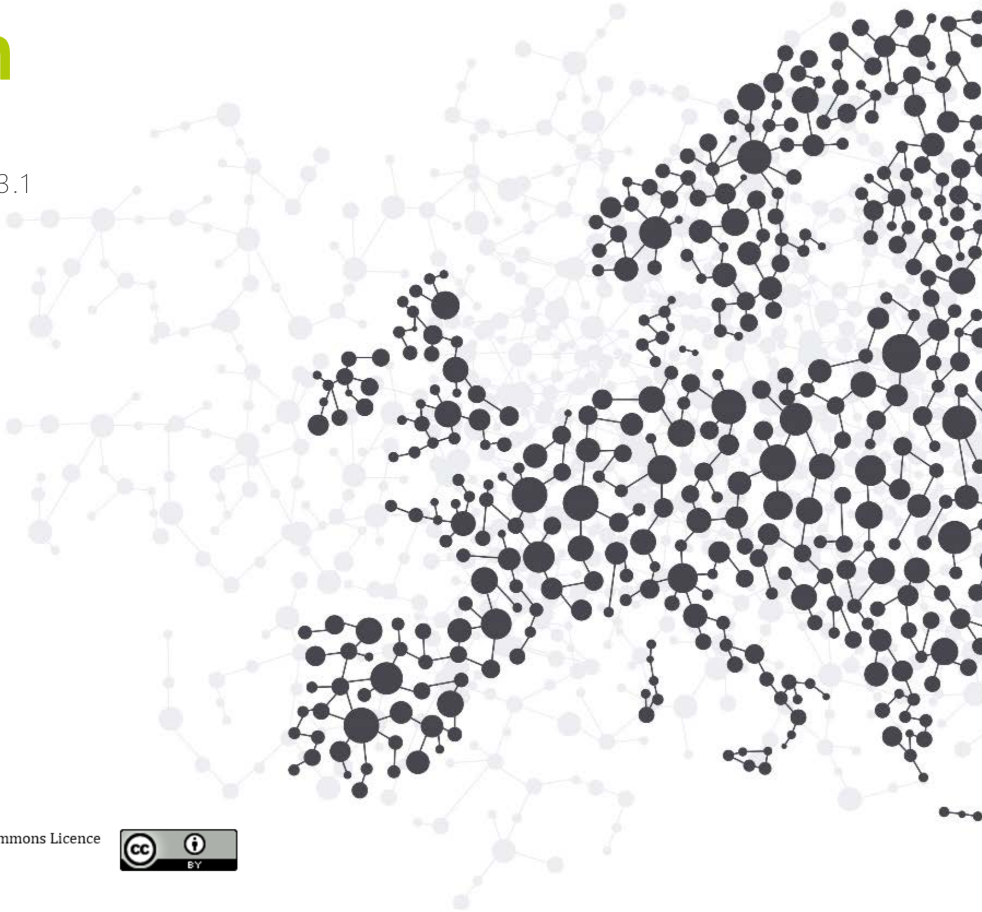
Quantitative Scenarios for Low Carbon Futures of the pan-European Energy System

DELIVERABLE NO. 3.1



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List of Acronyms

CCS	Carbon Capture and Storage
CO_2	Carbondioxide
DAC	Direct Air Capture
EAF	Electric Arc Furnance
GDP	Gross Domestic Product
GHG	Greenhouse Gas
H_2	Hydrogen
IAM	Integrated Assessment Model
IAMC	Integrated Assessment Modeling Consortium
IPCC	Intergovernmental Panel on Climate Change
MBtu	Thousand British thermal units
pkm	Passenger Kilometer
SSPs	Shared Socioeconomic Pathways
tkm	Tonne Kilometer
WEO	World Energy Outlook
WP	Work Package

1. Introduction

1.1 Global/European policy-related background

The ambition of the openENTRANCE project is to develop, use and disseminate an open, transparent and integrated modeling platform for assessing low-carbon transition pathways of the European energy and transport system. This fully open platform will be populated with a suite of modeling tools and datasets selected to cover the multiple dimensions of this transition process. This shall facilitate and improve the dialogue between researchers, policy makers and industry when investigating key questions linked to this transition in the next decades, notably as far as the European energy and transport system is concerned.

Naturally, the European economy is not decoupled from the rest of the world. There exists a strong link and trade relationships to other regions outside Europe. Thus it is straightforward that also models and analyses tools are needed in openENTRANCE for calibration, validation and robustness tests when determining the quantitative European portion needed to achieve particular global goals, e.g. like a global warming temperature ceiling benchmark of 1.5°C or 2.0°C. Therefore, the comprehensive ensembles of datasets on existing global pathway curves embedded into the model MESSAGEix-GLOBIOM play a core role in the openENTRANCE modeling and scenario generation exercises to align the empirical foundation of several quantitative scenario and case studies carried out in this project to the status quo of knowledge in the global climate modeling community.

When referring to the quantitative results presented in this report here, Deliverable D3.1, it is important to note, that the pan-European scenario results presented in the subsequent chapters of this document represent version v1.0. These empirical results are delivered now at the end of year 1 of the 4 years' openENTRANCE project (duration from 2019-2023) and build the empirical foundation for further scenario and case study exercises within this project. Naturally, in the upcoming years further insights will be made and lessons learnt, notably in the context of the further fine tuning of the open source energy system model GENESYS-MOD (which delivered the pan-European scenario results presented in this report, aligned to the qualitative openENTRANCE storylines presented in Deliverable D7.1 [1]) on European country-level. Therefore, an updated and finally settled version of input/output datasets on pan-European results are expected to be available together with the detailed European country-specific scenario results towards the end of the openENTRANCE project in year 2023. Ultimately, also the European energy system model GENESYS-MOD will be made available fully open source to the research and modeling community at the end of the openENTRANCE project to enable "barrier-free" use and further development by third parties beyond the project life-time.

A key novelty and strength of the openENTRANCE project (compared to previous projects), in addition, is that the empirical input/output datasets of version v1.0 of the pan-European scenario results presented in this report are uploaded already now to the open platform (and can be used within the consortium immediately).[1] Not only they can be used for further modeling activities within the openENTRANCE project but also experienced users outside the consortium can use them for own scenario studies. Moreover, in the course of time, the open platform will be further enriched with fully open case study results delivered in openENTRANCE (incl. the corresponding input/output datasets) at different geographical (national/regional/local) and granularity (spatial/temporal resolution) levels. This supports the understanding of transition pathways in the European energy[2] and transport[3] sector within the research and modeling community at different levels if several of the models and datasets are fully open, transparent and unambiguously assignable in terms of input/output datasets characterizing a particular study. Furthermore, any kind of adjustments of these available datasets can be made by third parties to conduct own studies.

It is important to note, that in the openENTRANCE project from the very beginning a strong focus has been put to support policy and decision making to succeed in decarbonizing the European economy. However, since future developments in the energy and transport system can't be foreseen exactly, four different storylines have been developed (i.e. narrative descriptions of equally possible energy futures) in the openENTRANCE project. They have been presented already in Deliverable D7.1. The corresponding quantitative scenario studies presented in this report directly built upon them. It is important to note that the openENTRANCE storyline descriptions are founded on a thorough analysis of already existing global and European pathway and scenario studies as well as a comprehensive review of the existing policy documents at European Commission level complying to the global climate challenges according to the Paris agreement [2] (see Section 2.2 in D7.1 in particular).

Policy making, however, is a significantly dynamic process. Recently, the so-called "European Green Deal" [3] has been announced, trying to specify more in detail implementation measures to mitigate the climate challenge. It is expected that in the years to come frequently new policy questions will arise in this context, where the research and modeling community is expected to

[1] For users outside the consortium it will be made accessible in spring 2021 at the latest.

[2] This includes several sub-sectors as there are industry, commercial, tertiary and private sector as well as the corresponding end-uses and energy services. It is important to note in addition that non-energy related demand (and subsequently emissions), e.g. agriculture, are not included in the energy system model GENeSYS-MOD.

[3] This includes both passenger and freight transport as well as several subsectors, end-uses and mobility services. It is important to note, however, that international shipping and aviation is not included in the energy system model.

deliver consolidated and robust answers very fast. And this is exactly what the open platform of openENTRANCE can deliver far beyond the end of the life-time of the openENTRANCE project. It is seen as a service platform to the community, where open datasets and open models are available unambiguously assignable. Any further development and use by third parties is provided with a clear version update and/or some kind of clearly defined "time stamp". This is seen as a unique selling point of the open platform delivered within the openENTRANCE project.

This report, Deliverable D3.1, presenting a glance of the four different scenario results at pan-European level shall be understood against the introductory notes mentioned above. Details of the corresponding input/output datasets of each of the scenarios are available on the open platform and thus for the sake of clarity mainly suppressed in this report.

1.2 Link to the openENTRANCE storylines

Whereas Deliverable D7.1 (Storylines for Low-Carbon Futures of the European Energy System) elaborates on four descriptive possible future developments of the European energy system, this Deliverable D3.1 takes a step further and presents the quantification of them at pan-European level. Therefore, the contents presented in D3.1 are the continuation of work from D7.1. The process for building the bridge between qualitative storylines and quantitative scenario results (as well as subsequently the overall openENTRANCE open platform implementation) has already been outlined in the final Chapter 5 of D7.1.

As far as the scenario quantification exercises part is concerned, Figure 1.1 outlines – starting from the four qualitative openENTRANCE storyline descriptions – the main cornerstones of this quantification process (see also Figure 5.2 in D7.1).

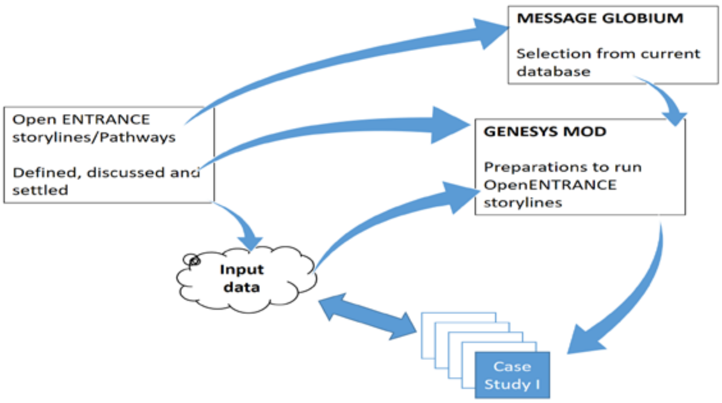


Figure 1-1 Bridge between qualitative storylines and quantitative scenario/case study analyses in openENTRANCE

The key energy system model qualified to deliver the tailor-made quantified openENTRANCE scenario results at both levels, pan-European and European country-specific, is GENeSYS-MOD which will be delivered fully open source within the openENTRANCE project. Therefore, the existing version of the model has been further developed (in terms of functionalities and granularity) in order to meet the openENTRANCE modeling requirements. Then it has been scaled and adjusted to the boundary conditions accordingly, representing the major cornerstones and features of the four different storylines. In addition, a plausibility/consistency test of the four pan-European GENeSYS-MOD scenario results was carried out by comparing them with the "most alike" quantified pathways from the big set of already existing pathway curves of the database of the model MESSAGEix-GLOBIOM, which plays a core role in the modeling and research community of the IPCC (Intergovernmental Panel on Climate Change). Consequently, the input data of several models used in this context must be coherent and consistent. Furthermore, a comprehensive input data cross-check and data adaption has been conducted with other relevant European models and ongoing project initiatives, e.g. model Green-X in terms of long-term renewable potential datasets on European country level (lately applied in the European SET-Nav (www.set-nav.eu) and MUSTEC (www.mustec.eu) project).

In Chapter 2 a more detailed approach is presented on the individual steps to derive the four quantitative openENTRANCE scenarios at the pan-European level. In addition, a flow chart illustrates the entire quantitative scenario generation process in the openENTRANCE project, predominantly focusing on the result generation at the pan-European level, but also outlining a possible final feedback loop (and final scenario result update) of experience gained during country specific GENeSYS-MOD fine tuning and scaling as well as the nine openENTRANCE case study analyses exercises. Frequent updates of model runs (incorporating new insights) is an inherent challenge in energy system modeling per se and underpins the need for transparent open source and open data modeling to know which datasets and versions have been used to conduct a particular analysis.

To enable transparent and open data exchange, in the openENTRANCE project simultaneously to the scenario generation and case study exercises a fully open platform is developed. The first datasets (version v1.0) of the four quantified pan-European scenario results are uploaded to this open platform for further use. They build the empirical foundation of the entire openENTRANCE project. These datasets as well as further generated ones during the openENTRANCE projects in the different tasks and exercises are also fully open available to the entire research community for further use to conduct own studies.

1.3 Objectives and scope of this report

Although some aspects already have been touched on in the introduction above, the core objective and scope of this report is summarized in the following: it mainly presents the four quantified openENTRANCE scenario datasets for low-carbon futures of the European energy systems at pan-European level, which reflect the quantitative consideration of the corresponding openENTRANCE storylines already described in Deliverable D7.1. These consistent and coherent input/output scenario datasets at pan-European level presented in this report build the foundation of the further scenario building exercises at different levels (country, regional) and case studies conducted within the openENTRANCE project and beyond. Moreover, the use of them is not only restricted to the applications during the openENTRANCE project, but also enables third parties in the research community to conduct own studies in a consistent manner.

However, in the context of this report it would not be sufficient to confront the readership with the four quantified pan-European scenario datasets only. It is also important to describe the quantitative scenario generation process itself and the plausibility/consistency check of the scenario results in detail. Therefore, these are either important objectives of this report. For completeness, the alignment of the openENTRANCE data format according to an extension of the IAMC template[4] (to meet the needs for upload to the open platform) also briefly is mentioned in this report. The open platform, however, is one of the key products of the openENTRANCE project itself. Thus, its interacting with the different pieces of the project is described in several upcoming deliverables more in detail.

1.4 Structure of this report

This Deliverable D3.1, building the empirical foundation of the openENTRANCE project at pan-European level, is organized as follows:

- Chapter 2 outlines the major cornerstones of the quantitative scenario generation process at the pan-European level. This process builds the bridge from the qualitative storyline descriptions to the quantitative scenario datasets and thus the empirical frame in the entire openENTRANCE project. A flowchart illustrates the entire process graphically. In addition, the different steps and the key models involved in the scenario generation and robustness testing of results are described more in detail in Chapter 2.
- Chapter 3 presents a glance of the quantitative results of each of the four pan-European openENTRANCE scenarios (further results per scenario are shown in the Appendix):

[4] IAMC…Integrated Assessment Modeling Consortium (http://www.globalchange.umd.edu/iamc)

Directed Transition, Societal Commitment, Techno-Friendly, and *Gradual Development*. In addition, a matching and robustness test of the scenario results (derived from the GENESYS-MOD model) is carried out with the most alike existing quantified pathways available in the database of the MESSAGEix-GLOBIOM model.

- Chapter 4 briefly outlines the implementation of the conversion of the pan-European scenario data sets and results to the openENTRANCE common data format (see Deliverable 4.2) in preparation for upload to the IIASA openENTRANCE Scenario Explorer, which forms part of the open platform developed in this project.
- Concluding remarks on the way forward (disaggregation on European country level) are presented in Chapter 5.

2. Scenario generation methodology, input data, consistency check of results

2.1 Bridge from qualitative storylines to quantitative scenarios

The starting point for the quantification of the four pan-European scenarios is the detailed storyline description presented in Chapter 4 in Deliverable D7.1. In order to recall the relationship to each other, in the following Figure 2.1 the Figure 4.2 of D7.1 is shown again.

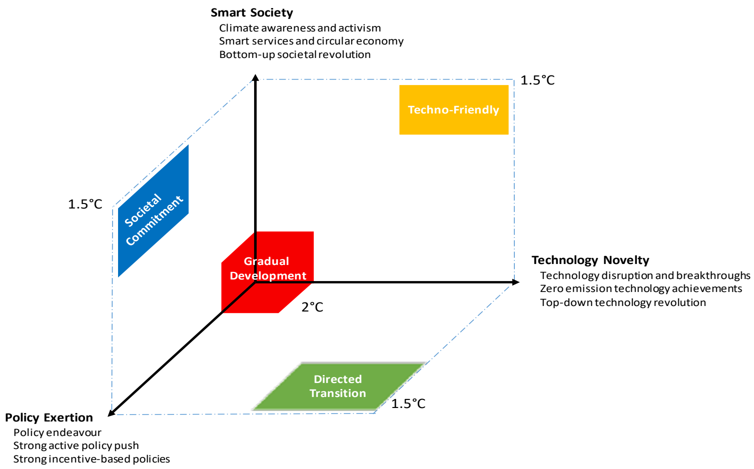


Figure 2-1 openENTRANCE storyline typoligy

These storyline descriptions in Chapter 4 of D7.1 include both an overview of the main cornerstones, drivers, and features of each of the stories, as well as an individual in-depth description elaborating on the unique properties. Moreover, Table T4.2a-d at the end of Chapter 4 in D7.1 already presents a structured comparative analysis of each of them in terms of

- Geopolitics and market/economic development
- Climate and energy policies
- Technology portfolio in the energy and transport sector
- Society's attitude and lifestyle

- Energy sector in detail
- Transport sector in detail

Each of these categories is further subdivided into subcategories which finally support the transition of the qualitative description into a "quantitative world" characterized by dedicated analysis parameters like costs, prices, resource potentials, technology portfolios available, technological learning rates, willingness to pay, and many others.

In the characterization of the four different storylines in Table 4.2a-d in these subcategories, some of these parameters have already been explicitly mentioned and provided with attributes like very high/high/medium/low or moderate/limited or else.

As already stated in Chapter 4 of D7.1, this categorization is denoted to be "preliminary", because it has been expected to gain further experience and insights during the scenario generation discussion process. This developed to be true when the details of model functionality of the model GENESYS-MOD and the needs to reflect upon the openENTRANCE storylines was discussed. This feedback-loop to fine-tune the final storyline description of openENTRANCE later on in the project is also indicated in the following flowchart (see Section 2.2).

Naturally, further precision of the GHG-emission reduction targets in the context of the four different storylines raised additional questions and resulted in further clarifications. One of the most important and sensitive parameters in this context is the CO_2 price assumption made for a particular storyline, and in addition the modeling implications and interdependences between CO_2 prices and CO_2 budgets for a predefined period of time. While GENESYS-MOD offers the functionality to model a CO_2 budget (based on different allocation methods like share of GDP, population, current emissions, or free distribution), for openENTRANCE's scenario generation, a CO_2 price modeling functionality has been implemented.[5] In addition, further discussions clarified vague specification in Table 4.2a-d, e.g. which target years have to be envisaged to fully decarbonize the European energy system to reach the 1.5°C/2.0°C global warming ceiling. The

[5] For three of the scenarios *(Techno-friendly, Societal Commitment, Gradual Development)* the CO_2 price has been determined by iterations over different price levels, which in the end ensured carbon neutrality, either in 2040 or 2050 (depending on the scenario). The carbon neutrality years in 2040/2050 result from the consideration of the global warming ceiling target, the corresponding remaining pan-European CO_2 budget and maximal possible technology exchange rates (in this context it is important to note, that the gradients of modelling results in individual cases/subsectors being subject of analyses might partly overwhelm the real, "physical" world. Nonetheless, constraints for technology exchange and exchange rates shall kept at a minimum). In the fourth scenario *(Directed Transition)*, characterized by significant intertemporal policy steering to meet intermediate targets, binding CO_2 constraints have been set (on a 5 years basis) which finally determined the trade-offs (shadow price) of the technology switch (from emitting to cleaner ones). This trade-off price has been implemented then as the CO_2 price in the *Directed Transition* scenario.

corresponding settings are years 2040 (1.5°C; relevant for the three ambitious storylines) and 2050 (2.0°C; relevant for the most conservative storyline *'Gradual Development'*) respectively.

These insights into the discussions presented above shall only serve as a snapshot. Many similar aspects have been further specified in this context. These further specifications and further 'sharpening' of the contours of each of the storylines are documented in an introductory subsection prior to the result presentation per storyline in Chapter 3 of this report, where a summary of the individual model parametrizations can be found as well.

2.2 Flowchart of the modeling approach for pan-European scenario generation

In the following Figure 2.2, the major steps of the modeling approach are briefly outlined.

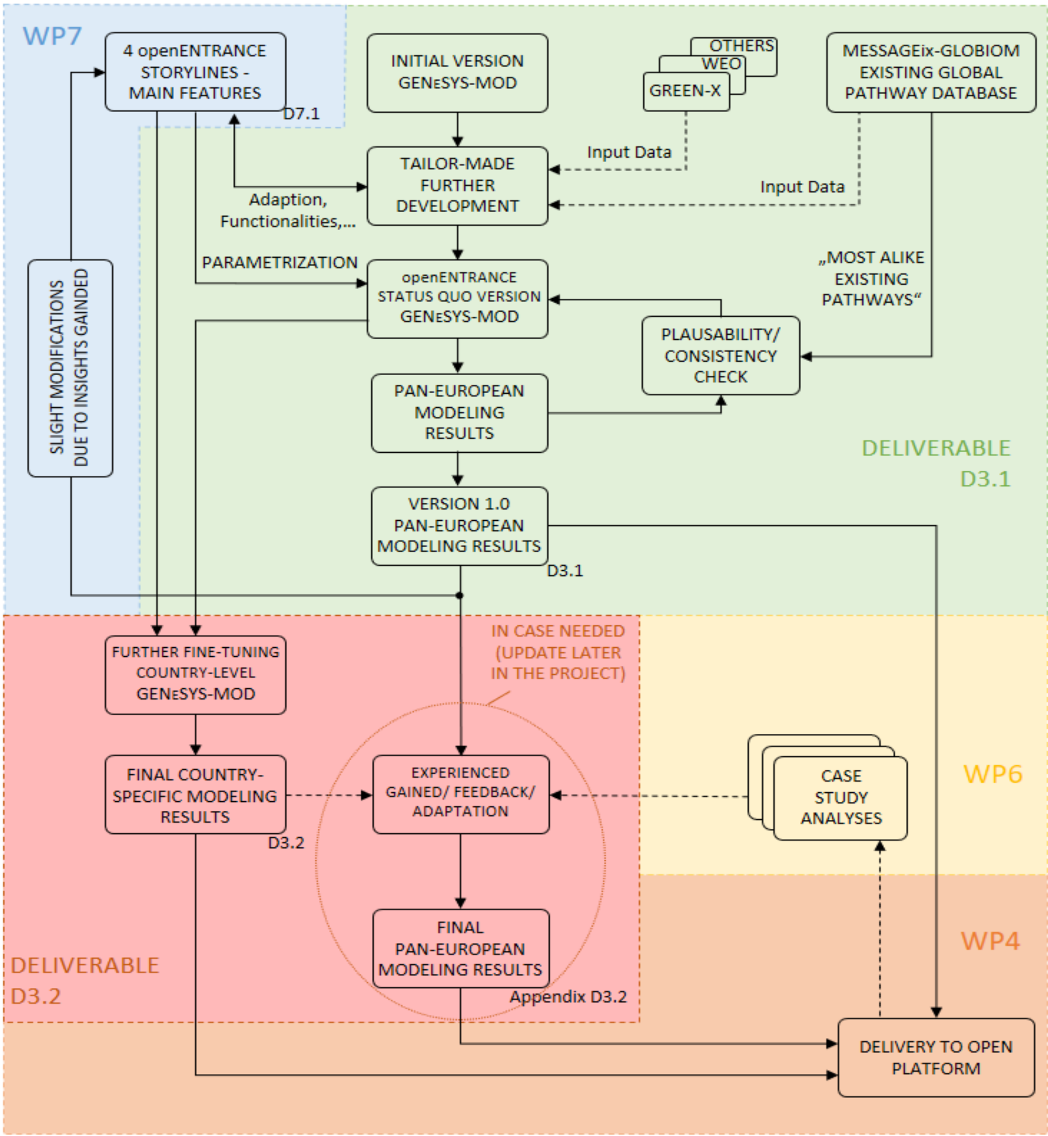


Figure 2-2 Flowchart of the quantitative scenario generation process in openENTRANCE

The major "flow" of the openENTRANCE scenario generation process can be summarized as follows (each of the individual steps listed below are further described in the subsequent Sections 2.3-2.9 more in detail):

1. Starting from the openENTRANCE storyline description and the initial version of the energy system model GENESYS-MOD in terms of geographical scope, granularity, functionalities, and further model-specific features, a tailor-made further development and adaptation has been conducted to meet the openENTRANCE storyline modeling requirements/needs. This also includes the tailor-made parametrization of the input parameters according to the individual storyline descriptions.
2. In addition to the storyline specific input parameter settings, it is also of vital importance to consider the input parameter settings of similar models and scenario studies to enable a comparison of the different scenario results. Moreover, consistent and coherent input parameter settings, notably in terms of key parameters like fossil fuel prices, CO_2 prices and/or CO_2 budgets, technology cost/learning rates, renewable resources potentials and energy demand are carefully cross-checked and aligned with work outside openENTRANCE in order to guarantee comparability as well as explanation of commonalities and differences of the individual scenario results. This not only includes models like MESSAGEix-GLOBIOM or Green-X, but also energy scenario studies with high shares of renewables as published in the World Energy Outlook (WEO) and others (for quantitative numbers and comparisons of them, see corresponding sections in Chapter 3 and notably Appendix 7.1).
3. The database on existing ensembles of quantified global de-carbonization pathways of the model MESSAGEix-GLOBIOM plays a core role to conduct consistiency/plausibility checks of the pan-European scenario results derived from the energy system model GENESYS-MOD. In detail, the individual "most alike" pathways in this database are matched with the corresponding quantified scenario results of the model GENESYS-MOD. This approach shall guarantee robustness of the quantified pan-European scenario results. Probably, later in the openENTRANCE project, a full validation of the GENESYS-MOD modeling result is planned with the model MESSAGEix-GLOBIOM. However, this can be carried out only if the empirical scaling of the model MESSAGEix-GLOBIOM meets the corresponding requirements in terms of geographical scope and granularity.
4. The process outlined above finally enables the derivation of the four quantitative pan-European scenario results reflecting the individual features of the four openENTRANCE storylines. Version v1.0 of them is presented in Chapter 3 of this report. Furthermore, the input/output datasets of these four pan-European scenarios are delivered to the open platform of openENTRANCE for further use within the project and beyond.
5. At this point, there are two obvious feedback loops which need further consideration (both of them, however, are not within the scope of this Deliverable D3.1): (i) The experience gained during the entire scenario generation process is expected to result in a slight

update/fine-tuning of the individual storyline descriptions (@WP7; task foreseen for the synthesis of different openENTRANCE results). (ii) The further use of the pan-European scenario datasets in the modeling activities within openENTRANCE (e.g. case study analyses) and the experience gained in the further fine-tuning of the GENESYS-MOD model on European country-level might result in slightly modified quantitative pan-European scenario results at the end. In case, these final pan-European datasets (version v2.0) can be reported later in the openENTRANCE project in Appendix of Deliverable D3.2 (D3.2 mainly reports on the European country-specific scenario results aligned to the four openENTRANCE storylines).

2.3 Tailor-made further development of the open source energy system model GENESYS-MOD

One of the most challenging tasks has been the tailor-made further development of the initial version of the energy system model GENESYS-MOD to perfectly meet openENTRANCE storyline needs. The initial version (version v2.0) of the model GENESYS-MOD is well documented and published. Moreover, there exist several scientific publications, working papers and conference papers where the main functionalities, sectors covered, and empirical scaling are presented and the continuous updates and further developments of the model GENESYS-MOD can be followed. E.g. an early version in Löffler et al (2017) [4][6], an updated version in Burandt et al (2018) [5][7], an application to the European energy system in Hainsch et al (2018) [6][8], and finally the most recent scenario study on 100% renewables in Oei 2020 [7][9].

It is important to note here that it is <u>not</u> the intention of this report to fully describe several details of the initial version (i.e. version v2.0) of the model GENESYS-MOD once more. It is rather referred to the references given in the footnotes above. However, it <u>is</u> the intention in the

[6] Löffler Konstantin, Karlo Hainsch, Thorsten Burandt, Pao-Yu Oei, Claudia Kempfert, and Christian von Hirschhausen: Designing a Model for the Global Energy System – GENeSYS-MOD: An Application of the Open-Source Energy Modelling System (OSeMOSYS), Energies 2017, 10(10), 1468; https://doi.org/10.3390/en10101468

[7] Burandt Thorsten, Konstantin Löffler, Karlo Hainsch: GENeSYS-MOD v2.0 – Enhancing the Global Energy System Model: Model Improvements, Framework Changes, and European Data Set, Data Documentation 94, DIW Berlin, 2018

[8] Hainsch Karlo, Thorsten Burandt, Konstantin Löffler, Claudia Kempfert, Pao-Yu Oei, and Christian von Hirschhausen: Emission Pathways Towards a Low-Carbon Energy System in Europe – A Model-Based Analysis of Decarbonization Scenarios, Proceedings, 41th IAEE International Conference, 10-13 June, Groningen, The Netherlands, 2018.

[9] Oei Pao-Yu, Thorsten Burandt, Karlo Hainsch, Konstantin Löffler, Claudia Kempfert: Lessons from Modeling 100% Renewable Scenarios Using GENeSYS-MOD, Economics of Energy and Environmental Policy, 9(1), 2020, DOI: 10.5547/2160-5890.9.1.poei

following, to briefly summarize the tailor-made further developments, adaptations and improvements of the model (starting from the version v2.0 of GENESYS-MOD with the focus on the European region) as far as special considerations in the context of the openENTRANCE modeling needs are concerned.

Besides the necessary functionalities (incl. implementation of different policy instruments), an appropriate granularity and coverage in terms of generation/production/sector-coupling technologies, network/trade representations, demand sectors (incl. subsectors) and several important end-uses in the energy and transport sector is of vital importance. GENESYS-MOD fulfills these requirements. In addition, consistent and coherent input data settings in terms of fossil fuel prices, CO_2 prices and/or CO_2 budgets, technology cost/learning rates, renewable resources potentials and energy demand are of key importance to enable comparability of results also with scenario studies outside openENTRANCE. Further elaboration on these input data related aspects can be found in the next Section 2.4.

In the following, the tailor-made further developments of the model GENESYS-MOD (starting from version v2.0) according to the openENTRANCE needs are briefly summarized:

- A regional update has been conducted from initially 17 European countries/regions to 30 (i.e. Mainland-EU25, UK, Switzerland, Norway, Turkey, and the Balkan region)[10]. The new country/region-specific granularity meeting openENTRANCE needs can be found on the right hand side in Figure 2.3 below (version v2.9.0-oE).
- In terms of temporal resolution, the following modification has been conducted: the initial time slices were replaced by a reduced hourly resolution and a time-clustering algorithm. The methodology of the time clustering algorithm applied can be found in Gerbaulet/Lorenz (2017) [8][11]. The settings used for the results presented in Chapter 3 of this report are as follows: each 364th hour throughout the year is used. This results in 24 time slices in total (i.e. 4 representative days based on 6 4-hours slices each, as well as an automatic adaptation of the reduced time series to the maximum/minimum/average values of the total time series).[12] This represents a 50% increase in time resolution compared to the v2.0 of GENESYS-MOD.

[10] The two islands Cyprus and Malta are not covered.

[11] Gerbaulet Clemens, Casimir Lorenz: dynELMOD: A Dynamic Investment and Dispatch Model for the Future European Electricity Market, Data Document No. 88, Deutsches Institut für Wirtschaftsforschung (DIW) Berlin, ISSN 1861-1532, 2017

[12] In a further development of GENeSYS-MOD, most probably for deriving the European country-specific results later in the openENTRANCE project (reported in D3.2), the selection of each 122nd hour (and possibly even more detailed runs) throughout the year is planned.

- A more disaggregated representation of the industry sector (in terms of energy carriers/technologies used)[13] has been implemented.
- Data collection has been conducted and data disaggregation made for all the new countries/ regions implemented. This also includes cross-checks/consistency checks with relevant data from other relevant models (e.g. in terms of long-term European country-specific renewable resource potentials with the model Green-X).
- Calibration of the new countries/regions for year 2015 has been conducted (i.e. the starting year for scenario result presentation in 5-years' steps until 2050). Together with the reduced hourly resolution based on the time clustering algorithm described above, this results in a simulation running time to drive the pan-European scenario results per storyline of about 24 hours.
- The CO_2 budget functionality has been disabled and replaced by a CO_2 price mechanic (as a result of the storyline implementation discussion; see also discussion in Section 2.1 above, notably footnote 5).
- Last but not least, a Python script has been developed to enable conversion of GENESYS-MOD scenario results exactly according to the required openENTRANCE data format, which is an extension of the IAMC template (i.e. also aligned to those modeling exercises conducted later on in the openENTRANCE project in the case study analyses).

Figure 2.3 below (right hand side) presents the improved regional granularity and extension of the model GENESYS-MOD in a European context. This version (v2.9.0-oE) has been used to derive the four pan-European scenario results shown in Chapter 3 (and the Appendix) of this report.

It is important to note that the further development of the model GENESYS-MOD form a continuous process and slight amendments/improvements are implemented whenever a particular question arises and there is a need to address this within the modeling approach. Moreover, the four different storylines may also expect partly different modeling features. Notably, the *Directed Transition* storyline, which significantly relies on national energy policies.

Any storyline-related amendments and/or particular fine-tunings of the model GENESYS-MOD as well as the individual empirical scaling/parametrization per Storyline are briefly summarized in an introduction to each of the quantitative scenario result sections in Chapter 3 as well as in Appendix 7.1 of this report.

[13] Oil, Natural Gas (with/without CCS), Hard Coal (with/without gas-co-firing and CCS), Synthetic Gas, Biogas, Bioenergy, Hydrogen, Electricity (EAF (Electric Arc Furnace), Steam Boilers).

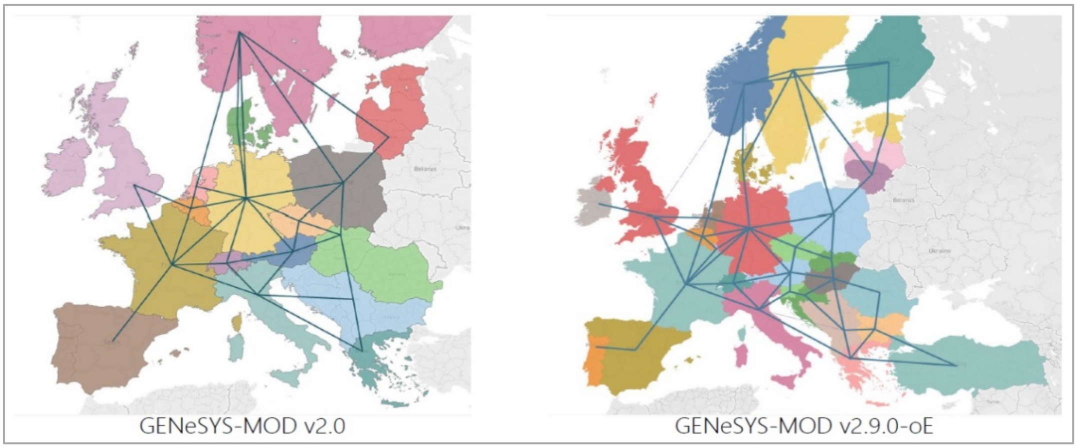


Figure 2-3 Initial version (left) and improved regional granularity and extension of the model GENESYS-MOD according to openENTRANCE needs (right)

2.4 Consistency/coherence of input data settings

As already mentioned in the previous sections of this report, to enable comparability of quantitative scenario results delivered from GENeSYS-MOD with scenario studies outside openENTRANCE, it is important to work with consistent and coherent input datasets. In the context of the openENTRANCE scenario studies this is essential when carrying out plausibility checks and robustness tests with the *'most alike'* existing global pathway datasets developed with the MESSAGEix-GLOBIOM integrated assessment model, on the one hand. On the other hand, an alignment to existing European energy system related input datasets used by other research teams for studies to support policy making, like long-term renewable resource potentials per country, is also important to guarantee the comparability of delivered results.

Therefore, both are relevant for a particular quantitative scenario study in openENTRANCE, input and output/result datasets. These *'twin datasets'* is exactly what is delivered to the open platform for further use within the openENTRANCE project and beyond.

As already stated earlier in this report, a selection of the most prominent representatives on input datasets in energy system modeling are briefly listed below:[14]

[14] It is noteworthy, however, that these are not the only data sets hat have been addressed in the model amendment of GENeSYS-MOD.

- *Fossil fuel prices* essentially determine economics of energy production/generation technologies as well as trade-offs among competing (low/zero emission) technologies qualified to deliver the same energy services (like heating, cooling, mobility, and others). In the different quantitative pan-European scenarios shown in Chapter 3 it is of particular interest how the fossil fuel prices have been set in the four different GENESYS-MOD model runs representing the openENTRANCE storylines compared to other well-known studies, e.g. those published in the World Energy Outlook (WEO). The corresponding quantitative numbers of fossil fuel price parametrization in GENESYS-MOD in each of the scenario-related Subsections in Chapter 3 is compared in Appendix 7.1 with the recently published *"Sustainable Development Scenario"* of the World Energy Outlook 2019 (WEO2019).[15] For further details and citations in this context it is referred to Appendix 7.1.
- *CO_2 prices and/or CO_2 budgets:* Both CO_2 emission mitigation instruments can be used in modeling as an exogenous parameter to govern decarbonization pathways accordingly. In modelling, CO_2 prices usually add cost elements to an emitting production/generation technology or a surcharge to energy services in the retail sector. In general, a CO_2 budget defines a particular quota (usually over a longer period of time), which can be consumed to the maximum. Depending on the individual design of both instruments and the emitting technology/energy service portfolio, a decarbonization pathway can be more or less continuous/discontinuous within the time period considered. In an openENTRANCE context, as already discussed in Section 2.1 of this report, three out of four storylines envisage a fully decarbonized European energy system in 2040 in order to reach the global warming ceiling of 1.5°C. The fourth is the 2.0°C setting in 2050. These targets years for full decarbonization used in openENTRANCE are not set arbitrarily, but implicitly reflect the overall remaining CO_2 budget for Europe in a global context (e.g. see IPCC (2014) [9])[16] as well as a reasonable technology exchange rate. Moreover, consistency of data used and assumptions made in energy and climate modeling is of vital importance.[17]
- *Technology cost/learning rates:* Aligned assumptions on technology costs and expected technological learning in the future are essential ingredients in modeling to enable comparability of different studies. Notably, the empirical scaling of renewable technology

[15] https://www.iea.org/reports/world-energy-outlook-2019

[16] IPCC (2014), Summary for Policymakers. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. New York, NY, last accessed July 16, 2016 at http://ipcc-wg2.gov/AR5/images/uploads/WG2AR5_SPM_FINAL.pdf

[17] In this context it is also important to note that emission from non-energy related demand (e.g. agriculture), international shipping and aviation, and LULUCFs (Land Use, Land Use Change, and Forestry) are not considered in the GENESYS-MOD model and thus in the net zero emission targets.

cost (onshore/offshore wind, solar PV, etc.) and cost assumptions of upcoming new technologies like different energy storages, CCS (Carbon Capture and Storage), and/or H_2-production are determining parameters defining the timing of market penetration of future technologies/technology portfolios and thus decarbonziation pathways.

- *Renewable resource potentials:* In an almost renewable European energy system in the long-term, robust estimates and reliable input data on the renewable resource potentials in the different European regions and countries are very important. Both, transparent methodologies on renewable potential/cost estimation and cross-check on empirical input datasets in this context among different research teams/models in Europe improve the overall quality of scenario results and, subsequently, policy recommendations delivered. The model GENESYS-MOD cross-checked its initial renewable resource potential datasets in this context with the model Green-X (extensively used in the past for renewable technology/policy scenario generation in Europe; recently in the H2020 project *SET-Nav*) and – where needed – selectively updated and aligned its long-term renewable resource potentials accordingly.
- *Energy demand projections:* Last but not least, empirical datasets on energy demand projections in the different sectors and end-uses are either sensitive input data in energy system modeling. Therefore, careful cross-checking of these input datasets used (incl. its disaggregation to different sectors and end-uses) with related work outside openENTRANCE has been conducted. Among others, different energy demand projections with high granularity having been used in the recently finished H2020 project SET-Nav[18] (see also Deliverable D7.1, Section 2.3.1, for an executive summary of the SET-Nav scenarios) are used here as some kind of reference in the GENESYS-MOD model. Subsequently, deviating energy demand projections in the different openENTRANCE storylines are argued against these references in SET-Nav. The empirical settings and comparisons can be found in the corresponding Appendix 7.1, which is related to the parametrization sections in Chapter 3. For further details and citations in this context it is referred to Appendix 7.1.

[18] http://www.set-nav.eu/; In SET-Nav the analysis and projections of energy demand in the different sectors buildings, industry, and transport is built upon the demand sector models *Astra, Invert and Forecast*.

2.5 Using "most alike" pathways from the MESSAGEix-GLOBIOM IAM as boundary conditions

The implementation of the four pathways in GENESYS-MOD was complemented by selecting four "most-alike" pathways from recent studies or ongoing work with the MESSAGEix-GLOBIOM Integrated Assessment Model (IAM).[19] MESSAGEix is a global systems engineering optimization model used for long and medium term energy system planning (see [10][20], [11][21]). In its current implementation, the world is disaggregated into 11 regions, each of which is characterized by a detailed energy system representation. The model's main objective is to optimize the contributions of various energy supply options over time in order to meet specified regional energy demands at the lowest overall discounted cost. MESSAGEix also tracks the sources and sinks of greenhouse gases (GHG) and estimates anthropogenic GHG emissions as part of its optimization procedure. The model is coupled with the GLOBIOM (GLobal BIOsphere Management) model, which is a recursive-dynamic partial-equilibrium land-use dynamics model. It represents the competition between different land-use based activities. It includes a bottom-up representation of the agricultural, forestry and bio-energy sector, which allows for the inclusion of detailed grid-cell information on biophysical constraints and technological costs, as well as a rich set of environmental parameters, incl. comprehensive AFOLU (agriculture, forestry and other land use) GHG emission accounts and irrigation water use.

The MESSAGEix-GLOBIOM IAM is applied in a plethora of climate-change mitigation and energy-system transformation studies. Most notably, it submitted many scenarios to the IPCC Secial Report on Global Warming of 1.5°C. We select four scenarios from recent or ongoing work which are "most-alike" to the openENTRANCE storylines. This means that these scenarios exhibit similar societal developments and policy measures. These pathways are described in more detail in the respective sections in Chapter 3.

For each of the selected most-alike scenarios, the outcomes in terms of demand and energy mix at the aggregate European level as well as global indicators including imports, exports and

[19] Read the documentation at https://message.iiasa.ac.at/projects/global/

[20] Huppmann, Daniel et al. The MESSAGEix Integrated Assessment Model and the ix modeling platform (ixmp): An open framework for integrated and cross-cutting analysis of energy, climate, the environment, and sustainable development, *Environmental Modelling & Software,* Volume 112:,143-156, 2019, doi: 10.1016/j.envsoft.2018.11.012.

[21] Fricko, Oliver et al. The marker quantification of the Shared Socioeconomic Pathway 2: A middle-of-the-road scenario for the 21st century, *Global Environmental Change,* 42:251-267, 2017, doi; 10.1016/j.gloenvcha.2016.06.004

energy prices were used to provide reasonable boundary conditions to the GENeSYS-MOD calibration.

2.6 Processing of scenario results to the openENTRANCE data format

openENTRANCE aims at developing an open and transparent modeling platform for disseminating and reusing modeling results. In order to assess, compare, and validate these results, a common nomenclature (i.e., common names of variables, regions, or units) is developed.[22] This openENTRANCE common data format is an extensions of the existing Integrated Assessment Modeling Consortium (IAMC) data format,[23] which is already in use in several different integrated-assessment modeling comparisons. Overall, the proposed new data format is as generic as possible to ensure the inclusion of a wide range of parameters and variables and thus enabling a plethora of different model types.

To also generate comparable scenario results, the outcomes of GENeSYS-MOD were also transformed to fit the openENTRANCE common data format. A python script was developed that handles the mapping of the internal GENeSYS-MOD variables and parameters to the new data format. Also, the names of technologies or energy carriers are adjusted accordingly. The script will be executed automatically after the modeling runs of GENeSYS-MOD are finished. Therefore, the original results and result parsing methods of GENeSYS-MOD are still in place with the results additionally reported in the openENTRANCE common data format. Primarily, reported variables by now are primary energy demand, secondary energy demand, emissions, and capacities for the sectors, technologies, and regions included in GENeSYS-MOD.

2.7 Validation and robustness checks

Following the numerical implementation and calibration of four openENTRANCE storylines with the GENeSYS-MOD framework, the quantifications of key indicators were compared to the most-alike scenarios from the MESSAGEix-GLOBIOM IAM. This ensured that the calibration to the global boundary conditions supplied by the global model for each storyline was implemented correctly. The comparison of each GENeSYS-MOD quantification of the openENTRANCE pathways to the most-alike MESSAGEix-GLOBIOM scenarios is presented in the respective sections in Chapter 3.

[22] See https://github.com/openENTRANCE/nomenclature

[23] Compare https://pyam-iamc.readthedocs.io/en/stable/data.html

2.8 Further GENESYS-MOD scenario generation exercises beyond pan-European level

The scenario generation exercises are not finished within the openENTRANCE project with the delivery of the pan-European quantitative results per storyline to the open platform.

Moreover, the model GENESYS-MOD will be further fine-tuned on European country-level and granularity on empirical scaling might be further improved selectively. This enables modeling and delivery of quantitative country-specific scenario results according to the individual storyline descriptions later in the openENTRANCE project, on the one hand. Deliverable D3.2 will report on the outcomes of these quantitative European country-specific scenario results accordingly. Naturally, these datasets will also be made fully available and open on the open platform to the energy research/modeling community for further use.

On the other hand, several of the already existing pan-European datasets available on the open platform are further used by the case study analyses within the openENTRANCE project. In addition, they can already be used by experienced modelers outside the project consortium to carry out own scenario studies based on the use of these datasets (or modifications of them according to the individual needs). As already stated earlier in this report as well as in the flowchart (Figure 2.2), these pan-European results presented in this report are version v1.0, being subject to probable updates later on in the project, as a result of further use and additional experience gained in the different activities in the ongoing openENTRANCE project. If this is needed, an updated version representing the final quantitative pan-European scenario results are reported e.g. in an Appendix of Deliverable D3.2, which focuses on the main part of the report on the corresponding European country-specific results per storyline.

The experience gained so far in deriving the quantitative pan-European scenario generation results also expects a slight update / fine-tuning of the individual storyline descriptions (incl. reporting on them). This is foreseen also later in the project in the corresponding tasks and deliverable in WP7 dealing with the synthesis of different openENTRANCE results.

3. Quantitative pan-European scenario results

In the following Chapter 3, a selection of the most important quantitative pan-European scenario results derived from GENESYS-MOD are presented. In the following four subsections, the following structure is used for result presentation and discussion for several of the four openENTRANCE scenario results at pan-European level:

- Recall of the main features and unique properties of the underlying storyline (for a comprehensive description see Deliverable D7.1, Chapter 4, in detail) and summary of the most important parametrization details of the GENESYS-MOD model.
- Presentation of a glance of each of the scenario results, containing both a 1-page executive summary and a selection of the most meaningful figures. These figures comprise important developments up to 2050 (in 5-year time steps) of primary energy use, emissions, electricity generation technology portfolios, technologies/energy carriers for residential/commercial heating, industry, and passenger as well as freight transport. Further interesting results per scenario (e.g. representing installed electricity generation capacities) are presented in the corresponding Appendix 7.2 of this report).
- Comparison of the scenario results with the "most alike" existing MESSAGEix-GLOBIOM scenario. These „most alike" existing scenarios already have undergone a comprehensive peer-review process in the past and are (with the exception of one) already published in renowned scientific journals. This comparison of each of the openENTRANCE scenarios with its „counterpart" of MESSAGEix-GLOBIOM is very important to check the plausbibility and test the robustness of the openENTRANCE scenario results.
- At the end of Chapter 3 (Section 3.5), an additional section comparing the four openENTRANCE pathway computations derived from GENESYS-MOD has been appended to the analysis of the results in the previous Sections 3.1-3.4. It contains some key findings across the multitude of four scenario model results.

As already stated earlier in this report, it is not the intention of this Deliverable D3.1 to present quantitative numbers of the individual input/output datasets per pan-European scenario in detail. These datasets can be found on the open platform in the near future (version v1.0 of pan-European scenario results). Instead, the presented results shall provide a first impression on the quantitative storylines delivered within the openENTRANCE project. Nevertheless, some tables can be found in Appendix 7.1, comparing some of the input parameter values to others scenario studies having been published recently to allow first insights on model parametrizations.

3.1 Directed Transition: glance of results

3.1.1 Recall of main features of this storyline and parametrization of model

In this storyline, as a result of an indifferent public attitude and lacking societal commitment, a strong and continuous incentive-based policy push (at least in Europe) is necessary to deploy existing and novel technologies in the energy and transport sectors. At both European and country levels, active and aligned policy support is necessary to optimally exploit several potentials and available synergies. In a challenging global and European market environment the industry is gaining confidence in continuous technology-specific public policy support and takes responsibility to deliver low-carbon mitigating technology portfolios in the absence of significant active societal contributions.

With the lack of societal participation and technological breakthrough, decarbonizing the energy system by 2040 is mainly being facilitated by political actions and technology-specific support (e.g. also to push the CCS (Carbon Capture and Storage) technology development), which are also represented in the GENeSYS-MOD implementation of this scenario. But first of all, all currently planned phase-out/phase-in dates of technologies and energy carriers for each country were implemented. Instead of a carbon price being one of the major forces in the further development of the energy system, a GHG-reduction target is implemented (end year 2040), which, in modeling terms, functions in a very similar way by assigning an implicit price to each unit of carbon which is being emitted (see also explanation in this context in Section 2.1).

The demand for all sectors is slightly lowered due to policy incentives for demand reduction. While this effect is not significant in most sectors, the residential heating demand sees a higher decrease in demand due to a constant process of building modernization and therefore reduced heating demand. In the industrial sector, heavy subsidies, which are implemented as decreasing costs of technologies, help in electrifying most of the process heating demand. Especially hydrogen-based solutions meeting energy services, which are already past their initial state of development today, see significant reductions in their associated costs (as a result of significant policy support) and thus considerable market deployment.

In contrast, currently not available technologies, at least from a technical point-of-view, are not being considered by the model (except CCS technology). Net imports of hydrogen to Europe are not being considered as a result of the global market situation and reliance on energy security, and fossil fuel prices drop due to lowered global demand. Carbon Capture and Storage (CCS) is an option after the initial model periods due to heavy incentives by politics to reduce emissions, especially in the industrial sector.

3.1.2 Selected GENeSYS-MOD scenario results

Total primary energy demand decreases notably until 2050. Coal and oil face a steady phase-out until 2035, while natural gas experiences a steady decline but still plays a relevant role in the later stages of the modeling period. Due to the higher efficiencies of electricity based technologies and high shares of electrification across all sectors, the overall primary energy consumption decreases by about 50% and wind and solar power become the main source of primary energy compared to the abundant usage of fossil fuels we see today.

Annual emissions see a steep decline until 2035, with the remaining emissions being removed until 2040. CCS technologies allow for a rapid decarbonization of the industrial sector and account for some (minor) negative emissions. The transportation sector is the most difficult to decarbonize with substantial amounts of emissions until and in 2030.

The power sector sees a rapid phase-out of fossil capacities in the first half of the modeling period, with especially hard coal and lignite power plants being removed from the technology landscape. Nuclear will remain, but steadily decrease. Only natural gas remains beyond 2040 as a fossil energy carrier, due to the availability of CCS technologies. These gas capacities are mainly being used in Poland (partly substituting today's coal-based electricity generation system), UK and The Netherlands. Wind onshore is the dominant technology, accompanied by solar PV and wind offshore in the later stages.

The residential sector is defined by a rapid phase-out of coal and oil, while natural gas remains longer in the sector. Heat pumps are being phased-in as soon as 2025 and play the major role in decarbonizing the sector. In the later periods, these heat pumps are being complemented by small amounts of biofuels and hydrogen. The industrial sector is split into electrified generation and process heat generated by fossil fuels with CCS in the later periods. The remaining demand is covered by a combination of hydrogen and biofuels.

In the transportation sector, BEV take over as soon as 2025 and become the dominant technology until 2040. After that, they are partly replaced and complemented by hydrogen-fueled vehicles which become competitive by then. Internal combustion engines are rapidly being phased-out, in contrast, and the remaining vehicles in later periods are being fueled by biofuels. For freight transportation, hydrogen becomes the major fuel while biofuels serve as the intermediate solution to reduce some of the emissions in this carbon intensive sector. Transferring some of the load onto rails is also a trend, which can be seen across all scenarios due to the higher efficiency and, hence, lower costs of train-based transportation compared to trucks.

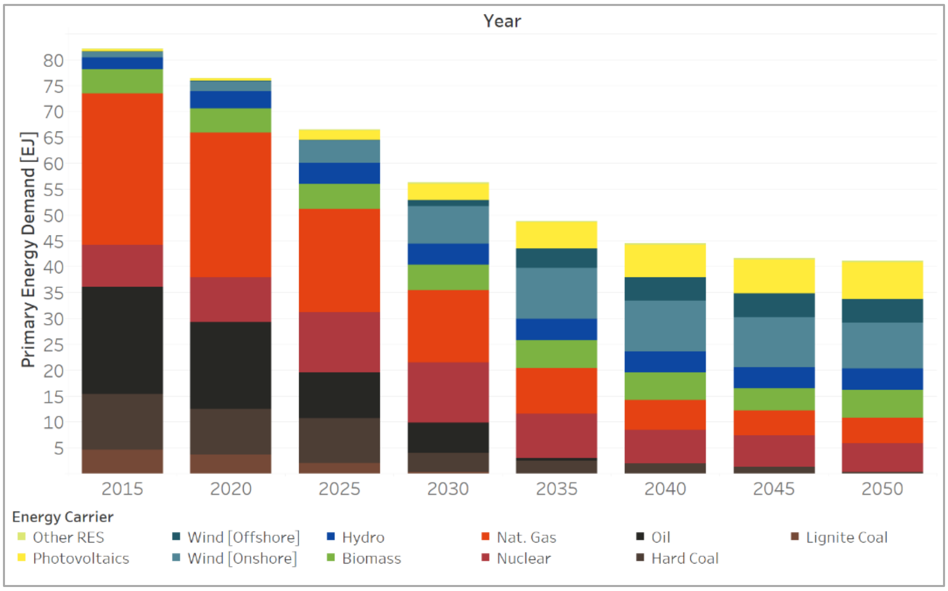


Figure 3-1 Primary Energy until 2050 (Directed Transition)

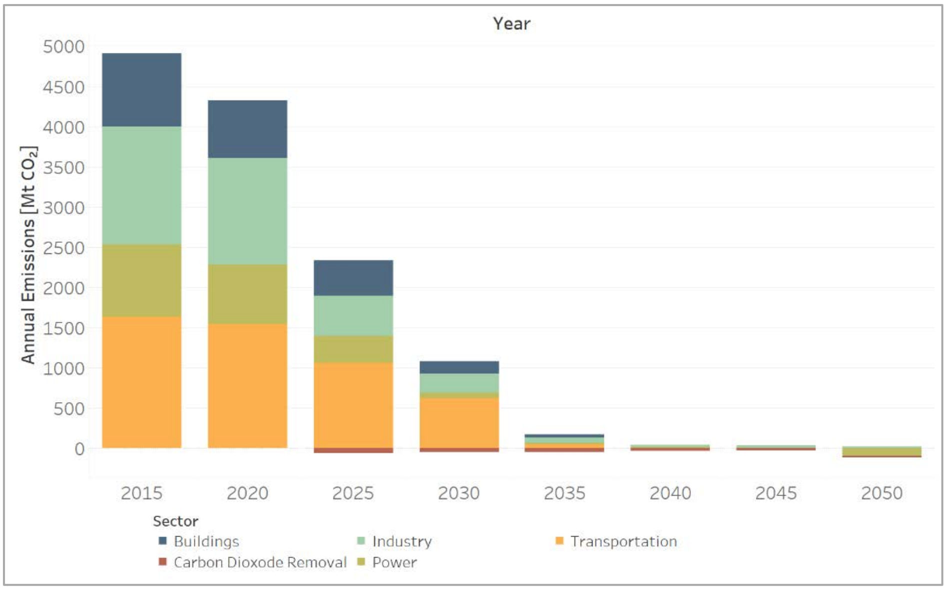


Figure 3-2 Emissions until 2050 (Directed Transition)

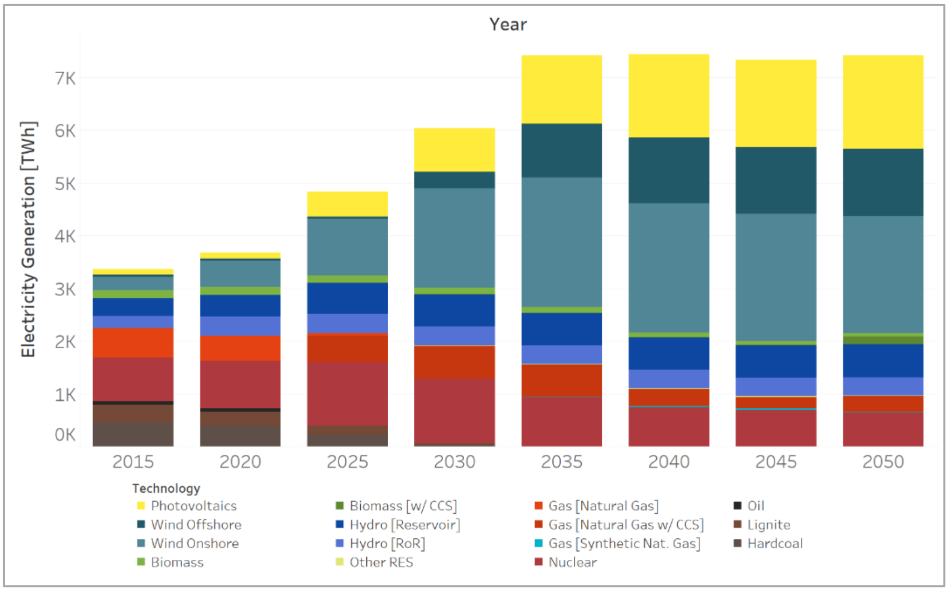


Figure 3-3 Electricity Generation until 2050 (Directed Transition)

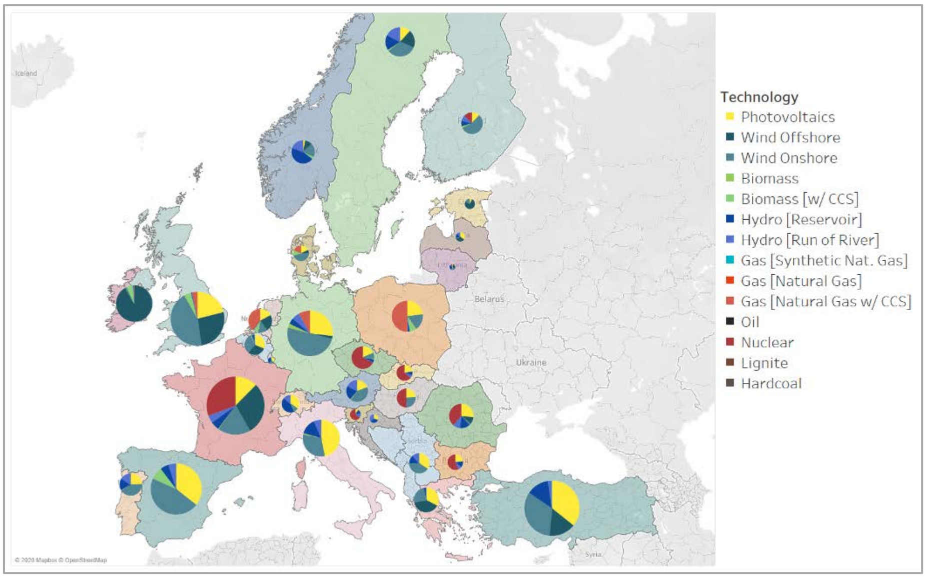


Figure 3-4 Electricity Generation per Country in 2050 (Directed Transition)

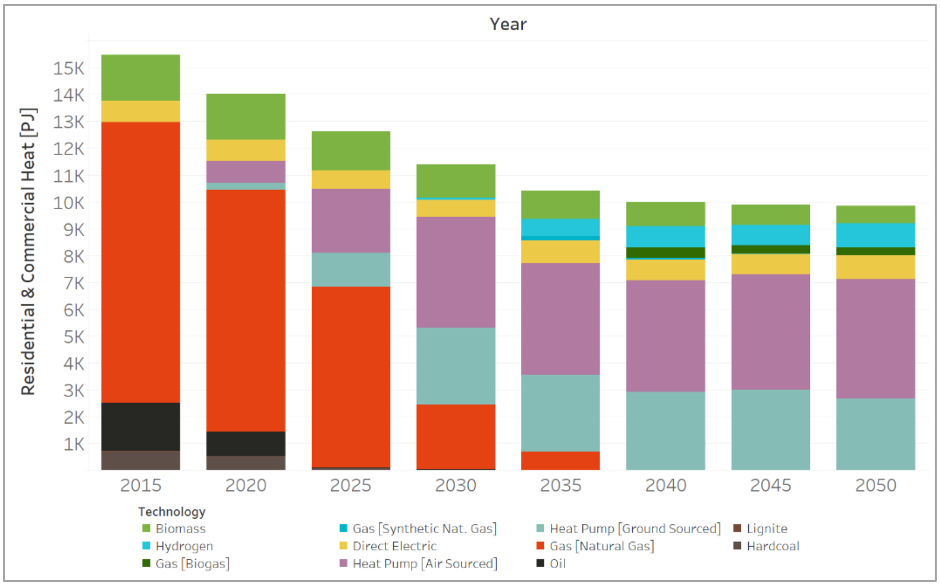


Figure 3-5 Residential and Commercial Heating until 2050 (Directed Transition)

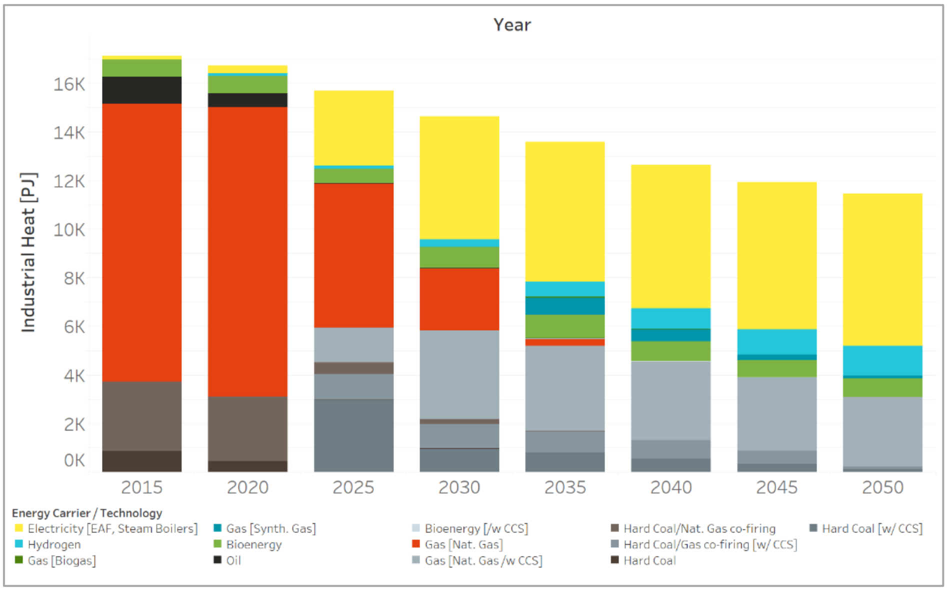


Figure 3-6 Industry (Energy/Technologies) until 2050 (Directed Transition)

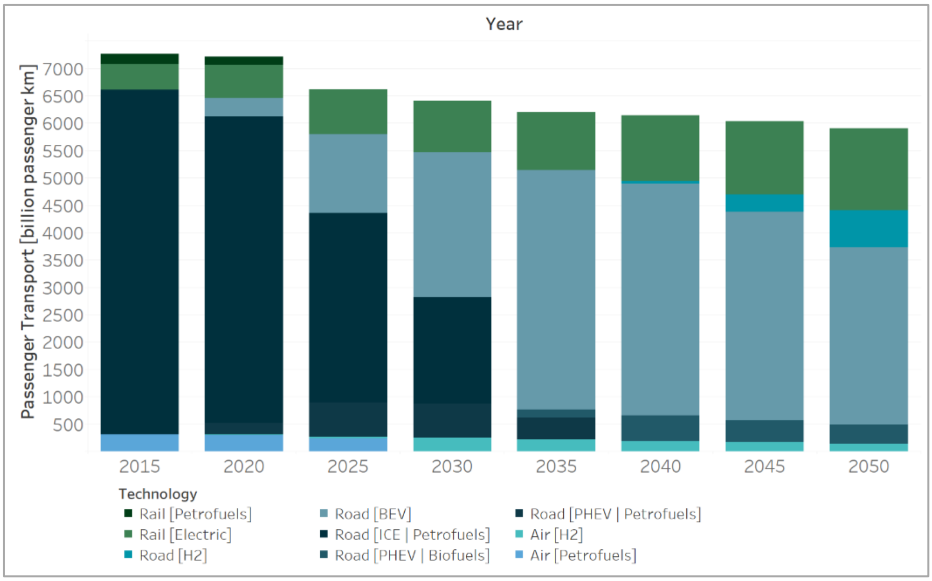


Figure 3-7 Passenger Mobility until 2050 (Directed Transition)

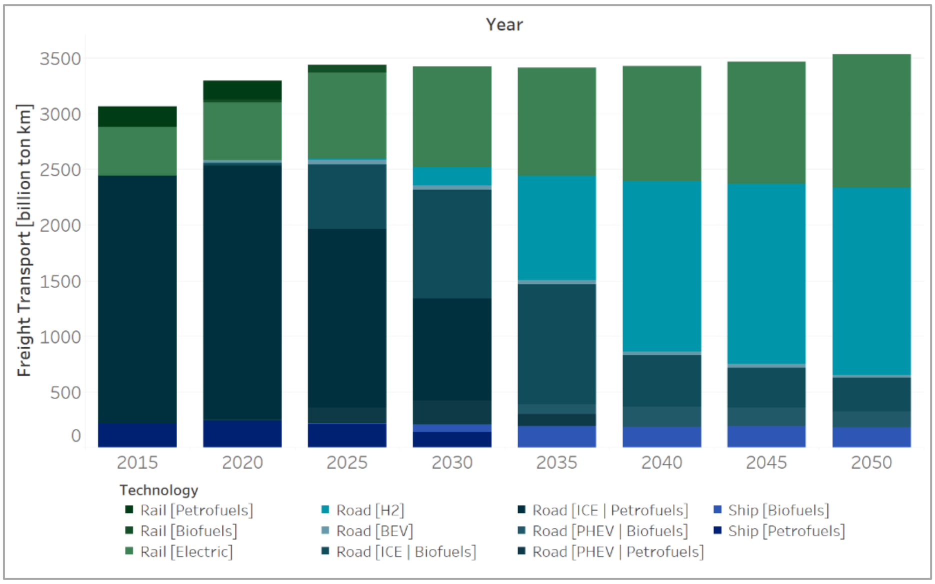


Figure 3-8 Freight Transportation until 2050 (Directed Transition)

3.1.3 Comparison with "most alike" existing MESSAGEix-GLOBIOM scenario

The scenario selected from the global MESSAGEix-GLOBIOM IAM is the "NPi2020_400_V4" scenario developed in the Horizon 2020 project CD-LINKS. The quantification is an updated version of the scenario published in the literature, [12][24]. The scenario assumes an underlying SSP2 trajectory for population and GDP growth as well as technology development. National policies are maintained in line with current regulations until 2020 (the scenario protocol was first specified in 2016), and the cumulative greenhouse gas emissions for 2011-2100 period stay below 400 $GtCO_2e$ budget. This corresponds to a >66% chance of staying below 1.5°C at the end of the century.

The two Figures 3.9 & 3.10 below compare the scenario quantifications from GENESYS-MOD with the NPi2020_400_V4 scenario in terms of total (primary) energy demand in Europe and the fuel mix in the electricity-sector.

Both figures show that the near-term assumptions of energy demand in Europe are quite different between the two models. NPi2020_400_V4 assumes a demand reduction in the next decade but energy demand then increases again beyond current levels. In contrast, the *Directed Transition* quantification sees a strong demand reduction (or increase of energy efficiency) in the next decades. One notable difference is that the NPi2020_400_V4 scenario sees a strong increase in the use of natural gas as a bridge fuel, with a string growth of non-biomass renewables in the second half of the century. The *Directed Transition* quantification exhibits a direct switch to renewables without an intermediate role of (fossil) natural gas.

[24] McCollum, D.L. et al. Energy investment needs for fulfilling the Paris Agreement and achieving the Sustainable Development Goals. *Nature Energy* 3, 589–599 (2018). doi: 10.1038/s41560-018-0179-z

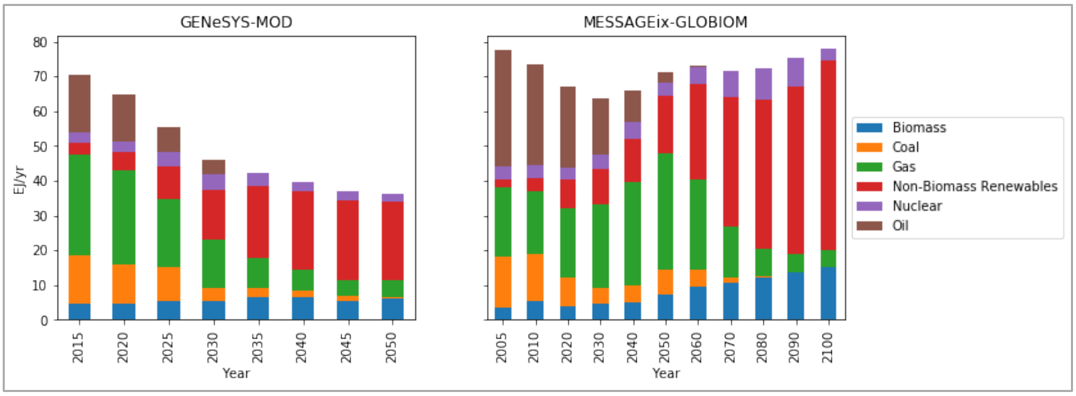


Figure 3-9 Directed Transition - Comparison of pathway quantification with most-alike MESSAGEix-GLOBIOM scenario in terms of primary energy demand

Comparing the demand level and fuel mix in the electricity sector, it can be observed that the total electricity consumption in Europe roughly double in the next two decades and then remains relatively constant until the middle of the century in the *Directed Transition* quantification. In the NPi2020_400_V4 scenario, electricity consumption increases in every period until the end of the century. Still, in both scenarios, wind and solar supply the lions share of demand. The use of gas as a bridge fuel in the NPi2020_400_V4 scenario around the middle of the century, evident in Figure 3.9 above, can also be observed here.

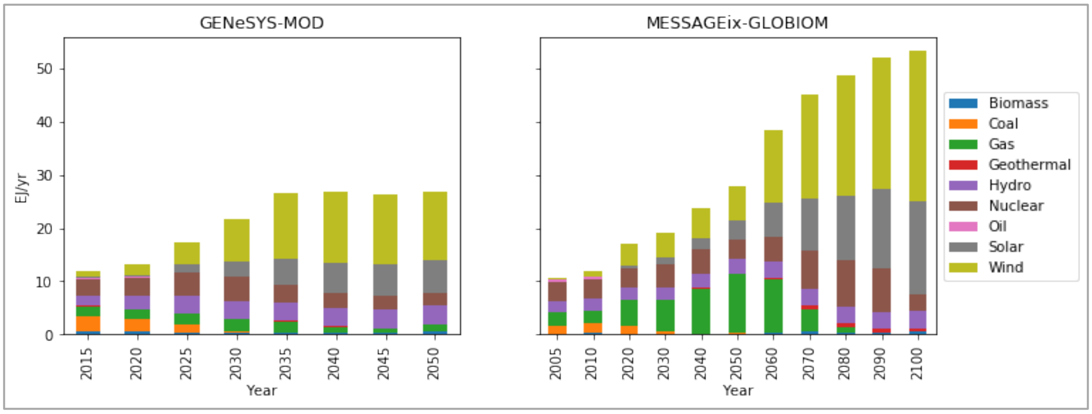


Figure 3-10 Directed Transition - Comparison of pathway quantification with most-alike MESSAGEix-GLOBIOM scenario in terms of electricity fuel mix

3.2 Societal Commitment: glance of results

3.2.1 Recall of main features of this storyline and parametrization of model

This storyline mainly describes a prudent society, characterized by a sustainable life style and behavioural changes which includes a significant reduction of energy use for delivering energy and transport services, the implementation of a circular (and partly sharing) economy, as well as the exploitation of digitalization potentials to support individual and local service needs (including those of communities). Completely new business models and market solutions will emerge, partly only locally. Significant shares of local self-consumption (individual prosumers, communities of different sizes) of renewable generation (notably PV) characterizes this story. These ambitions and developments will be supported by tailor-made policymaking, not least as a result of lacking breakthrough of novel technologies (except digitalization) in the energy and transport sectors.

With the main characteristic of this storyline being focused on sustainability and behavioral changes, overall energy demand, as well as demand patterns are being changed in GENeSYS-MOD to reflect said aspects. The overall energy demand is reduced consistently across all sectors and, to a certain degree, demand shifting from peak consumption hours to peak production hours is being implemented in the residential sector which smoothens the load profile.

Overall, renewable technologies see higher potentials and market penetration than usually, due to their public support and politics focus on removing regulatory barriers. Society is willing to invest into the sustainable transformation of the energy system (with significant contributions of local self-generation at different levels), which is being implemented by adding a penalty on conventional technologies and, thus, promoting renewable solutions. In addition, the sharing nature of society is simulated by decreasing the costs of passenger vehicles and increasing their efficiency. The former characterizes the sharing nature of the society, with car sharing vehicles usually driving more kilometers per year than privately owned ones, while the latter simulates higher occupancy rates in vehicles due to pooling effects.

Regarding the technology landscape, no negative emission technologies are being allowed in this storyline. Moreover, no new nuclear power plant capacities are being considered as an option (not this is the only openENTRANCE scenario of four in total where this assumption is made). Fossil fuel prices drop due to lowered demand but a high carbon price, the highest in all four pathways, offsets this effect. This high carbon price can be explained by a widespread recognition of environmental externalities caused by greenhouse gases and leads to an almost decarbonized energy system by 2040.

3.2.2 Selected GENeSYS-MOD scenario results

The societal commitment pathway is characterized by decreased energy demands and a higher willingness by society to facilitate a sustainable decarbonized future. Consequently, this decrease in demand can be seen across all sectors and especially in the primary energy demand. Hard coal and lignite are being phased-out until 2030, with oil experiencing the same development in the following years. This can be explained by CCS technologies not being available which demands a faster decrease of fossil fuel usage to reach carbon neutrality compared to the other pathways.

The lack of CCS and other carbon dioxide removal technologies (e.g. like DAC (Direct Air Capture)) is also illustrated in the overall emission graph, where annual emissions are reduced more drastically and almost reach zero by 2040. Here, the industry sector is the most difficult to decarbonize one, since it is the last sector with notable emissions in 2035.

The power sector is once more the quickest to decarbonize, a trend seen across all pathways. Hard coal disappears after 2025 and even natural gas and nuclear generation decreases steadily until 2040, after which they only play a minimal role. In contrast, onshore wind power carries the majority of the load, especially in early years, while it is complemented by solar PV (both local self-consumption and utility-scale applications) and offshore in the later periods. While wind is being used in all regions across Europe, with offshore wherever possible. Solar PV sees major usage in all regions except Scandinavia and the UK, where hydropower and wind are much more viable options.

The residential sector is defined by a rapid phase-out of coal and oil, while natural gas remains longer in the sector. Heat pumps are being phased-in as soon as 2025 and play the major role in decarbonizing the sector. In the later periods, these heat pump are being complemented by small amounts of biofuels and hydrogen. Similarly, in the industrial sector, electricity based technologies are replacing natural gas in the later periods, while coal and oil are being phased out until 2025. Here, as well, hydrogen and biofuels play a relevant role in the later periods after 2040.

As for the transportation sector, BEV’s play the most important role for passenger mobility, replacing combustion engines completely until 2040. This is also partly facilitated by the decrease in demand and increase in efficiencies due to higher load factors of vehicles. Freight transportation in later periods rely heavy on hydrogen and biofuels as a combination for road freight transportation. Interestingly, the overall demand for freight transportation peaks in 2025, and decreases afterwards due to the pathway parametrization (e.g. assumption of circular and sharing economy, etc.).

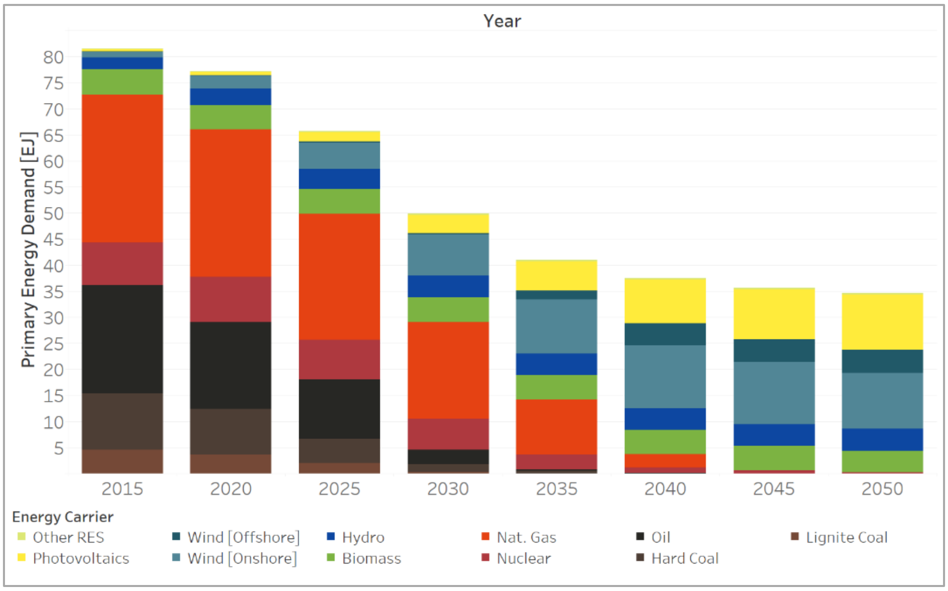


Figure 3-11 Primary Energy until 2050 (Societal Commitment)

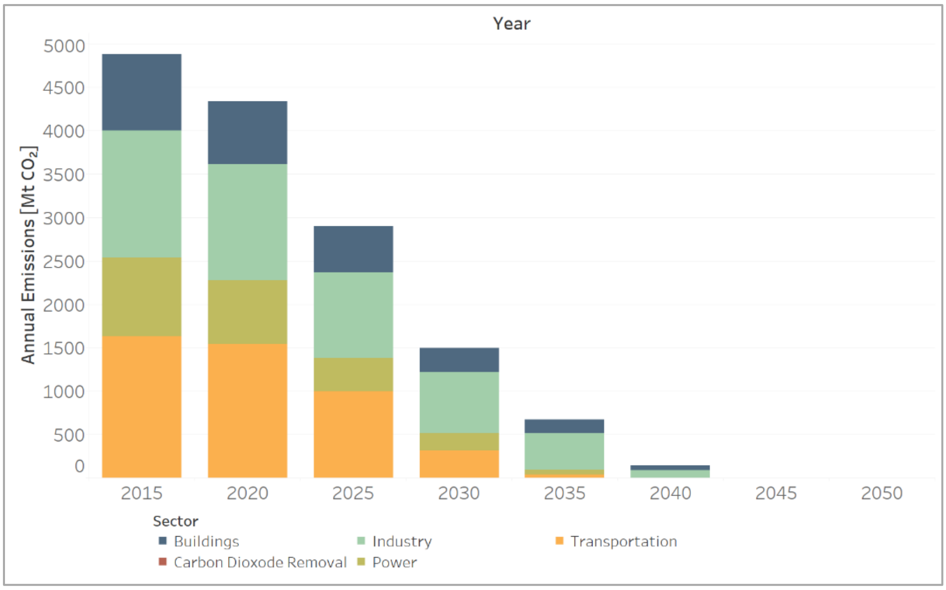


Figure 3-12 Emissions until 2050 (Societal Commitment)

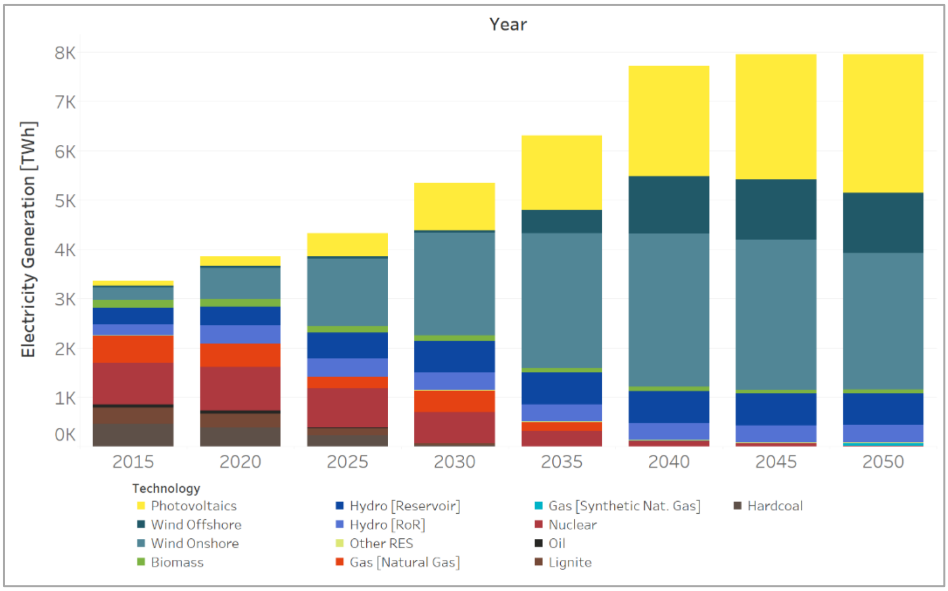


Figure 3-13 Electricity Generation until 2050 (Societal Commitment)

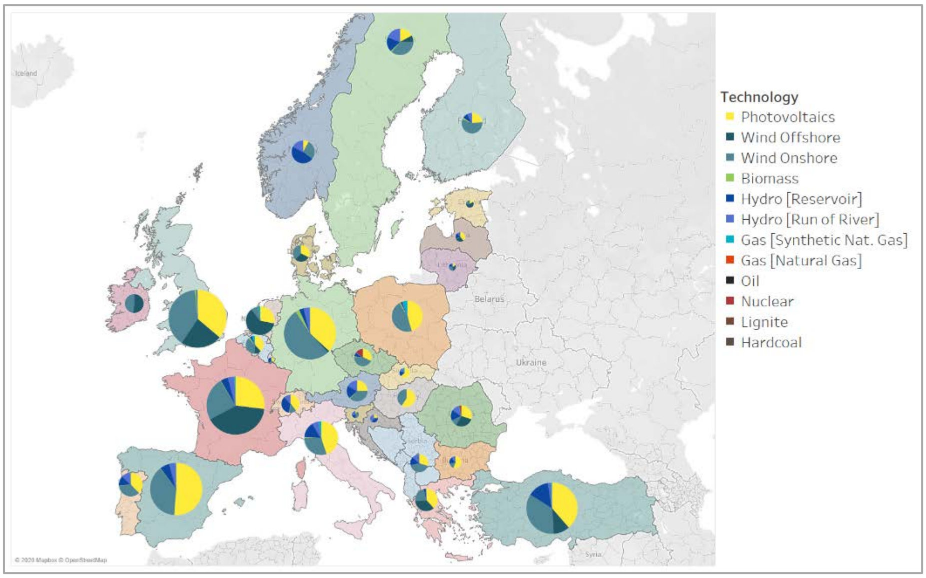


Figure 3-14 Electricity Generation per Country in 2050 (Societal Commitment)

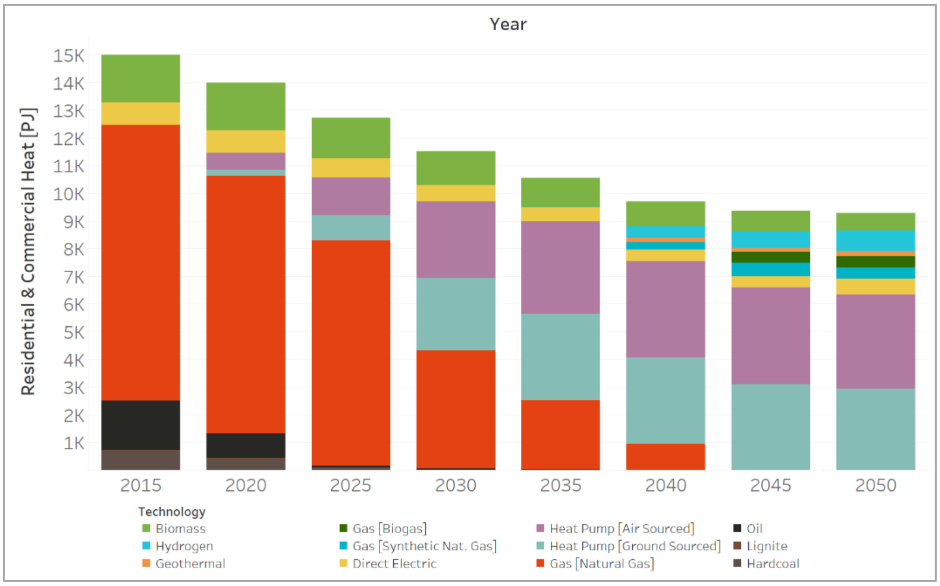


Figure 3-15 Residential and Commercial Heating until 2050 (Societal Commitment)

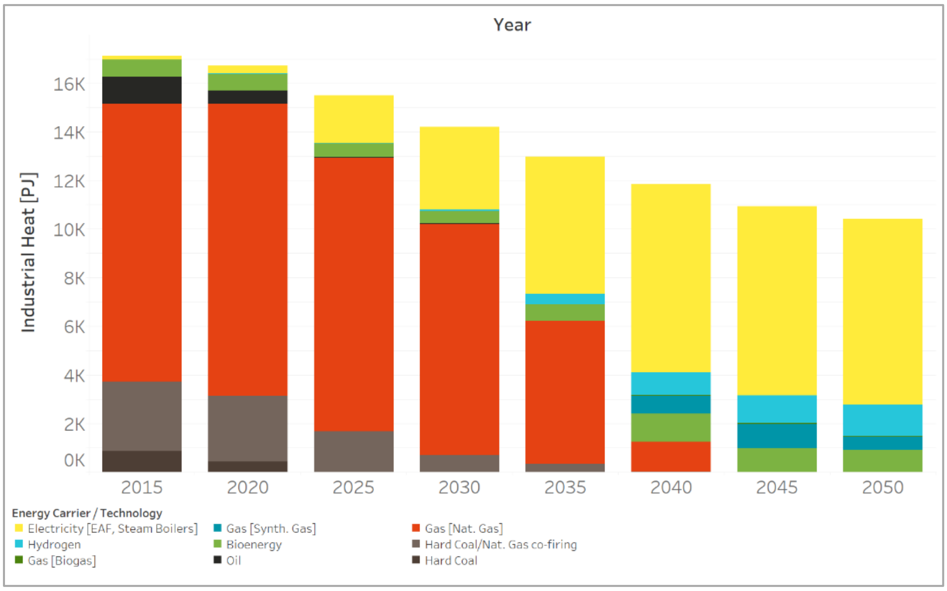


Figure 3-16 Industry (Energy/Technologies) until 2050 (Societal Commitment)

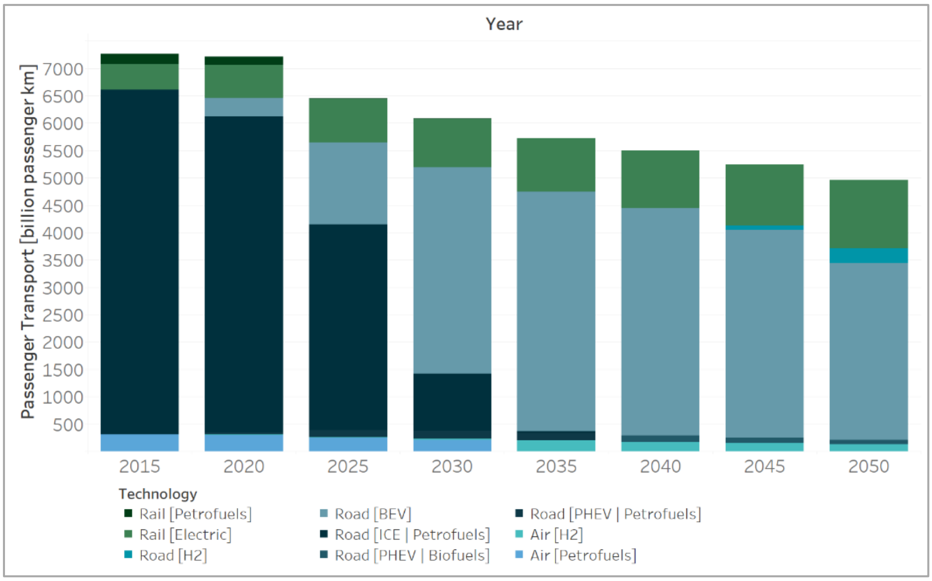


Figure 3-17 Passenger Mobility until 2050 (Societal Commitment)

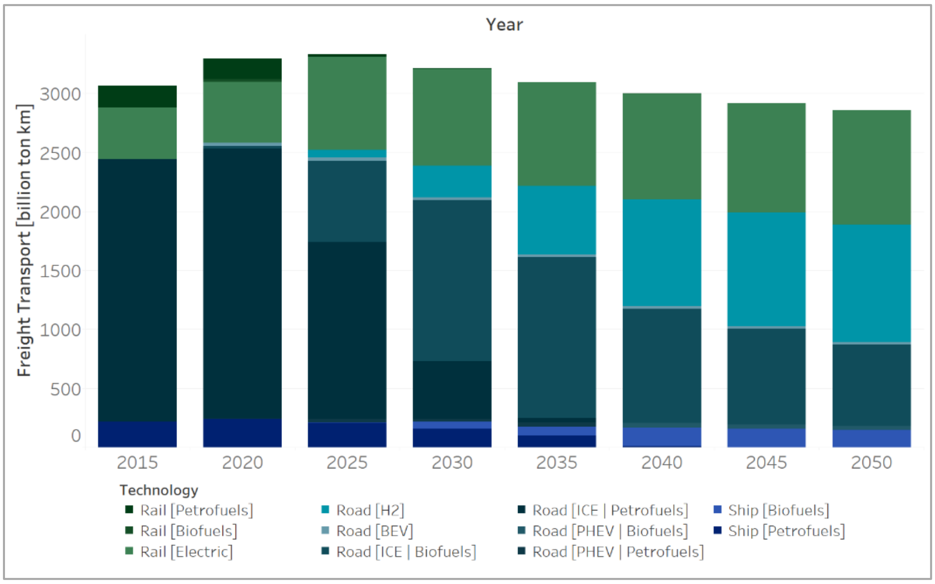


Figure 3-18 Freight Transportation until 2050 (Societal Commitment)

3.2.3 Comparison with "most alike" existing MESSAGEix-GLOBIOM scenario

The scenario selected from the global MESSAGEix-GLOBIOM IAM is an updated version of the "Low Energy Demand (LED)" scenario, [13][25]. This scenario provides a contrasting perspective to other commonly used mitigation scenarios by developing a narrative that results in low energy demand. The quantification of changes in activity levels and energy intensity in the global North and global South is based on observable trends for all major energy services. We project that global final energy demand by 2050 is reduced around 40% compared to current demand levels, despite rises in population, income and activity. The scenario highlights how energy services drive structural change in intermediate and upstream supply sectors (energy and land use). Down-sizing the global energy system dramatically improves the feasibility of a low-carbon supply-side transformation. The scenario meets the 1.5 °C climate target as well as many sustainable development goals, without relying on negative emission technologies.

The two Figures 3.19 & 3.20 below compare the scenario quantifications from GENESYS-MOD with the LED scenario in terms of total (primary) energy demand in Europe and the fuel mix in the electricity-sector. Both the *Societal Commitment* quantification and the LED scenario show a complete transition to a mix of biomass and non-biomass renewables in the next decades. Natural gas plays a minor role in the LED scenario until the middle of the century, whereas it is phased-out completely already in 2045 in the *Societal Commitment* quantification.

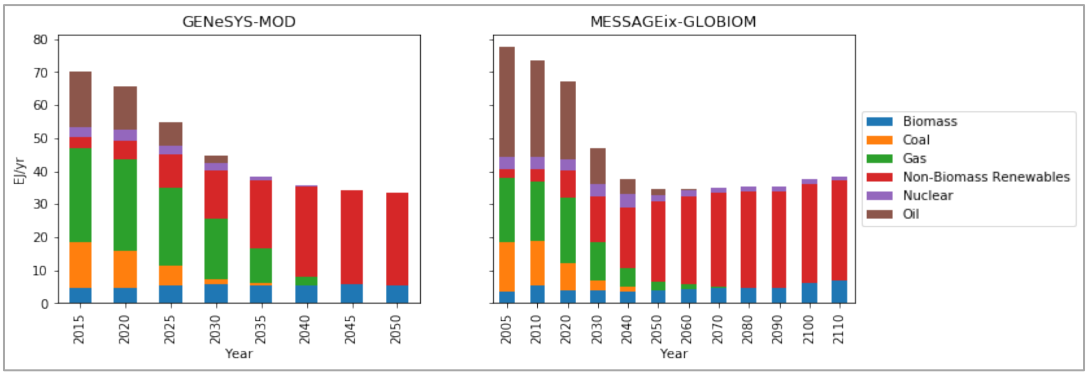


Figure 3-19 Societal Commitment - Comparison of pathway quantification with most-alike MESSAGEix-GLOBIOM scenario in terms of primary energy demand

[25] Grubler, A. et al. A low energy demand scenario for meeting the 1.5 °C target and sustainable development goals without negative emission technologies. *Nature Energy* 3:515–527 (2018) doi: 10.1038/s41560-018-0172-6

Comparing the demand level and fuel mix in the electricity sector, both models exhibit growing electrification, though the rate of increase diminishes in the *Societal Commitment* quantification towards the end of the GENESYS-MOD model horizon. Nuclear energy is virtually phased out in the *Societal Commitment* quantification by 2050, whereas it continues to play a minor role throughout the second half of the century in the LED scenario.

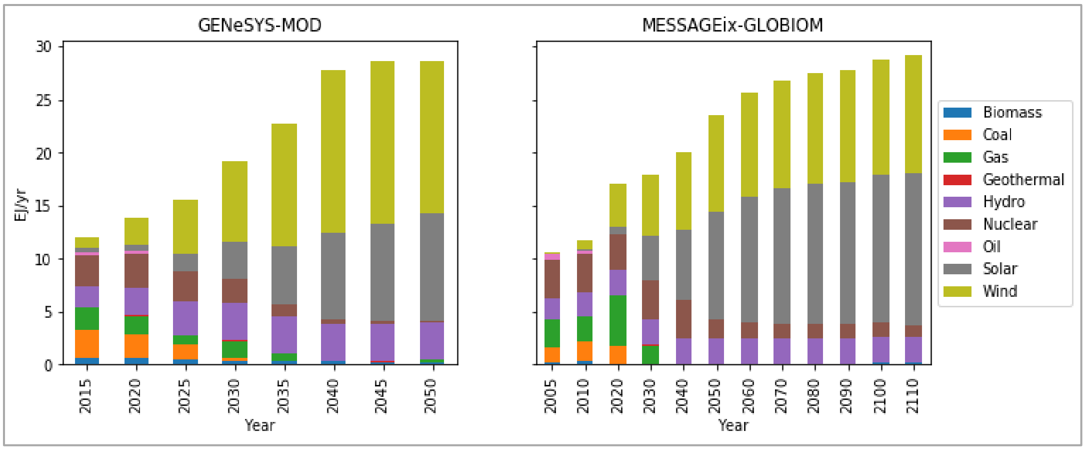


Figure 3-20 Societal Commitment - Comparison of pathway quantification with most-alike MESSAGEix-GLOBIOM scenario in terms of electricity fuel mix

3.3 Techno-Friendly: glance of results

3.3.1 Recall of main features of this storyline and parametrization of model

This storyline focuses on the promising breakthrough of novel technologies (incl. floating offshore wind, H_2, and CCS), being rolled out on a large-scale to meet energy and transport service needs. In addition, this storyline is characterised by the positive attitude of society towards large-scale infrastructure projects mitigating the climate challenge. A strong globalized market-pull triggers technology choice and implementation. Active policymaking is pushed into the background. As a consequence of sufficient low-carbon technology availability, energy demand reductions and active demand side participation of consumers/prosumers are less important, but still needed.

When it comes to the parametrization of this storyline for GENeSYS-MOD, multiple technology and infrastructure based characteristics are being incorporated. Generally, they can be classified into two groups of adaptations: (i) features usually not considered by the model are now included, and (ii) existing features are being changed to reflect the characteristics of the storyline.

With respect to the first group, a number of technologies is now available for the model to being used. These include Carbon Capture and Storage (CCS) capacities, significant net hydrogen (H_2) imports to Europe, and the inclusion of certain breakthrough technologies like Direct Air Capture (DAC) or trucks powered by an overhead power line. These technologies follow cost and efficiency projections, which usually makes them very unattractive in the current time periods, but opens up their possibility to significantly contribute in the later periods.

As for the second group of adaptations, these are features and functionalities already included in the basic formulation of the GENeSYS-MOD, but are being reevaluated for the purpose of this exercise. First of all, as the title of the storyline already suggests, optimistic values for cost and efficiency development of technologies under consideration are implemented. Higher technological learnings can be seen for technologies, which are currently in a less mature state of development, showcasing their potential for a breakthrough. Additionally, new capacities can be built at a higher implementation rate between two periods since infrastructure investments and capacity expansions are facilitated through the storyline. A medium to high carbon price is included as is a cross-sectoral and cross-regional emission trading system (ETS). Fossil fuel prices drop due to lowered demand, yet the combination of the carbon price and technology improvements of carbon-free technologies offset this reduction in prices.

3.3.2 Selected GENeSYS-MOD scenario results

Primary energy use is reduced by around 50% until 2050 (compared to 2020). In terms of fossil fuels, there is not only a significant reduction of oil use (phase-out in 2040), but also a significant reduction of natural gas, visible already until 2040. Similarly, coal usage sees a decline until 2040. The remaining quantities of both natural gas and coal are coupled to the availability of CCS technologies, which become available in 2025 and play a role in the industry and power sector. These changes are also seen in the emission graph, where the energy system is almost decarbonized by 2040 and use of negative emission technologies is observable as soon as 2025.

The power sector is rapidly decarbonized until 2030 with only small amounts of natural gas remaining, which is being neutralized due to the availability of CCS. Renewable electricity generation development is characterized by a slight increase of hydropower, a significant steady further increase of onshore wind, and a significant take-off of offshore wind and a significant take-off of solar PV (mainly utility-scale applications) starting in 2030. A snapshot of the regional distribution of electricity generation in 2050 shows the significant share of solar PV in Southern Europe, hydropower in the Alps and Northern Europe, Wind onshore/offshore in the (North-) Western part of Europe, and the remaining amounts of natural gas in Poland, The Netherlands and UK. Nuclear power steadily decreases and almost disappears until 2050, being only present in the Eastern European Countries and France.

The residential sector is rapidly decarbonized in two steps: (i) in the very short-term until 2025, coal and lignite virtually disappear; (ii) natural gas is reduced to a minimum until 2040. Moreover, the still dominant share of natural gas in 2030 is drastically replaced by electric heat pumps, both, ground and air sourced. In the industry sector, a phase out from oil is observed until 2025. In addition, the dominant share of natural gas is reduced slightly until 2025 and complemented by CCS technologies for hard coal and natural gas. However, natural gas remains relevant in the industrial sector and is only being phased-out by 2040. In addition to these developments, the electrification of the industry sector (EAF, electric steam boilers) significantly increases, notably beyond 2030 with hydrogen becoming increasingly relevant after 2035.

Passenger mobility is characterized by a significant, steady phase-out of petro-fuels until 2040. Use of battery electric vehicles (BEVs) will significantly increase in 2025 with a rapid take-off in 2030 and beyond. BEVs will cover 2/3 of passenger mobility from 2035 onwards. Starting in 2035, the share of H_2-based vehicles (road) will slowly increase which are being facilitated by lower generation costs of hydrogen and available hydrogen imports from outside Europe. The electric rail share will also increase slightly up to 2050. Freight transportation on roads is being dominated by overhead trucks, a unique feature of the techno friendly scenario, complemented by plug-in hybrids which serve as a bridge technology in the intermediate future.

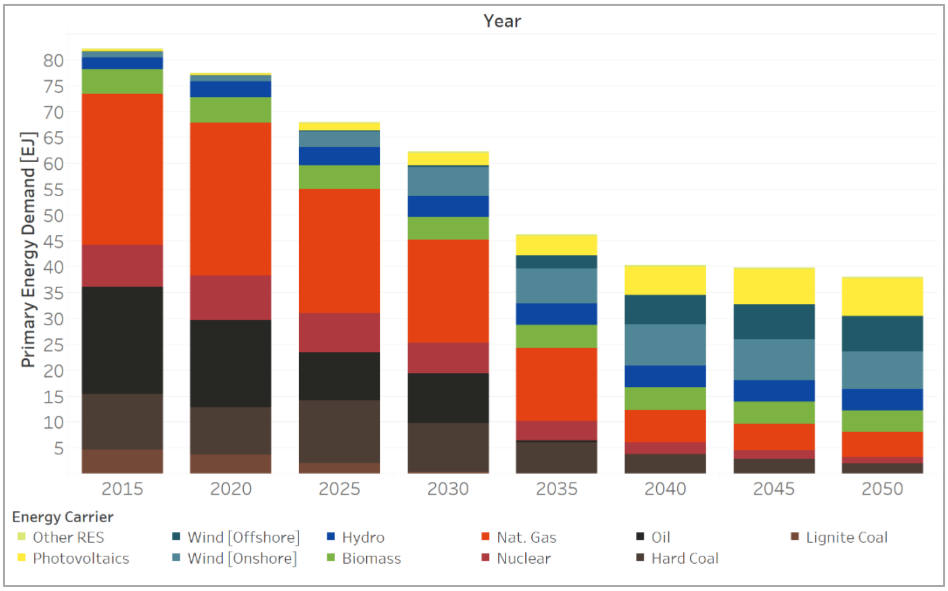


Figure 3-21 Primary Energy until 2050 (Techno-Friendly)

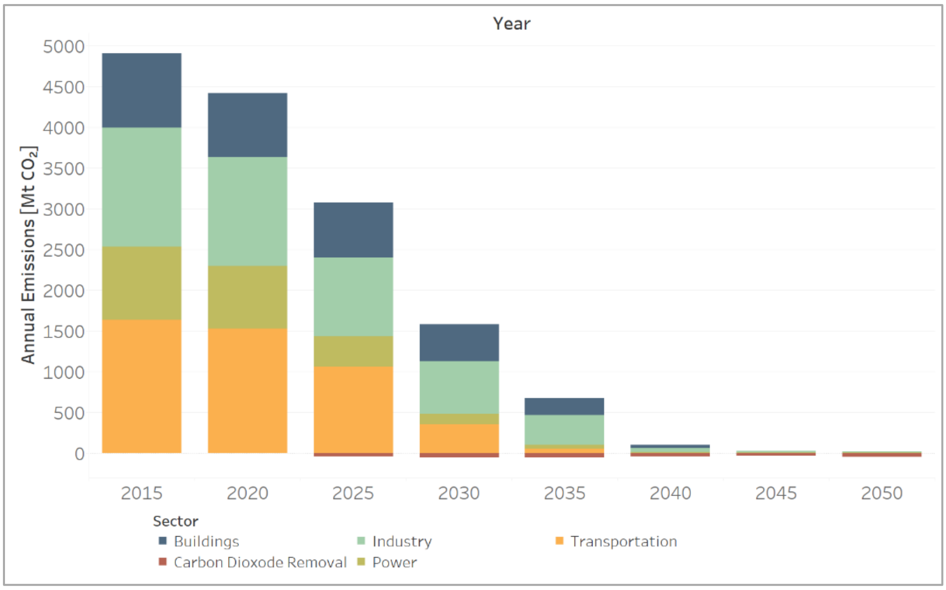


Figure 3-22 Emissions until 2050 (Techno-Friendly)

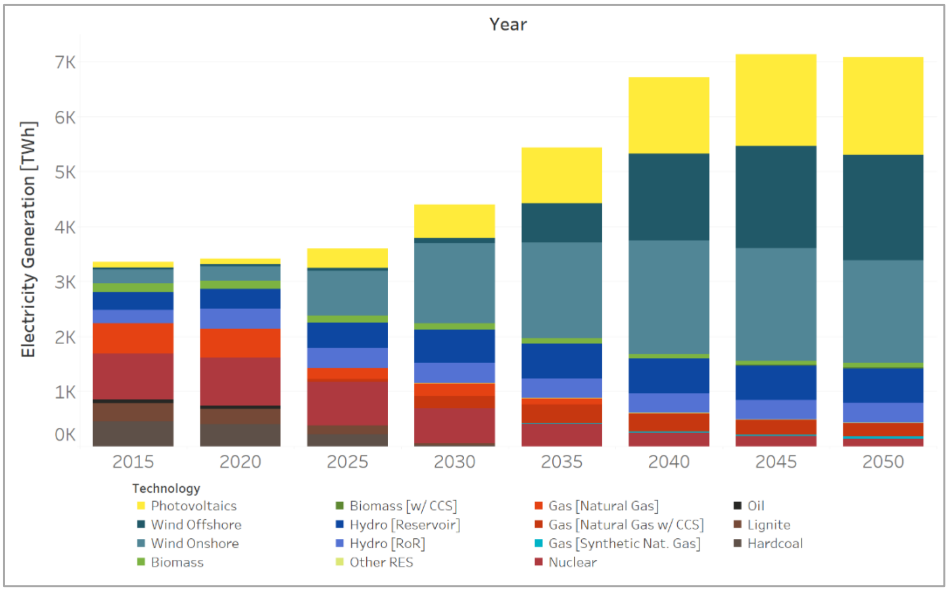


Figure 3-23 Electricity Generation until 2050 (Techno-Friendly)

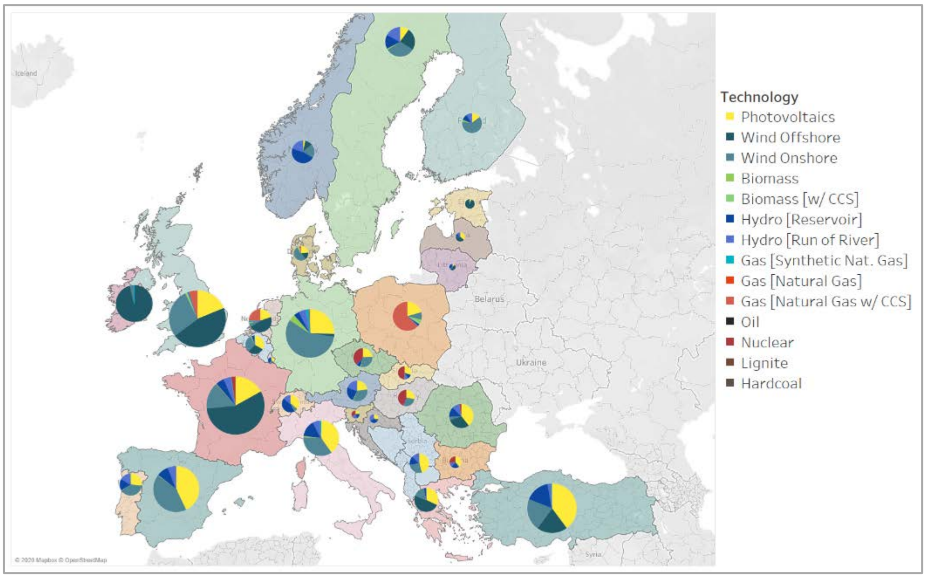


Figure 3-24 Electricity Generation per Country in 2050 (Techno-Friendly)

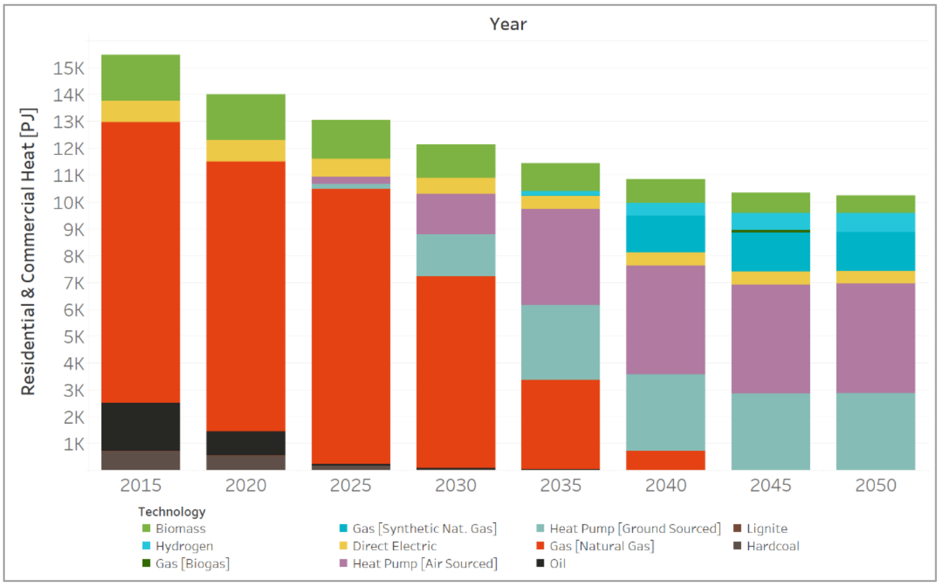


Figure 3-25 Residential and Commercial Heating until 2050 (Techno-Friendly)

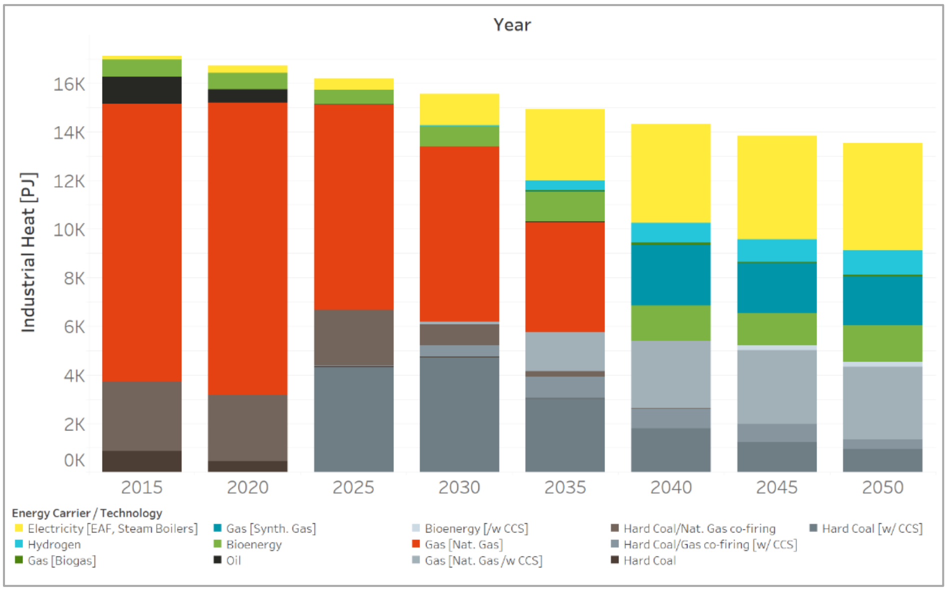


Figure 3-26 Industry (Energy/Technologies) until 2050 (Techno-Friendly)

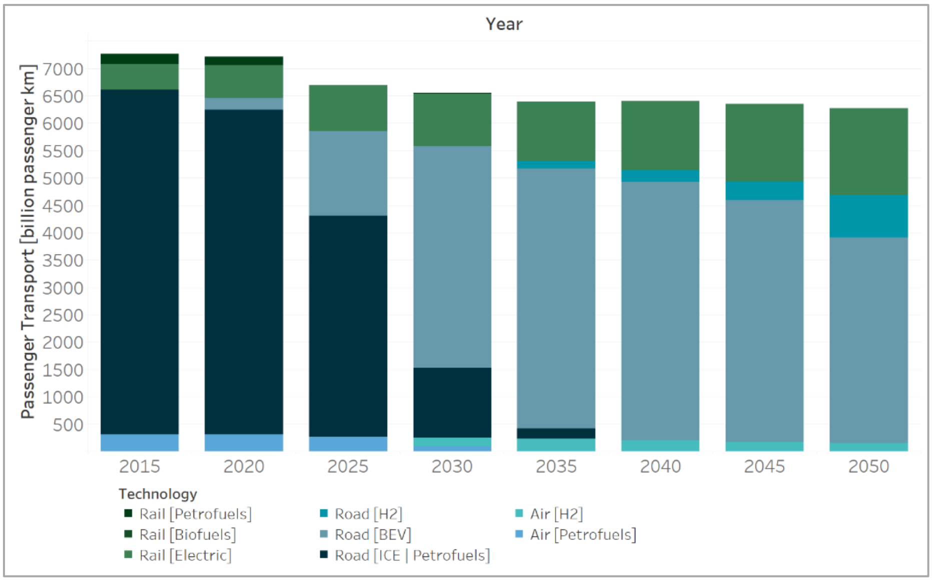


Figure 3-27 Passenger Mobility until 2050 (Techno-Friendly)

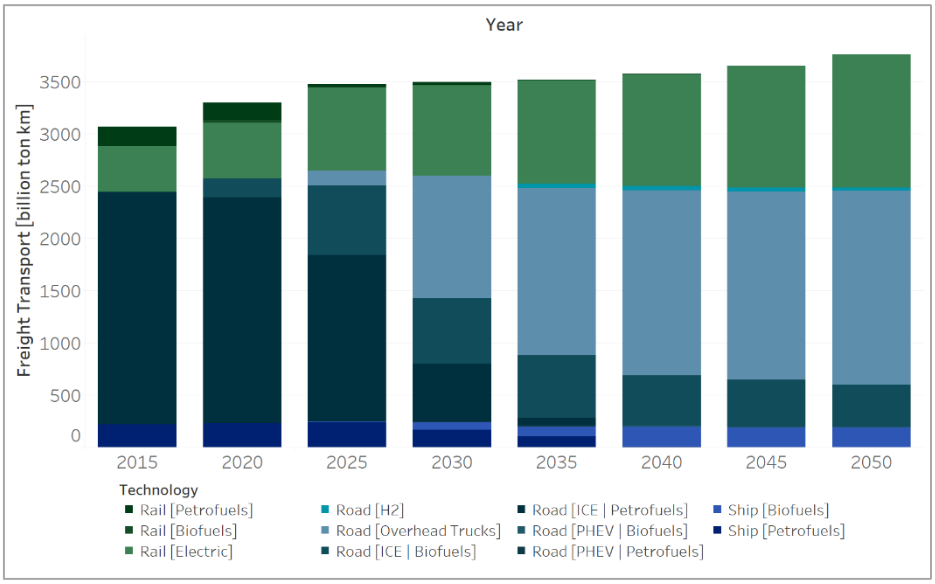


Figure 3-28 Freight Transportation until 2050 (Techno-Friendly)

3.3.3 Comparison with "most alike" existing MESSAGEix-GLOBIOM scenario

The scenario selected from the global MESSAGEix-GLOBIOM IAM is the "NPi2020_400_SSP1_V4" scenario developed in the Horizon 2020 project CD-LINKS. This scenario has not yet been published in the literature. The scenario assumes an underlying SSP1 trajectory for population and GDP growth as well as technology development. National policies are maintained in line with current regulations until 2020 (the scenario protocol was first specified in 2016), and the cumulative greenhouse gas emissions for 2011-2100 period stay below 400 GtCO_2e budget. This corresponds to a >66% chance of staying below 1.5°C at the end of the century.

The two Figures 3.29 & 3.30 below compare the scenario quantifications from GENESYS-MOD with the LED scenario in terms of total (primary) energy demand in Europe and the fuel mix in the electricity-sector.

The notable difference of the *Techno-Friendly* quantification is that coal continues to play a minor role until the year 2050; this can also be observed in the NPi2020_400_SSP1_V4 scenario. Similar as in the section comparing the *Directed Transition* quantification to the most-alike MESSAGEix-GLOBIOM scenario, GENESYS-MOD exhibits a strong demand reduction, whereas the MESSAGEix-GLOBIOM scenario shows increasing demand after an initial reduction and natural gas plays a major role as a transition fuel.

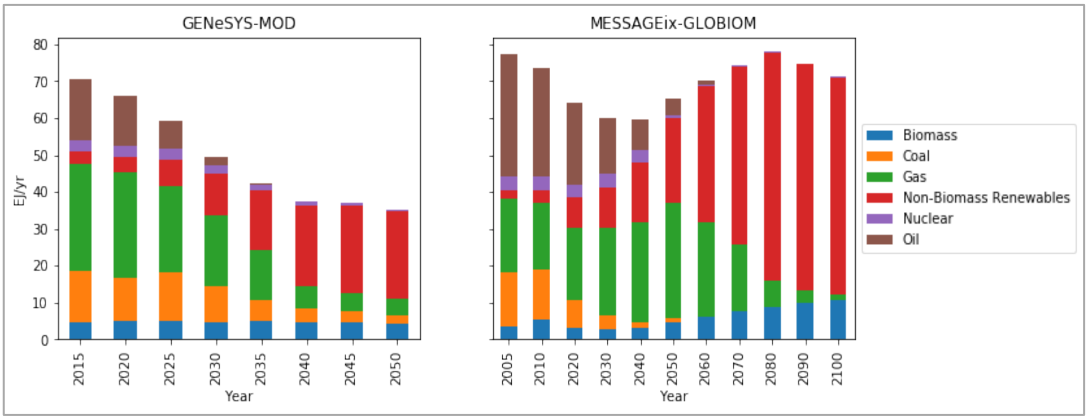


Figure 3-29 Techno-Friendly - Comparison of pathway quantification with most-alike MESSAGEix-GLOBIOM scenario in terms of primary energy demand

As already evident in the primary-energy development in the Figure 3.29 above, natural gas plays a crucial role as a bridge fuel in the NPi2020_400_SSP1_V4, whereas it only contributes a minor share of the electricity fuel mix in the *Techno-Friendly* quantification.

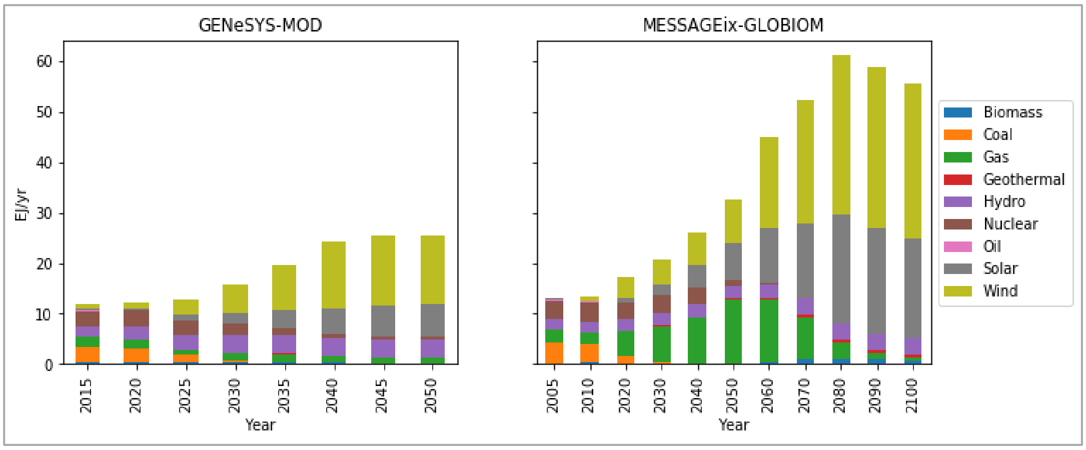


Figure 3-30 Techno-Friendly - Comparison of pathway quantification with most-alike MESSAGEix-GLOBIOM scenario in terms of electricity fuel mix

3.4 Gradual Development: glance of results

3.4.1 Recall of main features of this storyline and parametrization of model

This storyline entails ingredients of *'a little of each'* of the remaining openENTRANCE storylines and therefore represents an already ambitious reference scenario in openENTRANCE.[26] The uniqueness of this storyline is that it describes the challenging energy transition with an equal part of societal, industry/technology, and policy action. Several of these three dimensions take responsibility and deliver tailor-made contributions to reach the least ambitious climate mitigation target (2°C; remaining storylines envisage 1.5°C). Carbon pricing in this scenario is more conservative compared to the others.

Compared to the other three pathways, instead of focusing on one specific aspect, features and characteristics from *Techno-Friendly*, *Societal-Commitment*, and *Directed Transition* are included in this pathway. Since this pathway culminates in a decarbonization by 2050, the transformation of the energy system is not as drastic as in the other three and measures are more moderate. Therefore, as already mentioned in the previous paragraph, the carbon price, which is implemented in GENeSYS-MOD, is substantially lower.

Costs and efficiencies of all technologies are changed slightly to reflect the pathway characteristics, similar to the *Techno-Friendly* implementation. Yet, the values are less optimistic and improvements happen at a slower rate. Also, novel and not already proven technologies are not integrated (e.g. Direct Air Capture, overhead trucks, Carbon Capture and Storage) and there is no option foreseen to have net imports of hydrogen from regions outside of Europe.

Similar to *Societal Commitment*, this pathway is also characterized by reductions in energy demand of all different sorts. These reductions, however, are less substantial as in *Societal Commitment* and, additionally, the potential for demand shifting is far more limited.

[26] It is important to note here again (see also Deliverable D7.1) that openENTRANCE storylines/scenarios intentionally avoid the *"Business-as-Usual (BAU)"* nomenclature having been (and being) widely used in the energy system modelling community and corresponding policy making. As already stated in the first sentence of this Section 3.4.1, the *Gradual Development* storyline/scenario is denoted to describe something more ambitious already that what is traditionally understood as *Business-as-Usual (BAU)* in the community. Moreover, if somebody has in mind that *Business-as-Usual* rather is a prolongation of past and existing patterns of energy system development and energy policies with simply a bid higher ambitions than in the past (without anticipating significant deviations/disruptions of the different determinants (technology/society/policy) determining the future energy system) this might not be sufficient at all to achieve at least conservative global temperature increase targets far above 2°C. Having said that, the questions arises, if the *Business-as-Usual* nomenclature possibly might be outdated (both in energy system modelling and policy making) when trying to mitigate the global warming challenges ahead.

3.4.2 Selected GENeSYS-MOD scenario results

Primary energy demand sees a similar development compared to the *Techno-Friendly* pathway and sees a reduction of nearly 50% in 2050 compared to 2020. Oil and natural gas play a significant role even until 2040 but are phased-out thereafter to achieve the carbon neutrality targets in 2050. Contrary, hard coal and lignite are phased-out until 2040. The lesser carbon price compared to the other scenarios result in significantly higher emissions in 2040. However, the carbon price is high enough to lead to nearly net-zero emissions from 2045 on.

A rapid phase-out of coal until 2030 can be observed in the electricity sector, followed by a phase-out of natural gas until 2040. Overall, the decarbonization of the electricity sector is completed in 2040. The predominant electricity generation technologies are wind onshore, followed by wind offshore and solar PV. Also, hydropower and nuclear power plants provide baseload capacities in this predominantly renewable European power system. Looking at the regional distribution, a similar pattern compared to the *Techno-Friendly* pathway can be observed. Wind Onshore capacities are built in most of the European countries with most of the offshore wind capacities additionally installed in the North Sea. Nuclear is still utilized in 2050 with capacities located in France and the eastern European countries.

In the residential and commercial heating sector, the subsequent addition of heat pumps replaces natural-gas-based heating systems from 2025 on. Heating by coal and oil-based boilers are phased-out very fast. In the later model periods, hydrogen and synthetic methane are added to the technology mix, and natural gas-based heating is reduced to a minimum. Still, the heating sector is not fully decarbonized in 2050.

Similarly, the industrial heating generation sees a steady reduction in natural gas usage and later additions of hydrogen (despite high prices) and synthetic methane. Contrary to residential and commercial heating, coal is kept longer in the system and is only completely phased-out in 2045. Also, the industrial heating sector sees a high usage of electrified technologies, which results in an electrification rate of around 60%.

The transportation sector sees a twofold development. Overall, in both freight and passenger transport, low carbon technologies play a significant role in 2050. However, the passenger sub-sector is characterized by large shares of BEVs with additional hydrogen-based transportation options being introduced from 2035 onwards. Contrary, freight transportation is mainly based on hydrogen trucks and electric rail-based transportation. However, BEVs are introduced earlier compared to hydrogen trucks, but their share in the technology mix stays small.

Overall, this pathway is the only scenario where no imminent decarbonization in 2040 can be observed. Instead, albeit CCS technologies not being available, a nearly complete decarbonization of the whole energy system is reached in 2050, which requires strong measures in the later years.

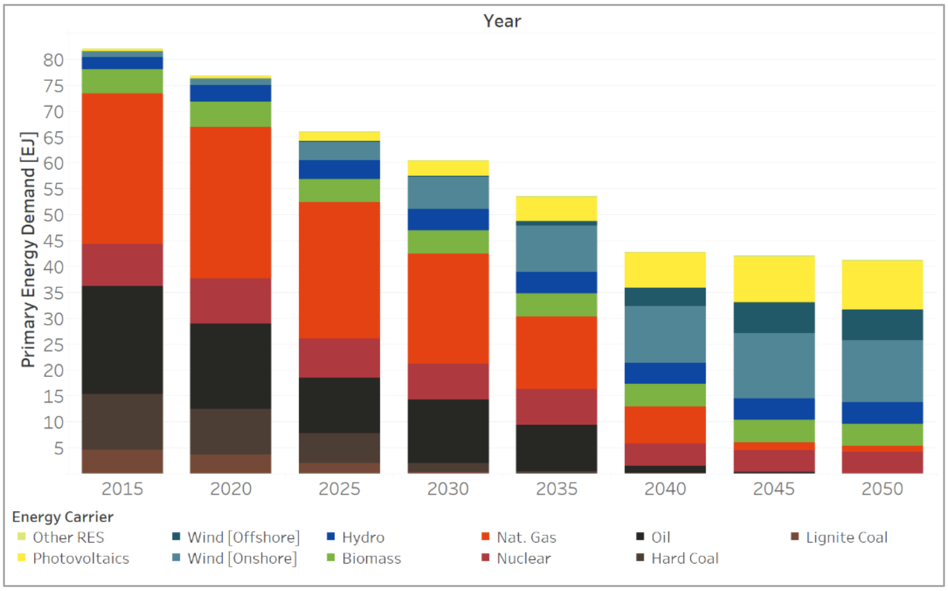


Figure 3-31 Primary Energy up to 2050 (Gradual Development)

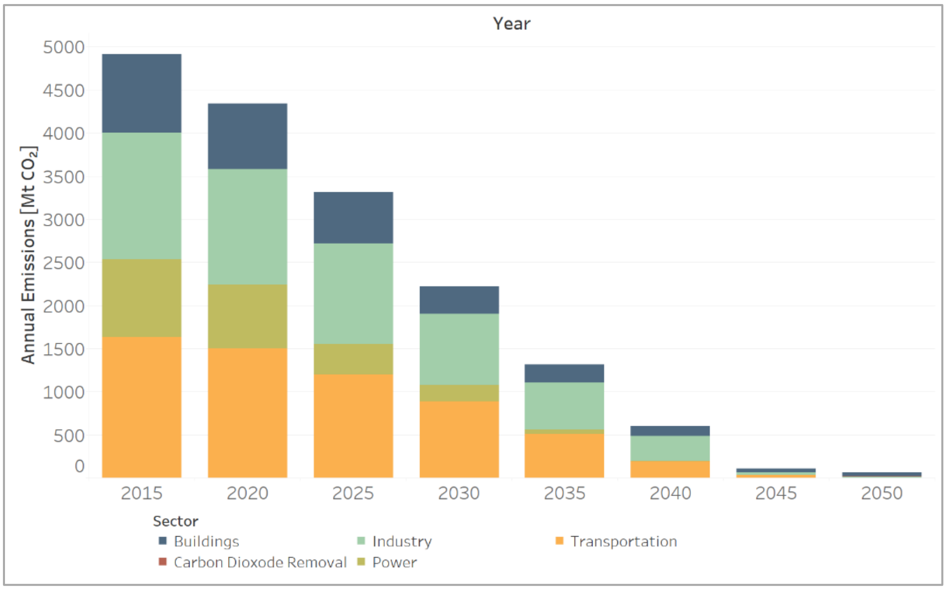


Figure 3-32 Emissions up to 2050 (Gradual Development)

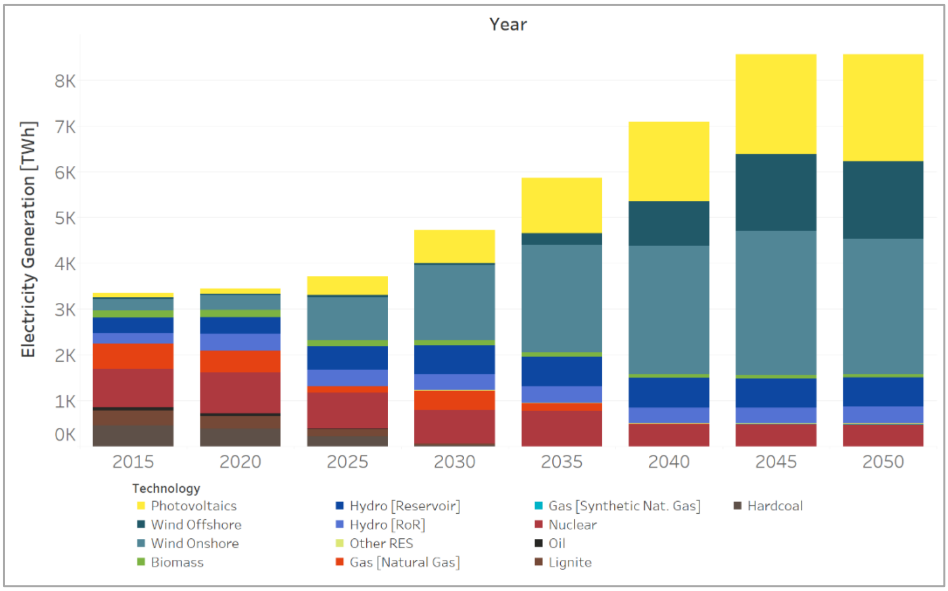


Figure 3-33 Electricity Generation up to 2050 (Gradual Development)

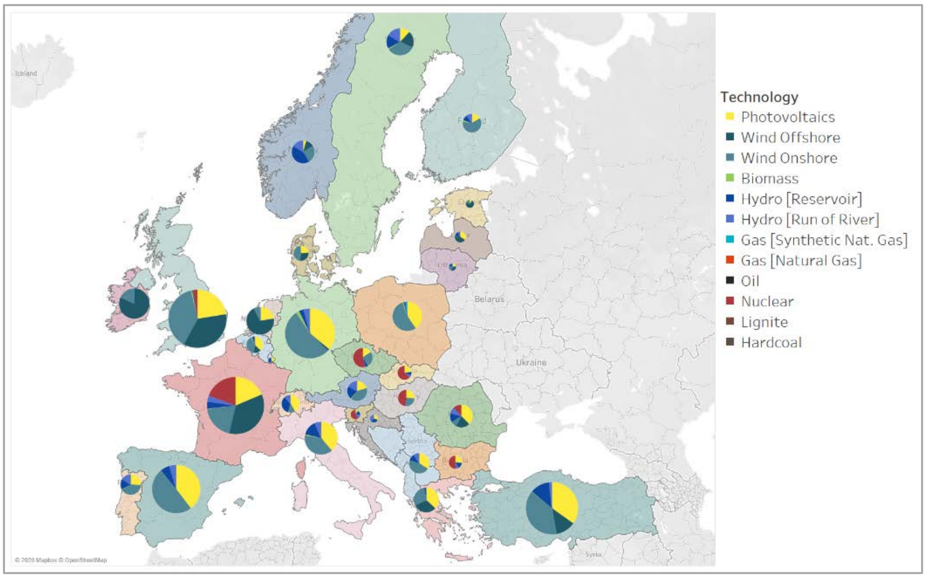


Figure 3-34 Electricity Generation per Country in 2050 (Gradual Development)

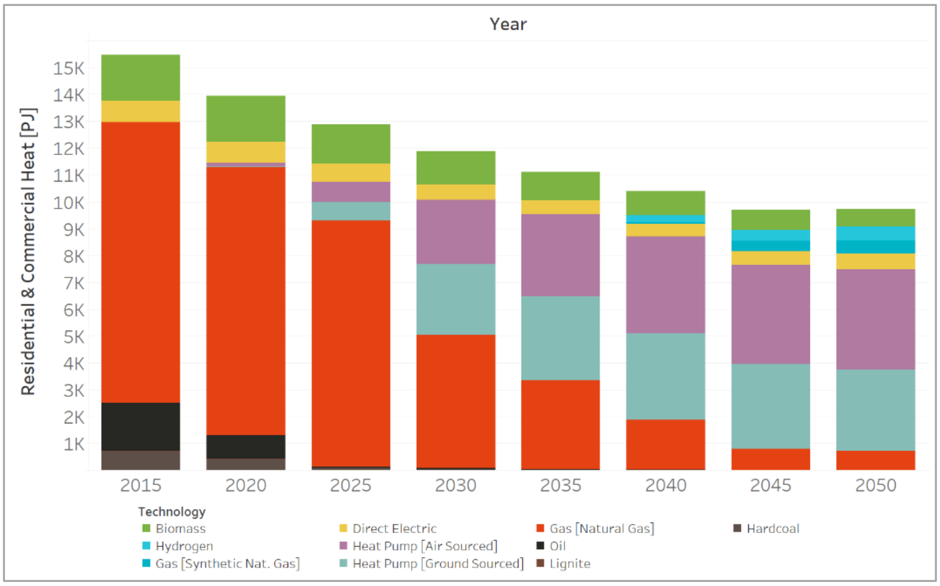


Figure 3-35 Residential and Commercial Heating up to 2050 (Gradual Development)

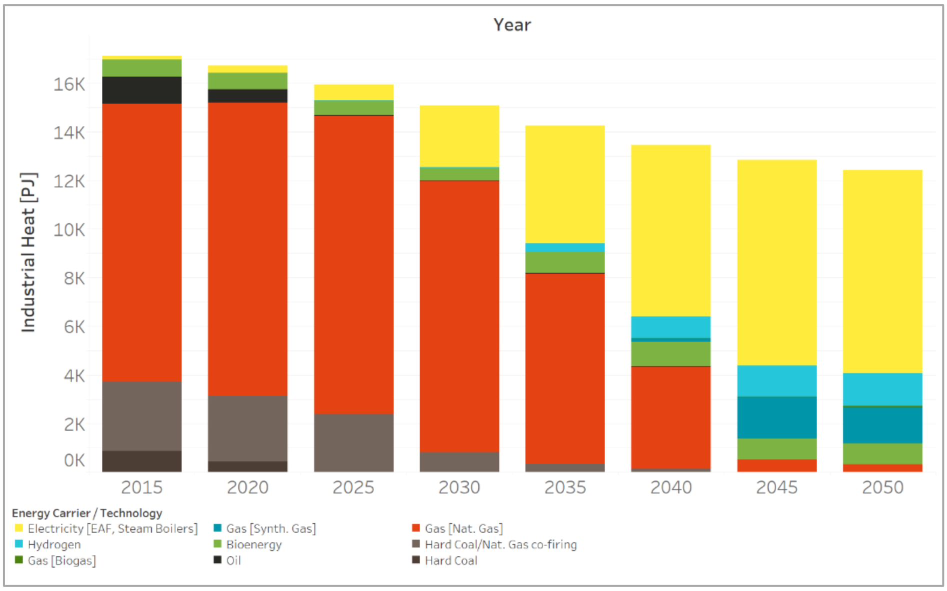


Figure 3-36 Industry (Energy/Technologies) up to 2050 (Gradual Development)

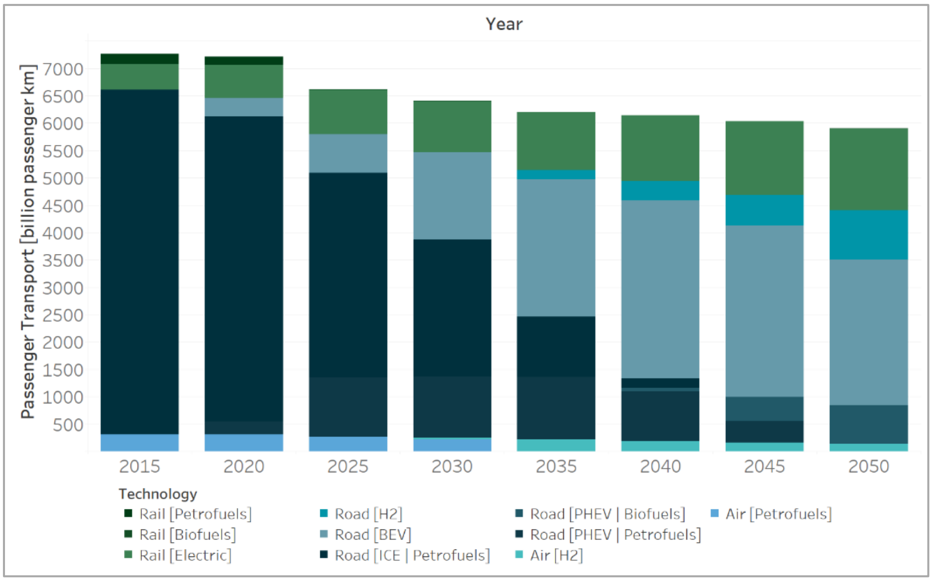


Figure 3-37 Passenger Transport up to 2050 (Gradual Development)

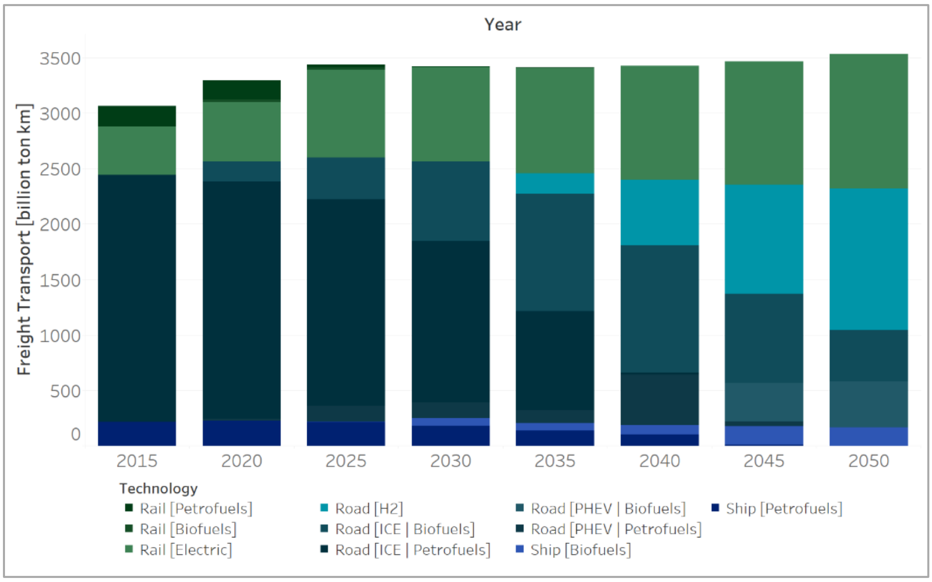


Figure 3-38 Freight Transport up to 2050 (Gradual Development)

3.4.3 Comparison with "most alike" existing MESSAGEix-GLOBIOM scenario

The scenario selected from the global MESSAGEix-GLOBIOM IAM is the "NPi2020_1000_V4" scenario developed in the Horizon 2020 project CD-LINKS. The quantification is an updated version of the scenario published in the literature, [14][27], and used in the quantitative scenario ensemble underpinning the IPCC Special Report on Global Warming of 1.5°C. The scenario assumes an underlying SSP2 trajectory for population and GDP growth as well as technology development. National policies are maintained in line with current regulations until 2020 (the scenario protocol was first specified in 2016), and the cumulative greenhouse gas emissions for 2011-2100 period stay below 1000 $GtCO_2e$ budget. This corresponds to a >66% chance of staying below 2.0°C at the end of the century.

The two Figures 3.39 & 3.40 below compare the scenario quantifications from GENeSYS-MOD with the LED scenario in terms of total (primary) energy demand in Europe and the fuel mix in the electricity-sector. The NPi2020_1000_V4 scenario is the least ambitious pathway from current MESSAGEix-GLOBIOM scenarios used as most-alike references in this report. Consequently, it exhibits the slowest transition to renewables; coal continues to play a role until the end of the century. In contrast, the *Gradual Development* quantification is also less ambitious than other storylines described in openENTRANCE but still transitions to an almost fully decarbonized energy system by the year 2050.

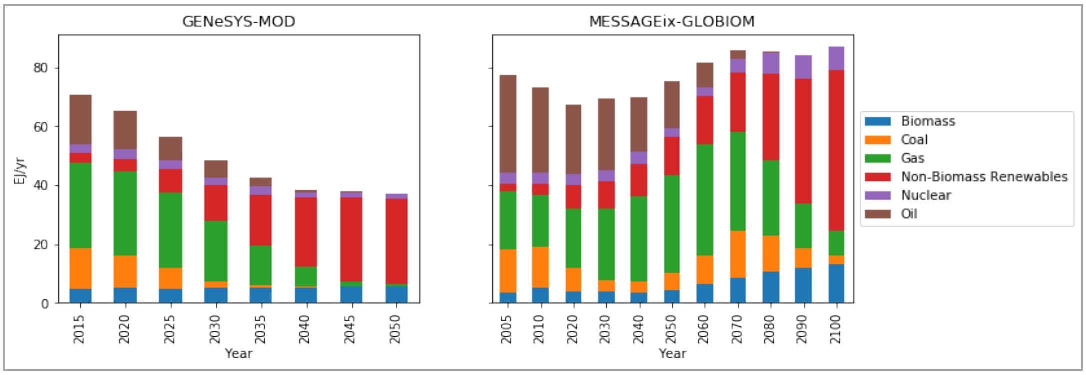


Figure 3-39 Gradual Development - Comparison of pathway quantification with most-alike MESSAGEix-GLOBIOM scenario in terms of primary energy demand

[27] McCollum, D.L. et al. Energy investment needs for fulfilling the Paris Agreement and achieving the Sustainable Development Goals. *Nature Energy* 3, 589–599 (2018). doi: 10.1038/s41560-018-0179-z

As in previous comparisons, most MESSAGEix-GLOBIOM scenarios rely on natural gas as a bridge fuel around the middle of the century, whereas GENESYS-MOD reduces energy demand generally and exhibits stable electricity demand towards the end of its model horizon. One observation that holds in both the *Gradual Development* quantification and the NPi2020_1000_V4 scenario is that nuclear power plays a comparable role, providing a stable contribution to the energy mix throughout the model horizon.

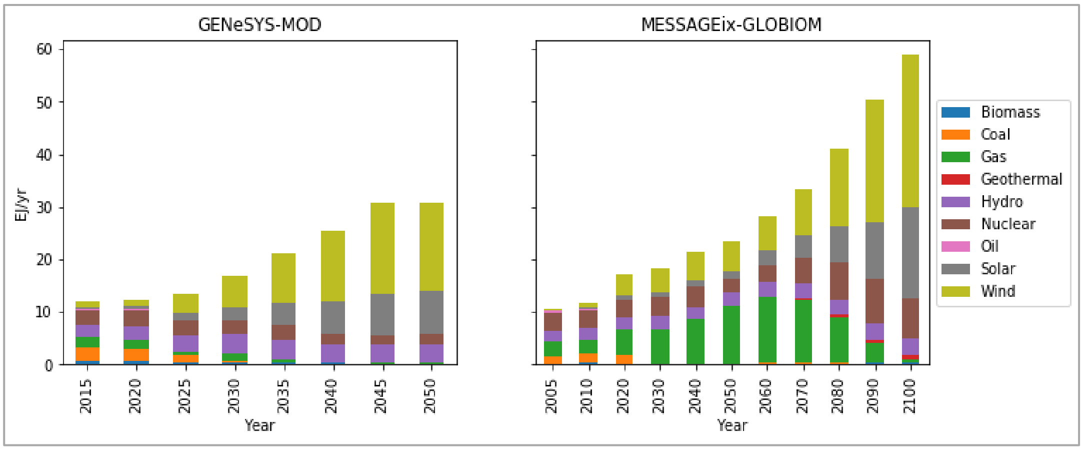
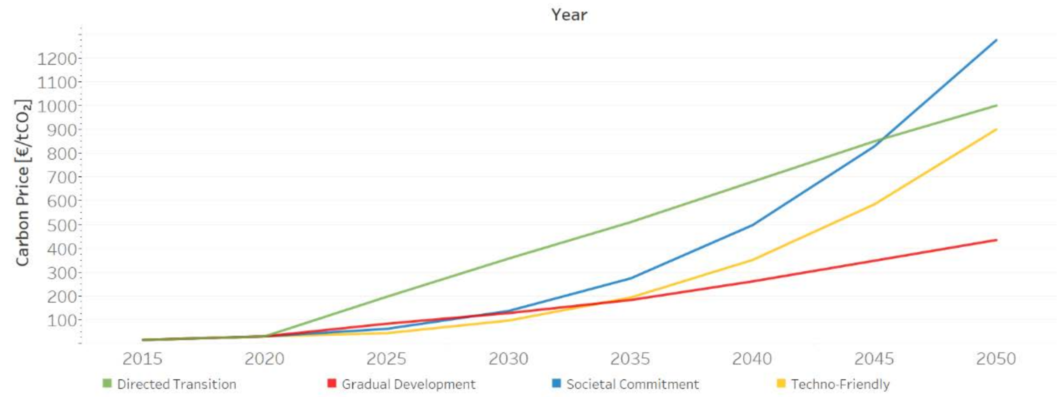


Figure 3-40 Gradual Development - Comparison of pathway quantification with most-alike MESSAGEix-GLOBIOM scenario in terms of electricity fuel mix

3.5 General comparison of GENeSYS-MOD scenario results

One of the primary differences between the four calculated openENTRANCE scenarios are the implemented carbon prices and their respective developments. For *Gradual Development*, *Societal Commitment*, and *Techno-Friendly* an exponential development with a low carbon price in the first model periods and a high price in the later periods is implemented. For *Directed Transition*, on the other hand, a linear growth of the carbon price is assumed. This results in substantially higher carbon prices in the time period between 2025 and 2040 compared to all other scenarios, due to the strong policy measures put in place. Overall, in 2050 *Societal Commitment* requires the highest carbon price to reach its 1.5°C compatible pathway goal with 1275€/tCO_2 (mostly due to the absence of carbon dioxide removal technologies being available making a complete carbon neutrality challenging), followed by *Directed Transition* with a required carbon price of 1000€/tCO_2, see Figure 3.41.



Pathway	2015	2020	2025	2030	2035	2040	2045	2050
Directed Transition	15	30	196	357	510	680	850	1,000
Gradual Development	15	30	83	128	183	261	348	435
Societal Commitment	15	30	62	137	273	497	829	1,275
Techno-Friendly	15	30	43	97	193	351	585	900

Figure 3-41 Carbon Price Development for all four Scenarios

Comparing the general results of all four scenarios, a decrease in primary energy use can be observed, as outlined by the previous sections. In 2050, the primary energy demand has a difference of 10 EJ across the various scenarios. This describes a significant difference. *Societal Commitment*, with its focus on societal change, sees meaningful demand reductions due to a change in lifestyle, as well as demand patterns. *Gradual Development* forms the other end of the spectrum, being the least ambitious scenario (featuring a 2°C compatible target).

Looking at the different installed electricity generation capacities, a general similarity among the scenarios exists when it comes to major dominating renewable technologies (the driving forces, however, are significantly different in the different scenarios): there is a slight increase of hydropower generation and a significant increase of wind (onshore and offshore) as well as PV generation up to 2050. However, the shares of onshore and offshore wind as well as PV are quite different in the different scenarios (e.g. the *Techno-friendly* scenario reaches an equal offshore wind deployment as onshore wind). In addition, also the speed of the capacity deployment varies between the scenarios. Here, *Directed Transition* sees a strong early increase in installed capacities, which stay nearly constant from 2040 onward. Contrary to that, *Gradual Development* sees fewer capacity additions in the earlier model periods, but in 2050, this scenario sees the overall highest installed generation capacities. This is due to the absence of carbon dioxide removal technologies, as well as a lack for strong demand-side reductions compared to other scenarios. Lastly, *Techno-Friendly* has the lowest installed electricity generation and storage capacities of all scenarios, with its much stronger reliance on hydrogen. Regarding storage capacities, all scenarios see the same development as for the overall capacities. *Directed Transition* has the earliest addition of storage capacities but is topped in 2045 and 2050 by *Gradual Development* and *Societal Commitment*. The observed patterns of the installed electricity generation capacities are also visible when looking at the actual power generation per year.

The (politically enforced) early transformation of the energy system in the *Directed Transition* scenario is also eminent when looking at the hydrogen usage per scenario. Regarding the role of hydrogen in the future European energy system, significant differences across the scenarios can be observed. For example, whereas in the *Societal Commitment* and *Techno-Friendly* scenario the hydrogen usage increases significantly between 2035 and 2040 and reaches a high share in 2050, the *Gradual Development* sees a rather late adoption towards 2050 only.

In addition, further electrification of the energy system in several sectors plays a core role in all scenarios. In the residential and commercial sector, this mainly comprises fuel-switch to heat pumps, in the industry sector the increasing electrification of process heat and in the transport sector this reaches from BEV and electric rail to overhead trucks. The *Techno-friendly* scenario shows the smallest share of electrification in the industrial and transport sector due to the availability of carbon dioxide removal technologies.

Regarding CO_2 emissions, the *Techno-Friendly* and *Societal Commitment* scenario face nearly the same development. Both see nearly a complete decarbonization from 2040 onwards, with *Techno-Friendly* even having negative Emissions in 2045 and 2050. Contrary to *Techno-Friendly* and *Societal Commitment*, *Directed Transition* has a substantial early decrease of CO_2 emissions and, therefore, the lowest emissions of all scenarios between 2025 and 2040. On the other hand, *Gradual Development* has the highest emissions of all scenarios from 2025 onwards. Still, this scenario reaches nearly net-zero emissions in 2050. The availability of carbon dioxide removal technologies also has a significant influence on the scenario results, when strong climate targets, such as limiting the global temperature increase to 1.5°C, are enforced. The two scenarios without any carbon dioxide removal technologies top the charts in required electricity generation and capacities, usually (among others) due to high amounts of electrolysis to produce renewable hydrogen.

Figure 3-42 Comparison of Key Indicators for all four Scenarios

The pan-European openENTRANCE scenario results show that a strong policy enforcement of climate goals in the short-term does drastically affect the speed of the energy transition. Especially when considering the accumulated emissions, *Directed Transition* with its lower short-term emissions leads the way. While the other scenarios also reach their designated climate targets, the decarbonization process moves further into the future, since break-through technologies and societal behavior require significant time to change. Moreover, this is accompanied with the risk (from today's point-of-view), that the technology breakthrough and lifestyle change of society actually takes place in time.

As a resume of the comparative analysis of the quantitative pan-European openENTRANCE scenario results in the following a selection of some of the most important findings are listed which need further investigations in the different modeling and case study activities in the ongoing project, before final conclusions and policy recommendations can be formulated at the end of the openENTRANCE project:[28]

- If we are going to limit the global temperature increase to 1.5 °C (and in this context conduct our "homework" in Europe), significant efforts need to start now!
- Already in 2030 the emissions in Europe must be around 1/3 of today's level only!
- This underlines the importance of corresponding policy measures to ease the future energy transition in case of reliance on a less risky strategy *(Directed Transition)*!
- A novel technology breakthrough *(Techno-friendly)* or a fundamental society's life style change *(Societal Commitment)* also can meet the ambitious goals, but the risk seems to be higher that the corresponding novelties and adaption processes can be achieved in time in the next decades until 2050!
- Half or more of the residential and commercial heating needs to be provided by heat pumps already in 2035, unless carbon dioxide removal technologies are available!
- The same is true (half or more) for passenger transport and BEV, but already in 2030!
- Removing the last 1/3 of the emissions from 2030 to 2050 expects increases of CO_2 prices several times and remains at high levels in 2050!
- ....

[28] It is important to note, that this report is a "technical report" mainly presenting the four quantitative pan-European openENTRANCE scenario results, building the empirical foundation for further analyses in the ongoing project. Therefore, these findings shall not be interpreted as policy recommendations. Policy recommendations are derived at the end of the openENTRANCE project, after synthesising several important results and findings of the entire project.

4. Implementation of scenario data sets on open platform

To compare, use, and disseminate the results created with the modeling tools utilized in openENTRANCE, a common data platform will be used. This open data platform is built on the IIASA Scenario Explorer that has been built to explore the different modeling results used in the Special Report on Global Warming of 1.5°C (SR15) by the Intergovernmental Panel on Climate Change (IPCC), [15].[29,30] This scenario explorer presents a plethora of quantitative, model-based emission pathways.

To upload the results of each model, common nomenclature and a common data format will be used. Therefore, the results of GENeSYS-MOD also have been transformed into the common openENTRANCE data format (compare Section 2.6). The upload of data to the platform will be accessible via the python packages. For now, a first set of test data has successfully uploaded to the data platform.

model	scenario	region	variable	unit	year	subannual	value
GENeSYS-MOD 2.9.0-oe	Techno-Friendly 0.2	Europe	Primary Energy	EJ/yr	2050	Year	19.565908
GENeSYS-MOD 2.9.0-oe	Techno-Friendly 0.2	Europe	Primary Energy|Non-Biomass Renewables	EJ/yr	2050	Year	19.445190
GENeSYS-MOD 2.9.0-oe	Techno-Friendly 0.2	Europe	Primary Energy|Nuclear	EJ/yr	2050	Year	0.120718
GENeSYS-MOD 2.9.0-oe	Techno-Friendly 0.2	Europe	Secondary Energy|Electricity|Geothermal	EJ/yr	2050	Year	0.056573
GENeSYS-MOD 2.9.0-oe	Techno-Friendly 0.2	Europe	Secondary Energy|Electricity|Hydropower	EJ/yr	2050	Year	4.877374
GENeSYS-MOD 2.9.0-oe	Techno-Friendly 0.2	Europe	Secondary Energy|Electricity|Ocean	EJ/yr	2050	Year	0.000005
GENeSYS-MOD 2.9.0-oe	Techno-Friendly 0.2	Europe	Secondary Energy|Electricity|Solar	EJ/yr	2050	Year	4.925758
GENeSYS-MOD 2.9.0-oe	Techno-Friendly 0.2	Europe	Secondary Energy|Electricity|Wind|Offshore	EJ/yr	2050	Year	3.305083
GENeSYS-MOD 2.9.0-oe	Techno-Friendly 0.2	Europe	Secondary Energy|Electricity|Wind|Onshore	EJ/yr	2050	Year	6.280292
GENeSYS-MOD 2.9.0-oe	Techno-Friendly 0.2	Europe	Secondary Energy|Residential and Commercial He...	EJ/yr	2050	Year	0.000105

Figure 4-1 Snapshot of GENeSYS-MOD results in the openENTRANCE common data format

[29] https://iiasa.ac.at/web/home/research/researchPrograms/Energy/IAMC_Scenario_Explorer.html

[30] Joeri Rogelj, Drew Shindell, Kejun Jiang, et al. Mitigation pathways compatible with 1.5°C in the context of sustainable development, in "Special Report on Global Warming of 1.5°C (SR15)". Intergovernmental Panel on Climate Change, Geneva, 2018.

The key results of the scenarios presented in this report, calculated by GENESYS-MOD, are uploaded in all detail to the openENTRACE data platform (see a snapshot in Figure 4.2 below). The platform will also allow for other models in the openENTRANCE modeling toolset to upload their datasets. Furthermore, it is planned to not only upload results of the modeling efforts but also to provide input data and key assumptions on the platform. This will simplify the needs for data transformation when linking different types of models.

Figure 4-2 Snapshot of openENTRANCE scenario results on the data platform[31]

[31] Available at https://data.ene.iiasa.ac.at/openentrance

5. Concluding remarks

This report has been focusing on presenting the methodology and the quantitative results of the four openENTRANCE scenarios at pan-European level, being in line with the corresponding storyline descriptions. The corresponding input/output datasets are delivered to the open platform and can be used for further work within the openENTRANCE project as well as experienced modelers outside the consortium. As already stated throughout this report, the quantitative scenario generation process is still ongoing work at both levels, pan-European and Europe country-specific. Naturally, further experience/insights are gained in the different activities of the ongoing openENTRANCE project, which are expected to result in slight update needs of the pan-European quantitative scenario results also in the meantime (characterized by new version numbers) until a final version will be delivered together with the final European country-specific results towards the end of the openENTRANCE project. Several datasets of the different pan-European scenario versions are delivered to the open platform for further use.

In addition, also the discussion process in recent months on the functionality extension and parametrization of the main model used to derive the quantitative scenario results, GENESYS-MOD, has shown that slight updates and fine tunings of the storyline descriptions (status quo see in Deliverable D7.1) are needed. This will be done later in the project (in order to enable incorporation of further lessons learnt) in the context of WP7 where the synthesis of openENTRANCE results is conducted and the final openENTRANCE transition pathways are outlined.

6. References

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7. Appendix

7.1 Fossil fuel prices and energy demand settings

Table 7-1 Fuel Prices in GENeSYS-MOD compared to World Energy Outlook (WEO2019)

	2015[32]	2030	2040	2050
Crude Oil [€/barrel]				
openENTRANCE	53.34	36.59	33.02	29.80
World Energy Outlook[33]	-	57.35	54.56	-
Natural Gas [€/MBtu]				
openENTRANCE	5.62	3.85	3.48	3.14
World Energy Outlook	-	6,93	6,93	-
Hard Coal [€/tonne]				
openENTRANCE	88.40	60.63	54.72	49.39
World Energy Outlook	-	53.65	55.50	-

Table 7-2 Energy demands in GENeSYS-MOD for the different sectors

	2015	2020	2030	2040	2050
Power Sector [PJ]	10,762	10,703	10,587	10,493	10,414
Industry [PJ]	17,162	16,748	15,555	14,320	13,415
Residential Heating [PJ]	14,575	13,926	12,122	10,841	9,595
Passenger Transport [Gpkm]	7,267	7,216	6,545	6,397	6,276
Freight Transport [Gtkm]	3,065	3,297	3,492	3,570	3,759

[32] Values from 2015 are taken from: The World Bank http://pubdocs.worldbank.org/en/633541587395091108/CMO-April-2020-Forecasts.pdf, [16]

[33] The *„Sustainable Development Scenario"* from the World Energy Outlook (2019) [17] is used as a reference since it shows the highest degree of similarities compared to the openENTRANCE pathways. Yet, die openENTRANCE scenarios aim for higher ambitions and therefore the values differ, especially in the later periods.

Energy demand values for the different sectors were adopted from the SET-Nav project, which are based on the different demand sector-specific models *Astra, Invert and Forecast* (see corresponding report of the assessment and comparative analyses of the SET-Nav pathways in [18][34]). Please note, that in Table 7-2 the units for the power sector, industry and residential heating are given in [PJ], whereas for passenger and freight transport in [Gpkm] and [Gtkm] respectively. This is a necessity to comply with the GENESYS-MOD model format. For passenger and freight transport, therefore, demand decrease/increase in Table 7-2 rather describes the mobility service, but not energy demand per se.

One overall observation in Table 7-2 is worth mentioning: whereas the overall electricity production in several of the four openENTRANCE scenarios significantly increases up to 2050 (i.e. by the factor of ~2; see results in Chapter 3 of this report), electricity demand in the power sector itself slightly decreases. This is due to efficiency improvements in this sector (e.g. appliances, etc.). However, the overwhelming share of additional electricity production up to 2050 covers the fuel-switch in the residential, industrial and transport sector towards electricity based technologies, end-uses and services.

In a next step, these values were adjusted to fit with the openENTRANCE scenarios. For example, in the *Directed Transition* scenario, power demand until 2050 decreases by 10% compared to the values in Table 7-2, with the reduction increasing linearly over time starting in 2025. The following Table 7-3 gives an overview of the demand reduction compared to the original values given in Table 7-2 for all scenarios and all sectors.

Table 7-3 Reduction of demands compared to reference values across the pathways

	Directed Transition	Societal Commitment	Techno Friendly	Gradual Development
Power Sector	10.00%	12.50%	5.00%	5.00%
Industry	12.5.%	18.33%	0.00%	7.50%
Residential Heating	15.00%	13.75%	0.00%	5.00%
Passenger Transport	5.00%	17.50%	0.00%	5.00%
Freight Transport	5.00%	20.00%	0.00%	5.00%

[34] http://www.set-nav.eu/sites/default/files/common_files/deliverables/WP9%20Pathways%20Summary%20Report%20%28D9-4%29.pdf

7.2 Further results

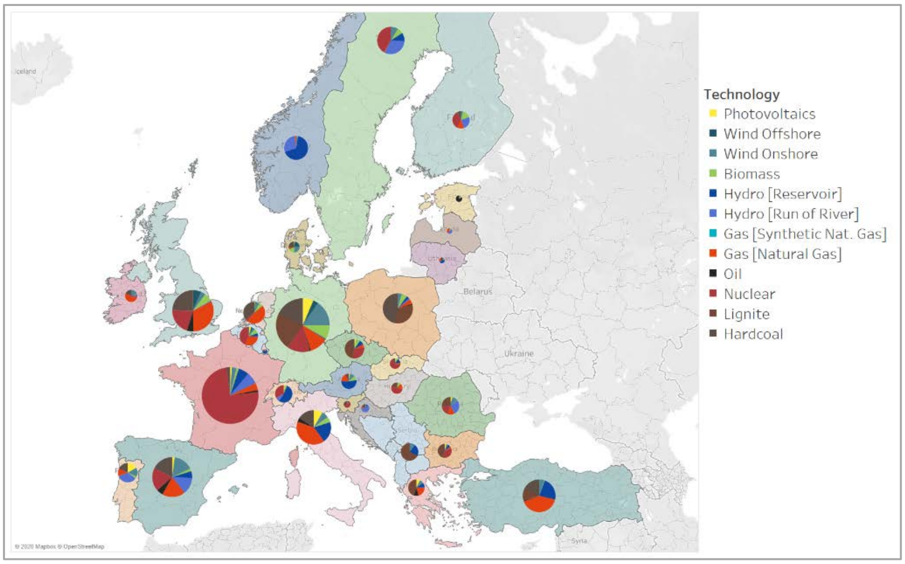

Figure 7-1 Electricity Generation per Country in 2015

7.2.1 Directed Transition

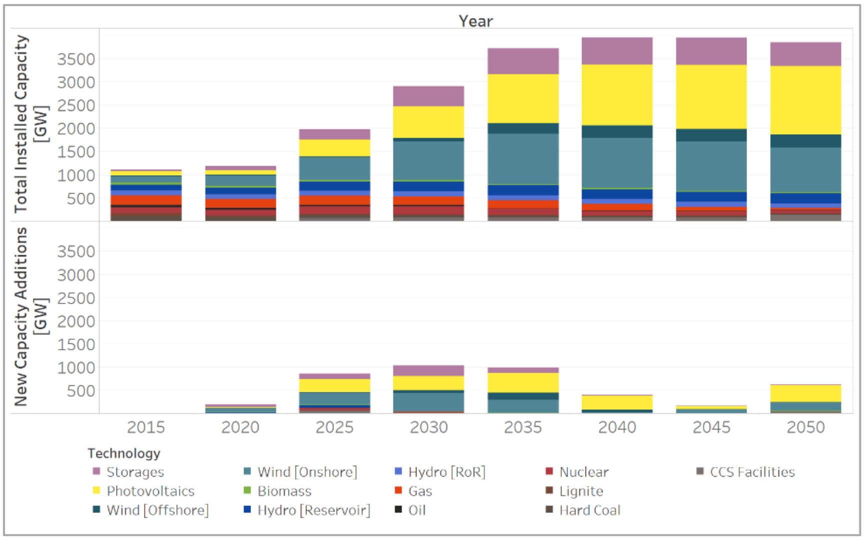

Figure 7-2 Electricity Generation Capacities until 2050 (Directed Transition)

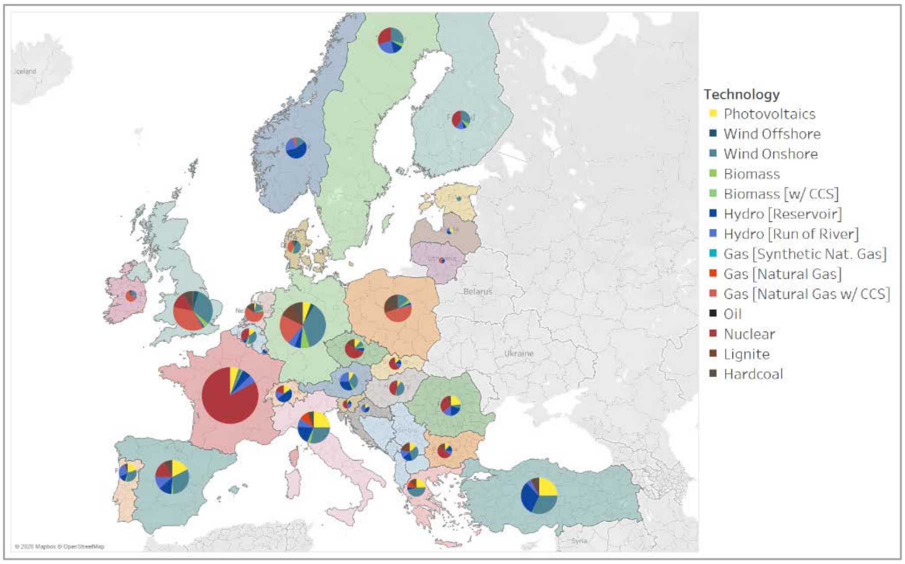

Figure 7-3 Electricity Generation per Country in 2025 (Directed Transition)

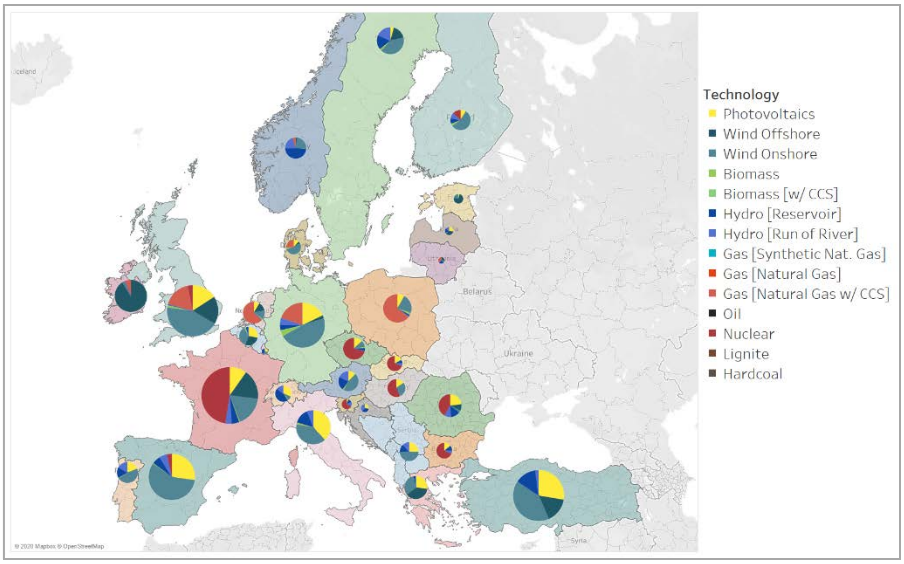

Figure 7-4 Electricity Generation per Country in 2035 (Directed Transition)

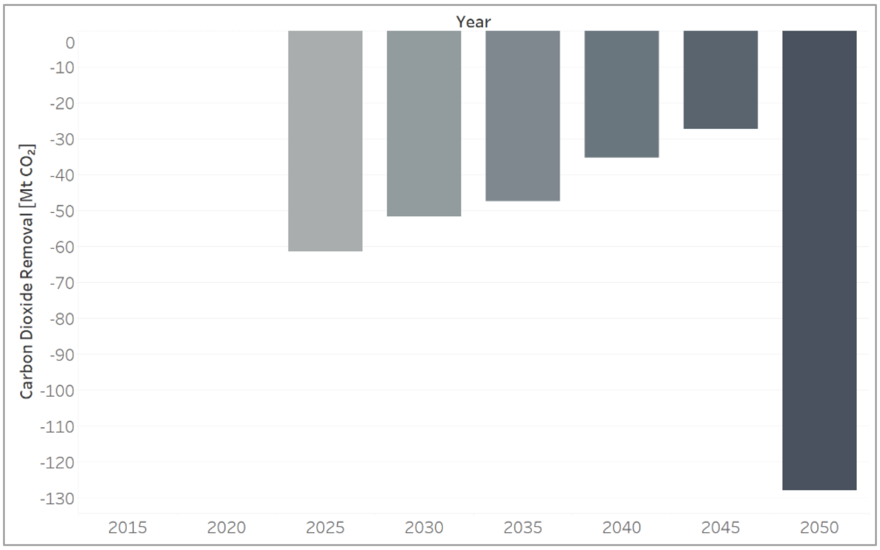

Figure 7-5 Usage of Carbon Dioxide Removal Technologies (Directed Transition)

7.2.2 Societal Commitment

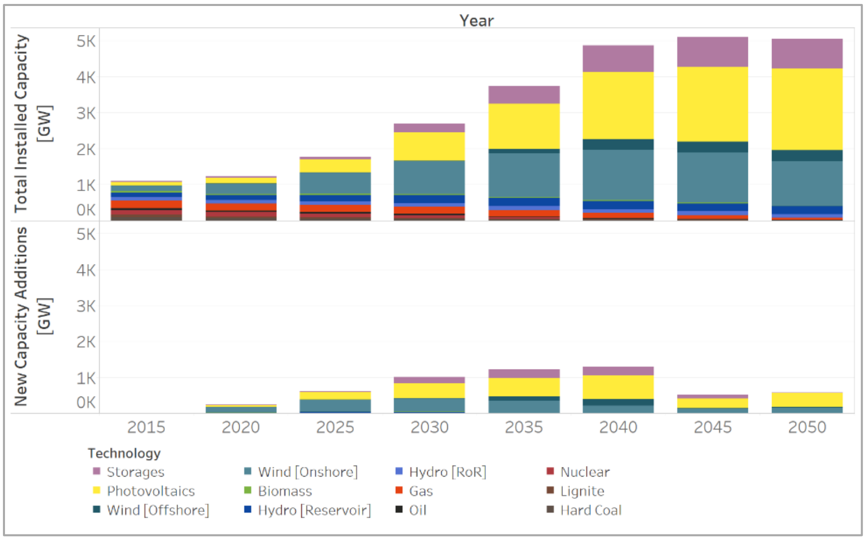

Figure 7-6 Electricity Generation Capacities until 2050 (Societal Commitment)

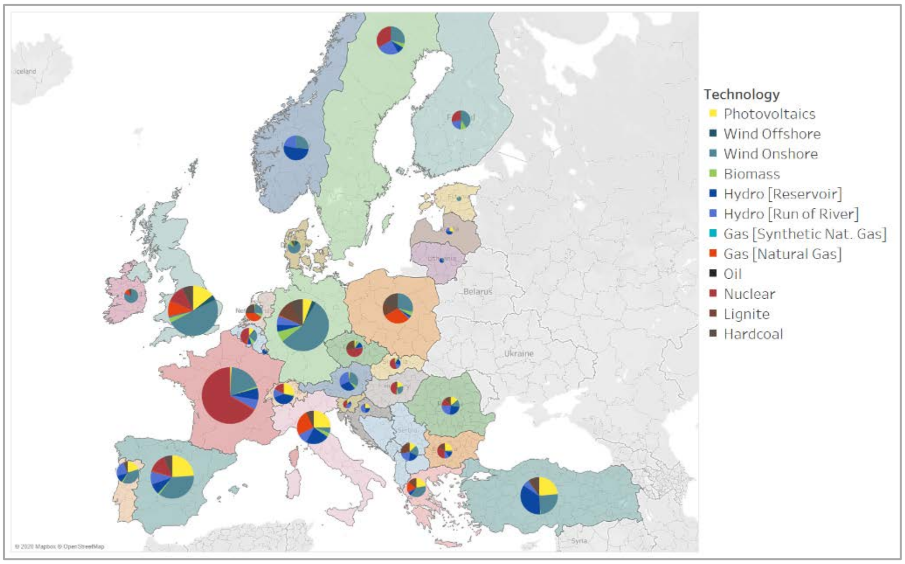

Figure 7-7 Electricity Generation per Country in 2025 (Societal Commitment)

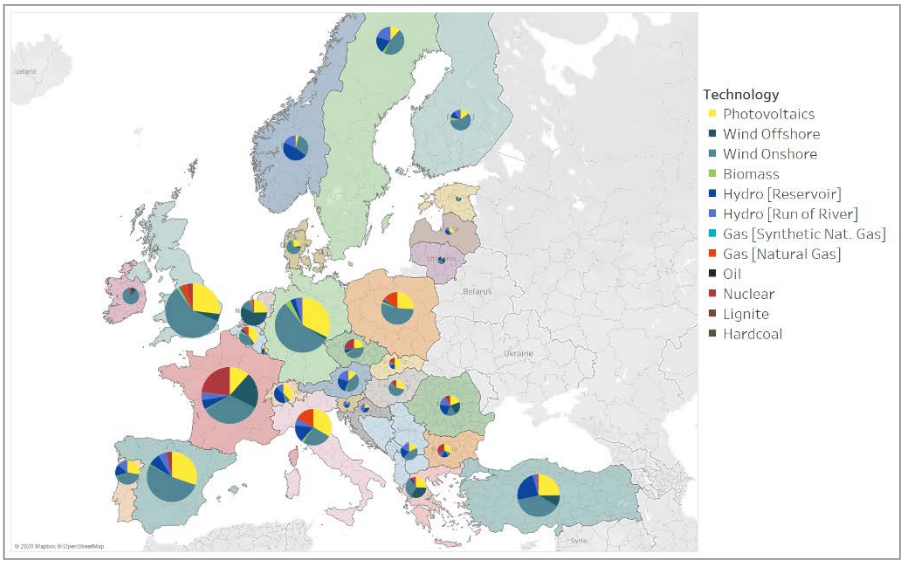

Figure 7-8 Electricity Generation per Country in 2035 (Societal Commitment)

7.2.3 Techno-Friendly

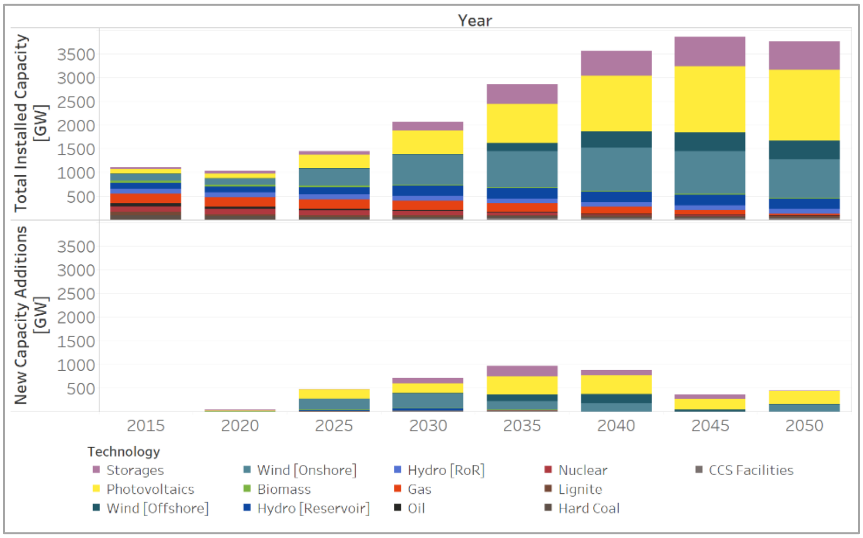

Figure 7-9 Electricity Generation Capacities until 2050 (Techno-Friendly)

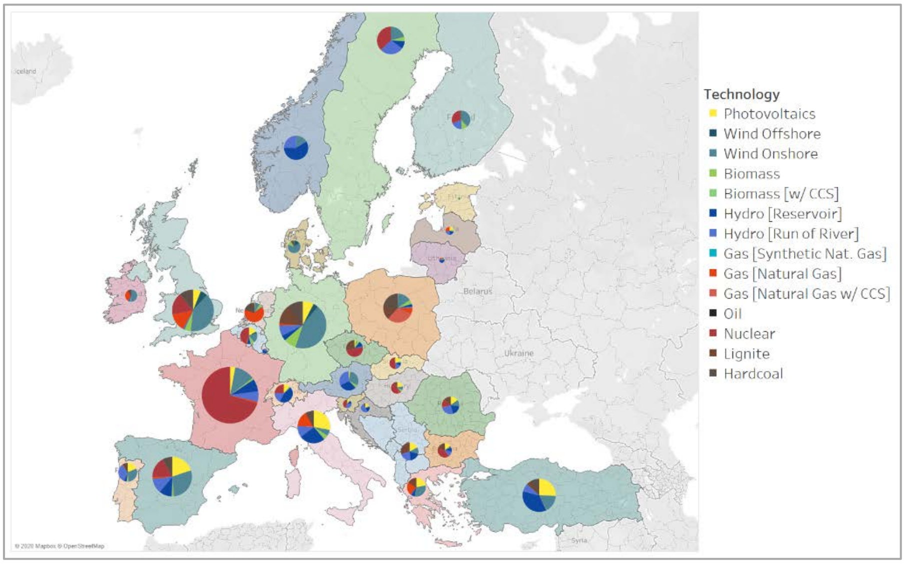

Figure 7-10 Electricity Generation per Country in 2025 (Techno-Friendly)

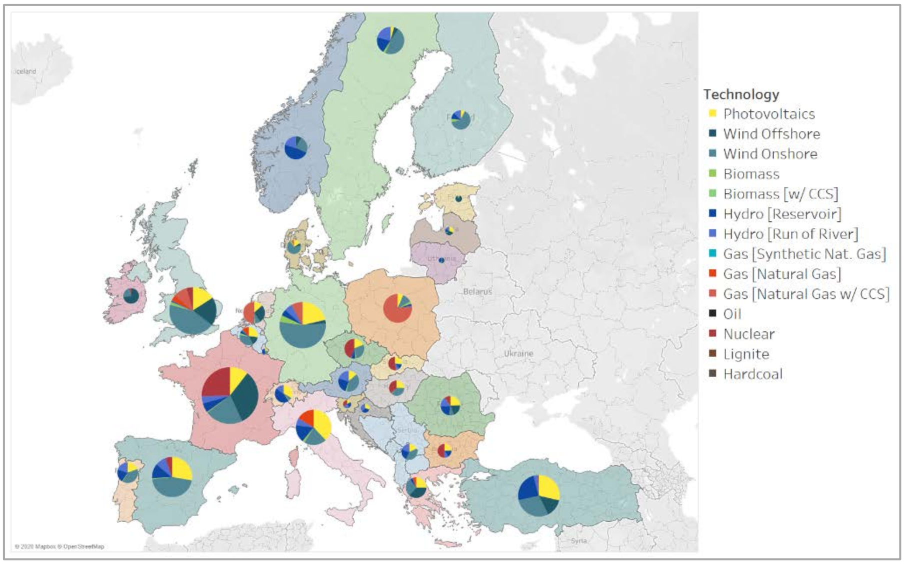

Figure 7-11 Electricity Generation per Country in 2035 (Techno-Friendly)

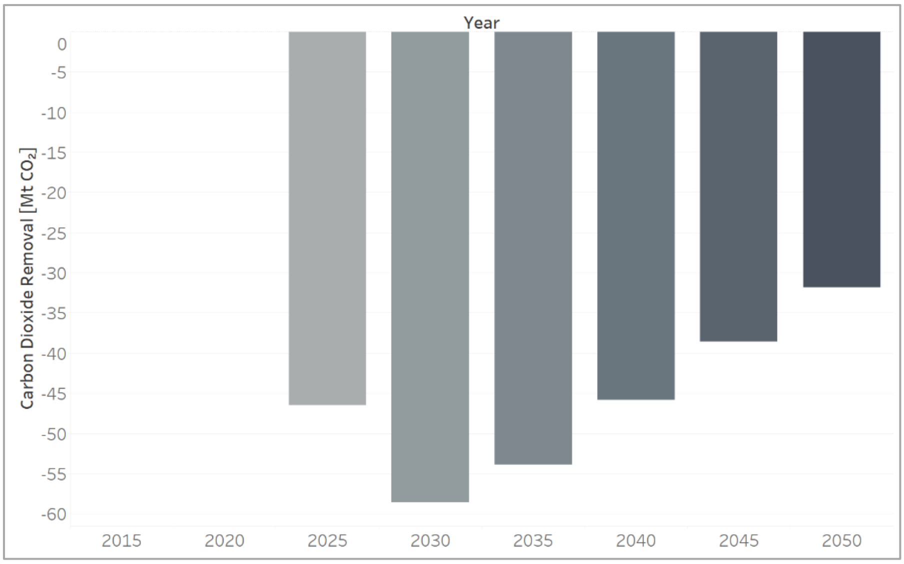

Figure 7-12 Usage of Carbon Dioxide Removal Technologies (Techno-Friendly)

7.2.4 Gradual Development

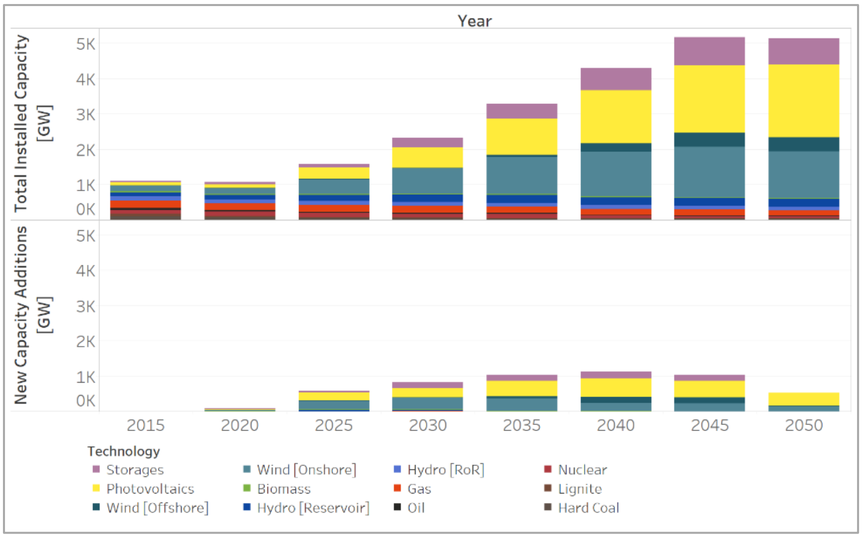

Figure 7-13 Electricity Generation Capacities until 2050 (Gradual Development)

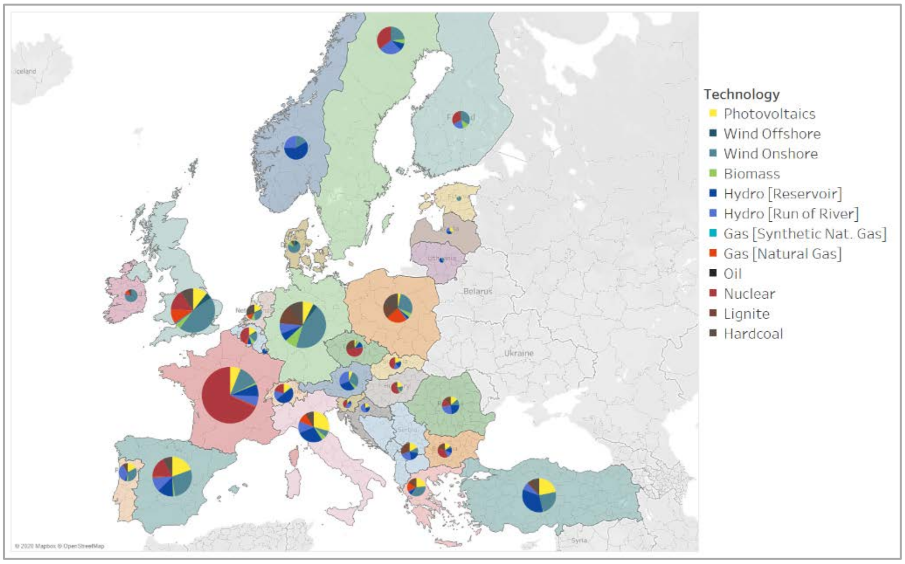

Figure 7-14 Electricity Generation per Country in 2025 (Gradual Development)

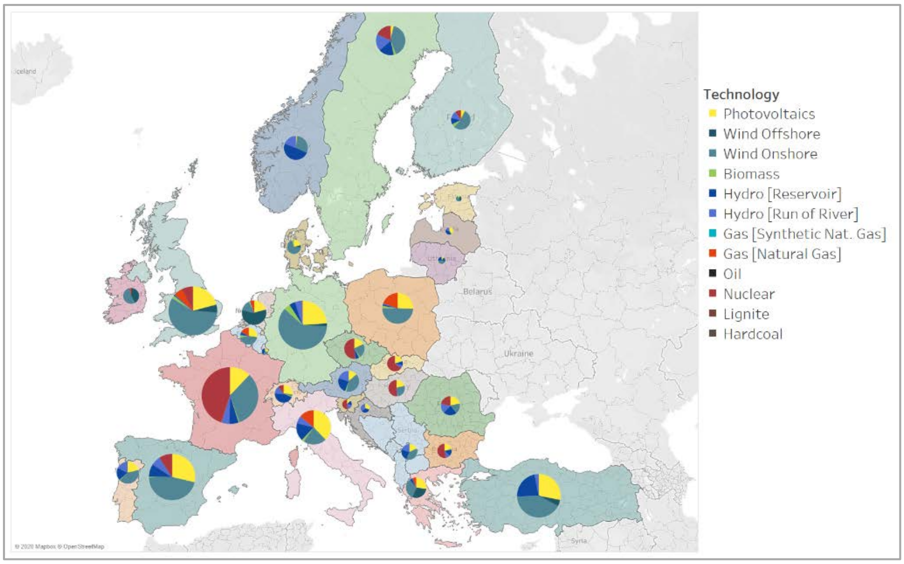

Figure 7-15 Electricity Generation per Country in 2035 (Gradual Development)