D1.2

First Integrated Impact Report

January 2018

About this report

The current report highlights the key indicators that provide the main insights from the REEEM modelling exercise. The indicator selection process is described followed by the illustration of key results coming from 5 different models. The methodology builds on "REEEM D1.1 Report on Pathway definition". This report is the outcome of a collective effort of the REEEM consortium.

Authors

Georgios Avgerinopoulos (KTH Royal Institute of Technology), Francesco Gardumi (KTH Royal Institute of Technology), Ulrich Fahl (University of Stuttgart), Pinar Korkmaz (University of Stuttgart), Roland Montenegro (University of Stuttgart), Julia Welch (University of Stuttgart), Steve Pye (University College London), Xi Pang (KTH Royal Institute of Technology), Ulla Mörtberg (KTH Royal Institute of Technology), Sanna Syri (Aalto University), Aira Hast (Aalto University), Anna Darmani (InnoEnergy), Bo Normak (InnoEnergy), Ashad Salem (InnoEnergy).

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.

The REEEM project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691739. This publication reflects only the views of its authors, and the European Commission cannot be held responsible for its content.

Contents

List of figures

List of tables

1. Introduction

Sustainable development has been high on the global agenda over the past couple of decades. The challenges facing developed countries differ significantly from the ones developing nations encounter, though. The former need to transform their resource management adapting to a less carbon-intensive pattern, while the latter strive for meeting fundamental needs for their population such as access to electricity. The EU in particular appears to be at the leading edge of sustainable development [1] with really ambitious targets been set, both mid and long term.

One of the key components of sustainable development is the decarbonisation of the energy system. Access to energy services is the cornerstone of most contemporary activities and, consequently, a well-functioning energy system constitutes the spine of economic development. However, fossil fuel based energy production (which has been the dominant case so far) can cause severe environmental impacts. Moving towards an energy system with a significantly low carbon footprint can be a challenging task. Several factors need to be taken into account when different options are explored and the various trade-offs need to be identified. An energy system affects and is affected by a plethora of aspects and, therefore, its transition to a different pattern may have economic, social and environmental impacts.

Usually, when one tries to quantify and analyse the impacts of a long-term energy transition, a set of indicators is adopted. An indicator can convey a certain message either directly or through further analysis (e.g. GDP growth does not directly imply competitiveness but it may signify elements of that). The selection of the indicators depends on the objectives that have been set and the prospective audience. For example, an investment fund might be interested in the total potential for investments in a certain technology while an environmental NGO would be rather interested in the pollutant emissions and relative health impacts caused by the energy sector. In order to get a holistic picture, a certain number of indicators needs to be used to capture the impact of energy transition pathways on different dimensions (i.e. economic, social and environmental). Subsequently, the indicators may provide insights into one particular pathway or compare the performance of the energy system in different pathways.

Once the indicators have been selected and the corresponding values are available, it is critical to find out what the overall performance of a particular pathway is, how it performs in different dimensions and how it compares to alternative pathways. To achieve this, a multi-criteria analysis (MCA) is carried out. MCA is the process under which several indicators are normalised and weighed, to obtain an aggregate indicator which signifies the overall score. The weighting factors corresponding to each of the indicators contributing to the MCA are not standard but rather adjustable and case specific. To determine those factors, one may refer to comparable examples in literature and/or define them based on the judgement and the interests of the stakeholders involved.

The REEEM project aims at analysing how different technologies can impact the transition to a low carbon economy in the EU28+2 (Norway and Switzerland) by 2050. To do so, a suite of models is used, looking at different aspects (macroeconomics, energy system optimisation, LCA of energy technologies etc.) and on different scales spanning from pan EU28+2 to case studies covering either single countries or even municipalities. In many cases those models are soft-linked resulting in multi-modelling framework. To analyse the insights this framework can give into the impacts of the energy transition pathways, certain pathway diagnostic indicators are selected and at a later stage an MCA will be also performed.

The current report aims at assessing the main impacts from the transition to a heavily decarbonised energy system in the EU28+2. This is performed by analysing the outcome of the aforementioned modelling framework applied on a number of pathways defined in the REEEM project. More specifically, in Section 2 a literature review is firstly carried out, in order to get an understanding of which indicators were deemed relevant in similar, past cases. In Section 3, the rationale followed in the REEEM project for the selection of the indicators is explained. Section 4 describes the pathways analysed in REEEM so far and extracts insights with the help of selected indicators. Section 5 presents the conclusions of the report, in terms of lessons learnt, and 6 presents the future work planned in REEEM on the integrated impact assessment of decarbonisation pathways.

1.1. Interlinkages within the REEEM project

A number of reports and other outputs is produced based on the work carried out within the REEEM project. Although each deliverable is a stand-alone piece of work, certain pieces of information relevant to one item might be found in different deliverables. For that reason, the interlinkages between the current report and other REEEM material are described here and also shown schematically below in Figure 1 in order for the reader to get an understanding of the complete storyline of the project. All the public REEEM deliverables can be accessed http://www.reeem.org/index.php/deliverables/.

- The pathways analysed in the current work are derived from the already published **D1.1 - Report on pathway definition with drivers, assumptions, indicators and input data**, which also includes a preliminary list of pathway diagnostic indicators.
- The key messages and the values for the indicators that help communicate them are taken from the modelling work done in Work Package (WP) 3 (Economy), 4 (Society, consumers and behaviour), 5 (Environment, health and resources) and 6 (Energy system integration) and from the technology and innovation assessments carried out in WP2. The description of each WP can also be found on the REEEM website.
- The impact assessment described in the current report lays the foundations for the policy recommendations made in **D1.3a - Policy Briefs,** delivered at the same time as D1.2a.
- Finally, the rationale for the selection of the indicators developed for the current task will be used (and potentially further improved) for the integrated impact assessment of the application of the complete modelling framework and on different pathways. This assessment will be described in the **D1.2b - Integrated Impact report** due in July 2019.

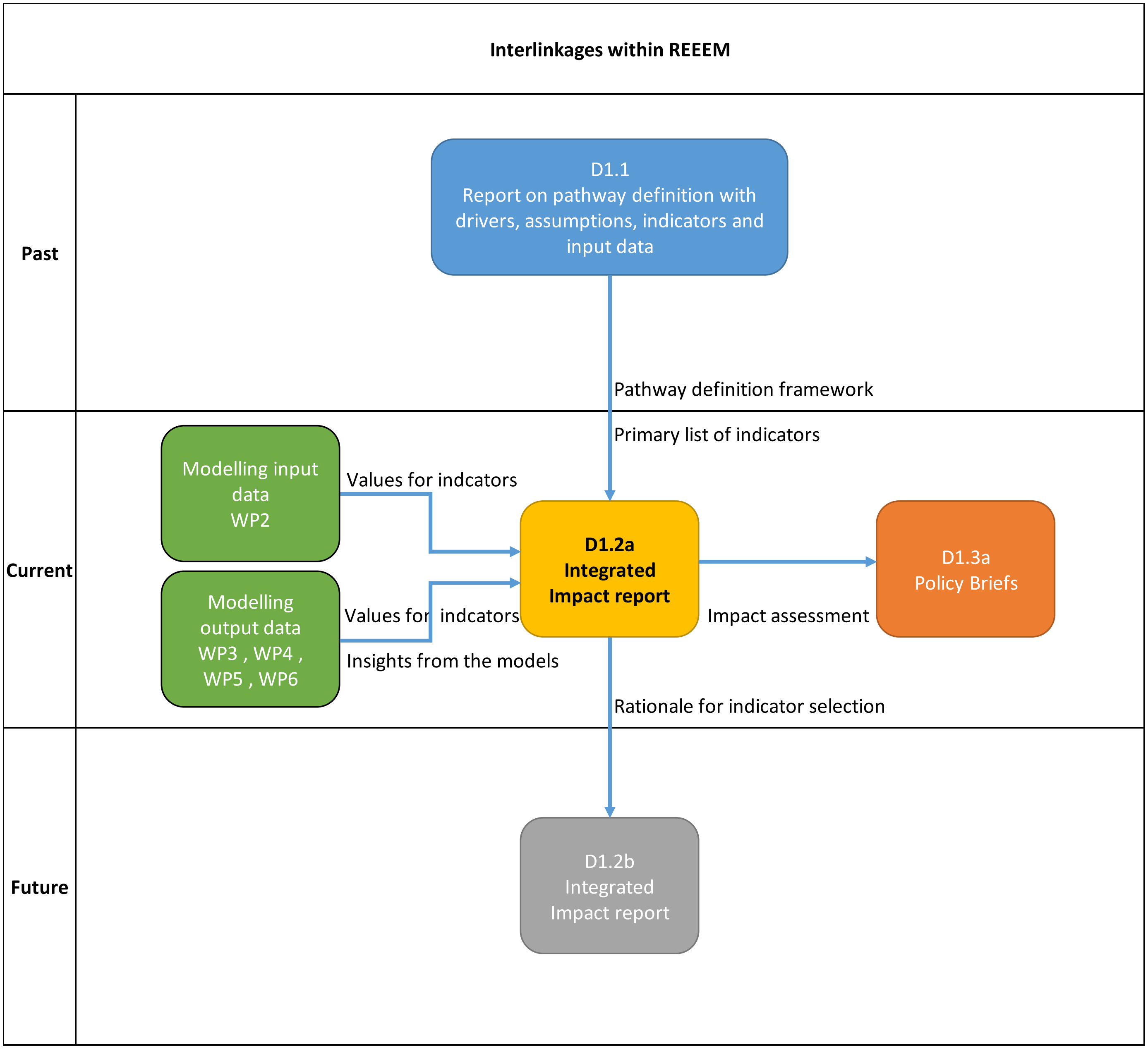

Figure 1. Interlinkages within the REEEM project.

2. Literature review: selection of indicators for energy transition pathways

In part, the indicator selection process is based on already established approaches found in literature. This section provides a review of previous studies that are relevant to the current report and help determine some key indicators.

Following the conceptualisation of "sustainable development" in 1987, various institutes started coming up with lists of indicators in an attempt to measure the progress recorded. Given that the broader energy sector plays a catalytic role in sustainable development, compiling a list of energy-focused indicators becomes an imperative. The joint effort between the International Atomic Energy Agency (IAEA), the United Nations Department of Economic and Social Affairs (UNDESA), the International Energy Agency (IEA) and other organisations [2] constitutes a milestone in the development of a comprehensive list of Energy Indicators for Sustainable Development (EISD). The latter consider several aspects pertaining to energy production and use and categorise the indicators under 3 dimensions, namely economic, environmental and social.

The transition from an energy system pattern to another (e.g. decarbonisation) may cause significant impacts on all the aforementioned dimensions. Measuring or calculating the value of the selected indicators for particular cases throughout the entire period of the analysis and not focusing on a single year is critical when one is interested in capturing the dynamic changes and the impacts caused by a transition. Kriegler et al. in 2015 released a publication [3] in which they analyse the outcome of 11 Integrated Assessment Models (IAMs) using diagnostic indicators. The models are applied on a global scale and their objective is to assess the effect of different climate policies by 2050. More specifically, they run a number of scenarios with different carbon tax levels. In order to get a better understanding of how a deviation from the base case could affect the overall GHG emissions, they introduce a comparative index which expresses the relevant emission reduction compared to the base scenario (to be adopted also in REEEM in the future). Among others, one index used also in this study is the carbon intensity over energy intensity: it illustrates how different combinations of relative reductions in each can have the same final result in terms of overall CO_2 emission abatement (to be also considered in the future development of REEEM).

An energy system transition and the associated impacts are likely to generate stresses in the system. The ability of the system to withstand those stresses and sustain its ability to function with minimal or zero disruptions is called "resilience". The latter is an intricate concept for which metrics are derived from a combination of several aspects. In an attempt to quantify the resilience of a system in different cases, Binder et. al. developed a list of indicators [4] which aim at capturing social and technological aspects. More specifically, the indicators are designed to measure the *diversity* properties of the system looking at variety, balance and disparity, as well as the basic *connectivity* properties looking at network analysis literature—path length, centrality and modularity. Each of those 6 sub-indicators considers both social and technical dimensions. It is worth noting though, that no single aggregated index is formulated based on the aforementioned metrics.

When transforming an energy system, there will inevitably be significant technological shifts taking place. Gralla et. al. [5] attempted to evaluate the overall environmental, societal and economic impacts of nuclear energy based on historical data (1960-2013). To do so, they selected a list of indicators for each category, not necessarily strictly associated with the energy sector. Metrics like central government debt (%) and human development index (HDI) were used. Several correlations (both positive and negative) between nuclear production and different indicators were recorded, giving insights into how the former could potentially impact the economy, society and the environment of a nation. However, they also clarify that correlation does not always imply causality and explain further possible reasons behind those trends.

Choosing the right set of indicators that can convey the right messages really depends on the objectives and the scope of a particular study. Therefore, when one selects indicators from a standard list, adaptations might be required to make them suitable for a particular case. Rösch et. al. did a study [6] assessing the sustainability and the transition of the German energy system through monitoring indicators. A prime example of how a classic indicator was adapted accordingly is the "monthly energy expenditures of households with a monthly net income less than 1300 Euros" which would not be relevant for a country with a considerably lower average national income. That reveals the necessity to select indicators that can be tailored to a particular case study respecting their characteristics.

3. Methodology

3.1. Selection of pathway diagnostics indicators in the REEEM project

As mentioned in the previous section, a large pool of indicators might have to be adapted to address the objectives of a particular case study. The REEEM project examines the role of technologies in the transition to a low-carbon energy system in the EU28+2 (i.e. Norway and Switzerland) by 2050. More specifically, it attempts to assess the transition itself, the pace at which that takes place under different pathways and the associated impacts on the economy, society and the environment. Thus, the selection of indicators must be made along these lines.

In the examples referred to in the previous Section, the authors collected indicators describing a few key dimensions of energy transitions, namely:

- Environmental impacts (GHGs emissions abatement);
- Energy security (resilience of the energy system);
- Socio-economic impacts (government debt and HDI).

Through the modelling work carried out in REEEM, in WP2 to 6 (see Section 1.1 and Figure 1) and a suitable set of indicators, we aim at investigating specific impacts of the energy transition on the following dimensions:

- **Security, solidarity and trust**, including distributional, societal and equity impacts (WP3 and 4);
- **Economic competitiveness and growth** (WP3);
- **Fully integrated internal energy market** in the energy transition (WP3 and 6);
- **Technology innovation** (WP2): the Innovation Readiness Level metrics is introduced, combining concepts traditionally analysed separately (technology readiness level, Intellectual property (IP) readiness level, market readiness level, consumer readiness level and society readiness level); additionally, the crowding out and co-development of technologies is assessed;
- **Health** damage costs of energy-related pollutant emissions (WP5);
- **Impact of climate change on the Energy-Water-Land use nexus** (WP5);
- **Resource efficiency**, also from a Life Cycle perspective (WP3, 5 and 6);
- **Ecosystem services** (bioenergy yield, carbon storage, recreation and habitat networks for relevant and prioritised biodiversity components).

The quantification of the impacts of the energy transition on these dimensions shall provide metrics to monitor the progress of:

1. **SET plan** [7]**:** a research and innovation plan focusing on how to accelerate the development and deployment of low-carbon technologies.
2. **Energy Union** [8]**:** a framework strategy with the aim to ensure access to affordable, secure, competitive and sustainable energy services to European consumers have.

3. **Clean Energy for all Europeans** [9]**:** a package of proposed measures aiming at keeping the competitiveness of the European Union high as the clean energy transition transforms the global energy markets.

From the above, it is clear that the indicator selection process in REEEM is based on three pillars: *literature review*, *specific objectives defined in the project* and *relevance for EU strategies*. With these in mind, a preliminary set of indicators was defined in D1.1 and extended for D1.2 (to be further extended later).

The modelling teams involved in the tasks of WP2 to 6 were asked to provide a set of outputs which can communicate key messages coming out of their models. These would constitute primary indicators. In parallel to that, a number of documents were reviewed to reveal further indicators that were deemed relevant in comparable studies. Those (secondary) indicators were not direct outputs of the models used in REEEM but rather derived from calculations of (two or more) primary indicators either from the same or different models. These two sets are presented in Annex A.

For the purpose of this report, given that the impact assessment is in progress, the full set of indicators is shortlisted in order to convey certain messages. The reasoning governing the shortlisting process consists of two elements. Firstly, the modelling teams provide results and insights (and consequently the main, relevant indicators) based on what seems to be the important outcome of their analysis. It has to be noted though that, in the case of techno-economic data for certain technologies, the values are not modelling outputs but rather inputs resulting from the analysis carried out by InnoEnergy (added to the list as a separate category). The second element is the relevance to the very specific objectives of the project. It must be noted, though, that the significance of the indicators will be reassessed during the course of the project. The full set of REEEM indicators will be accessible through the REEEM Pathway Diagnostic Tool when the complete modelling framework is applied.

4. Sample applications, modelling insights and indicators

In REEEM, the indicators serve the purpose of delivering messages about and insights into possible energy transition processes and their impacts on the society, economy and environment. As extensively described in REEEM Deliverable 1.1, a pathway is the complete description of one possible energy transition process (in modelling terms, a collection of inputs and outputs). While the modelling effort in REEEM is still ongoing and will be completed just at the end of the project, a few pathways have already been modelled and first-try messages can be drawn from them.

To give a first idea of the applicability of the methodology described in the previous sections, this chapter presents the first pathways analysed in REEEM, followed by the outputs and the types of messages they deliver, and it lists a selection of indicators which help convey those messages.

In REEEM, the assumptions of a Base Pathway for the transition of the whole EU to a low-carbon society have been collected, through the work in WP1 and one Stakeholder Workshop. In addition, a number of pathways describing decarbonisation routes for specific countries, regions or cities has also been designed, to be analysed in case studies. All of these Pan-EU and region-specific pathways and their rationale are described in the following sub-sections.

It is important to notice that, at the current stage, the assumptions of different pathways are not in all cases fully harmonised (e.g., in different pathways, different sources for the techno-economic characteristics of one technology may be used). Those assumptions for which harmonisation is needed and possible will be cross-checked and aligned through the duration of the whole project and the final results will be presented in the second Integrated Impact Report (due July 2019).

4.1. A Base Pathway for the EU energy transition

First of all, lowest cost pathways for the low-carbon transition of the EU energy system as a whole were studied, in order to obtain indications about how the system could evolve during the years, under political, environmental, economic, social, technological and global constraints. These indications include, e.g., which technologies could play a role, what investments would be needed and when, if the network infrastructure should be expanded and how the emission patterns would change.

The inputs for this study were collected in two steps: 1) a qualitative image of the **future** of the EU28+2 was first elaborated, with indications about its internal politics, economics, society, environment, technology innovation aspects and collocation in the global context; 2) this qualitative image was translated into **numerical assumptions** for the models. In the following, the future and the relative numerical assumptions of the REEEM Base Pathway are presented.

FUTURE: 'Coalitions for a low-carbon path'

This Future was agreed upon as a useful Base case for REEEM by the participants of the First REEEM Stakeholder Workshop held on October 6th in Brussels. It resembles, in general terms, features of the current EU context and one possible future course it could take. It has characteristics of two of the five scenarios described in the 'White paper on the future of Europe' [10] discussed by President Jean-Claude Juncker at the State of the Union 2017: 'Carrying on' and 'Those who want more do more'. Table 1 describes synthetically the assumptions on how the future could play out on the political, economic, social, environmental, technological and global ground.

Table 1. Qualitative representation of the future for the Base Pathway.

Political	***Economic***	***Social***	***Environmental***	***Technological***	***Global***
Stronger decision making / policy parallels within clusters of Member States.	*Growth at different speeds.*	*Likely passive society in transition.*	*Low availability of water (drying climate) and scarce resources.*	*Reliance on currently commercial technologies. No breakthrough foreseen.*	*Climate change mitigation effort driven by some regions / countries.*

KEY ASSUMPTIONS:

Political dimension – Stronger decision making / policy parallels within cluster of Member States

According to the Future presented above, the current policies are complied with. There is a common general ambition to also comply with the Paris Agreement, even though with different commitment across Member States, depending on the current socio-economic situation, the domestic availability of resources and the geographical location.

- 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 [10] 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 set by the Member States individually, according to the current socio-economic situation, the domestic availability of resources and the geographical location. The targets are indicated in Annex C.
- The existing 2020 and 2030 binding targets of renewable share in gross final consumption for the whole EU are complied with (and overshot, due to the high decarbonisation targets).

- The current plans of development of the electricity network in the EU are taken into account, according to the Ten-Year Network Development Plan 2016 [11].

Economic dimension – Growth at different speeds

- The GDP growth is uneven across the EU and follows the projections of the EU Reference Scenario 2016 [12]; the population growth follows the current trend, according to The 2015 Ageing Report [13].

Social dimension – Likely passive society in transition

No constraint linked to the consumers behaviour is introduced. This corresponds to assuming the society passively accepts the changes brought about in the energy sector through policies and public investments, without raising barriers (e.g. not-in-my-backyard behaviours) and without engaging in the transformation. However, the consistency of such assumption with the ambitious decarbonisation targets imposed will be checked a-posteriori, through the results of the models.

Environmental dimension – 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 buildup/recharge of water storage in soil and groundwater. Also, periods of droughts are likely to occur more frequently and for longer periods. An a-posteriori check will be made from the results of the EU energy system model to verify whether the changing climate patterns may cause issues of water availability for energy use and where.

Technological dimension – Reliance on currently commercial technologies. No breakthrough foreseen.

The decarbonisation targets are met by rollout of existing low carbon technologies. The absence of strong national R&D efforts hinders the potential for breakthroughs. This is reflected by assuming for the techno-economic characteristics of the technologies (to a large extent) projections from JRC's Energy Technology Reference Indicators 2014 [14]. These collect existing literature and expert judgement on likely developments in the absence of specific breakthroughs.

Global dimension – Climate change mitigation effort driven by some regions / countries

Globally, there is an uneven push towards climate change mitigation, where certain regions will pursue more ambitious targets than others. In this context, two distinct groups are expected to rise. The first one includes the countries which have the economic means to decrease their emissions, or are threatened the most by climate change, or both. The second group will be formed by countries which don't have the economic means to pursue more ambitious environmental targets or see the measures against climate change as an unnecessary burden and decide not to take part in the effort.

VARIANTS OF THE BASE PATHWAY

In order to analyse more deeply the impact of the introduction of high shares of Renewable Energy Sources (RES) in the energy system and the role of technology innovation in supporting this transition, two sub-pathways were derived from the Base Pathway.

- ''High RES'' pathway: it includes the same assumptions as the Base Pathway, with addition of targets of renewable share in gross final energy consumption in 2050: specific targets by country clusters are introduced, ranging between 45 % and 85 %, to aim at 75 % share of renewables in final energy consumption at EU28 level. All the values are reported in Annex D.
- ''Storage Innovation'' pathway: it includes the same assumptions as the High RES pathway, with addition of a step-reduction in the cost of Lithium-Air batteries after 2030. Details on the storage technologies outlook for this pathway and the numerical assumptions included in the models are given in Annex B.

4.1.1. Main insights from the Base Pathway (TIMES Pan-EU)

A few synthetic insights from the models are presented in the following, starting from general considerations on the burden sharing for achieving the EU decarbonisation targets:

- France, Portugal, Netherlands, Belgium, Austria, Sweden, Finland and Ireland reduce less than 83 % their ETS emissions and shift the burden **to the other countries** while they reduce 80 % their Non-ETS emissions and take over the responsibility **from the other countries**.
- The energy systems of the UK, Germany, Denmark and Italy are less costly to decarbonise, not only for the ETS emissions but also for the Non-ETS emissions. Therefore, from a EU-wide perspective, it is cost optimal for these countries to take the burden for the reduction of the ETS emissions from the other countries, while still being able to achieve the 80 % reduction in the Non-ETS emissions.
- The energy systems of Bulgaria and Slovenia are the costliest ones to decarbonise. They reduce their ETS and Non-ETS emissions by less than 75 % and 60 %, respectively.

Technology-specific outlooks are also obtained:

- Nuclear/conventional power plants contribute to supplying secure energy, with a higher capacity factor compared to renewable technologies.
- From the solar technology deployment perspective, rooftop solar PV without any battery application is the most widely utilised technology. Such result provides reasons to further analyse the role of this and other renewable technologies and innovations in their supply chain through the next REEEM Technology and Innovation Roadmap (D2.1b, due in July 2018).
- Overall, the EU-wide cost optimal capacity deployment of on-shore wind is higher than off-shore wind technology. This could be explained by the fact that off-shore wind potential is limited to certain countries in Europe. However, this needs further investigation.

Finally, observations on the potential of energy storage technologies are obtained, as likely key players in the transition to a low-carbon and high-RES energy system:

- Na-S (sodium–sulfur) and Vanadium Redox Flow batteries do not become part of the cost optimal generation mix by 2050, due to their high cost. These technologies need sharper cost reduction than expected, to be competitive with the other battery storage technologies.
- Investments in new capacity of energy supply technologies, especially of storage technologies, mainly occur after certain cost reductions and are driven by climate targets.

4.1.2. Main insights from the variants of the Base Pathway (TIMES Pan-EU)

By comparison with the results of the Base Pathway, these additional insights were obtained from the two variants (High RES and Storage Innovation):

- The figures of ETS Emissions burden sharing are similar to the Base Pathway, except for a few countries.
- In the presence of a renewable share target, part of the installed nuclear capacity is replaced by renewable technologies in several countries, resulting in higher overall installed capacity[1].
- The deployment of hydropower technologies is almost identical in all the pathways not only in terms of the type of technologies but also in terms of installed capacity.
- The presence of a target of high renewable share in the energy supply drives higher investments in storage capacity compared to the Base Pathway.
- In the Storage Innovation pathway, Lithium-Air technology replaces the Lead-Acid technology compared to the Base Pathway. This means a breakthrough in the Lithium-Air technology, likely according to some experts (see Annex B), could change its competitiveness compared to other existing and deployed battery storage technologies. However, this change seems not to have high impact on the overall capacity deployment of energy supply technologies.

4.1.3. Key indicators

The insights drawn from the Base Pathway and its variants, presented above, are here described through numerical (and graphical) indicators. A selection of indicators is listed, together with the graphical representation.

- Capacity deployment of power and CHP plants in EU28, by steps of five years until 2050 (GW);
- Electricity production by power plant type in EU28, by steps of five years until 2050 (TWh)[2];
- Capacity deployment of renewable energy technologies in EU28, by steps of five years until 2050 (GW);
- Capacity deployment of storage technologies in EU28, by steps of ten years until 2050 (GW);
- ETS Emissions-Burden sharing between EU28+NO.

[1] Due to the lower full load hours of wind and solar PV compared to conventional power plants, the whole installed capacity in the High RES and Storage Innovation pathway is higher than in the Base Pathway.
[2] Electricity production from storage technologies is also accounted for under the relevant power plants which produce the electricity surplus that is stored.

It is worth noting that some of the insights are given directly by the aforementioned indicators while some others are implied.

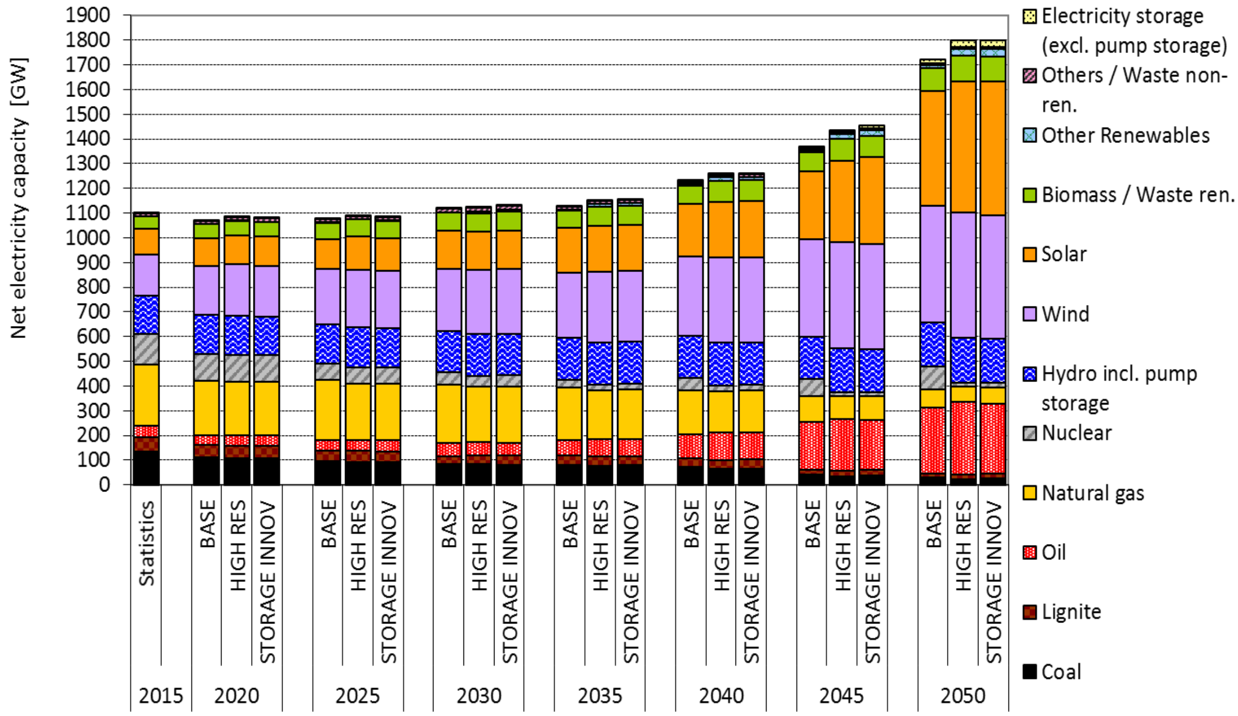

Figure 2. Capacity deployment of power plants per energy source in EU28.

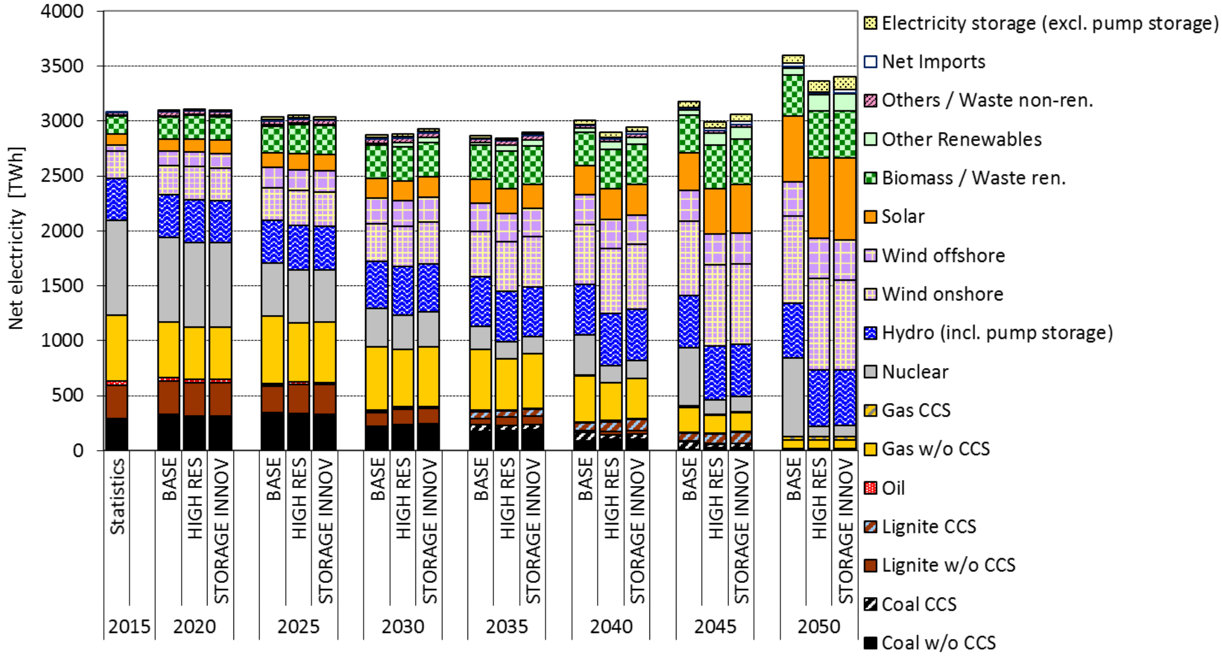

Figure 3. Electricity production by power plant type in EU28.

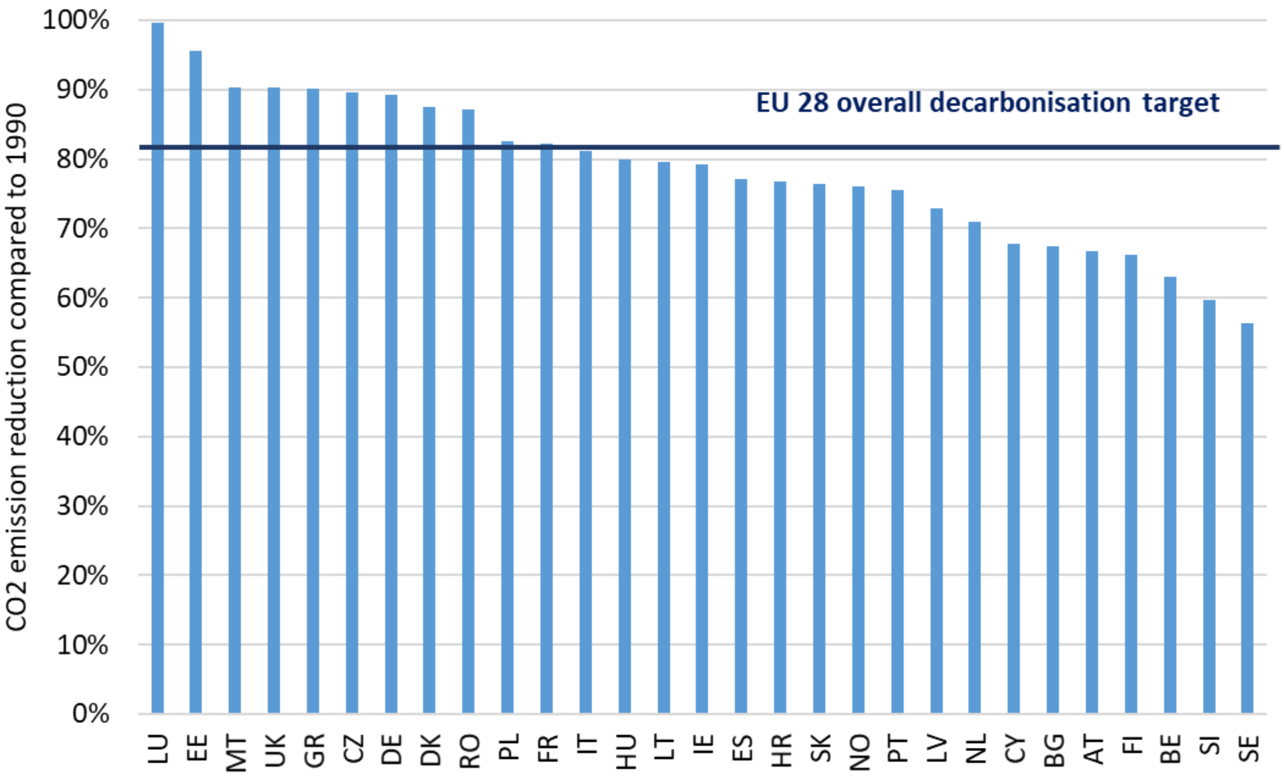

Figure 4. ETS Emissions 2050 (Base Pathway).

4.2. Further pathways and foci

This section presents a number of pathways developed in parallel with the Base Pathway, to zoom into national, regional and local case studies and assess specific aspects of the transition to a decarbonised energy system. As in the previous paragraphs, first the main assumptions are described and then the insights obtained from the application of the modelling framework are presented. Figure 5 provides an overview of the models employed for these pathways and the scope of the studies. The descriptions inside each of the shapes mention from top-down the focus of the model, the geographical scope and the name of the model.

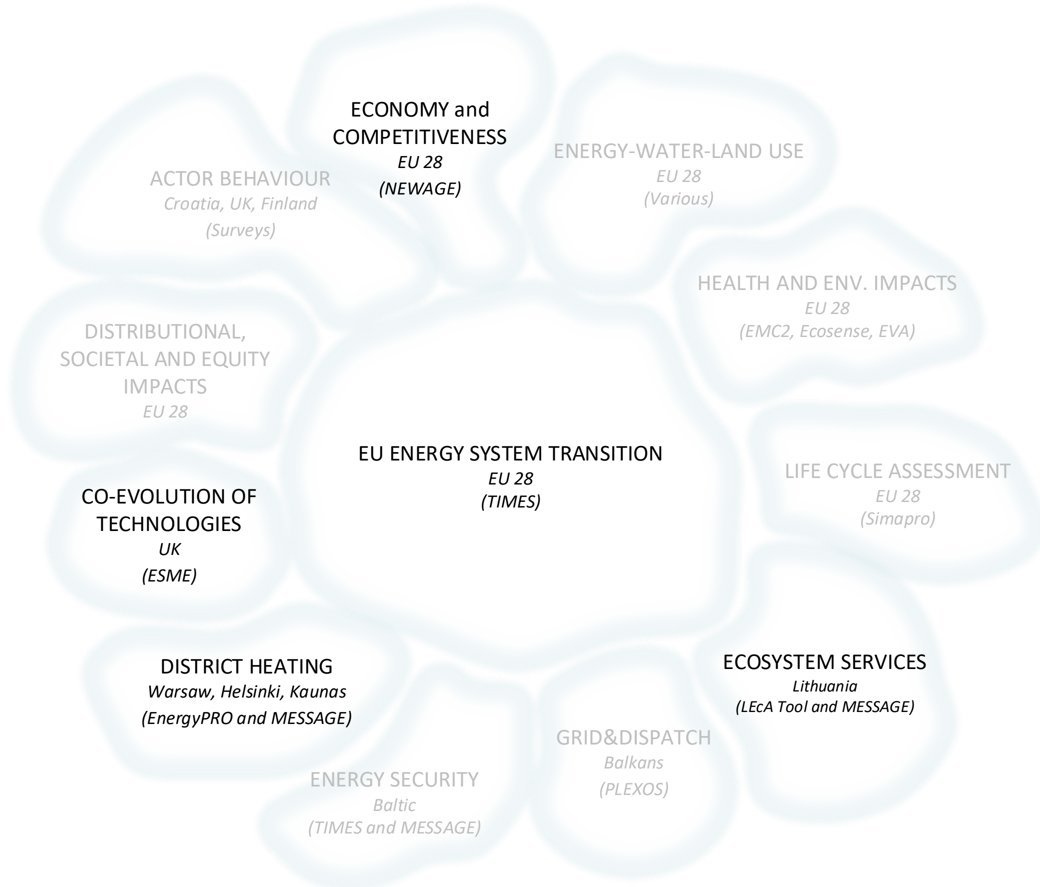

Figure 5. Overview of the models employed in the case studies.

As can be seen, this report only present insights from part of the modelling suite. Other modelling activities are still on course, as foreseen in the time plan of REEEM. Therefore, the complete set of results will be presented in D1.2b, the Second Integrated Impact Report, due in July 2019.

4.2.1. Focus on carbon leakage - *NEWAGE model*

One of the policy areas of the Energy Union and Climate, as well as one of the objectives of the Energy Roadmap 2050, targets the competitiveness of the EU. The latter depends not only on decisions taken at the EU-level, but also on global (extra-EU) and national (Member State) pushes.

The Base Pathway described in Section 4.1 looks at the evolution of the energy system, but it does not make any considerations on how this impacts the overall economy and competitiveness of the EU. Therefore, one case study in REEEM looks at the impacts of the abovementioned Base Pathway and other EU decarbonisation pathways on the economy and the competitiveness of the Union, taking into account different possible global and EU levels of commitment to the decarbonisation transition. Such levels are briefly described in Table 2.

Table 2. Possible global and EU levels of commitment to the decarbonisation transition considered in carbon leakage cage study.

	World
Weak ambition	There are no emission targets outside the EU-28
Current policies	Emissions outside of the EU-28 follow the Reference Technology Scenario (RTS) from the Energy Technology Perspectives 2017 (ETP) [15], issued by the IEA.
Regional push	Only a selected group of regions outside the EU-28 follow the 2°C target scenario.
2 °C target	Emissions outside of the EU-28 follow the 2DS Scenario from Energy Technology Perspectives 2017 (ETP), issued by IEA, which is the maximal emission pathway to reach a 2 °C target.
	EU
Weak ambition	Europe continuing as it is today. It follows the same rationale as Scenario 1 from the White paper on the future of Europe [16], issued in 2017 by the European Commission. The EU and its Member States follow the current emission trend, for both ETS and non-ETS sectors, as presented by the EU Reference Scenario [12], issued in 2016 by the European commission.
Cluster union	It follows the same rationale as Scenario 3 from the White paper on the future of Europe, issued in 2017 by the European Commission. In this case, the countries who want to follow more ambitious targets in the environmental area are free to do so, even if the rest of the EU member states don't follow this path and, thus, decide to do less. This scenario accounts for agreed targets of 80% reduction of emissions from the ETS sectors in 2050, compared to 1990 values. For the non-ETS sectors, clusters of countries agree on different reduction targets, according to their socio-economic situation, availability of resources and geographic collocation.
Strong ambition	This case follows the same rationale as Scenario 5 from the White paper on the future of Europe, issued in 2017 by the European Commission. In this case, the EU Member States decide to increase their cooperation across all policy areas.

The pathways analysed in this case study are created by considering feasible combinations of the above listed levels of commitment at the global and at the EU level. In Table 3, the pathways (and combinations of states of the world and of the EU) are listed.

Table 3. Pathways considered in carbon leakage cage study.

Pathway ID	World	EU
1	Weak ambition	Weak ambition
2	Weak ambition	Cluster Union
3	Weak ambition	Strong ambition
4	Current policies	Weak ambition
5	Current policies	Cluster Union
6	Current policies	Strong ambition
7	Regional push	Weak ambition
8*	**Regional push**	**Cluster Union**
9	Regional push	Strong ambition

10	2 °C target	Cluster Union
11	2 °C target	Strong ambition

* Also the Base Pathway, aligned with the description in 4.1.1.

4.2.1.1. Main insights

The main insights refer to the impact of the world and EU climate change mitigation ambitions. They are here briefly presented and shall be further investigated. Starting from the world ambition (related to decisions made outside of the EU-28):

- Results indicate that the overall ambitions of emission reduction from outside the EU-28 do indeed impact the GDP and employment rate in this region, especially for the two last time periods, 2045 and 2050.
- When pursuing the 2 °C target, in comparison to the current policies, the aggregate GDP and Employment growth in the EU-28 are always lower for equivalent European policies.
- By analysing specific regions within the EU-28, it is possible to observe that the effects vary for each region. The overall effect of lower GDP for the 2 °C target still applies for most regions, while Spain, Portugal and Italy have the highest negative impact. For the South-East European countries, however, and only for this specific region, there is a GDP increase.

As far as the European ambitions are concerned:

- The aggregate results for GDP and employment development in the EU-28 indicate that, either under high or low World ambition, the Business-as-usual scenario produces the best economic outcome, followed by the Cluster Union and, finally, the 80% target.
- Only in 2050 it is possible to see higher GDP development for the 80% target than for Cluster Union. However, that is not true for the employment development.
- For the cases where there is a combination of both high ambition in the EU and in the rest of the World it is possible to see the lowest GDP growth and lowest employment levels. Additionally, in 2050 the employment levels are expected to be lower than 2011 levels.

4.2.1.2. Key indicators

The key indicators representing the insights given in Section 4.2.1.2. are listed here and a graphical representation is provided below. The Pathway IDs are reported again for convenience in Table 4.

- GDP growth in the EU28, by steps of 5 years, relative to 2011;
- GDP growth in specific EU-regions, by steps of 5 years, relative to 2011;
- Employment development in the EU28, by steps of 5 years, relative to 2011.

Table 4. Further information on pathways considered in carbon leakage cage study.

Pathway ID	World Policy	European policy
1	2°C target	Business as usual
2	2°C target	Cluster Union
3	2°C target	80% overall reduction target
4	Current policies	Business as usual
5	Current policies	Cluster Union

6	Current policies	80% overall reduction target

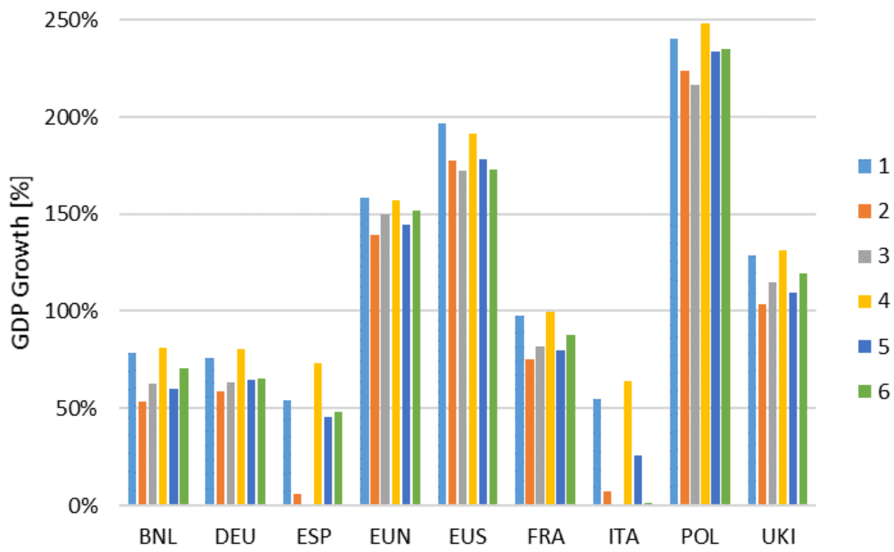

Figure 6. EU-28 GDP growth relative to 2011.

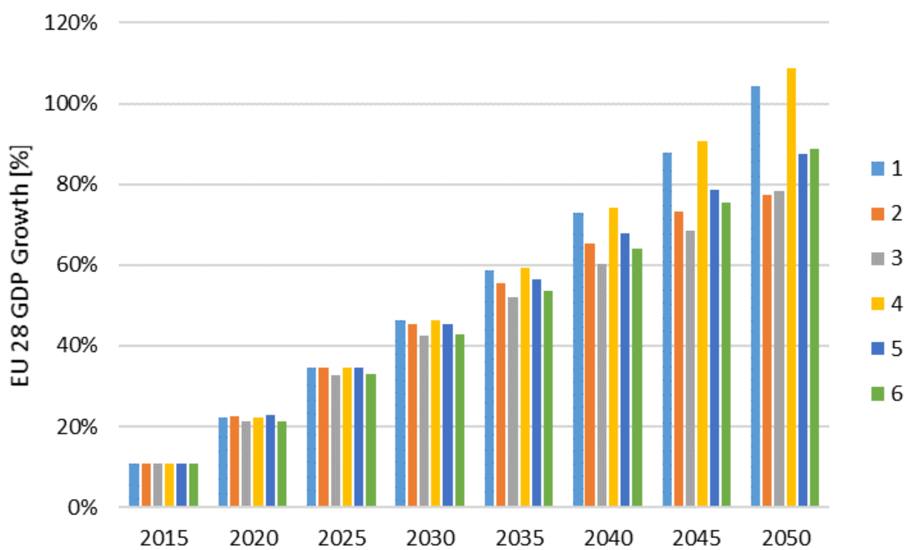

Figure 7. GDP growth in 2050 relative to 2011 in specific EU regions.

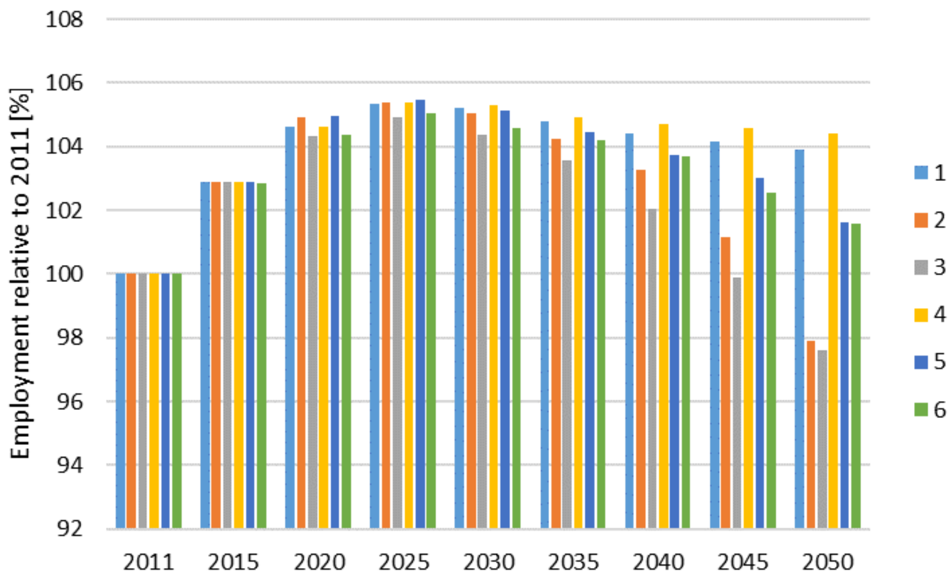

Figure 8. Employment development in the EU-28 relative to 2011.

4.2.2. Focus on the co-evolution of technologies in the UK– *ESME model*

The Energy Roadmap 2050 highlights the objective of reducing GHG emissions by 80-95% by 2050 compared to 1990 [10]. This moves beyond some of the incremental policies to date to real structural change of the energy system [17]. Key to this structural change of the system will be large-scale investment in a range of low carbon technologies. To this end, the Commission has established the Strategic Energy Technology (SET) Plan, which prioritises research and innovation across a range of technology groups. Key actions are further elaborated in the Progress in 2016 report [7].

The question is how do the many technologies recognised as important for the low carbon transition play out together in the same system? The uncertainty around R&D, commercialisation, policy support and social acceptability means that there are numerous eventualities in terms of system design. If one technology subject to rapid cost reduction is deployed at scale, this will have an impact on the role of alternative competing technologies. Furthermore, inter-temporal dependencies may emerge, where specific technologies and their use in the system rely on deployment of others.

This UK-based case study investigates the interplay and interdependencies between different technologies by exploring the range of uncertainties through the simulation of a large number of plausible pathways. To do this, it is crucial that a whole systems perspective is taken so that the impacts of choices in one part of the system are captured in another part. In addition, it is important that the analysis provides for an explicit representation of different technology groups, to understand the characteristics that enable deployment.

The analysis therefore uses the ESME (Energy Systems Modelling Environment) model to simulate a range of different low carbon pathways. ESME is an integrated energy systems model for the UK, used to explore the different technology investments across conversion and end use sectors required for energy system decarbonisation [18]. It is spatially resolved, providing insights on the energy system change in different regions of the UK [19]. ESME also features a module for simulating large numbers of runs to explore parametric uncertainty of model inputs, through Monte Carlo sampling [20], [21]. This specific feature is used in this analysis.

The case study models three distinctive futures, with 600 simulations generated for each to explore parametric uncertainty (thereby generating 1800 model simulations). The three futures include:

- Climate ambition consistent with UK goals (57% GHG reduction in 2030; 80% in 2050 - **RM**);
- Climate ambition not consistent with UK goals, in line with 40% GHG reduction in 2030, and 60% in 2050 (**RM-CT**);
- As for RM, but with no large scale CCS deployment (**RM-NCCS**).

The uncertainties reflected in the modelling are first introduced in the futures. These reflect what we understand to be key factors impacting on the resulting pathways. Under each future, we then consider a range of parametric uncertainties, relating to technology costs, fuel prices, resource availability and rates of technology deployment.

The spanned range of uncertainties depends on the geographical scope of the study. Therefore, the present case study does not cover the whole EU, but it rather focuses on the energy system of a country, the UK. The aim is to provide insights on the co-evolution of technologies and consider the extent to which some of these may be transferable to other Member State contexts.

4.2.2.1. Main insights

Exploring future uncertainty in an integrated analysis can provide insights into the strategic planning process about the role of different technologies under different circumstances. In other words, for the high deployment of technology X, what are the characteristics of technology X, those of technologies Y and Z, and the broader system e.g. carbon price signal, resource availability etc. In this regard, specific insights of the REEEM case study on co-evolution of technologies include:

- The role of different technologies (included in the SET Plan) in the low carbon system of a country, based on similar levels of climate ambition to that considered in the EU. This includes both timing and level of deployment;
- The technology and system level characteristics observed that are necessary for specific technology groups. In other words, the conditions for deployment - technology cost reductions, wider system dynamics, climate policy incentives etc;
- The interdependency or competition between technologies that allow for the roll-out or not of a given technology.

4.2.2.2. Key indicators

The insights are represented through the following indicators, which a graphical representation is given for, in Figure 9 to Figure 11:

- Consumption levels of resources in the system under different futures and by steps of 10 years, including fossil fuels (TWh);
- Total system costs of different pathways, across varying levels of CCS penetration (billion £);

- Marginal costs of mitigation across different pathways, across varying levels of CCS penetration (billion £).

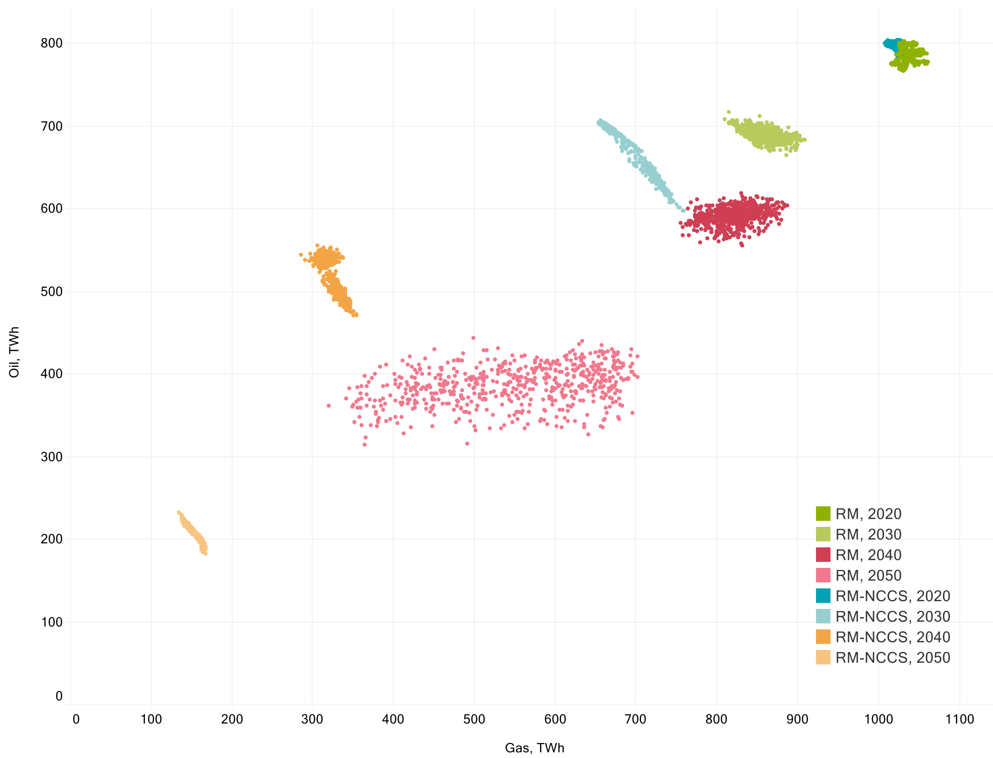

Figure 9. Consumption levels of oil and gas under RM and RM-NCCS futures, 2020-2050.

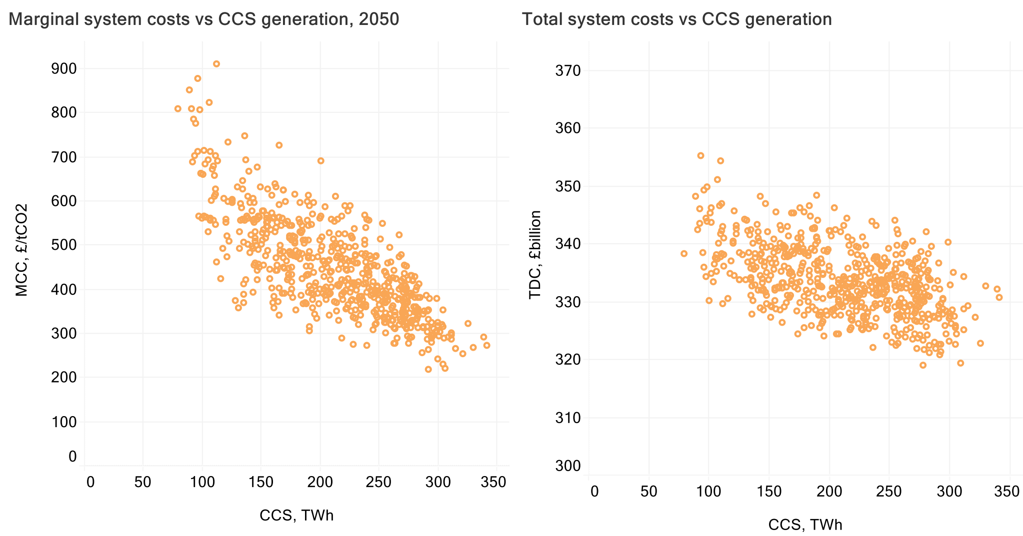

Figure 10. Impact of different levels of CCS (RM future) on the marginal cost of mitigation across the system (left) and total system cost (right).

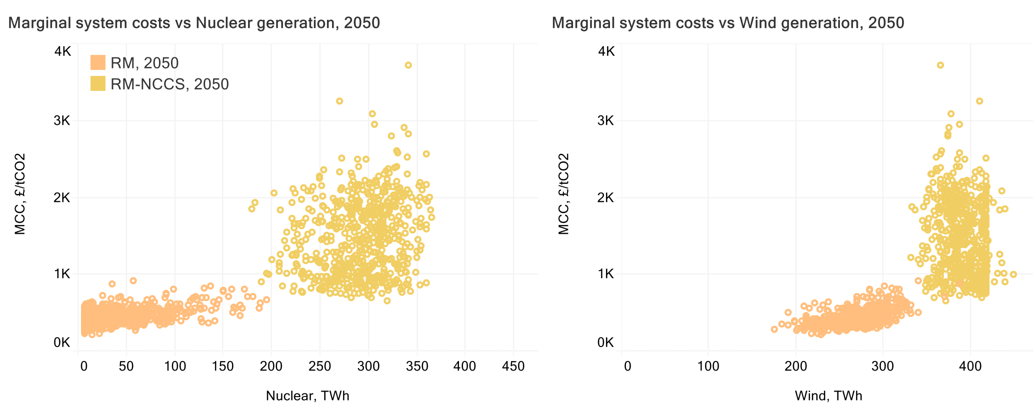

Figure 11. Deployment of nuclear (left) and wind (right) against marginal abatement costs generated under futures RM (orange) and RM-NCCS (yellow).

Other indicators obtained through this case study (but not shown for brevity) are:

- Timing and level of deployment across a range of technologies;
- Emission reduction contribution by sectors;
- Factors impacting deployment of technologies e.g. technology costs, system wide characteristics, deployment of competing technologies etc.

4.2.3. Focus on ecosystem services in Lithuania - *LEcA Tool*

The cost optimal primary energy supply mix of the EU in the presence of renewable targets includes biomass in some countries. The use of biomass poses challenges, since, as in the case of forest bioenergy, it might come with potential conflicts with other environmental goals, such as preserving ecosystem services and biodiversity. This may in turn impact on the environmental sustainability of the energy mix, which is one of the three overarching policy challenges mentioned in SET-Plan.

Traditionally, analyses focusing on the optimal development of EU or national energy systems do not take into account such constraints related to the use of biomass. Hence, the choice in REEEM to integrate multiple ecosystem services and biodiversity in the assessment of energy transition plans and, specifically, plans for increasing use of forest biomass as a renewable energy source.

This case study looks at the local impacts of the use of forestry biomass for energy supply in Lithuania. It aims to create a link between national scale energy system models and assessment of multiple ecosystem services. This allows for balancing various ecosystem services and biodiversity implications and analysing their synergies and trade-offs relative to energy policy and related forest bioenergy options.

The case study uses the Landscape Ecological Assessment (LEcA) tool [22], which consists of modules for simulation of forest management and growth, as well as for estimation of the resulting ecosystem services bioenergy yield, industrial wood, carbon storage, recreation and habitat networks for relevant biodiversity components. Two pathways derived by the MESSAGE energy model of Lithuania were run, **Biomass Low and Biomass High**, in order to gain knowledge on expected demands of forest bioenergy feedstock. Both pathways represent the possible Lithuanian energy sector development under the current European Union energy policy and an orientation of the country towards the widest possible integration into the international energy markets and the optimal use of the existing energy infrastructure [23]. The two pathways differ only by the assumptions related to wood biomass price projections and assumed wood biomass availability for centralised energy production purposes:

- Biomass low considers lower availability and higher prices;
- Biomass high considers higher availability and lower prices.

The forest development is simulated across Lithuania, applying **two forest management strategies**: **BAU**, based on the current forest management regime in Lithuania; and **INT**, where a more intensive forest management is applied for higher harvest. Environmental restrictions related to soils were applied, transport restrictions to harvest residues extraction versus the location of demand nodes were tested and different assumptions concerning the allocation of stemwood for bioenergy use were applied.

For energy generation, different compartments of forest biomass can be used: firewood, primarily stemwood that has no alternative industrial uses, but secondarily it could also be some fraction of industrial roundwood useful for pulpwood or sawmilling; industrial waste (sawdust and wood chips); and **logging residues** (tops, branches and stumps). Assumptions regarding the allocation of forest compartments for bioenergy feedstock are made.

Regarding the **allocation of stemwood**, three sets of assumptions are made:

- Assumption Set 1: **schoolbook** allocation aiming to maximise the total economic value with the lowest priority given to firewood.
- Assumption Set 2a: **empirical-optimistic** allocation a, based on the observed average allocation of harvested stemwood according to the Lithuanian forestry statistics for 2015 [24]. The 'optimistic' part refers to the use of industrial waste being assumed as 100%, while 26% of the total harvest is used as firewood.
- Assumption Set 2b: **empirical-optimistic** allocation b, based on the observed average allocation of harvested stemwood according to the Lithuanian forestry statistics for 2015 [24]. The 'optimistic' part refers to the use of industrial waste being assumed as 100%, while 39% of the total harvest is used as firewood.

Finally, **environmental and transport restrictions** are accounted for, as follows. Extractable logging residues were restricted with minimising soil-related damages on forest ecosystems according to [24]. These environmental restrictions involve 1) poor soils, where the objective is to maintain the natural fertility; 2) for soil with a slope of more than 15 degrees, remaining cutting residues are supposed to make such soil stable; 3) for eroded soils, the aim is to minimise the erosion process; 4) for moist soil, the objective is to minimise the damage on soil; and 5) for organic soil, extraction is not allowed due to both damage avoidance and maintaining the property.

When it comes to logging residues, there may also be limitations on extraction distances to the demand nodes. Therefore, the extraction of harvest residues with and without transport restrictions was taken into consideration. A limit of 1 km distance between the extraction and the collection spots was applied, and transport distances from the collection spots to combined heat and power (CHP) plants or equivalent were assumed to be 30 km.

All the feasible combinations of the sets of assumptions described above result in **48 pathways**. Table 5 summarises the combination of assumptions and the resulting pathways, run with LEcA tool, as well as the overall coverage of forest bioenergy feedstock estimated by the LEcA tool, compared to the use projected by the energy pathways Biomass Low and Biomass High, for the period 2016-2050.

Table 5. The overall coverage of forest bioenergy feedstock estimated by the LEcA tool, compared to the use projected by the energy scenarios Biomass Low and Biomass High, for the period 2015-2050. Two forest management stragegies, BAU and INT, were run.

BAU forest management strategy	Assumption Set 1		Assumption Set 2a		Assumption Set 2b	
Energy pathway	Biomass Low	Biomass High	Biomass Low	Biomass High	Biomass Low	Biomass High
Use of logging residues and transport restrictions						
Full use	76%	60%	121%	96%	148%	117%
Using only tops and branches	50%	39%	95%	75%	115%	91%

Full use – applying transport restrictions	43%	34%	88%	70%	122%	97%
Using only tops and branches – applying transport restrictions	36%	28%	81%	65%	108%	86%

INT forest management strategy	Assumption Set 1		Assumption Set 2		Assumption Set 2b	
Energy pathway	Biomass Low	Biomass High	Biomass Low	Biomass High	Biomass Low	Biomass High
Use of logging residues and transport restrictions						
Full use	83%	66%	133%	105%	162%	128%
Using only tops and branches	54%	43%	104%	83%	126%	100%
Full use – applying transport restrictions	47%	37%	97%	77%	133%	106%
Using only tops and branches – applying transport restrictions	39%	31%	89%	71%	118%	94%

* The table refers to average value for the period 2015-2050.

4.2.3.1. Main insights

Comparing the forest bioenergy feedstock between the energy pathways and the forest management strategies (BAU and INT), the results are illustrated in Figure 12 and Figure 13. As can be seen, the difference between the assumption sets for allocation of stemwood into bioenergy feedstock compartments is substantial. Applying Assumption Set 1 (Schoolbook) would mean that also the Biomass Low pathway would be exceeding what can be extracted from the forest. Applying Assumption Sets 2a and 2b (Empirical-optimistic) makes big differences, especially 2b, where the Biomass Low pathway would be well below the resource limits. The forest management strategy INT was run in order to increase the overall harvest. However, since there are restrictions in the model against decline of the forest productivity, the high productivity could only reach a certain level. For both forest management strategies, the MESSAGE pathway Biomass High seem to put very high demands on the system at the end of the period, when forest biomass might need to be imported instead of produced domestically.

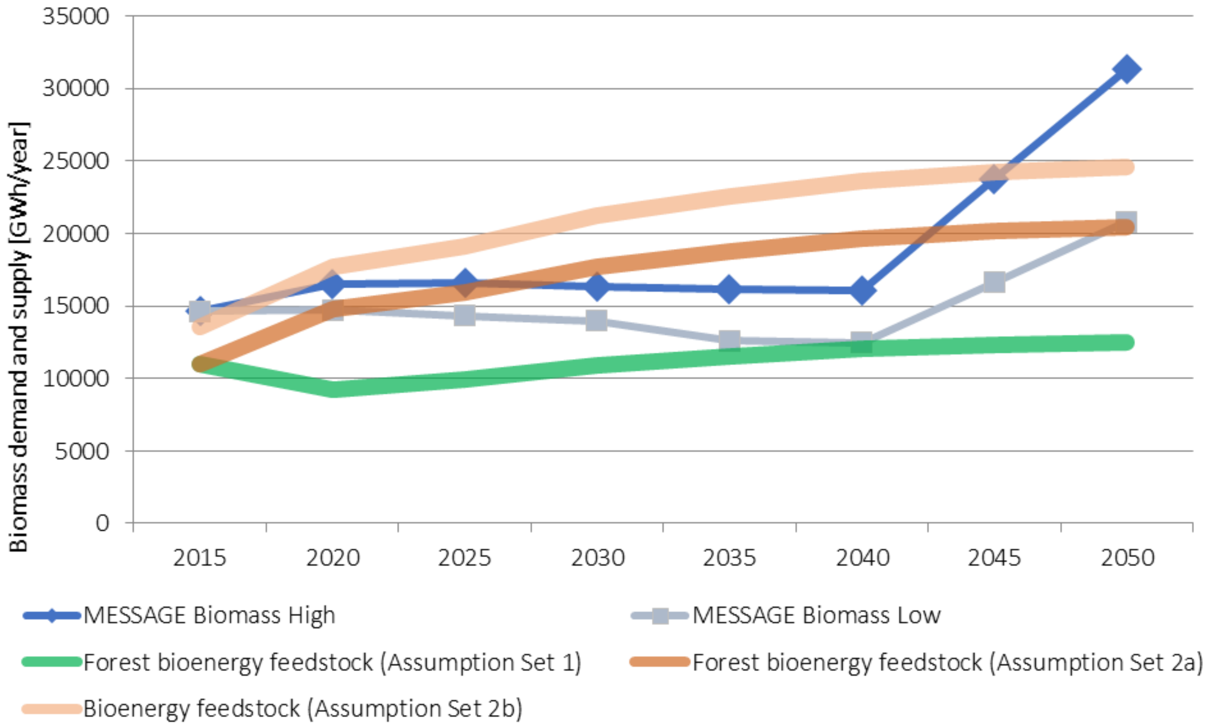

Figure 12. Comparison of the projected use of forest bioenergy feedstock according to the energy pathways, versus the supply according to the LEcA tool estimations. BAU forest management strategy.

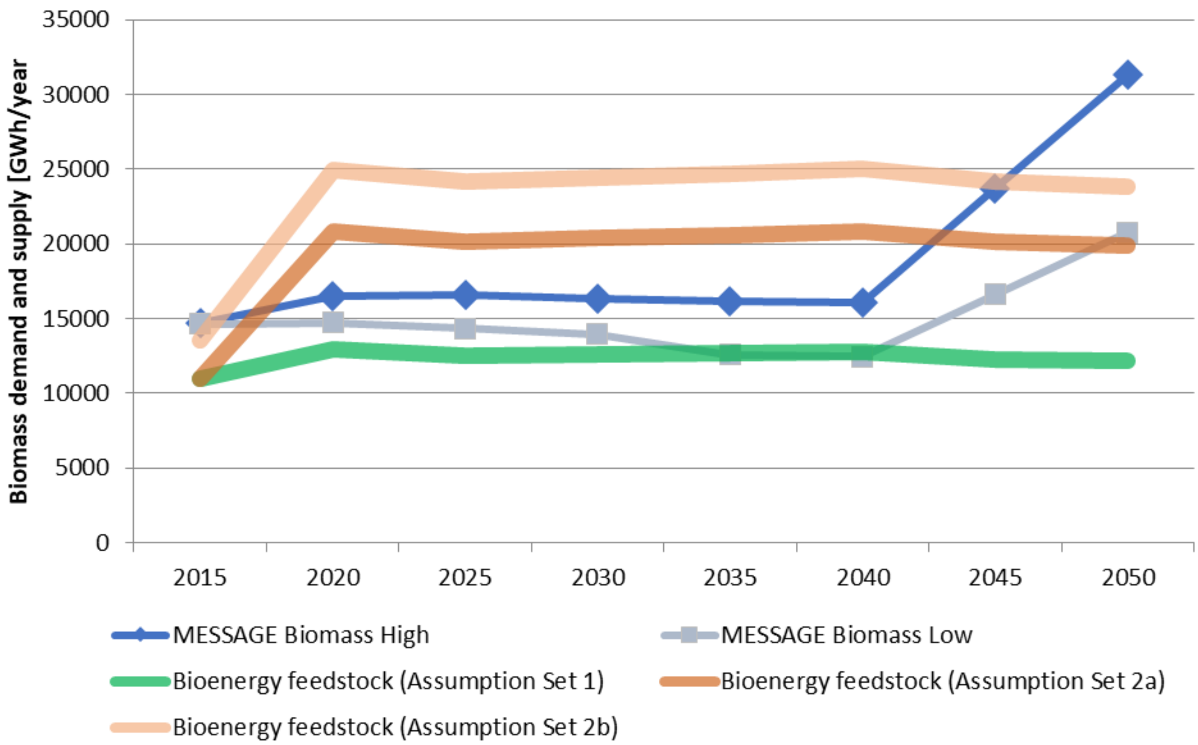

Figure 13. Comparison of the projected use of forest bioenergy feedstock according to the energy pathways, versus the supply according to the LEcA tool estimations. INT forest management strategy.

The trade-offs between the ecosystem services bioenergy feedstock, industrial wood, carbon storage, recreation area and habitat networks are illustrated in Figure 14. The situation in year 2030 was compared to the starting year for the simulations, 2015, applying Assumption Set 2a. Compared to the empirical data for year 2015 [24], the yields increased in both forest management strategies, especially bioenergy feedstock. This can be due to which assumption set was applied, to the absence of transport restrictions, but also to an expected increase of the total stemwood harvest due to the initial state of the forest [25]. When comparing with the forest management strategy INT, the increased harvest levels come with trade-offs such as lower carbon storage, smaller recreation area and smaller habitat networks.

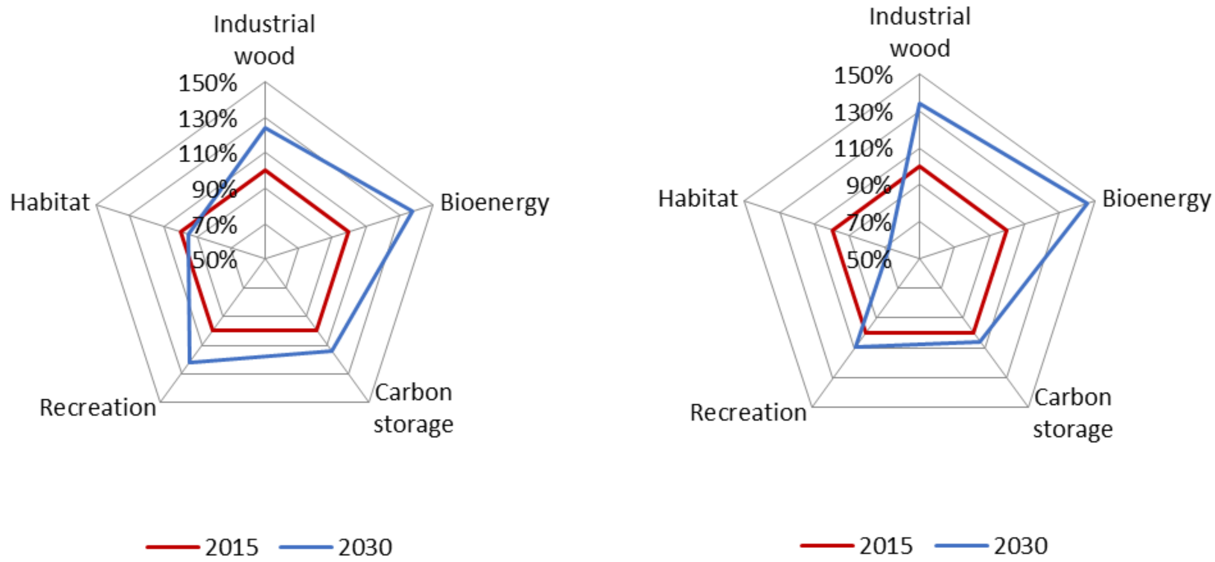

Figure 14. Trade-offs between ecosystem services, applying Assumption Set 2a to the allocation of the total harvest into industrial wood and bioenergy feedstock, for the BAU (left) and INT (right) forest management strategies.

Summing up, the key insights drawn from this case study come from the comparison of the results of the MESSAGE energy system model of Lithuania and the LEcA tool assessing ecosystem services, including the forest management strategies applied. The results indicate that the country-wide energy policies should take into account the local availability of resources:

- The demand for forest bioenergy feedstock obtained through the Biomass High pathway of the MESSAGE model cannot be met without exceeding the resource base;
- The demand for forest bioenergy feedstock obtained through the Biomass Low pathway of the MESSAGE model can be met without exceeding the resource base;
- Assumptions concerning allocation of harvested stemwood to bioenergy feedstock compartments play a major role for the results and should be investigated further;
- Trade-offs between ecosystem services occur between bioenergy feedstock and industrial wood, while when intensifying the forest management also between those on the one hand, and carbon storage, recreation areas and habitat networks on the other hand.

4.2.3.2. Key indicators

The insights pointed out above are synthesised by the following indicators (and related graphical representation):

- Annual production of forest bioenergy feedstock (GWh of Lower Heating Value);
- Annual production of industrial wood (million m^3);
- Annual carbon stock (tonnes);
- Annual area of forest with high recreational value (km^2);
- Annual size of habitat networks for relevant biodiversity components (km^2).

4.2.4. Focus on district heating in Northern Europe (Helsinki, Kaunas and Warsaw) – *EnergyPRO and MESSAGE*

This case study zooms from the EU- and country-wide perspective into the one of cities and municipalities. It aims to add insights on how the transition to a low-carbon energy system and society described so far at the EU and national scale could be technically carried out on the local scale. Specifically, the case study looks at how carbon neutrality could be reached in the District Heating (DH) systems of Helsinki region, Warsaw and Kaunas by 2050.

Potential pathways towards this target were formed and examined based on the plans and objectives of the cities and DH companies and on expert opinions. In addition to emissions, heat production costs were considered since the objective was to find DH development pathways that are sustainable both in terms of CO_2 emissions and energy poverty.

Different pathways were formulated for the three municipalities of Helsinki, Warsaw and Kaunas, as described in below.

Helsinki region (cities of Helsinki, Espoo and Vantaa)

Studied pathways and main assumptions:

- Reference pathway:
    - Planned projects are implemented.
- 2030 pathway:
    - Projects assumed in the reference pathway;
    - Coal and oil replaced by natural gas and wood chips/pellets.
- 2050 pathway:
    - Project assumed in the reference and 2030 pathway;
    - Utilisation of waste heat increased to 20% of heat demand;
    - Geothermal energy in Helsinki (heat output 40 MW);
    - Heat storages included in the system (capacity 1% of the annual heat demand);
    - CCS in gas-fired plants.

Projects planned by the DH companies:

- Espoo
    - Utilisation of excess heat from a hospital (would cover heat demand for around 50 single-family houses);
    - Geothermal heat in Otaniemi district (heat output around 40 MW).
- Vantaa
    - Refurbishment of Martinlaakso 1 CHP plant (earlier fired by oil and gas) so that it would use bio fuels in 2019.
- Helsinki
    - Hanasaari coal-fired CHP plant decommissioned in 2024;
    - New pellet-fired heating plant will be built (DH output 92 MW);

- Pellet systems will be used in Hanasaari and Salmisaari CHP plants (5-7% of coal can be replaced by wood pellets).

Warsaw

Studied pathways and main assumptions

- **Reference pathway:**
  - Planned projects are implemented.
- **2030 pathway:**
  - Projects assumed in the reference pathway;
  - Network losses cut to half;
  - Plants are modernised: in existing plants, efficiency is increased from 75% to 85%. In the new Pruszkow CHP, efficiency is 92%;
  - Biomass use is increased: 15% of total heat capacity use biomass.
- **2050 pathway:**
  - Projects assumed in the reference and 2030 pathways;
  - Coal-fired CHP plants equipped with CCS;
  - Coal-fired HOB replaced by waste CHP;
  - Oil-fired HOB replaced by bio-HOB and natural gas HOB.

Projects planned by the DH companies

- New waste-to-energy facility
  - Electricity output 50 MW, heat output 25 MW.
- Upgrading Zeran CHP plant
  - Coal-fired boilers replaced by natural gas, power output increased to 450 MW.
- New gas-fired block in Pruszkow CHP plant
  - Electricity output 16 MW, heat output 15 MW.
- Zeran and Siekierki CHP plants
  - Measures that allow them to use bio fuels.

Kaunas

- Planned new waste-to-energy CHP plant and gas-fired CHP plant taken into account;
- Two pathways considered:
  - Business as usual, BAU: no emission limitation assumed;
  - Carbon free, C-Free: linear decrease of CO_2 emissions to zero by 2050 is assumed.

4.2.4.1 Main insights

The three case studies briefly described above give indications on the site-specific and more technical aspects related to the implementation of decarsbonisation strategies, guiding towards their practical implementation. Insights on the role of particular technologies and profitability of investments particularly emerge:

- The optimal production strategy for the studied DH system(s) is obtained;

- The heat and electricity production costs are computed, together with the fuel consumption and CO_2 emissions.
- Once the framework is created:
    - The effects of various inputs (such as electricity and fuel prices) can be tested.
    - Pathways assuming different investments in capacities of DH components (heat storage, heat pump etc.) and production units can be analysed and the profitability of various investment decisions can be assessed.

4.2.4.2 Key indicators

The insights are expressed through the following indicators:

- Overall fuel and electricity consumption in each DH system for each scenario (GWh);
- Annual GHG emissions in each district ($MtCO_2$-eq);
- Total heat and electricity production costs (€/MWh);
- Profitable share of efficient co-generation (%);
- Heat production by plant (MW);

Table 6. Annual emissions, heat production costs and shares of heat production in CHP plants, heat only boilers (HOBs) and heat pumps.

Region	Pathway	Annual GHG emissions [$MtCO_2$-eq]	Heat production costs [€/MWh_{heat}][3]	Share of energy production in CHP plants [%]	Share of energy production in HOBs [%]	Share of energy production with heat pumps [%]
Helsinki region	Reference pathway	2.94	50	55	31	14
	2030	0.64	39	29	57	14
	2050	0.27	58	29	39	32
Warsaw	Reference pathway	4.65	66	80	20	

[3] Average variable cost for 1 MWh of produced heat (investment cost are included in the costs in 2030 and 2050 scenarios) in Helsinki and Warsaw cases. Marginal heat production cost in Kaunas DH case.

	2030	2.56	42	83	17	
	2050	1.19	93	82	18	
Kaunas	BAU pathway 2020	0.102	59	18	82	
	2030	0.105	68	40	50	10
	2050	0.087	76	48	24	28
	C-Free pathway 2020	0.101	60	17	83	
	2030	0.082	77	30	50	20
	2050	0	93	7	27	66

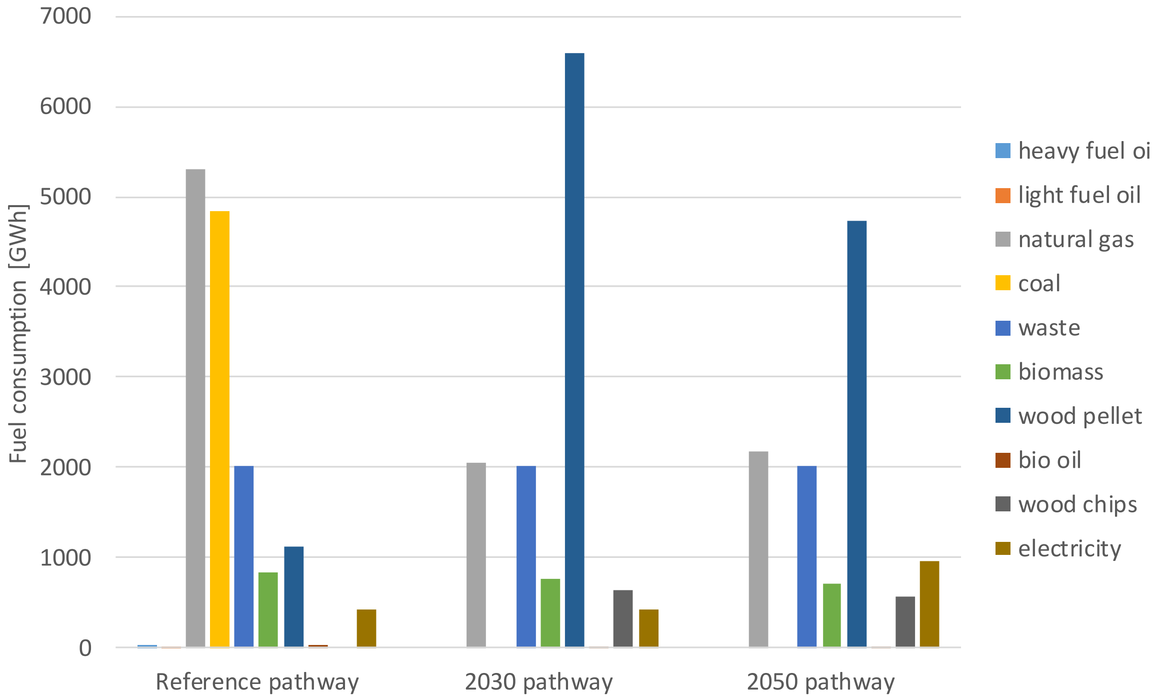

Figure 15. Fuel and electricity consumption in the DH system of Helsinki region in different pathways.

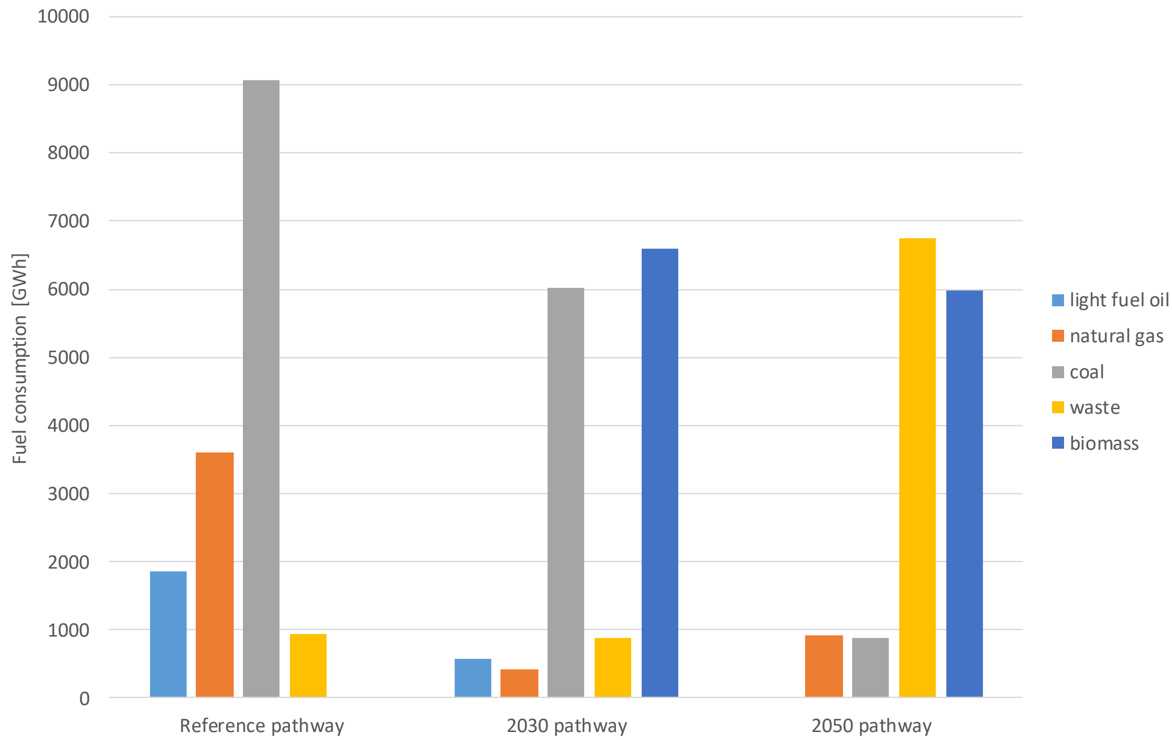

Figure 16. Fuel consumption in Warsaw DH system in different pathways.

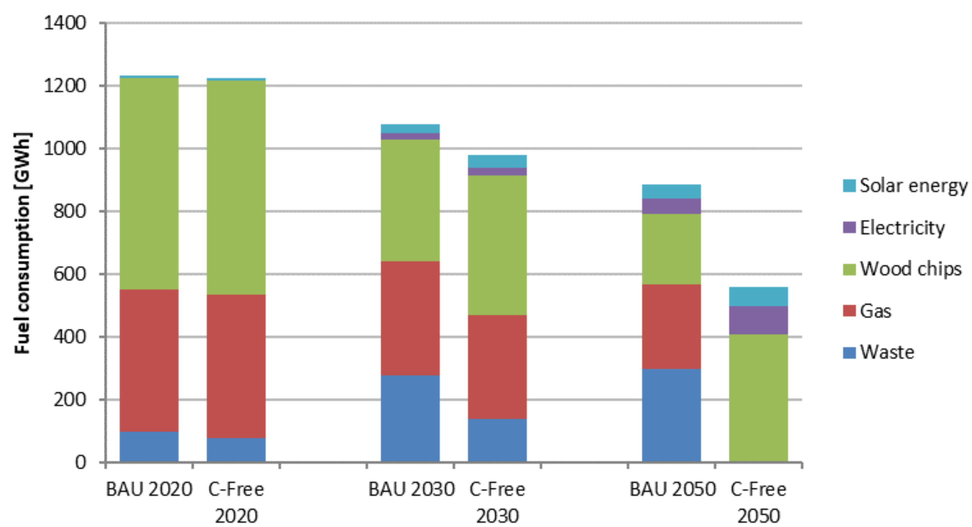

Figure 17. Fuel consumption in Kaunas DH system in different pathways.

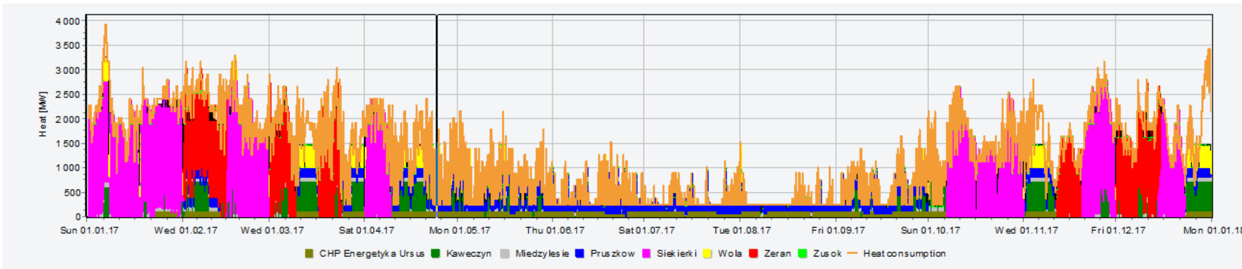

Figure 18. Heat production by plant.

Additionally, a number of other indicators can be extracted from the analysis, but are not graphically shown for brevity:

- Optimal investment decisions and operation scheduling for the entire time period;
- Heat and electricity production by unit;
- Revenues from electricity sales;
- Profitable penetration of heat pumps and heat storages.

5. Lessons learnt

This report described the process under development in REEEM for conducting an integrated impact assessment of EU decarbonisation pathways and present the insights through diagnostic indicators. Although the integrated modelling framework is not yet fully developed and the models loosely linked, a few conclusions can be drawn from the developed methodologies and the first stages of the analysis:

- The first selection of indicators highlights key impacts of the transition to decarbonised energy systems in each of the applications considered;
- Especially, impacts at different scales are unveiled, arguing the necessity of integrating models which carry out analyses at the EU, national and local level.

Thus conceived, the messages conveyed by the indicators are meant to reach out to various stakeholder groups:

- **General audience.** European (and other) citizens of what are the main trends in the energy sectors and how the system could transform in the coming years;
- **European Commission.** The indicators assess the progress towards certain policy objectives related to the EU energy sector and decarbonisation of the economy;
- **Energy modellers and modelling projects.** A comprehensive list of diagnostic indicators, suitable for long-term decarbonisation pathways;
- **Stakeholders.** The current report gives an understanding of how the work in REEEM has progressed up this point;
- **The REEEM partners and modellers.** This report lays the foundations for the analysis of the complete REEEM modelling framework (to be reported in the next Integrated Impact Report due in July 2019).

However, one needs to consider the fact that when different groups of stakeholders and audience look at these insights, they might weigh and even understand the indicators in different ways. Additionally, as mentioned, the modelling framework and the corresponding list of indicators are still incomplete and planned to be extended/refined by end of the project. The final outcomes will be published in the second Integrated Impact Report, due July 2019.

6. Next steps

Based on the above, the next steps required in the activities of the project emerge. All the new advancements and findings will be included in the next REEEM Integrated Impact Report (D1.2b).

- **Improved modelling framework.** The models will re-run following the guidelines of the complete framework (including increased data harmonisation and feedback loops between selected models). This will consolidate the picture of how analyses focusing on specific sectors and spatial scales impact the overall EU energy transition;
- **New pathways.** Besides the Base Pathway, new ones will be formulated and tested at the EU28 level;
- **Secondary indicators.** Indicators that derive their value from the calculation of two or more primary indicators will be included;
- **Comparative indicators.** Indicators that derive their value from the comparison between the base pathway and another (expressed in % terms) will also be included;
- **New indicators and refinement of the short-list.** Further literature review and experience acquired in the next modelling phases may result in the adoption of new indicators as well as in further refinement of the short-list;
- **Link to pathway diagnostic tool.** The full set of indicators will be available and publicly accessible on the - currently under development - REEEM pathway diagnostic tool;
- **Multi-criteria decision analysis (MCDA).** Different weighting factors will be assigned to certain indicators in order to assess the performance of each pathway in different dimensions as well as to compare pathways;
- **Stakeholder workshop.** A second stakeholder workshop will be organized in 2018, aiming at bringing experts together to make suggestions and provide feedback on: further indicators to be adopted, refinement of the short-list and the weighting factors for the MCDA.

References

[1] “SDG INDEX & DASHBOARDS.” [Online]. Available: http://kniknowledgebase.org/wp-content/uploads/2016/04/sdg_index_and_dashboards_compact.pdf. [Accessed: 30-Jan-2018].

[2] *Indicateurs Energetiques Du Developpement Durable Lignes Directrices Et Methodologies.* Intl Atomic Energy Agency, 2008.

[3] E. Kriegler *et al.*, “Diagnostic indicators for integrated assessment models of climate policy,” *Technol. Forecast. Soc. Change*, vol. 90, pp. 45–61, Jan. 2015.

[4] C. Binder, S. Mühlemeier, and R. Wyss, “An Indicator-Based Approach for Analyzing the Resilience of Transitions for Energy Regions. Part I: Theoretical and Conceptual Considerations,” *Energies*, vol. 10, no. 1, p. 36, Jan. 2017.

[5] F. Gralla, D. J. Abson, A. P. Møller, D. J. Lang, and H. von Wehrden, “Energy transitions and national development indicators: A global review of nuclear energy production,” *Renew. Sustain. Energy Rev.*, vol. 70, pp. 1251–1265, Apr. 2017.

[6] C. Rösch, K.-R. Bräutigam, J. Kopfmüller, V. Stelzer, and P. Lichtner, “Indicator system for the sustainability assessment of the German energy system and its transition,” *Energy. Sustain. Soc.*, vol. 7, no. 1, p. 1, Dec. 2017.

[7] European Commission, “PDF ISBN 978-92-79-63468-0 Transforming the European Energy System Through INNOVATION - Integrated SET Plan Progress in 2016,” 2016.

[8] European Commission, “SWD(2017) 32 final Second Report on the State of the Energy Union COMMISSION STAFF WORKING DOCUMENT Monitoring progress towards the Energy Union objectives – key indicators,” 2017.

[9] European Commission, “COM(2016) 860 final COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE, THE COMMITTEE OF THE REGIONS AND THE EUROPEAN INVESTMENT BANK Clean Energy For All Europeans,” 2016.

[10] European Commission, “COM(2011) 112 final COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS A Roadmap for moving to a competitive low carbon economy in 2050,” 2011.

[11] ENTSO-E, “Ten-year network development plan 2016,” Brussels, Belgium, 2016.

[12] P. Capros, A. De Vita, N. Tasios, P. Siskos, and M. Kannavou, “EU Reference Scenario 2016-Energy, transport and GHG emissions Trends to 2050,” Luxemburg, 2016.

[13] European Commission, “The 2015 Ageing Report EUROPEAN ECONOMY 3|2015 Economic and Financial Affairs ISSN 1725-3217 (online) ISSN 0379-0991 (print) Economic and budgetary projections for the 28 EU Member States (2013-2060),” 2015.

[14] JRC, “ETRI 2014 - Energy Technology Reference Indicator projections for 2010-2050 Report,” 2014.

[15] IEA, “Energy Technology Perspectives 2017,” 2017.

[16] European Commission, “White paper on the future of Europe and the way forward,” 2016.

[17] T. Spencer *et al.*, “Tracking sectoral progress in the deep decarbonisation of energy systems in Europe,” *Energy Policy*, vol. 110, pp. 509–517, Nov. 2017.

[18] C. Heaton, “Modelling Low-Carbon Energy System Designs with the ETI ESME Model,” 2014.

[19] F. G. N. Li, S. Pye, and N. Strachan, “Regional winners and losers in future UK energy system transitions,” *Energy Strateg. Rev.*, vol. 13–14, pp. 11–31, Nov. 2016.

[20] S. Pye, N. Sabio, and N. Strachan, “An integrated systematic analysis of uncertainties in UK energy transition pathways,” *Energy Policy*, vol. 87, pp. 673–684, 2015.

[21] S. Pye, W. Usher, and N. Strachan, “The uncertain but critical role of demand reduction in meeting long-term energy decarbonisation targets,” *Energy Policy*, vol. 73, pp. 575–586, 2014.

[22] X. Pang, E. Nordström, H. Böttcher, R. T.-E. Services, and U. 2017, “Trade-offs and synergies among ecosystem services under different forest management scenarios–The LEcA tool,” *Ecosyst. Serv.*, vol. 28, no. A, pp. 67–79, 2017.

[23] G. et. Al., “Lietuvos energetikos sektoriaus plėtros tyrimas. 1 dalis. Techninė ekonomine energetikos sektoriaus plėtros analizė,” 2015.

[24] State Forest Service, *Lithuanian Statistical Yearbook of Forestry 2016*. Kaunas, 2016.

[25] State Forest Survey Service, “Lithuanian State Forest Cadastre,” Kaunas, Lithuania, 2016.

[26] REEEM, “REEEM Technology and Innovation Roadmap - Energy Storage Application,” 2017.

[27] “REEEM Innovation Readiness Level - Energy Storage Technologies,” 2017.

[28] Bloomberg New Energy Finance (BNEF), “Lithium-ion Battery Costs: Squeezed Margins and New Business Models,” 2017.

[29] IRENA, “Electricity Storage and Renewables: Cost and Markets to 2030,” Abu Dhabi.

[30] IRENA, “Battery storage technology improvements and cost reductions to 2030: A Deep Dive,” 2017.

[31] Black & Veatch for NREL, “Cost And Performance Data For Power Generation Technologies,” 2011.

[32] EASE, “European energy storage technology development and application roadmap towards 2030,” (forthcoming), 2017.

[33] Bloomberg New Energy Finance (BNEF), “ ’Energy smart technologies – power storage – research note,” 2011.

[34] B. J. Institution of Electrical Engineers. *et al.*, *IEE proceedings. A, Physical science, measurement and instrumentation, management and education, reviews.*, vol. 127, no. 6. Institution of Electrical Engineers,

1980.

[35] A. Ozarslan, “Large-scale hydrogen energy storage in salt caverns,” *Int. J. Hydrogen Energy*, vol. 37, no. 19, pp. 14265–14277, 2012.

[36] European Commission, “Hydrogen storage in salt caverns as the new way forward,” *2015*. .

[37] UBS, “UBS Evidence Lab Electric Car Teardown – Disruption Ahead?,” 2017.

[38] ABC News, “Battery breakthroughs? Here’s how your devices could be powered in the future,” 2017.

[39] “Lithium-Air Batteries: An Overview.” [Online]. Available: http://large.stanford.edu/courses/2011/ph240/zhong2/. [Accessed: 27-Feb-2018].

Annex A: list of indicators

Below is the full list of indicators that have been identified so far as relevant.

Table 7. List of primary indicators.

Primary indicators (outputs of models)
TIMES/OSeMOSYS/MESSAGE
Final energy consumption by sector
Net electricity consumption by sector
Primary energy consumption (renewables and not)
Capacity deployment of industrial and public power plants and CHP plants by technology and energy carrier
Capacity deployment of storage technologies
Electricity production of industrial and public power plants and CHP plants by technology and energy carrier
Fuel input to industrial and public power plants and CHP plants by technology and fuel
Electricity exchange - net imports
Electricity exchange – capacities
Emissions by emittant and sector
ETS Emissions-Burden sharing
Prices of energy carriers
System costs
Loss of load hours?
Investments in new capacity by technology and energy carrier
MESSAGE
Production of centralised heating by fuel
Production of district heating by fuel
Installed capacity of district heating by fuel
Electricity production by municipality
Expenditures of primary energy resources
Investments in heat generation by technology and energy carrier

EnergyPRO
Fuel and electricity consumption by DH plan
Annual GHG emissions from by DH plan
Heat production by plant
Profitable share of efficient co-generation
System and production costs
Prices of energy carriers
CO2 prices
Operation of power and heat plants, storage, heat pump etc.
Heating demand
Energy technology mix
NEWAGE
GDP by country by steps of 5 years
GDP growth by country or region by steps of 5 years
Employment development
Competitiveness – RCA
Competitiveness – RWS
Emissions
ESME
Timing and level of deployment across a range of technologies;
Emission reduction contribution by sectors;
Factors impacting deployment of technologies
EMC2
Spatially allocated GHG emissions (kt CO2 equivalent) by electricity and heat production processes
Spatially allocated emissions of: CO, PM2.5, PM10, SO2/Sox, NO2/NOx, NVMOC by heat and electricity production processes
ECOSENSE
Spatially allocated health impacts by heat and electricity production in DALYs
Spatially allocated health damage costs by heat and electricity production in €
Biodiversity losses (potentially disappeared fractions of species) due to air pollution

External cost (avoidance cost) for biodiversity losses due to air pollution
Loss in yield?
T5.1
Spatially allocated change in heating and cooling demand by 2030 and 2050 (degrees-day and %)
CORDEX
Water availability
LEcA Tool
Annual industrial wood waste biomass production
Annual firewood production
Annual production of residues from harvest
Habitat
Bioenergy
Recreation
Carbon stock
LCA
Climate change
Freshwater eutrophication
Marine eutrophication
Freshwater ecotoxicity
Land use
Ozone depletion
Particulate matter formation
Impact of ionizing radiation on human health
Photochemical ozone formation
Impact of acidification on terrestrial and freshwater ecosystems
Terrestrial eutrophication
Terrestial ecotoxicity
Marine ecotoxicity
Agricultural land occupation
Urban land occupation
Natural land transformation
Water depletion

Metal resource depletion
Fossil resource depletion
Single substance emissions and resource consumption over entire life cycle and, for some substances, a differentiation between emission compartments (to air, water, soil)

Table 8. List of secondary indicators.

Secondary indicators (collection from literature)
CO2 emissions reductions by country compared to 1990
LCOE
Primary energy savings compared to baseline projection (% change)
Efficiency of thermal electricity production (%)
CCS indicator (% of electricity from CCS)
Fuel Inputs for Thermal Power Generation
Non fossil fuels in electricity generation (%)
Combined heat and power generation
Gross electricity generation from CHP plants by energy source, in TWh
Efficiency of energy conversion and distribution
ETS emissions and carbon prices over time
Share of renewable energy sources in final energy consumption (by technology)
Share of renewable energy sources in electricity consumption
Share of renewable energy in fuel consumption of transport
Energy intensity of of the economy (energy consumption/GDP)
Energy demand in transport (ktoe)
Intensity of goods transport or Transport Performance / FEC Freight Transport Pkm / GJ
Intensity of passenger transport or Transport Performance / FEC Passenger Transport Pkm / GJ
Energy consumption by transport mode
Emissions of nitrogen oxides (NO_x) from transport
Emissions of particulate matter from transport
Average CO_2 emissions per km from new passenger cars
Electricity consumption of households
Carbon intensity over energy intensity
Soil area where acidification exceeds critical load

Greenhouse gas emissions intensity of energy consumption
Forest area as a proportion of total land area
Proportion of important sites for terrestrial and freshwater biodiversity that are covered by protected areas, by ecosystem type
Species diversity and landscape quality

Annex B: energy storage technology inputs

Introduction: An overview on energy storage technologies

In the framework of the REEEM project, Deliverable 2.1 is dedicated to the roadmap on “energy storage applications” [26]. In the roadmap, different potential applications and services of energy storage technologies have been identified. For each application, the technical requirements are listed and suitable storage technologies are identified. Deliverable 2.2 of REEEM was dedicated to the assessment of the “Innovation Readiness Level” of storage technologies. The assessments were conducted on 5 storage technologies namely, li-ion, flow batteries, supercapacitors, CAES and hydrogen[27].

Both reports underline that energy storage technologies have a great potential to contribute to the European system. Energy storage technologies can perform different services and can contribute to different parts of the energy system including generation, network and demand. These technologies allow decoupling energy production and consumption and hence contribute to enhancing the reliability, flexibility and security of the European energy industry. Their role in the future European energy industry could become even more significant, given the ambitious targets to increase the share of renewable energy.

In order to understand the potential role of storage technologies in the future low carbon energy economy, in REEEM a number of energy storage technologies are modelled. While different energy storage technologies are introduced in the market (see Figure 19), in our study we suffice to the analysis of the storage technologies which are expected to play a significant role in the future energy industry. These include: Pumped Hydro Storage (PHS), Lithium ion(li-ion) batteries, lead acid, Compressed Air Energy Storage (CAES), Sodium Sulphur (NaS) batteries, Vanadium flow redox batteries (VFRB), Hydrogen cavern and Lithium air.

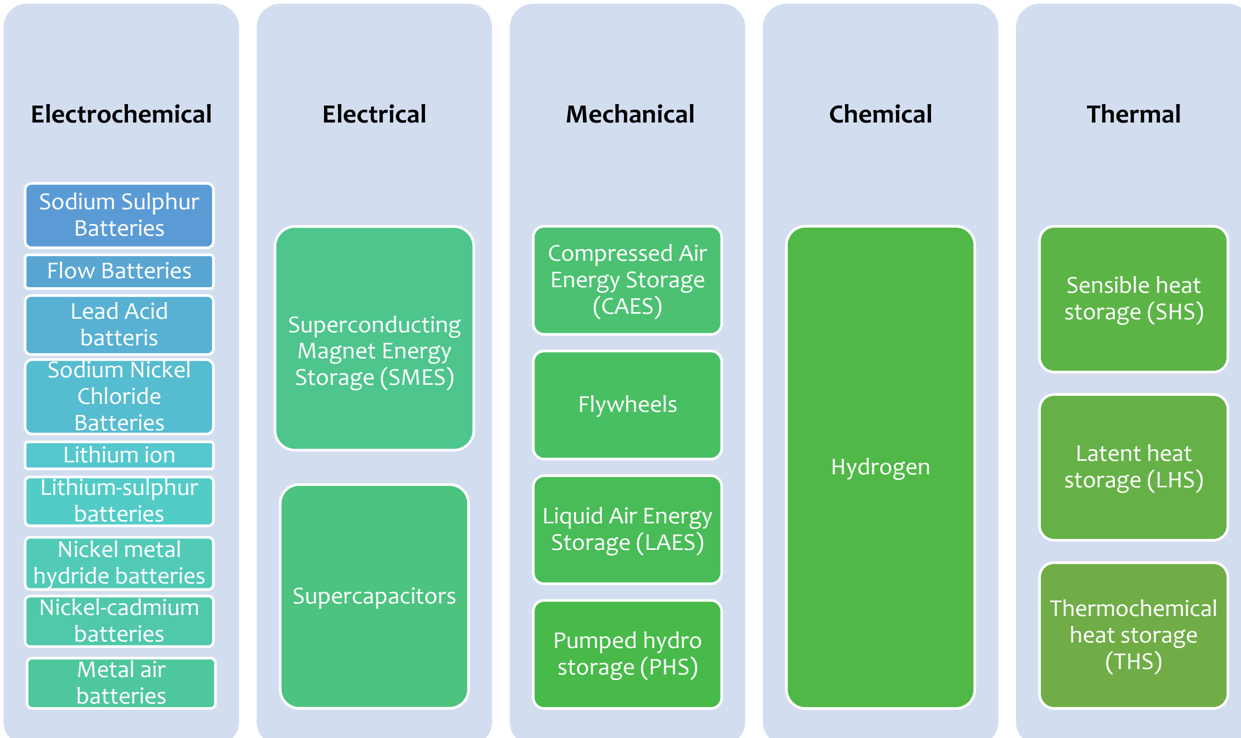

Figure 19. An overview of energy storage technologies.

In this report, the REEEM roadmap on energy storage application has been used as a reference to understand the role of storage technologies and select assumptions for their techno-economic characteristics in the future energy storage industry. Note that due to the fast development of the energy storage market, it is difficult to make concrete predictions on these techno-economic characteristics. To illustrate, the price of li-ion batteries has dropped more than 80% in the past 6 years [28], further than any made predictions.

In order to have a more reliable prediction, all the data obtained for this report is consolidated with several experts in the network of InnoEnergy. The projections are directly used in the REEEM modelling framework as numerical assumptions on the pathways toward a low-carbon EU society.

Methodology: Evaluation of Techno-economic data

In order to study the impact of technological innovation in the transition pathways toward a low carbon economy, the *first* step was to select energy storage technologies with high potential to play a role in the future energy industry [29]. This selection was after consolidated with InnoEnergy experts and based on storage technology's technical characteristics, performance, price or availability. Consequently, eight storage technologies and two electric vehicle types were selected for the techno-economic evaluation.

The selected storage technologies include: Pumped Hydro Storage (PHS), Lithium ion(li-ion) batteries, lead acid, Compressed Air Energy Storage (CAES), Sodium Sulphur (NaS) batteries, Vanadium flow redox batteries (VFRB), hydrogen cavern and Lithium air. Initially two additional technologies, flywheel and supercapacitors, were also considered for evaluation, but they were eliminated from the analysis because of their high cost We also studied two groups of electric vehicles: Battery Electric Vehicles (BEV) and hydrogen vehicles powered by fuel cells (FCV).

In the *second* step, we considered and studied different methodologies to estimate and select technological innovation data for the REEEM models (i.e., techno-economic data for the storage technologies under study). For choosing the most proper methodology, a number of factors were considered, namely availability of market data, maturity and development status of the selected technologies.

As one possible methodology, we considered the integration of the Delphos tool, developed by InnoEnergy, in REEEM. Delphos studies the impact of innovation on the future cost of energy technologies[4]. However, the implementation of Delphos for energy storage technologies was not feasible, as the technologies have limited available historical data. We will aim at the integration of Delphos in REEEM for the analysis of the next REEEM energy technology group (i.e., renewable energy).

We carried out a literature and market study to assess the impact of innovation on the cost of energy storage technologies and select techno-economic data for the purpose of REEEM. Several sources were reviewed, but only part of the projections was selected that comply with the following criteria:

- Consistency with the view of the future of the EU and the global perspectives expressed in the REEEM pathways;
- Consistency with the market outlooks for each application presented in the Technology and Innovation Roadmaps and the Innovation Readiness Level assessment of each technology;
- Judgement of InnoEnergy experts, with an overview of the status of deployment and market potential of each technology;

Among all the studied sources, two were primarily used: Energy Technology Reference Indicators (ETRI), published by JRC in 2014 [14], and the IRENA report Electricity storage and renewable energy: cost projection till 2030, published in 2017 [30], [29][5]. The data presented in the JRC report is based on several assumptions built on the work of other researchers, in particular [31]. All the numbers have been reviewed and adjusted by InnoEnergy experts[6].

In addition, 2 workshops were carried out and hosted by InnoEnergy as platforms to collect the views of industrial players on the future of the energy storage technologies in Europe and thus revise and consolidate the data. The first workshop was held on 9th May 2017 in Brussels, presenting and discussing the REEEM energy storage roadmap. The second workshop was on held October 13th 2017, hosted by InnoEnergy and European Political

[4] Read more on http://www.innoenergy.com/delphos/

[5] The data was first presented in an workshop in Düsseldorf by IRENA [5] and were published after some modification in an official report [6].

[6] We encourage the readership to refer to JRC report [5] in order to better understand the assumptions behind the numbers and references used.

Strategy Centre (EPSC), exploring how Europe could be a world leader in the battery industry. Finally, the choices were reviewed and finalised by InnoEnergy experts.

The types of techno-economic data retrieved from the reviewed sources are listed in Table 9. The data were fed as inputs to TIMES PanEU. Where other models in REEEM need the same inputs, they source them directly from TIMES PanEU. The baseline year for all the energy storage data is set to 2015[7] and unless noted otherwise we assume that FOM and VOM remain constant through the years.

Table 9. Input data format for technology innovation in TIMES PanEu.

	Unit	2015	2020	2030	2040	2050
Roundtrip efficiency	%					
Technical lifetime	*years*					
CAPEX $_{ref.}$ (Storage related)	*€/kWe*					
CAPEX (Energy related)	*€/kWh*					
*FOM**	*% CAPEX $_{ref.}$*					
*VOM***	*€/MWh*					

**FOM=Fixed operation and management cost. This parameter is assumed to be a fixed percentage of CAPEX (storage related).*
***VOM= Variable Operation and Management cost*

A base deployment pathway: analysis and results

The projections presented in the following sub-sections represent what the literature sources and experts judged to be likely development trends for the selected technologies, assuming no heavy disruptions occur in the market. Thus, such projections are in line with the REEEM Base Pathway, described earlier in this Deliverable, and they were fed as modelling inputs for such case.

1. Pumped Hydro Storage

Pumped Hydro Storage (PHS) is a mature and exploited technology in Europe. The investment cost is site-specific, due to different civil work and site requirements.

In REEEM, the techno-economic data for PHS is taken from [26]. CAPEX data is taken from the reference scenario, which considers the average price of the technology in different European sites. Given the technology maturity, changes in the technology price in the future are considered unlikely.

[7] Note that when the reference data was available only for a year between 2010-2015, we entered that data in TIMES PanEU as an input for 2015.

In TIMES PanEU, two types of PHS technologies have been modelled. Table 10 and Table 11 below present the data employed for the two of them: 1) PHS based on one existing reservoir and including one new reservoir, and 2) PHS based on two existing reservoirs.

Table 10. Techno-economic data for PHS based on one existing reservoir and including one new reservoir[8,9] .

	Unit	2015	2020	2030	2040	2050
Roundtrip efficiency	%	80	82	85	88	90
Technical lifetime	years	60	60	60	60	60
$CAPEX_{ref.}$ (Storage related)	€/kWe	1500	1500	1500	1500	1500
CAPEX (Energy related)	€/kWh	16	16	16	16	16
FOM	% $CAPEX_{ref.}$	1.5	1.5	1.5	1.5	1.5
VOM	€/MWh	0	0	0	0	0

Table 11. Techno-economic data for PHS with two existing reservoirs.

	Unit	2015	2020	2030	2040	2050
Roundtrip efficiency	%	80	82	85	88	90
Technical lifetime	years	60	60	60	60	60
$CAPEX_{ref.}$ (Storage related)	€/kWe	650	650	650	650	650
CAPEX (Energy related)	€/kWh	16	16	16	16	16
FOM	% $CAPEX_{ref.}$	1.5	1.5	1.5	1.5	1.5
VOM	€/MWh	0	0	0	0	0

2. Lead acid batteries

Lead acid batteries are among the first forms of rechargeable battery technologies in the world. Lead acid batteries have been installed in different parts of the energy system, including grid applications or uninterruptable power supply (UPS) systems, among others.

Lead acid batteries have technical specifications, such as low energy density and limited number of cycle, which make them suitable particularly for bulk storage applications. Hence, in TIMES PanEU lead acid batteries were considered only for such use.

Note that TIMES PanEU does not take number of cycles as an input. This could be problematic for the analysis of the model, as it could consider lead acid batteries for services requiring frequent cycles during the batteries' potential lifetime. Currently, the technical lifetime of lead acid batteries for applications requiring about *one*

[8] As mentioned, when the reference data was available only for a year between 2010-2015, we entered that data in TIMES PanEU as an input for 2015.

[9] The Euro prices in JRC report [5] are for 2013, but here are reported for 2015. This means the Euro price difference between these two years has been neglected for all the studied technologies, as the model decisions are made for the years after 2015 and the price difference is marginal.

cycle per month is 5-10 years, but it is shorter for applications with frequent cycles. To address this gap, in the models the technical lifetime of lead acid batteries is adjusted to represent the utilisation of lead acid batteries for services requiring frequent cycles. Technical data for other parameters of this technology is collected from [14] and [30], and listed in Table 12.

Table 12. Techno-economic data for lead Acid battery for bulk storage applications.

	Unit	2015	2020	2030	2040	2050
Roundtrip efficiency	%	80	83	85.5	88	90
Technical lifetime	years	1	1	1	2	2
CAPEX $_{ref.}$ (Storage related)	€/kWe	410	390	370	350	330
CAPEX (Energy related)	€/kWh	80	42	38	32	30
FOM	% CAPEX $_{ref.}$	1.4	1.4	1.4	1.4	1.4
VOM	€/MWh	0.8	0.8	0.8	0.8	0.8

3. Li-ion batteries

Li-ion batteries are relatively new in the market, but have shown a high potential to play a role in the future energy industry given their decreasing cost, remarkable energy density, durability and efficiency [32]. The price of li-ions batteries has dropped from about 1000 to 250 €/kWh between 2010 and 2015 [28] and according to Bloomberg it is expected to be below 200 by 2025 [33]. These batteries are widely used in portable devices and they are the primary option for electric vehicles industry and residential renewable energy integration.

Li-ion batteries are suitable for different applications, including grid-scale or behind the meter and mobility. Currently, the cost of these batteries is different depending on the application. Hence, in REEEM, different price projections are considered for the two main applications: grid connected and behind-the-meter (residential use). The data for the grid-scale application of li-ion batteries is taken from [30] (Table 13). The price for behind-the-meter applications is calculated as a percentage of their price for grid-scale applications (Table 14):

- In the Base Pathway, it is assumed that the price of the batteries for residential purposes is 100% higher than the one for grid-scale application. This percentage is assumed to drop to 70% in 2020, 20% in 2030 and 0% in 2040 and 2050.

The CAPEX (energy related) as well as VOM and FOM are assumed to be similar for both applications.

Table 13. Techno-economic data for li-ion applied for the grid-scale application.

	Unit	2015	2020	2030	2040	2050
Roundtrip efficiency	%	90	92	93	95	97
Technical lifetime	years	10	13	18	20	25
CAPEX $_{ref.}$ (Storage related)	€/kWe	490	170	140	120	100
CAPEX (Energy related)	€/kWh	752	255	205	150	125
FOM	% CAPEX $_{ref.}$	1.4	1.4	1.4	1.4	1.4
VOM	€/MWh	2.6	2.6	2.6	2.6	2.6

Table 14. Techno-economic data for li-ion applied for behind-the-meter application.

	Unit	2015	2020	2030	2040	2050
Roundtrip efficiency	%	90	92	93	95	97
Technical lifetime	years	10	13	18	20	25
$CAPEX_{ref.}$ (Storage related)	€/kWe	980	289	168	120	100
CAPEX (Energy related)	€/kWh	752	255	205	150	125
FOM	% $CAPEX_{ref.}$	1.4	1.4	1.4	1.4	1.4
VOM	€/MWh	2.6	2.6	2.6	2.6	2.6

4. Sodium Sulphur (NaS) Batteries

Sodium based batteries, particularly NaS batteries, are among the promising storage technologies for the future energy industry. NaS batteries are in the development and demonstration phase and installed in large scale for services such as arbitrage, integration of renewables and frequency control. Currently, in the market there are only a few operating NaS batteries and that partly explains the high technology cost. Due to the limited penetration of these batteries, the cost projections are limited and uncertain. Hence, the techno-economic data could change fast with a larger application of this technology in the market. These data for NaS batteries is taken from [14] and [30] and presented in Table 15.

Table 15. Techno-economic data for NaS energy storage for energy system applications

	Unit	2015	2020	2030	2040	2050
Roundtrip efficiency	%	80	81	85	87	90
Technical lifetime	years	10	18.8	21.4	22	24
$CAPEX_{ref.}$ (Storage related)	€/kWe	1000	950	930	890	840
CAPEX (Energy related)	€/kWh	350	332	331	313	294
FOM	% $CAPEX_{ref.}$	1.5	1.5	1.5	1.5	1.5
VOM	€/MWh	2	2	2	2	2

5. Flow batteries – Vanadium Redox Flow Battery (VRFB)

Flow batteries have entered the energy industry and can supply different services to the system, in particular for the integration of renewable energy. The batteries present promising technical characteristics such as short response time, long lifetime and little need for maintenance and high efficiency, but suffer from low energy density and technical complexity. VRFB is suited for different services such as load levelling and integration of renewable power.

The potential role of VRFB batteries in the EU energy system was studied using TIMES PanEU. The data for this battery is taken from [14] and [30] and presented in Table 16.

Table 16. Techno-economic data for vanadium Redox flow energy storage for power system applications.

	Unit	2015	2020	2030	2040	2050
Roundtrip efficiency	%	70	72	78	80	80
Technical lifetime	years	12	13	19	20	25

CAPEX ref. (Storage related)	€/kWe	1240	810	730	310	310
CAPEX (Energy related)	€/kWh	405	109	861	104	104
FOM	% CAPEX ref.	2	2	2	2	2
VOM	€/MWh	2	2	2	2	2

6. Compressed Air Energy Storage (CAES)

CAES is suitable for large scale applications. The technology requires to be installed in locations with particular geological formations (salt, hard rock and porous rock or aquifer). Currently, in Europe there is only one installed diabatic CAES plant, in Huntorf, Germany. It dates back to 1978 [34] and has a capacity of 290MW. The main issues associated with CAES are its low efficiency and the site requirements. R&D efforts on CAES are going on, in order to improve the technology's technical features, specifically its efficiency. In the REEEM modelling framework, two types of CAES are modelled: 1) diabatic CAES, in which air is pressurised and heated by burning fuel and next this heat is expanded in the gas turbine to generate electricity. Data for this type of CAES is collected from [14] and illustrated in Table 17; 2) Adiabatic CAES, in which improvements have been made to use the thermal energy generated during the compression phase, by storing the heat in a thermal storage centre. While this process increases the technology capital cost (Table 18), it enhances the technology efficiency by 70 %. The data for adiabatic CAES is collected from [27] We assumed that the FOM and VOM remain constant through the years and are similar for both types of CAES technology.

Table 17. Diabatic underground compressed air storage (CAES) for large scale energy storage.

	Unit	2015	2020	2030	2040	2050
Roundtrip efficiency	%	40	40	40	40	40
Technical lifetime	years	40	55	55	55	55
CAPEX ref. (Storage related)	€/kWe	600	600	530	510	450
CAPEX (Energy related)	€/kWh	35	35	31	29	26
FOM	% CAPEX ref.	1.3	1.3	1.3	1.3	1.3
VOM	€/MWh	1.2	1.2	1.2	1.2	1.2

Table 18. Techno-economic data for Adiabatic CAES for large scale applications.

	Unit	2015	2020	2030	2040	2050
Roundtrip efficiency	%	60	64	68	70	72
Technical lifetime	years	50	50	50	50	50
CAPEX ref. (Storage related)	€/kWe	850	702	623	550	455
CAPEX (Energy related)	€/kWh	47	43	40	35	33
FOM	% CAPEX ref.	1.3	1.3	1.3	1.3	1.3
VOM	€/MWh	1.2	1.2	1.2	1.2	1.2

7. Hydrogen - Cavern

Large scale energy storage methods are necessary to meet the peak demand and facilitate integration of intermittent renewable source into the energy system. Traditionally PHS was used to meet grid storage requirements. Hydrogen Caverns could be an alternative for traditional PHS [35]. The potential role of hydrogen caverns in the future energy system has been acknowledged [36]. For example, in the UK converting power from stored hydrogen deep underground is identified as a method to meet future UK's peak demand. In fact, one cavern could have the capacity to meet the demand of a single UK city. There are already several caverns available in the UK (more than 30), which are used to store oil or gas.

Note that in this report the data for hydrogen caverns is collected with a different approach than the other technologies presented in this annex. For this technology we employ the data already available in TIMES PanEU. These are illustrated in Table 19. According to it, the techno-economic data will remain constant throughout the years and there is no significant innovation expected for this technology.

Table 19. Techno-economic data for Hydrogen Cavern storage technology.

	Unit	*2015*	*2020*	*2030*	*2040*	*2050*
Roundtrip efficiency	*%*	98	98	98	98	98
Technical lifetime	*Years*	30	30	30	30	30
CAPEX ref. (Storage related)	*€/kWe*	560	560	560	560	560
CAPEX (Energy related)	*€/GJ*	64.815	64.815	64.815	64.815	64.815
FOM	*.(€/GJ*	185.185	185.185	185.185	185.185	185.185
VOM	*€/GJ*	4.63	4.63	4.63	4.63	4.63

8. Electric Mobility

As has been explained in the REEEM roadmap on energy storage applications [26], different types of energy storage technologies have been utilised in the electric mobility. In REEEM we study the contribution of different types of electric vehicles to the transportation industry, namely Electric Vehicles (EV) powered by batteries, hydrogen fuel cell vehicles (FCV) and Hybrid Electric vehicles (HEV).

Table 20 and 21 illustrate the average price of Internal Combustion Engines (ICE), EVs, FCV and HEV from 2015 to 2050.

In order to make realistic cost projections, we incorporated a number of assumptions in different pathways. The assumptions are partly taken from [37], partly suggested by InnoEnergy experts and partly origin from TIMES PanEU. The more aggressive or promising assumptions were applied in the Storage Innovation pathway. The techno-economic characteristics for different types of electric mobility are suggested by the University of Stuttgart, partner of REEEM (Table 20 and Table 21). The assumptions are listed below:

- The cost of all types of vehicles will decrease as their sale number increases;

- It is assumed that there will not be any technology innovation related to ICE cars to reduce the cost. However, the different types of applications will have to comply with the certain environmental requirements. Therefore, it is foreseen that the cost will slightly increase through the years till 2050;
- EVs are 2 times more expensive than ICE cars, but this rate decreases gradually and will be equal to ICE car in 2050 (in the Storage Innovation pathway);
- EVs will account for 30% of the total car sales in Europe by 2030 and 35% by 2050 (equal to 6 million Unit), as shown in Figure 20. EV share by region - % of total car sale (source: *[37]*). [37] (in the Storage Innovation pathway);
- The cost of both BEVs and FCVs will decrease until 2030 and 2040, respectively, and will remain constant afterward. This is because, although the price of batteries or hydrogen fuel cells is expected to be lower, the vehicles facilities and equipment will improve and increase the total cost of vehicles;
- Even though different types of FCVs, EVs and HEVs are modelled in TIMES PanEU, the prices in the table refer to the average prices.

Table 20. Average cost of battery and hydrogen electric vehicles - Base Pathway & High Renewables pathway.

E-mobility	Unit	2015	2020	2030	2040	2050
ICE*	Average vehicle price €	43700	44300	45500	45500	45500
EV**	Average vehicle price €	72350	53900	50000	50000	50000
FCV***	Average vehicle price, €	91660	78800	53000	53000	53000
HEV****	Average vehicle price, €	56000	54000	52000	51000	51000

*Internal Combustion Engine | **Electric Vehicle | ***Hydrogen Fuel Cell Vehicle | ****Hybrid Electric Vehicle

Table 21. Average cost of battery and hydrogen electric vehicles – Storage Innovation pathway.

E-mobility	Unit	2015	2020	2030	2040	2050
ICE*	Average vehicle price €	43700	44300	45500	45500	45500
EV**	Average vehicle price €	72350	53900	45500	45500	45500
FCV***	Average vehicle price, €	91600	78800	53000	53000	53000
HEV****	Average vehicle price, €	56000	54000	52000	51000	51000

*Internal Combustion Engine | **Electric Vehicle | ***Hydrogen Fuel Cell Vehicle | ****Hybrid Electric Vehicle

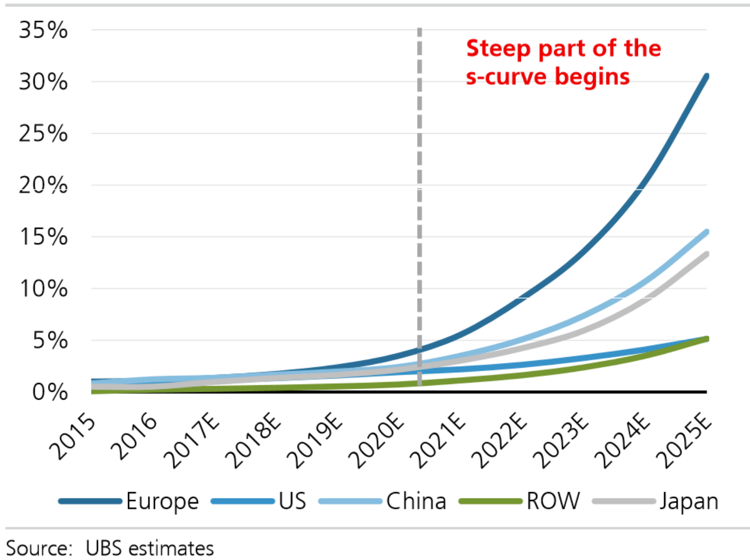

Figure 20. EV share by region - % of total car sale (source: [37]*).*

A breakthrough pathway: analysis and results

Large R&D investments are currently made in the battery industry by governments, industries and universities. The research efforts target both commercialised and developing storage technologies and aim at improving their technical characteristics such as storage capacity, efficiency and lifetime, while reducing cost.

Among the developing technologies, lithium Air (li-air) batteries are often acknowledged among the most promising solutions for the future energy industry. This type of battery can theoretically store 40 times more energy than li-ion batteries in the same weight [38]. However, there are still several issues associated with li-air batteries, such as their limited power density and efficiency, or chemical reactions that constrain the batteries' lifetime and performance [39]. Accordingly, despite their promising technical specifications, currently there are doubts about the feasibility and development process of li-air batteries. Yet, optimistic scenarios consider li-air battery a technology that will create a breakthrough in the future energy industry. Besides, research and innovation on other types of energy storage technologies are going on. This means that there is a chance that another type of storage technology reaches the techno-economic potential expected of li-air batteries [38].

In REEEM, we considered the potential development and emergence of li-air batteries in the energy industry as a breakthrough pathway, deviating from the Base Pathway described above. The primary objective of this REEEM breakthrough pathway is to study how the energy market would react, if a new energy storage technology (e.g., li-air) with competitive techno-economic performance entered the energy market. This break-through pathway is presented earlier in this Deliverable and its main results are explained.

For this breakthrough case, we assumed that li-air batteries will enter the market on a commercial level around 2030 and would need another 10 years of investment and development to reach their potential technical performance and become cost competitive. While different projections have been made on the batteries cost, in REEEM we assume that li-air batteries' cost would be as low as 1/3 the one of li-ion batteries, while their CAPEX (energy related), FOM and VOM would be the same. These assumptions are based on online sources (e.g., [38]) and are revised by InnoEnergy experts. Table 22. Techno-economic data lithium air battery storage. illustrates the techno-economic data assumed for li-air batteries in this breakthrough pathway.

Table 22. Techno-economic data lithium air battery storage.

	Unit	2015	2020	2030	2040	2050
Roundtrip efficiency	%	20	40	80	90	92
Technical lifetime	years	1	1	15	20	25
CAPEX $_{ref.}$ (Storage related)	€$_{2015}$/kWe	5000	1000	400	50	30
CAPEX (Energy related)	€$_{2015}$/kWh	752	255	205	150	125
FOM	% CAPEX $_{ref.}$	1.4	1.4	1.4	1.4	1.4
VOM	€$_{2015}$/MWh	2.6	2.6	2.6	2.6	2.6

Annex C: Specific GHG reduction targets

Table 23. Targets for emission reduction.

	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	-9%	-30%	-75%

Annex D: Targets for share of renewable energy in gross final energy consumption

Table 24. Targets for renewable energy share.

	2020	2030	2040	2050
France	23%	39%	62%	85%
Portugal	31%	45%	65%	85%
Spain	20%	37%	61%	85%
Italy	17%	35%	60%	85%
United Kingdom	15%	33%	59%	85%
Austria	34%	47%	66%	85%
Germany	18%	30%	48%	65%
Netherlands	14%	27%	46%	65%
Belgium	13%	26%	46%	65%
Luxembourg	11%	25%	45%	65%
Denmark	30%	44%	65%	85%
Sweden	49%	58%	72%	85%
Finland	38%	50%	68%	85%
Ireland	16%	34%	59%	85%
Poland	15%	23%	34%	45%
Czech Republic	13%	21%	33%	45%
Bulgaria	16%	31%	53%	75%
Romania	24%	37%	56%	75%
Estonia	25%	38%	56%	75%
Latvia	40%	49%	62%	75%
Lithuania	23%	36%	56%	75%
Croatia	20%	34%	55%	75%
Hungary	13%	29%	52%	75%
Greece	18%	33%	54%	75%
Slovakia	14%	30%	52%	75%
Slovenia	25%	38%	56%	75%
Cyprus	13%	29%	52%	75%
Malta	10%	27%	51%	75%
EU-28	20%	35%	55%	75%