Development and modelling of different decarbonization scenarios of the European energy system until 2050 as a contribution to achieving the ambitious 1.5°C climate target - Establishment of open source/data modelling in the European H2020 project openENTRANCE

Hans Auer[1], Technische Universität Wien (TU-Wien) - Energy Economics Group (EEG)
Gusshausstrasse 25-29/E370-03, 1040 Vienna, AT, Email: auer@eeg.tuwien.ac.at

Pedro Crespo del Granado[2], Norwegian University of Science and Technology (NTNU), Trondheim, NO
Pao-yu Oei, Karlo Hainsch, Konstantin Löffler, Thorsten Burandt[3], Technische Universität Berlin (TU-Berlin), DE
Daniel Huppmann[4], International Institute for Applied Systems Analysis (IIASA), Laxenburg, AT
Ingeborg Grabaak[5], Sintef, Trondheim, NO

Abstract
The ambition of the openENTRANCE project is to develop and establish an open, transparent and integrated modelling platform for assessing low-carbon transition pathways of the European energy system. In this context, the open source energy system model GENeSYS-MOD is one of the core models having been developed enabling quantitative scenario pathway studies of the future European energy system. The four quantitative studies presented in the openENTRANCE project and in this paper build upon the four storylines developed at the beginning of the openENTRANCE project. A storyline is a narrative describing possible future trajectories (pathways) of the energy transition. Storylines should be understood as possible future developments of the European energy system, which could occur equally without having a preference for one of them. Three of the storylines, and subsequently quantified scenario pathway studies in openENTRANCE comply with the (European fraction of the) 1.5°C global temperature increase limit. The fourth one approaches the 2.0°C limit. The quantified scenario pathway results not only show the needs of the fully open energy system model GENeSYS-MOD to find feasible solutions of the underlying analytical optimisation problem, but more importantly highlight *what needs to be done in the future European energy system if we seriously intend to limit global warming!*

Keywords
Decarbonization Scenarios, Energy System, Europe, Global Temperature Increase, Open Source/Data Modelling, GENeSYS-MOD

[1] Corresponding author, Leader of storyline and scenario development
[2] Leader of synthesis of overall openENTRANCE modelling and pathway results as well as policy recommendations
[3] TU-Berlin team: tailor-made GENeSYS-MOD model development and quantitative scenario pathway modelling
[4] Leader of development of the open platform in openENTRANCE and MESSAGEix-GLOBIOM modelling contributions
[5] Overall openENTRANCE project coordinator

Entwicklung und Modellierung verschiedener Dekarbonisierungsszenarien des europäischen Energiesystems bis 2050 als Beitrag zur Erreichung des ehrgeizigen 1,5°C Klimaziels - Etablierung von Open Source/Datenmodellierung im europäischen H2020-Projekt openENTRANCE

Kurzfassung

Das Ziel des openENTRANCE-Projekts ist die Entwicklung einer offenen, transparenten und integrierten Modellierungsplattform zur Analyse zukünftiger kohlenstoffarmer Entwicklungspfade des europäischen Energiesystems. In diesem Zusammenhang ist das Open-Source-Energiesystemmodell GENeSYS-MOD eines der Kernmodelle, das entwickelt wurde, um quantitative Szenarienanalysen des zukünftigen europäischen Energiesystems durchführen zu können. Die vier quantitativen Studien, die im openENTRANCE-Projekt und in diesem Papier vorgestellt werden, bauen auf den vier Storylines (Erzählungen) auf, die zu Beginn des openENTRANCE-Projekts entwickelt wurden. Eine Storyline ist eine Erzählung, die mögliche zukünftige Entwicklungspfade des Energiesystems beschreibt. Storylines sollten als mögliche zukünftige Entwicklungen des europäischen Energiesystems verstanden werden, die in gleicher Weise stattfinden könnten, ohne eine Präferenz für eine von ihnen zu haben. Drei der Storylines und anschließend quantifizierte Szenarioanalysen in openENTRANCE entsprechen dem europäischen Anteil der 1,5°C-Grenze des globalen Temperaturanstiegs. Die vierte nähert sich der 2,0°C-Grenze. Die Ergebnisse der quantifizierten Szenarienanalysen zeigen nicht nur die notwendigen Bedingungen des analytischen Ansatzes des Energiesystemmodells GENeSYS-MOD auf, um Lösungen für das zugrundeliegende Optimierungsproblem zu finden, sondern - was noch wichtiger ist - *was im zukünftigen europäischen Energiesystem getan werden muss, wenn wir ernsthaft beabsichtigen, die globale Erwärmung zu begrenzen!*

Schlagwörter

Dekarbonisierungs-Szenarien, Energiesystem, Europa, Globaler Temperaturanstieg, Open Source/Datenmodellierung, GENeSYS-MOD

1. Introduction

The ambition of the openENTRANCE project (https://openentrance.eu) is to develop, use and disseminate an open, transparent and integrated modelling platform for assessing low-carbon transition pathways of the European energy system. This fully open platform will be populated with a suite of modelling tools and datasets selected to cover the multiple dimensions of this transition process. This shall facilitate and improve the dialogue between researchers, modelers, policy makers and industry when investigating key questions linked to this transition in the next decades, notably as far as the European energy 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 increase limit of 1.5°C or 2.0°C. Therefore, the comprehensive ensembles of datasets on existing global pathway curves embedded into the Integrated Assessment Model (IAM) MESSAGEix-GLOBIOM[6] play a core role in the openENTRANCE modelling and scenario generation exercises to align the empirical foundation of several quantitative scenario carried out in this project to the status quo of knowledge in the global climate modelling community.

The four quantitative scenario studies for low-carbon futures of the European energy system presented in openENTRANCE and in this paper build upon the four storylines developed at the beginning of the openENTRANCE project. A storyline is a narrative describing ideas for future trajectories (pathways) of the energy transition. It is important to note that a storyline should not be understood in the sense of a prediction/forecast about a most likely future development. Each of the four possible energy futures described in the openENTRANCE project could occur equally without stating a preference or bias for a single outcome. Instead, they should be understood as four possible future developments, which could occur equally without preferring one of them. Consequently, the corresponding quantified scenarios, determined by means of the open source energy system model GENESYS-MOD,[7] represent the more concrete empirical frames of the four possible future developments of the European energy system.

Since the ambition of the openENTRANCE project is to study low-carbon futures of the European energy system, three of the quantified scenarios comply with the (European fraction of the) 1.5°C global temperature increase limit. The fourth one (called 'Gradual Development') approaches the 2.0°C target. This means that the remaining CO_2 budget available for Europe (derived from the IAM MESSAGEix-GLOBIOM) fixes one of the challenging external constraints in the openENTRANCE scenario modelling exercises. In addition, available technology portfolios/breakthroughs (notably this also includes the availability/non-availability of carbon dioxide removal technologies like CCS (Carbon Capture and Storage) in the different storylines/scenarios as well as maximum feasible technology exchange rates (triggered by corresponding CO_2 price needs) are determining parameters for achieving carbon neutrality in Europe in the years 2040 or 2050. In this context, it is important to note that the gradients of modelling results in terms of technology exchange rates in individual cases/sub-sectors presented in the scenario results might be difficult to imagine what is feasible in the real, physical world. Nonetheless, the quantified scenario results not only show the needs of the energy system model GENESYS-MOD to find feasible solutions of the underlying analytical optimisation problem, but more importantly highlight *what needs to be done in the future European energy system if we seriously intend to reach the ambitious global heating targets!*

The remainder of the paper is organised as follows: Section 2 presents four narrative descriptions (storylines) on possible future developments of the European energy system. Section 3 builds the bridge between qualitative descriptions and quantitative pathway scenario studies based on the open source energy system model GENeSYS-MOD. A selection of the most interesting results of the three quantitative pathway scenarios approaching the 1.5°C temperature increase limit is presented in Section 4. Finally, Section 5 carries out a comparative discussion of the results of several of the four scenario pathways (incl. the fourth 2.0°C one) and concludes the paper.

---

[6] see https://docs.messageix.org/projects/global/en/latest/

[7] see Section 2.3 in https://openentrance.eu/wp-content/uploads/openENTRANCE-D3.1.pdf

2. Storylines – Narratives on low-carbon European energy transition

In the openENTRANCE project, four storylines have been developed. They describe possible future developments of a low-carbon European energy system. Since, currently, there are many uncertainties about the possible future development of the European energy system, we do not have any preference for one (or a most probable) robust long-term future development. On the contrary, we are indifferent and expect several of the narratives to happen likewise. Even though there are different key drivers characterizing each of the four different storylines, the following common features can be found in all four storylines:

- The characterization of each storyline emphasises the most salient key drivers and features only that distinguish the storylines from one another. However, this does not mean that particular drivers/features of one storyline are not also important for other storylines (at least to a certain extent). But they are most pronounced there where they are explicitly quoted and discussed.
- All four storylines incorporate high shares of renewable technology penetration in the future European energy system and, in addition, (different ambitions of) demand side participation of individuals and communities/aggregates. These are prerequisites to reach the ambitious energy and climate policy goals of a low carbon future of the European energy system.
- The openENTRANCE storylines are interpreted in the context of the existing analyses of global emission reduction pathways necessary to limit global warming to 2.0˚C or the even more ambitious target of 1.5˚C. Top-down (global targets) need to be linked with the European boundary. Although 2.0°C represents an extraordinary ambitious ceiling, this shall be the least ambitious target in the narrative storyline set-up in openENTRANCE and, subsequently, quantitative scenario study analyses. We will focus on even more ambitious 1.5°C pathways.

In general, openENTRANCE storyline descriptions are not limited to a certain (geographic) boundary, e.g. Europe. However, it can be meaningful to distinguish European storylines from the global ones, both intellectually and politically, as Europe may pursue more ambitious climate policy instruments and developments that diverge from the rest of the world. Exemplarily, different scenario studies inside a storyline referring to a policy related uncertainty can tackle aspects like that.

The objective of the openENTRANCE storylines is closely aligned with the EU (European Union) long term strategy and related studies. Most current scenario building exercises about the European energy transition rely on multiple technology options, policy strategies embedded into an energy market environment and to some extend also behavioral/lifestyle changes to outline possible decarbonisation of Europe. In the same spirit, openENTRANCE pathways contribute to understand the drivers, uncertainties, strategies and consequences of the energy transition by exploring research questions as the following:

1. If there are no major technological developments in the next decades, to what extent can the energy transition rely on the societal commitment and stronger cooperation within the EU? What drivers and strategies will be key to achieve emissions reduction under these circumstances?
2. What technological innovations (e.g. CCS, hydrogen, and others) could have a major impact on an effective European energy transition? What policy incentives and regulatory framework will steer their successful development and adoption?
3. In case of significant technological breakthroughs accompanied by economies of scale of sustainable energy production and use, can we rely on market forces, new business models and social innovations picking up the slack from the lack of policy action? What are the associated risks if we are mainly dependent on market decisions governing energy transition?
4. Which other options exist in energy transition if neither significant technological innovations nor societal commitment are visible? Moreover, what to do in an even more challenging situation of a little cooperation within the EU Member states where energy policy making rather is fragmented and collusive than homogeneous?

Bringing together all these insights and open questions, the following three-dimensional topology shown in Figure 2.1 emerges as a meaningful approach to set stories around key drivers and uncertainties of the energy transition. This topology indicates the place of three exposed future qualitative storylines (and thus subsequently quantitative pathways) on the extreme ends of a three-dimensional space as well as a more conservative future development in the centre: each exposed storyline is defined by the combination of two sets of (key) drivers. These individual drivers in Figure 2.1 represent the societal, technological and policy dimensions:

- *Smart Society:* This dimension maximises the engagement and awareness of the society to take concrete actions to combat climate change. It is characterised by strong support from the public and active participation (climate activism) on changing attitudes and behaviour in lifestyles.
- *Technology Novelty:* Innovation and technological breakthroughs dominate the quadrants surrounding this axis. Rapid technological learning helps to bring various technological options to commerciality and hence has an active role in the energy transition.
- *Policy Exertion:* This dimension represents a world in which effective policy measures successfully steer the energy transition to decarbonisation. Institutions and regulations drive the energy transition (top-down decisions) based on cooperation, low-geopolitical tensions, centralized initiatives and a strong EU.

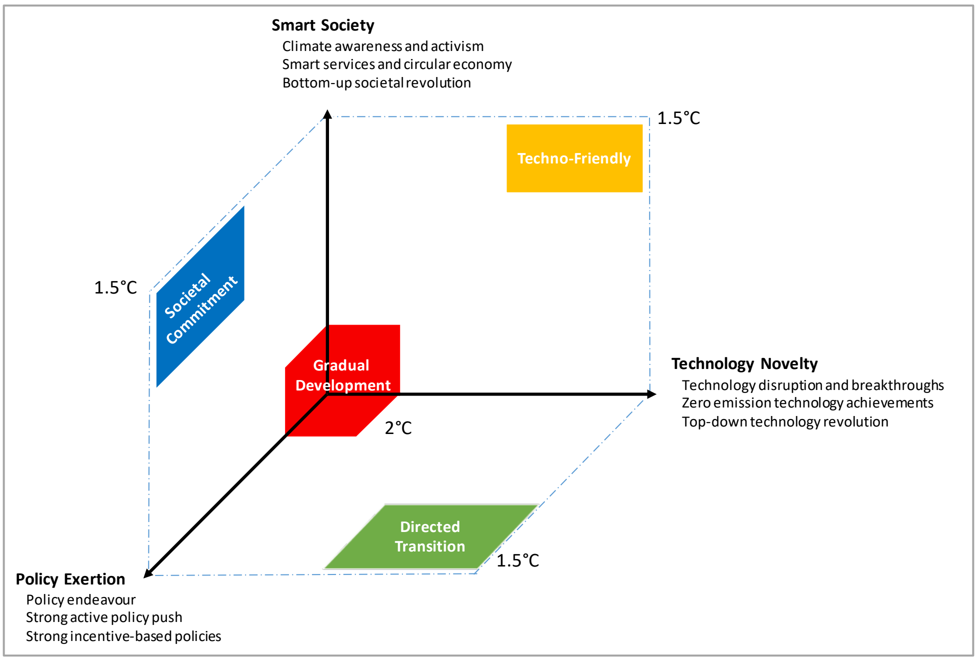


Figure 2.1 openENTRANCE storylines typology = policy exertion x technological novelty x smart society

In the 3-dimensional space span in Figure 2.1, we finally can allocate the four different openENTRANCE storylines: *Societal Commitment, Techno-Friendly, Directed Transition,* and *Gradual Development*. In the following, they are briefly summarized at a glance (for a more comprehensive description it is referred to the corresponding openENTRANCE Deliverable D7.1, Auer et al. (2019)):

- ***Societal Commitment:*** High societal engagement and awareness of the importance to become a low-carbon society characterizes this storyline. Individuals, communities, and overall public attitudes support strong policy measures to accelerate the energy transition. Both grassroots (bottom-up) and top-down government led approaches meet to drive the strong uptake of behavioural changes in energy usage and energy choices from European citizens. Hence, "green" government initiatives drive and direct ambitious measures in decarbonizing the energy and transport sectors. However, the pathway assumes that no technological breakthroughs occur and there is a lack of major achievements in technology development. It relies on a policy mix that has wide-support from the public. The key driver of this storyline is that society as a whole embraces cleaner and smarter lifestyles with the public sector working with and supporting grassroots initiatives.

- ***Techno-Friendly:*** Positive societal attitudes towards lowering Greenhouse Gas (GHG) emissions translates into welcoming the deployment of new technologies and changes in behavioural energy choices and grassroots movements in energy. Little resistance to adopting new technologies (e.g. floating offshore wind turbines, CCS, hydrogen, etc.) and openness to large-scale infrastructure projects characterizes the social developments of this storyline. Centralized decision-making and policy steering are difficult to reach and hence limited in this storyline, and thus the drive of this storyline comes from grassroots initiatives and industry taking action to deliver novel technology. The narrative centres on technological novelties complemented with sustained technology uptake by citizens such that demand for new carbon-mitigating energy technologies drives market-based development of these technologies on the part of industry actors. Partly new business models and social innovations pick up the slack from the lack of policy action.

- ***Directed Transition:*** Carbon-mitigating energy technologies emerge and require strong policy incentives for their uptake and development. The storyline assumes that the effect of grassroots and citizen-led initiatives will be minimal but that strong policy incentives can drive the needed engagement of citizens to reach the climate target. The driver of this storyline then comes from a strong centralized vision on the part of policymakers and direct partnerships with industry and technology developers who respond to incentives provided by the public sector and provide broad advances in low-carbon energy-related technologies.

- ***Gradual Development:*** This storyline envisions that the climate target (2°C) is reached through an equal part of societal, industry/technology, and policy action. Knowing that a continuation of current public policies and developments are expected not to be sufficient, significantly higher efforts are needed than the current level of commitment of several of the actors. Thus, this storyline entails ingredients of *'a little of each'* of the remaining openENTRANCE storylines and therefore represents an already ambitious reference scenario in openENTRANCE.

3. Building the bridge from qualitative storylines to quantitative pathway scenarios – The open source energy system model GENeSYS-MOD

3.1 Building the bridge

The narrative descriptions of the openENTRANCE storylines 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. Hereafter, a structured comparative qualitative analysis of each of them is carried out in terms of the following categories: geopolitics and market/economic development, climate and energy policies, most likely technology portfolio in the energy (and transport) sector, society's attitude and lifestyle, energy and transport sector in detail (incl. several subsectors and end-uses).

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 addition, some of the parameters in the storyline descriptions have already been explicitly denoted with attributes like very high/high/medium/low or moderate/limited or else.

Naturally, further precision of the GHG-emission reduction targets in the context of the four different storylines raises additional questions and needs further clarification. 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 modelling implications and interdependencies between CO_2 prices and CO_2 budgets for a predefined period of time. While GENeSYS-MOD initially offered the functionality to model a CO_2 budget only (based on different allocation methods like share of GDP (Gross Domestic Product), population, current emissions, or free distribution), for openENTRANCE's scenario generation, a CO_2 price modelling functionality has been implemented into the model (for methodological details in this context see D3.1, Auer et al. (2020)). In addition, further clarifications have been necessary before starting the modelling exercises, e.g. which target years to be envisaged to fully decarbonize the European energy system to reach the 1.5°C/2.0°C global temperature increase limit. The 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 prior to the modelling presented above shall only serve as a snapshot. Many similar aspects had to be further specified in this context. For further elaboration on the individual model parametrizations, it is referred to the corresponding D3.1 report, Auer et al. (2020).

3.2 Tailor-made further development of the open source energy system model GENeSYS-MOD

The initial version (version v2.0) of the model GENESYS-MOD prior to openENTRANCE modelling 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), an updated version in Burandt et al. (2018), an application to the European energy system in Hainsch et al. (2018), and finally the most recent scenario study on 100% renewables in Oei et al. (2020).

It is important to note that it is not the intention of this paper 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 above. It is also not the intention in the following, to elaborate comprehensively on the tailor-made further developments, adaptations and improvements of the GENESYS-MOD model to meet the openENTRANCE needs (details can be found in D3.1, Auer et al. (2020)). Rather a brief summary on the GENESYS-MOD functionalities and its extensions to comply with the openENTRANCE needs is outlined below:

- 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). The new country/region-specific granularity meeting openENTRANCE needs can be found on the right hand side in Figure 3.1 (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 time-clustering algorithm. The methodology of the time clustering algorithm applied can be found in Gerbaulet/Lorenz (2017). The settings used for the results presented in Section 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). This represents a 50% increase in time resolution compared to the v2.0 of GENESYS-MOD.

- The CO_2 budget functionality has been disabled and replaced by a CO_2 price mechanic.
- 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. In this context, notably a much more disaggregated representation of the demand sector in general and the industry sector in particular (in terms of energy carriers/technologies used) 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.
- Calibration of the new countries/regions for the 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.

Figure 3.1 (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 present in the following Section 4 of this paper.

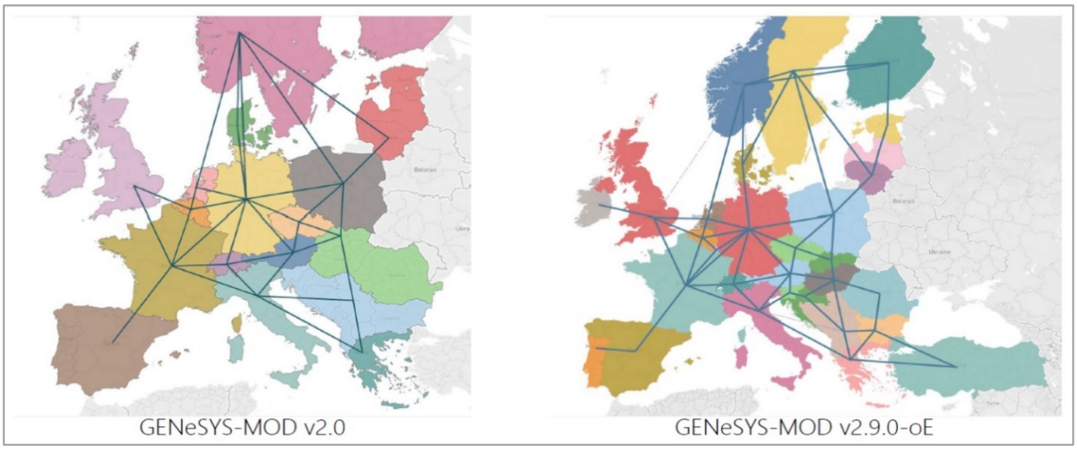


Figure 3.1 Initial version (left) and improved regional granularity and extension of the model GENeSYS-MOD according to openENTRANCE needs (right). Note, lines represent the simplified transmission grid between the country nodes of the national electricity systems.

Last but not least, it is important to note that 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. A selection of the most prominent representatives on input datasets in energy system modelling is briefly listed below (for a more comprehensive elaboration again it is referred to D3.1, Auer et al. (2020)).

- _Fossil fuel prices_ essentially determine the 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 European scenarios shown in Section 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).
- _CO_2 prices and/or CO_2 budgets:_ Both CO_2 emission mitigation instruments can be used in modelling 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. Three out of four openENTRANCE storylines envisage a fully decarbonized European energy system in 2040 in order to reach the global temperature increase limit of 1.5°C. The fourth is the 2.0°C setting in 2050. These target 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)) as well as a reasonable technology exchange rate.

- *Technology cost/learning rates:* Aligned assumptions on technology costs and expected technological learning in the future are essential ingredients in modelling to enable comparability of different studies. Notably, the empirical scaling of renewable technology cost (onshore/offshore wind, solar PV (Photovoltaics), etc.) and cost assumptions of upcoming new technologies like different energy storages, CCS, and/or H_2-production are determining parameters defining the timing of market penetration of future technologies/technology portfolios and thus decarbonization 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*)[8] 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 modelling. 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*.

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

[8] see http://www.set-nav.eu (as consulted online on 19 August 2020)

4. Scenario pathway results based on GENeSYS-MOD

In the following, a small selection of openENTRANCE scenario pathway results is presented. It mainly shows quantitative GENeSYS-MOD modelling outputs of the *Societal Commitment* and *Techno-Friendly* scenario pathways, followed by a few unique characteristics of the *Directed Transition*. A comparative analysis of the main output indicators of several of the four pathways is carried out in the final Section 5.

4.1 Societal Commitment

The *Societal Commitment* scenario pathway is characterized by a more pronounced decreasing energy demand and a higher willingness of society to facilitate a decarbonized European energy system. Consequently, this decrease in energy demand can be seen across all sectors and especially in the primary energy demand (Figure 4.1). 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 expects a faster decrease in 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 (Figure 4.2), 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 electricity sector (Figure 4.3 & 4.4) is once more the quickest to decarbonize, a trend is seen across all pathways. Hard coal disappears after 2025 and even natural gas and nuclear generation decrease steadily until 2040, afterward they play a minimal role only. In contrast, onshore wind power covers the majority of the load, especially in the 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 wind wherever possible. Solar PV sees major usage in all regions except Scandinavia and the UK, where hydropower and wind are much more viable options. Whereas Run-of-River (RoR) hydro power remains constant throughout Europe until 2050, reservoir based storage/pumped storage hydro power doubles (significantly adding flexibility to the electricity system).

The residential sector (Figure 4.5) is characterized 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. Similarly, in the industrial sector (Figure 4.6), 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 (Battery Electric Vehicles) play the most important role in passenger mobility (Figure 4.7), replacing ICE's (Internal Combustion Engines) completely until 2040. This is also partly facilitated by the decrease in demand and an increase in efficiencies due to higher load factors of vehicles. Freight transportation (Figure 4.8) in later periods rely heavily 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 the circular and sharing economy, etc.).

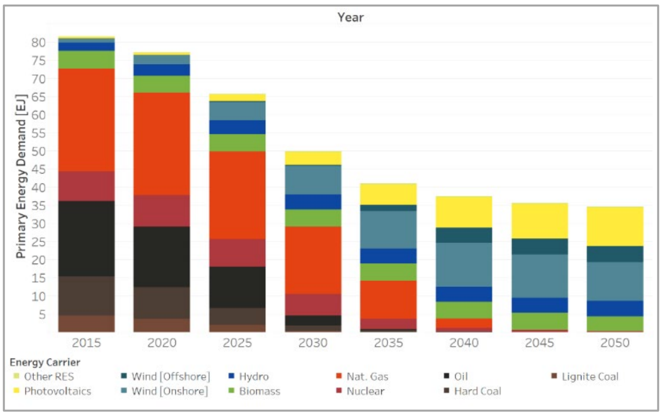


Figure 4.1 Primary Energy until 2050 (Societal Commitment)

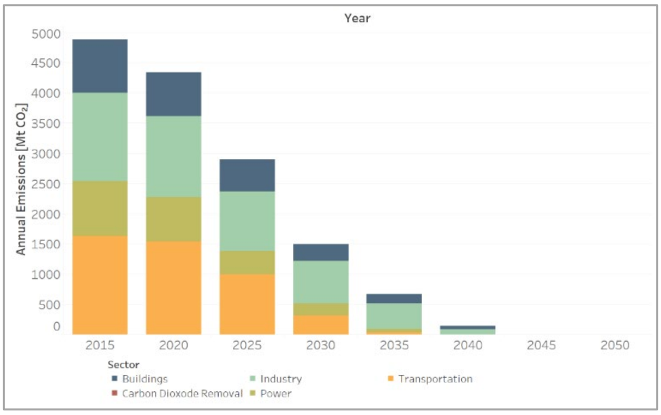


Figure 4.2 Emissions until 2050 (Societal Commitment)

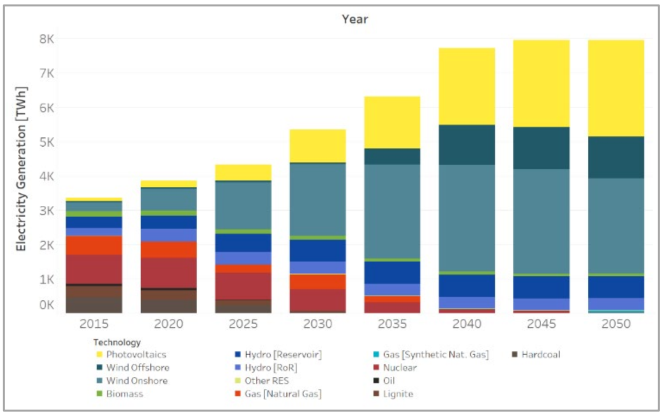


Figure 4.3 Electricity Generation until 2050 (Societal Commitment)

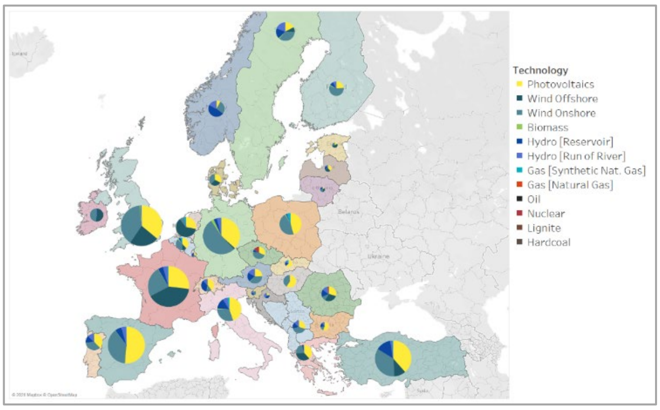


Figure 4.4 Electricity Generation per Country in 2050 (Societal Commitment)

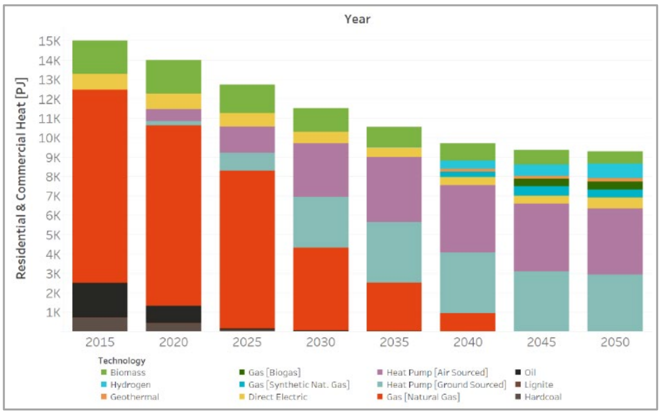


Figure 4.5 Residential and Commercial Heating until 2050 (Societal Commitment)

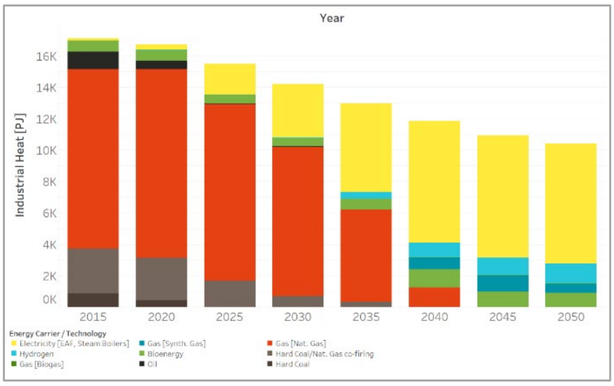


Figure 4.6 Industry (Energy/Technologies) until 2050 (Societal Commitment)

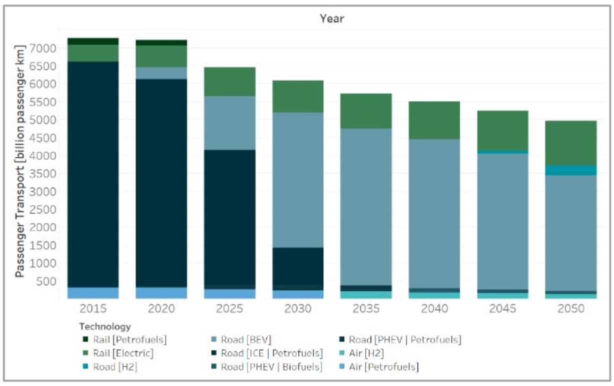


Figure 4.7 Passenger Mobility until 2050 (Societal Commitment)

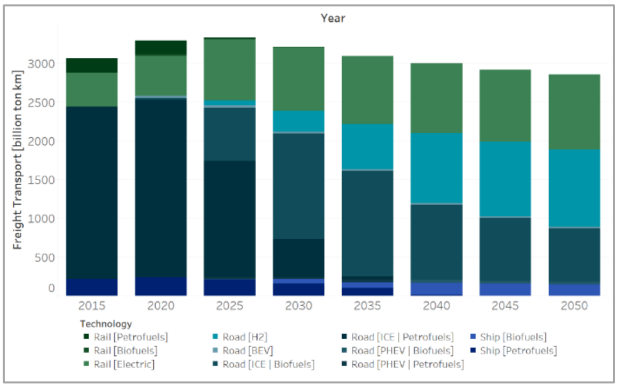


Figure 4.8 Freight Transportation until 2050 (Societal Commitment)

4.2 Techno-Friendly

Primary energy use is reduced in this scenario pathway by around 50% until 2050 (compared to 2020), see Figure 4.9. 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 (Figure 4.10), where the energy system is almost decarbonized by 2040 and use of negative emission technologies is observable as soon as 2025.

The electricity sector (Figure 4.11 & 4.12) 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, 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 (Figure 4.13) 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 (Figure 4.14), 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 Arc Furnance), 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 (Figure 4.15). The 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 4.16).

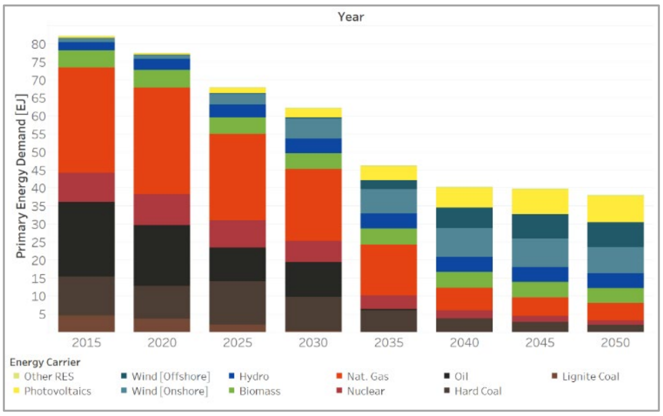


Figure 4.9 Primary Energy until 2050 (Techno-Friendly)

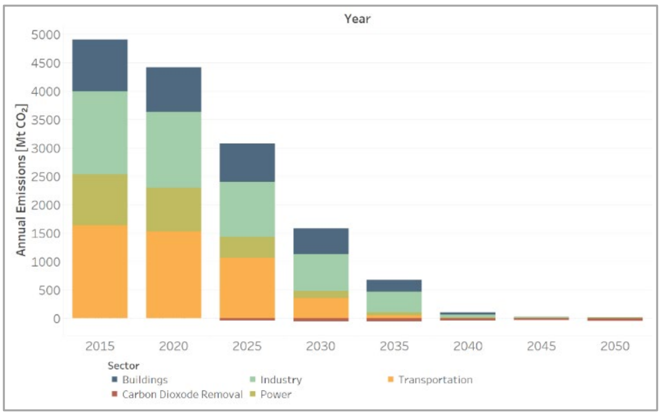


Figure 4.10 Emissions until 2050 (Techno-Friendly)

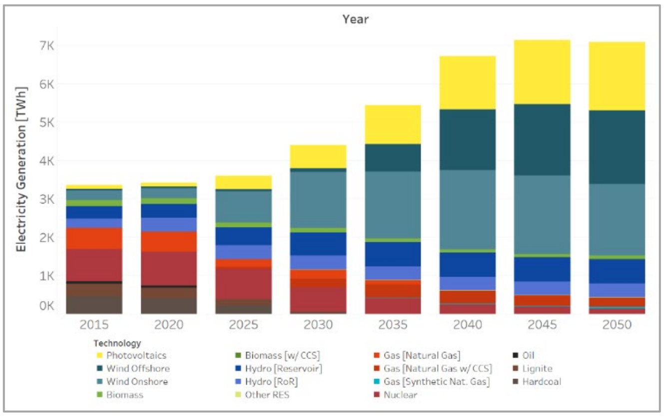


Figure 4.11 Electricity Generation until 2050 (Techno-Friendly)

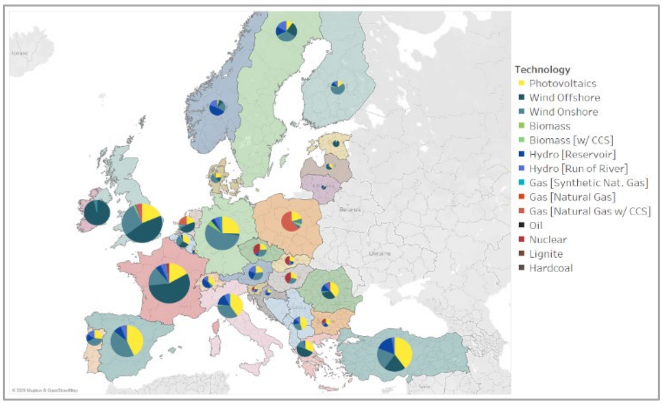


Figure 4.12 Electricity Generation per Country in 2050 (Techno-Friendly)

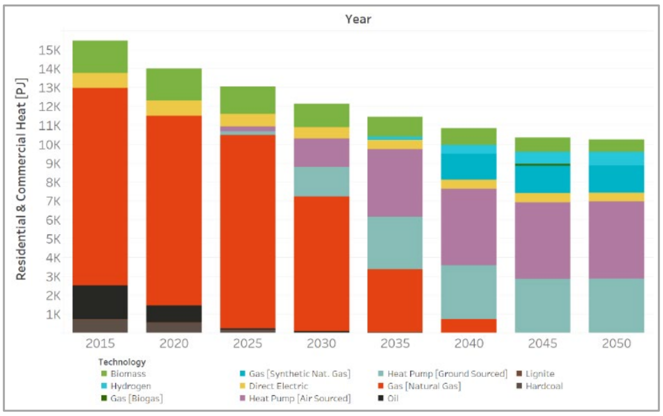


Figure 4.13 Residential and Commercial Heating until 2050 (Techno-Friendly)

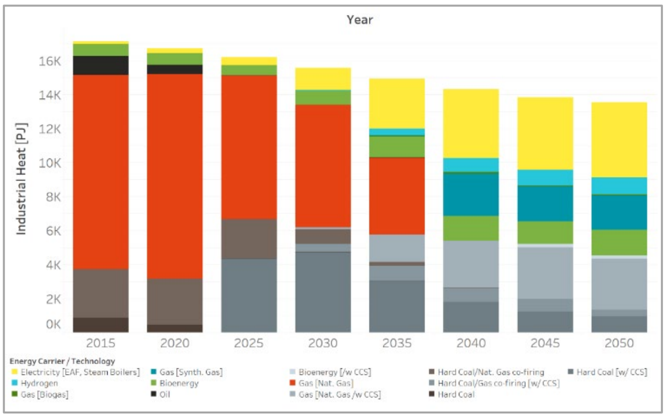


Figure 4.14 Industry (Energy/Technologies) until 2050 (Techno-Friendly)

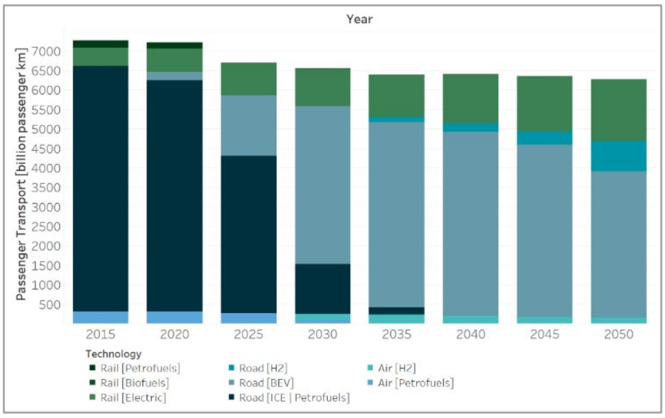


Figure 4.15 Passenger Mobility until 2050 (Techno-Friendly)

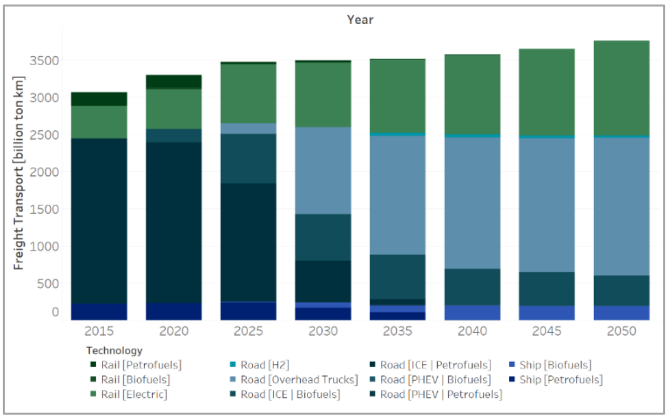


Figure 4.16 Freight Transportation until 2050 (Techno-Friendly)

4.3 Directed Transition

Total primary energy demand decreases notably until 2050 (Figure 4.17). 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 modelling 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 electricity become the main source of primary energy compared to the abundant usage of fossil fuels we see today.

Annual emissions (Figure 4.18) see a steep decline until 2035, with the remaining emissions being removed until 2040. CCS technologies allow for 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 electricity sector (Figure 4.19 & 4.20) sees a rapid phase-out of fossil capacities in the first half of the modelling 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.

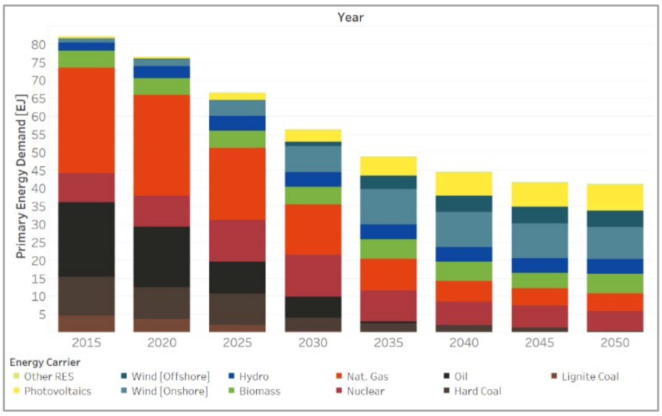


Figure 4.17 Primary Energy until 2050 (Directed Transition)

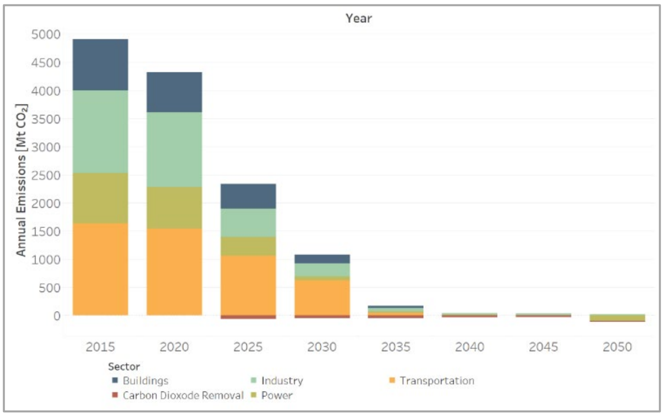


Figure 4.18 Emissions until 2050 (Directed Transition)

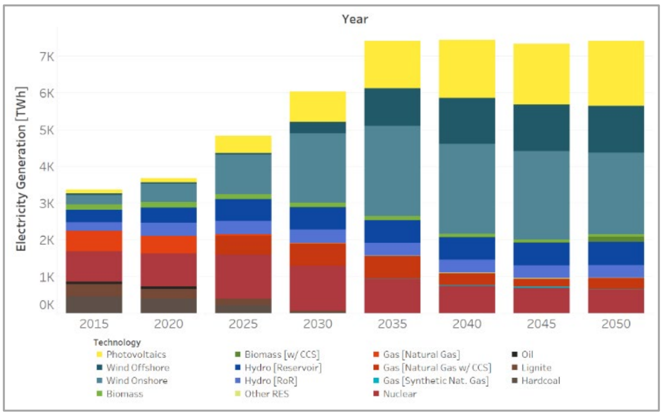


Figure 4.19 Electricity Generation until 2050 (Directed Transition)

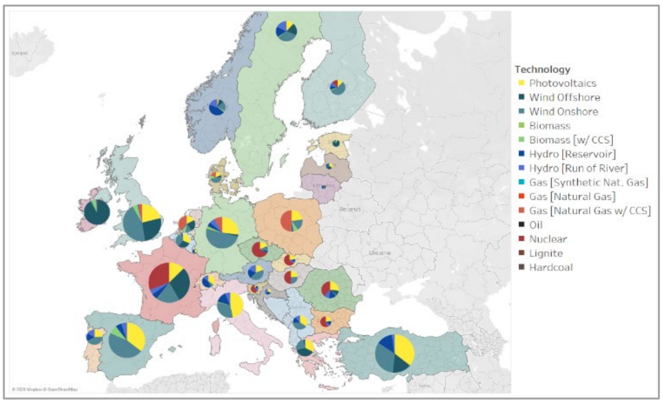
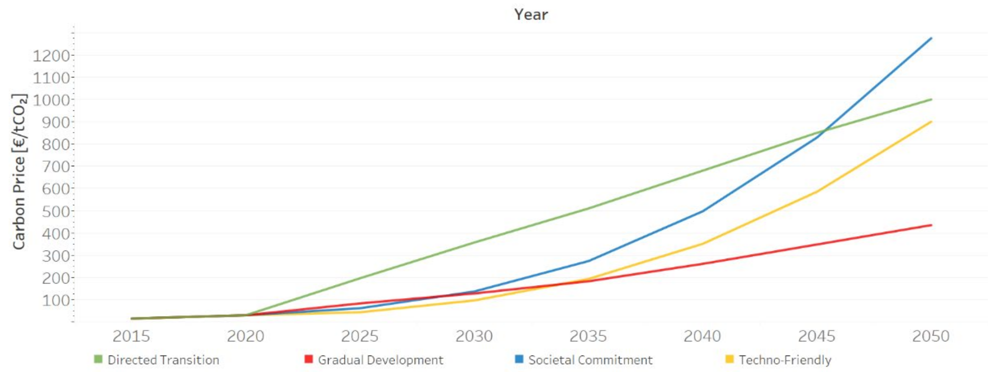


Figure 4.20 Electricity Generation per Country in 2050 (Directed Transition)

5. Comparative discussion of scenario pathway results and conclusions

One of the primary differences between the four calculated openENTRANCE scenario pathways are the implemented carbon prices and their respective developments (see Figure 4.21). 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.



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 4.21 Carbon Price Development for all four Scenario Pathways

Comparing the general results of all four scenarios pathways (Figure 4.22), a decrease in primary energy use can be observed. 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 scenario pathways 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 hydro-power 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. *Techno-Friendly* reaches an equal offshore wind deployment as onshore wind). In addition, also the speed of capacity deployment varies. 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 of 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 electricity 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 4.22 Comparison of Key Indicators for all four Scenario Pathways

The European openENTRANCE scenario results show that 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 by the risk (from today's point-of-view), that the technological breakthrough and lifestyle change of society actually takes place in time.

As a resume of the comparative analysis of the quantitative 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 modelling and case study activities in the ongoing project, before final conclusions and policy recommendations can be formulated at the end of the openENTRANCE project:[9]

- 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 lifestyle change *(Societal Commitment)* also can meet the ambitious goals, but the risk seems to be higher than 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!
- ….

[9] It is important to note, that this paper is a "technical report" mainly presenting the four quantitative 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.

References

Auer et al (2019): Storylines for Low-Carbon Futures of the European Energy System, Deliverable D7.1, openENTRANCE, https://openentrance.eu

Auer et al (2020): Quantitative Scenarios for Low-Carbon Futures of the pan-European Energy System, Deliverable D3.1, openENTRANCE, https://openentrance.eu

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.

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.

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.

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

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

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

World Energy Outlook 2019 (WEO2019), https://www.iea.org/reports/world-energy-outlook-2019, as consulted online on 19 August 2010.

Hans Auer, Energy Economics Group (EEG), TU-Wien
Foto: privat

Hans Auer ist Associate Professor für Energiewirtschaft an der Technischen Universität Wien (TU-Wien). Er hat an der TU-Wien Elektrotechnik studiert (Dipl.-Ing., 1996) und wurde im Jahr 2000 im Fach Energiewirtschaft promoviert (Dr. techn.) bzw. 2012 habilitiert (Privatdozent). Seit dem Beginn seiner akademischen Karriere hat er sich in Forschung und Lehre mit verschiedenen Aspekten im Bereich der Modellierung von Strommärkten, insbesondere im Zusammenhang mit der Netz- und Marktintegration von erneuerbaren Energien beschäftigt.
Hans Auer is Associate Professor of Energy Economics at Technische Universität Wien (TU Wien). He studied electrical engineering at TU-Wien (Dipl.-Ing., 1996) and received his PhD in 2000 (Dr. techn.) and his habilitation in 2012 (Privatdozent). Since the beginning of his academic career, he has been focusing in research and teaching on various aspects of electricity market modelling, especially in the context of grid and market integration of renewable energy technologies.

Pedro Crespo del Granado, Norwegian University of Science and Technology (NTNU)
Photo: Private

Pedro Crespo del Granado is a senior research scientist at the department of industrial economics and technology management at the Norwegian University of Science and Technology (NTNU). His major fields of research are energy system modelling via operations research analytical methods. He is also a scientific advisor and senior research scientist at SINTEF Energi, Norway. From 2014-2017 Pedro was a post-doctoral researcher at ETHZ (Eidgenössische Technische Hochschule Zürich). Pedro holds a PhD in operational research and management science from Lancaster University (2014) and a MSc. in systems engineering and operations research from The George Washington University (2009).

Pao-Yu Oei, Head of Research Group CoalExit, TU Berlin
Photo: TU Berlin

Pao-Yu Oei is head of the 20-member research group CoalExit and the corresponding CoalTransitions.org Research Hub at the Technische Universität Berlin examining the transition from fossil fuels towards renewable energy sources. He has been involved in numerous projects on the German and Global coal phase-out, worked for the German Advisory Council on the Environment (SRU) and as managing editor of the Journal Economics of Energy & Environmental Policy (EEEP). He holds a Dipl. Ing. as industrial engineer and a PhD in Economics from TU Berlin and spent research visits at the University of Maryland and the International Institute of Applied System Analysis (IIASA). He is also a guest researcher at the German Economic Research Institute (DIW Berlin) and has been part of several International Energy Policy partnership delegations.

Karlo Hainsch, CoalExit Research Group, TU Berlin
Photo: TU Berlin

Karlo Hainsch holds a MSc in industrial engineering (Technische Universität Berlin, TU Berlin), is a PhD student at TU Berlin and is part of the CoalExit research group examining the transition from fossil fuels towards renewable energy sources across the entire energy system. His research focusses on energy system modelling with a main emphasis on scenario development and the transportation sector. Additionally, he is one of the developers of GENeSYS-MOD, an open-source energy system model being used for long-term projections of national, international and global energy systems featured in various German and European projects.


Konstantin Löffler, CoalExit Research Group, TU Berlin
Photo: TU Berlin

Konstantin Löffler holds a MSc in industrial engineering (Technische Universität Berlin, TU Berlin), is a PhD student at TU Berlin and is part of the CoalExit research group examining the transition from fossil fuels towards renewable energy sources across the entire energy system. His research focusses on energy system modelling. Together with his colleagues Karlo Hainsch and Thorsten Burandt he is one of the developers of GENeSYS-MOD.


Thorsten Burandt, CoalExit Research Group, TU Berlin
Photo: TU Berlin

Thorsten Burandt holds a MSc in industrial engineering (Technische Universität Berlin, TU Berlin), is a PhD student at TU Berlin and is part of the CoalExit research group examining the transition from fossil fuels towards renewable energy sources across the entire energy system. His research focusses on energy system modelling. Together with his colleagues Karlo Hainsch and Konstantin Löffler he is one of the developers of GENeSYS-MOD.


Daniel Huppmann, International Institute of Applied System Analysis (IIASA)

Photo: Private

Daniel Huppmann is a research scholar at IIASA (International Institute of Applied System Analysis), Laxenburg, Austria. He graduated with a doctorate in economics from Technical University Berlin after successfully completing the structured PhD program at DIW Berlin, defending his dissertation summa cum laude in June 2014. He also studied Mathematics at the Vienna University of Technology, where he earned an MSc degree in 2010. Daniel Huppmann is an author of the 2018 IPCC Special Report on Global Warming of 1.5 °C (SR15). His responsibility for the SR15 was the compilation of a scenario ensemble of quantitative scenarios (Chapter 2) and the assessment of the interaction across different Sustainable Development Goals (SDG, Chapter 5). In parallel to his contribution to the IPCC, he was the lead developer of the energy system and integrated assessment framework MESSAGEix, an open-source platform for integrated and cross-cutting modelling.

Ingeborg Graabak; SINTEF Energy Research
Photo: SINTEF Energy Research

Ingeborg Graabak is a Senior Research Scientist at SINTEF Energy Research in Trondheim, Norway. She is the coordinator of the H2020 project openENTRANCE. In this project fourteen European research partners develop an open modelling platform for analyses of decarbonization of the European energy system in a long-term perspective. Ingeborg Graabak holds a MSc in Engineering Cybernetics and a PhD in Electric power engineering. Her main field of interest is modelling and analyses of the transition of the European and Nordic energy and power systems towards low-emission solutions.