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EXECUTIVE SUMMARY

The European Union is confronted with a generation-overlapping challenge of combatting climate change or at least mitigating the impacts of climate change on the welfare of human beings. Such compromise demands diligent policies that take care of systemic effects of ways and means to find pathways for economies and societies to support prosperous and peaceful living in the EU and outside. Systemic models are a standard instrument to assess the impacts of policies, particularly regarding decarbonisation and competitiveness. Next to adequate models, a holistic assessment of impacts needs respective indicators.

The following report, Deliverable 3.2, "Selected indicators to measure progress towards decarbonisation and competitiveness", summarises and presents the activities performed in SUPEERA Work Package 3: Task 3.1 "Selecting indicators to analyse the effect of policies". Task 3.1 was targeted to formulate a facilitating framework to analyse policies' effect by several selected indicators.

IndiModel was developed at a general and conceptual level as an outcome of this task. IndiModel is a methodological combination of **Indi**cators and **Modell**ing. Indicators present a comprehensive and applicable methodological format to measure the objective aimed for this Deliverable, the progress towards decarbonisation and the competitiveness of the energy sector compared to the international landscape. This task emphasized depicting the reported development situation in each European Union Member State as well as in Norway, Switzerland, and UK on a comparable basis. The modelling interconnection secured a scenario-based analysis of future decarbonisation and competitiveness based on energy systems or energy-related models. The selected indicators were implemented as variables of the studied models, with or without additional calculations. This Deliverable made use of the H2020 project openENTRANCE, open **EN**ergy **TR**ansition **AN**alyses for a low-Carbon Economy. OpenENTRANCE "aims at developing, using and disseminating an open, transparent, and integrated modelling platform for assessing low-carbon transition pathways in Europe" (www.openentrance.eu; accessed 11.04.2023). Within the openENTRANCE project, four future European narratives (Societal Commitment, Techno-Friendly, Directed Transition and Gradual Development) were studied through the conceptual approach of IndiModel. There are 12 open-source optimization models within the openENTRANCE project with different scope and functionalities. A practical exercise for the further investigation of IndiModel was performed using the energy system model GENeSYS-MOD. GENeSYS-MOD was selected due to its scope and maturity in the openENTRANCE project.

The main findings of this Deliverable are related to the challenges to find adequate indicators which have to fulfil two requirements:

- give sufficient information about decarbonisation and competitiveness, two complex concepts, and
- be suitably linked to the available systemic energy system models.

With the application of IndiModel through the openENTRANCE models as a reference, many important indicators, in particular, addressing decarbonisation, can be captured by energy systems models. However, not all valuable indicators are recognised by the models; in particular, competitiveness needs other models; just transformation is not captured at all.

ABBREVIATION LIST

CAPEX	Capital Expenditure
CCS	Carbon Capture and Storage
CO_2	Carbon dioxide
CH	Switzerland
CY	Cyprus
DE	*Deutschland* (Germany)
DK	Denmark
EEA	European Economic Area
ES	Spain
EU	European Union
EU27	European Union as of February 1st, 2020
FR	France
GDP	Gross Domestic Product
GENeSYS-MOD	Global Energy System Model
GHG	Greenhouse gas
H_2	Hydrogen
ML	Malta
NECP	National Energy and Climate Plan
NL	Netherlands
NO	Norway
OPEX	Operational Expenditure
PtG	Power-to-Gas
R&D	Research and Development
R&I	Research and Innovation
RES	Renewable energy sources
SET-Plan	Strategic Energy Technology Plan
UK	United Kingdom of Great Britain and Northern Ireland
w/	with
w/o	with out

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1 INTRODUCTION

The Energy Transition entails a sustainable and socially fair transformative process, encompassing technological, social, economic, and political dimensions towards a cleaner and integrated energy system (European Commission, 2019). The Energy Transition requires the reconciliation of ideals and self-interests across technological, economic, societal, and environmental aspects with the same purposes of political demands to bring a new reality for all. In this regard, decarbonisation and competitiveness became relevant to be understood. In Deliverable 3.1- v.2 (Poganietz, et al., 2021), short remarks were introduced to re-examine the fundamental understanding of both terms as the backbone for the subsequent development of this Deliverable 3.2.

Decarbonisation describes the process of dissolving the use of fossil-carbon-related energy carriers for energy purposes (European Commission, 2018). Although decarbonisation is the focus of the energy policy of the EU, according to the European Commission, the required transformation shall not be accomplished at the expense of energy security and affordability, framing possible policy options (European Commission, 2019).

Energy security consists of two facets: Secure provision of

- useful energy to satisfy the demands of companies and households; and of
- primary energy carriers and technologies to the European energy sector as a pre-condition for a secure provision of energy use.

Realising a secure provision of useful energy in an energy system characterised by a high share of fluctuating renewable energy sources (RES) demands a more flexible setting of the energy system. Increased security regarding energy carriers and energy technologies implies policies addressing available energy carriers, energy exporting countries outside the European Economic Area (EEA), the availability of critical resources and the competitiveness of energy technologies constructed in the EU. To deal with both facets, digitisation of energy generation, transport, and use is needed.

Nevertheless, despite different measures to achieve better energy security, the 'energy efficiency first' principle must be part of policy actions (Directive 2018/2002/EU, 2018). That means efficient use of available energy resources will reduce the severity of the challenges.

Considering the comprehensive understanding of decarbonisation, indicators measuring it should focus on more than just greenhouse gas emissions. Deliverable 3.2 also tackles energy security, energy dependency, and digitisation, i.e., considering factors influencing the fulfilment of climate policy targets as part of the indicators' framework.

While there is a relatively common understanding of what describes the decarbonisation of energy systems, this differs from the competitiveness case. Competitiveness is defined as the capacity to produce and use affordable, reliable, and accessible clean energy through clean energy technologies and compete in energy technology markets, aiming to benefit the EU economy and people (European Commission, 2020). That means competitiveness of the energy sector addresses two aspects:

- The generation of clean energy, and
- the provision of competitive innovative energy technologies.

Nevertheless, competitiveness is a multi-dimensional concept and can be monitored through a number of indicators. They are best interpreted by reference and comparison to other indicators, but also to other countries.

In the past, the Deliverable 3.1 (v.2) considered two facets for defining indicators to disclose competitiveness:

- Disclosing of today's competitiveness of the energy sector. The indicators address the current situation in the markets for energy and for energy technologies as well as the position of the involved companies;
- Indicating the future perspective of competitiveness. The indicators consider research and investment-relevant activities regarding energy technologies.

The indicators considered in Deliverable 3.1 (v.2) have been revised periodically according to the common understanding among project members regarding the definitions of decarbonisation and competitiveness mentioned above. Those indicators were discussed with the working team throughout the integration process according to the background of the energy systems or energy-related models from OpenENTRANCE project models. They will be presented in the following sections, 2, 3 and 4.

This present Deliverable is organised as follows. Section 1 reviews the activities provided in Deliverable 3.1 (v.2) as part of the introduction of this Deliverable. Section 2 describes the conceptual approach of IndiModel. Section 3 shows the results of the practical exercise performed through GENeSYS-MOD. Section 4 illustrates the further functionality of IndiModel as a model-based indicator in compliance with energy systems or energy-related models from the openENTRANCE project. Section 5 provides some final remarks.

2 INDIMODEL

2.1 Introduction

IndiModel represents the interaction between indicators, policies, and energy system modelling. Figure 1 demonstrates the illustration of the workflow and the respective interactions. Methodologically, indicators are considered in Task 3.1 in a communicative format to assess and show the implications of a new reality for all by concretizing different knowledge disciplines in a flexible, robust and accessible way. The selected indicators (Section 2.1) were taken as the starting point for IndiModel established and presented in Deliverable 3.1 (v.2) (Poganietz, et al., 2021). The selected indicators measure the progress of energy transition by comparing the indicator value for different countries or comparing the indicator value today with the value in 2030 or 2050. However, the value of each indicator in 2030 or 2050 is currently unknown. Therefore, to support the evaluation of whether the **indicator framework** is appropriate, **energy system models** that analyse the energy transition over the coming decades can be used to quantify the indicators in the future.

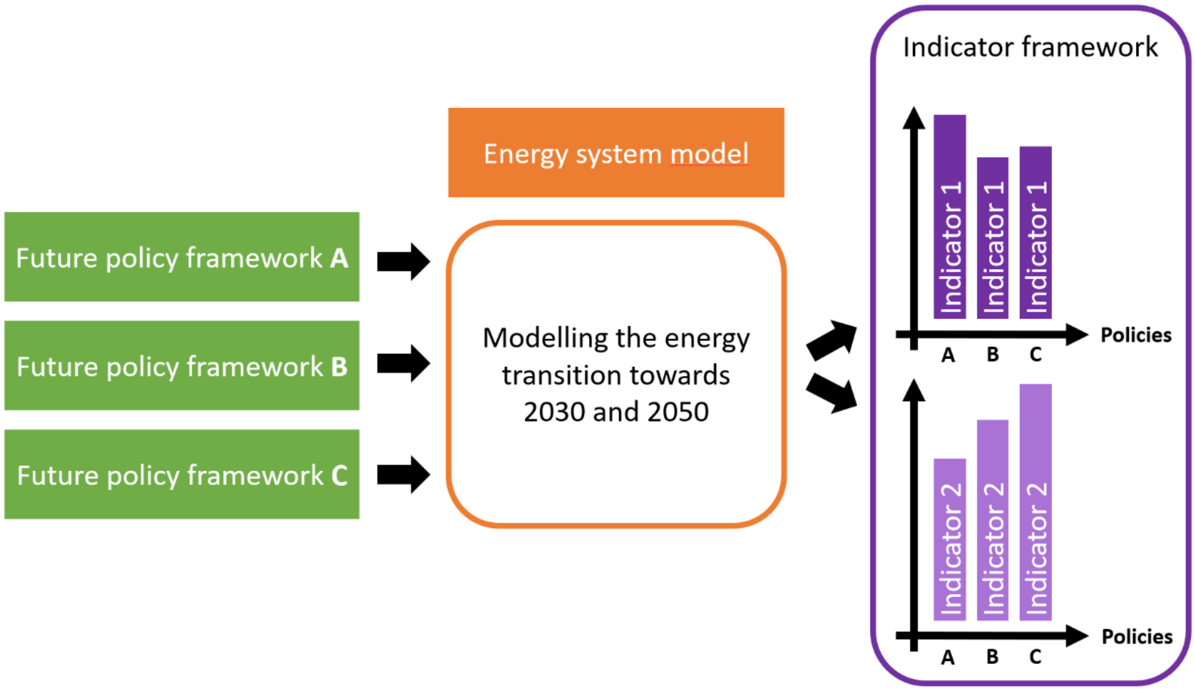

Figure 1 *Illustration of the workflow and the interaction between indicators, policies, and the energy system modelling*

The indicator values resulting from the **energy system models** are scenario-based, and the resulting indicator values from the models are strongly impacted by assumptions and input data to the **energy system models**, including the assumptions related to the **future policy framework** towards 2030 or 2050. In this regard, scenarios show development options by revealing important interdependencies and their relevance within civil society, as well as between civil society, politics, technology, and the economy (Poganietz & Weimer-Jehle, 2020). Energy system models are an instrument to calculate different scenarios proposed. As Figure 1 shows, different policy frameworks could be seen and understood as different (political) scenarios (e.g., future policy framework A, B, C).

In this way, the **indicator framework** can be used to understand which key results from the **energy system models** that should be compared to measure how different **future policy frameworks** impact the progress towards decarbonisation and competitiveness of the energy sector compared to the international landscape.

Within the openENTRANCE project, four future European narratives (Auer, et al., 2020) were developed, representing different future development pathways towards a decarbonised future. The overarching differences between the four narratives are introduced in Section 2.2. Through the project openENTRANCE, twelve models support the approach of IndiModel (section 2.4).

2.2 Selected Indicators

The indicators were assigned to five topics referred to the facets of decarbonisation and competitiveness and first presented in Deliverable 3.1 (v.2) (Poganietz, et al., 2021). They also link to the dimensions of the Energy Union. The dimensions are energy security, energy efficiency, internal energy market/market integration, decarbonisation and innovation & competition (Regulation 2018/1999/EU, 2018). Topics and indicators are presented in table 1.

Table1. *Topics and selected indicators*

Topic	Indicators
Decarbonisation of the economy	Greenhouse gas emission reduction Gap between greenhouse gas emissions and NECP target in Effort-Sharing sectors Greenhouse gas intensity Renewable energy share Relative costs to implement decarbonised systems
Energy security, solidarity and trust	Net import dependence
Energy efficiency and moderation of demand	Primary energy consumption Final energy consumption Final energy intensity – industry Final energy consumption – transport: traffic Final energy consumption – transport: freight
Integrated internal energy market	Electricity interconnection capacity Gas interconnection capacity Installed capacity of energy storage resources Installed capacity of electrolyzes for Power-to-Gas applications Wholesale electricity prices Share of electricity at total energy use in non-energy sectors
Research, innovation and competitiveness	Capacity installed Trade openness

Source: (Poganietz, et al., 2021).

2.3 Future policy scenarios in the open-ENTRANCE project

The storylines in open-ENTRANCE project represent plausible scenarios of the future, including technology cost development, energy policies, and demand projections. The storylines are entitled (Auer, et al., 2019):

- Societal Commitment;
- Techno-Friendly;
- Directed Transition;
- Gradual Development.

The four storylines are societal awareness (innovative society), policy exertion and technology novelty. A target regarding the average temperature increase against the pre-industrial level is added.

Policy exertion represents a world where 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, centralised initiatives, and a strong EU.

Technology novelty represents innovation and technological breakthroughs. Rapid technological learning helps bring various technological options to commerciality and has an active role in the energy transition.

Societal awareness (innovative society) maximises the engagement and awareness of society to take concrete actions to combat climate change. It is characterised by strong support from the public and active participation (e.g., climate activism) in changing attitudes and behaviour in lifestyles.

Three narratives are designed to focus on developments along two possible dimensions intensely. The differences between the four narratives are illustrated in Figure 2 and wholly found in (Auer, et al., 2019). More details about the scenarios are available in Appendix 1.

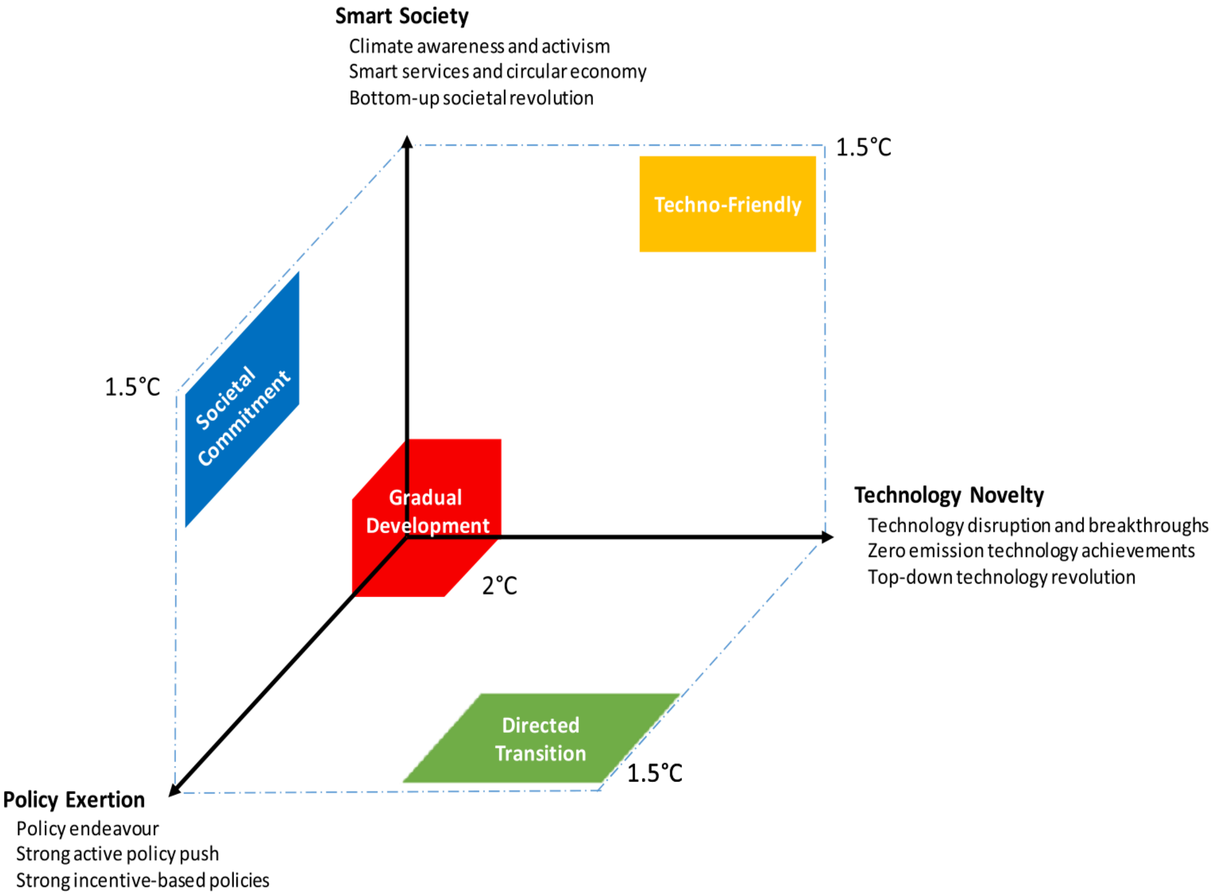

Figure 2 *Overview of the four future narratives in the openENTRANCE project representing different degrees of political, social, and technological developments*
Source: (Auer, et al., 2020)

2.4 Open-source models in the openENTRANCE project

The societal, technical, and economic implications of the four narratives in the openENTRANCE project are studied with open-source models within the project. There are 12 open-source optimization models within the openENTRANCE project with different scope and functionalities. The 12 models are entitled:

- GENeSYS-MOD
- REMES
- INTEGRATE
- EMPS-W
- EMPIRE
- EXIOMOD 2.0
- MESSAGEix-GLOBIOM
- openTEPES
- SCOPE
- GUSTO
- Plan4EU (modelling suite)
- FRESH:COM

All models have some representation of the energy system. Most of the models can be run with a European geographical coverage, while some models are mostly or only used for smaller geographical coverage, e.g., community level (incl. GUSTO and FRESH:COM).

Several models focus mostly on power systems and electricity markets (incl. EMPS-W, EMPIRE, openTEPES, and Plan4EU), while most models cover several energy carriers within sectors like transport, industry, and buildings.

Most models produce capacity expansion pathways (investments) as output, while a few models focus on producing macroeconomic output like gross domestic product (including REMES). A complete description of each model is available in the Appendix 2.

3 APPLICATION OF INDIMODEL APPROACH THROUGH GENESYS-MOD

3.1 Introduction

GENeSYS-MOD is an open-source **energy system model** to analyse the transition towards future decarbonised energy systems in Europe towards 2050. To select three indicators to study with GENeSYS-MOD, discussions between SINTEF and KIT were organized regarding the relevance of the indicators to measure *decarbonisation* and *competitiveness*. It was also discussed if the three selected indicators could produce complementary insights such that similar indicators could be avoided.

Further, the indicators in Deliverable 3.1 were categorized based on their availability as input/output from the energy system model GENeSYS-MOD. It was studied the modelling features of GENeSYS-MOD, including details regarding its scope and outputs. This resulted in a map of the difficulty in quantifying the indicator using the model illustrated in Figure 3**Figure** .

Available in GENeSYS-MOD

- 3.1.1 Greenhouse gas emission reduction
- 3.1.4 Renewable share in gross final energy
- 3.2.1 Fuel import (energy carriers) per gross inland energy consumption
- 3.3.1 Primary energy consumption
- 3.3.2 Final energy consumption
- 3.3.4 Final energy consumption, traffic
- 3.3.5 Final energy consumption, freight
- 3.4.3 Installed capacity of energy storage resources
- 3.4.4 Installed capacity of electrolyzes for Power-to-Gas applications
- 3.5.1 Capacity installed

Indirectly available in GENeSYS-MOD

- 3.1.2 Gap between greenhouse gas emissions and NECP target in Effort-Sharing sectors
- 3.5.2 Trade openness
- 3.4.6 Share of electricity at total energy use in non-energy sectors
- 3.4.5 Wholesale electricity prices
- 3.4.1 Electricity interconnection capacity

Not available in GENeSYS-MOD

- 3.1.3 Greenhouse gas intensity
- 3.1.5 Relative costs to implement decarbonized systems
- 3.3.3 Final energy intensity – industry

Figure 3 *Indicators from Deliverable D3.1 and their availability in GENeSYS-MOD*

While most indicators from Deliverable 3.1 (v.2) are available as direct output from GENeSYS-MOD, several indicators need supporting data from external sources and/or complementary economic models to be quantified. For a complete assessment, there is the need to search for the availability of external data to support the quantification of the indicator in combination with GENeSYS-MOD results data (e.g., country-level greenhouse gas emissions in 1990).

Based on this methodology, the following three indicators from Deliverable 3.1 (v.2.) were selected to be evaluated across a small set of future policy scenarios by solving several instances of GENeSYS-MOD:

- 3.1.1 Indicator: Greenhouse gas emission reduction
- 3.2.1 Indicator: Net import dependence
- 3.4.6 Indicator: Share of electricity at total energy use in non-energy sectors

The reasoning behind the choice of each indicator is the following:

- **The greenhouse gas indicator (3.1.1)** was selected as a key indicator to measure decarbonisation since it directly quantifies carbon emissions. In Deliverable 3.1, it is defined as the change in emissions with reference to 1990 levels, and the 1990 reference data was found through open data through Eurostat and the European Environment Agency (EEA).

- We also discussed the relevance of the indicators in pressing political situations, i.e., the war in Ukraine. The indicator regarding **import dependence (3.2.1)** was therefore identified as especially relevant. It is also an indicator relevant for competitiveness.
- Further, there was a need to find an indicator that represented sector coupling since it has been identified in recent energy research as a key element of the future decarbonised energy system. Sector coupling can be hard to quantify and measure. However, we found that **the share of electricity in non-energy sectors (3.4.6)** gives some representation of the degree of sector coupling.

3.2 Application of IndiModel through the Gradual Development Policy Scenario

The Gradual Development storyline is the least ambitious of the storylines of the openENTRANCE project, and it therefore includes fewest policies among the four storylines in openENTRANCE. Therefore, the Gradual Development storyline was selected as the baseline storyline.

Gradual Development represents a future narrative in line with the 2°C target, and it includes a mix of assumptions reflecting a balance between the three dimensions illustrated in Figure 2**Figure** . It's important to note that the Gradual Development narrative ensures 2°C compliance, which requires CO_2 policies to be ensured. The baseline in the context (Gradual Development) is therefore NOT a "no policy" or business-as-usual pathway towards 2050, but it includes the following:

- Net zero GHG emissions by 2050 (2°C) is ensured.
  - Assumed an increasing **CO_2 price** (€30 /ton in 2020 → €355 /ton in 2050);
  - **CO_2 cap** is also implemented for power/industry to simulate EU emission trading system (EU ETS).
- No hydrogen (H_2) imports are allowed from outside the system (Europe).
- No carbon capture and storage (CCS) is allowed.
  - Combined with CO_2 price and cap, the unavailability of CCS leads to a phase-out of fossil fuels by 2050.

In the modelling exercise, to capture additional three policies Gradual Development was modified in GENeSYS-MOD to compare the impact of the policy modifications on the three selected indicators. Discussion between SINTEF, KIT, and external experts identified which policy scenarios to solve and compare using GENeSYS-MOD. The specific policy scenarios are:

- **Base:** Gradual Development (as described above);
- **CCS policy:** Base with the opportunity to develop carbon capture and storage;
- **Hydrogen policy:** Base with the opportunity to import H_2 from outside Europe;
- **Fossil gas policy:** Base with no import of fossil gas from outside Europe (including Russia);
- **Combined policy:** Base with all the policies above (CCS allowed + H_2 import allowed + banned fossil gas imports).

In the following, it was discussed differences across the three selected indicators for EU27 Member States + Norway, Switzerland, and UK. Results for selected countries were also discussed to highlight where impacts are significantly high and low, as part of the lessons learned taken along the development of this Task 3.1.

3.3 Greenhouse gas indicator analysis

Figure 4 shows the development of greenhouse gas (GHG) emissions from 2018 to 2050 for the five different future scenarios. In Gradual Development, all emissions are steadily reduced from around 80% compared to 1990 to 0 by 2050. It observes similar results on the European level for greenhouse gas emission reductions with the other policy modifications, and this is because the same CO_2 policy is active in all policy scenarios (CO_2 price and CO_2 cap for power/industry).

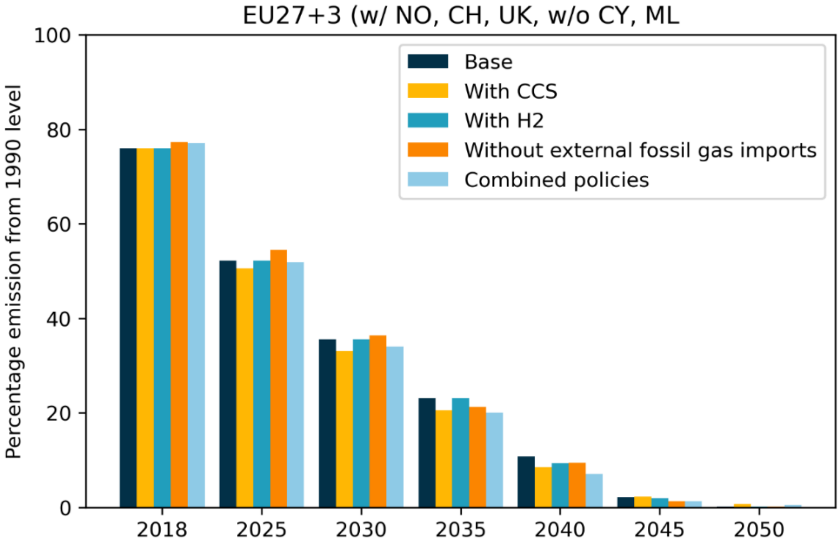

Figure 4 *Greenhouse gas emission reduction for future years as a share of emissions in 1990 by policy scenarios*

With CCS, some emissions are generally decreased compared to the baseline Gradual Development. This is because CCS is applied to fossil fuel plants that get an extended economic lifetime because their CO_2 emissions are reduced. However, some emissions also remain in 2050 with CCS. This is because CCS cannot remove all GHG emissions from fossil fuel plants, and therefore some emissions remain even in the long-term future.

With import of hydrogen from outside Europe, there is little difference from the baseline regarding GHG emission reductions before 2040. After 2040, there are significant hydrogen imports from outside Europe. The external hydrogen replaces fossil fuels in the long-term, which again causes GHG emissions to reduce compared to Gradual Development.

Without fossil gas import from outside Europe, emissions are generally increased compared to the baseline until 2030. This is because coal and oil are the most economic alternatives when large volumes of fossil gas are unavailable. However, the GHG emission increase without fossil gas imports is compensated by a decrease in emissions from 2035 and on compared to Gradual Development. This is because less investments are done in fossil gas technologies, and the shift away from fossil fuels is accelerated.

When we combine all policy modifications, GHG emissions are decreased in all investment periods except 2018 and 2050 compared to Gradual Development. This is because the use of CCS avoids increased emissions from increased use of coal/oil, which is a consequence of banned fossil gas imports. However, there are also some emissions in 2050 when all policies are combined because CCS (not capturing all GHG emissions) is still used in the long-term.

The impact of the policies is different for each European country. Figure 5 and Figure 6 show GHG emission reductions compared to 1990 for the Netherlands (NL) and France (FR), respectively. For the Netherlands, GHG emissions are impacted by the availability of CCS and banned fossil gas imports. For France, GHG emissions are hardly affected by any single policy in the short-term, but GHG emissions are significantly decreased in 2035 and 2040 with banned fossil gas imports or when all policies are combined.

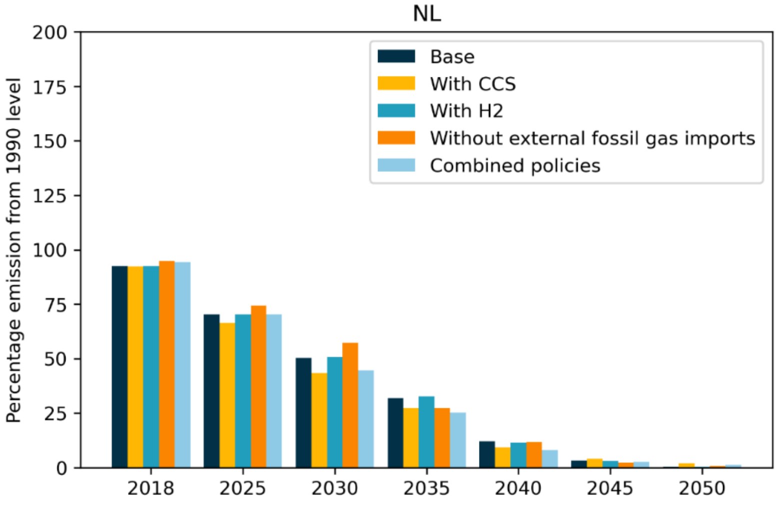

Figure 5 GHG emissions in future years for the Netherlands compared to 1990

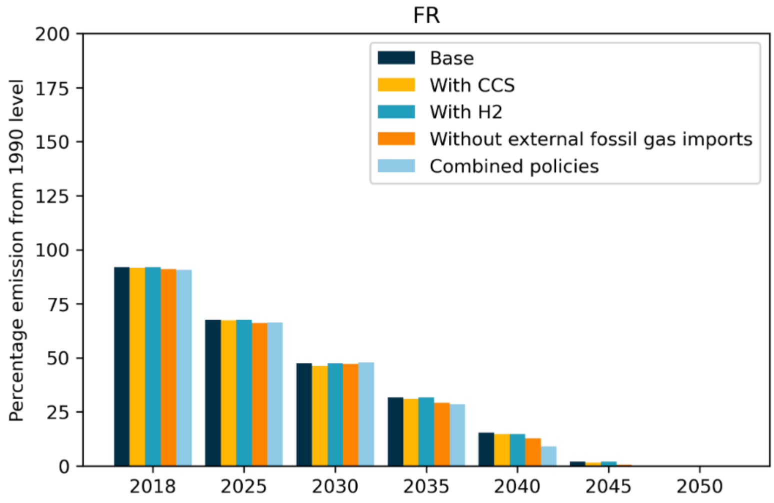

Figure 6 GHG emissions in future years for France compared to 1990

- Reflections on quantifying the indicator

There is a need to get the 1990 emissions from external data sources as a reference for the considered countries/region. It is unclear how to delimit the 1990 emission reference, i.e., which sectors to include in the reference. It makes most sense to include only the sectors that are modelled in GENeSYS-MOD, however, the sectoral categories provided by Eurostat for the 1990 emission reference does not overlap perfectly with the sectoral scope and the considered emissions in GENeSYS-MOD. We chose to use the 1990 emission reference that covers the entire sector called "1 – Energy" in Eurostat data which includes "fuel combustion (1.A)" and "fugitive emissions from fuels (1.B)".

As there is a need to use external data with the current indicator 3.1.1 (1990 reference), it can be worth considering absolute emissions as an alternative indicator. For several energy system models, GHG emissions are quantified as a result from the model, and this could make the indicator easier to adopt by energy system modellers.

- Reflections on the usefulness of the indicator

The 4.1.1 indicator is key when measuring progress related to decarbonisation, as it is a direct quantification of reduction of GHG emissions. By scaling GHG emission reductions using the 1990 reference, it becomes easier to compare different countries/regions to each other in terms of their relative decarbonisation. However, it becomes more tedious for modellers to quantify the indicator because there is a need for external data (see above). The 3.1.1 indicator gives limited insights related to competitiveness.

3.4 Net import dependence (with non-EU imports) indicator analysis

The net import dependence of European countries has gained attention recently due to the weaponization of gas exports from Russia to Europe highlighting the risks associated with import dependence in the energy sector. It is thus important to explore the impact of policy decisions on the net import dependence of European countries.

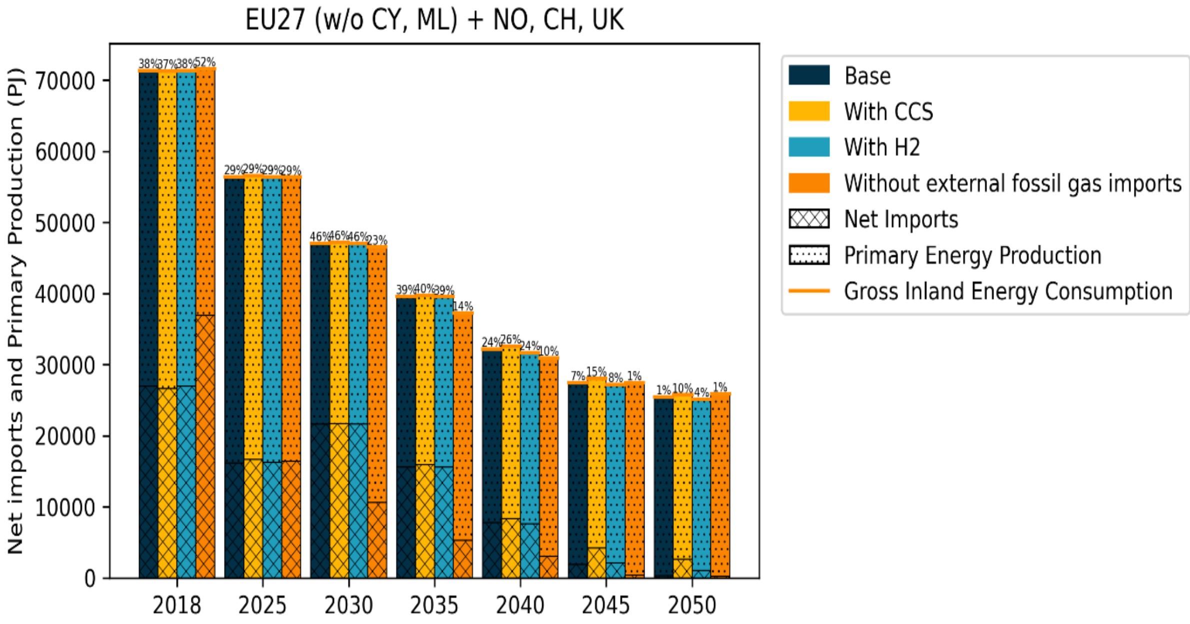

Figure 7 *Net imports and primary energy production*

Figure 7 shows the net imports and primary energy production in the geographical area defined for the indicator in Deliverable 3.1 (v.2). Towards 2050, the gross inland energy consumption is reduced from 70 000PJ to around 25 000PJ across all cases. The share of the net imports in this are, however, varying depending on the cases. While being reduced across all cases, significant deviations appear. A significant difference is the share of net imports for the case without fossil gas imports. Indeed, due to the state of the existing system in 2018, additional imports are necessary in 2018. The additional imports correspond to hard coal to some extent but mostly natural gas. Even though the case prevents imports from natural gas, it is necessary to allow it in the first period, as it represents the state of the existing system, which relies on gas. The subsequent periods can invest in other technologies to phase out gas. This means that the model tries to take advantage of the existing gas infrastructure in the first period before being forced to stop using them.

The subsequent years however see a more rapid reduction of net imports than in the other cases; this case reaching for instance shares of net imports under 15% of gross inland energy consumption in 2035, 10 years before the other cases.

Another significant result is the case with CCS. Indeed, even though it follows a very similar trajectory like the Base and H_2 case until 2040, it results in a significantly higher share of net imports from 2045 and 2050 at respectively 15 and 10%.

Figure 8 shows a waterfall chart of the hydrogen trade (both as a gas and liquefied) inside the geographical area covered for the four cases. This supplement the information from Figure 9 and Figure 10 by giving information about the trade between countries. In the base case, 11 countries are exporting with most of the exports coming from 4 countries (Greece, NONEU_Balkan, Romania and Spain) while there are more countries importing. The largest importers are Italy, France, Germany, Belgium, Czechia and Slovakia.

In both the case with CCS and with no fossil gas import, the results are similar. The total trade increase by about 15-20% (from around 700PJ to 800-850PJ) with the main importers and exporters remaining unchanged.

In the case where import of hydrogen from outside is allowed, the main difference is a reduction of total trade to 550PJ (about 20% reduction). Another significant change is that France's imports from inside are reduced to almost nothing, which is compensated by more import from outside (Figure 10).

Note that no primary energy production is reported for hydrogen as it is derived from either electricity or fossil fuels.

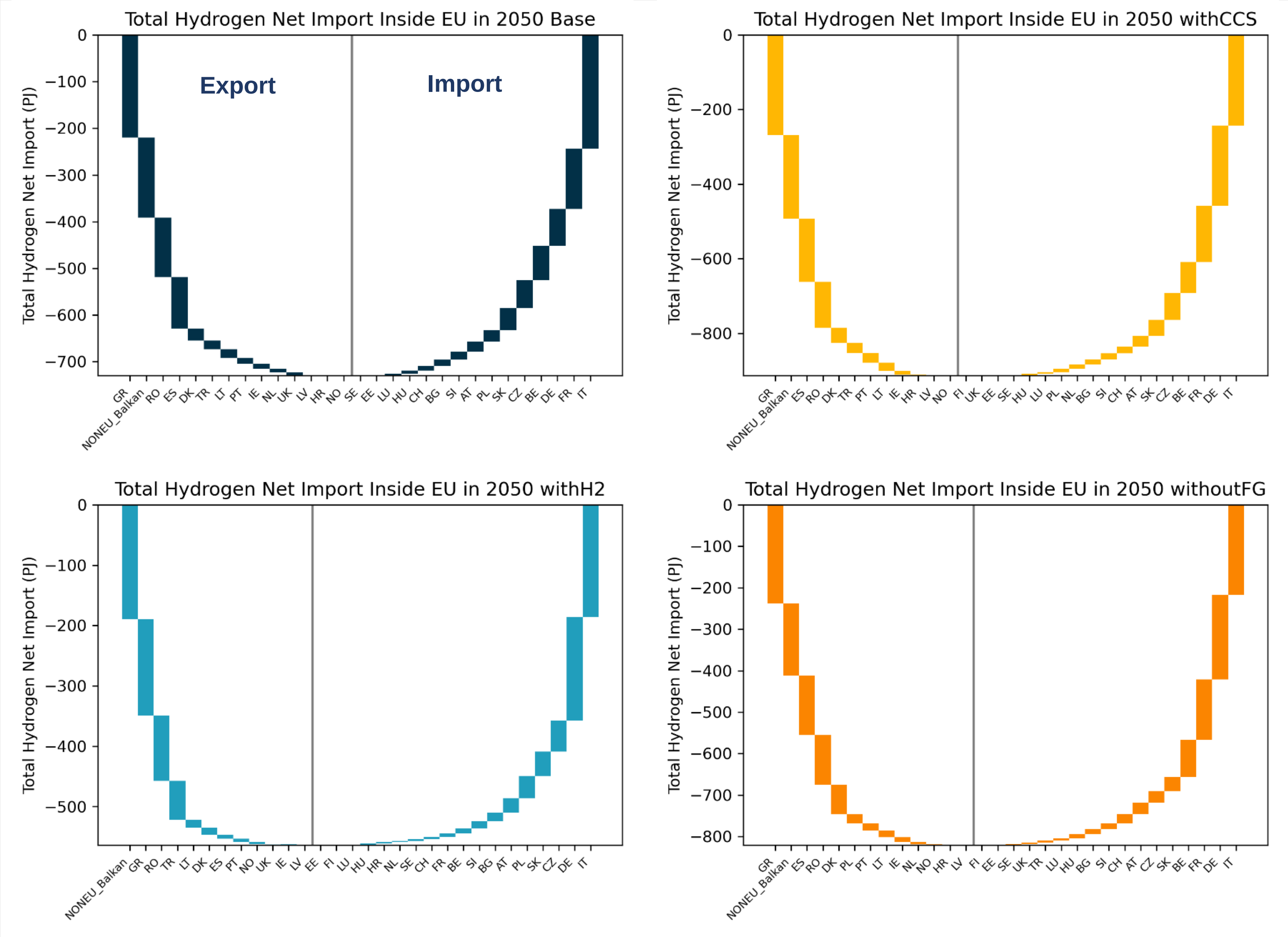

Figure 8 *Waterfall chart of the net imports of hydrogen included liquefied hydrogen by country in 2050 in the four cases. Net exports to the left and net imports to the right. Countries below* $5x10^{-5}$ *PJ are not show*

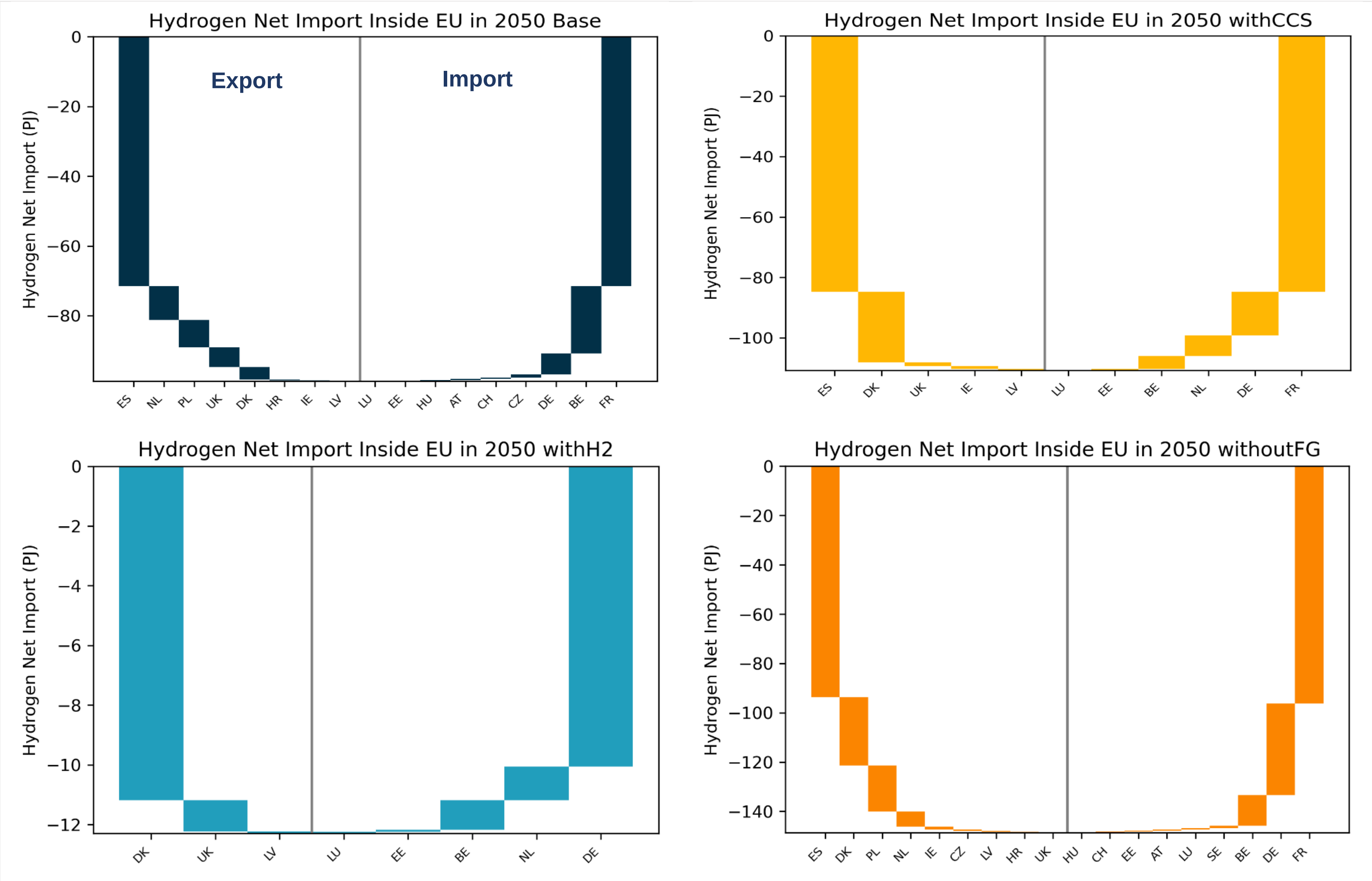

Figure 9 *Waterfall chart of the net imports of Hydrogen by country in 2050 in the four cases. Net exports to the left and net imports to the right. Countries below 5x10^{-5} PJ are not show*

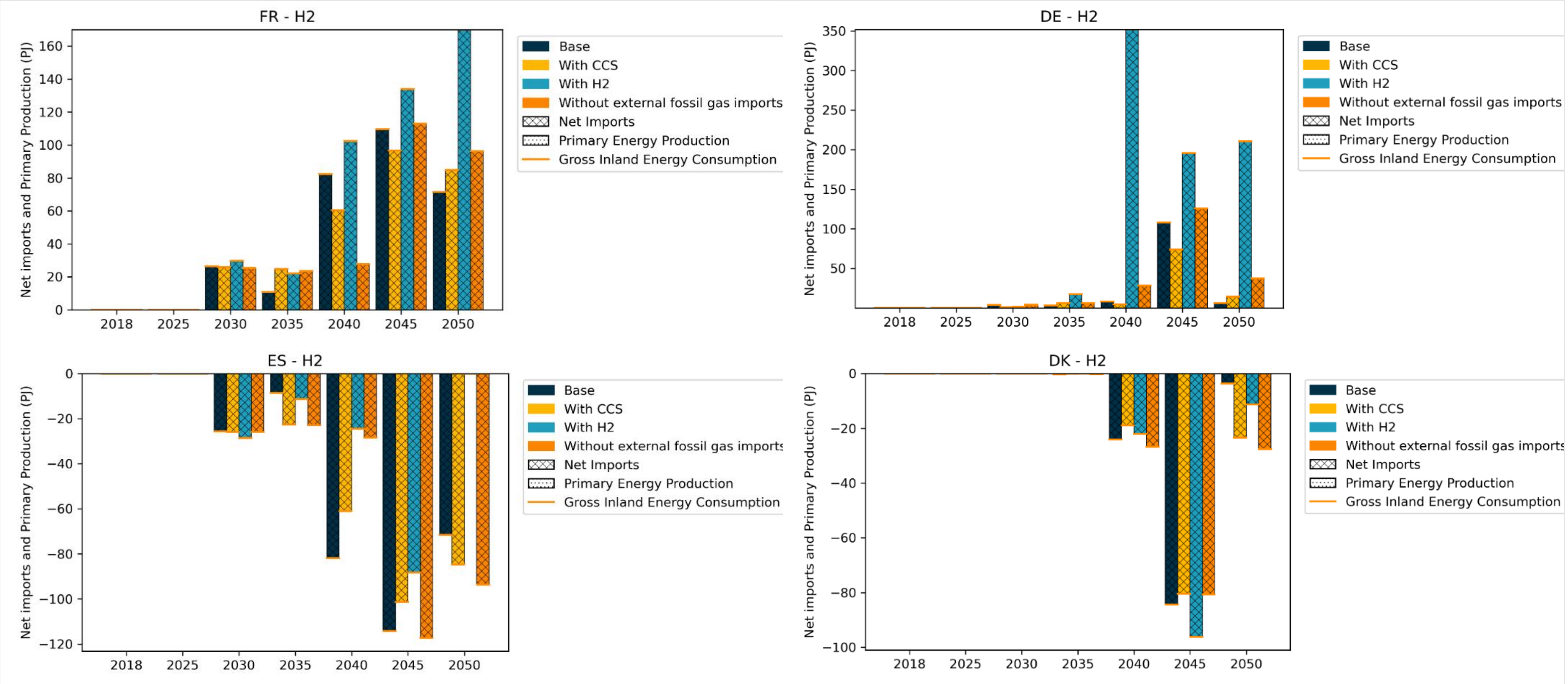

Figure 10 *Net imports and primary energy production of hydrogen in selected countries through the years.*

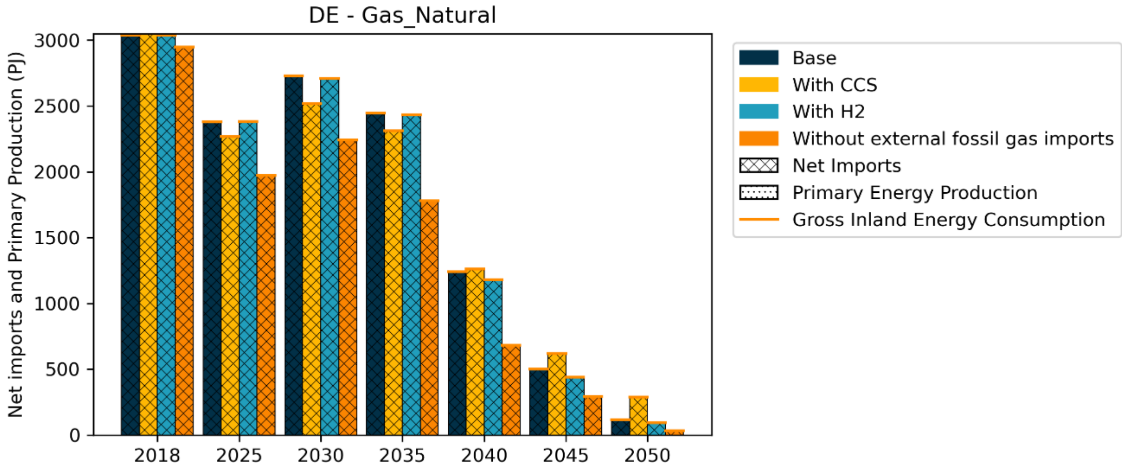

Figure 11 *Net imports and primary energy production of natural gas in selected countries through the years*

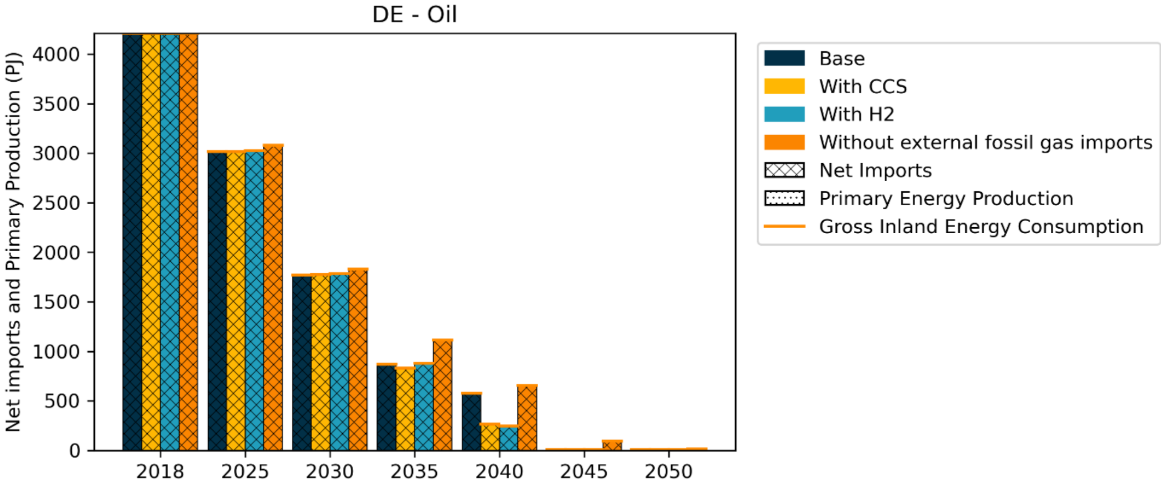

Figure 12 *Net imports and primary energy production of oil in selected countries through the years*

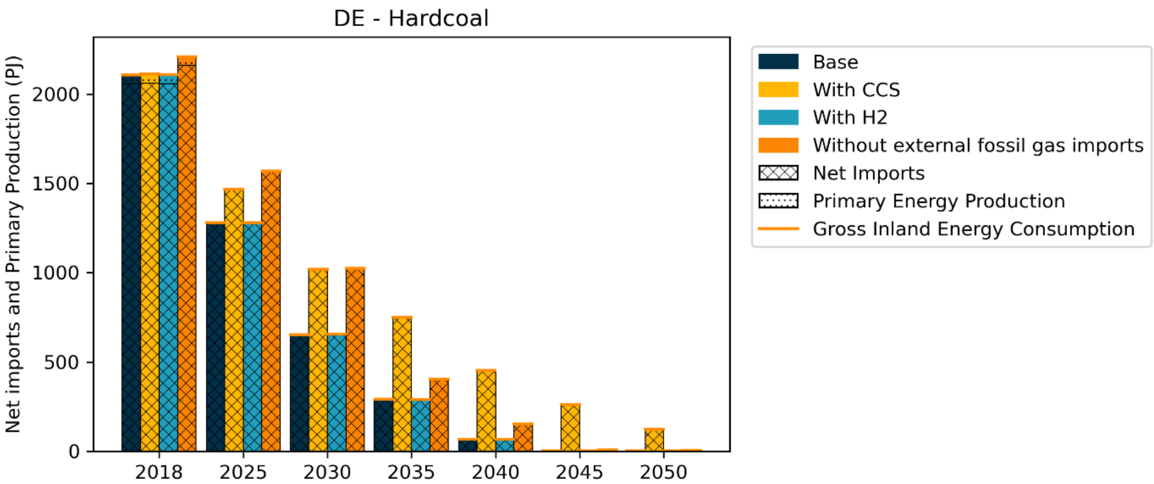

Figure 13 *Net imports and primary energy production of hard coal in selected countries through the years*

It is also interesting to look at net imports of fossil fuels and here we will focus on Germany.

Figure 11, Figure 12 and Figure 13 present the net imports and primary energy production of respectively natural gas, oil and hard coal in Germany. There is no primary energy production of those fossil fuels in Germany except a small amount of hard coal in 2018.

When it comes to net imports, in all cases the trend is a reduction of the use of fossil fuels towards 2050, with a complete phase out of oil and hard coal in 2045. In the case with CCS, some amount of hard coal remains in 2050, while some oil imports remain in the case with fossil gas to replace the gas imports.

In the case without fossil gas imports, the phase out of oil and hard coal is also less steep than in the other cases. The case with CCS also reduces the speed of the phase out of hard coal, with some imports remaining in 2050.

The case with hydrogen imports from outside is very similar to the base case for fossil fuels imports with slightly less natural gas in the last periods.

Even though natural gas cannot be imported from outside the EU in one of the cases, there is still production and trade inside the EU (Figure 14) with production mainly in Norway and the Netherlands. Norway phases out its production from 2030 to 2050 going from 8 000 PJ exports in 2030 to 700 PJ in 2045 and zero in 2050.

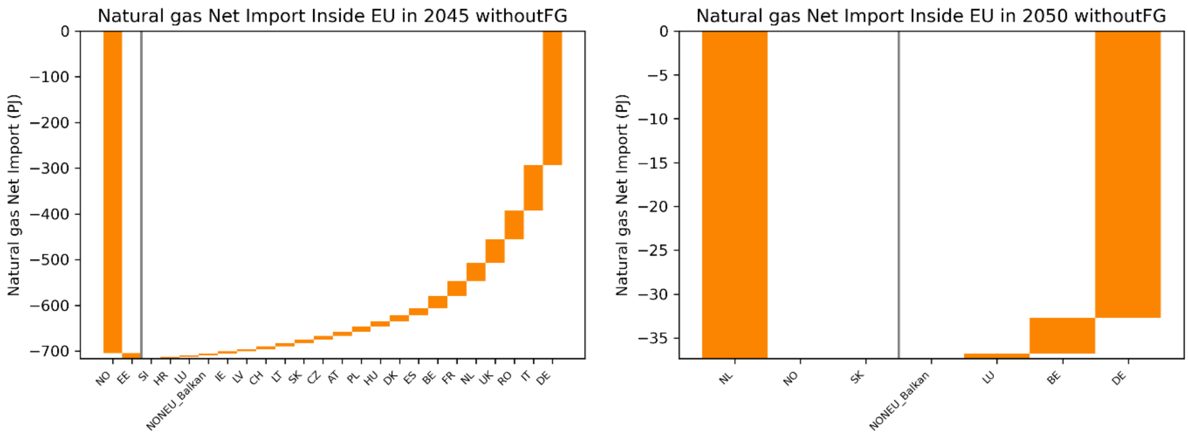

Figure 14 *Waterfall charts of Natural gas trad in Europe in 2045 and 2050 in the case without import of external natural gas*

- Reflections on quantifying the indicator

The whole indicator name is net import dependence, i.e., net import as a share of the gross inland energy consumption. The first part of the indicator is quite straightforward to fetch from the model results. Indeed, the imports and exports between the various countries inside the EU and the imports from outside the EU are variables in the optimization and, as such, are direct model results. The second part is more challenging. The gross inland energy consumption is not a direct model result, and it is necessary to carefully select the elements that should belong to the category. In GENeSYS-MOD, we select the resource production of oil, nuclear fuel, hard coal, lignite, gas, and renewable energy sources. The variation of stocks is not relevant for this model.

This type of indicator being less common in this field of energy system optimization could lead to more errors in its quantification.

- Reflections on the usefulness of the indicator

The importance of the indicator has been highlighted by the war in Ukraine and the geo-political implication of the dependence on Russian gas. Indeed, security of supply is partially covered by this indicator.

In the case of GENeSYS-MOD, the full picture is not necessarily given. An example is the case of nuclear, which assumes a nuclear fuel generated in the country where the demand is needed and thus does not represent the dependence on imports from Russia and outside Europe.

The indicator should however be used in combination with others. On its own, it is not enough to understand the dynamics inside Europe. The waterfall charts above are good complements, as they allow to see the exports and exports inside Europe, but on their own do not carry information about the primary energy production and the net import dependence of the countries.

3.4 Electricity share of energy use in non-energy sectors indicator analysis

Non-energy sectors are not explicitly defined in GENeSYS-MOD as it is an energy system model. The sectors included are industry, transport, and buildings. In this context, we focus on electricity use within industry because industry also uses significant amount of "energy feedstocks" for purposes beyond energy (e.g., chemical feedstock).

Figure 15 shows the energy use and electricity share for the industry sector in GENeSYS-MOD for Gradual Development and the policy modifications. Energy use in all instances is declining towards 2050 because of energy efficiency improvements. Simultaneously, electricity use in industry increases towards 2045, and then flattens out in 2050.

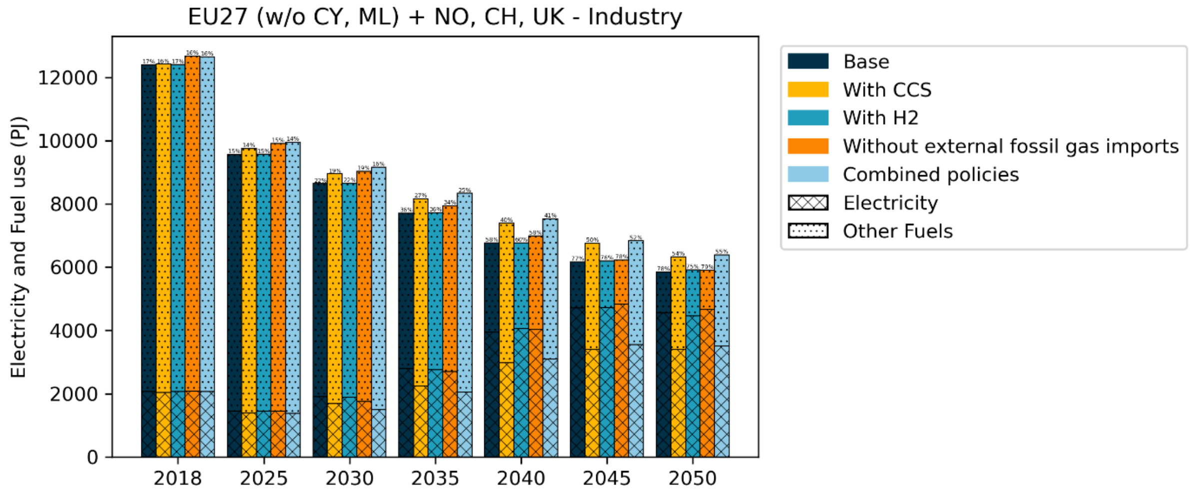

Figure 15 *Electricity and other fuel use in the industry sector for future periods*

With CCS, we observe a lower electricity share in industry compared to Gradual Development. We also observe an overall higher final energy use by industry compared to Gradual Development. These two observations are related, and it happens because the availability of CCS leads to less electrification of industry, which again causes a lower electricity share and lower energy efficiency.

With import of hydrogen from outside Europe, the electricity share in the industry sector is mostly unaffected in GENeSYS-MOD compared to Gradual Development. This is because the total use of hydrogen is similar to Gradual Development, although more hydrogen is imported from outside Europe. Only from 2045, we observe a slightly lower electricity share in the industry sector, which is because non-European hydrogen replaces some of the industry electrification in the long-term.

With banned fossil gas import from outside Europe, the electricity share is slightly reduced in the industry sector in the 2030s and then slightly increased after 2040 compared to Gradual Development. This is because electrification of industry takes longer to become economically viable when there is less available fossil gas. The total energy use in the industry sector is also increased until 2040 because less efficient coal/oil partly replace fossil gas.

When we combine all policy modifications, the electricity share is decreased in every investment period after 2018 compared to Gradual Development. The results of all policies combined and only allowing CCS are similar, which indicates that the electricity share in industry in GENeSYS-MOD is mostly affected by the availability of CCS.

- Reflections on quantifying the indicator

It is unclear which sectors are included in the term "non-energy sectors" for indicator 3.4.6, especially given that electricity is consumed within this sector.

- Reflections on the usefulness of the indicator

The electricity share quantified by indicator 3.4.6 give some indication of sector coupling, however, it provides an incomplete picture. For example, the use of hydrogen is often studied in the context of sector coupling. However, when only quantifying the electricity share within a sector, there is no information about the mix of other energy carriers, including hydrogen. The 3.4.6 indicator give some indication of decarbonisation given that the power sector (electricity supply) will likely be one of the first sectors to fully decarbonise. The 3.4.6 indicator gives limited insights related to competitiveness.

4 MAPPING INDICATORS IN OTHER OPEN-SOURCE MODELS

4.1 Introduction

As part of the Task 3.1 process, the selected indicators were reviewed under the five defined topics (section 2.1) according to the models from the openENTRANCE project. All models available in the openENTRANCE project provides a direct or indirect indicator assessment result. The direct connection means that the energy system model provides a result for the indicator. The indirect connection means that the result is partially available in the energy system model, but data processing or external data is required to fully quantify the indicator. For instance, the indicator “Gap between greenhouse gas emissions and National energy and climate plans (NECP) target in Effort-Sharing sectors” is partly assessed through GENeSYS-MOD. Although the model provides results regarding greenhouse gas emissions, the NECPs for countries needs to be integrated in a post-processing of the model results for the complete assessment of the indicator proposed. In the followings, each indicator is depicted in a table containing the following information:

- Area of relevance;
- Description of indicator;
- Models with directly assessment[1];
- Unit;
- Geographical coverage;
- Additional remarks;
- Reference.

Among the models from the openENTRANCE project, INTEGRATE, GUSTO and FRESH:COM are not considered in any indicator assessment in the context of SUPEERA because the geographical scope of those models is on the local level instead of country or European level.

[1] An extensive model description is available in the Annex.

4.2 Topic 1: Decarbonisation of the economy

4.2.1 Indicator: Greenhouse gas emission reduction

Item	Explanation
Area of relevance	Renewable energy
Description of indicator	Total greenhouse gas emissions of a country in a specific year compared to 1990. The indicator includes indirect CO_2 emissions and emissions from international aviation.
Supporting indicators	▪ Greenhouse gas emission reduction – Industry ▪ Greenhouse gas emission reduction – Transport ▪ Greenhouse gas emission reduction – Services ▪ Greenhouse gas emission reduction – Households
Model	REMES; GENeSYS-MOD, EXIOMOD 2.0, MESSAGEix-GLOBIOM, openTEPES, SCOPE and Plan4EU
Unit	Index number, base year 1990 = 100
Geographical coverage	EU27 Member States, Norway, Switzerland and UK
Additional remarks	GENeSYS-MOD, EXIOMOD 2.0, MESSAGEix-GLOBIOM, openTEPES, SCOPE and Plan4EU assess indirectly this indicator. The additional data required for those models is the 1990 data reference. Specifically, GENeSYS-MOD lacks emissions from agriculture, land use, land use change. Eurostat is a source for supporting data to quantify this indicator through the models mentioned above.
Reference	European Commission (2017)

4.2.2 Indicator: Gap between greenhouse gas emissions and NECP target in Effort-Sharing sectors

Item	Explanation
Area of relevance	Renewable energy
Description of indicator	Greenhouse gas emissions of Effort-Sharing sectors compared to NECP target The indicator is used to monitor the progress in the sectors not covered by the EU emissions trading system. The Effort-Sharing Decision sets national binding targets to be met through mitigation action in the Effort-Sharing sectors (transport, buildings, small businesses and services, agriculture and waste).
Supporting indicators	-
Model	GENeSYS-MOD, REMES, EMPIRE, EXIOMOD 2.0, MESSAGEix-GLOBIOM, openTEPES, SCOPE, Plan4EU
Unit	%
Geographical coverage	EU27 Member States, UK
Additional remarks	This indicator requires the NECPs targets for countries from all the above models as additional data requirements. Specifically, EMPIRE and openTEPES can only cover selected NECP targets for the power system. The NECP targets need to be taken from the respective homepage https://ec.europa.eu/energy/topics/energy-strategy/national-energy-climate-plans_en. An observation is that only Member States are obliged to deliver NECPs. UK submitted their NECP shortly before the end of 2020 (European Commission , 2023).
Reference	European Commission (2017)

4.2.3 Indicator: Greenhouse gas intensity

Item	Explanation
Area of relevance	Renewable energy
Description of indicator	Greenhouse gas emissions of a country in respect to national Gross Domestic Product (GDP) The indicator is relevant from the decarbonisation perspective and is used as a global sustainability indicator.
Supporting indicators	▪ Greenhouse gas intensity per capita [Unit: Mg/inhabitant] ▪ Greenhouse gas intensity of power & heat generation [Unit: Mg/MWh]
Model	REMES, EXIOMOD 2.0, MESSAGEix-GLOBIOM
Unit	Mg/EUR
Geographical coverage	EU27 Member States, Norway, Switzerland and UK
Additional remarks	-
Reference	European Commission (2017)

4.2.4 Indicator: Renewable energy share

Item	Explanation
Area of relevance	Renewable energy
Description of indicator	Energy generation by renewable energy sources in respect to gross final energy consumption The progress on renewable energy penetration gives an important indication of the extent of decarbonisation of the energy system.
Supporting indicators	▪ Renewable energy share – Electricity ▪ Renewable energy share – Heating & cooling ▪ Renewable energy share – Transport Additionally, following indicators are taken into account: ▪ Fossil fuels avoidance by RES ▪ Greenhouse gas emissions avoided due to RES
Model	GENeSYS-MOD; MESSAGEix-GLOBIOM; SCOPE
Unit	%
Geographical coverage	EU27 Member States, Norway, Switzerland and UK
Additional remarks	MESSAGEix-GLOBIOM provide result for aggregated European region The assessment of this indicator can also be modelled in EMPIRE, Plan4EU and openTEPES for electricity only.
Reference	European Commission (2017)

4.2.5 Indicator: Relative costs to implement decarbonised systems

Item	Explanation
Area of relevance	Business regulation of the EU Member States
Description of indicator	Costs to implement decarbonised energy system in respect to per-capita income. This indicator can provide an indication of the business dynamism of the decarbonised system.
Supporting indicators	--
Model	REMES; MESSAGEix-GLOBIOM
Unit	%
Geographical coverage	EU27 Member States, Norway, Switzerland and UK
Additional remarks	This indicator is assessed in REMES in terms of GDP loss. The model does not consider CAPEX and OPEX. MESSAGEix-GLOBIOM provide results for aggregated European regions.
Reference	Schwab (2019)

4.3 Topic 2: Energy security, solidarity and trust

4.3.1 Indicator: Net import dependence

Item	Explanation
Area of relevance	Self-sufficient market-size
Description of indicator	Total net imports of energy carriers in respect to total gross inland energy consumption. The indicator includes energy consumption of maritime bunkers. Net import dependence is the basic indicator to reflect the self-sufficient market-size.
Supporting indicators	▪ Net import dependence – Natural gas ▪ Net import dependence – Crude oil ▪ Net import dependence – Hard coal ▪ Net import dependence – Nuclear fuels ▪ Net import dependence – Electricity ▪ Net import dependence – Biomass ▪ Net import dependence – Hydrogen
Model	GENeSYS-MOD; REMES; EXIOMOD 2.0; MESSAGEix-GLOBIOM; SCOPE
Unit	MJ/MJ
Geographical coverage	EU27 Member States, Norway, Switzerland and UK
Additional remarks	REMES provide results in monetary unit. The assessment of this indicator can also be modelled in EMPS-W, EMPIRE, openTEPES and Plan4EU for electricity only.
Reference	European Commission (2017)

4.4 Topic 3: Energy efficiency and moderation of demand

4.4.1 Indicator: Primary energy consumption

Item	Explanation
Area of relevance	Overarching
Description of indicator	Total energy demand of a country. The indicator covers the consumption of the energy sector itself, losses during transformation and distribution of energy, and the final consumption by end users, but excludes energy carriers used for non-energy purposes. The indicator monitors the changes in primary energy consumption. The Energy Efficiency Directive translates the energy efficiency targets into maximum levels of primary energy consumption by 2020 and 2030
Supporting indicators	▪ Net import dependence – Natural gas ▪ Net import dependence – Crude oil ▪ Net import dependence – Hard coal ▪ Net import dependence – Nuclear fuels ▪ Net import dependence – Electricity ▪ Net import dependence – Biomass ▪ Net import dependence – Hydrogen
Model	GENeSYS-MOD; REMES; EXIOMOD 2.0; MESSAGEix-GLOBIOM; SCOPE
Unit	TWh
Geographical coverage	EU27 Member States, Norway, Switzerland and UK
Additional remarks	REMES provide results in monetary unit. The assessment of this indicator can also be modelled in EMPS-W and Plan4EU for electricity only.
Reference	European Commission (2017)

4.4.2 Indicator: Final energy consumption

Item	Explanation
Area of relevance	Overarching
Description of indicator	Total energy consumed by end users, excluding self-consumption by the energy sector. levels of primary energy consumption by 2020 and 2030 The indicator monitors the changes in final energy consumption. The Energy Efficiency Directive translates the energy efficiency targets into maximum levels of final energy consumption by 2020 and 2030.
Supporting indicators	▪ Final energy consumption – Industry ▪ Final energy consumption – Transport ▪ Final energy consumption – Services ▪ Final energy consumption – Households
Model	GENeSYS-MOD; REMES; EXIOMOD 2.0; MESSAGEix-GLOBIOM; SCOPE
Unit	TWh
Geographical coverage	EU27 Member States, Norway, Switzerland and UK
Additional remarks	REMES provide results in monetary unit. The assessment of this indicator can also be modelled in EMPS-W and Plan4EU for electricity only.
Reference	European Commission (2017)

4.4.3 Indicator: Final energy intensity – industry

Item	Explanation
Area of relevance	Energy intensity/efficiency – industry
Description of indicator	Energy consumption in respect to value added of industry and construction sector. Monitoring sectoral energy-intensity developments can provide an indication of progress in terms of energy efficiency by revealing the extent to which energy consumption is decoupled from economic growth, or the specific energy used in producing a unit of GDP or value added.
Supporting indicators	-
Model	REMES; EXIOMOD 2.0; MESSAGEix-GLOBIOM
Unit	MWh/EUR
Geographical coverage	EU27 Member States, Norway, Switzerland and UK
Additional remarks	This indicator is included in REMES as data to analyse the effects on the economic system. MESSAGEix-GLOBIOM provide results for aggregated European regions.
Reference	European Commission (2017)

4.4.4 Indicator: Final energy consumption – transport: traffic

Item	Explanation
Area of relevance	Energy intensity/efficiency – transport
Description of indicator	Energy used in respect to passenger-kilometre travelled The indicator can compile an accurate picture of transport activities and related energy consumption and enable in-depth analysis of energy-efficiency developments in transport.
Supporting indicators	▪ Share of collective transport in all passengers' transport ▪ Final consumption in transport vs. passengers and freight activities
Model	GENeSYS-MOD; REMES; EXIOMOD 2.0; MESSAGEix-GLOBIOM; SCOPE
Unit	MWh/Pkm
Geographical coverage	EU27 Member States, Norway, Switzerland and UK
Additional remarks	This indicator is included in REMES as data to analyse the effects on the economic system. MESSAGEix-GLOBIOM provide results for aggregated European regions.
Reference	European Commission (2017)

4.4.5 Indicator: Final energy consumption – transport: freight

Item	Explanation
Area of relevance	Energy intensity/efficiency – transport
Description of indicator	Energy used in respect to ton-kilometre travelled The indicator can compile an accurate picture of transport activities and related energy consumption and enable in-depth analysis of energy-efficiency developments in transport.
Supporting indicators	▪ Final consumption in transport vs. passengers and freight activity
Model	GENeSYS-MOD; REMES; EXIOMOD 2.0; MESSAGEix-GLOBIOM; SCOPE
Unit	MWh/tkm
Geographical coverage	EU27 Member States, Norway, Switzerland and UK
Additional remarks	MESSAGEix-GLOBIOM provide results for aggregated European regions.
Reference	European Commission (2017)

4.5 Topic 4: Integrated internal energy market

4.5.1 Indicator: Electricity interconnection capacity

Item	Explanation
Area of relevance	Electricity and gas interconnections
Description of indicator	Electricity interconnection capacity of a country in respect to its total generation capacity. The 2030 climate & energy framework (European Commission 2020e) referred to the need to monitor the deployment of smart grids and interconnections between Member States against the agreed 2020 objective of electricity interconnections of at least 10% of national installed production capacity, moving towards 15% by 2030.
Supporting indicators	-
Model	GENeSYS-MOD; EMPIRE; MESSAGEix-GLOBIOM; openTEPES; SCOPE; Plan4EU
Unit	%
Geographical coverage	EU27 Member States, Norway, Switzerland and UK
Additional remarks	MESSAGEix-GLOBIOM provide results for aggregated European regions. This indicator is a data input for EXIOMOD 2.0 and EMPS-W
Reference	European Commission (2017)

4.5.2 Indicator: Gas interconnection capacity

Item	Explanation
Area of relevance	Electricity and gas interconnections
Description of indicator	Gas interconnection capacity of a country in respect to its total generation capacity. Apart from electricity, gas is another important type of energy in the energy market.
Supporting indicators	-
Model	GENeSYS-MOD; MESSAGEix-GLOBIOM; openTEPES; SCOPE; Plan4EU
Unit	%
Geographical coverage	EU27 Member States, Norway, Switzerland and UK
Additional remarks	MESSAGEix-GLOBIOM provide results for aggregated European regions. This indicator is a data input for EXIOMOD 2.0. SCOPE does not provide results for investments in gas network, but it will quantify gas volumes consumed at a given price.
Reference	European Commission (2017)

4.5.3 Indicator: Installed capacity of energy storage resources

Item	Explanation
Area of relevance	Electricity and gas interconnections
Description of indicator	Installed capacity of energy storage resources connected to the electricity grid. Energy storage resources as a flexibility option are getting more and more important in the electricity system with high shares of renewable energy sources.
Supporting indicators	▪ Electricity delivered to the market [Unit: MWh]
Model	GENeSYS-MOD; EMPIRE; MESSAGEix-GLOBIOM; openTEPES; SCOPE; Plan4EU
Unit	%
Geographical coverage	EU27 Member States, Norway, Switzerland and UK
Additional remarks	MESSAGEix-GLOBIOM provide results for aggregated European regions. This indicator is a data input for EMPS-W model.
Reference	European Commission (2017)

4.5.4 Indicator: Installed capacity of electrolysers for PtG applications

Item	Explanation
Area of relevance	Electricity and gas interconnections
Description of indicator	Total installed capacity of electrolysers for Power-to-Gas applications Power-to-Gas is seen as a promising technology to store excess energy from RES.
Supporting indicators	-
Model	GENeSYS-MOD; MESSAGEix-GLOBIOM; openTEPES; SCOPE;
Unit	MW
Geographical coverage	EU27 Member States, Norway, Switzerland and UK
Additional remarks	This indicator is not yet considered in EMPIRE model, Power-to-Gas demand must be defined exogenously. MESSAGEix-GLOBIOM provide results for aggregated European regions. In openTEPES model power-to-gas demand is defined as energy outflow from virtual storage.
Reference	(CoGEnN Project , 2019)

4.5.5 Indicator: Wholesale electricity prices

Item	Explanation
Area of relevance	Energy market coupling
Description of indicator	Electricity prices at wholesale market The 2030 climate & energy framework (European Commission 2020e) referred to the need to monitor competition and market concentration on wholesale and retail energy markets at both national and (for regions with functioning coupling) regional level.
Supporting indicators	-
Model	REMES; EMPS-W; MESSAGEix-GLOBIOM; openTEPES; SCOPE;
Unit	EUR/kWh
Geographical coverage	EU27 Member States, Norway, Switzerland and UK
Additional remarks	GENeSYS-MOD, SCOPE and Plan4EU indirectly assess this indicator. There is a dual variable of electricity market balance (supply/demand) constraint and capacity limits of power lines in Plan4EU. This indicator is not part of the conventional results provided by the GENeSYS-MOD model. EMPIRE indirectly assesses this indicator. There is a dual variable of electricity market balance (supply/demand) constraint. This indicator can be modelled after including such variables. MESSAGEix-GLOBIOM provide results for aggregated European regions. This indicator can be estimated in openTEPES model as the short-run marginal costs or as the cheapest marginal cost of a commitment unit with spare capacity.
Reference	European Commission (2017)

4.5.6 Indicator: Share of electricity at total energy use in non-energy sectors

Item	Explanation
Area of relevance	Energy market coupling
Description of indicator	Electricity use compared to total energy use in non-energy sectors The indicator could assess the degree of electricity used in non-energy sectors, giving an indication for sector coupling.
Supporting indicators	-
Model	REMES; EXIOMOD 2.0; MESSAGEix-GLOBIOM;
Unit	%
Geographical coverage	EU27 Member States, Norway, Switzerland and UK
Additional remarks	GENeSYS-MOD and SCOPE indirectly assesses this indicator for sectors covered. REMES model assesses this indicator monetarily. MESSAGEix-GLOBIOM provide results for aggregated European regions.
Reference	(European Commission, 2017)

4.6 Topic 5: Research, innovation and competitiveness

4.6.1 Indicator: Capacity installed

Item	Explanation
Area of relevance	Innovation deployment
Description of indicator	Installed capacity per technology The indicator shall give an indication of the situation in respect to the energy mix / technology mix. The indicator shall differ between technologies.
Supporting indicators	-
Model	GENeSYS-MOD; EMPIRE; MESSAGEix-GLOBIOM; openTEPES; SCOPE; Plan4EU
Unit	MW
Geographical coverage	EU27 Member States, Norway, Switzerland and UK
Additional remarks	This indicator is a data input in EMPS-W model. MESSAGEix-GLOBIOM provide results for aggregated European regions.
Reference	(European Commission , 2020)

4.6.2 Indicator: Trade openness

Item	Explanation
Area of relevance	Innovation deployment
Description of indicator	Imported and exported energy The indicator shall give an indication of the global market situation
Supporting indicators	-
Model	GENeSYS-MOD; EMPS-W; EXIOMOD 2.0; MESSAGEix-GLOBIOM; SCOPE; Plan4EU
Unit	Depends on the energy carrier
Geographical coverage	EU27 Member States, Norway, Switzerland and UK
Additional remarks	REMES indirectly assesses this indicator but the sum of imports and exports might not be balanced. EMPIRE, openTEPES indirectly assesses this indicator only for electricity system. MESSAGEix-GLOBIOM provide results for aggregated European regions.
Reference	(European Commission , 2020)

5 FINAL REMARKS

Scientific-based policy advice needs appropriate instruments and suitable indicators to assess the outcomes of instrument-based findings. In energy and climate policy, energy system models are widely used to calculate the impacts of possible future-oriented policy frameworks. The necessity for appropriate indicators to measure, amongst others, decarbonisation and competitiveness is also widely accepted; however, the energy system's complexity and both concepts lead to discussions about what indicators are suitable and whether the selected indicators sufficiently capture the different aspects of decarbonisation and competitiveness.

Deliverable 3.2 aggregates information and knowledge gained during the execution of the activities within Work Package 3 (Task 3.1), which formulate the IndiModel conceptual approach as part of the workflow.

The conceptual approach presented in Section 2 (IndiModel) provides a very useful link between policy frameworks, indicators, and models. As demonstrated in Section 3, the IndiModel approach can be applied to concisely quantify the impact of policy changes on the progress towards decarbonisation and competitiveness. Thus, the IndiModel approach supports understanding the quantitative consequences of policymaking successfully. The indicator regarding import dependence, in section 3.3, was therefore identified as especially relevant because of the present war in Ukraine. The assessment of such indicators promotes the visualisation of which countries import and export more. A such assessment provides, for example, a possibility to analyse strategic balancing measures for efficient use of available energy resources. Such strategies can become measures to achieve better energy security to improve existing related policies (e.g., Directive 2018/2002/EU, 2018, COM/2016/860/final[2],COM/2015/080/final[3]).

However, the three selected indicators also show the challenges of executing IndiModel. The most important one is the boundaries of the used system: The intended system boundary of an indicator could not coincide with one of the used energy system models. The relevance of the challenge emerges if additional data sources beyond the energy system model are needed to provide the relevant information; see, for example, the indicator of greenhouse gas emissions. A mismatch of system boundaries devalues the explanatory quality of the indicators.

Typically, a single system model will only capture some relevant indicators, as shown in Chapter 4. There is no *"ultimate model to answer everything",* and several models are needed to cover the full range of aspects related to decarbonisation and competitiveness. A possibility to overcome this challenge is to couple different energy system models (Möst, et al., 2021; Fuss & Xu.L., 2021), considering their different sectoral scope, geographical coverage, and technical details. Coupling of different models could also help to reduce the mismatch of systems boundaries between an indicator and of a model.

However, the principles of decarbonisation and competitiveness came as a goal to promote immediate action and comparison, as described in section 1. In this task 3.1, it has also become apparent that as the knowledge about decarbonisation and competitiveness is

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[2] (Clean Energy For All Europeans, 2016)

[3] (A Framework Strategy for a Resilient Energy Union with a Forward-Looking Climate Change Policy , 2015)

dispersed among disciplines (e.g., environmental, social, financial and business). The aim of conventional energy system models is rather straightforward, i.e. to provide information about the techno-economic features of a future energy system. To fulfil these aims, these models focus on modelling technologies mostly in a simplified cost frame. Thus, different aspects which determine for example competitiveness, like quality of education, can be hardly recognised by this type of models. Another aspect, which comes more and more in the focus of political and societal discussion, is how a just energy transformation can be organised (European Commission, 2020a; European Commission, 2020b; European Commission, 2020c). Thus, the limits of the energy models become apparent and more topic-oriented models for the proposed indicator are needed. For instance, in Deliverable 3.1 (v.2) (Poganietz, et al., 2021), additional indicators have been proposed. These indicators are presented in the Appendix 3. These additional indicators represent a specific way of checking the consequences (e.g., unintended environmental impacts, business impact and financial circumstances) and local positiveness of such system transformation (e.g., health life expectation and macroeconomic stability) that may be connected with decarbonisation.

The improvement of the quality of scientific-based policy advice to measure progress towards decarbonisation and competitiveness needs models, which addresses the missing indicators and thus, which could supplement the information of conventional energy system models. Of utmost importance is the opportunity to couple such “new” models with energy system models to achieve comprehensive but also consistent systems boundaries (Weimer-Jehle, et al., 2020), which are necessary to provide relevant information from a systematic perspective.

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APPENDIX 1: DIFFERENT DECARBONISATION SCENARIOS IN THE EUROPEAN H2020 PROJECT OPENENTRANCE

In the openENTRANCE project, four storylines have been developed. They describe possible future developments of a low-carbon European energy system. The description below is part of the publication available by Auer, et al., 2020.

– **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 decarbonising 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 lifestyle 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 acting 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.

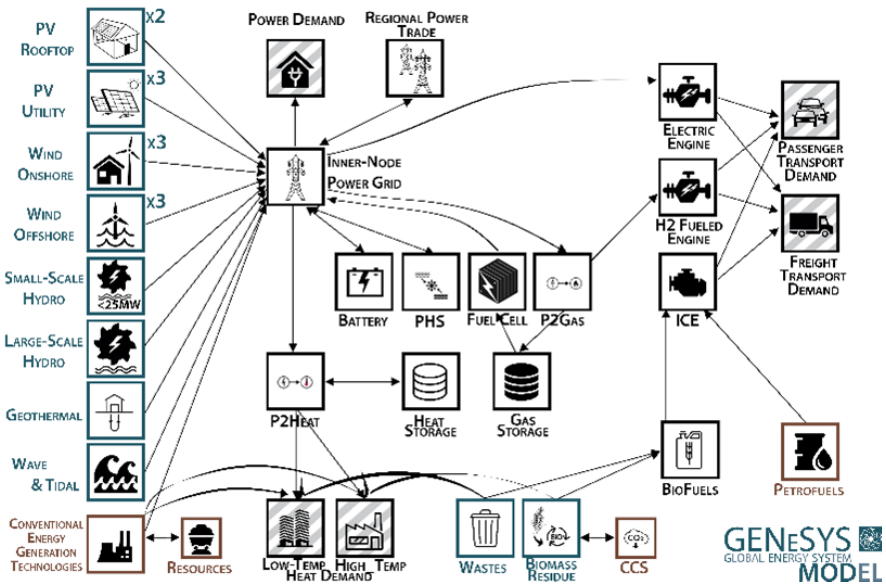
APPENDIX 2: DESCRIPTION OF OPEN-SOURCE MODELS IN THE OPENENTRANCE PROJECT

GENeSYS-MOD

The Global Energy System Model (GENeSYS-MOD) is an open-source energy system model, originally based on the Open-Source Energy Modeling System (OSeMOSYS) framework. While still part of the OSeMOSYS family of models, various aspects have been redesigned, expanded, or added. GENeSYS-MOD is a linear program, minimizing total system costs. Energy demands are inputs to the model, and the outputs include the necessary technologies to meet the energy demand. The modeling framework is very flexible in its use cases. Based on research question and input data, calculations can be done from a household-basis to a global aggregation of regions.

In essence, GENeSYS-MOD can be illustrated as a flow-based cost-optimization model. The different nodes are represented as Technologies, which are connected by Fuels. Examples for Technologies are production entities like wind or solar power, conversion technologies like heat pumps, storages, or vehicles. Fuels serve as connections between these technologies and can be interpreted as the arcs of the network. In general, Fuels represent energy carriers like electricity or fossil fuels, but also more abstract units like demands of a specific energy carrier or areas of land are classified as Fuels. Also, Technologies might require multiple different Fuels or can have more than one output fuel. As an example, a combined heat and power plant could use coal as an input fuel and produce electricity and heating energy as an output fuel. Efficiencies of the technologies are being accounted for in this exact process, which would allow to model energy losses due to conversion. Energy demands are classified into three main categories: electricity, heating, and transportation. They are exogenously defined for every region and each year. The model then seeks to meet these demands through a combination of Technologies and trade between the different regions.

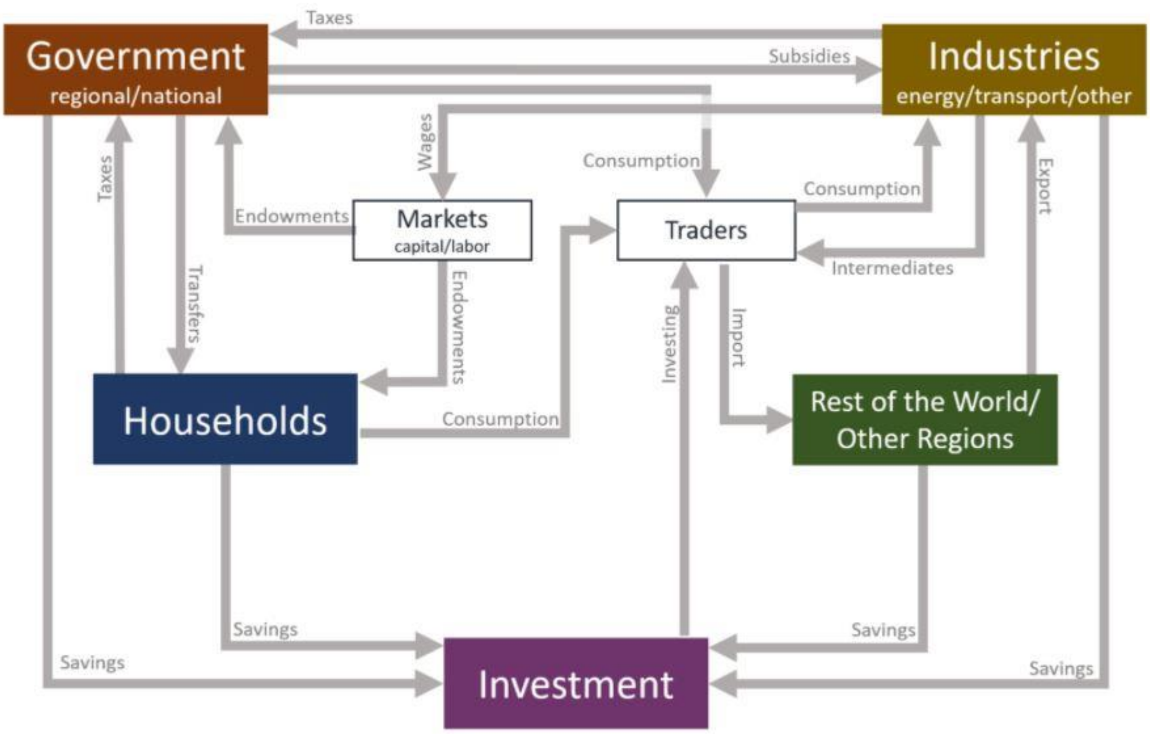
The following figure gives a general overview of the different Technologies and the connections between them:



REMES

REMES is a Computable General Equilibrium model that represents the Norwegian economy with a particular focus on the energy system. REMES is used to study the effects of macroeconomic policies on the Norwegian economy.

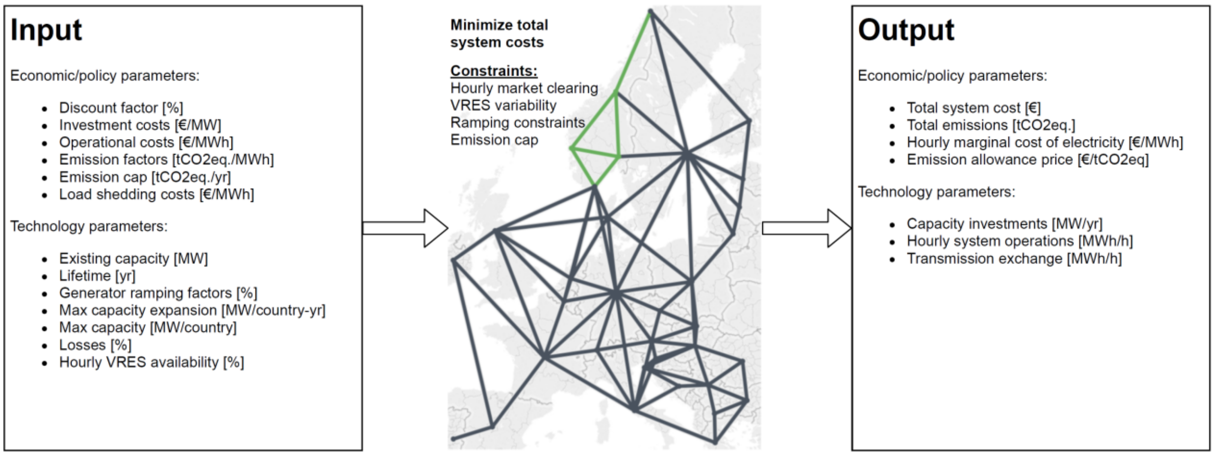
The model splits the national economy into five regions, which coincide with the five Norwegian energy market zonal prices. It includes 36 production sectors and 32 products and considers demand from households, investors and government alongside international imports and exports. Policies are modelled as shocks, which influence the economy by means of taxes or subsidies. Effects are considered on prices, activity levels exports, imports and technology changes. The structural interconnections between the main building blocks in the model are displayed below, where the arrows illustrate the payments direction between the elements of the model.



EMPIRE

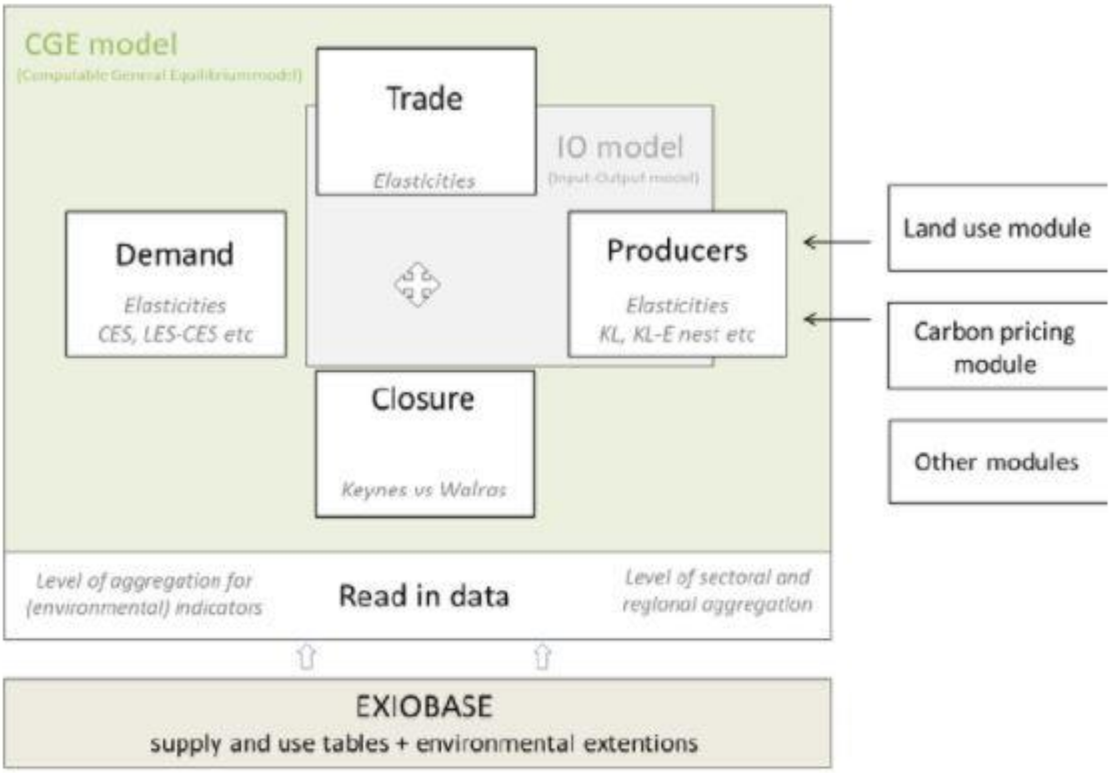
EMPIRE is a comprehensive power system model including generation, storage, and transmission capacity expansion. It is designed to determine optimal capacity investments under operational uncertainty, while also incorporating long- and short-term dynamics. To achieve these objectives, EMPIRE is a stochastic linear program endogenously considering uncertainty on an hourly operational resolution of (1) nationally aggregated load and (2) availability of variable renewable supply. The model considers net transfer capacity (NTC) of power exchange between countries, up-ramping constraints for generators and investment and operation of storage technologies.

EMPIRE has three key advantages in contrast to other power sector models. The first is the special handling of challenges given by the variability of renewable technologies, especially wind and solar power, which highly impacts the supply and demand balance. Another major contribution of EMPIRE is that it simultaneously incorporates short- and long-term dynamics, in conjunction with short-term uncertainty. Dynamics refer to multiple investment periods co-existing with multiple sequential operational decision periods, while uncertainty is enhanced through multiple input scenarios that captures different operating conditions. Lastly, EMPIRE uses representative time periods (days or weeks) with an hourly resolution within each investment period to preserve computational tractability.



EXIOMOD

EXIOMOD is an economic model able to measure the environmental impact of economic activities. As a multisector model, it accounts for the economic dependency between sectors. It is also a global and multi-country model with a consistent trade linking between countries at the commodity level. Based on national account data, it can provide compressive scenarios regarding the evolution of key economic variables such as GDP, value-added, turn-over, (intermediary and final) consumption, investment, employment, trade (exports and imports), public spending or taxes. Thanks to its environmental extensions, it makes the link between the economic activities of various agents (sectors, consumers) and the use of a large number of resources (energy, mineral, biomass, land, water) and negative externalities (greenhouse gases, wastes)

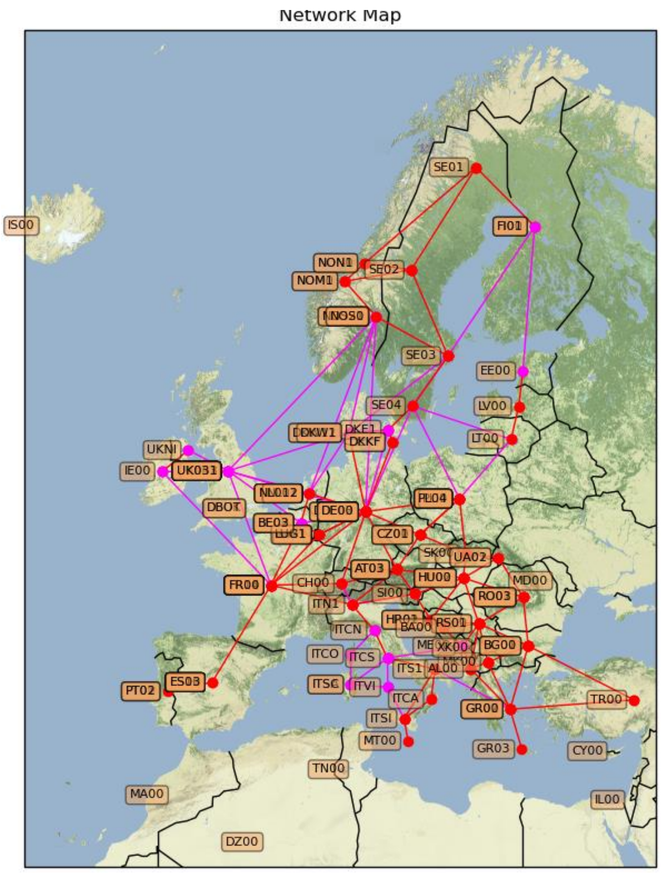


openTEPES

The Open Generation and Transmission Operation and Expansion Planning Model with RES and ESS (openTEPES) determines the investment plans of new facilities (generators, ESS and lines) to supply the forecasted demand at minimum cost. Tactical planning is concerned with time horizons of 10-20 years. Its objective is to evaluate the future generation, storage and network needs. The main results are the guidelines for the future structure of the generation and transmission systems. The openTEPES model is a decision support system aimed at defining the generation and transmission expansion plan of a large-scale electric system at a tactical level. This plan is defined as a set of generation and network investment decisions for future years. The expansion candidates, generators, ESS and lines, are pre-defined by the user. The model determines the optimal decisions among those specified by the user.

The main results produced by openTEPES:

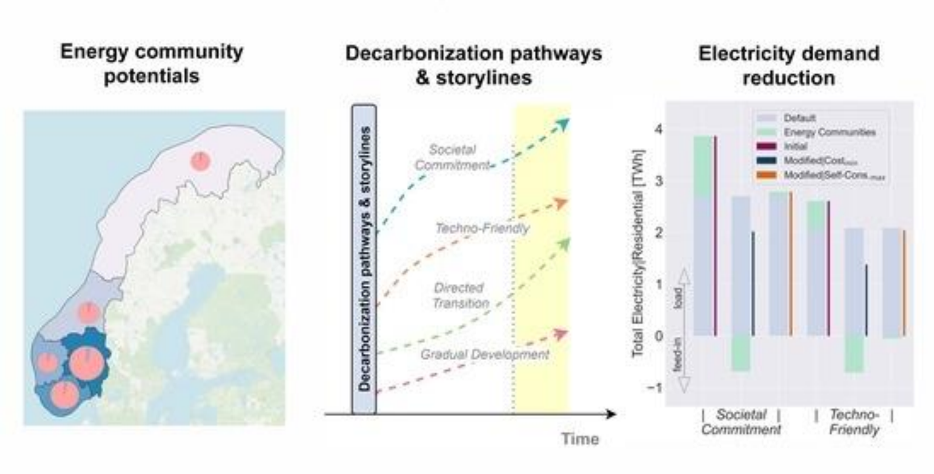
- Investment: investment decisions and costs
- Operation: the output of different units and their aggregation by technologies (thermal, storage hydro, pumped-storage hydro, RES), RES curtailment levels, line flows, line ohmic losses, and node voltage angles
- Emissions: CO2 emissions by unit
- Marginal: Locational Short-Run Marginal Costs (LSRMC)



GUSTO

The GUSTO model is an open-source model (OSM) optimizing the energy technology investment (portfolio decision optimization) and the technology dispatch on a local level. It is an extension of the existing OSM urbs. The expansion of the model's framework includes additional features and functionalities. Hence, the model is tailor-made for analysing local energy systems such as neighbourhoods and energy communities.

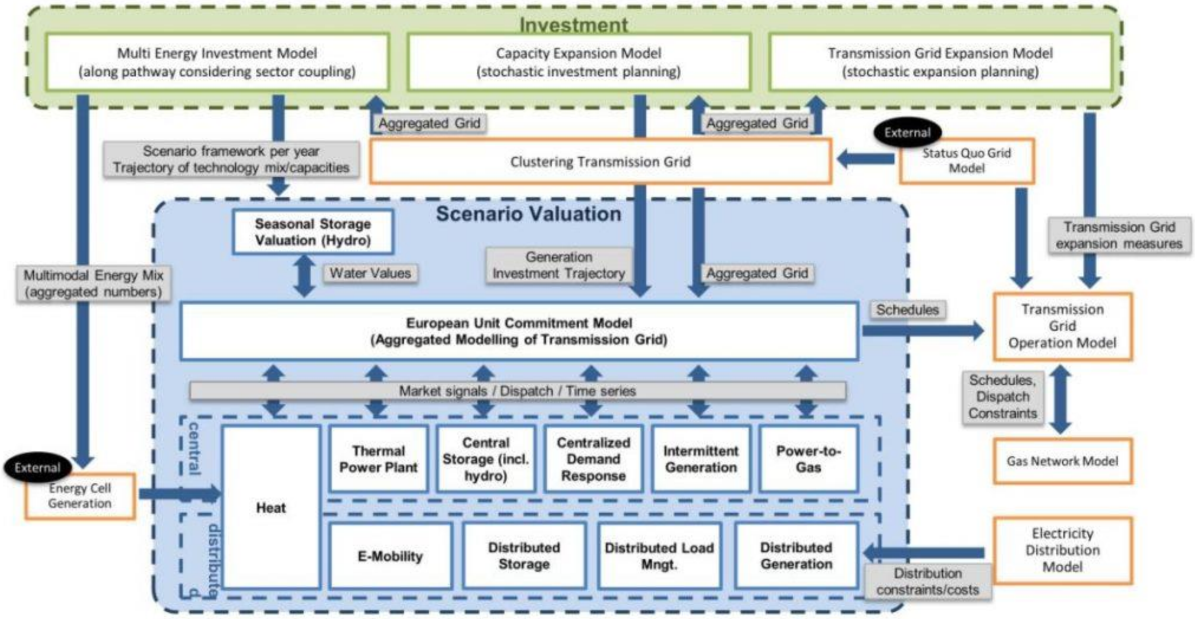
The extended model is a mixed-integer linear program (MILP) and provides the following objective functions: (i) minimizing total costs of supply, (ii) minimizing total greenhouse-gas emissions, (iii) maximizing local self-consumption, and (iv) scheduled generation compliance within the neighbourhood. Maximizing local self-consumption is an essential operational strategy for energy communities or neighbourhoods. Thereby, the optimal utilization of the local flexibility options (e.g., small-scale battery storage) and energy technologies minimize the purchase (or exchange) of energy from the public grid. The model includes the provision of multiple local energy services (e.g., electricity, heat, cooling) and the use of commodities. Besides, the model framework also incorporates temporal and spatial clustering algorithms.



See the model application in the publications https://doi.org/10.1016/j.apenergy.2020.116166 and https://doi.org/10.3390/en14020305. The first one includes a detailed description of the model's extension.

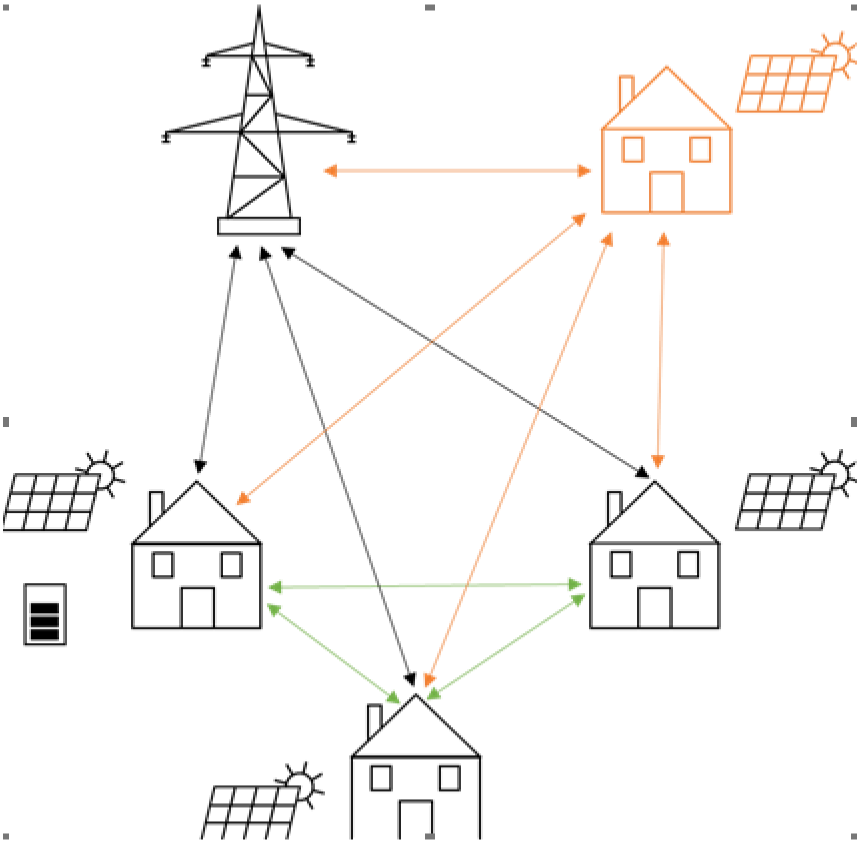
PLAN4RES

The goal of plan4res is to develop a modelling framework that allows to obtain a holistic assessment of the energy system. Having such an ambitious goal, it is required to divide the energy system in models that cover the different aspects of the energy system. This modular framework allows to make use of the most promising solving techniques and the most efficient optimization solvers, each tailored towards the needs of every single submodel. In order to guarantee a flawless workflow, it is vital to have a detailed description of the interconnections between these models. The goal of this Deliverable is to give an overview of the plan4res modelling framework and describe these model interconnections.



FRESH:COM

The peer-to-peer electricity trading model FRESH:COM developed by TU Wien is part of the case study "Behaviour of communities of actors" within the H2020 project openENTRANCE. The model was transformed to an open-source model during the project. It is now publicly available on GitHub at https://github.com/tperger/FRESH-COM implemented in Python.



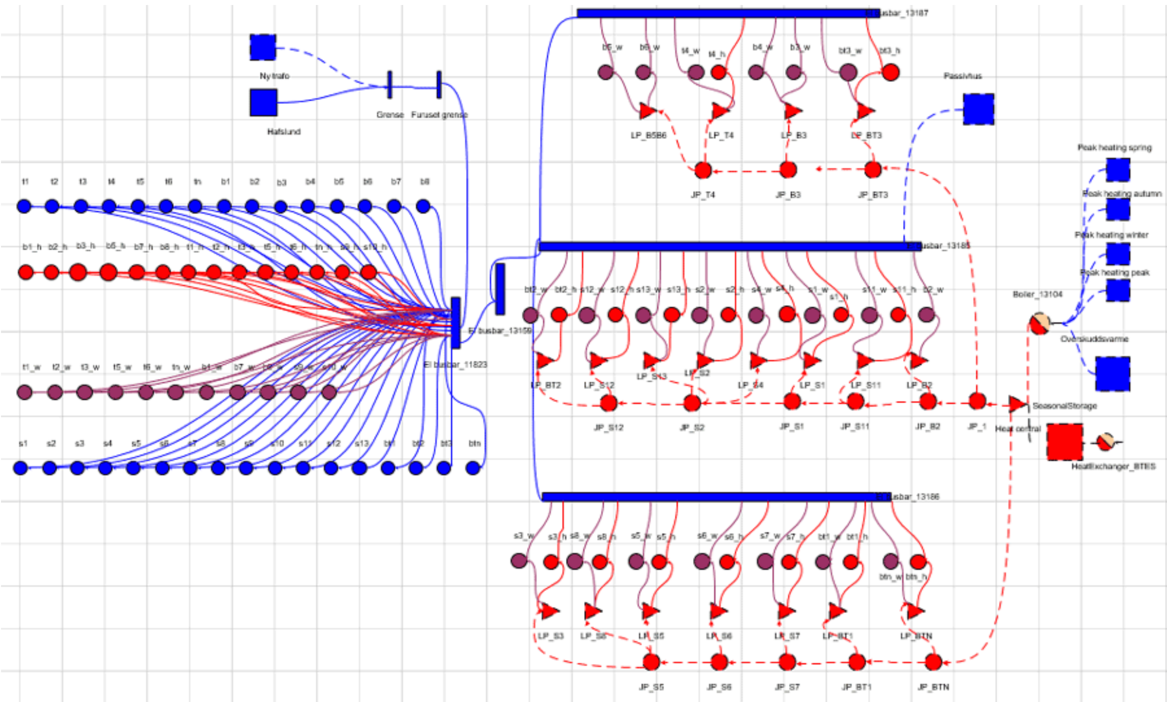
The linear optimization model perfectly allocates prosumers' renewable electricity generation from PV systems supported by battery energy storage systems (BESSs) among the actors of the community, considering each actor's willingness-to-pay for avoiding emissions and for purchasing PV electricity generated by the community. The prosumers become active participants in decentralized energy markets, in this case a peer-to-peer trading mechanism.

For references and future updates regarding FRESH:COM see https://www.researchgate.net/profile/Theresia-Perger

INTEGRATE

Integrate is an optimization model for planning of local energy systems where different energy carriers and technologies are considered simultaneously. The model gives the user a graphical overview of a given energy system (e.g. municipality, city, suburb) with respect to costs, environmental consequences and use of local energy resources. The current version can optimize the construction of infrastructure for most relevant energy carriers; electricity, district heating, cooling, gas, waste and biomass, including conversions between these. It is not limited to continuous transport like lines, cables and pipes, but can also include discrete transport by ship, road or rail.

The main task of the model is to optimize investments in infrastructure over a planning horizon of several decades to bring available energy to the end user in such quantities and in such form that the end users demand is covered in the economically and environmentally best way possible. As part of the investment analysis, however, the model also optimizes diurnal operation for different periods of the year for each alternative system design. This operational module can be run independently from the investment module. Mathematically, the model uses a combination of linear programming (LP), mixed integer programming (MIP) and dynamic programming (DP).



EMPS-W

Hydropower is the most important power production resource in Norway, and the country has approximately half of Europe's reservoir capacity. Ca 85 TWh of storage capacity is distributed on more than 1000 reservoirs and in a number of cascade-coupled river systems. Long term optimisation of the use of the water resources is a complex problem that need to consider for example the complexity of the topology as well as the large seasonal and annual variation in inflow to the system. In the future, the flexibility of the hydropower system will be even more useful since the flexibility can be used to balance the variability in the increasing wind and solar power production. The stochastic optimisation model EMPSW can be used for long-term planning of hydrothermal system, for example the Scandinavian system [1]. EMPSW simulates the northern European power supply market with detailed description of hydropower and individual water values for all reservoirs in Scandinavia. The operation of each individual hydroelectric reservoir is based on the result of formal stochastic optimisation in which all the relevant physical attributes of the market are represented. Decisions for each week are determined by solving weekly linear programming problems considering uncertainty in weather and exogenous market prices. The overall scheduling problem is obtained by solving a sequence of weekly decision problems spanning a chosen period of time. Comparisons are made with a widely used long-term hydro-thermal scheduling model, the EMPS model, which is based on aggregation-disaggregation techniques [2]. The results indicate that the model is well suited to evaluate the flexibility of hydropower in systems with a high share of intermittent renewable generation.

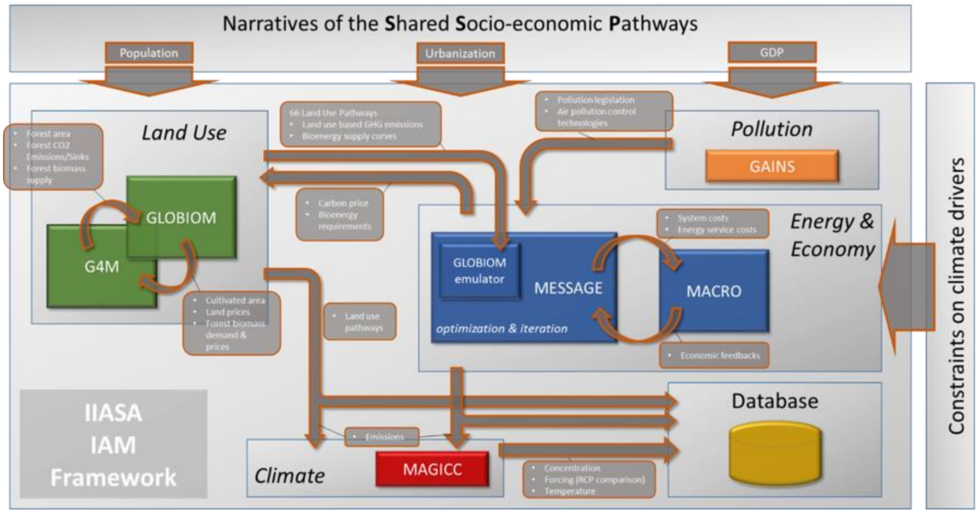
https://www.sintef.no/en/software/emps-multi-area-power-market-simulator/

MESSAGEix-GLOBIOM

The MESSAGEix modelling framework, briefly known also as MESSAGE (Model for Energy Supply Strategy Alternatives and their General Environmental Impact), is a linear programming (LP) energy engineering model with global coverage. As a systems engineering optimization model, MESSAGEix is primarily used for medium- to long-term energy system planning, energy policy analysis, and scenario development. The model provides a framework for representing an energy system with all its interdependencies from resource extraction, imports and exports, conversion, transport, and distribution, to the provision of energy end-use services such as light, space conditioning, industrial production processes, and transportation. In addition, MESSAGEix links to GLOBIOM (GLObal BIOsphere Model, cf. Section Land-use (GLOBIOM)) to consistently assess the implications of utilizing bioenergy of different types and to integrate the GHG emissions from energy and land use and to the aggregated macro-economic model MACRO (cf. Section Macro-economy (MACRO)) to assess economic implications and to capture economic feedbacks.

MESSAGEix covers all greenhouse gas (GHG)-emitting sectors, including energy, industrial processes as well as - through its linkage to GLOBIOM - agriculture and forestry. The emissions of the full basket of greenhouse gases including CO2, CH4, N2O and F-gases (CF4, C2F6, HFC125, HFC134a, HFC143a, HFC227ea, HFC245ca and SF6) as well as other radiatively active gases, such as NOx, volatile organic compounds (VOCs), CO, SO2, and BC/OC is represented in the model.

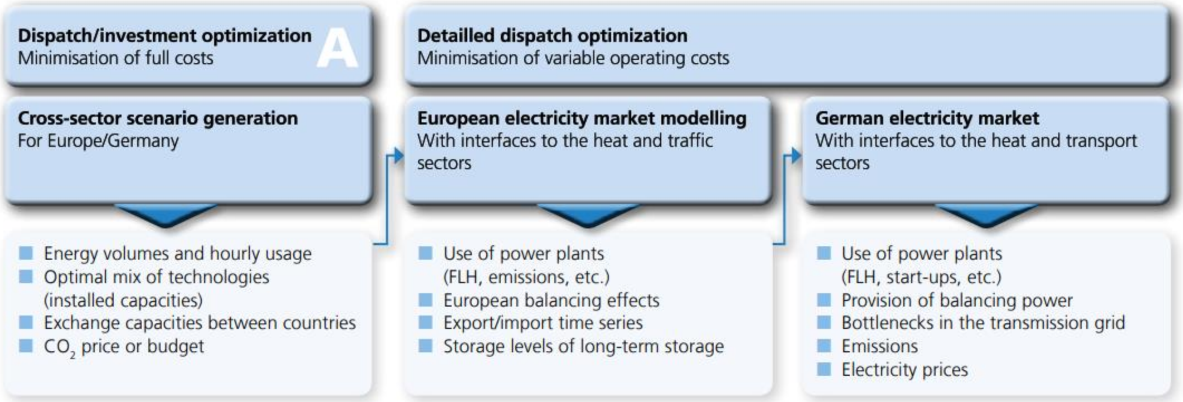
The model is designed to formulate and evaluate alternative energy supply strategies consonant with the user-defined constraints such as limits on new investment, fuel availability and trade, environmental regulations and policies as well as diffusion rates of new technologies. Environmental aspects can be analysed by accounting, and if necessary, limiting the amounts of pollutants emitted by various technologies at various steps in energy supplies. This helps to evaluate the impact of environmental regulations on energy system development. Its principal results include estimates of technology-specific multi-sector response strategies for specific climate stabilization targets. By doing so, the model identifies the least-cost portfolio of mitigation technologies. The choice of the individual mitigation options across gases and sectors is driven by the relative economics of the abatement measures, assuming full temporal and spatial flexibility (i.e., emissions-reduction measures are assumed to occur when and where they are cheapest to implement).



SCOPE

The »SCOPE« model approach is a modularly constructed fundamental model for the generation and analysis of cross state and multi-area energy scenarios. The model determines the minimum cost of covering demand profiles from the electricity, heat, and transport sectors by the various energy units from a macroeconomic perspective. To determine a cost-minimal technology mix for future scenarios, investment decisions based on annuitized technology costs can be considered in the objective function.

Thanks to the hourly modelling of the supply and demand characteristics of a scenario year, it is possible to model both the renewable energy producers and conventional power plants, as well as the use of storage technologies and flexibility options, in detail. A wide variety of conventional and renewable generation technologies are available for power generation. The necessary flexibility for the integration of renewable power generation is modelled using various storage technologies, load management options, and European cross-border exchanges of energy. Depending on the research question, the heat and transport sector, with their interfaces with the power sector, can be modelled with a high degree of temporal and spatial detail. In addition to hourly demand coverage in all sectors, other boundary conditions can be applied to the target system. For example, an upper budget limit for CO2 emissions in specific countries or sectors for compliance with specific climate targets can be considered instead of a fixed CO2 certificate price.



SCOPE – Model configuration and potential interactions

APPENDIX 3: Additional indicators

Topic 1: Decarbonisation of the economy

Indicator	Unit
Area of relevance: Macroeconomic stability	
Sectoral added value growth rate	%
Area of relevance: Health life expectation	
Disability-Adjusted Life Year (DALY)	Years
Particulate matter emissions	Mg
Area of relevance: Unintended environmental impacts	
Eutrophication	kg P-Equivalents
Metal depletion	kg Fe-Equivalents
Ozone depletion	kg CFC-11
Change of land occupation in respect to energy systems transformation	Hectare
Area of relevance: Social costs	
Average income of employees compared to total income average	%
Area of relevance: Financial system	
Capital availability for renewable energy sources	EUR
Capital availability for new jobs	EUR
Credit to the energy sector	EUR
Area of relevance: Business regulation	
Insolvency recovery rate in the energy sector	%
Growth rate of innovative companies in the renewable energy sector	%

Topic 2: Energy security, solidarity and trust

Indicator	Unit
Area of relevance: Self-sufficient market size	
Net import dependency of energy technologies, e.g. wind turbines	Value of net imports per domestic investments of the technology
Area of relevance: Electricity supply (market)	
Aggregate supplier concentration index	Index number
System Average Interruption Duration Index (SAIDI)	Time
Area of relevance: Smart grid infrastructure	
Grid length	km
System Average Interruption Frequency Index (SAIFI)	Average number of interruptions per customer
Roll-out plan for smart meters[1]	Share of households
Area of relevance: Electricity supply quality	
Electric power losses	%
Area of relevance: Digitization	
Investment costs	EUR/MW
Operating costs	EUR/MWh
Energy cost savings	EUR per avoided MWh
Area of solidarity and justice	
Energy affordability	Share of energy expenditure at final consumption expenditure for the lowest quintile
Energy consumption support	Amount of financial support regarding energy costs for the lowest quintile
Energy investment support	Support for private households to invest in renewable energy technologies
Remaining carbon budget that is consistent with the Paris Agreement goal of limiting global warming to 1.5°C	Gt $CO_{2eqiv.}$
Proportion of households whose share of energy expenditure at income is more than twice the national median share of energy expenditure	%
Proportion of households whose absolute energy expenditure is below half the national median	%
Share of socialized energy system costs (direct and indirect subsidies for renewables and fossils) covered by 20% of lowest-income households vs. 20% highest-income households	%
Direct and indirect subsidies for fossil fuels	EUR
Direct and indirect subsidies for renewable energy	EUR
Gender pay gap in the energy industry	EUR or %
Public opinion on the extent to which the transformation is perceived as fair and inclusive	--

Note: [1] affects also Topic 3: Energy efficiency and moderation of demand

Topic 3: Energy efficiency and moderation of demand

Indicator	Unit
Area of relevance: Energy intensity/efficiency – residential	
Energy consumption of households per m^2 of floor area in residential buildings, climate corrected	kWh/m²
Area of relevance: Energy intensity/efficiency – services	
Final energy intensity in services sector	MWh/EUR

Topic 4: Integrated internal energy market

Indicator	Unit
Area of relevance: Energy market coupling	
Gas price at wholesale market	EUR/GWh
Area of relevance: Market concentration	
Market concentration index – electricity	Herfindahl-Hirschman-Index
Market concentration index – gas	Herfindahl-Hirschman-Index
Area of relevance: Switching rates	
Annual switching rates – electricity (household customers)	Share of switching households
Annual switching rates – gas (household customers)	Share of switching households

Topic 5: Research, innovation and competitiveness

Indicator	Unit
Area of relevance: Technology analysis	
Energy costs in respect to value added in manufacturing, excluding refinery sector	EUR/EUR
Area of relevance: Value chain analysis	
Levelized costs of energy (LCOE)	EUR/kWh
Turnover per technology groups	EUR/TWh
Employment in the energy sector	Number
Labour productivity	Value added / output per employment
Energy generation per legal entity	Annual production values / outputs per legal entity
Area of relevance: Global market analysis	
Resource efficiency of energy generation	Non-energy resources / metal resources / strategic metals per output
Resource dependency	Share of imported non-energy resources / metal resources / strategic metals at domestic investments in respect to energy technologies
Area of relevance: Research and Innovation funding (R&I)	
Public R&I funding	EUR
Private R&I funding	EUR
Area of relevance: Public Research and Development (R&D)	
Public investments on Energy Union related Research & Innovation	% of GDP
Patents related to Energy Union R&I priorities	Annual patents per inhabitant
Area of relevance: R&D	
Patent application regarding energy technologies	Annual number of patents
Scientific publications regarding energy	Annual number of scientific publications
Area of relevance: Collaboration	
Co-inventions with partner outside the EEA in respect to energy technologies	Number of co-inventions per inhabitant
Multi-stakeholder collaboration	Annual number of collaborations
Area of relevance: Technology market	
Number of companies in the supply chain incl. EU market leaders	Number
Market share of EU companies at global market	%
Financial efforts (taxes and subsidies) to support the energy sector[1]	EUR
Area of relevance: Skills	
Capacity building for energy research and innovation	EUR
Average years of schooling	Years

Further education and training measures in the energy sector	Days per year

Note: [1] The indicator will differ between electricity and gas