but also opportunities in the transition to a low-carbon EU society. At a national level, as there will be “winners” and “losers” a - stronger union could emerge in an attempt to minimise the impacts. Policies supporting freedom of movement and re-training/re-focusing of skills within sectors will be needed. Thus, jobs lost in one location in one industry can be replaced by retrained workers from another. This will require brave EC intervention, creating an opportunity to advance faster in the two dimensions of the Energy Union: 1) Security, solidarity and trust and 2) Fully-integrated internal energy market. Without doing so will hamper the potential for equitable decarbonisation.

Integrated message 2: Broader engagement is imperative for deep decarbonisation

From the analysis carried out in REEEM, deep decarbonisation requires active contribution from a plethora of actors. Given the complexity of energy systems and the number of actors that can influence their course in different ways. As noted above decisions made only by central governments could lead to a high cost and diverse transitions with various negative impacts. The penetration of certain technologies (e.g. renewables) has to increase, which depends not only on government support, but also on R&D investments by businesses, funding schemes and mechanisms by certain funds, public acceptance and a shift in market structure and mindset. Citizens’ behaviour in particular and the choices they make will be a key factor in the evolution of the system. As noted earlier and later we identify that household appliance and technology choice is not a matter of economics and service only, but also familiarity and loyalty.

Further, interventions will need to cut across what is often considered as the energy sector, as well as its supporting industries. This is particularly the case for a system that might be dominated by variable renewables and batteries. These will require careful management. Concepts such as circular economy, more efficient logistics and recycling need to be regulated at all levels of the energy supply-consumption chains. This is especially for segments of the supply expected to rely heavily on rare materials. An example is the platinum group metals

(PGM) which could be replacing platinum with palladium, while from rare earths an example would be substituting samarium for dysprosium

Moreover, national government decisions should be made in conjunction with both sub- and transnational stakeholders. This is in order to account for different issues which are critical for the development of the system. For example, a national government needs to consider the system characteristics of neighbouring countries when a high load is expected to be transmitted through interconnectors as part of a broader energy security strategy. At the same time, regional development (e.g. district heating systems) may help reduce GHG emissions and thus, governments could engage more with local stakeholders to better understand what schemes would benefit certain projects. The same applies to the EC strategy which could benefit from delving deeper into national realities. This might explicitly exploit the strengths (and mitigate the weaknesses) of each Member State and adjust the goals accordingly. For instance, a common national, binding decarbonisation target could lead to countries that have a high potential reducing emissions to a degree that does not correspond to their capabilities while others with a lower potential could undergo a significantly high-cost transition. While a common regional target would allow those with high potential to deliver greater impact reducing the burden for those with lower potential.

Broader -and country sensitive- engagement may present the European Union with an opportunity to accelerate the transition to low-carbon societies. A higher level of engagement can be helped by science-informed discussions, open and transparent analytical tools and dissemination towards all interested actors.

Integrated message 3: The EU low-carbon transition is strongly linked to non-EU drivers

To be effective, the deep decarbonisation of the EU energy sector would need to take into account developments outside the EU. As revealed in the REEEM analysis, a number of technologies (e.g. lighting, renewables and electric vehicles) which are expected to play a catalytic role in the transition, rely heavily on critical materials. The latter are, for the most part, concentrated and produced in regions beyond the EU borders. Therefore, given the limited control that the EC may have over the exploitation of those materials, certain development plans -linked to the aforementioned technologies- could be put at risk. Judicious use of critical material resources at a global level is expected to be a determinant of global decarbonisation and thus, a greater level of cooperation and potentially regulation[6] will need to be investigated to help reduce risk of material scarcity/overheated prices.

The development rates of technologies used in the EU energy system are, to some extent, linked to decarbonisation targets and supporting schemes in different parts of the world. Therefore, decarbonisation targets in the EU and outside may impact exports and consequently competitiveness in the EU and outside. Leveraging on the different market shares that regions have in different parts of the technology value chains could positively impact competitiveness and, ultimately, cooperation between regions.

Integrated message 4: There are non-trivial multidimensional path dependencies that cannot be ignored

[6] For example, an organisation similar to the OPEC but dealing with critical materials could be established.

Deep decarbonisation will lead us into path dependencies that will require active multidimensional intervention. Those dimensions can go across timing, sectors and within a sector:

- As mentioned in the previous messages, deep decarbonisation is expected to have significant impacts on the economy and society. But the impacts of these are often not necessarily in the hands of EU decision makers. Further, they will depend on the timing of the intervention. For example, the study on macroeconomic impacts in particular, illustrates how the fulfilment of the Paris Agreement could reduce GDP growth more compared to other pathways. Even though in those other pathways the ambition for curbing emissions is lower. That is because in the scenario examined the rest of the world acts to invest locally to reduce its emissions. In so doing it reduces its investment in Europe. In fact, it competes with Europe. That is because the scenario in question is accompanied by a roughly 10% higher consumption of critical materials (compared to the Coalition for a Low-carbon path pathway) as well as biomass and water. Thus, the timing of the intervention is important.
- At the same time, when the Paris Agreement target is achieved, there is an incremental increase in the relevant benefits such as lower health impacts. Interventions impact other sectors. Comparing the marginal cost to the marginal benefits of the transition to a significantly low-carbon pattern is not a straightforward process as it depends heavily on the perspective of each actor engaging in the decision-making. It is therefore critical, as mentioned in previous messages, to assess the pros and cons diligently. That is not only with regards to how the transition should materialise (i.e. which countries/regions/sectors to be affected the most) but also up to which level of decarbonisation the benefits are considered greater than the cost in other sectors.
- Lastly, there are important energy sector quirks. Importantly, the higher the need for electrification of sectors of the economy, the greater the need for low carbon baseload generation, or variable renewable energy technologies with flexibility. CCS, biomass and/or nuclear could represent the most affordable low-carbon options to reduce the need for flexibility, but they too come with risk. 100% decarbonisation of sectors will be very hard without negative emission technologies such as biomass coupled with CCS (BECCS) and the adoption of a net balance[7] approach. For different reasons, the use of the above technologies (Biomass, CCS and Nuclear) has been debated in the EU as they have environmental, social and economic impacts that go beyond GHG emissions. Flexible generation options, include grid-connected storage, smart end-use technologies and increase of interconnections between Member States. They also come with risk. The appropriate mix between these options does not depend only upon cost and investment considerations, but also highly on security concerns, long-term purchase agreements and, not least, affordability of electricity prices. A larger base of comprehensive studies on the cross-sectoral and cross-scale implications of different mix of flexible and low-carbon generation options is needed to inform investments and policy decisions (such as those on capacity markets or support towards specific technological solutions). It is worth noting also that deeper changes to material and infrastructure systems, such as biomass building material, increased telecommuting etc. may hold

[7] Net balance means that a country might still emit CO2, but also remove from the atmosphere, so the total sum matters.

much higher and lower cost mitigation potential than options that would ordinarily be included in a an energy policy makers remit.

Integrated message 5: Among the technology trends, energy efficiency and electrification of transportation are consistently confirmed as potential enablers of the decarbonisation

Some key technology trends emerge as potential drivers of deep decarbonisation, consistent with previous studies. Electrification of several energy supply chains is a robust finding in REEEM with supply allocated efficiently between decentralised and centralised sources, depending on the availability of primary and renewable resources and on the potential for cross-boundary transmission. Potential for electrification emerges in industry, through increased power-to-heat uses, and in the transportation sector.

Road transportation has high potential for decarbonisation and electrification. At the same time, the associated, negative, system-wide impacts are not trivial. As revealed by the study on health impacts and LCA, when it comes to particulate matter emissions (derived from road abrasion, tyres and break wear), electric vehicles are no more environmentally friendly than those that run on biofuels. On top of that, EVs are heavy reliant on critical materials which -as discussed in the current report- may have various implications. Consequently, if those impacts are accounted for and stricter regulations are set in place (with regards to either the use of critical materials or particulate emissions limits), the potential of EVs to curb emissions might be significantly increased. Recycling and efficient use of materials may represent a way to reduce impacts. An implication of this message, is that, expansion of public transportation and, in general, a shift across modes of transportation may lead to a decrease in the use of resources for meeting transportation service demands. These have to be further evaluated to better understand potential behavioural barriers from consumers. Surveys in three Member States have shown that consumers consistently tend to hold onto the same type of vehicle even when it does not represent the cost- or environment-optimal alternative. Support for information campaigns, eco-labelling and easy costing of choices could help win the inertia. Finally, further research in order for new technologies to emerge might be critical for the vehicle sector to overcome those issues.

In the residential sector, one low-hanging fruit for deep decarbonisation is represented by energy efficiency, especially through renovation of buildings. Technologically mature measures are available at low cost. Constraints to the pace of renovation seem to come mostly from the absence of business models and incomplete regulations.

Integrated message 6: Focusing on direct mitigation misses important leakage effects

Initial analysis indicates that meeting a target of 90% direct GHG mitigation might be achieved by simply pushing close to half of those emission elsewhere. Specifically, when the life cycle carbon footprint of technologies is examined (taking into account indirect emissions), the actual decarbonisation rate is lower than the one based on direct emissions. EU decarbonisation targets are at risk of incentivising indirect-carbon leakage towards other regions of the world, if global strategies towards the reduction of emissions along the entire value chains are not established. In addition to the local benefits, the overarching target of reducing GHG emissions is a global issue, and therefore one could examine whether the marginal cost of investing in reducing the emissions outside the EU is lower and the marginal, global benefits (as well as those for the EU economy) higher.

Integrated message 7: New energy security paradigms

Moving beyond the direct analysis of the REEEM integrated framework, various observations call for an urgent new look at security, beyond the traditional metrics of import vulnerability. According to the pathways we examine there are potential pictures of concern:

- There are the traditional risks associated with fossil fuels that will transform in value from supplying energy to flexibility services. Arguably these may result in a higher value (and thus vulnerability to a unit used).
- Supply security of new carriers, materials and technology will need to be undertaken. For example, biofuel imports may increase; RET technologies will be produced elsewhere and materials needed to produce or refurbish them will not be under the control of the EC.
- With an increase in extreme weather events key new energy sources are at risk.
    - On the supply side: By far the greatest concern lies with biofuels, where forest fires during heat waves can have enormous effect. While recent windstorm in Holland destroyed wind-turbines and hailstorms elsewhere damaged solar farms.
    - On the demand side: increase cooling demands required to keep power stations, industry and homes both cool and warm are stressing the system in ways unexpected. Yet we expect a rapid increase in the frequency and severity of hot and cold spells as well as rainy and dry spells. Each of which amplify demands on energy
- Finally, with increased flexibility to accommodate variable renewable energy technologies (rather than non-variable renewable energy technologies and nuclear) comes the need for increased ICT control and automation. That automation requires increased deployment of communication and processing power. With its increase comes the risk of cyber-attacks and security. Whether this is from a heavy, external attack, such as an electromagnetic pulse, or internal hacking, new vulnerabilities arise that must be carefully managed.

4.2 REEEM Database

In the REEEM project, a large group of modelling teams from different institutes has developed, used and linked different software with different programming languages and modelling paradigms. This results in a large variety of data structures. In the integrated assessment modelling framework of REEEM, data from different sectors are used and created, of different types, formats and with different levels of aggregation. In addition, as the REEEM pathways are iteratively revised (as described in Section 2), the input and output data of each model need to be revised several times throughout the project. This requires modellers to upload and download data to and from the database frequently. Finally, several models are soft-linked and some are iterated (such as NEWAGE and TIMES PanEU). Data versioning is crucial in order to ensure consistency in the inputs and outputs exchanged between the models and, ultimately, in the formulation of the REEEM pathways (see Section 2).

Thus, the project database needs to meet different requirements. Besides complying with basic data security and access regulations as described in the Data Management Plan (deliverable D6.6), the structure must be flexible and database usage should be as automated and comfortable for modellers as possible. This challenge was solved by developing scripts for importing and exporting data to and from the project database, customised for each modelling team according to their data structures and formats. All open support documentation from the different data processing and modelling activities is either available on GitHub or in the relevant open access publications.

The above complexities also led to challenges in the data classification and categorisation. These were solved by developing and implementing a ***flexible tagging system*** for model inputs and outputs. This allows for data in the database to be tagged with different tags, assigned by modellers and users according to their understanding of the meaning of the data. The data tagging adds a flexible top layer of data categorisation according to general definitions. It aims at making input and output data from different models and modelling teams more comparable. For instance, all cost variables or technical parameters can be accessed across the database. Besides the technical aspects, the legal aspects were considered as well. The project aims at publishing the data sets under open licenses. All openly licensed input and output data of the models and pathways (of the REEEMPathways tool) in the REEEM database are publicly available also on the OpenEnergyPlatform (OEP) and can then be identified under the tag "REEEM". The links between the REEEM Database and other REEEM activities as well as with the OEP are shown below in Figure 44. The database concept and the data structures are presented in great detail in the Technical Documentation of the REEEM Pathway Database (deliverable D6.5).

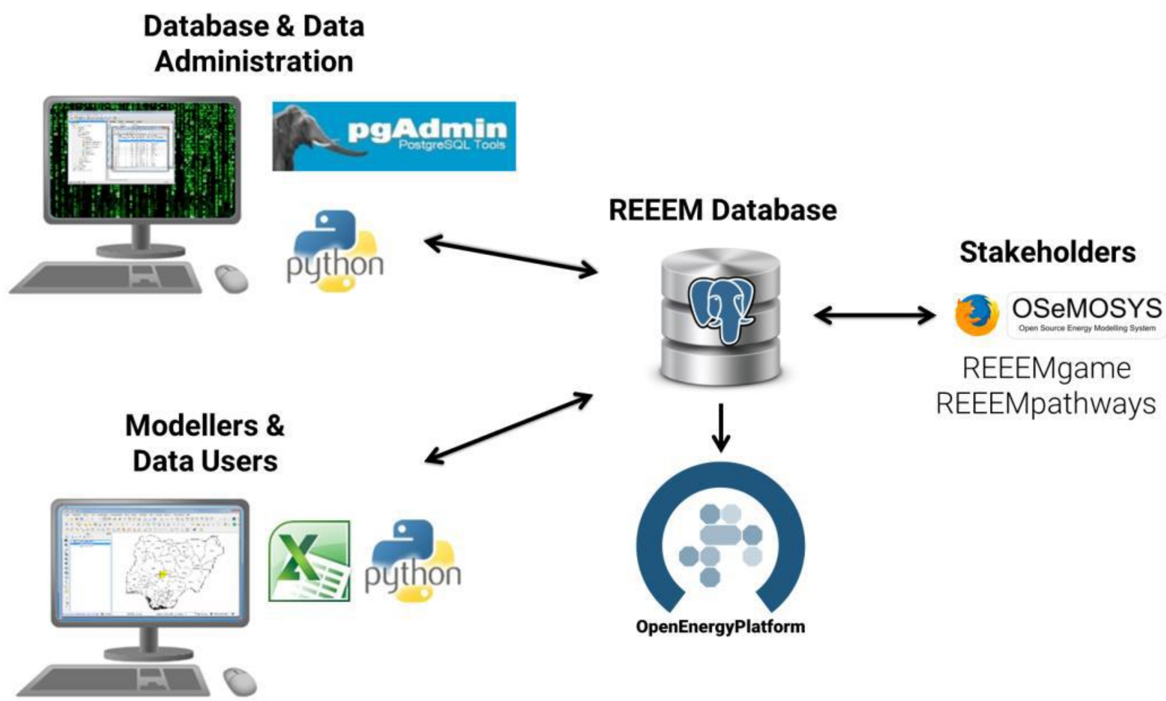

Figure 44. REEEM data management and dissemination.

4.3 OSeMBE: Open Source energy Model Base for the EU

The Open Source energy MOdelling SYStem (OSeMOSYS) was used to build the Open Source energy Model Base for the European Union (OSeMBE). Within the scope of REEEM, OSeMBE is configured as a model of the electricity system of the EU28, with addition of Norway and Switzerland, covering a time span from current years until 2050. OSeMBE, its code base, its input data and metadata and all related documentation are available on REEEM.org as well as on the OSeMOSYS community's website. Its factsheet (summary of key information for model comparison purposes) is also available on the Open Energy Platform, managed by the Open Energy Modelling Initiative according to best practices of open modelling science. The model is documented in deliverable D7.3 – Open Source Engagement Model, available here.

OSeMBE is purposefully and in accordance with the Grant Agreement of REEEM designed as a ***stakeholder engagement model***. As such, it aims to illustrate to expert and non-expert stakeholders key dynamics of the transition to a low-carbon EU energy system featured in TIMES PanEU, however leaving out its detail and complexity. Its structure includes the 28 EU Member States, Norway and Switzerland as connected regions. Each region has a set of technologies and fuels available and can exchange electricity with its neighbours. The energy resources considered are: liquid biofuels, solid biomass, coal, geothermal energy, heavy fuel oil, natural gas, oil, oil shale, solar energy, uranium, waste, waves, and wind. The model distinguishes between domestic resources and imported resources. The resources can be converted to electricity by using combined cycle power plants (PPs), CHP PPs, fuel cells, gas cycle PPs, integrated gasification combined cycle PPs, internal combustion engines, nuclear reactors of generation II and III, solar photovoltaic, steam cycle PPs, and wind turbines. The model covers the years 2015 to 2050. Per year it has five seasons and one typical day per season represented by three time slices. To allow the analysis of the environmental impact of the power system, CO_2 and particle matter 2.5 are considered. The latter was chosen after being identified as the most harmful emission by the EcoSense model. The key output metrics of OSeMBE in REEEM relate to economic, environmental and social impacts of the transition to a low-carbon EU electricity system. They are:

- Economic: Discounted investment per citizen, this indicator is available for entire Europe and per country, which allows to compare the investment needs among countries.
- Environmental: CO_2 per citizen. The carbon intensity per citizen allow the comparison in between countries but also the comparison over time. Of interest is not only what the countries might reach in 2050 but also the different starting situations in 2015
- Social: Levelised Cost of Electricity (LCOE) – do not indicate the final price. However, the LCOE gives a good indication on the cost for electricity generation which have an impact on the final price.

By focusing on the most relevant dynamics in the evolution of the energy system, OSeMBE aims to provide a starting point for policy makers, academia and the public to familiarise with energy systems investment modelling. It constitutes an open source research infrastructure which can serve as a showcase, but also as a starting point for further research. It has been and will be used at in Higher Education Institutions as a ground for 1) teaching kits on energy systems investment modelling, 2) research within Master and PhD theses, 3) flexible and light model base for large numbers of explorative scenario runs (spanning several ranges of uncertainties on future energy prices), 4) open source base for model comparisons at the Energy Modelling Platform for Europe and other European events and 5) model infrastructure to carry out regional or national analyses. For the latter case, scripts are under development within new funded actions to extract regional of national models out of OSeMBE, modify/improve them within the scope of group teaching activities and individual research and re-introduce them into the European model. In short, OSeMBE is not only an engagement model, but also a space for collaborative open research. As such, it fulfils the purpose to communicate the features of the modelling effort carried out in REEEM and facilitate the creation of impact.

As the model is smaller and flexible, more than 100 scenarios have been run during the REEEM project to provide the background data for the REEEMgame.

4.4 REEEMgame

The REEEMgame aims to support learning sessions with stakeholders to provide them with a low-threshold understanding of energy system dynamics. It shows key outcomes and disseminates the data behind a large number of scenarios run with the REEEM Open-source Engagement Model: OSeMBE.

In the current version, the user is assigned a specific "point-of-view" expressed as a set of economic, environmental and social preferences. The player mission is simple: make climate policy choices in 2020, 2030, and 2040 to maximise the weighted 2050-score for the assigned preferences. The decisions impact the score components as follows:

- Economic: Higher Gross Domestic Product (GDP) in 2050 is better
- Social: Cheaper access to energy for everyone in 2050 is better
- Environmental: Lower annual CO_2 emissions in 2050 are better

Figure 45. Interface of the REEEMgame.

The game aims to let the player interactively discover how policy decisions, investments in infrastructure and technology developments might affect the development of the European electricity sector in the transition to a low-carbon system. At three points in time (2020, 2030, 2040) levers may be changed by the player concerning the emission reduction pathway, the expected capital costs of Renewable Energy Technologies, and the upgrade of the trans-border electricity transmission between European countries, according to the 10-Year development plan by ENTSO-E.

The learning simulation has been run at stakeholder meetings and will also be made available to educational institutions and the general public online.

Stakeholders and partners within the REEEM project have contributed to the learning simulation throughout the development process by providing feedback on design, implementation and testing of the learning simulation.

The REEEMgame can be accessed through the project website.

4.5 REEEMpathways

Stakeholder engagement in the project builds largely on enabling tools and Work Package 7 has the function of disseminating the insights gained from the project, and to get feedback from stakeholders to improve the models and other material being developed in the project.

To reach this objective, an article-based open access online tool, REEEMpathways, has been developed to visualise the results/key messages derived from the integrated impact assessment modelling framework presented in Section 3 and enable stakeholder feedback and interaction.

The tool is populated by data stored in the REEEM Pathways Database and provides public access to modelling insights, input data and pathway assumptions from the project.

The user interface is designed with an emphasis on organising and showing model data on charts. A number of developed features enhance usability and accessibility. Among these, the possibility of downloading the data underlying the charts.

The tool enables REEEM partners to publish and update their own articles providing multiple types of static and dynamic charts to choose from to visualise their own key messages and the data behind it.

Figure 46. REEEMpathways interface.

Following the concept of the REEEM project, this allows policy makers and stakeholders to explore and compare possible decarbonisation pathways. This may assist in understanding the effects of and requirements for energy system changes.

The tool has been integrated with Twitter and this enables the public to discuss the results/key messages with REEEM partners and allows other modellers to contribute with their knowledge.

The tool can be accessed [here](#).

4.6 Energy Modelling Platform for Europe (EMP-E)

Computational models can provide insights into potential decarbonisation pathways, create a ground for consultations and help roadmap long-term strategies. The modelling effort carried out in the REEEM project fulfils this purpose. Yet, it is one of many in Europe and it has limitations like all others. The strength of all these efforts lies in their complementarity, comparability, legacy and possibility to be taken further by future actions. Energy system modelling efforts across Europe are scattered, attempts towards inclusive and structured EU-wide fora bringing researchers and EU policy makers are scarce and transparency of modelling tools is in many cases limited.

With this view, the REEEM project created in 2017 the Energy Modelling Platform for Europe (EMP-E) as one of its deliverables. The Platform was created with inputs from the European Commission's Directorate General Energy, Research and Innovation and Joint Research Centre.

The EMP-E aims to provide a ***peer-reviewed digest of models and policy insights*** to inform the transition towards a low-carbon European society, vis-à-vis the Energy Union and Climate objectives. It brings together researchers from across Europe and EU policy makers. It facilitates the transition towards new open and transparent modelling paradigms. The EMP-E constitutes the last ring of the chain leading in REEEM from the co-design of model-based assessment of decarbonisation pathways, to the documentation, simplification for expert and non-expert and finally sharing of outcomes and infrastructure. It does not only constitute a platform for sharing outcomes of the project, but rather for many more efforts to share their outcomes, thereby creating long-lasting impact.

The modelling platform culminates in a yearly event held at the Headquarters of Directorate General Research and Innovation (DG R&I), in Brussels. The first event took place on May 17-18th 2017 and was attended by around 80 participants, from research institutions across Europe, the European Commission and, to a lesser extent, industry. After the success of the first event, the REEEM project opened the organisation of the yearly events to the other projects funded under LCE21-2015, MEDEAS, REflex and SET-Nav, as part of a collaboration started by INEA. Attendance and participation grew and in its third edition the platform is co-organised by 9 funded projects. Its quick transformation into a collegial effort owned by research actions and promoted by the European Commission is a measure of the sustainability and impact of the Platform.

More impact resides in the Special Issue of Energy Strategy Reviews (Elsevier) '*Energy Transition and Decarbonisation pathways for the EU*'. Completed early 2019, it collects outcomes of and hot topics covered at the first EMP-E meeting. This Special Issue does not merely present a collection of articles covering a pre-defined topic. It provides a synthesis of highly complementary tools, practices, experiences and views to inform the research and innovation agenda for the European energy system. The full set of articles provides a holistic view of technical, cross-sectoral, financial, societal challenges of the transition to a low-carbon system. These challenges reflect research questions, highly relevant for national energy agencies and EU decision makers.

This knowledge repository is available not only as a number of open access articles, but also as a number of freely accessible online toolkits. Among these are toolkits developed within the European Commission, toolkits traditionally employed in scenario analyses for the EU, emerging open source toolkits and ground-breaking new, open databases.

A solid body of research infrastructure emerges, building on vast literature and experiences collected in the past few decades, and clearly moving towards the establishment of standards for: 1) creating open modelling tools and structuring open data sets, 2) make existing and widely-employed modelling tools transparent, 3) juxtaposing new tools to specifically analyse new challenges.

A large body of manuscripts was submitted by the participants of EMP-E 2017, synthesising decades of research from all over Europe on EU energy system transitions. The final outcome features 22 peer-reviewed articles, of which 10 with unlimited full open access and several presenting results of EU-funded actions.

The Special Issue is introduced by a preface from three Directorates General of the European Commission: Directorate General for Research and Innovation, Directorate General Energy and Directorate General Joint Research Centre.

5. Conclusions

The REEEM project sheds light on a number of pervasive issues pertaining to the transition of the EU energy system to one that is low carbon, equitable and economically competitive. Various characteristics associated with the transition have been identified e.g. economy, people's behaviour, material resources, and the implications for different sectors. The outcome of this analysis is to provide a knowledge base for different stakeholders across a range of critical issues for the low carbon transition. That knowledge base is constituted by three types of outputs: data, analytical tools and insights.

From a policy-maker's point of view, insights into the feasibility of different strategies, including multi-faceted trade-offs that need to be considered across environmental, social and economic domains. The research also provides sketches of how the future of the energy system may unfold, dynamics between different parts of the system, and the opportunities that emerge. For example, an energy intensive industry whose activity within the European Union is expected to be negatively affected, may start exploring (clearly identified) market opportunities related to the decarbonisation process. Or workers might be trained move to growth areas freely within the union.

From a general audience's perspective, the transparent approach adopted in the analysis, the representation of key dynamics though accessible tools and the presentation of key messages increases accessibility to a level exceeding preceding project. It is hoped that this may increase trust in science-based approaches to planning and increase engagement. Lastly, researchers, energy analysts, academics and private consultants are provided with a comprehensive set of data, and a modelling and assessment framework with related research infrastructure. This can be built on, reworked or targeted to assess how aspects related to their own field of expertise are expected to unfold and actively provide feedback.

Further, REEEM deliberately adds to the knowledge created under previous and parallel actions at a number of levels. And seeks to make future work easier.

The integrated modelling framework used for the analysis of decarbonisation pathways is **flexible** and shaped around the challenges of interest for the realisation of the Energy Union and those brought about by stakeholders. It is modified throughout the project (and can be modified in the future), while maintaining scientific rigor and consistency in the analysis. It is not locked into a structure defined a priori by the composition of the Consortium that may wish to take it (or parts of it) up.

The pathways analysed in REEEM are designed so as to unveil challenges **across spatial, temporal and sectoral scales**. A fully harmonised EU-wide assessment highlights overall social, economic and environmental challenges and the case studies complement the analysis by shedding light on non-obvious regional and local dynamics which may slow down the transition if ignored.

This setting allows the emergence of a number of key insights, described in Section 4.1. The concept of "winners" and "losers" is, to some extent, subjective as there will be a number of actors performing better in particular areas, while lagging behind in others. Broader engagement, as well as looking at non-EU drivers which may have an impact on the EU energy transition, appears to be quite critical, while weighing the incremental benefits over the marginal cost of decarbonisation beyond a certain point, may play a key role in the course EU decides to follow. The role of **choices and behaviour** of consumers in affecting the pace of the transition is looked into, through large surveys in three European countries. Despite the wide differences between the countries, it is interesting to notice how archetypal patterns seem consistent across very different groups of citizens. A comprehensive view on the impact of the transition on the **use of resources** is developed, filling a gap of previous actions. At one end it consolidates existing practices for the evaluation of water uses, emission changes due to land uses and health impacts, by increasing the number of categories looked at and the resolution of the analyses; at the other it extends the perspective to life cycle (and cross-borders) assessments of resources, **use of critical materials** and influence on ecosystem services. A sector that seems to be particularly pivotal, is that of vehicles. The latter has, on the one hand, a great potential to help reduce emissions, but it may be accompanied by a number of adverse effects worth looking at in future actions.

Comparing the three REEEM pathways investigated, two main conclusions can be drawn. Firstly, as expected, deeper decarbonisation in a globally enforced Paris Agreement pathway (where Europe is not a leader) leads to lower GDP growth (with a limited classical analysis). But at the same time brings higher health and environmental benefits. The "Local Solutions" pathway is slightly less cost-effective than the CL pathway - which may bring some relief given the urgency of the transition, knowing that government action may be easier to implement than self-organised citizenry. Yet, there are a number of other unexpected trends and related insights. For example, in the Local Solutions pathway, there is higher consumption of critical materials but also higher production of biomass). Secondly, some key trends seem to appear consistently in the transition to a low-carbon system, regardless of the pathway. For example, there is growth in renewable energy technology-related industry, drops in fossil-fuel related activities and increasing demand for critical materials. One way of interpreting this fact (i.e. consistent trends in all pathways) is to realise that *if the macro-scale of the transition is expected to be almost equal regardless of the particular course chosen, it is important to focus on the micro-scale impacts and set priorities accordingly*.

Key insights from the project analysis include:

1. The impacts of the transition to a low carbon EU energy system are multi-dimensional and spatially varied;
2. Broader engagement is imperative for deep decarbonisation;
3. The EU low-carbon transition is strongly linked to non-EU drivers;
4. There are non-trivial multidimensional path dependencies that cannot be ignored;
5. Among the technology trends, energy efficiency and electrification of transportation are consistently confirmed as potential enablers of the decarbonisation;
6. Focusing on direct mitigation misses important leakage effects;
7. New energy security paradigms.

The list of indicators synthesising the impact assessment is derived from an integrated comprehensive modelling framework. In fact this is the most extensive exercise of its kind to date in the EC. The indicators create an opportunity for deriving consolidated, non-silo conclusions and holistic policy-making which span across SDGs and inform the Clean Planet for all strategy. The list of indicators shown in the current report can be found in Appendix B. Interpreting indicators can be a subjective exercise, and for this reason, it is critical that different viewpoints are considered. In the course of REEEM, several workshops have been carried out which have helped discuss the analysis results and draw useful insights. The workshops featured participation either from local stakeholders (those related to the case studies) or international (i.e. EU level, those linked to the PanEU activities).

Further to the above, the REEEM project has contributed to a culture of openness, transparency, engagement and incremental research. It addressed the need for an approach combining **co-designing**, **documenting**, **simplifying** and **sharing** scientific outcomes. As described in Section 4.2-4.5, a number of open and accessible tools and platforms have been developed, namely, OSeMBE, REEEMgame, REEEMpathways and REEEM database. Those may provide researchers with a best-in-class base for further analysis. That analysis may include integrated systems and relevant impacts and provide policy-makers with an engagement platform for model-based assessments. The scientific reports produced under the scope of REEEM are publicly accessible and can be found here. Numerous journal publications featuring details of the analyses and results are already available and more will become available through a Special Issue of the Gold Open Access journal Energy Strategy Reviews (Elsevier), expected to be completed after the end of the project, in Spring 2020. Finally, the establishment of the Energy Modelling Platform for Europe opened a space for disseminating outcomes of the project's assessments, create new science and compare models and insights with all other modelling groups in Europe. The EMP-E is now set out to be a long-lasting and inclusive effort calling together numerous funded actions and receiving inputs from the European Commission. The Special Issue of Energy Strategy Reviews related to EMP-E 2017 constitutes one of the largest Special Issues available to date (including 22 peer-reviewed publications, of which 10 with unlimited open access), represents the first comprehensive digest of modelling efforts across Europe and sets intentions and course for the Platform as intended by REEEM (in the Preface) and by the European Commission (in the introduction).

Improvements may be made in different aspects of the framework; particular ones have been identified and described below:

- The 5 case studies considered in REEEM shed light on critical issues which cannot be captured in an EU-level analysis. In future studies, it would be prudent to carry out similar studies in different part of the EU in order to get more bottom-up understanding of the system-wide impacts of the transition.
- In terms of input data and assumptions, delving deeper into national policies could make the results more country relevant. At the moment, not all the latest country-level dynamics are captured.
- Parts of the input data of some of the models are not yet fully complying with open data standards, because they became integral part of the models before standard open data management practices emerged or because they are copyrighted. These shall be replaced in the future with the increasingly available large and spatially resolved sets of open data. The process started within REEEM, where, for instance, sets of data included in the TIMES PanEU model were updated with open data included in the OSeMBE model.
- Further integration between the models (i.e. soft-linking) could be pursued, leading to even more robust results. More specifically, there is potential for establishing iterative linking between different models until they reach convergence (similar to that between TIMES PanEU and NEWAGE).

Furthermore, there is a certain level of uncertainty governing the integrated framework, as the models are used and maintained separately by different institutions. To some degree, this has been be minimised during the REEEM project by documenting data exchange processes, establishing data processing infrastructures (shared also on platforms which will live beyond the project, within the open modelling community), laying the ground for further bilateral modelling efforts, ensuring a space for discussions and scientific publications within the Energy Modelling Platform for Europe.

5.1 Further research

The key findings of the REEEM project were discussed with a group of stakeholders from the EC, during the final project meeting held in Brussels on July 16th 2019. The key outcome of this discussion was a list of research ideas related to the current project, which would be of interest to the EC. Those ideas are listed below:

- Apply the REEEM modelling framework on a number of new pathways which incorporate new policy options and mitigate risks. Those could include:
    - Look into the production potential in the EU in order to foster competitiveness.
    - Explore alternatives mechanisms to the ETS.
    - Investigate impact balancing mechanisms across the MS. Examine impact on public budgets.
    - Consider more technologies in the models, even disruptive ones.
    - Better understand (and incorporate findings) the role of global geopolitics.
- Investigate whether GDP is sufficient to measure economic well-being; whether new indicators should be developed/applied; or if externalities might be increasingly internalised to produce a representative rather than partial GDP that includes health and ultimately productivity gains.
- Incorporate drivers/trends/risks/opportunities for specific sectors/groups of sectors in the analysis.
- Increase the level of granularity in the analysis; from Member States down to regions and especially cities.
- Develop a Just Transitions [35] observatory. This would be tasked with understanding in a transparent manner the trade-offs and support needed to balance the multifaceted nature of a deep transition, while ensuring that advances in the technological and policy toolkit are continuously and transparently assessed. The assessment should take into account impacts across sectors, social groups, geographies and security. This might parallel an activity that spun off of a preceding effort that involved the bulk of the REEEM consortium: the Energy Poverty Observatory [36].
- Investigate, incorporate and update regional constraints on water and biomass use in the analysis. Understanding the natural limitations on the use of those resources associated with the energy supply may result in a different energy mix.
- Further enhance transparency by disclosing all assumptions used in the different models. This would further enable sharing and comparability with other actions, extend the research infrastructure and enable further engagement with relevant stakeholders.

Appendix A – Key pathway assumptions

A.1. Common assumptions on policy for Coalitions for a Low-carbon path and Local Solutions

Table 9. CO_2 emission targets by EU Member State: Coalitions.

	Targets for 2020 (compared to 2005)	*Targets for 2030 (compared to 2005) - Proposal*	*Target for 2050 (compared to 2005) – REEEM clusters*
EU-28 ETS	**-21%**	**-43%**	**-83%**
	Effort sharing decision (ESD)	Effort sharing decision (ESD)	Effort sharing decision (ESD)
France	-14%	-37%	-80%
Portugal	1%	-17%	-80%
Spain	-10%	-26%	-80%
Italy	-13%	-33%	-80%
United Kingdom	-16%	-37%	-80%
Germany	-14%	-38%	-80%
Netherlands	-16%	-36%	-80%
Belgium	-15%	-35%	-80%
Luxembourg	-20%	-40%	-80%
Austria	-16%	-36%	-80%
Denmark	-20%	-39%	-80%
Sweden	-17%	-40%	-80%
Finland	-16%	-39%	-80%
Ireland	-20%	-30%	-80%
Poland	14%	-7%	-50%
Czech Republic	9%	-14%	-50%
Bulgaria	20%	0%	-60%
Romania	19%	-2%	-60%
Estonia	11%	-13%	-60%
Latvia	17%	-6%	-60%
Lithuania	15%	-9%	-60%
Croatia	11%	-7%	-60%
Hungary	10%	-7%	-60%
Greece	-4%	-16%	-60%
Slovakia	13%	-12%	-60%
Slovenia	4%	-15%	-60%
Cyprus	-5%	-24%	-60%
Malta	5%	-19%	-60%
EU-28 non-ETS	**-9%**	**-30%**	**-75%**

The utilised criteria to define the members of the different clusters are:

- **Geographical location:** Countries located near each other have several similarities that could encourage a partnership and the pursuit of similar environmental objectives. They typically use similar, if not identical, languages, have comparable wind and sun resources and stronger commercial partnerships, thus facilitating a possible cooperation around a common environmental goal.
- **Wind and sun availability:** Wind and solar, more specifically PV, are the fastest growing technologies in terms of installed capacity. Although the installed capacity for hydro power is still larger than wind and PV, as of 2016 [37], its growth potential is much more limited due to the uneven geographical distribution of its resources.
- **Economic situation:** When coming to economic terms, the term "optimal solution" comes inevitably in mind, however, installing and utilising energy from renewable sources may not always be the cost optimal scenario (at least when costs due to environmental and public health damages are not internalized in the objective equation). Additionally, on a deregulated energy market the consumers are the one who chose where their energy comes from, so the market is subject to their preferences, which is a parameter rather difficult to quantify. Therefore, the economic situation will be used here as proxy to the willingness of a certain country to invest, or not, on renewables, as it, ultimately, represents the country's potential to invest on this technology.
- **Coal resources:** Around every political decision there are economic interests from different groups and with the coal companies it is not different. Coal was specifically chosen as it is still the fossil fuel more broadly utilised for primary energy generation in Europe by 2015 (Coal: 144874, Crude oil: 69144, Gas: 111117. All in 1000 tons of oil equivalent. Source: Eurostat). This criterion helps identify possible economic interests in favor of the coal industry.
- **Effort Sharing Decision:** The Effort Sharing Decision sets national emission targets for 2020, while the targets for 2030 are still under discussion by the European Parliament, but the first proposal can already be accessed ([38]). These targets concern emissions from most sectors outside not included in the EU Emissions trading system, such as transport, building, agriculture and waste. As the emission targets take into account the GDP per capita of each country and have to be voted by the European Parliament, they can be used as an indicator for the environmental ambitions of each Member State.

Clusters

a. Green (or "Clean") is optimal

- **Members:** France, Portugal, Spain, Italy, United Kingdom, Austria
- **Rationale:**

  For this group of countries, due to the availability of resources, the optimal solution is to utilize energy from renewable or cleaner sources. Additionally, Spain, Portugal and Italy have quite good access to natural gas due to proximity to north Africa and liquified natural gas (LNG) terminals, while France has already a relatively large clean energy supply due to its installed capacity of nuclear power plants.

- **non-ETS:**

Higher reduction than the EU target of 75% for non-ETS by 2050: 80%.

- **Renewable energy share:**

  Higher share than the EU target of 75% for Renewables by 2050: 85%.

b. Politically and economically aligned

- **Members:** Germany, Netherlands, Belgium, Luxembourg
- **Rationale:**

  This group of countries have good or very good economic situation, a history of working together and similar wind and solar resources availability. All the countries, except for Luxembourg, have access to the North Sea, which indicates their high off-shore wind potential. Although Germany has one of the largest resources of coal in Europe and still depends heavily on it, its economic force and recent environmental efforts indicate that it is following the path in favor of more ambitious environmental targets.

- **non-ETS:**

  Higher reduction than the EU target of 75% for non-ETS by 2050: 80%.

- **Renewable energy share:**

  Due to the geographic location in the middle of the EU lower share than the EU target of 75% for Renewables by 2050: 65%.

c. Politically and economically aligned – the Nordic league

- **Members:** Denmark, Sweden, Finland, Ireland
- **Rationale:**

  This group could also be a part of group "b" depending on the application. Although this group can be further divided into the old EU-member (Denmark, Sweden and Finland), who have similar economic situation and higher GDP per capita, and the new EU-members (Estonia, Latvia and Lithuania), it also presents several similarities that justify this composition. Starting with the geographical location, resulting into similar access to wind and solar resources and similar challenges regarding the impacts of climate change. Second there is the share of petroleum products and renewables on the gross inland energy consumption, which in 2015 represented more than 55% for every member of the group, except for Estonia. Finally, none of the countries in this group have considerable coal mines.

- **non-ETS:**

  Higher reduction than the EU target of 75% for non-ETS by 2050: 80%.

- **Renewable energy share:**

  Higher share than the EU target of 75% for Renewables by 2050: 85%.

d. Coal for the economy

- **Members:** Poland, Czech Republic
- **Rationale:**

  Both Poland and Czech Republic are large producers of coal in Europe and extensively utilize this resource inside their borders, as it represents 39% of the gross inland energy consumption of Czech Republic in 2015 and 51% of Poland's in the same year. Any limitation to the use of coal would have consequences in this two countries.

- **non-ETS:**

  Much lower reduction than the EU target of 75% for non-ETS by 2050: 50%.

- **Renewable energy share:**

  Much lower share than the EU target of 75% for Renewables by 2050: 45%.

e. The cheapest way

- **Members:** Bulgaria, Romania, Estonia, Latvia, Lithuania, Croatia, Hungary, Greece, Slovakia, Slovenia, Cyprus, Malta
- **Rationale:**

  Although this group presents some economic disparities, they present a similar access to solar and wind resources. Due to the economic condition of most members, this group depends heavily on the cost reduction of the renewable energy technologies in order to be able to fully deploy it and will most likely apply the cheapest option in regards to energy generation. They also have relatively easy access to both gas, due to proximity with Russia, and coal, due to proximity with Poland and Czech Republic, so cost will play an important role on the environmental ambitions of this group.

- **non-ETS:**

  Lower reduction than the EU target of 75% for non-ETS by 2050: 60%.

- **Renewable energy share:**

  Same target for Renewables by 2050 as the EU: 75%.

A.2. Common assumptions on the Global setting for Coalitions for a Low-carbon path and Local Solutions

Table 10. CO_2 emission targets in regions outside the EU: Regional push.

Region	CO_2 emission targets in 2050	Rationale
USA	Halfway between 2 °C target and current policies	Despite Trump's presidency, an expressive number of an expressive number of states, cities, tribes, universities and business, including the states of New York and California, signed an open letter confirming their support to the Paris Agreement.

China	2 °C target	Although it does not have high GDP per capita, as the EU or the USA, its economy is growing fast and it is also home to 7 of the 10 largest photovoltaic cell manufacturers and 4 of the top 10 wind turbine manufacturers.
Japan	Halfway between 2 °C target and current policies	Part of OECD, high GDP per capita and HDI. Would seek a higher ambition reduction target than the current policies, but its current high dependency on fossil fuels and lack of resources would undermine its willingness to pursue the 2 °C target
Republic of Korea	2 °C target	Part of OECD, high GDP per capita and HDI. It would oppose pursuing the 2 °C target
Canada	Halfway between 2 °C target and current policies	Part of OECD, high GDP per capita and HDI. Would seek a higher ambition reduction target than the current policies, but as its economy also depends on production of oil, it is possible that they do not follow the 2 °C target
Mexico	Halfway between 2 °C target and current policies	Part of OECD, medium GDP per capita and HDI. Would seek a higher ambition reduction target than the current policies, as this ambition has already been shown through the creation of a long-term strategy to reduce emissions. However, due to its economy, it might end up not following the reduction cuts necessary for the 2 °C target
Australia	Halfway between 2 °C target and current policies	Part of OECD, high GDP per capita and HDI. Would seek a higher ambition reduction target than the current policies, but as its economy also depends on production of oil, it is possible that they do not follow the 2 °C target
Norway	80% reduction compared to 1990 levels	Would seek similar target to the EU's as it is also part of the EU ETS and an important partner
Switzerland	80% reduction compared to 1990 levels	Would seek similar target to the EU's as they signed an agreement in 2017 to link their emissions trading systems
New Zealand	2 °C target	Part of OECD, high GDP per capita and HDI. They would oppose pursuing the 2 °C target
Iceland	2 °C target	Would seek similar target to the EU's as it is also part of the EU ETS

A.3. Coalitions for a Low-carbon path

Economy: *'Growth at different speeds'*

This is the entry point of the narrative. The EU economies re-start growing after the financial crisis. There is population and GDP growth, though uneven across the EU.

For the models, assumptions are based on The 2015 Ageing Report and the EU Reference Scenario 2016.

Policy: *'Stronger decision making / policy parallels within cluster of Member States'*

There is a common general ambition to comply with the Energy Union Strategy, even though with different commitment across Member States, according to the current socio-economic situation, the domestic availability of resources and the geographical location.

For the models, the key numerical assumptions for the near and longer term are based on current decarbonisation targets. These are reported in Table 9 and summarised here:

- The existing binding decarbonisation targets set by the EU 2020 Climate and Energy Package and the 2030 Climate and Energy Framework are taken into account:
    - By 2020, 20% decarbonisation target for the ETS sectors in the EU as a whole, compared to 2005 levels;
    - By 2030, 43% decarbonisation target for the ETS sectors in the EU as a whole, compared to 2005 levels;
- The indicative 2050 decarbonisation targets, expressed in the EU Roadmap 2050 and in line with the Paris Agreement, are taken into account.
    - By 2050, 83% decarbonisation target for the ETS sectors in the EU as a whole, compared to 2005 levels;
    - Decarbonisation targets for 2020, 2030 and 2050 for the non-ETS sectors by groups of countries, according to the current socio-economic situation, the domestic availability of resources and the geographical location.
- The existing 2020 and 2030 binding targets of renewable share in gross final consumption for the whole EU are kept in consideration and complied with.

Global setting: *'Global push to climate change mitigation, driven by some countries / regions'*

There is an uneven push towards climate change mitigation, where certain regions will pursue more ambitious targets than others. In this context, at least two distinct groups are expected to rise outside of the EU:

- One of those having the economic means to decrease their emissions, or threatened the most by climate change, or both.
- The second group includes countries without the economic means to pursue more ambitious environmental targets or seeing the measures against climate change as an unnecessary burden.

Since the focus of the REEEM project is on the European countries, the main numerical assumptions made for this dimension are the GHG emission paths taken by each region outside of the EU. These paths were adopted from the Energy Technology Perspectives 2017, by the International Energy Agency, where a number of global GHG emission pathways based on different ambitions were created. For this work only two were utilised: Reference Technology Scenario (RTS), which considers only current and announced policies and commitments, and the 2°C Scenario (2DS), which takes into account the necessary emissions' reduction in order to reach the 2°C target consistent with the Paris agreement.

Society: *'Likely passive society in transition'*

Consumers do not perceive climate change as likely to affect their lives. Therefore, change their consumption habits towards more efficient end-use technologies with high inertia and only in the medium to long term.

Constraints are added to TIMES PanEU as inspired by part of the results of surveys on consumers choices of heating technologies in the UK, Croatia and Finland. The shares of end-use technologies for this sector are fixed in the early years of the modelling in all EU countries and slowly changed towards greener habits from 2030 on. The user-defined constraints are added to allow for a slow transition between existing technologies and the mitigation technologies.

Technology: *'Large penetration of centralised renewable energy supply options'*

The decarbonisation targets are met mainly by rollout of large renewable energy supply investments, such as Wind on- and off-shore and Solar PV. Breakthrough in off-shore wind by introduction of floating platforms for wind turbines contributes to the penetration of the technology. Biomass and CCS play a role.

For the Pan-European energy system model, the techno-economic characteristics of the technologies are assumed to a large extent according to projections from JRC's Energy Technology Reference Indicators 2014. Here a summary of the key bounds assumed for technologies in different sectors.

Table 11. Key technology assumptions in the CL pathway.

Health and climate	Health damage costs for selected pollutants are included in the system cost minimisation function, as computed in REEEM WP5 (see whole study in D5.2 – Focus report on environmental impacts, available **here**); RCP4.5 is assumed as reference for cooling and heating degree-days changes.
Industry	Decarbonisation target imposed to industry-processes + industry-energy in TIMES PanEU, to simulate the increased pressure on large consumers. See assumptions in Table 12 below.
Residential	
Heat pumps	Share of ambient heat (used by heat pumps) in final energy consumption in residential limited to 8%.
Building renovation	Renovation costs for the 'usual scenario', as provided in the third REEEM Technology and Innovation Roadmap, D2.1c, Appendix I, available **here**. Measures included in renovation: addition of insulation for walls, roofs and floors; replacement of windows. Upper limit annual renovation rate to 1.5% (which leads to 45% renovation of all stock by 2050).

Solar heaters	Solar limited to 5% share of energy consumption in Residential sector, to allow decarbonisation of residential in other ways.
Transportation	No target or limit, nor particular assumptions.
Electricity	
RES Targets	No target on final consumption, as the drive of the scenario is supply. Targets on the share of centralised renewables in electricity generation unnecessary, as their share already higher than 70% in 2050.
Off- and on-shore wind	No target or limit, nor particular assumptions.
Floating off-shore wind	A breakthrough is assumed. Techno-economic assumptions from page 38 of the second REEEM Technology Roadmap, D2.1b (available **here**).
Ocean energy	No target. Techno-economic assumptions from page 91 and 92 of the second REEEM Technology Roadmap, D2-1b (available **here**). Higher exploitation should occur especially in UK and Denmark (where highest potentials). However, this does not occur, as in the same countries wind is very competitive. *The only case where penetration can be higher is when infrastructure is used for both floating off-shore wind and ocean. This case is considered for future developments of the REEEM framework.*
Centralised PV	No target or limit, nor particular assumptions.
Sector coupling	No target or limit, nor particular assumptions.

Table 12. Upper emission limits assumed in TIMES PanEU for industrial processes and energy in CL [Mt].

2015	2020	2025	2030	2035	2040	2045	2050
762.522	796.427	810	750	700	610	480	300

Environment: *'Low availability of water (drying climate) and scarce resources'*

The average temperature, which is positively correlated with evaporation, is projected to rise albeit at a varying level on a European scale. The regional variations include dryer regions of southern Europe becoming relatively warmer. At the same time, Southern Europe is likely to experience less yearly average precipitation resulting in a decreased net availability of water in already dry regions. In addition, although associated with a larger uncertainty, the variability is also projected to change into more extreme events concentrating e.g. rainfall to shorter periods where a larger share is lost through runoff as opposed less intense events supporting the build-up/recharge of water storage in soil and groundwater. Also, periods of droughts are likely to occur more frequently and for longer periods.

The assumptions on the climate are included in the analysis through the environmental models and databases: i.e. in REEEM data from the Cordex database for RCP4.5 feeds the Heating and Cooling demand changes analysis and the water availability.

A.4. Local Solutions

Environment: '*Recognition of the impacts of climate change*'.

Entry point for the narrative. Citizens recognise the impacts of climate change, with the media and information campaigns reinforcing this with more comprehensive coverage of events inside and outside the EU.

The real effects of climate change are the same as in the CL pathway. Only their recognition by the society is stronger. Therefore, the assumptions are the same as in the CL pathway: i.e. data from the Cordex database for RCP4.5 feeds the Heating and Cooling demand changes analysis and the water availability.

Society: '*Change of EU citizens' perception towards climate change and resulting behavioural shifts*'.

This change in perception is driven by the factors described under the environmental dimension. It leads households to change their energy investment and using behaviour, thereby accelerating the transition.

In the models, the change in perception by consumers is represented by pushing the residential and road transportation sectors (not included in the Emission Trading Scheme) to decarbonise more than they would on pure cost optimisation grounds. Detailed assumptions shared under the technology dimension.

Technology: *'Accelerated renovation of residential buildings and uptake of low-carbon technologies in households and road transport'*

Consumers are more concerned of climate issues and take decisions in order to reduce their carbon footprint. Therefore, low-carbon technologies emerge in the residential and transportation sector even if they do not represent the least cost option. Detailed assumptions below.

Table 13. Key technology assumptions in the LS pathway.

Health and Environment	Health damage costs for selected pollutants are included in the system cost minimization function, as computed in REEEM WP5 (see whole study in D5.2 – Focus report on environmental impacts, available **here**); RCP4.5 is assumed as reference for cooling and heating degree-days changes.
Industry	No target or limit, nor particular assumptions
Residential	Ad hoc decarbonisation targets are introduced for the whole sector. See assumptions in Table 14 below.
Heat pumps	No target or limit, nor particular assumptions

Building renovation	Renovation costs for the 'advanced scenario', as provided in the third REEEM Technology and Innovation Roadmap, D2.1c, Appendix I, available **here**. Measures included in renovation: addition of insulation for walls, roofs and floors; replacement of windows. Upper limit annual renovation rate increased from today's rate to 2% in 2020, 3% in 2030 and 3.5% in 2040. Linear interpolation in between years and constant after 2040.
Solar heaters	No target or limit, nor particular assumptions
Rooftop PV	Breakthrough in Building Integrated Photovoltaic (BIPV) technology. Techno-economic assumptions from page 52 of the second REEEM Technology Roadmap, D2.1b (available **here**). List of advancements the assumptions correspond to at page 47 of the same document.
Transportation	Ad hoc decarbonisation targets in the whole transport sector to favour electrification are introduced. See assumptions in Table 15 below.
Electricity	CCS and expansion of nuclear not allowed. Breakthrough in Li-ion/Air batteries assumed, according to assumptions in of the First REEEM Technology Roadmap, D2.1a (available **here**).
RES Targets	No target or limit, nor particular assumptions
Off- and on-shore wind	No target or limit, nor particular assumptions
Floating off-shore wind	No target or limit, nor particular assumptions
Ocean energy	Techno-economic assumptions from page 91 and 92 of the second REEEM Technology Roadmap, D2.1b (available **here**).
Centralised PV	No target or limit, nor particular assumptions
Sector coupling	No target or limit, nor particular assumptions.

Table 14. Upper emission limits assumed in TIMES PanEU for the residential sector in the LS pathway [Mt].

EU28	402	337	282	233	190	151	120	95
CH	9.644	9.306	8.981	8.648	8.303	7.929	7.572	7.231
NO	0.702	0.677	0.654	0.630	0.604	0.577	0.551	0.526

Table 15. Upper emission limits assumed in TIMES PanEU for the transport sector in the LS pathway [Mt].

EU28	1033	842	635	446	294	184	165	150
CH	20.400	19.584	18.507	17.248	15.869	14.440	12.996	11.593
NO	17.183	16.496	15.588	14.528	13.366	12.163	10.947	9.765

Policy: '*Pace of local solutions leaves policy making lagging behind in the near to medium term*'

Society moves quicker than realised by decision makers, resulting in a shift in policy emphasis from influencing household decisions in the near to mid term to those more centralised sectors (power, industry, conversion, agriculture) which may require stronger government intervention. Post 2030, a comprehensive policy package is needed across all sectors to deal with 'lagards' and hard-to-mitigate sectors, including all of those policies already planned. While such package is solid and in place for sectors under the Emission Trading Scheme, it is more fragmented in the non-ETS sectors depending on the higher or lower level of ambition of Member States.

In the modelling, the same policy assumptions regarding ambition as in the CL pathway are made.

Economy: '*Growth at different speeds*'

The market offer for technologies for low-carbon decentralised supply follows the demand by consumers. However, the change in demand by consumers is driven by increased awareness rather than financial considerations. No subsidies, nor increased availability of capital drive such change. The behavioural change is expected to impact deeply the structure of investments in low-carbon technologies. This, in turn, is expected to bear an effect on the development of energy supply chains, employment, structure of economy and, ultimately, GDP.

For the models, the initial assumptions are based on The 2015 Ageing Report and the EU Reference Scenario 2016. The potential effect of the different structure of energy investments on the economy is not an a-priori assumption, but is derived within the REEEM modelling framework by soft-linking the energy model TIMES PanEU and the CGE model NEWAGE.

Global setting: *'RCP4.5 - Global push to climate change mitigation driven by some regions / countries'*

There is an uneven push towards climate change mitigation, where certain regions will pursue more ambitious targets than others. In this context, at least two distinct groups are expected to rise outside of the EU:

- One of those having the economic means to decrease their emissions, or threatened the most by climate change, or both.
- The second group includes countries without the economic means to pursue more ambitious environmental targets or seeing the measures against climate change as an unnecessary burden.

Since the focus of the REEEM project is on the European countries, the main numerical assumptions made for this dimension are the GHG emission paths taken by each region outside of the EU. These paths were adopted from the Energy Technology Perspectives 2017, by the International Energy Agency, where a number of global GHG emission pathways based on different ambitions were created. For this work only two were utilised: Reference Technology Scenario (RTS), which considers only current and announced policies and commitments, and the 2°C Scenario (2DS), which takes into account the necessary emissions' reduction in order to reach the 2°C target consistent with the Paris agreement.

A.5. Paris Agreement

Environment: '*General strong recognition of the impacts of climate change*'.

Entry point for the narrative. Both Governments and citizens recognise the impacts of climate change, with the media and information campaigns reinforcing this with more comprehensive coverage of events inside and outside the EU.

The real effects of climate change are the same as in the CL pathway, at the beginning. However, the strong recognition and immediate action taken by Governments and societies around the world changes the tendency of climate change and mitigates global warming in the long run. Therefore, RCP2.6 is assumed, to compute the changes in heating and cooling demands in the EU.

Policy: '*The EU takes the lead in fulfilling its obligations under the Paris Agreement*'

The commitment of the EU to lead the way to decarbonisation and fulfil the Paris Agreement translates into a target of 95% GHGs emission reduction by 2050 in the Union, compared to 1990.

Society: '*Change of EU citizens' perception towards climate change and resulting behavioural shifts*'.

This change in perception is driven by the factors described under the environmental dimension. It leads households to change their energy investment and using behaviour, thereby accelerating the transition.

In the models, the change in perception by consumers is represented by pushing the residential and road transportation sectors (not included in the Emission Trading Scheme) to decarbonise more than they would on pure cost optimisation grounds. Detailed assumptions shared under the technology dimension.

Technology: ' *Large penetration of low-carbon energy technologies both in centralized supply and at end-use level*'

Investments in low-carbon technologies are made by consumers, energy carrier suppliers and Governments. Detailed assumptions below.

Table 16. Key technology assumptions in the PA pathway.

Health and environment	Health damage costs for selected pollutants are included in the system cost minimization function, as computed in REEEM WP5 (see whole study in D5.2 – Focus report on environmental impacts, available here); RCP2.6 is assumed as reference for cooling and heating degree-days changes.
Industry	No target or limit, nor particular assumptions
Residential	No target or limit, nor particular assumptions
Heat pumps	No target or limit, nor particular assumptions

Building renovation	Renovation costs for the 'advanced scenario', as provided in the third REEEM Technology and Innovation Roadmap, D2.1c, Appendix I, available **here**. Measures included in renovation: addition of insulation for walls, roofs and floors; replacement of windows. Upper limit annual renovation rate increased from today's rate to 2% in 2020, 3.5% in 2030 and 7% in 2040. Linear interpolation in between and constant after 2040.
Solar heaters	No target or limit, nor particular assumptions
Rooftop PV	Breakthrough in Building Integrated Photovoltaic (BIPV) technology. Techno-economic assumptions from page 52 of the second REEEM Technology and Innovation Roadmap, D2.1b (available **here**). List of advancements the assumptions correspond to at page 47 of the same document.
Transportation	No target or limit, nor particular assumptions
Electricity	Breakthrough in Li-ion/Air batteries assumed, according to assumptions in of the First REEEM Technology and Innovation Roadmap, D2.1a (available **here**).
RES Targets	No target or limit, nor particular assumptions
Off- and on-shore wind	No target or limit, nor particular assumptions
Floating off-shore wind	A breakthrough is assumed. Techno-economic assumptions from page 38 of the second REEEM Technology and Innovation Roadmap, D2.1b (available **here**).
Ocean energy	No target or limit, nor particular assumptions
Centralised PV	No target or limit, nor particular assumptions
Sector coupling	No target or limit, nor particular assumptions

Economy: '*Competitiveness of the EU potentially affected by rapid shift to low-carbon economy*'

The markets observe the sharp change in the climate policy framework initially passively. The energy industry is forced to change deeply and move away to fossil fuel-fired generation. This might affect its competitiveness and the job market until after 2030. In the longer run, some sectors are affected negatively, while others emerge/flourish (unevenly distributed between countries).

For the models, the initial assumptions are based on The 2015 Ageing Report and the EU Reference Scenario 2016. The potential effect of the different structure of energy investments on the economy is not an a-priori assumption, but is derived within the REEEM modelling framework by soft-linking the energy model TIMES PanEU and the CGE model NEWAGE.

Global setting: *'RCP2.6 - Global R&D push to climate change mitigation'*

Appendix B – List of indicators

- Net electricity generation capacity [GW];
- Net electricity generation [TWh or PJ];
- Primary and final energy consumption in different sectors [TWh or PJ];
- Primary Energy Consumption [TWh or PJ];
- CO2 emissions [Mton];
- Factors affecting consumers' heating technology choices (for three countries) [-];
- Factors affecting consumers' vehicle technology choices (for three countries) [-];
- GDP growth rate [%];
- Competitiveness index (GVA) development [%];
- Changes in emissions of air pollutants and GHG (overall and sector-specific) [%];
- Health costs associated with air pollution [bn €];
- Disability Adjusted Life Years (overall and country-specific) [DALYs];
- Share of households by NUTS1 regions who report that they are unable to adequately heat their homes [%];
- Distribution of coal sector employees across EU [normalised to 1];
- AdWarmth and SevArrears [normalised];
- Climate change per capita [kg CO_{2eq}/capita];
- Sector distribution for climate change [share];
- Cumulative critical material demand by technology [Thousands ton];
- Overview of Supply Risks for Selected Materials [-];
- Critical material demand [Thousands ton];
- Water consumption for electricity generation [Million cubic metres];
- Country level relative changes in weighted heating and cooling degree days [%];
- Median generation levels across power sector technologies between 2020 and 2050 [TWh];
- Extraction of logging residues [Million cubic metres per year];
- Fuel and electricity consumption in the DH system [GWh].

Appendix C – List of stakeholder workshops

Stakeholder workshop on Energy transition pathways for the EU, Brussels, Belgium, October 6th, 2017

19 participants from the European Commission, the LCE21-2015 projects MEDEAS, SET-Nav and REflex (in the framework of a collaboration between funded actions started by INEA), industry and the REEEM Consortium attended the workshop. During the workshop, the participants worked in plenary sessions and groups to define the qualitative narratives and the key numerical assumptions for the REEEM pathways, with a methodology inspired to the Morphological approach and the Cross-balance impacts. The inputs were collected and resulted in the definition of two of the three REEEM pathways, namely Coalitions for a Low-carbon path and Local Solutions.

Stakeholder workshop on Impact Assessment decarbonisation pathways, Brussels, Belgium, September 27th, 2018

16 participants from European Universities, Fortum, CEPS, ENTSO-E and the REEEM Consortium attended the workshop. Divided in groups, they worked on defining key dimensions and research questions for the integrated impact assessment to be carried out in REEEM and relative indicators. The collected inputs fed into the integrated impact assessment work carried out within REEEM WP1.3 and into the elaboration of this report.

Technology and innovation workshop – Energy storage application roadmap, Brussels, Belgium, May 19th, 2017

Around 30 participants from the European Commission (DG Ener, DG RTD, DG JRC), the International Energy Agency, European Associations), industry – start-ups – and finance within the network of InnoEnergy, the LCE21 projects SET-Nav, MEDEAS and REflex and the REEEM consortium attended the meeting. Participants worked in groups to provide insights on barriers and enablers to the diffusion of key storage applications, which were incorporated in the REEEM Technology and Innovation Roadmap on Energy storage application.

Technology and innovation workshop – Renewable energy integration roadmap, Brussels, Belgium, April 17th, 2o18

Around 30 participants from the European Commission, renewable energy associations, industry and start-ups and the REEEM consortium attended the meeting. Participants worked in groups to provide insights on barriers and enablers to the diffusion of key renewable energy applications, which were incorporated in the REEEM Technology and Innovation Roadmap on Renewable energy integration.

Technology and innovation workshop – Energy efficiency in buildings, Brussels, Belgium, March 19th, 2019

Around 30 participants from the European Commission, policy agencies, industry and start-ups and the REEEM consortium attended the meeting. Discussions were introduced by presentations from start ups on innovative technologies for building-integrated photovoltaic (solar tiles) and net-zero energy house modules. Subsequently, participants worked in groups to provide insights on barriers and enablers to the diffusion of measures to improve energy efficiency in buildings, which were incorporated in the REEEM Technology and Innovation Roadmap on Energy efficiency in buildings.

Stakeholder workshop on Carbon Leakage and Competitiveness: Macroeconomic projections for the European Union until 2050 – Brussels, Belgium, April 16th, 2018

At the workshop, the preliminary results of this analysis were shown to a group of selected stakeholders from industry, academy and the European Commission. By the end of the meeting, the main request of the attendees was to add one extra policy to the ones being analysed, the free allocation of ETS allowances as part of the European Commission's policy to support industrial installations exposed to a significant risk of carbon leakage. A description of this policy and how it was implemented in this analysis is provided in the Case study report on Carbon Leakage and Competitiveness.

District heating workshop – Kaunas, Lithuania, April 4th 2017

The aim of the workshop was to refine the scope of the case study on district heating. Preliminary scenarios and results were presented, and feedback and comments were received. Altogether, 20 people participated in the workshop, from the energy industry operating in Lithuania, Poland and Finland (Fortum, Kauno energija and industry associations).

Prospective investments in the DH systems were discussed and their viability assessed. A questionnaire on the future of district heating in Kaunas was performed in connection to the workshop and the questions dealt with prices and costs, technologies as well as regulations and market conditions. Feedback concerning Helsinki and Warsaw regions was collected by in-depth discussions with stakeholders. In the workshop, regulations affecting the DH sector and its development in each country were addressed and issues caused by the commonly changing regulations in Poland were discussed. The feedback and comments received in the workshop were taken into account when the studied DH scenarios were formed and refined.

Workshop on ecological assessment and forest simulation – Kaunas, Lithuania, February 14th, 2017

The workshop was attended by 12 participants from Lithuanian universities, the Lithuanian State Forest Service, the Institute of Forest Management and Wood Science, the Institute of Forestry and Forest Biology, the Nature Research Centre and the REEEM Consortium. Participants worked in groups on issues around forest management strategies, methods for assessing forest biodiversity and selection of indicative habitat networks, parameters and data.

Expert workshop on grid and dispatch in South Eastern Europe, Zagreb, Croatia, May 16th, 2018

Around 25 participants attended the workshop, from E4SMA, Pannon Pro Innovations Ltd., Independent Bulgarian Power Exchange (IBEX), Hrvatska elektroprivreda (HEP), CEZ Group, the University of Zagreb, the University of Ljubljana and the REEEM Consortium. During the workshop, the REEEM project and preliminary results from the case study on grid and dispatch in South Eastern Europe were presented. Subsequently, participants provided feedback in group work on potential issues identified in the modelling approach and suggested relevant pathways to deepen and complete the analysis. Inputs were taken into account for the refinement of the model underlying the case study and for the refinement of the pathway assumptions specific to the case study. Furthermore, the refined pathway assumptions were harmonised with assumptions for South Eastern Europe in the TIMES PanEU model at the base of the EU28+2 integrated modelling framework of REEEM.

Stakeholder workshop on energy security and other regional aspects of the European energy transition, Vilnius, Lithuania, June 4th, 2019

A well-mixed group (representatives of parliament, ministries, enterprises, NGOs, consulting companies, and research institutions) of more than 30 participants attended the workshop. The workshop was aimed at discussing energy security and other energy transition issues that are especially relevant for the Baltic region. It was opened by Lina Sabaitienė, Vice-Minister of Energy of Lithuania, and Virgilijus Poderys, member of Lithuanian Parliament and Chair of the Commission for Energy and Sustainable Development. REEEM team members presented the main results of the REEEM project, special attention was paid to specific studies on district heating in Helsinki, Kaunas, and Warsaw; energy security in Baltic countries and Finland; distributional and energy poverty impacts of the energy transition. The presentations were followed by the discussions that covered both research and policy questions.

Annex D - Gas supply security in the Baltic countries (supplementary to REEEM D6.2)

Introduction

In the past decades, natural gas supply was one of the major energy security concerns in Estonia, Latvia, and Lithuania since these Baltic countries were dependant on Russia as the single gas supplier. The situation was improved by building a natural gas terminal in Klaipėda (Lithuania) but natural gas still plays an important role in Baltic energy security narrative. Therefore, gas interconnection between Poland and Lithuania (GIPL) project is being implemented.

In this research, we use the gas supply case in the Baltic countries to study energy security indicators and to present a newly developed framework to evaluate energy security measures in a systematic way. For this analysis, a new model called "TIMES Baltic Gas Security (TIMES BGS)" has been created. This model utilizes the general results of the TIMES PanEU model runs and provides more details on the security of gas supply in the Baltic countries. To evaluate the impacts of energy transition, the CL and PA pathways are considered. Although TIMES BGS is a relatively simple model, the methodological principles presented in the present research can be implemented in more comprehensive models as well.

This study supplements and extends deliverable D6.2 Regional Energy Security Case Study of the Baltic region and Finland of the REEEM project, available here.

Methodology

The TIMES BGS model is developed in VEDA[8] environment and describes all gas supply options depicted in Figure 47. Those include pipeline gas imports from Russia, imports through the GIPL interconnection between Poland and Lithuania, and imports through the liquified natural gas (LNG) terminal in Klaipėda. Natural gas terminals provide a plethora of diversification options. Thus, four possible LNG imports sources (GS1, GS2, GS3, and GS4) are assumed. Imported gas is supplied to consumers through gas transmission and distribution networks. In case of a failure in the gas system, the demands can be satisfied by the fictitious very expensive supply of natural gas unserved.

[8] https://iea-etsap.org/index.php/etsap-tools/data-handling-shells/veda

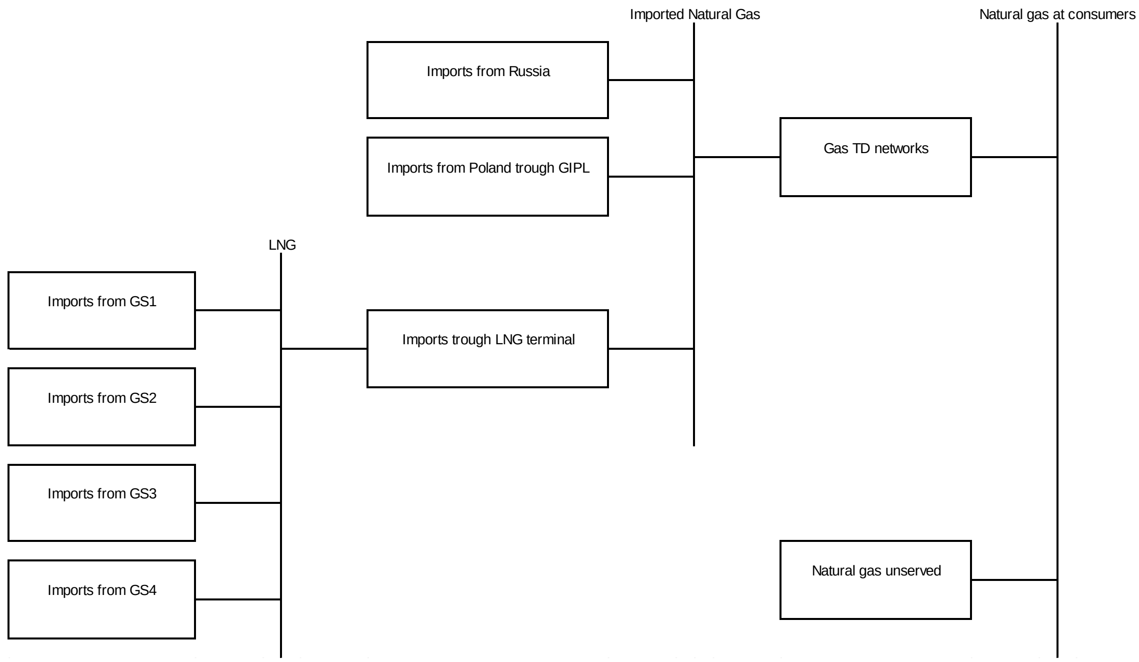

Figure 47. The reference energy system of TIMES BGS model.

The role of energy security indicators is analysed by constraining amounts of natural gas imports. Two broadly used indicators, the largest supplier's share and Herfindahl-Hirschman Index (HHI), are explored. Both of them are most frequently calculated based on activity levels (in the present case, annual import amounts).

A methodological novelty of this research is the calculation of required minimal system disruption probabilities associated with corresponding energy security measures. The basic idea behind is that every security measure is reasonable only in the case if the probability and cost of disruption it overcomes are high enough. The situation can be described by (1) equation:

$$p_d \times c_{od} + (1 - p_d) \times c_o \geq p_d \times c_{odm} + (1 - p_d) \times c_{om}, \quad (1)$$

where p_d is the probability of disruption in the energy system; c_{od} is the cost of energy (system cost) in the case of a disruption; c_o is the cost of energy in the case without disruption; c_{odm} is the system cost in a case of disruption when energy security measure implemented; c_{om} – is the system cost when there is no disruption but the energy security measure is still in place. In other words, (1) equation shows that an energy security measure is reasonable only if it does not increase the total system cost under a full variety of alternative futures.

The lowest probability p_d under which an energy security measure is still desirable, is derived from (1) equation:

$$p_d \geq \frac{c_{om} - c_o}{c_{om} - c_o + c_{od} - c_{odm}}. \quad (2)$$

In the less general case, an energy security measure might fully overcome the consequences of a disruption (c_{odm} is equal to c_{om}). Then the probability p_d can be calculated as follows:

$$p_d \geq \frac{c_{om} - c_o}{c_{od} - c_o}. \quad (3)$$

In contrast to most energy security indicators, the minimal probability of system disruption is focused on the preconditions to apply energy security measures rather than on calculation of energy security levels using synthetic indicators. The estimation of minimal disruption probability p_d is a model-based and practical way to determine the need of energy security measures as it shows the probability of disruptions under which an energy security measure under consideration would provide benefits to the society.

Data

This research is harmonised with the TIMES PanEU model runs in the REEEM project. The main data describing natural gas prices and demand in Baltic countries (Estonia, Latvia, and Lithuania) is provided in Table 17.

Table 17. Natural gas import prices and demands in Baltic countries.

	Unit	2015	2020	2025	2030	2035	2040	2045	2050
Natural gas import price[9]	€/GJ	6.37	6.45	7.72	9.00	9.16	9.32	9.12	8.92
Natural gas demand, CL pathway[10]	PJ	161.79	156.97	156.17	146.48	149.51	133.20	119.31	104.35
Natural gas demand, PA pathway[11]	PJ	176.51	152.06	151.82	143.64	131.22	97.74	71.99	71.54

This data was directly used in the present modelling exercise with the exception of gas demand for 2015 (168.130 PJ) which was taken directly from the *nrg_cb_gas* table in the Eurostat database.

Additional assumptions were made to differentiate the gas price by the source of imports: it was assumed that natural gas price in the table above represents possible imports through existing pipeline while imports via new GIPL is assumed to be 10 per cent more expensive, imports from GS1-GS4 is assumed to be more costly by 1, 5, 20, and 200 per cent respectively. It should be noted that the actual prices are fluctuating over time and are dependant on a variety of factors. Thus, these assumptions do not reflect any attempt to predict actual price ratio or competitiveness of a particular import source. On the contrary, assumptions about price differences are used only to reflect differences between possible gas import sources.

[9] TIMES PanEU input data, file 2019-05-06_AllPathways_TIMESPanEU_Input.xlsx
[10] TIMES PanEU output data, file 2019-04-17_Base_TIMESPanEU_FrameworkV3_DataV1_Output_fixed.xlsx
[11] TIMES PanEU output data, file 2019-05-20_ParisAgreement_TIMESPanEU_FrameworkV3_DataV1_Output.xlsx

The investment cost of GIPL is assumed to be 500 million Eur[12], 50 year lifetime and 2025 as starting year of operation, maximum LNG import volume 167.5 PJ per year[13], minimal LNG import volume 17.7 PJ per year[14]. The cost of natural gas unserved was assumed to be 500 Eur/GJ and is in line with the largest estimation for domestic consumers in the UK[15]. 5 per cent discount rate was used in the main calculations.

Energy security indicators and system cost

To study the linkage between energy security indicators and energy security defined in economic terms, different scenarios of constrained natural gas flows were modelled using TIMES BGS model. The descriptions of scenarios as well as system cost calculation results are provided in Table 18.

Table 18. Scenarios analysed and discounted system cost in million Euro.

	CL Pathway	PA Pathway
No restrictions	21483.60	19611.34
Without imports trough existing pipeline	21638.14	19747.06
Without imports trough existing pipeline and from GS1	22334.21	20368.71
Without imports trough existing pipeline and from GS1 and GS2	23999.83	21908.03
Without imports trough existing pipeline and from GS1-GS3	36081.66	33575.85
Without imports trough existing pipeline and LNG terminal	416298.72	398141.94
50 % share of the largest import source	21550.05	19668.38
33 % share of the largest import source	132999.63	126885.26

In general, three types of scenarios were modelled: scenarios without restrictions, scenarios with disruptions (the loss of the most attractive import options), and diversification scenarios which imply bounds on the share of the largest natural gas supply source. All the bounds are put into force since 2020 and valid until the end of the study period in 2050. As can be seen from Table 18, the lowest system cost is obtained in the unrestricted case. However, the level of diversification in the scenarios with no restrictions is extremely low. The main part of the gas is imported from a single supplier through the existing pipeline, and some diversification is determined only by the necessary imports through the LNG terminal. Therefore, the HHI is able to reach only 6271.23 under the Paris Agreement pathway and 7178.72 under the CL pathway. Reducing the share of the largest import

[12] Source: https://nlea.lt/data/public/uploads/2019/05/elektros-energijos-ir-gamtiniu-duju-rinku-apzvalga_2019-geguze.pdf

[13] Source: https://www.kn.lt/uploads/files/dir49/dir2/9_0.php

[14] Average calculated based on the range provided in https://www.regula.lt/Puslapiai/naujienos/2019-metai/2019-balandis/2019-04-01/per-sgdt-butinas-isdujinti-minimalus-duju-kiekis-nesikeicia.aspx

[15] See London Economics (2011). Estimating Value of Lost Load (VoLL). Final report to OFGEM. https://www.ofgem.gov.uk/ofgem-publications/40961/london-economics-estimating-value-lost-load-final-report-ofgempdf

source to 50% increases the system cost by approximately 0.3%. If the share of the largest import source is reduced to 0.33 (only primary import sources are included to the constraint), the system cost increases by 1.6%.

Putting the bound on the imports through existing pipeline that is assumed to be the cheapest gas source increases system cost by 0.7%. However, there is some probability that the loss of the existing pipeline would not happen, while the cost of forced diversification and loss of the economy of scale is more certain. Therefore, the diversification of supply capacities (options) is much more important energy security factor than activity diversification in a specific time period and policies focussed at activity diversification can be desirable just in case if they are aimed at creating prerequisites diversified supply options to be in place.

The impact of a possible loss of supply options is further illustrated by the scenarios without LNG import sources and LNG terminal as such. In the latter case, the extremely high system cost is obtained due to unserved natural gas demand in the time period when the GIPL import capacities are lacking.

Minimum probabilities of disruption under the case of GIPL

Energy security, along with other interrelated issues such as market integration, is mentioned among the main reasons for building the gas interconnector between Poland and Lithuania. On the other hand, the GIPL project is criticised as not necessary in the context of rapidly decreasing natural gas consumption in the Baltic countries and the natural gas infrastructure that is already in place (currently, there are at least two major gas supply alternatives: pipeline imports and LNG terminal with different supply sources possible). From an energy security perspective, GIPL would be necessary to ensure continuous gas supply to the Baltic region in the case of imports through both existing pipeline and LNG terminal is not available. Therefore, the system cost in the case of disruption is calculated assuming that the import from these sources is constrained to zero. In scenarios without this energy security measure, building a new gas pipeline is allowed but it is delayed (gas imports through GIPL is not allowed in 2025-2030). To calculate the minimum probabilities of the disruption, four scenarios were run for each pathway. The results of the calculations are provided in Table 19.

Table 19. Discounted system cost under different energy security scenarios, million Euro.

	CL Pathway	PA Pathway
Without disruption, without GIPL	21197.75	19325.49
Without disruption, with GIPL	21483.60	19611.34
With disruption, without GIPL	736207.02	714672.45
With disruption, with GIPL	416298.72	398141.94

The minimum disruption probability that would justify building GIPL is calculated using (2) formula and is equal to 8.93×10^{-4} under the CL pathway and 9.02×10^{-4} under the PA pathway. In other words, GIPL should be constructed due to energy security reasons if the probability to lose gas imports through both the existing pipeline and the LNG terminal is higher than the value calculated.

The higher probability in the case of the Paris Agreement pathway shows that the energy transition slightly decreases the need for energy security measures in the field of natural gas supply to the Baltic countries. However, the decrease is not significant (just about 1%) due to relatively close natural gas demand projections in the next decade.

Conclusions

Activity-based indicators, such as the HHI of supply or the share of the largest import source, have very limited relation with energy security level expressed in economic terms. Much more important role is carried by having real operable capacities that could enter in service in case of an accident to ensure continuous energy supply. Therefore, activity-based energy security indicators should be interpreted very carefully.

The need for energy security measures can be evaluated taking into account the cost of foreseen energy security measures, the losses these measures can help to avoid, and the probability of an accident. Even if the latter is not known, modelling of measures and accident situations can provide an important background for decisions and make them more rigorous. It should be noted that energy security measures are often implemented not only to avoid disruptions in the energy system but also to create some side benefits such as improving market processes or providing auxiliary services. Such impacts might increase the attractiveness of the investment to energy security measures and should be a part of the decision process.

The energy transition process has a modest impact on energy security in the case analysed. Although energy security measures often require large infrastructure investments, energy transition and decreasing consumption of fossil fuels might reduce the needs to invest in related energy security measures.

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