TYNDP 2020

SCENARIO METHODOLOGY REPORT

Decarbonised economy

GHG

Distributed Energy

Solar

National Trends

Wind

Biomethane

Hydrogen

Energy

CO₂

Europe

Paris

Hydro

Electricity

Climate Targets

Gas

Net-zero

Renewable energy

Beyond

NECP

Power-to-gas

COP21

2050

Carbon Capture

Hybrid System

Sector coupling

Scenarios

Methane

Global Ambition

Carbon budget

Bio-energy

entsog

entsoe

Scenario Methodologies

Introduction

12 November 2019

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Introduction

1   Introduction to the ENTSOs' TYNDP Scenario Building Process

1.1   Joint electricity and gas scenarios

For the 2020 Scenarios edition, the ENTSOs for gas and electricity have again pooled their expertise to provide a joint set of scenarios, like they did for the first time for the 2018 edition.The ENTSOs consistent and interlinked electricity and gas model in accordance with Article 11(8) of Regulation (EU) No 347/2013 of the European Parliament and of the Council of 17 April 2013, was submitted in December 2016 and details the foundations of the joint scenario building process.

What regulation states…

According to Article 8(3)(b) of Regulation 714/2009 and Article 8(3)(b) of Regulation715/2009, ENTSO-E and ENTSOG have to publish their TYNDPs on a biennial basis.
 	
 Annex V of Regulation (EU) No 347/2013, covering the methodology for a harmonised energy system-wide cost-benefit analysis for projects of common interest, specifies that:
 	
 (1) The methodology shall be based on a common input data set representing the Union's electricity and gas systems in the years n+5, n+10, n+15, and n+20, where n is the year in which the analysis is performed. This data set shall comprise at least:
 	
  (a) in electricity: scenarios for demand, generation capacities by fuel type (biomass, geothermal, hydro, gas, nuclear, oil, solid fuels, wind, solar photovoltaic, concentrated solar, other renewable technologies) and their geographical location, fuel prices (including biomass, coal, gas and oil), carbon dioxide prices, the composition of the transmission and, if relevant, the distribution network, and its evolution, taking into account all new significant generation (including capacity equipped for capturing carbon dioxide), storage and transmission projects for which a final investment decision has been taken and that are due to be commissioned by the end of year n+5;
 	
  (b) in gas: scenarios for demand, imports, fuel prices (including coal, gas and oil), carbon dioxide prices, the composition of the transmission network and its evolution, taking into account all new projects for which a final investment decision has been taken and that are due to be commissioned by the end of year n+5.

TABLE 1: REGULATORY REQUIREMENTS

Geographically, the scenarios go beyond the EU-28 to the ENTSO-E & ENTSOG perimeters that includes members, observers and associated partners. In total over 80 participants, covering more than 35 countries, are involved in the process.

Gas and electricity TSOs are in a unique position to provide quantitative European-focused scenarios on the impact of the energy transition on the European Electricity and Gas infrastructure needs and challenges for the long-term horizons.

The framework for the joint ENTSOs scenarios was agreed during the development process for TYNDP 2018. The framework enables the ENTSOs to create storylines that are consistent up to the 2050 time horizon and illustrates that uncertainty increases over the time horizon. However, storylines are translated into scenarios up to the 2040 time horizon providing sufficient data for the Ten-Year Network Development Plan. Figure 1 graphically represents this framework, using the circles to show that the spread between the scenarios becomes greater, but within a plausible range of possibility.
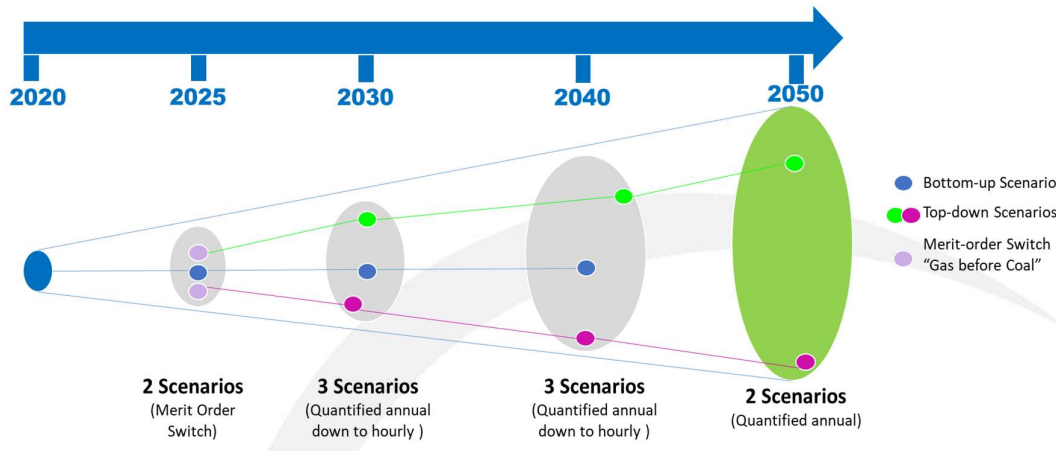
FIGURE 1: HIGH LEVEL FRAMEWORK FOR JOINT ENTSO-E & ENTSOG STORYLINES

1.2 A two-year long building process

The scenario development is a biennial process. ENTSOs initiated the development of the 2020 Scenarios in February 2018 with a lesson learned session on the previously published 2018 Scenarios. The first external communication occurred at a Storyline Workshop on 29th May 2018. This was followed by a public consultation on the proposed storylines and the publication of the Storyline Report. At the same time, the ENTSOs have worked on the quantification and drafting of the Draft Scenario Report.

The publication of the Draft Scenario Report marks a key milestone. It contains all the relevant information, assumptions and data of the ENTSOs' Scenarios. ENTSOs now ask all stakeholders for their feedback during a 6-week consultation. Taking the feedback received into consideration, ENTSOs will publish their final report in Q1 2020.
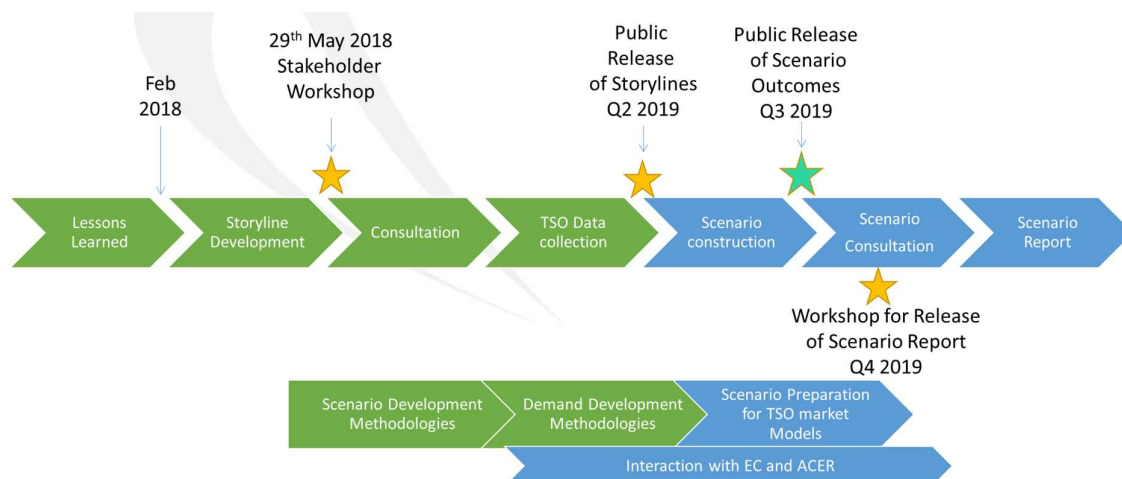
FIGURE 2: HIGH LEVEL STEPS OF GAS AND ELECTRICITY TYNDPS 2020 SCENARIO BUILDING, INCLUDING MORE DETAILED SCENARIO STEPS

1.3 From storylines to scenarios

ENTSOs' scenarios are built upon storylines providing the main characteristics and guidelines for the scenario quantification. They define the climate and energy targets, technology preferences and societal and economic aspects. Following the storylines, the scenario quantification and relevant data collection takes place in a multistep approach.

ENTSOs cross-sectoral scenario building combines the expertise of gas and electricity TSOs. Building upon the experience of previous scenarios, the joint scenarios combine ENTSOG's and ENTSO-E's methodologies, and where possible create new joint methodologies.

- •Storylines & Stakeholder Engagement
- •Consultation
- •Data Collection
- •Data Validation (Translation)
- •Total Energy Scenarios with ENTSOs' Ambition Tool
- •Gas peak demand cases and electricity demand curves
- •Investment Power Market Simulation
- •Biomethane Production Quantification
- •Extra-EU Gas Supply Potentials
- •Power-to-Gas Distribution and Optimisation
- •Results, Drafting, Visualisation
- •Consultation
- •Scenario Analysis, Discussion & Report

FIGURE 3: SCENARIO BUILDING STEPS

The joint ENTSOs' working group scenario building (WGSB) is composed of TSO members from both gas and electricity TSOs. Figure 4 provides an overview of the scenario building working group, the structure fits with the various processes described within this document
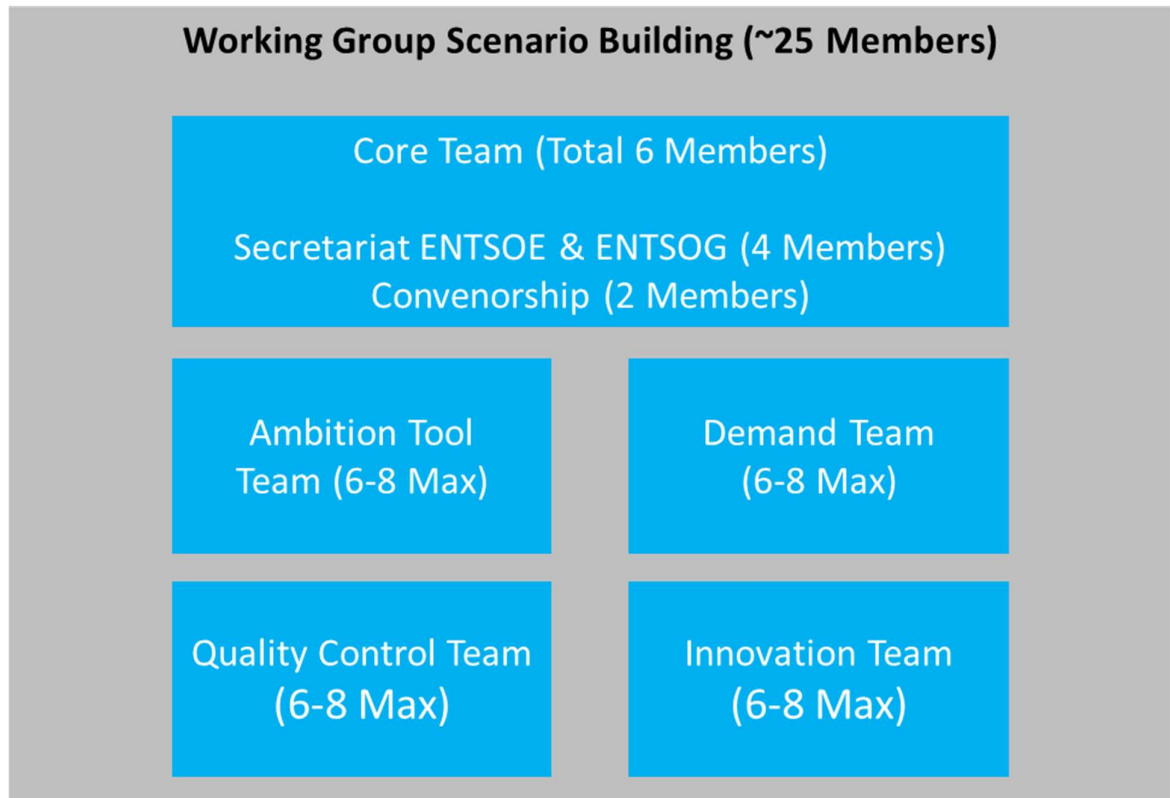
FIGURE 4 WORKING GROUPS SCENARIO BUILDING INTERNAL STRUCTURE

Taking into account the high-level scenario framework shown in Figure 1, ENTSOs used different approaches to build their three scenarios:

- Bottom-up Scenario: one scenario in particular uses bottom-up collected data, which is based on clear data collection guidelines defining the characteristics of the data requested. Both the gas and electricity TSOs were asked to provide data concerning gas and electricity demand, production of gaseous fuels and power generation fleet.
- Top-down Scenarios: two scenarios are full-energy scenarios capturing all fuel and sectors as well as a full picture of primary energy demand. For this, ENTSOs have developed their own energy balance tool called the Ambition Tool.

1.4 How to read this document

The structure of this documents follows the scenario building process:

- Section 2 - *Storyline development and selection* outlines the process steps: 'Storylines & Stakeholder Engagement', 'Consultation'

- Section 3 - *Bottom-up* outlines the process steps: 'Data Collection', 'Data Validation (Translation)'

- Section 4 - *Ambition Tool Methodologies and Calculations* outlines the process step 'Total Energy Scenarios with ENTSOs' Ambition Tool'

- Section 5 - *Final Use Energy Demand* outlines the process step 'Gas peak demand cases and electricity demand curves'

- Section 6 - *Allocation of* Power Sector Capacities outlines the process step 'Power Market Simulation'

- Section 7 - *Gas supply* outlines the process steps 'Biomethane Production Quantification' and 'Extra-EU Gas Supply Potentials'

- Section 8 - *Power-to-Gas* outlines the process step 'Power-to-Gas Distribution and Optimisation'

Storyline Development and Scenario Selection

2 Storyline development and selection

The scenarios which were developed for TYNDP 2018 used the following storyline names:

- Sustainable Transition
- Distributed Generation
- Global Climate Action

In order to retain some consistency between TYNDP reports, it is important that the essence of the scenarios should be continued to some degree. However, the energy landscape is continuously evolving, and it is important to capture the biggest drivers and trends influencing the energy system and most importantly the infrastructure development. During their «lessons learned» session the ENTSOs identified the following drivers to be taken into account in the Scenarios for the TYNDP:

- Decarbonisation: The level of decarbonisation is a main driver for investments and therefore technology improvements. Current climate targets of the EU and its member states vary between 80 % to 95 % CO_2 reduction by 2050. Some countries have also announced a full decarbonisation by 2050. Furthermore, the EU and therefore each of its member states has ratified the Paris Agreement. The recently published IPCC Special Report indicates much higher needs for decarbonisation for 2050. By formulating a carbon budget, the Special Report has also further solidified decarbonisation targets. Therefore, the decarbonisation target of the ENTSOs scenario draft storylines for consultation differed from «Behind the Targets» less than 80 % CO_2 reduction to 80 – 95 % CO_2 reduction to even more ambitious Paris-compliant 1,5-degree scenarios.
- Centralisation/Decentralisation: Trends like centralisation or decentralisation drive the preference and investments for technologies and infrastructure to decarbonise the system. Whereas one can assume higher investments in local photovoltaic and biomethane in a more decentralised scenario, a centralised scenario tends to consist of higher levels of offshore wind parks and energy imports.

The ENTSOs developed five draft scenario storylines. Based on the feedback received from external and internal stakeholders, three were chosen to be developed into final scenarios:

- **National Trends (NT)** is a scenario based on National Energy and Climate Plans (NECPs) in accordance with the governance of the energy union and climate action rules, as well as on further national policies and climate targets already stated by the EU member states. Following its fundamental principles, National Trends will be compliant with the EU's 2030 Climate and Energy Framework (32 % renewables, 32.5 % energy efficiency) and EC 2050 Long-Term Strategy with an agreed climate target of 80 – 95 % CO_2 reduction compared to 1990 levels.

- **Global Ambition (GA)** is a scenario compliant with the 1,5°C target of the Paris Agreement. It looks at a future that is led by economic development in centralised generation. Economies of scale lead to significant cost reductions in emerging technologies such as offshore wind and Power-to-X, but also imports of energy from cheaper sources are considered as a viable option.
- **Distributed Energy (DE)** is a scenario compliant with the 1,5°C target of the Paris Agreement. It embraces a de-centralised approach to the energy transition. A key feature of the scenario is the role of the energy consumer, who actively participates in the energy market and helps to drive the system's decarbonisation by investing in small-scale solutions and circular approaches.
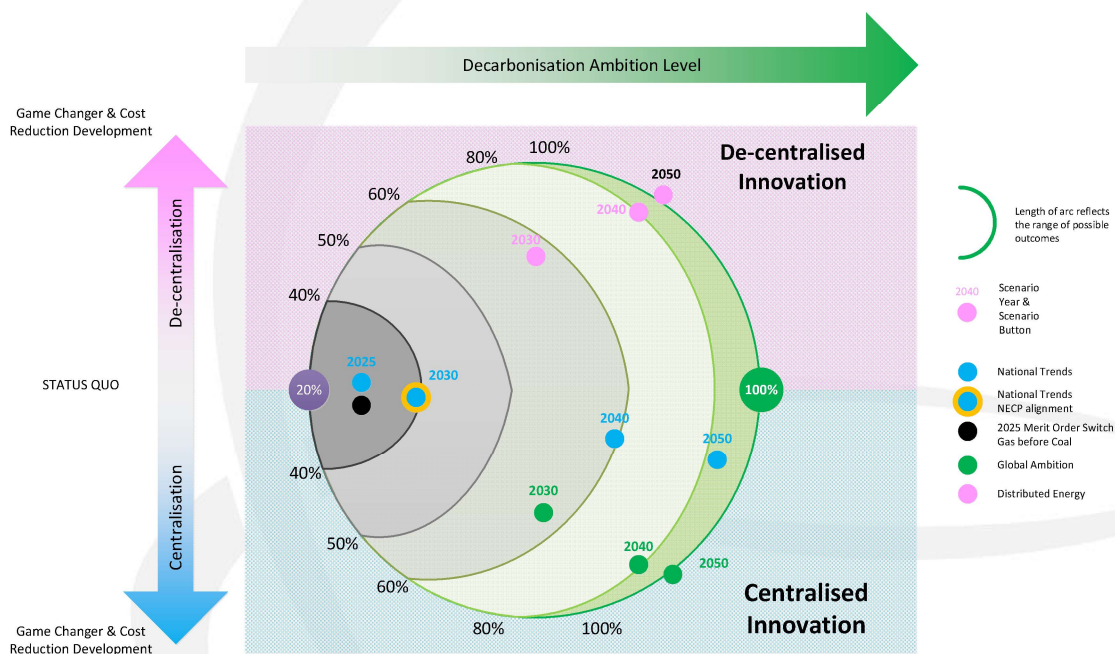
FIGURE 5: KEY DRIVERS OF SCENARIO STORYLINES

More information can be found in ENTSOs' Final Storyline Report (link).

2.1 The Storyline Central Matrix

The Scenario Building Central Matrix is a tool used to identify the key elements of the storylines. The Central Matrix enables creation of scenarios consistent along a pathway; yet differentiated from other storylines. It is important to remember that the Central Matrix represents an overall EU-level view.

The Central Matrix is a table that can provide an EU-wide qualitative overview of key drivers for the European energy system in 2050. The matrix uses +/- indicators to show how primary energy mix and final energy use change compared to sectors are assumed to change from today. It is important to note that country level and/or regional differences will be present, when compared to the EU-28 figures, the differences are driven by factors such as national policy, geographical and/or technical resource constraints.

To understand the matrix notation, the following assumptions must be considered:

o The growth or reduction indications are in relation to what is seen today, but also in relation to the rates observed within that category in comparison to other scenarios. For example, compared to today, solar generation is expected to increase significantly in all scenarios from today, but only receives a +++ in **Distributed Energy**.
o Equally, growth and reduction rates across the different categories are not directly comparable. For example, two categories with ++ rating may differ significantly in their actual percentage increase from today, based on the starting point and ultimate potential.

The use of the primary energy mix is an essential new feature of the TYNDP 2020 process, designed to enable the ENTSOs to gauge the overall shift in the energy sector required to ensure the decarbonisation pathways specified by the scenarios are met.

Final energy use sectors have been grouped into key categories (high/low temperature heat[1], transport, power and lighting), with indicators for the expected development of the total demand of energy use, and then the resulting effect on the electricity and gas demand in these sectors.

Due to this approach, it is important to understand the step between the primary energy mix and final energy usage, and the effect this has on some of the categories.

For example:

o The transport overall energy demand is expected to decrease as traditional internal combustion engines become more efficient, switch to alternative fuels or are replaced by electric motors. This can lead to positive indicators for both gas and electricity demand, whilst the total demand decreases, due to the displacement of oil in this sector.
o Biomethane is produced from anaerobic digestion or gasification feedstock, which are categorised under biomass.
o The primary energy source for gas produced from power-to-gas is solar and/or wind. However, power-to-gas has a separate row in the Central Matrix.
o Imported energy is represented in the primary energy mix as this is produced from primary energy outside the EU.

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[1] High temperature heat: usage for industrial processes (material transformations, chemical reactions, process steam, etc) which can be in excess of 1000°C, with the dominant range in Europe above 500°C. Low temperature heat: usage for space heating and hot water.

TABLE 1: STORYLINE MATRIX

Category	Criteria	2040 Scenarios		
		National Trends	Global Ambition	Distributed Energy
Primary mix	Coal	--	---	---
	Oil	--	---	---
	Nuclear	--	--	--
	Hydro	o	o	o
	Geothermal	o	+	++
	Biomass	+	++	+++
	Imported Renewable and decarbonised Gas	+	+++	+
	Natural gas	-	--	---
	Wind onshore	++	+++	+++
	Wind offshore	+++	+++	++
	Solar	++	+	+++
	Wind for P2G		+	++
	Solar for P2G	+	+	+++
	Imported Green Liquid Fuel	+	++	+
High temperature Heat	Total demand (all energy)	o	-	-
	Electricity Demand	+	+	++
	Gas Demand	+	++	o
Low temperature Heat	Total demand (all energy)	-	--	--
	Electricity Demand	+	++	+++
	Gas Demand	-	-	--
Transport	Total demand	-	--	--
	Electricity Demand	+	++	+++
Power and Lighting	Gas Demand	+	++	+
	Electricity Demand	o	-	-
CCS	CCS for power	o	++	+++
	CCS in Industry			

Legend

Change from Today	---	--	-	o	+	++	+++
	Not available	Moderate Reduction	Low Reduction	Stable	Low growth	Moderate growth	High growth

2.2 GHG Emissions and Scenario Targets

As the GHG reduction indicator is one of the most important political drivers for defining future national and/or pan-European climate ambitions, this parameter is introduced into the overall scenario building process at an early stage. Clear GHG emissions reduction targets have been set by the European Union for 2020 and 2030 as part of the pathway towards a low carbon society in 2050, by reducing GHG emissions by 80-95 % compared to 1990 levels. The 2020 Climate and Energy Package forms the basis for 20 % cut in GHG emissions by 2020 and the 2030 Climate and Energy Framework sets the target for 40 % reduction by 2030.

All storylines are translated into scenarios that, at a minimum, aim to achieve the aforementioned targets. **National Trends** will rely on the latest information available from draft National Energy and Climate Plans and National Development Plans (NDPs). This will ensure that the scenario is compliant with national and EU climate targets.

However, ENTSOs acknowledge that the target of the **Paris Agreement** of keeping temperature rise below 1.5°C, as compared to pre-industrial times, will not be met by only intermediate GHG emissions reduction targets for 2030 and 2050. Therefore, **Global Ambition** and **Distributed Energy** consider a carbon budget including emissions and removals from agriculture and from Land Use, Land Use Change and Forestry (LULUCF).

The IPCC Special Report on warming of 1.5°C (SR1.5 - 2018) provides evidence as to why a 1.5°C increase in global mean surface temperature is a critical threshold for the earth. The report addressed the question; what is the maximum level of anthropological emissions that can emitted (*set against various probabilities*), before irreversible climate damage is done. The report enables governments and agencies to calculate carbon budgets that are compatible with pathways to lower emissions within a 1.5°C increase in temperature.

The ENTSOs have sought expert opinion on what the carbon budget means for the "EU-28" and to this extent have consulted CAN Europe and the Renewables Grid Initiative. To build the Carbon Budget compliant scenario, the ENTSOs will use a carbon budget figure of 48.5 $GtCO_2$ based on the EU's population share.

Although all storylines are heading towards a decarbonised future for the EU, they all differ substantially in their energy transition approach. For instance, one emerging theme is that the European energy transition could be driven either by a centralised or decentralised pathway, and this general lever is considered in Figure 6 (Please note, that whereas the decarbonisation paths for DE and GA are based on own calculations, values given for NT are based on figures given in the EC's study "Clean planet for all" for 2030 and EU's 2050 decarbonisation targets for 2050).
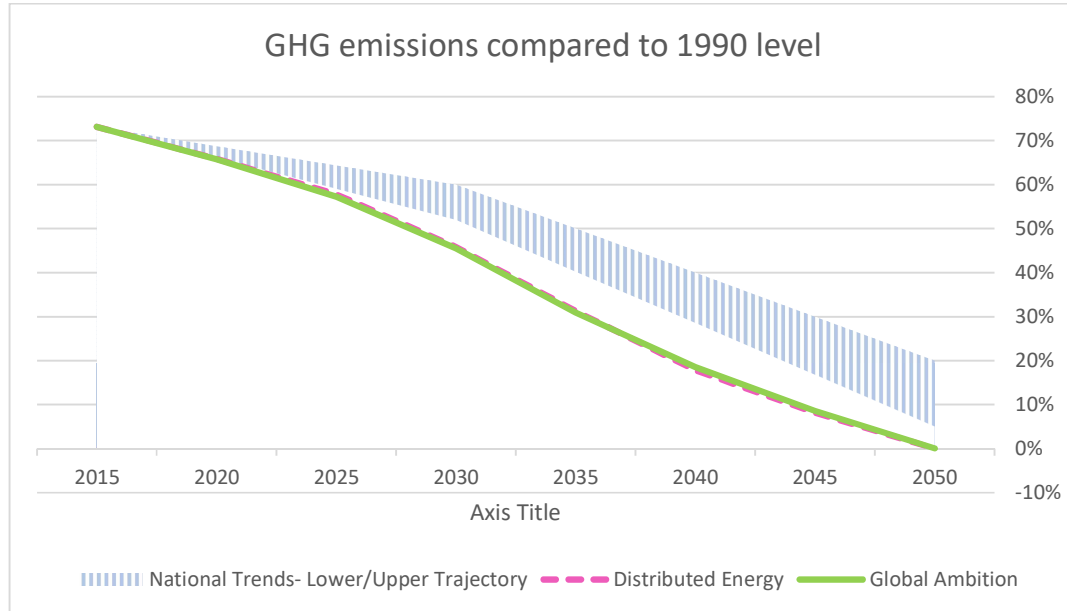
FIGURE 6: STORYLINE-SPECIFIC DECARBONISATION PATHWAYS (INCLUDING LULUCF)

As an example, **Global Ambition** looks at a future that is led by large development in centralised generation including offshore wind and Power-to-X. In contrast to that, **Distributed Energy** is a storyline that embraces a de-centralised approach to the energy transition, with rooftop solar installations linked with batteries, community or regional uses of biomass and geothermal resources.

It is important to understand that these levers are not absolute and are intended to give a strong indication of the future development anticipated in the scenarios. For example, decentralised technologies will still exist in a centralised scenario, but to a lesser extent. It's also worth mentioning that ENTSOs' Scenarios only focus on Europe's contribution to a global climate challenge. However, trends in centralisation or decentralisation are assumed to happen on a global scale.

What is a Carbon Budget?

Carbon budgets refer to the net total of CO_2 that can be emitted by an economy over a future time period; for example: the number of tonnes of CO_2 equivalent emissions that can be emitted by the EU-28 in the period 2020 until 2050. Carbon budgets account for emissions in CO_2equivalent, as well as accounting for CO_2 equivalent removals in the same period; i.e. carbon budgets include fossil fuel emissions and removals from LULUCF or BECCS technologies.

The IPCC Special Report on warming of 1.5°C (SR1.5 - 2018) provides scientific evidence on why 1.5°C is a critical threshold, and provides an assessment of 1.5°C compatible carbon budgets. These carbon budgets in SR1.5 are higher than those in the IPCC's Fifth Assessment Report (AR5 - 2014), mainly because of an effort of rebasing. The "Summary for Policy Makers of SR1.5" provides four 1.5°C compatible carbon budgets (for global CO_2 emissions), with differences due to:

- The likelihood of staying within the temperature threshold: 50 % or 66 % (which is an expression of the number of scenarios that allow a certain carbon budget);
- The means of temperature measurement: based on computer modelling only (global mean surface air temperature) or computer modelling combined with real-time observations (GMST).

The carbon budgets in the IPCC reports refer to the available budgets for CO_2-emissions, while they take into account certain limited reduction pathways for non-CO_2 emissions. Assuming stringent emission reductions of non-CO2 gases are in line with the deep reductions of CO2 emissions needed for 1.5°C compatible budgets, this could help in converting CO2-budgets into greenhouse gas budgets that would, according to SR1.5 Coordinating Lead Author Joeri Rogelj, be approximately 25 % higher.

Based on above mentioned parameters and assumptions, the global carbon budget is 712 $GtCO_2$ from 2018 onwards until the end of the century. There are multiple ways to divide the global carbon budget across countries. The main approaches take population and/or equity into account.

2.3 Top-Down Scenario Building with Carbon Budgets

New for TYNDP 2020 is the adoption of carbon budgets within the scenario development process. The Top-Down scenario process is used to convert the storylines developed through the consultation process into quantified scenarios that are suitable for techno-economic modelling exercises performed by both ENTSOs. The four main steps of the scenario building process are shown in Figure 7.

Step 1: The Ambition Tool team is responsible for creating EU-28 energy balance models that reflect the storylines in terms of final use demand. This process takes into account the primary energy sources and final use demand. The approach applies policies, such as, strong growth in electric vehicles, (hybrid) heat pumps and no coal in 2050 for heating or power. The annual demand from the ambition tool was handed over to the WGSB demand team to convert into hourly and daily profiles needed for Step 2 in the process.

Step 2: The supply mix for the scenarios are in terms of gas and electricity. For electricity the WGSB innovation team assumes responsibility for developing of the investment models required to distribute the renewable resources needed to balance the long term scenarios in line with the carbon budget. For Gas, ENTSOs followed a multi-step approach. Whereas indigenous production for natural gas was collected bottom-up from TSOs, the ENTSOs worked closely with the consultancy Navigant to quantify scenario-specific production levels for biomethane. For power-to-gas, ENTSOs have developed a new methodology to distribute and optimize hydrogen and synthetic methane production via electrolysis around EU28. For gas imports, ENTSOs has worked out extra-EU supply potentials.

Step 3: The result from the Ambition Tool energy balance model and the investment loop provides a projection for annual gas and electricity demand, whilst balancing oil and coal as changes in final use demand evolve.

Step 4: Since the Top-Down energy balance model considers primary energy fuels and the power market model estimated the gas usage, it is possible to compare the scenario emissions with a carbon budget.
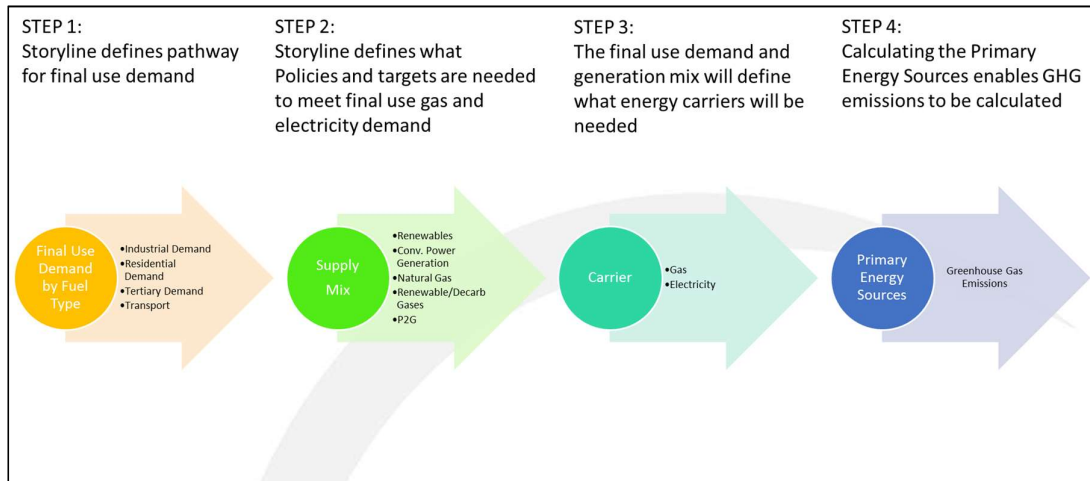
FIGURE 7: MULTI-STEP SCENARIO BUILDING PROCESS

For further information:

- On how the Ambition Tool annual figures are derived see Section 4.
- For gas and electricity demand profile methodologies see Section 5.
- For the supply mix, the ENTSOs have developed new methodologies for quantifying the electricity and gas supply; these methodologies take into account the theme of decarbonisation and the "carbon budget approach" (see Sections 6 & 7).

Bottom-up Data Collection

3   Bottom-up Scenario Principles

A core element of the ENTSOs' scenario building process has been the use of supply and demand data collected from both gas and electricity TSOs to build bottom-up scenarios. The bottom up data collection remains a key component of the scenario building exercise and provides useful insights and trends that exist at a national level. Bottom up scenarios are an important feature of TYNDP scenarios as they show how national plans come together from a European perspective.

For TYNDP2020, National Trends is the bottom-up scenario. For this storyline, best available information for the timeframe 2020 to 2040 was collected directly from the gas and electricity TSOs. The National Trends related data collection provides an important opportunity to collect in depth information stemming from the National Energy and Climate Plans, National Development Plans and other nationally recognized studies. Since most of the NECPs are based on an impact assessment till 2030, the TSOs' knowledge is key to build a consistent scenario till 2040.

Following our talks in the TYNDP Cooperation Platform with European Commission and ACER, initially submitted TSO data was further aligned with the respective NECPs where a difference was detected.

3.1   National Trends decarbonisation ambition

After consulting external stakeholders, ENTSOs decided to base the NT Scenario on country-specific NECPs. National Trends follows the trends developing the climate policies on a national level. The governance of the energy union and climate action rules, entered into force on 24 December 2018, require EU member states to develop NECP that cover the five dimensions of the energy union for the period 2021 to 2030 (and every subsequent ten year period). Member States had to submit draft NECPs by 31 December 2018. Most of the draft NECP provide an impact assessment with information on the energy consumption and supply.

On 18 June 2019, the European Commission published its review of the draft NECPs, including specific recommendations. Member States are now required to update their NECP and submit a final version to the European Commission by the end of 2019. ENTSOs worked closely with the European Commission and their members to align the NT Scenario with the latest draft NECPs.

Caveat upon new European RES and Energy Efficiency Targets
It is the intention of the National Trends scenario to achieve the targets agreed upon by EU Parliament, EC & Council on 14th and 19th June 2018. The ENTSOs are aware that it may not be possible to capture the latest National Energy and Climate Plans (NECPs) for each member state as the draft submissions were due in December 2018, and further negotiations will take place until end of 2019. That being said it is the intention of the ENTSOs to liaise with the EC to align the scenario as close as possible with additional measures that can deliver the 32 % RES and 32.5 % energy efficiency (link) targets for the EU28.

3.2 Bottom-Up Scenario Building Process

The bottom-up scenario building process requires direct communication between the Working Group Scenario Building and data collection correspondents for gas and electricity TSOs. In order to work efficiently between the groups involved and to ensure proper data alignment, the following steps have been implemented.

Step 1: ENTSOs create the bottom-up scenario chapter of the Data Collection Guideline, so that it is ensured that the data collection is in accordance with the storyline and the required boundary conditions.

Step 2: Bottom-up scenario guideline chapter is included with the ENTSO-E PEMMDB Data Collection Guidelines. ENTSOG incorporate guidance notes for the bottom-up data collection into ENTSOG's WG Scenario data collection process.

Step 3: The ENTSO-E data collection process is the responsibility of WG D&M, an email should be jointly composed that calls for action from **L**ong Term **A**dequacy **C**orrespondents (LACs) to complete the PEMMDB template files.

ENTSOG data collection process is the responsibility of WG Scenario.

Step 4: WG D&M, WG Scenario and ENTSOs' joint WGSB perform checks on the input data' basic errors and inconsistencies. Moreover, ENTSOs check the data on its alignment with the NECP and EU climate targets for 2030.

Step 5: ENTSO-E uses the bottom-up PEMMDB files and demand to create the bottom-up scenario. Power market simulations are run to provide the output volumes for each generation type necessary to balance supply and demand. The gas demand for power is an output from the model, which complements the gas final demand provided by gas TSOs.

ENTSOG collects bottom-up data for gas final demand figures (gross inland consumption excluding gas demand for power generation). To account for different climate conditions daily figures are collected for the average case including a seasonal demand factor, 2-Week-case, Design Case. Daily figures for the gas demand in power generation are computed based on the power market simulation results (simulations cases are explained in more detail in Section 5.3.2.).

Step 6: Bottom-up scenario results are circulated to ENTSO-E Regional Groups and ENTSOG Scenario Working Group for review.

3.3 Consistency checks

In order to have clarity and avoid potential misunderstanding between the electricity and gas experts during the data collection, validation and market runs, the experts on both sides were requested to interact with one another. During the data collection the experts cooperated with their respective counterpart, when there was a possibility of disagreement about common inputs like:

- Installed electricity generating capacities (gas-fired)
- Demand assumptions
- Any other values relevant for both sectors (e.g. installed P2G capacities)

Once the data collection was completed and initial screening of the input was done (initial checks and corrections), the data was used as main starting point for the overall scenario building process. In case of disagreement, a bilateral discussion with the disagreeing TSOs on both sides took place so that an agreement could have been reached.

Ambition Tool Methodologies

4 Ambition Tool Methodologies and Calculations

A top-down scenario building process requires a holistic view of the European energy system. The new Ambition Tool energy balance tool provides the ENTSOs with the opportunity to develop future energy pathways that ensure consistency and coherency across the time horizon 2015 to 2050. The Ambition Tool is an Excel energy balance model developed in house jointly by ENTSOG and ENTSO-E. The starting year for the model is 2015 energy balance data based on statistical country-specific EUROSTAT Energy Balance sheets for 2015 (see website). One of the main requirements for the scenario building process is to realise the Paris Agreement targets. Therefore, a complete energy system model (all sectors, all fuels) is necessary in order to quantify the CO_2 emissions in each scenario.

The purpose of the Ambition Tool is to translate qualitative storylines into quantified total energy scenarios. The tool ensures annual energy demand for all sectors and fuels and supply is balanced in detail for both gas and electricity. The quantitative translation of storylines into figures includes quantifying the technology changes in the residential, tertiary, transport and industrial sectors.

The Ambition Tool provides annual energy volumes that are consistent with the scenario storylines. The storylines were consulted on and agreed through the joint ENTSOs scenario building process. Figure 8 provides an overview of the high-level inputs and outputs that are addressed with the Ambition Tool. Since ENTSO-E and ENTSOG are responsible for electricity and gas transmission, a key output from the model is the annual energy volumes for each carrier.
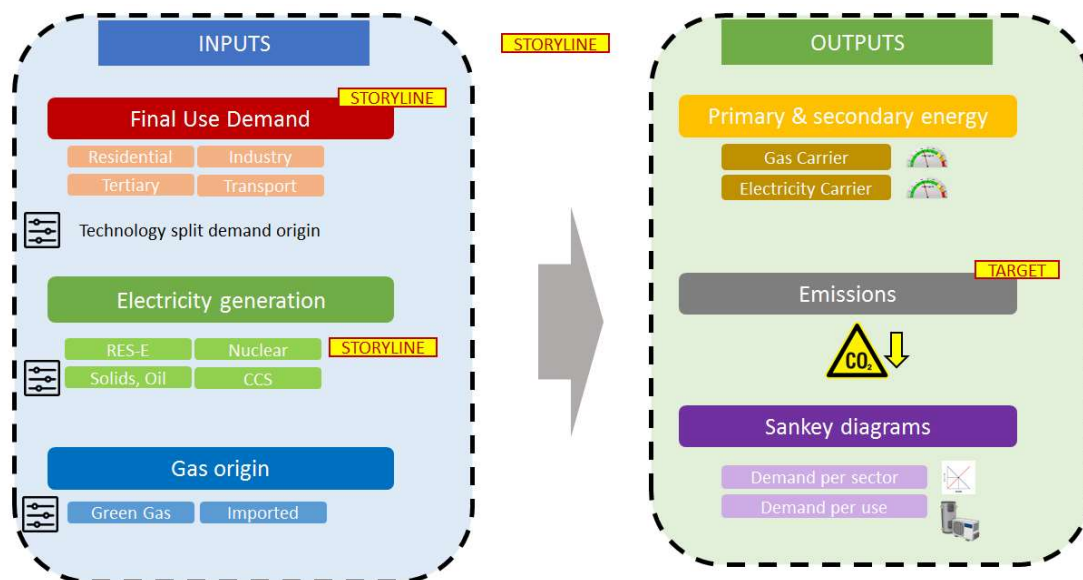
FIGURE 8: HIGH LEVEL DESCRIPTION OF THE AMBITION TOOL

Figure 9 describes the process that guarantees the consistency of the quantification of storylines in the Ambition Tool.

The Ambition Tool quantifies the final use demand and the supply mix, more specifically the primary energy supply mix, for the EU28 countries.

At this point it should be mentioned that the installed capacities and the generation of the electricity sector, as well as the associated gas demand of the gas power plants form a kind of proxy, as they are quantified later in the process in more detail with the help of the investment model (see Section 6).

A feedback loop within the overall scenario building tool chain guarantees that the following storyline aspects are fulfilled:

- Is a storyline compliant with the targets for energy efficiency in primary energy and final energy use?
- Does a storyline meet renewable energy targets for a given time horizon?
- Does a storyline meet a specific carbon budget?
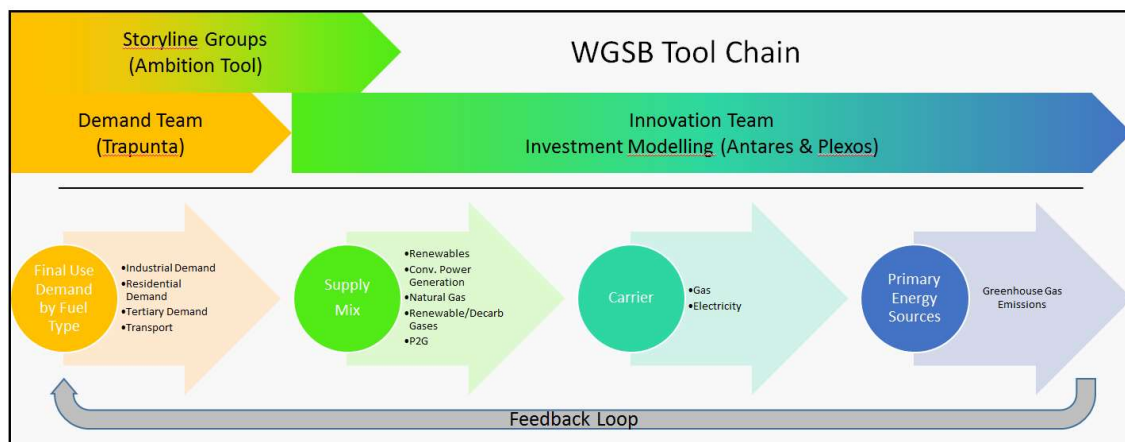
FIGURE 9: TOP-DOWN SCENARIO PROCESS - THE AMBITION TOOL STEPS

In general, the Ambition Tool provides the first quantification step in the scenario building process, the outputs from the model are then passed into the next stage of the process to develop hourly electricity demand profiles, daily gas volumes, and more detailed breakdowns of installed capacity for the electricity power market.

In order to account for the contrasting storylines of the Distributed Energy and Global Ambition scenarios two separate Ambition Tool files have been developed for each of the countries fitting to the interpretation of each of the scenario storylines and its qualitative definitions in the Storyline Matrix.

In the storyline related Ambition Tool files for DE and GA on the EU28 level the storyline was completely quantified (including iterations for the different setting) to form a consistent story. This includes:

- Demand development consistent with the (quantitative) storyline matrix
- Changes in demand structure are feasible (e.g. transition fitting to average lifetime of cars)
- Supply development consistent with storyline matrix
- Changes in supply are feasible (fitting to potential from different RES sources and fitting to (possible) expansion rates)
- CO_2 budget targets are met
- The import mix/share on the gas-supply side is met

In summary the Ambition Tool part of the scenario building process has the following two steps.

Step1

Quantifying the final energy demand according to storyline with the distribution on the different carriers (especially electricity and the gases methane and hydrogen)

Step2

Quantifying of the electricity generation and the gas supply mix according to the storyline.

ENTSOs' have applied assumptions based on expected Pan-European developments and included TSO input for scenario-/country-specific trends (more information on the incorporation of country specific details is provided in Section 4.4).The following sections will provide a guide on how each demand component is considered.

4.1 Step1: Final Energy Demand calculations

4.1.1 Residential Sector

The residential section in the Ambition Tool is used to quantify the future energy mix in residential buildings with respect to the assumptions on:

- Demand split for the residential sector between heating/cooling (including sanitary water) and lighting/power
- Insulation and lighting/power efficiency gains per year
- Heating/cooling technology mix per fuel type
- Heating/cooling technology efficiency evolution
- General final energy demand evolution depending on population and persons per household projections

Based on the demand split for heating/cooling and lighting/power in the reference year 2015, the demand for the Residential Sector is projected by the application of a specific compound annual growth rate (CAGR) for efficiency gains.

Lighting and Power

Lighting/power covers the electricity demand for home lighting, white goods and operation energy (e.g. for shutters).

Heating and Cooling

Heating/cooling covers the energy demand (all types of fuels) for heating and cooling a building.

Heating/cooling technology types include:

- For methane (including natural gas, biomethane and synthetic methane): stand-alone boilers, gas heat pumps, combined heat and power (CHP) and district heating
- For coal: stand-alone boilers and district heating
- For oil: stand-alone boilers and district heating
- For biomass: stand-alone boilers and district heating
- For hydrogen: stand-alone boilers/fuel cells
- Solar: thermal panels
- Electricity: direct heating, air source heat pumps, ground source heat pumps, district heating
- Hybrid solution (gas and electricity): hybrid heat pumps consisting of both an electric heat pump and a gas boiler

The heating technologies do not consider the source of the fuel as such. For example, if methane is the fuel of preference, this can be either natural gas or biomethane or synthetic methane (P2G). Source-specific supply assumptions for electricity (generation mix) and gas (quality

specific for methane and hydrogen including assumptions on self-sufficiency/imports) are made the electricity generation and gas supply section of the Ambition Tool (see Sections 6 and 7).

The logic follows a multi-step approach. First the normalized heating/cooling need per household in the reference year 2015 estimated (in terms of energy losses due to temperature difference between a comfort temperature and outside temperature). Following the assumptions on efficiency gains due to insulation, population growth and persons per household, the total heating/cooling need in a target year can be projected. Finally, the Ambition Tool computes the energy consumption considering the technology mix of the target year and the corresponding efficiency.

The objective is to estimate heating/cooling energy demand per fuel type and net sectoral CO_2 emissions.

The approach enables capturing the energy efficiency improvement originating from the shift from combustion–based boilers (especially for coal and oil) to electric and gas heat pump, fuel cell and CHP based technologies separately from the energy efficiency improvement originating from improved technology fuel efficiency.

The outcome for electricity and gas demand evaluation is the corresponding residential demand for electricity, methane and hydrogen per heating/cooling technology type.

4.1.2 Tertiary Sector

A similar approach as in the residential section of the Ambition Tool is used to quantify the future energy mix in Tertiary Sector (mainly buildings), as the methodologies are based on the ones applied to the Residential Sector.

Differences are:

- Instead of population growth and persons per household, the tertiary section considers a CAGR on volume growth. This volume growth is not to be equated with GDP growth, but refers to an additional energy demand due to increasing demand for services/goods. On top, and as for residential, efficiency gains are considered by separate compound annual growth rate (CAGR).
- The demand split also includes the energy demand for cooking and catering

4.1.3 Transport Sector

The transport section in the Ambition Tool is used to quantify the future energy mix in transport with respect to the assumptions on:

- Vehicle technology mix per energy source
- Transport efficiency evolution
- Transport need evolution per transport type

Transport types include:

- Passenger transport
- Freight transport (including inland shipping)
- Aviation (excluding extra-EU aviation)

While vehicle energy sources include:

- Fossil oil based fuels (such as fossil gasoline, diesel and kerosene)
- Methane (including fossil methane, biomethane and synthetic methane)
- Hydrogen (including other non-methane synthetic liquid fuels)
- Liquid biofuels (including liquid fuels produced from biomass or waste)
- Electricity

The logic is to estimate the transport need (in terms of passenger and freight kilometers) per transport and fuel type and derive the corresponding energy consumption based on the specific consumption of the fuel and transport type in question (including the impact of occupancy ratio in the vehicles, i.e. specific consumption is considered as kWh/100 passenger/tkm)[2].

The objective is to estimate transport energy demand taking per fuel for the energy demand and net emission calculations.

The approach enables capturing the energy efficiency improvement originating from the shift from internal combustion engine based vehicles to electric and fuel cell based vehicles separately from the energy efficiency improvement originating from improved vehicle fuel efficiency and modal shift (such as increased share of public transport).

The outcome for electricity and gas demand evaluation is the corresponding transport demand for electricity, methane and hydrogen per transport type (excluding international extra-EU shipping and aviation). The transport type was later utilized in the demand profile creation via different assumptions on the flexibility of different transport types.

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[2] Tonne-kilometre, a unit of measure of freight transport which represents the transport of one tonne of goods by a given transport mode over a distance of one kilometre.

4.1.4 Industrial Sector

The industry section in the Ambition Tool is used to quantify the future energy mix in the industry with respect to the assumptions on:

- Demand split in consumptions categories
    - Space heating
    - Water heating
    - Process use
    - Cooking
    - Drying and separation
    - Non-heat
    - Non-energy
- Efficiency and production growth in each consumption category
- Subsector split with an individual fuel mix
    - Iron & steel industry
    - Chemical and Petrochemical industry
    - Non-ferrous metal industry
    - Non-metallic Minerals (Glass, pottery & building mat. Industry)
    - Transport Equipment
    - Machinery
    - Mining and Quarrying
    - Food and Tobacco
    - Paper, Pulp and Print
    - Wood and Wood Products
    - Construction
    - Textile and Leather
    - Non-specified (Industry)
    - Agriculture/Forestry/Fishing/Others
    - Non-energy use

As for the other sectors, also the industry section differs between following fuel types: solid fuels (coal/lignite), oil, gas (mainly methane), total renewables, waste, hydrogen, derived heat and electricity. For the sake of simplification and due to purpose of the TYNDP scenarios with a special focus on gas and electricity, the fuel types total renewables, waste and derived heat are aggregated to biomass/bioliquids/waste on a primary side.

The logic is to estimate the energy consumption per fuel type per sub-sector. Efficiency and industrial production related CAGRs are applied to each consumption category and to each sub-sector. A basic assumption is that fossil fuels such as coal, lignite, oil and waste need to be completely replaced by carbon-neutral alternatives by 2050.

The objective is to estimate fuel-specific energy demand in the Industry Sector and net emission.

The outcome for electricity and gas demand evaluation is the corresponding industrial demand for electricity, methane and hydrogen.

4.1.5 Consumption of Energy Branch

To account for the energy demand for "consumption of the energy branch" an additional energy demand is added to the primary energy side. "Consumption of the energy branch" is generally defined as "own use" (self-consumption in power plants or natural gas consumption to support extraction in mining, oil or gas production). The additional energy amount for the "consumption of the energy branch" in a target year is calculated by applying a fraction to the sum of final energy demand and energy demand for power generation. The fraction is based on the relation of "consumption of the energy branch" to primary energy demand expressed in EUROSTAT energy balance sheets for 2015. The energy demand for "consumption of the energy branch" is calculated fuel specific.

4.2 Step2: Electricity Generation and Gas Supply

4.2.1 Electricity Generation

The electricity generation section in the Ambition Tool is used to give a first quantified indication of the future primary energy demand for electricity generation with respect to the assumptions on:

- Gross electricity generation including final electricity demand, electricity demand for power-to-gas, consumption of the energy branch and distribution losses
- Generation technology mix
  - Fossil fuels (solids, oil)
  - Gaseous fuels (natural gas, biomethane, synthetic methane, hydrogen)
  - Renewables (biomass/waste, wind, solar, geothermal)
  - Generation technology efficiency growth

The objective is to estimate the primary energy demand per technology type based on future generation mix and derive the corresponding primary energy consumption taking into account its conversion efficiency (fuel to power). In a subsequent step the primary energy demand per fuel for power generation and net emission calculations can be estimated.

The approach enables capturing the decreasing specific primary energy demand for electricity generation originating from the shift from conventional electricity generation to renewables like wind and solar separately from the energy efficiency improvement originating from improved generation technologies. The power plant self-consumption and distribution losses are calculated based on their ratio to the gross electricity generation in 2015.

The electricity generation demand for power-to-gas results from the decarbonisation and self-sufficiency target of the gas mix, which is described in more detail in the next section.

4.2.2 Gas Supply

The gas supply section in the Ambition Tool is used to quantify the future primary energy demand for the gas supply with respect to the assumptions on:

- Quality-specific consumption for methane and hydrogen including final gas demand, gas demand for electricity generation and consumption of the energy branch
- Targets for decarbonisation and import quota
- A fixed indigenous natural gas production based on bottom-up data collected from European gas TSOs and fixed biomethane production based on ENTSOG's biomethane methodologies (based on Navigant's "Gas for Climate" study)

The gas supply sources include:

- For methane: natural gas (with/without CCS), biomethane, power-to-methane
- For hydrogen: power-to-hydrogen, blue hydrogen (including SMR+CCS and Methane Pyrolysis)

The logic is to estimate the primary energy demand per gas source by:

- Applying a decarbonisation target, which can be reached by increasing the share of renewable gases or the application of pre- or post-combustive CCS
- Applying a specific import quota expressing the share imported gas and the need for indigenous production of gaseous fuels

The objective is to calculate the primary energy demand per gas type and source and net emissions calculations.

The methodology enables capturing limits of indigenous production for natural gas and biomethane, whereas it allows for technology neutral approach when it comes to the decarbonisation of the gas mix. It also accounts for the international character of gas supply allowing for different important quotas.

The electricity demand for P2G is an outcome of the gas supply methodology, which then must be considered in the electricity generation section.

4.2.3 Emissions calculation

The CO_2 emissions in the energy sector are calculated multiplying the primary energy demand per fuel with the fuel-specific CO_2 emissions factor (in g/kWh).

For non-CO_2 emissions and LULUCF, the Ambition Tool refers to country-specific values given by EC's EU Reference Scenario 2016. On an EU28 level, the EC-study "Clean Planet for all" has been taken as a reference.

Carbon Capture and Storage (CCS) as a carbon removal technology can be applied in industry and to power plants. The CO_2 capture rate is 90 %.

Bioenergy CCS as a net-negative emissions technology can be applied to biomethane production and power plants. It also has a CO_2 capture rate of 90 %, but due to its renewable CO_2 source, it results in negative emissions.

4.3 Data source and reference

For the Ambition Tool starting point ENTSOs adopted the use of official EU statistics from EUROSTAT. EUROSTAT data is provided by member states directly to European Commission (see [here](#)), for the purposes of energy balance it was deemed a suitable reference source. Other reference material was based on other EC studies, such as the PRIMES model or EC Long Term Strategy studies.

The following table gives an overview of data and references in the Ambition Tool:

Table 2 Source Reference data for Joint ENTSO Ambition Tool.

Data type	Source	Link
Final Energy Demand	EUROSTAT – Energy Balance sheets 2015	Link
Primary Energy Demand	EUROSTAT – Energy Balance sheets 2015	Link
Non-CO2 GHG Emissions and LULUCF	EC - EU Reference Scenarios 2016	Link
	EC - A Clean Planet for all, A European long-term strategic vision for a prosperous, modern, competitive and climate neutral economy	Link
Population projections	EC - EU Reference Scenarios 2016	Link
Sectoral technology and fuel mix	EUROSTAT – Energy Balance sheets 2015	Link
		Link
	EC - Mapping and analyses of the current and future (2020 - 2030) heating/cooling fuel deployment (fossil/renewables)	
		Link
	UK Department of Energy and Climate Change - United Kingdom housing energy fact file	
Efficiencies for heating technologies in residential and tertiary sector	ASSET - Technology pathways in decarbonisation scenarios	Link
Efficiencies in transport sector	ENTSOs' own forecast	

4.4 Moving from an EU-28 Ambition to Market Level Detail

4.4.1 Overview - Motivation

All European countries differ in their demand size, its sectoral structure and its supply structure. This boundary condition has a major influence on the future development of demand and supply side, which has been taken into account. This is why the process step "regional scenario feedback loop" was introduced into the overall scenario building process with the aim to incorporate country specific details in the quantification of the two top-down scenarios Distributed Energy and Global Ambition.

On a country specific level the following "demand size factors" are playing a key role:

- Residential sector (mainly heating demand)
  - o Number of people
  - o Persons per household
  - o Efficiency (e.g. isolation of buildings, improved efficiency of heating technologies)
- Tertiary sector
  - o Growth of the sector
  - o Efficiency
- Transport sector (split into passenger transport, freight, aviation)
  - o Evolution of transport need in different segments
  - o Vehicle energy efficiency development (excluding efficiency gains from fuel switching)
- Industry sector
  - o Growth of industrial production
  - o Efficiency

4.4.2 Gaining Insight from Regional Groups and ENTSOG Scenario Working Group

As already mentioned, the target of the "regional scenario feedback loop" was to take into account country specifics in the Ambition Tool files for the scenarios Distributed Energy and Global Ambition during the quantification of the final energy demand by sector (Residential, Tertiary, Industry and Transport).

Once the country-specific Ambition Tool files were available, they were aggregated to total figures for each of the top-down scenarios to display the EU wide trends on the gas supply, the electricity supply and GHG emissions sides.

For the compilation of the electricity demand time series, which is the next step of the scenario building process, the country and sector specific demand figures of the Ambition Tool files are one of the key inputs. In the end this input data specifies the future development in each of the market nodes in terms of hourly electricity demand as well as the daily demand for gaseous energy carriers.

The EU28 top-down scenarios built in Ambition Tool show an overall European perspective; therefore, it does not reflect country specific differences. To make the Ambition Tool files useful for each market area demand profiles it is necessary to check whether the generalised assumptions from a EU28 level are relevant on a country by country basis. To capture the local differences a "regional group scenario feedback loop" process, aimed at taking regional knowledge onboard. The regional group consistency checks with the process steps are described as follows:

First step

For all relevant countries the Ambition Tool files have been pre-parametrized centrally for the scenarios Distributed Energy and Global Ambition.

Second step

Then the countries specific Ambition Tool files were handed over to the different Regional Teams (see following section) for the feedback loop. For each Regional Team consistency checks where performed in two directions:

- Are the developments inside the group fitting together?
- Is the overall development of the team consistent with the two storylines?

Third step

After the finalization of the feedback loop, each file was subjected to a central consistency check of Working Group Scenario Building.

4.4.3 Regional Teams
Most of the relevant countries where assigned to a "Regional Team"

- North Sea
- Continental South West
- Continental Central East
- Continental Central South
- Continental South East
- Baltic Sea

consisting of the following countries:
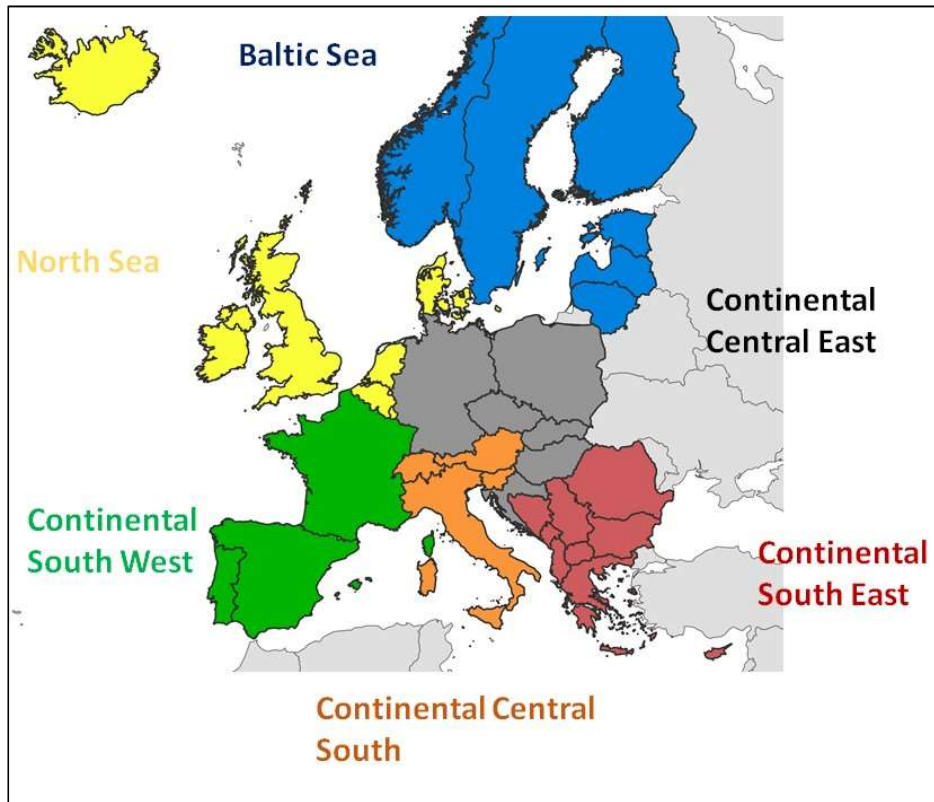
FIGURE 10: REGIONAL TEAMS

Each team assigned one member of the WGSB as a "POCAT" (**P**oint **o**f **C**ontact **A**mbition **T**ool) - to coordinate and support the data collection in the specific team.

For the task of per country data ENTSOG (Scenario Working Group) and ENTSO-E (Regional Groups) members were simultaneously requested to coordinate within each country (mainly between electricity- and gas-TSOs) and the POCAT of the Regional Team.

In order to support each country, one webinar and one joint WGSB, WG Scenarios, Regional Groups workshop were held.

4.4.4   Challenges in the "Regional Team scenario feedback loop"

The new feedback loop process of collecting country specific insight for the scenarios for the Ambition Tool files for otherwise purely "top-down" defined scenarios has generated new challenges for the TSOs in the different countries:

- The Ambition Tool files describe a consistent demand trajectory per sector – it is not just a collection of some (independent) electricity and gas input, but electricity- and gas- TSOs have to define together the development
- The Ambition Tool files should be consistent with the top-down storylines of the scenarios. These storylines do not necessarily represent the countries (TSOs)

views/plans or expectations for the future. The countries were nevertheless asked to provide data fitting to the storyline.

4.4.5 Default values

Some countries did not provide values for the two scenarios on their own. For these countries a process for generating default values based on

- 2015 EUROSTAT data (if available) and
- "Trends" defined in the EU28 Ambition Tool-files had been applied.

4.4.6 Additional countries

The ENTSOs' grid modeling is covering an area larger than the EU28 countries. In addition to EU28 the following countries are (partly) modeled and therefore data for the countries have to be collected/defined prior to further scenario building steps:

ENTSO-E:

- Crete (GR03)
- Corsica (FR15)
- Malta (MT)
- Ukraine (UA)
- Iceland (ISOO)
- Israel (IL00)– MEDTSO
- Morocco (MA)– MEDTSO
- Tunisia (TN) – MEDTSO
- Turkey (TK) – MEDTSO
- Algeria (DZ) – MEDTSO

ENTSOG:

- North Macedonia
- Switzerland
- Bosnia Herzegovina
- Serbia

Data for these countries have been collected through a bottom-up approach or via MED-TSO.

Demand

5 Final Use Energy Demand

Final use demand is an essential input to the scenario building process. Figure 11 provides an overview of the steps before and within the final use demand building process. The output of the process is higher time resolution electricity and demand profiles used in techno-economic modelling.

In the first step, the storylines and the scenario building matrix influence the composition of final use demand; this is reported at an EU-28 level in annual energy volume terms. The next step in the process is to breakdown the EU-28 annual volumes to market zone detail, once again in annual volume energy terms. Once the market zone annual demand is available, the demand profile building process can start. This section will provide detail on how higher temporal resolution electrical and gas demand profiles are created that can be used by power and gas market modelling tools.
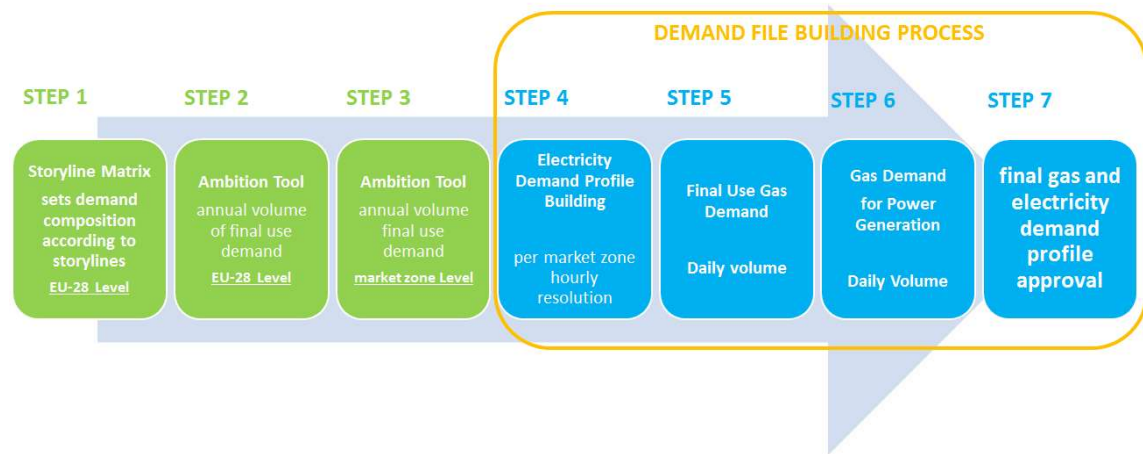
FIGURE 11: OVERVIEW OF DEMAND BUILDING PROCESS FOR GAS AND ELECTRICITY

The scenario building process uses the EUROSTAT definition of final use demand (consumption)[3], the Ambition Tool process quantifies the annual volume of demand in terms of residential, industry, tertiary and transport. Final use energy demand can be supplied from a variety of primary energy sources or energy carriers; these are solids such as coal and lignite, oil, gas and electricity carriers. For the purposes of ENTSO-E and ENTSOG scenarios the ENTSOs are interested in underlying demand growth along with fuel switching within sub-sectors of the economy. The changes in what fuels balance final use demand will impact the future demand for gas and electricity; for example, a high temperature industrial process, may switch from coal to gas, or oil based transport may switch towards electricity.

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[3] EUROSTAT Statistics Explained: Simplified balance for electricity and derived heat
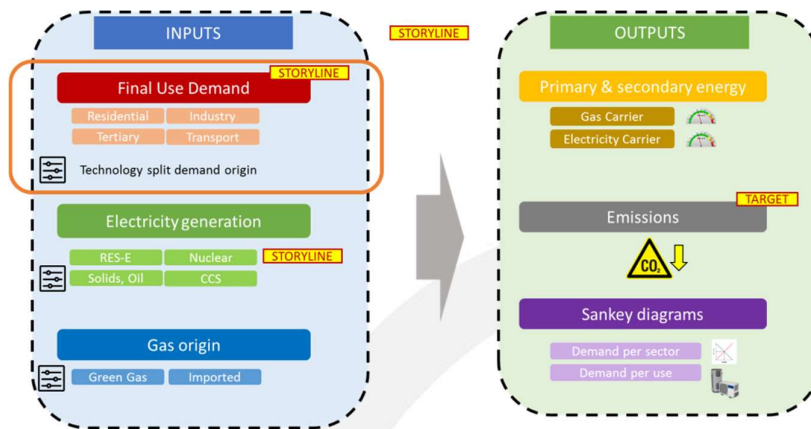
FIGURE 12: HIGH LEVEL DESCRIPTION OF SCENARIO BUILDING AMBITION TOOL, FINALE USE DEMAND HIGHLIGHTED IN ORANGE

A high-level summary of the overall description of the demand building process is detailed in Steps 1-7. These are consistent with Figure 11.

Step 1: Storyline Matrix

The storyline matrix provides an overview of what characteristics will be attributed to the "top-down" demand projections. Factors that will impact final use demand such as, energy efficiency of thermal insulation in buildings, efficiency of end-user appliances, industrial production growth rates, population growth, fuel-switching technology i.e. moving from internal combustion engine cars to electric vehicles. The application of the input levers will change the annual volume shares and composition of what makes up final used demand within the residential, tertiary, industry and transport.

Step 2: Ambition Tool: annual final use demand based EU-28

Final use demand is charted to show the evolution of final use demand projection over the time horizon for each storyline. The starting point of final use demand is based on EUROSTAT statistical energy balance data[4]. The charts are useful to ensure that the storyline consistency is maintained through the time period 2015 to 2050. Figure 13 provides an illustration of how final used demand could be projected to evolve over the 2015 to 2050 time horizon.

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[4] EUROSTAT Energy Balances: LINK
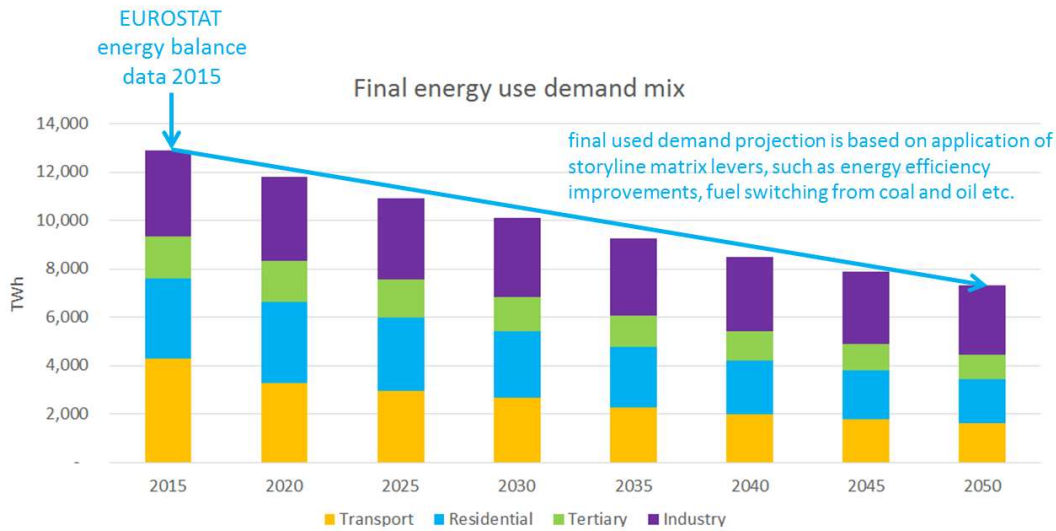
FIGURE 13: FINAL USE DEMAND COMPOSITION AND DEVELOPMENT

When the final use demand is created it is necessary to understand what final use energy is supplied by the electricity and gas carriers. The Ambition Tool provides a storyline summary chart, see Figure 14; it provides a summary of the annual energy volumes for electricity and gas demand. The volumes that are provided here are used to cross check that the final use demand once hourly and daily profiles are created in steps 3-7.

	2015	2020	2025	2030	2035	2040	2045	2050
Primary Energy Consumption (TWh)	19,080	17,476	16,055	14,540	13,309	12,146	11,255	10,400
Electricity Demand (TWh)	3,238	3,401	3,526	3,620	3,702	3,756	3,720	3,677
Gas Demand (TWh)	4,589	4,850	4,663	4,787	4,604	4,355	3,996	3,636
Emissions Reduction compared to 1990, based on Primary Energy Mix	21%	33%	44%	58%	70%	81%	88%	93%
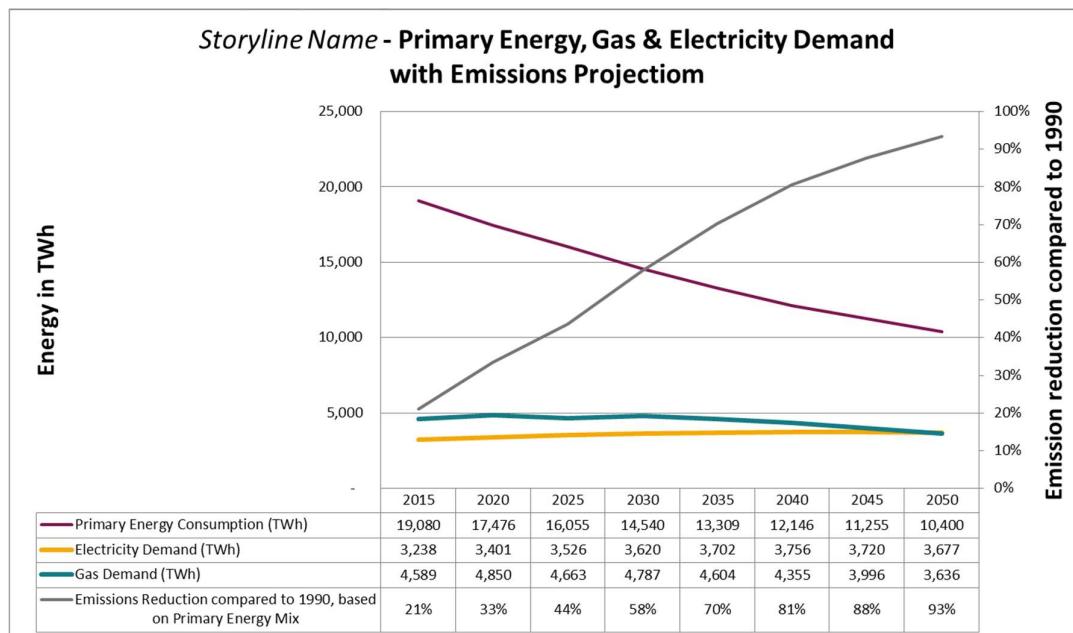
FIGURE 14: AMBITION TOOL-STORYLINE SUMMARY SHEET, PRIMARY ENERGY, GAS AND ELECTRICITY DEMAND WITH EMISSIONS PROJECTION (NUMBERS SHOWN FOR ILLUSTRATIVE PURPOSES ONLY)

Once the EU-28 gas and electricity demand annual volumes are known for each "top-down" storyline, it is important to check that they are consistent. The consistency check must compare the storyline electricity and gas demands with the attributes assigned in the scenario matrix table. A second important check is to ensure the "top-down" demand values are differentiated compared to each other.

Step 3: Ambition Tool moving from EU-28 to market zone level

The next stage in the process is to breakdown the EU-28 to market zone demand profiles. This process involves interaction with the ENTSOG Scenario Working Group and the ENTSO-E Regional Groups, to ensure regional demand characteristics are captured within the "top-down" demand. For example, it could be that a region within Europe has a high potential to move high temperature industrial processes from coal to gas, whether as another region has already seen this shift in energy use.

The market zone Ambition Tool sheets are created for the EU-28, but also the broader ENTSOs' perimeter. In total 34 countries areas are included in the demand building process. There is an additional step that creates the market zones within countries. In total there are 44 market areas created using the "top-down" demand building process.

Step 4-7: Demand file building process

Steps 4 to 7 are the main steps that will be described by Sections 5.1, 5.2 and 5.3. The output from this process is hourly demand files that can be used within ENTSO-E power market modelling and daily gas volumes needed to feed into ENTSOG gas models.

5.1 Demand profile building process

The demand profile building process is necessary to allow annual final use energy volumes to be converted to hourly and daily volumes required for the power and gas sector modelling tools. The high-level process steps are shown in Figure 15.
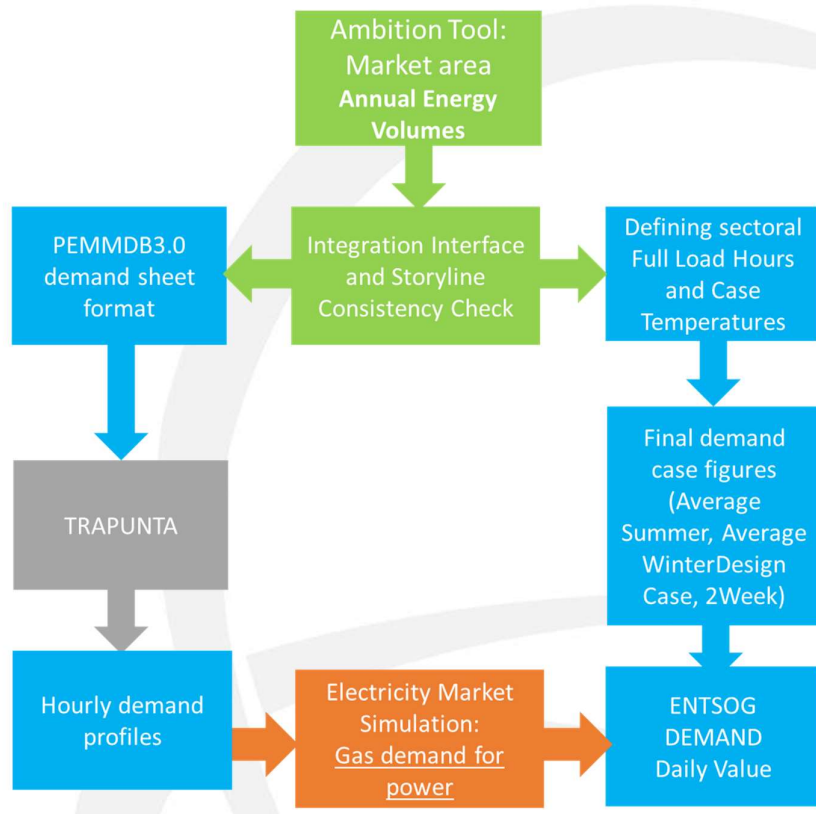
FIGURE 15: DEMAND PROFILE BUILDING PROCESS STEPS

5.2 Electricity Demand

Electricity demand is a fundamental input to the power sector investment modelling step in the scenario building process, see Figure 16. Electricity demand is projected in two ways depending on whether a scenario is build using a "bottom-up" or "top-down" methodology;

- Bottom-up models use hourly profiles that are built by the ENTSO-E Working Group Data & Models based on TSO validation, or directly submitted by the TSO.
  - o The data files are based on normalised profiles spanning 35 climates years, 1982 - 2016
- Top-down models require a process to convert the annual electricity demand figures into hourly profiles as explained in the following sections.
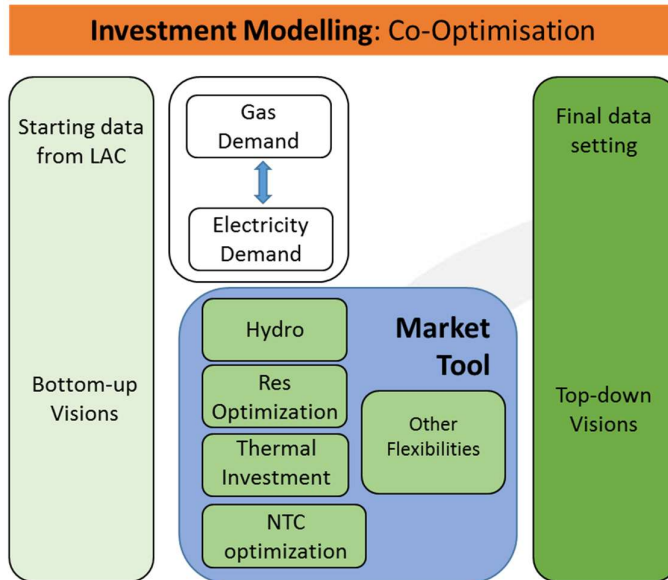
FIGURE 16: INVESTMENT MODEL

5.2.1 Top-down electricity demand construction

The following section describes the steps necessary to convert the outputs from the Ambition Tool into a data format that can be used as input for the investment tool used by the scenario building models. The steps are described in the process diagram in the Figure 17.
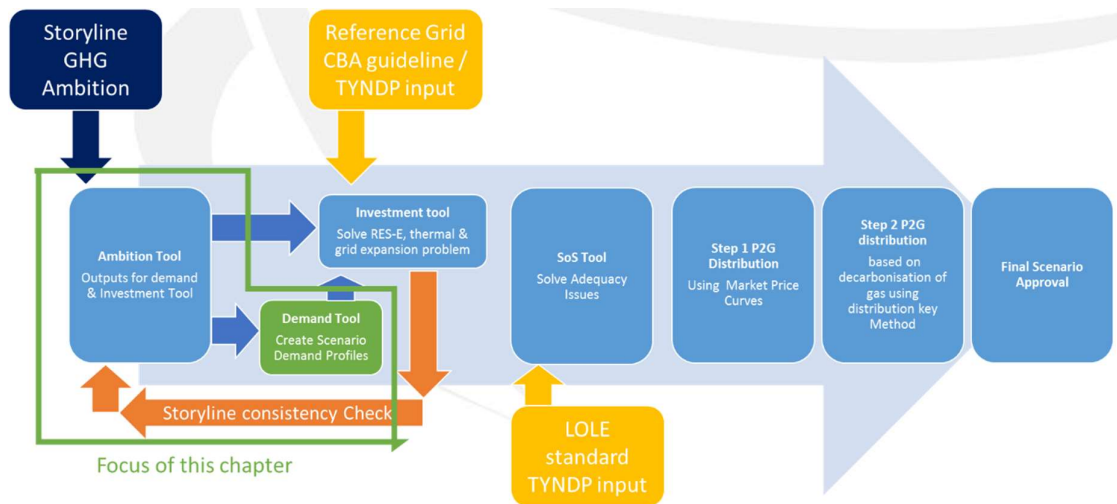
FIGURE 17: SCENARIO BUILDING PROCESS DIAGRAM

In the electricity demand file building process, interactions between various teams are required in order to enable an efficient delivery of the final hourly demand profiles. Figure 18 provides a comprehensive description of roles and responsibilities to enable the demand file building process.
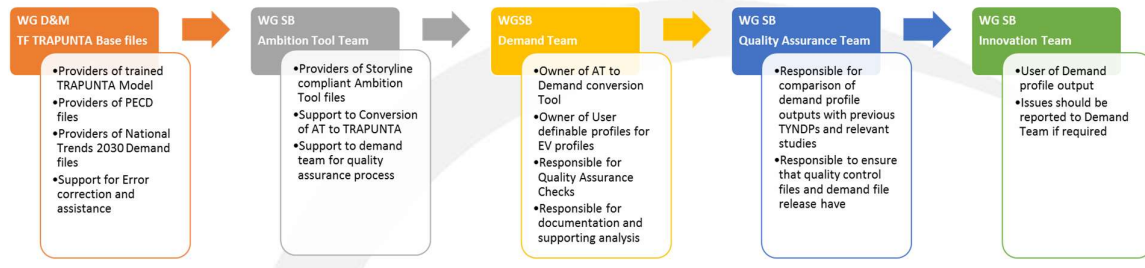
FIGURE 18: ELECTRICITY DEMAND FILE BUILDING PROCESS - TEAM INTERACTIONS

- The Working Group Data & Models provides key input data to the process in the form of trained normalized demand models along with the necessary PECD.
- The Ambition Tool team provides Excel-based individual market zone Ambition Tool files required to construct the demand input sheet (PEMMDB "demand sheet"). This is then to be read by the TRAPUNTA tool.
- The Demand Team is in charge to develop the simulations with TRAPUNTA in order to create the profiles for each market nodes, each time horizons and each scenario.
- Quality Assurance team is in charge to check if results are consistent and, if necessary, to calibrate the outputs.
- The Innovation Team is the final user of the demand profiles

5.2.1.1 Ambition Tool to TRAPUNTA Conversion tool

In order to transform annual level electricity demand projected with the Ambition Tool into TRAPUNTA software used to create hourly-level electricity demand profiles, a specific conversion process was applied. Space heating and cooling-related demand was transferred per technology, i.e. splitting air-source heat pumps, ground-source heat pumps, direct electric heating and electrified district heating.

Generic assumptions were taken for categories that were required by TRAPUNTA but not considered by the Ambition Tool (namely heat pump split between sanitary water and other heat sources). This enabled the hourly load profiles of these technologies to be influenced by the ambient temperature assumption for the climate years used in the TRAPUNTA tool. Non-heating related demand was quantified as a sum of industrial demand evolution (including electrified heating for industrial processes) as well as lighting, power, cooking and catering demand from residential and tertiary sectors. This demand was assumed by the non-temperature dependent demand profiles in TRAPUNTA.

Transport demand was broken down to several transport segments, namely private vehicles, passenger rail, bus transport, rail freight transport and other freight transport, which were assigned type-specific transport demand profiles.

In case generic assumptions made in Ambition Tool, Conversion Tool and/or TRAPUNTA resulted in TRAPUNTA projection differing in annual level from the original Ambition Tool projection, the hourly profiles were afterwards adjusted evenly to match the annual values from the Ambition Tool.

5.2.2 TRAPUNTA

In the following are presented the steps necessary to use TRAPUNTA and to define the hourly Electricity demand profiles for each market area, each scenario and each target year.

FIGURE 19: ELECTRICITY DEMAND FILE BUILDING STEPS

The use of TRAPUNTA involves three main steps that are accomplished by the three main functions of the tool (Figure 20).

STEP 1: The creation of the forecast model *(this was provided by WG D&M)*
This is the first step of the methodology for the electric load prediction. It consists of creating a regression model able to explain the correlations between the electrical load and the climatic variables present in the PECD info (population weighted temperature, city temperature, irradiance, wind speed, humidity etc.). The model is based on a training set of information, i.e., the electrical load and climatic variables time series. Since the regression is created based on this data, it should be representative of the market situation the user wants to simulate.

STEP 2: The creation of a normalized year *(this was provided by WG D&M)*
This function allows the user to create a normalized year for the different climatic variables. It could be used as input during the prediction of the electrical load. The normalized year is the mean value of the time series for a given climatic variable.

STEP 2: The computation of the scenario year (Process step for WGSB Demand Team)
The computation of the electrical load with the application of the forecast model to a future (or the normalized) year and the load adjustment for market evolution

This function is the final aim of TRAPUNTA, and the step used by WGSB to build the demand projections for each scenario and climate year. Starting from the information on the climatic variables (as normalized year or generic data) and the forecast model developed at the first step, the tool will provide the user with a prediction of the electrical load for future years characterized by the climatic variables given as input.
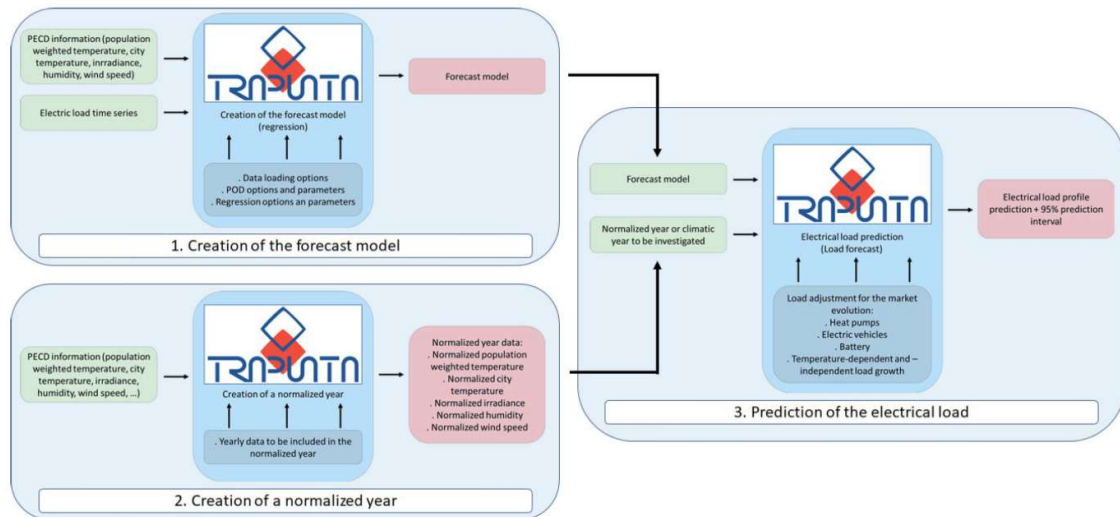
FIGURE 20: THREE PROCESS STEPS IN TRAPUNTA

The last version of the software (TRAPUNTA L) is able to run a single simulation (with detailed information useful to investigate the effectiveness of the created model) or "a loop" of simulations simultaneously including all the climate years for all of the market zones, all scenarios and all target years.

5.2.3   Different EV patterns

In TRAPUNTA the additional load for electric vehicles is considered based on the following inputs:

- **Additional EVs:** the number of additional electric vehicles with respect to the training period
- **Consumption**: the average consumption of a specified electric vehicle, expressed in kWh/100km
- **Effective usage**: the average use of a specified vehicle type, divided into weekdays and weekends (each one with a chosen charge profile), expressed in km per day
- **Daily distribution** of the aforementioned effective usage divided into weekdays and weekends

TRAPUNTA allows creation of additional load, which includes four types of electric vehicles. During analytical work, the following types have been developed (see Sections 5.2.3.1, 5.2.3.2, 5.2.3.3, 5.2.3.4):

I. **Type A** – Electric private cars
II. **Type B** - Buses
III. **Type C** – Passenger trains
IV. **Type D** – Heavy goods vehicles

Additionally, rail heavy goods and aviation have been calculated and added to the rest of the load profile with an even repartition of daily value within the day.

The number of EVs is one of the Ambition Tool results for top-down scenario for every market node.

5.2.3.1 *Electric private cars*

Since TRAPUNTA differentiates load profiles with working days and weekends or seasonal changes using electricity consumption and effective usage values as input data, the daily load pattern should be as universal as possible. The current load pattern was created taking daily activity of potential users into account.
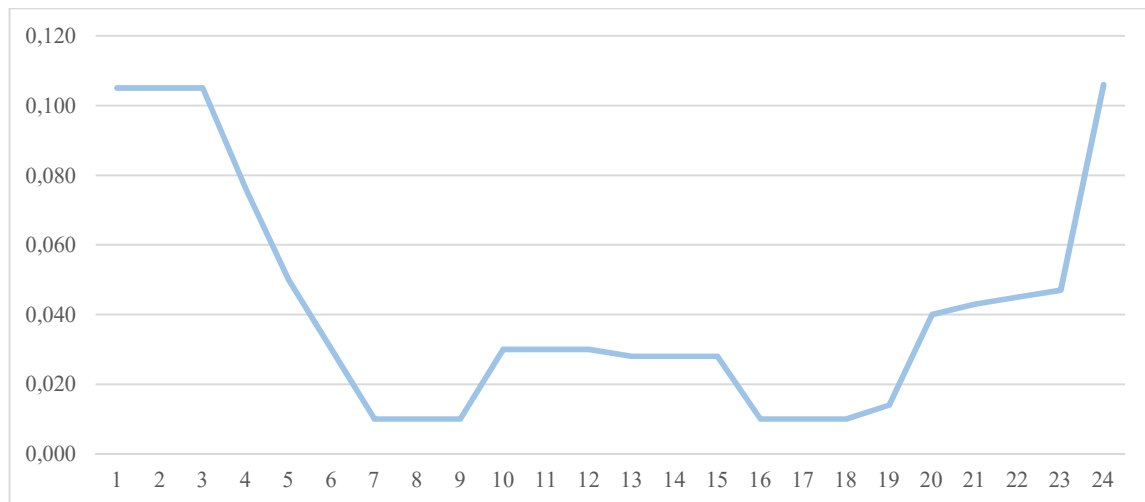
FIGURE 21: PRIVATE CARS LOAD PATTERN

5.2.3.2 Buses

The daily load profile was created based on the assumption that most of buses uses slow night charging. Fast chargers at bus depots are also available for around 30-35 % of the fleet. This profile reflects mainly public transport in cities.
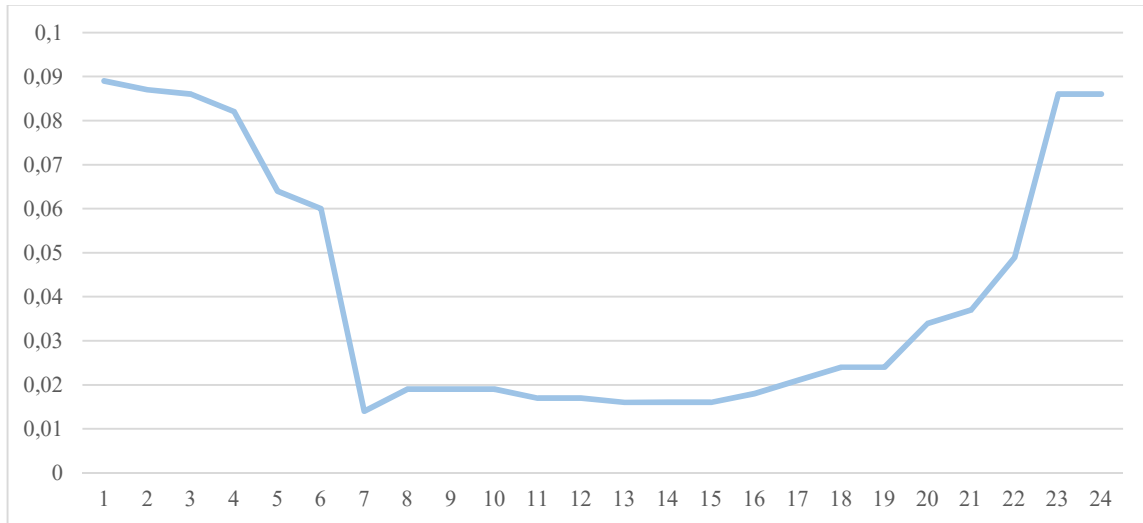
FIGURE 22: BUSES LOAD PATTERN

5.2.3.3 Passenger trains

The daily load profile is based on live data about the number of passenger trains operating 24 hours a day. According to live data, in simplified form, the railway line loading looks as follows.
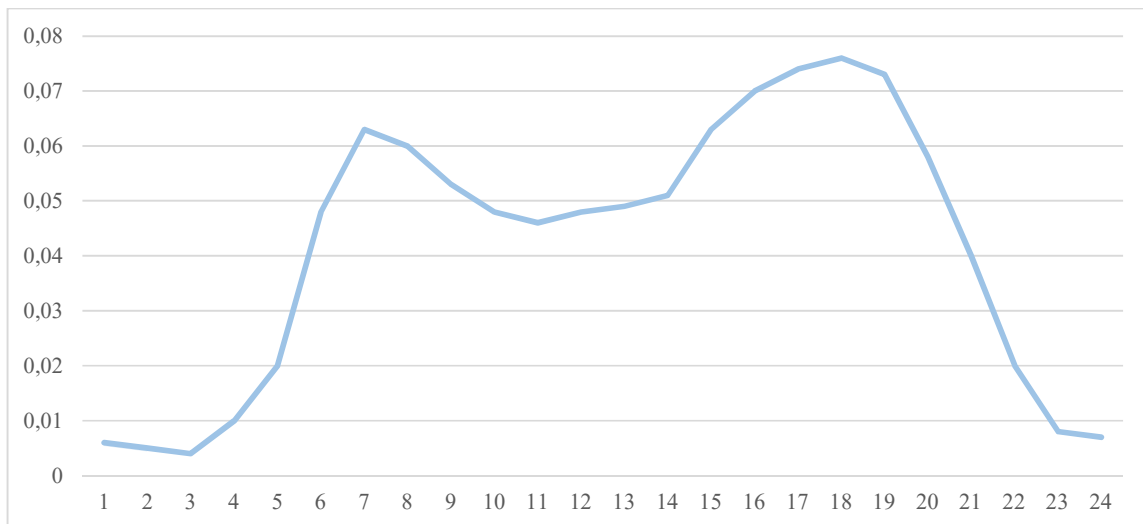
FIGURE 23: PASSENGER TRAINS LOAD PATTERN

5.2.3.4 Heavy goods vehicles

The daily load profile is focused on the fleet of a small trucks and was based on the assumption that trucks will be charged mostly at night. Nevertheless, the same assumption for Transport International Routier vehicles can be applied.
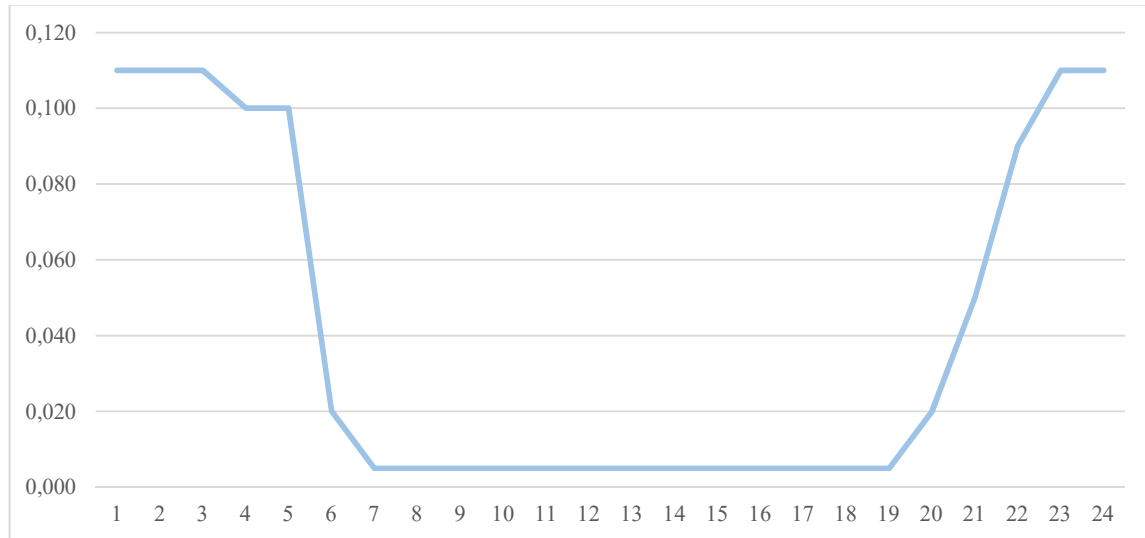
FIGURE 24: HEAVY GOODS CHARGING PROFILE

5.2.4 HP assumptions

TRAPUNTA models the scenario-dependent heat pump profiles on the basis of the temperature-dependent load analysing the historical load time series. For Germany, this approach leads to incorrect heat pump profiles, since the temperature-dependent load identified in the historical load time series is almost exclusively characterized by night storage heaters.

This issue is derived from the way TRAPUNTA calculates the heat pumps adjustments:

1. TRAPUNTA calculates a percentage of temperature-dependent load evolution.
   - Example 1: Replacement of 50 % of the existing electric heat with heat pumps with a COP of 2.2. For an equivalent thermal load, only 72% (50% of resistive electric heating not replaced by HP + 50 %/2.2 resistive electric heating replaced by HP) of the electricity that would have used without these replacements could be used.

   - Example 2: Replacement of 50 % of the existing electric heat with heat pumps with a coefficient of performance of 2.2 plus new electric HP replacing non-electric heating. The thermal load of the new HP not replacing electric heating is equal to half of the initial existing electric heating. For calculating an equivalent load the percentage will be 94 % (50 % of resistive electric heating not replaced by HP + 50 %/2.2 of resistive electric heating replaced by HP + 50 %/2.2 of HP not replacing electric heating).
2. TRAPUNTA multiplies on an hourly basis the temperature-dependent load by this percentage.

For Germany, most of the existing electric heating is not pure resistive heating but night storage heating. Replacing this kind of heating with heat pumps will change the shape of the profiles significantly as the electric load will not be concentrated in the night anymore. Therefore, it is not appropriate to multiply the current temperature-dependent load (which is high during the nights and low during the day) by this percentage on an hourly basis.

This is why some special post-treatments on Excel were made in order to redistribute the new HP load over a new daily profile for every day. This method did not change the total energy consumption, only the shape of the heat pump load profiles.

5.2.5 Demand Quality checks

At the end of the process some steps are necessary to verify the quality of the profiles as shown in the Figure 25. The quality control is a critical step order to identify mistakes and check if the assumptions made in the previous processes are consistent or not.

A quality check process is required to identify differences between Ambition Tool projected demand and the demand profiles created by TRAPUNTA. If a difference is identified then calibration of the demand profile is required to ensure that the forecasted electricity energy was met at a market zone and EU-28 level.

Some demand profiles are created in a different manor using TSOs own tools, or by TRAPUNTA but in the TSOs. In some nodes such as in LU the demand does not change due to node specific reasons.
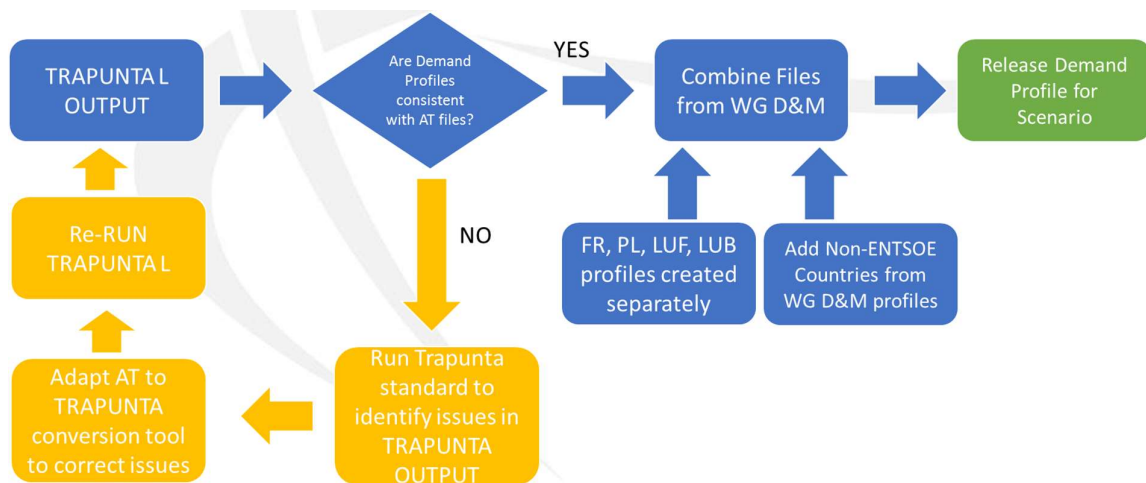
FIGURE 25: QUALITY ASSURANCE CHECKS

5.3 Gas Demand

This section provides the methodology and processes used to collect and calculate the total gas demand for the scenarios to be used for TYNDP 2020. Total gas demand is made up of final gas demand (defined as residential, tertiary, industrial (including non-energy use) and transport sectors) and gas demand for power generation.

Gas demand for power generation is the result of the ENTSO-E modelling process, with a conversion from the electricity generation into gas demand.

For this TYNDP process there is a different approach for short-term demand (2020, 2025) and long-term demand (2030, 2040) that will be explained in the following section.

5.3.1 Seasonal and high case demand situations

Gas demand in Europe shows a strong seasonal pattern, with higher demand in winter than in summer. These variations are largely driven by temperature-related heat demand in the residential and tertiary sectors. In the long-term, considering some level of electrification in the heating sector, also an increasing seasonality in the gas demand for power generation is assumable. This is due the role of gas-fired power plants being the back-up for variable renewables in a "kalte Dunkelflaute" (German for "cold dark doldrums" describing a 2 week cold spell with very low variable renewable electricity generation).

In addition, the day of highest consumption in the year is a key input that represents one of the most stressful situations to be covered by the gas infrastructure (including transmission, distribution and storage).

As a result of these situations, seasonal variation and high case demand data is contemplated. In the following table the different cases are represented:

TABLE 3: SEASONAL AND HIGH CASE VARIATIONS

	Final Injection Period Demand
Average Summer (AS)	Power Injection Period Demand
Average Winter (AW)	Final Withdrawal Period Demand
	Power Withdrawal Period Demand
Design Case (DC)	Final Peak Demand
	Power Peak Demand
2 Week Cold Spell (2W)	Final 2W Demand
	Power 2W Demand
Dunkelflaute (DF)	Final 2W Demand
	Power Demand Dunkelflaute

5.3.1.1 Seasonal variation

Seasonal variation is divided into two periods: storage injection period and withdrawal period. These periods correspond to the average summer and average winter Demand respectively.

The storage injection period covers seven months (April-October), while the storage withdrawal period covers five months (January, February, March, November, December).

Seasonal Demand Factor (SDF)

The Seasonal Demand Factor (SDF) is a parameter to calculate average winter and average summer demand as part of the total annual demand for the TYNDP Simulations.

SDF represents a yearly factor to derive the final demand for the 7-month storage injection period from the yearly demand.

Storage injection period average demand = "SDF" * Yearly average demand

These values were given by TSOs in the data collection questionnaire and used both for bottom-up and top-down scenarios.

5.3.1.2 High case demand

5.3.1.2.1 Design Case (DC)

The Design Case (DC) is the maximum level of gas demand used for the design of the network to capture maximum transported energy and ensure consistency with national regulatory frameworks. The peak day takes place based on the modelled situation from the over-the-whole-year simulation and is modelled on 31 January (after day 91 of storage withdrawal period).

Depending on the type of scenario the methodology varies:

- Bottom-up scenarios: Final demand values are collected from TSOs in the Data Collection Questionnaire. Gas demand for power generation is calculated from the results of ENTSO-E modelling process, as it is explained in Section 5.3.3.

- Top-down scenarios: Final demand values are calculated following the *Gas Peak Demand Methodology,* explained in Section 5.3.2.3. Gas demand for power generation is calculated from the results of ENTSO-E modelling process, as it is explained in Section 5.3.3.

5.3.1.2.2 2 Week demand (2W)

Maximum aggregation of gas demand reached over 14 consecutive days once every 20 years in each country to capture the influence of a cold spell on supply and especially on storage. The 14 days high demand period takes place based on the modelled situation from the over-the-whole-year simulation and is modelled starting on 15 February (after day 106 of storage withdrawal period).

Depending on the type of scenario, the methodology varies:

- Bottom-up scenarios: Final demand values are collected from TSOs in the Data Collection Questionnaire. Gas demand for power generation is calculated from the results of ENTSO-E modelling process, as it is explained in Section 5.3.3.

- Top-down scenarios: Final demand values are calculated based on the *Gas Peak Demand Methodology,* explained in Section 5.3.2.3. Gas demand for power generation is calculated from the results of ENTSO-E modelling process, as it is explained in Section 5.3.3.

5.3.1.2.3 Kalte Dunkelflaute (DF)

The so-called "Kalte Dunkelflaute" (German for "cold dark doldrum") describes an extended period of time with very low outside temperature as well as low production of wind and solar energy. This weather phenomenon is frequently seen, e.g. in Germany from 16 to 26 January 2017, with up to 90 % of the generation coming from conventional power plants at peak demand.

With higher electrification of final demand sectors, especially the residential and tertiary sector, and high penetration of renewables in the power market, the "Kalte Dunkelflaute" becomes a new security of supply case for a hybrid energy system.

Final demand values are the same as for the 2 Week demand as explained in above section, and further explained in following sections. Gas demand for power generation is calculated from the results of ENTSO-E modelling process, as it is explained in Section 5.3.3.

5.3.2 Final gas demand

5.3.2.1 Short-term demand (bottom-up data)

Short-term demand is the data for the years 2020 and 2025. For these years only one scenario is considered, Best Estimate, based on the best-knowledge of ENTSOG's members.

A sensitivity analysis regarding the merit order of coal and gas in the Emissions Trading System Sector is included for 2025 following stakeholder input regarding the uncertainties on prices for the short-term.

The Best Estimate scenario is a bottom-up scenario. Demand data is submitted from TSOs in accordance with the National Trends storyline, parameters and prices, using national expertise to provide country-level specifics. A data collection questionnaire is provided, which covers all bottom-up scenarios as well as any gas demand as a result of newly gasified areas enabled by future projects where applicable, which is classified as gasification demand.

Where no data was provided by a country, data from Best Estimate from TYNDP 2018 was used for TYNDP 2020 (Cyprus and Sweden).

TABLE 4: ENTSOG SHORT-TERM SCENARIO TYPES

Years	Scenario name	Type	Demand derived from
2020	Best Estimate (BE)	Bottom-up	TSO Data Collection
2025	Best Estimate, coal before gas (CBG)	Bottom-up	TSO Data Collection
2025	Best Estimate, gas before coal (GBC)	Bottom-up	TSO Data Collection

5.3.2.2 Long-term demand

Long-term demand is the data for the years beyond 2030. For these years three scenarios are considered: National Trends, Global Ambition and Distributed Energy.

TABLE 5: ENTSOG LONG-TERM SCENARIO TYPES

Years	Scenario name	Type	Demand derived from
2030-2040	National Trends (NT)	Bottom-up	TSO Data Collection
2030-2040	Global Ambition (GA)	Top-down	Ambition Tool
2030-2040	Distributed Energy (DE)	Top-down	Ambition Tool

Whereas National Trends relies on bottom-up collected data, for Distributed Energy and Global Ambition, ENTSOs' computed the final demand figures with top-down methodologies.

5.3.2.2.1 Bottom-up data

Demand data is submitted from TSOs in accordance with the National Trends storyline, parameters and prices, using national expertise to provide country-level specifics. A data collection questionnaire is provided, which covers all bottom-up scenarios as well as any gas demand as a result of newly gasified areas enabled by future projects where applicable, which is classified as gasification demand.

Values are provided for all years up to 2040 for the yearly average volume, seasonal variation, upper and lower trajectories as well as high demand cases for the peak day (Design Case) and the 2-week high demand case.

5.3.2.2.2 Top-down data

Annual demand data is calculated using the Ambition Tool. The Ambition Tool calculates country-level demand (gas and electricity) based on historical data and using different end-user technology shares for each country. Each country specific input was obtained using an EU-28 default approach, adjusted by the trends of each country and then reviewed by TSOs, both electric and gas.

The EU-28 default approach is a sectoral approach based on the storylines for Global Ambition and Distributed Energy, considering fuel and technology switch, energy efficiencies and decarbonization.

5.3.2.3 Gas peak final demand methodology for top-down scenarios

In order to calculate the gas high case demand for top-down scenarios a new methodology is used.

The methodology has two approaches depending on the data collected from TSOs. TSOs were asked to provide Full Load Hours (FLH) per sector. FLH is the number of hours a year that a sector works at its maximum performance. TSOs were also asked to provide reference temperatures for different cases (Average Year, Design Case and 2 Week Case) for each country.

The two approaches to calculate the gas high case demand figures are:

A) **Using bottom-up data as reference**
   This approach is used for countries that could not provide reference case temperatures or when TSOs have chosen this option.
   For the calculation of the final high case demand in the residential and tertiary sectors for top-down scenarios the same relation between final high case demand and final average demand from bottom-up scenarios is used.
   For non-temperature-related sectors (industrial and transport) the high case demand was calculated based on the average demand and the FLH per sector.

B) Linear temperature interpolation

This approach is used for countries that provided case temperatures or when TSOs have chosen this option.

This approach consists of calculating the demand for 2 Week Case by linear interpolation from the Design Case and the Average Year demand values and the different case temperatures per country. Design Case demand is based on average demand and FLH per sector. Figure 26 illustrates the temperature-demand-relation in the gas sector and how it is applied to calculate the different daily case figures for the gas demand.
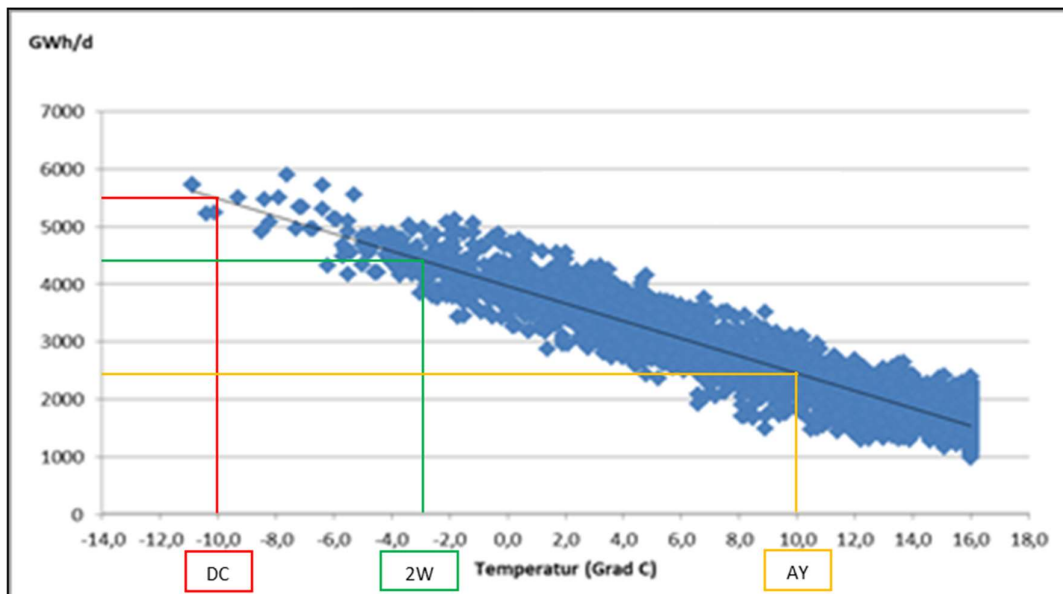
FIGURE 26: TEMPERATURE VS DEMAND INTERPOLATION

For tertiary and residential peak demand, the behaviour of hybrid heat pumps need to be considered. Hybrid heat pumps are used for space heating and sanitary water. ENTSOs' made the assumption that hybrid heat pumps start running when the outside temperature is below 16 °C, consuming electricity to heat up a building. When the outside temperature reaches around 5 °C, the consumption switches to gas. The major part of sanitary water heating is gas consumption.

Therefore, gas peak demand from hybrid heat pumps was calculated according to the average temperature profiles of each country, considering the number of hours of a year with outside temperatures below 16 °C and below 5 °C.

5.3.3 Gas demand for power generation

5.3.3.1 Methodology

Gas demand for power generation is based on the results of the electricity market simulation. The only exception is for 2020, where ENTSO-E has not run a market simulation and ENTSOG relies on bottom-up collected best estimates from its TSOs. During the data collection phase, gas and electricity TSOs worked together to discuss gas installed capacity on a country-level basis.

For the 'Design Case' and the '2-Week-case', the highest gas generation during the period of one day and 14 days, respectively, coming from electricity simulation results for the climate year 1984 and using a single model that was available across all scenarios was calculated.

For Kalte Dunkelflaute, following assumptions are made:

- First a base demand for power generation is considered, which is equal to the gas demand for power generation in aforementioned 2-Week-case

- Second, an additional gas demand for power generation during a Kalte Dunkelflaute is calculated:
    1. Regular Generation: As the Kalte Dunkelflaute occurs during the same period of time as the 2 Week case (cold spell), the generation by wind and solar was calculated during that period.
    2. Minimum Generation: For the calculation of the guaranteed electricity generation from wind and solar during a Kalte Dunkelflaute, the lowest generation from wind and solar during a two-week period in the annual scenario results was considered (market node specific).
    3. To calculate the additional gas demand for power generation during a Kalte Dunkeflaute, the difference between Regular and Minimum Generation from wind and solar was divided by an efficiency of 0.5 (to account for efficiency of a gas power plant).
    4. If the gas demand for power generation for the Kalte Dunkelflaute case is higher than for the Design Case, the value for Design Case is used (to avoid any overestimation and to consider installed capacities for gas-fired power plants).
- The sum of additional demand during Kalte Dunkelflaute and the gas demand in a 2-Week-case gives the gas demand for power generation during a Kalte Dunkelflaute.

5.3.3.2 Gas share of Other Non-RES (ONR)

Other Non-RES (ONR) are non-market-based generation, mainly small scale generators such as part of combined heat and power (e.g. in district heating). The gas share in ONR are based on bottom-up data submitted by ENTSO-E members and, therefore, reflected in the electricity market modelling.

5.3.3.3 Electricity generation to gas consumption

In order to convert the data outputs from the ENTSO-E modelling results, which are in the form of net generation, to the data format used in the ENTSOG model, several factors need to be applied.

5.3.3.3.1 Conversion factor for net to gross generation

Taking into account plant own use of energy, the losses are likely to have been effectively reduced to improve profitability, some energy efficiency improvement is assumed over time.

TABLE 6: CONVERSION FACTOR FOR NET TO GROSS GENERATION

Factor	2020-2025	2030	2040
Net to Gross Generation	3.0 %	2.5 %	2. 0%

5.3.3.3.2 Efficiency of power plants

This has been determined by the ENTSO-E dataset detailing standard efficiency per power plant classification.

TABLE 7: EFFICIENCY OF GAS POWER PLANT TYPES

Fuel Type	Standard efficiency in NCV terms (%)
gas_conventional old 1	36 %
gas_conventional old 2	41 %
gas_ccgt old 1	40 %
gas_ccgt old 2	48 %
gas_ccgt new	60 %
gas_ccgt ccs	51 %
gas_ocgt old	35 %
gas_ocgt new	42 %
gas_ccgt present 1	56 %
gas_ccgt present 2	58 %

For ONR an average annual efficiency of 46,5% (35% - 58%) was used. For daily figures an efficiency of 33% was used.

5.3.3.3.3 Net Calorific Value (NCV) to Gross Calorific Value (GCV)

Power plant efficiency is calculated on NCV, in order to bring gas demand for power generation in line with other data collected for the scenarios, this needs to be represented in GCV.

TABLE 8: NCV TO GCV CONVERSION FACTOR

Factor	2020-2025	2030	2040
NCV to GCV	110 %	110 %	110 %

5.3.3.3.4 Country and zonal demand

Due to differences in balancing zones for electricity and gas, some data has been grouped and split accordingly.

TABLE 9: GROUPING ENTSO-E & ENTSOG BALANCING ZONES

ENTSO-E ZONES	Grouping
DE00	DE
DKE1 DKKF DKW1	DK
FR00 FR15	FR
GR00 GR03	GR
ITCN ITCS ITN1 ITS1 ITSA ITSI	IT
LUG1 LUV1	LU
SE01 SE02 SE03 SE04	SE

5.3.3.3.5 Quality check and comparison

Gas for power generation for National Trends was bottom-up collected from gas TSOs as well. This data was used as a comparison of results from the ENTSO-E market modelling processes. It is also important in terms of the high demand situations against which the gas infrastructure is tested. Peak and 2-Week high demand cases are part of the ENTSOG TYNDP assessment, usually representing 1-in-20 or national design case situations driven by regulation. ENTSO-E models have been run against three climatic years that may not provide the demand levels required (e.g. peak gas demand for power generation might not be fully considered in the climatic years used). To avoid this, an average of bottom-up collected data from gas TSOs and top-down modelled data with ENTSO-E market models was taken for the gas demand for power generation, in case the top-down calculated gas demand was lower than the bottom-up collected data.

Power Sector Modelling Methodologies

6   Allocation of Power Sector Capacities

A key component of developing scenarios converting storylines into placement of installed capacities for generation. As one of the main process enhancements for the TYNDP2020 scenario building process a power market investment modelling approach has been adopted. The purpose of this section is to describe the processes and assumptions used to build the 2030 and 2040 power market models suitable for long-term investment models. Please note that the 2050 horizon was not subject to a detailed quantification phase.

Error! Reference source not found. provides a high level comparison of the bottom-up and top-down scenarios approaches. The bottom-up process is based on data collected by TSOs, whereas the top-down scenarios use bottom-up data along with power system market tools to optimize the total cost of the system based on CAPEX and OPEX for generation technologies.

As displayed on the left hand side of figure 27, **bottom-up scenarios** are built with a single block by using the predefined data collected in line with bottom-up scenario Data Collection Guideline (see chapter 3).

Top-down scenarios however as seen on the right hand side require three main building blocks:
1. **Bottom-up data block**
   Start with a bottom-up data collection year, for example 2025
2. **Trajectory block**
   Shape the investment model inputs based the trajectory file inputs
3. **Investment block**
   Run the power market model with investment options switched on

Optimization

Trajectories & Boundary Conditions

National Trends
Bottom-Up 2030 Data

Bottom-Up
2025 Data

Bottom-Up Scenario Approach   Top-Down Scenario Approach
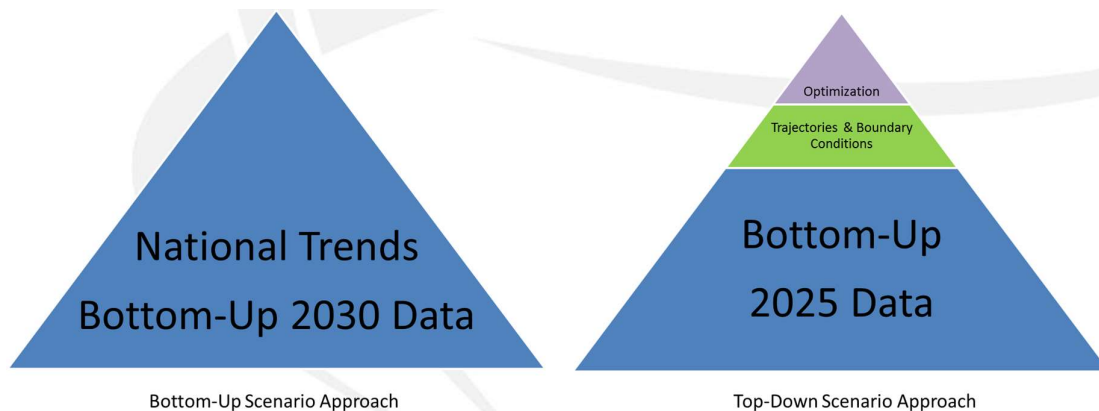
FIGURE 27: COMPARISON OF TOP-DOWN AND BOTTOM UP SCENARIOS

A fundamental feature of TYNDP power market scenarios is that they should closely reflect country specific details. TYNDP2020 has introduced an interim step in the distribution of generation by collecting generation and demand trajectory files for each country. This process was implemented in order to set country specific boundary conditions for the models. The trajectory files provide low, medium and high trajectories for power sector supply and demand technologies until the year 2050. The trajectory collection process requires the TSO to justify the projections, by referencing national scenarios or relevant national studies that inform the trajectories. In general, the trajectories are mapped to the scenario storylines, to enable scenario consistency and respect national projections for generation roll out and demand.

6.1 Top-Down Scenario Investment Modelling Assumptions

As already described briefly at the beginning of this chapter the placement of new generation capacity evolution is based on a method that combines trajectory based capacity allocation on a market by market basis and European wide power system investment modelling subject to constraints shaped by trajectory and technical boundary constraints.

Investment models are used to quantify the scenarios in detail. They offer interesting perspectives in terms of process, enabling greater automation and improvement in the quality of the optimization. They are used as a substitute to ENTSO-E's former process in previous TYNDPs, which consisted of a series of simulation iterations in market models to optimize RES[5] and thermal generation capacity.

The top-down electricity modelling process combines investment modelling with bottom-up data collection from TSOs for National Trends. A further TSO data collection of trajectories resulted in a broader availability of national scenario data, which in turn helped to account for national potential and dynamics for various demand and supply technologies. The optimization can be represented by the pyramid diagram illustrated in Figure 28**Error! Reference source not found.**.

For TYNDP 2020 the top-down scenario building loop is constructed as follows:

- **Bottom-up data block**
  The foundation for the scenario is TSO validated modelling input from the National Trends 2025 scenario.

- **Trajectory block**
  Trajectory data is used to develop boundary conditions for the investment models. The trajectory files show low, medium and high growth rates for various technologies, such as nuclear, coal (typically phase-out related), wind and solar. Minimum build out rates are developed based on these trajectories, so that current technology trends are continued, where applicable.

- **Investment block**
  This step builds on a strong foundation of bottom-up data and trajectory guidelines that ensure optimization of the pan-European system is within reasonable boundary conditions. The method ensures power sector progression at member state level, based on minimum values and credible optimized build out rate based on national data used to shape the upper boundaries.

  The optimization step allows a pan-European investment optimization for thermal, renewable and electricity grid. The objective function is used to minimize total system cost including CAPEX and OPEX, subject to a maximum annual level of carbon emissions as one of the key boundary conditions.

(Note: it was not always possible to gain trajectory information for all market areas. Trajectories are a significant improvement to the process, it is hoped that the next process will build upon the improvements.)

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[5] Solar PV, Wind onshore, Wind offshore.
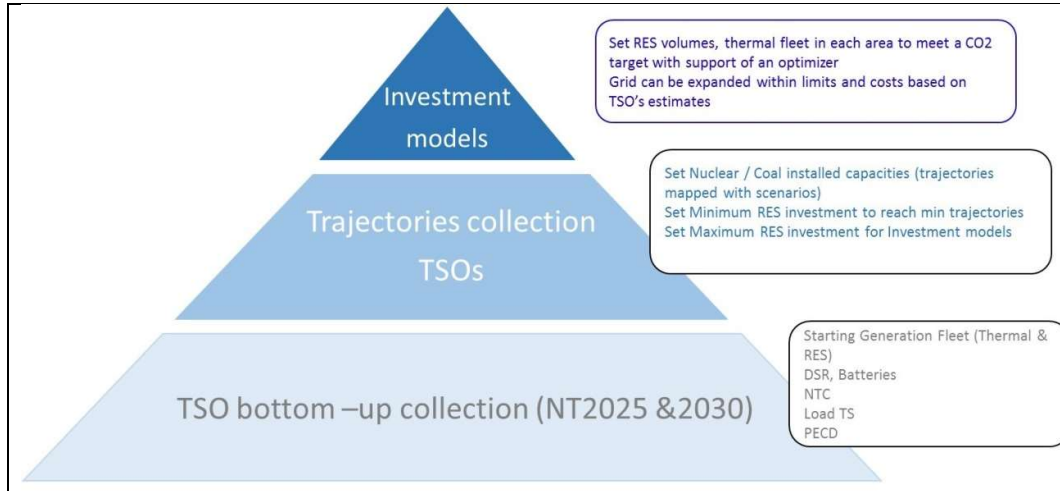
FIGURE 28: TOP-DOWN MODELLING PYRAMID DIAGRAM

6.2   Power Sector Investment Block Overview

The Investment block can be divided into three sub-steps:

- **Demand tool step**
  Calibration of the electrical load curves by market area for each horizon in accordance with the energy demand targets of the Ambition Tool (see 4 Ambition Tool Methodologies and Calculations). In order to account for the thirty-five historical climate years of the Pan European Climate Data Base (PECD) thirty-five load curves are computed. (*For further information refer to Section 5*)

- **Investment tool step**
  Development of installed capacities for the generation fleet. Includes:
  - Ex-ante calibration of the thermal generation fleet
  - Joint allocation/optimization of variable renewable energy sources, CCS gas-fired plants (only in 2040) and NTC based interconnection capacities

The results obtained in the investment tool step are compared with the qualitative objectives expected from the storyline matrix and thus ensure the expected overall scenario consistency.

- **SoS tool step**
  In order to finalize the scenario, an in-depth adequacy study is run to ensure the top-down scenarios built are adequate in relation to different probable boundary conditions depending on different climatic conditions.

  The SoS tool step needs to be performed separately to keep the computation time of the Investment tool step in reasonable boundaries. Essentially, the SoS process step requires the analysis of a broader climate year and outage/maintenance base than the previous step, for which a limited number of climatic years (load, RES generation) combined with unavailability (thermal units outage and maintenance) patterns is sufficient. A more detailed description of the SoS process step can be found in Section 06.2.6.

The schematic diagram of the detailed quantification phase is provided in the Figure 29 below.
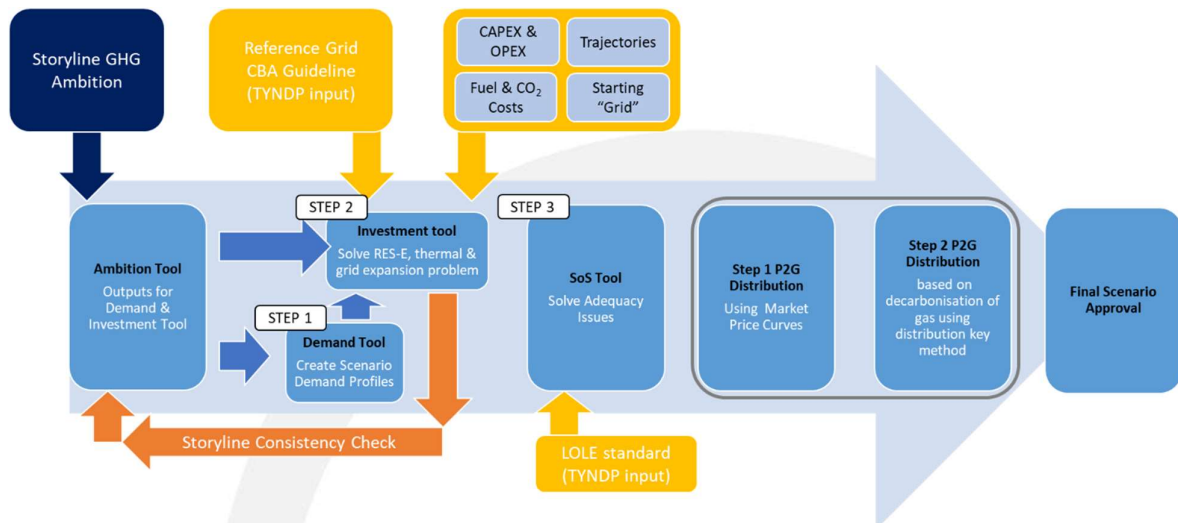
FIGURE 29: OVERVIEW OF POWER SECTOR QUANTIFICATION PROCESS

6.2.1 Investment models

Investment models make it possible to optimize (in this case minimize system cost) on an interconnected system not only the operating costs[6] of a given system (OPEX: mainly fuel costs) but also the investment costs (CAPEX) in new means of generation and storage for example, but also new interconnections. These models can therefore choose to invest in new assets providing that their profitability is acquired (positive NPV).

In order to increase consistency, two models, offering this feature among the tools used available at ENTSO-E[7], were used. A thorough alignment process was carried out to test the functionalities of the investment models and ensure consistency in generation dispatches, interregional flows, and short run marginal cost pricing output. Figure 30 shows the alignment of the expansion model used in PLEXOS and ANTARES, the models reach an R^2 of 0.99. This is the basis for how the investment modeling was then set up for the scenario building. To build the final scenarios PLEXOS was used.

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[6] Traditional market simulator
[7] PLEXOS (LT plan) and ANTARES (Xpansion)

Investment Module Comparison: Plexos vs Antares

Unit ● Solar ● Wind Offshore ● Wind Onshore

FIGURE 30: RESULTS OF ALIGNMENT BETWEEN ANTARES AND PLEXOS

6.2.2 What is the scope for optimization with the top-down scenarios?

Figure 29**Error! Reference source not found.** clearly shows that the optimization phase is one element of an overall process. Secondly within the model there are some options that are not viable for investment, such as nuclear in regions that have policies against development, or coal power plants given the application of coal phase out policies.

Table 10 provides an overview of the investment candidates by time horizon and scenario. For the purposes of the TYNDP2020 scenarios there are limited in number of investment options available. These are the renewable energies such as PV, wind onshore, wind offshore and gas power plants. In addition, it should be noted that the interconnection capacity can be expanded within the scenario building process (*please see Section 0 for further information*).

It should be pointed out that coal, lignite and nuclear power plants are not optimized for investment. The installed capacities of the coal, lignite and nuclear power plants are guided by the trajectory files and the storyline matrix table to ensure scenario consistency.

Investment Candidate	DE2030	DE2040	GA2030	GA2040	NT2030	NT2040
Coal	No	No	No	No	No	No
Nuclear	No	No	No	No	No	No
CCGT	No	No	No	No	No	No
CCGT CCS	No	Yes	No	Yes	No	No
Hydro	No	No	No	No	No	No
Wind Onshore	Yes	Yes	Yes	Yes	No	Yes
Wind Offshore	Yes	Yes	Yes	Yes	No	Yes
Solar PV	Yes	Yes	Yes	Yes	No	Yes
Solar CSP	No	No	No	No	No	No
Batteries	Yes	Yes	Yes	Yes	No	Yes
P2G	Yes	Yes	Yes	Yes	No	Yes
Grid Expansion	Yes	Yes	Yes	Yes	No	Yes
Thermal Decommissioning	No	Yes	Yes	Yes	Yes	Yes

TABLE 10 POWER SECTOR INVESTMENT CANDIDATES

Once the electricity demand time series has been determined, and the nuclear, coal and lignite production capacity has been calibrated, the investment model makes it possible to determine the optimal development of the renewable energy capacity and interconnection capacity under given economic conditions such as fuel prices CAPEX and OPEX prices of the new resources.

6.2.3 Investment Options

The following paragraphs detail the rationale of the choices made. For the scenario building process it is necessary to constraint the number and extent of investment. For investment options and costs assumptions the ENTSOs have used options compatible with the EC PRIMES model. (Note: investment options represent an average technology capacity and associated investment cost.)

Carbon Capture and Storage investment assumptions

The CCS process is based on the ability to retrofit a carbon capture plant onto gas plants currently installed in all the countries, therefore the maximum capacity of CCS in any country is limited to how many gas plants are already installed.

Wind onshore, wind offshore and solar PV

Wind onshore, wind offshore and solar PV technologies are key components of the future decarbonized energy mix. The investments are available in 1 MW blocks based on an annualized cost assumption.

The cost assumptions (for more detailed information see Section 6.5) are an important factor in shaping how technologies investment is driven. The technology-specific and country specific Climate Data is another important factor in where the different RES technologies will be located. For example, where offshore wind is not an option due to for example no coast line or a policy measure, the model will naturally not invest in this option, this should be reflected in either the boundary conditions given by TSOs or the climate data.

Household batteries

With the aim of taking new decentralized technology leaps into account, PV and battery investments are optimized through a modification of the hourly climate data for solar. The modification uses the hourly demand profile of one home in Europe. The solar PV climate data of the country is used to access self-sufficiency of a household with rooftop solar.

Household batteries are then added to explore how a home can increase self-sufficiency, by redistributing the load factors through the day to emulate a battery.

Batteries are limited to three hours, in line with current technology and the tool optimizes battery power and storage capacity to minimize cost over an economic life of twenty-five years (net present value approach). The highest self-sufficiency of a home is limited to 80 %.
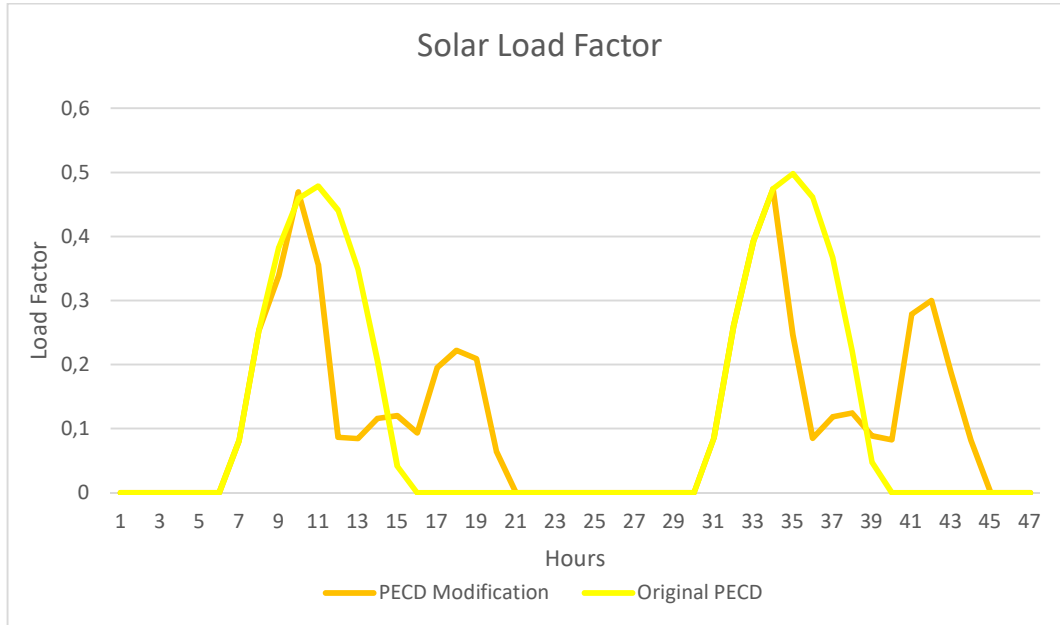
FIGURE 31: SOLAR PV AND BATTERIES PROFILES FOR INVESTMENT MODELLING

Grid expansion

Grid expansion is a necessary component in transitioning towards full decarbonization. By neglecting this option, there is high risk for inefficient RES generation placement and therefore would lead to irrational scenarios due to market effects, such as price collapse and an exaggerated increase of the overall system costs. It is important that the scenario building process does not impede member states pathways to decarbonization, especially those who are electrically isolated from the central European market.

The grid expansion within the scenario building phase uses a linear expansion approach. This provides a signal that cross border congestion is an issue, but since the problem is linearized it does not consider the blocky nature of interconnection projects. The grid expansion problem is simplified, but the intention is to ensure rational generation placement and not network needs identification. The costs for these interconnection project are taken from experience in previous TYNDPs and can vary a lot from border to border, due to factors such as terrain or policy.

CAVEAT:
It should be clearly stated that the expansion of interconnection capacity within the scenario building phase does not signify a particular transmission need or indeed the identification of a project for a future time horizon. The Identification of System Need process within the TYNDP is the correct pathway where European needs are investigated and presented.

The increases in cross border interconnection NTC can be extracted from the investment model, but they are not used within the following TYNDP processes. The NTCs from the investment model should however, be compared to the TYNDP Identification of System Needs (IoSN) processes past and present, as it is important to understand if the optimization is rational and expanding grid within a credible envelope of development shown by expert studies within other processes.

6.2.4 DSR Vehicle to grid

Vehicle to grid is used to simulate the use of electric vehicles as batteries which can be used in the system when prices are high. In the scenarios the EV battery capacity is used as peaking capacity at an activation price of 142 €/MWh. Assumptions are made for the timeframe in which the battery capacities can be activated.

An average battery capacity of 31.2 kWh is assumed based on current technology.

- 10:00 – 16:00

    - 50 % of people can charge at work, should be left with 80 % capacity at 16:00 (10 % of capacity)

    - 10 % of battery capacity (31.2 kWh) is 3.12 kWh

- 19:00 – 00:00

    - 70 % of people participate at home, should be left with 50 % capacity at 00:00 (35 % of capacity)

    - 35 % of battery capacity (31.2 kWh) is 11 kWh

The readiness of infrastructure must also be considered. Some assumptions can be made on the development of infrastructure.

- In 2030 infrastructure can accommodate

    - 25 % of the V2G related battery capacity in Distributed Energy

    - 10 % of the V2G related battery capacity in Global Ambition

- In 2040 infrastructure can accommodate

    - 70 % of the V2G related battery capacity in Distributed Energy

    - 50 % of the V2G related battery capacity in Global Ambition

Finally, if we assume DSR will be active for two hours on average, the final capacities, in 2030 able to contribute per EV are:

- Band 1 = 1.56 kW/EV (3.12 * 2 * 25 %)

- Band 2 = 5.5 kW/EV (11 * 2 * 25 %)

6.2.4.1 Trajectories data collection

As already briefly described in Section 6.1, early in the process ENTSO-E's TSOs were asked to report possible development trajectories (low, medium and high scenarios) or ongoing datasets being studied at national level between 2020 and 2050, with a 5-year granularity, for different components of the electricity system (generation, storage, electricity demand, number of EVs, P2G volume, etc.).

The purpose of this collection is to provide a better framework for the quantification phase for this very large and heterogeneous geographical area.

The components collected cover:
- Most of the generation types (coal, lignite, biomass, nuclear, wind onshore, wind offshore, Solar PV and Solar CSP)
- Load and DSR
- Batteries and P2G capacities

The data collection had a high response rate and the collected data was comprehensive. This gave a good basis to fill in the missing information and complete the dataset, where the data was incomplete (missing horizon or component). A methodology for each parameter was developed to fill in the gaps in the trajectories, as shown in Figure 32 below.

Unit	Methodology
Electro Vehicles	% of Vehicle fleet
DSR (MW)	% Peak Demand
Heat Pumps	Annual Growth Rate from
Hybrid Heat Pumps	Annual Growth Rate from
Nuclear (MW)	Last Available Figure
Hard Coal (MW)	Last Available Figure
Lignite (MW)	Last Available Figure
Total Dispatchable & Non-Dispatchable Biomass (MW)	Last Available Figure
Onshore Wind (MW)	Installed Capacity/Annual Demand
Offshore Wind (MW)	Installed Capacity/Annual Demand
Solar PV (MW)	Installed Capacity/Annual Demand
Solar Thermal (MW)	Installed Capacity/Annual Demand
Batteries (2 hour storage)	Installed Capacity/Annual Demand
P2G (Capacity)	Last Available figure
Efficiency increase %	Average Efficiency

FIGURE 32. METHODOLOGY TO FILL IN THE GAPS WHERE THE TRAJECTORY COLLECTION DATASET WAS NOT COMPLETE.

The trajectories and calculated values from the above methodology was then used for each category in accordance with the scenario storylines. For the investment objects the trajectories were used to set the boundary conditions of the investment modelling.

6.2.4.2 Setting Coal, Lignite and Nuclear generation fleet

Since the evolution of the coal, lignite and nuclear generation fleet has lately proved to be not only run on economics but also heavily on political/social decisions, the level of the fleet is set ex-ante by matching the trajectories collected.

Coal and Lignite

For the 2030 horizon the fleet of coal and lignite units is based on the fleet of the collected scenario (National Trends 2030) which is then adjusted (downwards) to the level of the collected low trajectory for the top-down scenarios. For countries having not reported any low trajectory, power plants that are expected to be closed in mid-2030 or that are more than 60 years old are removed.

The same procedure is followed at 2040. The resulting coal and lignite base installed for Europe anticipates a very strong decline in both sectors and a more ambitious assumption in the top-down scenarios.

The two scenarios Global Ambition and Distributed Energy are set at the same level. The coal and lignite fleet is significantly reduced in 2040 as compared to 2025. At 2030 the volumes are slightly lower than in National Trends.

Nuclear

The nuclear fleet is also calibrated ex-ante by matching the trajectories collected to the scenario. For all countries except France, the low level is paired with the Distributed Energy scenario to match the Distributed Energy narrative and the high level with Global Ambition.

For France, the high level is paired with the Distributed Energy scenario, which has the highest electrification rate, thus guaranteeing a safer compliance over the 2030-2040 decade with the objective of a 50 % nuclear electricity demand supply share in the French mix set by the French government. Following the same reasoning, the low level is paired with Global Ambition.

Table 11 below includes the different starting points for the nuclear and coal fleet to adapt the thermal generation in accordance with the scenario storylines

Technology	Distributed Energy	Global Ambition
Nuclear	Low Trajectory (unless stated by country)	High Trajectory (unless stated by country)
Coal	Low trajectory	

TABLE 11: NUCLEAR CAPACITY

6.2.4.3 *Minimum RES investment share*

In order to avoid investments that would not respect the philosophy of the scenarios, would disrupt the investment curves or result in the lack of development of some technologies (e.g. wind offshore), a minimum share of RES investment is imposed in the investment modeling. As in the case of thermal power plants the proportions of imposed investment levels are linked to the scenario storylines.

For example, in the Distributed Energy scenario, the Solar PV developed between 2025 and 2030 will be at least 80 % of the fleet growth forecast in the National Trends scenario between 2020 and 2025.

Similarly, in the Global Ambition scenario, the wind offshore fleet in each country is taken to be equal to the National Trends scenario. The model is then free to invest in addition in the most favorable locations if the resulting profits cover the investment annuities. The potential provided to the investment model is therefore always deducted from these ex-ante added quantities.

In Table 12 below the starting point with ex-ante addition to the NT2025 capacities is summarized.

Technology	Year	Distributed Energy	Global Ambition
Solar PV	2030	80 % of NT2020 – NT2025 growth	50 % of NT2020 – NT2025 growth
	2040	Growth Rate Projected to 2040 from 2030 values	
Wind onshore	2030	50 % of 2020-2025 growth	80 % of 2020-2025 growth
	2040	Growth Rate Projected to 2040 from 2030 values	
Wind offshore	2030	Low Trajectory	NT2030 Value
	2040		Medium Trajectory

TABLE 12: EX ANTE CAPACITY ADDITION

6.2.4.4 *Renewable Energy Sources*

The calibration of the exploitable RES potentials by 2030 and 2040 in each area is a very complex task, particularly because of the technical (available space, capacity to be realized) and environmental (acceptance) dimensions.

Setting upper limits to the RES development per area and horizon

The proposed approach is a pragmatic one that aims to provide a realistic, but ambitious, framework for the development of renewable energies in Europe.

It is based on the collection of trajectories from TSOs (high trajectory) but also on the development history of recent years. This second source aims to compensate for the absence or pessimism of the high trajectory collected by setting a reference build-out rate (MW/year) based on the development actually observed in pioneer countries. For countries that have not yet begun the transition of their generating fleet, or only recently, a match is made with pioneer countries with similar characteristics (population and/or free space for example) or by scaling up the value according to these same characteristics.

Thus the development limit at 2030 for PV and onshore wind energy is calculated as the lesser of the following two values:

- ➢ 120 % of the maximum trajectory from which the installed capacity at 2025 is previously deducted (NT2025 scenario collected)
- ➢ 5*reference build-out rate (MW/year) (to cover the 2025-2030 period)

These two elements aim to better control the results of optimization over such a vast and highly contrasted geographical area (nature of the terrain, size of countries, population density) by integrating the dynamics reported by TSOs, and thereby improving the realism of the scenarios.

For the 2040 horizon, as less trajectories have been collected, the development limits were established as shown above, but reference was made to the maximum technical potentials outlined in e-Highway2050[8]. It is important to recall that the determination of the maximum deposit for the development of renewable energies remains very complex and is regularly updated in various studies to better integrate, for example, competition in land use, acceptance studies etc.

Differentiated PECDs

Three climatic databases labelled 2025, 2030 and 2040 now exist within ENTSO-E Pan-European Climate Database (PECD).

They are the result of complementary work carried out between ENTSO-E and the Technical University of Denmark reflecting the evolution of the wind load factors due to the commissioning of more efficient technologies (new farms or replacement of existing farms). The load factors provided show substantial progress in onshore and offshore wind energy production. The data in the climate database represents the evolution of technology with time, but does not consider the country specific (already existing) build out rates.

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[8] See e-Highway2050 study (https://docs.entsoe.eu/baltic-conf/bites/www.e-highway2050.eu/results/)

Therefore, to give a more accurate generation mix, the RES capacities were split and assigned to a PECD mix of technologies in the 2030 scenario time horizon. For that reason, an approach of a mix of the different PECDs were adopted to better reflect the technology mix for each time horizon in the scenarios.

For the 2030 horizon the approaches adopted consists in using the load factors as follows:

➢ the PECD 2025 for installed capacities present before 2018
➢ PECD 2030 for capacities installed between 2018 and 2025
➢ the PECD 2040 for capacities installed after 2025

In contrast to this for the 2040 horizon, the 2040 PECD was used for the entire wind farm fleet. This is due to the assumption of repowering of renewable technologies after 2030.

6.2.4.5 Interconnection level and NTC increase limits

The initial interconnection network (NTC modelling) is the MAF 2025 network, which avoids considering certain structures still at the project stage as these are not included in this reference network. Selecting an almost built interconnector network limits the risk of including a substantial number of uncertain projects (RES and/or grid), and avoids choosing between the option generation first or grid first.

The upper expansion limit offered on each interconnection to the optimizer is intended to reflect the existence of actual projects on the horizon considered (in particular 2030), based on the list taken from TYNDP2018, and/or, where no projects were proposed, symbolic interconnection increments (100 MW, 500 MW or 2000 MW) adapted to the size of the country and the pre-existing network.

For the 2030 top-down scenarios, the challenge is to manage the level of increase at a reasonable value avoiding too large increases in too short time for such infrastructures.

Whereas for the 2040 top-down scenarios, the maximum expansion limit for 2040 will be the same as the 2030 additional expansion limits. For example, if the maximum additional capacity built between Spain and France in 2030 is 3000 MW, the maximum additional capacity built between 2030 – 2040 is also 3000 MW. This may be a conservative assumption but the aim is to be realistic in the boundary condition.

The model is then capable of challenging various options, invest in RES in an area with high prices even with a rather low load factor, or co-invest in RES and grid, by selecting for example a high load factor area to develop RES together with an interconnector to export it into the high-priced area, if this is profitable.

6.2.5 Fuel Commodities and Carbon Prices

A key input to any power market modelling exercise is the fuel and carbon prices used to determine the low cost solution for a particular problem. There is a need for the ENTSOs to understand how the energy market is responding to the challenge of decarbonizing the European economy. Therefore it is important to carry out research in the field of future fuel commodities and carbon prices, which is required for the internal decision making process on the fuel price selection within the TYNDP process.

Fuel prices are key assumptions as they determine the merit order of the electricity generation units, hence the electricity dispatch and resulting electricity prices. Future fuel and CO_2 prices will depend on global energy demand/supply but also on European and world policies. Moreover, one should also distinguish short term variations/volatility from long-term trends.

In order to understand and capture the possible futures (in-line with the scenarios' storyline), a three-step approach was followed as illustrated in the figure below.
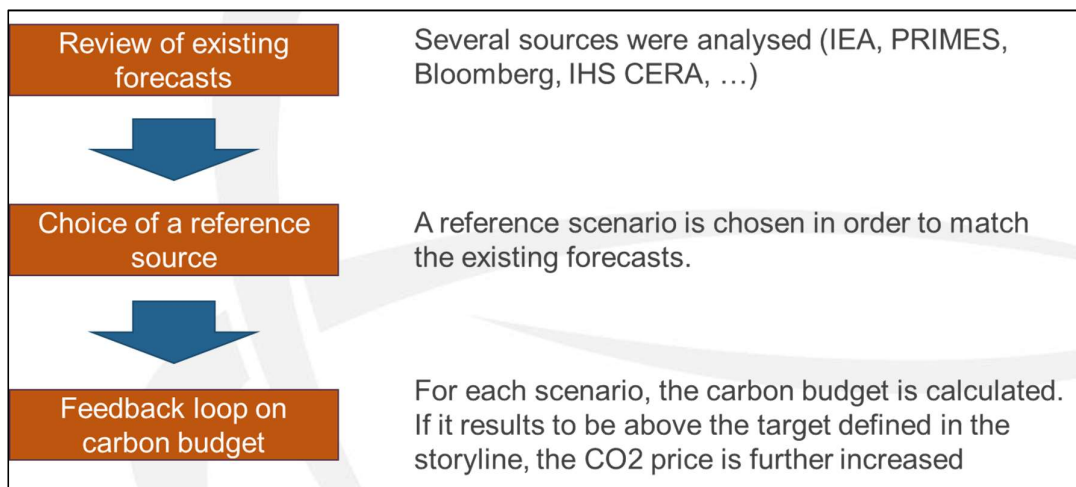
FIGURE 33: COMODITY PRICE REVIEW

6.2.5.1 Fuel and CO_2 prices categories

The fuel and CO_2 prices that are needed to be quantified can be listed in three categories and its related commodities with prices in real terms (in € 2017).

1. Stable or 'low volatility' prices/country dependent: Nuclear, Lignite and Biofuel
2. Driven by world/regional demand & supply: Oil, Coal and Natural Gas
3. Driven by European policies: CO_2

Stable or 'low volatility' prices/country dependent: Nuclear, Lignite and Biofuel

Nuclear and lignite prices have very little variations over time. Nuclear given its market and lignite given its local aspect. Biofuel depend a lot on the type and country.

Given those particularities, it was chosen to use only one price for those categories for all the scenarios and time horizons. Those will be based on the TYNDP 2018 prices and are listed below. (Note: Biofuel prices (if any) are specific for each country based on TSOs input).

The nuclear and lignite prices are assumed to stay stable over the time horizons and across the scenarios and are equal to:

- Nuclear: 0.47 €/GJ
- Lignite: 1.1 €/GJ

Driven by world/regional demand & supply: Oil, Coal and Natural Gas

Coal, oil and natural gas are mainly driven by world/regional and supply demand in the future, hence their evolution will depend on many variables. In order to assess their evolution, several sources will be first analyzed. The evolution over time will also be different. It is assumed that the price of coal, oil and natural gas are the same across Europe.Coal, oil and natural gas are mainly driven by world/regional and supply demand in the future, hence their evolution will depend on many variables. In order to assess their evolution, several sources will be first analyzed. The evolution over time will also be different. It is assumed that the price of coal, oil and natural gas are the same across Europe.

Driven by European policies: CO_2

The carbon price for the electricity market is driven by the cap on emissions that policy makers set on the European Trading System (ETS) in order to reach the carbon emissions ambitions. The CO_2 price will be therefore defined in the scenarios so a certain carbon budget can be reached.

6.2.5.2 Review of existing forecasts
Natural Gas

For 2030, different sources were assessed:

- IEA – World Energy Outlook 2018 (New Policies)
- Bloomberg NEF
- IHS Markit
- PRIMES (EC)

All those sources lead to a price of around 6 to 7 €/GJ in 2030.

Coal

For 2030, different sources were assessed:

- IEA – World Energy Outlook 2018 (New Policies)
- Bloomberg NEF
- IHS Markit
- PRIMES (EC)

The different sources lead to a price between 2 and 4 €/GJ. The higher price is observed in PRIMES while the lower in the Bloomberg.

CO_2 price

In 'business as usual' scenarios, the price is around 30 €/tCO_2 in 2030. This is observed in the IHS Markit, Bloomberg NEF and IEA-New Policies.

In more ambitious scenarios (IEA – World Energy Outlook 2018 - Sustainable Development Scenario), the price reaches around 80 €/tCO_2 in 2030.

The carbon price in Europe has recently increased in the past. There are several uncertainties that can lift the prices up or down such as:

- National policies (e.g. carbon floor)
- European stability reserve intervention
- Coal phase outs in electricity generation
- Additional RES in the system lowering the generation of fossil units
- Brexit if UK leaves the ETS

6.2.5.3 Choice of a reference scenario

The ENTSOs' scenario building process is coordinated with the EC, and for the purposes of scenario building it was decided after the review of existing forecasts to base the fuel and carbon prices (only for NT2025 and NT2030) on the European Commission PRIMES modelling that feeds into the National Energy and Climate Plan (NECP).

The PRIMES cost assumptions consist the reference scenario for gas, coal that will be used across all scenarios. The CO_2 price from PRIMES will be used for the National Trends scenarios which reflects the current European ambition on CO_2 reduction.

> The PRIMES cost assumptions is used as reference for gas, oil and coal for all scenarios and time horizons. The CO2 price from PRIMES is used for the National Trends scenario.

The assumptions for fuel cost and baseline CO_2 are presented below. These costs are used as such in the National Trends scenario

€/net GJ		2020	2021	2023	2025	2030	2040
	Nuclear	0.47	0.47	0.47	0.47	0.47	0.47
	Lignite	1.10	1.10	1.10	1.10	1.10	1.10
	Hard coal	2.99	3.15	3.47	3.79	4.30	6.91
	Gas	5.59	5.76	6.11	6.46	6.91	7.31
	Light oil	12.87	14.06	16.43	18.80	20.51	22.15
	Heavy oil	10.56	11.10	12.18	13.26	14.63	17.21
	Oil shale	2.30	2.30	2.30	2.30	2.30	2.30
€/ton	CO2 price	19.69	20.35	21.68	23.00	28.00	50.00

FIGURE 34: COMODITY PRICE TABLE

For the other scenarios, the CO_2 price will set endogenously in order to match a certain carbon budget as defined in the next paragraph.

6.2.5.4 Feedback loop on the carbon budget

Starting from the PRIMES reference prices and taking into account the carbon budget defined in the storyline, the CO_2 price will be endogenously adjusted in order to achieve the defined carbon budget.

The CO_2 cost in the top-down scenario is endogenous to the approach. If necessary, it is increased to reach a lower CO_2 emissions target by promoting renewable investments.

Scenario	EC Long Term Strategy Scenario	Emissions Target (Mt CO_2)	CO_2 Price
DE2030	Linear approach from 2015 – 2040 of 1.5° scenarios	501	53
DE2040	Average of 1.5° scenarios	47.5	100
GA2030	Linear approach from 2015 – 2040 of 1.5° scenarios	501	35
GA2040	Average of 1.5° scenarios	47.5	80
NT2030	Baseline	620	28
NT2040	Average of 2° scenarios	182	75

TABLE 13: CO2 TARGET AND PRICE

6.2.5.5 Conclusion on fuel and CO2 prices for the different scenarios

Only thermal units without minimum generation commitment reported can potentially be decommissioned.
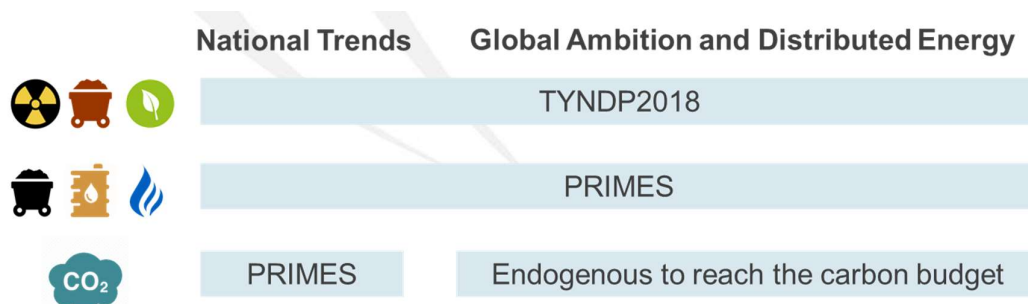
FIGURE 35: COMODITY PRICE SOURCE

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6.2.6 Thermal Decommissioning

The investment model also challenges the existing generation fleet in semi-base load plants [9](mainly CCGT) by ensuring the plants are viable (cover their fixed and variable costs). The thermal decommissioning is done separately after the optimization of RES and Grid in Investment tool step, to avoid overloading the solving of each optimization in the investment model.

6.3 Summary per scenario

In **Error! Reference source not found.** below is an overview of the scenario building process step 1 and 2, starting values and investment modeling. In the following sections a summary for each scenario, including starting values and methodology.

Summary: detailed quantification – "step2" in a nutshell

The bottom-up data collection and the storyline matrix allows to define a starting point for the top-down scenario to investment models as illustrated below (for 2030).
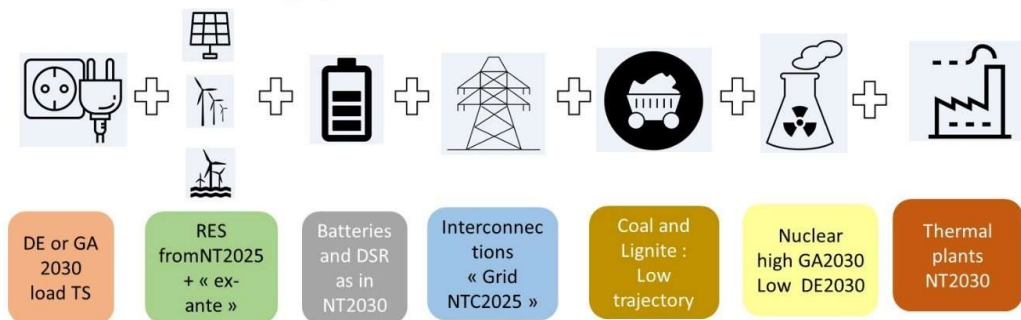
FIGURE 36: SUMMARY OF SCENARIO BUILDING PROCESS STEPS 1 & 2

On this base, investment model completes the picture by allocating RES and potentially decommissioning gas power plants to reach a certain CO_2 level.

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[9] This refers to power plants that run between 4000 and 6500 hours per year.

6.3.1.1 Global Ambition

Start Value & Methodology	GA2030	GA2040
Coal	2030 Low Trajectory + Decommissioning	2040 Low Trajectory + Decommissioning
Nuclear	2030 High Trajectory	2040 High Trajectory
CCGT	National Trends 2030 + Decommissioning	National Trends 2040 + Decommissioning
CCGT CCS	N/A	Expansion
Hydro	Sustainable Transition 2030	Sustainable Transition 2040
Wind Onshore	2025 + Global Ambition Minimum Investment + Expansion	GA2030 + Global Ambition Minimum Investment + Expansion
Wind Offshore	2025 + Global Ambition Minimum Investment + Expansion	GA2030 + Global Ambition Minimum Investment + Expansion
Solar PV	2025 + Global Ambition Minimum Investment + Expansion	GA2030 + Global Ambition Minimum Investment + Expansion
Solar CSP	2030 Trajectories	2040 Trajectories
Batteries	2030 Trajectories	2040 Trajectories
P2g	Curtailed RES + RES Optimization	Curtailed RES + RES Optimization
Grid Expansion	2025 + Expansion	2030 + Expansion

TABLE 14: GLOBAL AMBITION - METHODOLOGY OVERVIEW

6.3.1.2 Distributed Energy

Start Value & Methodology	2030	DE2040
Coal	2030 Low Trajectory + Decommissioning	2040 Low Trajectory + Decommissioning
Nuclear	2030 High Trajectory	2040 High Trajectory
CCGT	National Trends 2030 + Decommissioning	National Trends 2040 + Decommissioning
CCGT CCS	N/A	Expansion
Hydro	Sustainable Transition 2030	Sustainable Transition 2040
Wind Onshore	2025 + Distributed Energy Minimum Investment + Expansion	GA2030 + Distributed Energy Minimum Investment + Expansion
Wind Offshore	2025 + Global Ambition Minimum Investment + Expansion	GA2030 + Global Ambition Minimum Investment + Expansion
Solar PV	2025 + Global Ambition Minimum Investment + Expansion	GA2030 + Global Ambition Minimum Investment + Expansion
Solar CSP	2030 Trajectories	2040 Trajectories
Batteries	2030 Trajectories	2040 Trajectories
P2g	Curtailed RES + RES Optimization	Curtailed RES + RES Optimization
Grid Expansion	2025 + Expansion	2030 + Expansion

TABLE 15:DISTRIBUTED ENERGY - METHODOLOGY OVERVIEW

6.3.1.3 National Trends

Start Value & Methodology	NT2030	NT2040
Coal	2030 Low Trajectory + Decommissioning	2040 Low Trajectory + Decommissioning
Nuclear	National Trends 2030	National Trends 2040
CCGT	National Trends 2030	National Trends 2040
CCGT CCS	N/A	N/A
Hydro	ST2030	ST2040
Wind Onshore	2030 + Investment	NT2040 Values or 2030 + Investment
Wind Offshore	2030 + Investment	NT2040 Values or 2030 + Investment
Solar PV	2030 + Investment	NT2040 Values or 2030 + Investment
Solar CSP	National Trends 2030	National Trends 2040
Batteries	National Trends 2030	National Trends 2040
P2g	PEMMDB + Excess RES	PEMMDB + Excess RES
Grid Expansion	Ref Grid	2025 + Investment

TABLE 16: NATIONAL TRENDS - METHODOLOGY OVERVIEW

6.4 SoS calibration within the SoS tool step

6.4.1 What is SoS Calibration?

In order to finalize the scenario, a final step is added to ensure the top-down scenarios built are adequate. One key indicator used to measure adequacy is the **L**oss **o**f **L**oad **E**xpectation (LOLE in hours/year). It reflects the expectation of load curtailment in a year computed over a set of hundreds "potential years" (different weather conditions, different yearly PECDs etc.)

When performing adequacy assessments, it is important to model a large number of potential demand and generation availability scenarios. Demand scenarios are modelled using the regional demand profiles associated with the thirty-five climate year demand dataset developed for the TYNDP (and MAF). These profiles include examples of expected demand in each region during extreme weather events. A wide range of generation availability scenarios is modelled by simulating multiple forced outage patterns. Variations in the availability of renewable resources such as hydro, wind and solar are captured by using the associated resource profiles for each climate year. Network availability may also be modelled through outage patterns. The demand and renewable profiles for each climate year have already been prepared for the TYNDP and applying them in an approach similar to the MAF simulates a wide range of demand and generation availability scenarios, which inherently includes some high-impact low-probability events.

The methodology proposed here has already been deployed within a dedicated task force in TYDNP 2018 (link).

Enrich Investment tool step - more hazards → Simulate enrich base case → Calibrate peakers/DSR to meet target LOLE < x (default x = 3 hrs/year)
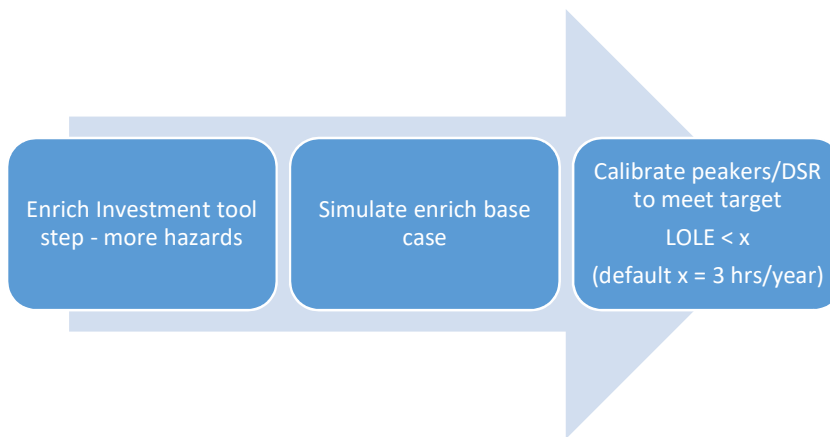
FIGURE 37: ADEQUACY STAGES

6.4.2 Enrich Investment tool step

The method uses as a starting point the scenarios as set after the Investment tool step (see Section 6.2) is completed. The used models used in the detailed quantification stage are enhanced with some additional features to enable the robust adequacy assessments. In addition the full climate data base is used (thirty-five vs. three in the quantification process). On top multiple outage patterns on thermal units and HVDC interconnectors are introduced (randomized).

6.4.3 SoS landscape from the starting point

The simulations are performed over 15 Monte Carlo years (35 climates years * 535 outage patterns) which enables the robust assessment of standard adequacy indicators[10]. Results of the adequacy assessments using the enhanced model are obtained giving a panorama of LOLE throughout all modeled areas.

6.4.4 Portfolio adaptation on the starting grid

The role of the generation portfolio adaptation in the base case scenario is two-fold:

- Some countries are exceeding their standard (national value[11] if it exists, default standard LOLE < 3hrs) in the base case. The rationale of the adaptation in this case is that countries will be, at worse, at their standard

- Countries having a Loss of Load Expectation of 0 in the base case may have non-viable peaking units (very low running hours)

These adaptations prove necessary as a complementary step to the Investment tool step building process which does not yet fully take this aspect into account[12]. It should also be noted that thermal fleet reduction performed account for less than 2 % of the total installed thermal capacity in all four scenarios.

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[10] For adequacy studies within the PAN EU system, it is recommended to extend the Monte Carlo scheme to a couple of hundred simulation years in order to obtain a robust estimate of adequacy indicator such as LOLE or EENS. SEW on the other hand does tend to converge more rapidly, allowing the process to be run on a significantly lower number of years.

[11] e.g : 3hrs for France, Belgium ; 8hrs for Ireland (Republic of Ireland and Northern Ireland)

[12] It is also worthwhile reminding that scenarios Best Esimate 2025 and Sustainable Transition 2030 are bottom-up scenarios resulting from the data collection; EUCO2030 is a scenario provided by European Commission;

The portfolio adaptation is achieved through an iterative process as illustrated below.
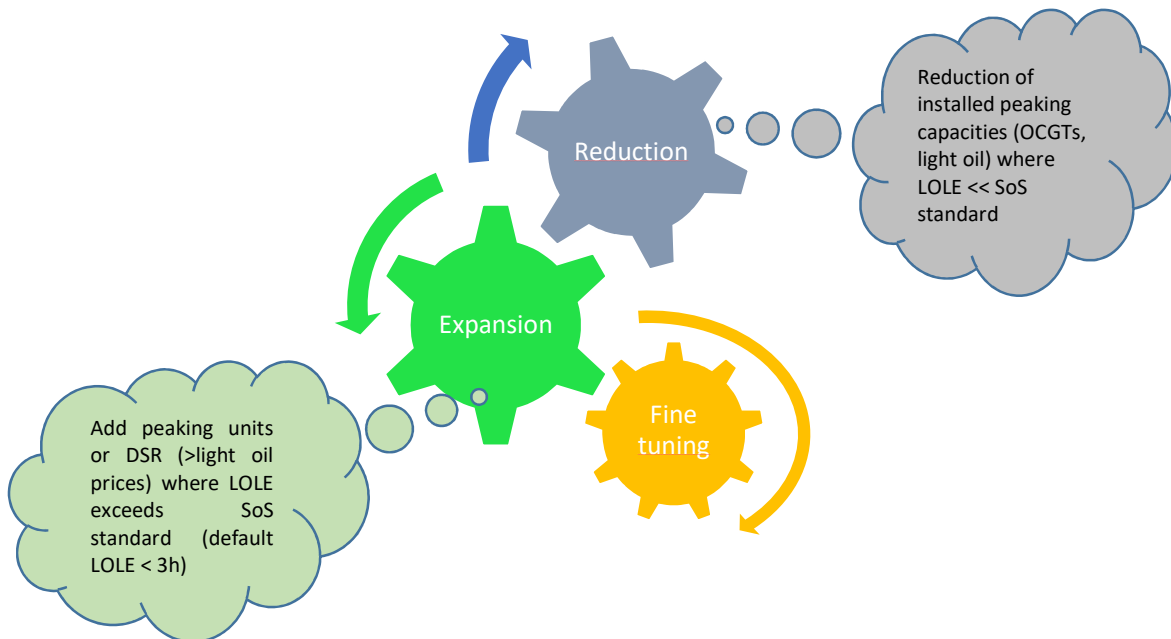
FIGURE 38: OVERVIEW OF THE GENERATION PORTFOLIO ADAPTATION PROCESS

The portfolio adaptation is limited to peaking units and does not necessarily bring all countries to their or the default adequacy standard. Two potential reasons for this are:

- Some countries structurally have a zero LOLE, due for instance to large hydro capacities, a limited sensitivity to climate conditions (e.g. temperature and subsequent heating), or very high level of interconnection with hydro dominated areas.

- It is possible that in some countries, a more detailed analysis of the mid-merit generation portfolio could show that there some potentially non-viable capacities. Given that one of the principles of this methodology was to only make very minor changes to the starting portfolio no mid-merit generation has been removed.

6.5 Investment Cost assumptions

THE ASSUMPTIONS ON POWER GENERATION CAPEX AND OPEX ARE PRIMARILY BASED ON ASSET REPORT "TECHNOLOGY PATHWAYS IN DECARBONISATION SCENARIOS". [13] TABLE 17: CAPEX ASSUMPTIONS PRESENTS THE CAPEX ASSUMPTIONS WHEREAS TABLE 18: OPEX ASSUMPTIONS

presents OPEX assumptions. All costs are quoted in real terms.

Technology	National Trends		Global Ambition		Distributed Energy	
CAPEX in EUR/kW	2030	2040	2030	2040	2030	2040
Wind onshore	1066	915	1066	915	1066	915
Wind offshore	2843	2689	1706	1345	2843	2689
Solar PV	627	455	627	455	439	319
OCGT New	440	440	440	440	440	440
CCGT New	770	750	770	750	770	750
CCGT CCS				1650		1650

TABLE 17: CAPEX ASSUMPTIONS

Technology	National Trends		Global Ambition		Distributed Energy	
OPEX in EUR/kW/year	2030	2040	2030	2040	2030	2040
Wind onshore	21	17	21	17	21	17
Wind offshore	43	40	26	20	43	40
Solar PV	14	12	14	12	9	8
OCGT New	13	13	13	13	13	13
CCGT New	15	15	15	15	15	15
CCGT CCS				38		38

TABLE 18: OPEX ASSUMPTIONS

Global Ambition and Distributed Energy scenarios assume certain deviations from the ASSET study, specifically that costs for offshore wind are assumed lower in Global Ambition while costs of solar PV is lower in Distributed Energy. The motivation of the changes is to enable the scenarios to capture uncertainty related to technological development and its impacts on the energy systems. The changes were made to enable the qualitative outcome described in the ENTSOs scenario storylines, namely larger role of wind power in Global Ambition and solar power in Distributed Energy. For all scenarios in 2030 as well as the National Trends 2040 scenario, nuclear and CCGT CCS evolution was assumed based solely on national plans so any specific costs were not considered.

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[13]   https://ec.europa.eu/energy/sites/ener/files/documents/2018_06_27_technology_pathways_-_finalreportmain2.pdf

Gas Supply

7 Gas supply

This chapter describes the main storylines assumptions and methodologies with regard to the gas supply mix, gas source composition and gas supply potentials.

ENTSOs scenarios differentiate between gas type, gas source and imports or indigenous production.

Gas types: There are two different gas types, which are methane and hydrogen. For National Trends a gas mix (based on methane as for natural gas) was considered. For Distributed Energy and Global Ambition, the quantification of the type-specific demand is described in Section 4.

Gas sources: The demand for the two different gas types can be supplied by multiple gas sources, which can be non-decarbonised, decarbonised and renewable.

For methane, gas sources are:
1. Natural gas as non-decarbonised source
2. Natural gas with post-combustive CCS as decarbonised source is
3. Biomethane and synthetic methane via P2G as renewable sources are

For hydrogen, gas sources are:
1. Natural gas with SMR as non-decarbonised source
2. Natural gas with SMR+CCU/S or methane pyrolysis as decarbonised source
3. P2G as renewable source

Imports and indigenous/national production: both gas types from each source can be either produced indigenously or imported from outside Europe.

7.1 Storyline assumptions on import share and gas supply decarbonisation

7.1.1 Import share

In 2015, the import share of natural gas was around 70%. Due to declining national production in the EU28, this share will further increase in the coming years.

Whereas for National Trends the import share is given as a difference of total gas demand and bottom-up national production data for natural gas, biomethane and P2G, the storylines for Distributed Energy and Global Ambition consider assumption on the import share in 2050. Global Ambition is based on the assumption that the gas import share will keep its 2015 level till 2050. Distributed Energy considers a halving of the import share to 35% of the total gas demand by 2050.

The import demand in terms of energy volumes is then the difference of the total gas demand and all indigenously produced gases.

7.1.2 Decarbonisation

For the National Trends, the decarbonisation is given by the bottom-up data for indigenous production of renewable and decarbonised gases. No further assumptions or methodologies were applied.

For both Global Ambition and Distributed Energy, the decarbonisation of the gas supply is based on "Storyline 2 – Strong development of methane (CO2-neutra)" of the study "The role of Trans-European gas infrastructure in the light of the 2050 decarbonisation targets"[14], done by Trinomics for the European Commission.
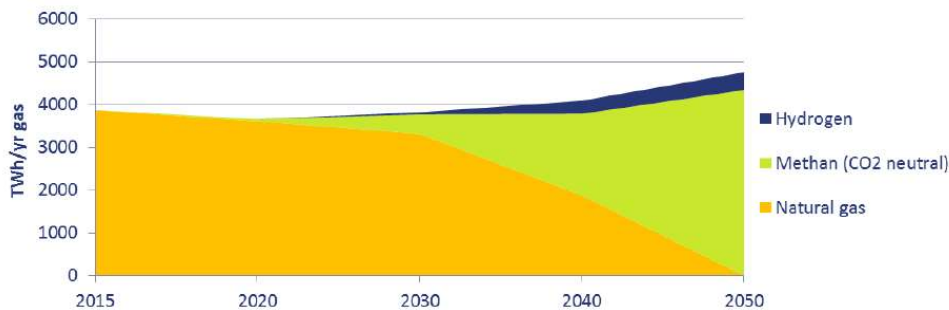
FIGURE 39: DEVELOPEMENT OF THE GAS MIX[15]

Following the increase in renewable and decarbonised gases as shown in Figure 39, the decarbonisation rate of the Global Ambition and Distributed Energy is as follows:

Year	2020	2025	2030	2040	2050
Decarbonisation rate	1%	5,00%	13,20%	53,70%	100%

7.2 Gas Supply Potential Methodology, Analysis and Results

The supply potential assessment is the basis of the supply adequacy analysis and gives the range of the possible supply mix for the scenarios. The results of the assessment can be found in Section 7.4.2.

The gas supply potentials are split between supply from national production (NP) in EU and the extra-EU supply that is imported from supply sources outside EU.

The NP will always be considered in the resulting supply mix for the scenarios as it is assumed, that national policy will decide in favour of indigenous production rather than imports (cheap as the cheapest extra-EU supply source). The specific extra-EU supply mix in the scenarios will be a result of the gas balance simulations with the Network Modelling tool.

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[14] "The role of Trans-European gas infrastructure in the light of the 2050 decarbonisation targets", European Commission and Trinomics, 2018

[15] Storyline 2 –Strong development of methane (CO2-neutral)

The TYNDP 2020 scenarios comply with ambitious CO_2 reduction targets, resulting in a demand for decarbonised gas types (e.g. hydrogen, biomethane and decarbonised natural gas by post/pre-combustive CCUS). The Network Model tool balances the energy supply and demand at the cheapest transport cost for EU considering technical and commercial constraints (e.g. supply potential, capacities, gas price etc.). The infrastructure simulations will, as in the previous TYNDPs, be done with energy units [GWh/d] for demand and supply, thereby not including information about gas types. The impact of the other gases on the infrastructure will be assessed from the simulations results in the TYNDP Assessment report. The TYNDP team are working on including this complexity in the simulations for TYNP 2020, but further methodology analysis is needed.

7.3 National Production Supply Potentials

The National Production (NP) consist of the individual countries' production of natural gas, biomethane and power-to-gas.

7.3.1 Natural Gas Production

The indigenous natural gas production is the gas made available for the gas market from oil and gas fields within the national territory.

The data on the indigenous natural gas productions is collected from ENTSOG members, thereby assessed by the individual TSOs. This is viewed as a bottom-up data collection. The data will in most cases be equal to the official national projection of the natural gas production (e.g. done by the national regulatory agencies or relevant authorities).

The indigenous natural gas production is independent of the scenario storylines, and therefore constant throughout all three scenarios.

7.3.2 Biomethane Production

Biomethane is a renewable source for methane, which is based on the conversion of biomass and waste into biogas (mainly methane and carbon dioxide) and its upgrading into biomethane. Biomethane production can be achieved using either anaerobic digestion or thermal gasification.

Anaerobic digestion technology is based on a series of biological processes by which microorganisms break down biodegradable material in the absence of oxygen. Agricultural residues from sustainably cultivated crops, animal manure and food waste are used as input and biogas and digestate are obtained as output. The resultant biogas contains approximately 50 - 60% methane, the rest being carbon dioxide. Biogas, therefore, needs to be upgraded to biomethane with at least 97% content before injecting it into the gas grid. In addition, resultant biogas digestate can be used as a fertilizer.

Thermal gasification technology is based on the thermal breakdown of a feedstock mix consisting of woody biomass and post-consumer wastes. In the presence of a controlled amount of oxygen and steam, the thermal breakdown takes place in a gasifier, in which syngas is produced. Syngas consists of a mix of carbon monoxide, hydrogen and carbon dioxide. Next, the

gas is cooled down and the ash content is removed. Subsequently, the gas is cleaned in a gas cleaning unit where chlorides and sulphur are separated. Finally, a methanation process takes place in a catalytic reactor producing biomethane, carbon dioxide and water. As a final step, carbon dioxide and water are removed in a gas upgrading unit.

The removed carbon dioxide from the biogas, which is separated from the biomethane stream can be captured and used in the methanation process as an additional step to water electrolysis (see P2G). Alternatively, the remaining carbon dioxide can be captured and stored underground allowing for net negative emissions.

The biomethane production potentials depend on the scenario storylines and are assessed by two different methods: National Trend scenario (bottom-up) and the Distributed Energy and Global Ambition scenarios (top-down).

7.3.2.1 *National Trends Scenario*
The National Trends data on the indigenous biomethane productions are collected from ENTSOG's members, thereby assessed by the individual TSOs. This is viewed as a bottom-up data collection.

7.3.2.2 *Distributed Energy and Global Ambition Scenarios*
For the Distributed Energy and Global Ambition scenarios an ENTSOG Excel based biomethane tool is used for assessing the biomethane production. This tool was developed together with Navigant (formerly known as Ecofys) and this tool is a further development of the methodology used by Navigant in the study by Gas for Climate[16]. The generic input assumptions[17] and methodology are described in Section 7.5.The injection rate of biomethane into the grid is assumed to be 80% for both thermal gasification and anaerobic digestion (produced sufficiently close to gas grids to be grid-injected). In line with the storylines of the scenarios, Global Ambition is assumed to have 20% less production of biomethane than Distributed Energy.

7.3.3 **Power-to-Gas**
Power-to-gas, or frequently called Power2Gas (P2G), is referring to the production of synthetic hydrogen via electrolysis and synthetic methane, after an additional methanation step.

The methodology is described in detail in Section 8.

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[16]https://www.gasforclimate2050.eu/
[17] For three countries (Spain, Ireland, Netherlands) the generic input parameters were adjusted to be more in line with the TSOs' assessment of the biomethane production in the country.

7.4 Import Supply Potentials

The extra-EU supply sources - that is sources of EU energy imports - today include Russia, Norway, Algeria, Libya and the LNG market. The LNG market is split into basins to reflect difference in supply potentials: Middle East, North Africa, Russia, North America and Others. Additionally, the EU will also be supplied from Azerbaijan by pipeline in the near future (as of 2020).

The methodology of the assessment is described in Section 7.4.1 and applied in Section 7.4.2.

7.4.1 Methodology

The extra-EU supply potentials are assessed as a range between the minimum and the maximum potential for each source. These supply specific ranges are boundary conditions in the gas balance simulations, thereby always respected in the resulting supply mix. They are introduced to avoid unrealistic supply mix situations. The simulation will find the optimal supply mix within the given supply range for the given market assumptions. Supply mix results are thereby determined by a combination of the supply potentials, network constraints and market assumptions.

7.4.1.1 Definition of Extra-EU Gas Supply Potential

The gas supply potentials are given as a range between minimum and maximum supply potentials.

The minimum supply potential of a supply source is defined as the current long-term contracts, and their expected extension with reference to the national projection of production and domestic demand, possible production and infrastructure constraints, as well as the historical EU supply share.

The maximum supply potential of a specific source is defined as the export potential to EU with reference to the national projection of production and domestic demand, possible production and infrastructure constrains as well as the historical EU supply share.

7.4.1.2 Literature Review

The assessment of the extra-EU supply potentials is done by a literature review of recent published studies on the future energy mix of EU. For TYNDP 2020 extra-EU supply potential, the IEA's World Energy Outlook 2018[18] is chosen as a key reference and used as a benchmark. This report has been analysed in comparison with TYNDP 2018 extra-EU supply potentials, historical market share of supply sources and ENTSOG's members own analyses for the future supply potentials. For the ENTSOG member assessment, five sub-groups where established for the analyses: Russia, Norway, LNG, North Africa and Caspian. The result was subsequently reviewed by stakeholders and benchmarked with the supply source market share from other relevant reports.

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[18] https://www.iea.org/weo2018/

7.4.1.3 Historical Gas Supply

The historical data is taken from ENTSOG's data warehouse, which contains EU supply data provided by ENTSOG members.

7.4.1.4 Infrastructure Projects

For new and future extra-EU supply sources, the potentials are assumed to be correlated with the submitted infrastructure projects for the TYNDP 2018, which can be found on ENTSOG's webpage[19]. The potential of export production from a given source is very much dependent on the willingness of investment in new exploration fields and connecting infrastructure projects.

7.4.1.5 Stakeholder Engagement

ENTSOG has engaged stakeholders during the development of the extra-EU supply potential. This has been done by both bilateral meetings[20] with key stakeholders and hosting a public workshop[21] for stakeholders to give their view on extra-EU supply potentials and feedback on ENTSOG's draft of the TYNDP 2020 Supply Potentials.

7.4.1.6 Import of Hydrogen and Decarbonised gases

The extra-EU supply potentials of hydrogen and decarbonised gases import are a review of the feasible technical import potentials, which could be made available on the EU gas market in a future going towards a carbon neutral energy system in 2050. The review includes both gases produced with established technologies and with technologies currently in the research and development phase. Apart from direct hydrogen and renewable methane imports, also natural gas imports are considered, but assumed to be decarbonised pre- or post-combustive. For hydrogen, this includes the pre-combustive conversion from natural gas to hydrogen via steam methane reforming and CCU/S or methane pyrolysis at import points, city gates or at the consumption site. For methane, natural gas needs to be decarbonised post-combustive with CCU/S.

The long-term research and development of source and technology are highly unpredictable with high risk of picking the wrong "winner" early in the process. Therefore, the review will be done with the principles of source and technology neutrality.

7.4.2 Analysis and Results

In the following section the individual supply potentials are analysed and the results for the TYNDP 2020 are presented.

7.4.2.1 Historical Supply

Indigenous production has continuously decreased since 2009 inducing an increasing dependency on extra-EU supply. With the recent public announcement of a further drop in gas

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[19] https://www.entsog.eu/tyndp#

[20] GAZPROM, EQUINOR, SOCAR, GASSCO, IEA, DELEK.

[21]ENTSOG WORKSHOP ON THE SUPPLY POTENTIALS AND MARKET RELATED ASSUMPTIONS FOR TYNDP 2020

production from the Groningen field (Netherlands) [22], this overall trend will most likely accelerate in the near future. Russia is currently listed as the main extra-EU supplier with an increasing market share reaching 36% in 2017.

The second largest supplier is Norway with a constant market share of around 20-24%. The North African supply from Algeria and Libyan has been constant at approximately 8% the last decade. LNG supply is the source with the most fluctuating market share due to price changes in the global LNG market. In 2011 LNG had a significant share of the market of 15% which subsequently decreased to 8% in 2013. Presently (2019), the share of LNG in the market has returned to 2011 levels and may increase further still. In Figure 40 the historical supply mix for the EU is illustrated with data from ENTSOG's database.
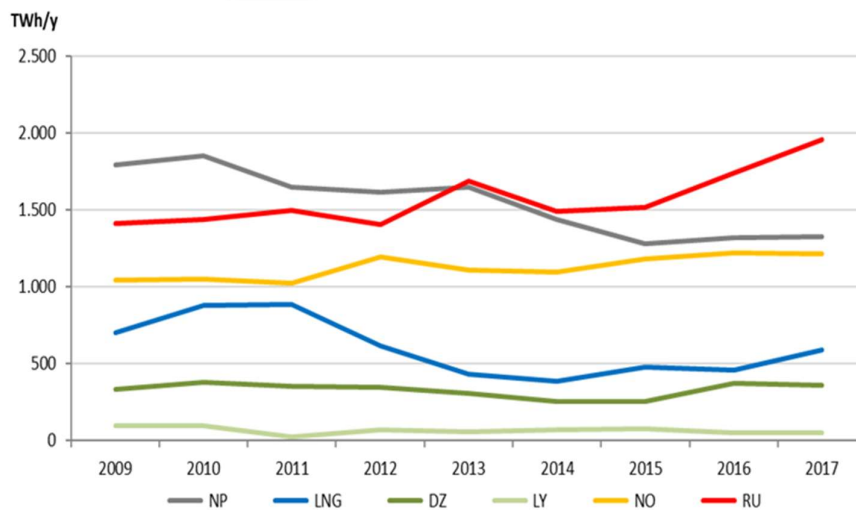
FIGURE 40: EU GAS SUPPLY MIX IN THE PERIOD 2009-2017 (ENTSOG)

7.4.2.2   Russian Supply Potential

The Russian Federation is currently the main gas supplier to the EU gas market and supplied 173 bcm (1,959 TWh) in 2017 via pipeline. This represented 36% of the EU market share and resulted in a load factor of utilised capacity at about 0.64.

Russia has its own domestic demand that can influence its export potential. The gas production in Russia is about 700 bcma and the internal demand was 391 bcm in 2016[23].

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[22]   https://www.reuters.com/article/groningen-gas/update-1-groningen-gas-production-to-drop-20-faster-than-planned-govt-idUSL8N23O44B
[23] IEA World Energy Outlook 2018

The maximum potential projection for EU is constant at 210 bcma, which accounts for 44% of EU demand (2016). Gazprom can increase its export potential to EU if the right investment incentives are given[24]. The minimum potential is an assessment of the long-term contracts (CEDIGAZ) and decrease through the period. The projection is aligned with WEO 2018. For TYNDP 2018, both potentials were in general a bit higher.

The future of Russian export potential for EU imports will basically depend on the European demand level, on the competition from other big consumers in Asia to import Russian gas and the amount of investment in the upstream sector (e.g. LNG). The projected Russian supply potentials for the EU are illustrated in Figure 41.
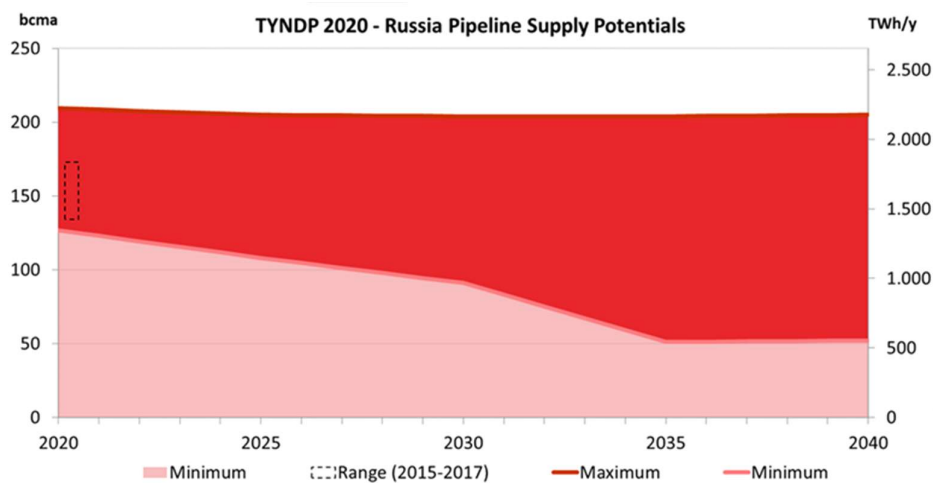
FIGURE 41: RUSSIA PIPELINE SUPPLY POTENTIAL FOR EU

7.4.2.3   Norwegian Supply Potential

Norway is currently the second largest gas supplier to the EU and supplied 110 bcm (1,213 TWh) via pipeline in 2017. This accounted for a load factor of utilised capacity at approximately 0.74 and an EU market share of 22%.

The uncertainty of the Norwegian supply to the EU is mostly related to investment in discovered and undiscovered resources in the southern gas fields, which is well connected to the EU gas market by pipelines[25]. Norway has no significant domestic demand and almost solely supplies the EU market (excluding LNG production). The northern gas fields are not connected to the EU market via pipelines, and LNG is produced for the global gas market. If an infrastructure investment to connect these gas fields with the southern infrastructure going to EU is made, the Norwegian supply potential for the EU would increase notably, but also affect the production and transport cost.

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[24] ENTSOG Workshop: GAZPROM'S NATURAL GAS PRODUCTION AND EXPORT STRATEGY
[25] ENTSOG Workshop: Norwegian Supply (Gassco)

The Norwegian maximum supply potential (excluding LNG) is forecasted by both the Norwegian Petroleum Directorate[26] (including discoveries and undiscovered resources) and IEA (WEO NPS additional supply) to decrease towards approximately 80 bcma in 2040. This is slightly less than the TYNDP 2018 projection which had 90 bcma in 2040. For the TYNDP 2020 projection of maximum supply potential, ENTSOG has used both the Norwegian Petroleum Directorate and the World Energy Outlook New Policy Scenarios as guidance.

The TYNDP 2020 minimum supply potential is more dependent on the long-term contracts. This is a significant change from the TYNDP 2018 potential, where the assessment was more related to the historical supply. For the Norwegian minimum supply potential, ENTSOG has used the IEA's assessment of committed supply (WEO NPS). The projected Norwegian supply potentials are illustrated in Figure 42.
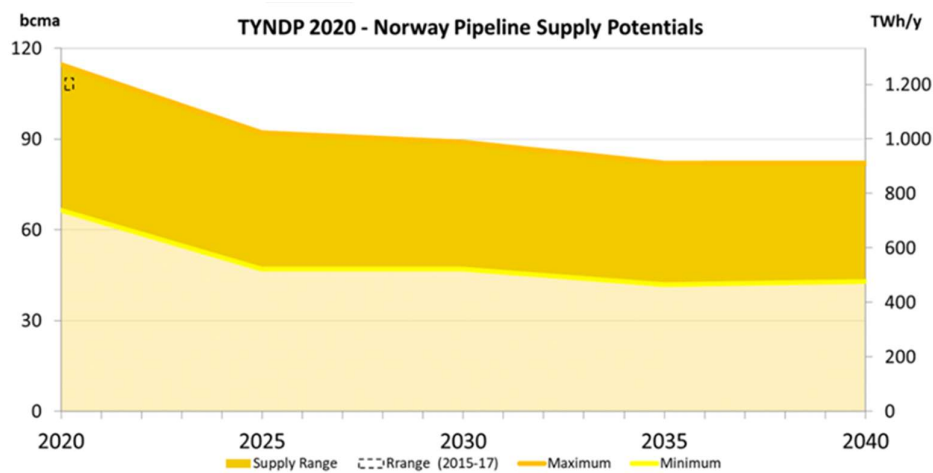
FIGURE 42: NORWEGIAN PIPELINE SUPPLY POTENTIAL FOR EU

7.4.2.4   North African Supply Potential

The North African supply from Algeria and Libya had an EU market share of approximately 8% the last decade. In average, that is 36 bcma with a load factor of utilised capacity on approx. 0.45.

The North African potential is highly reliant on the Algerian Hassi R'Mel field and the trend of the country's domestic demand. The gas production of the field is decreasing, and the domestic demand is increasing reported by Oxford Institute for Energy Studies[27] in 2016 and confirmed in the WEO18.

For the short-term the North African maximum supply potential is expected by ENTSOG not to exceed highest historical recorded supply, and for the long-term the projection is aligned with the expectation from the WEO 2018. For the minimum potential, ENTSOG expect the potential to follow the trend of the export potential, thereby an extension of the current long-term

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[26] https://www.norskpetroleum.no/en/production-and-exports/exports-of-oil-and-gas/
[27] Algerian gas troubling trends troubled policies (OIES, 2016)

contracts is expected. The projected North African Supply potentials for EU are illustrated in Figure 43.

Compared to TYNDP 2018, the supply potentials are in general reduced due to the expectations for the Algerian gas market.
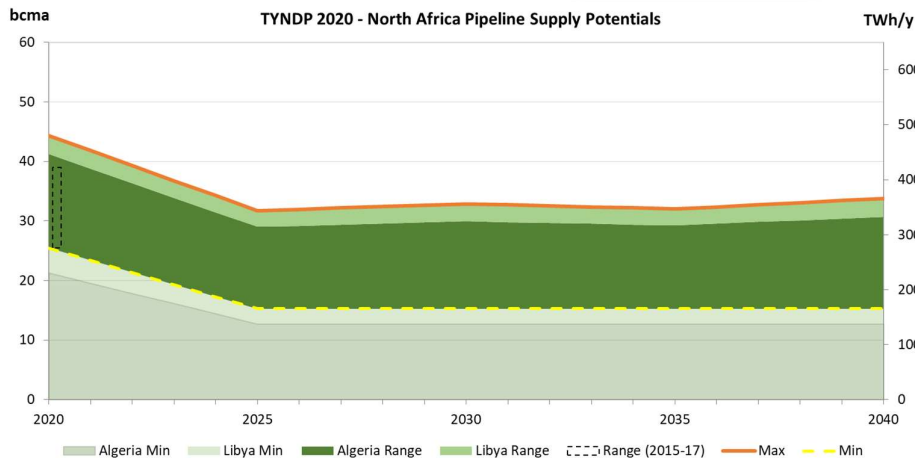
FIGURE 43: NORTH AFRICA PIPELINE SUPPLY POTENTIAL FOR EU

7.4.2.5 Caspian and Turkish Supply Potential

The Caspian supply potential consist of gas production from Azerbaijan and Turkmenistan, where the Turkish supply potential is gas redirected to EU from a diversity of supply sources. This can in principle be all the gas sources supplying the Turkish gas market (included LNG). The Caspian region is a new supply source to EU and are very much dependent on the current infrastructure projects.

The potential exports of gas from Azerbaijan to EU are closely linked to the development of the Shah Deniz field, but other fields can potential be relevant for export in the future. The existing Shah Deniz facilities' production (Stage 1) produced 11.5 bcm in 2018 for Turkey, Georgia and the domestic market. This contract expires in 2023. The next Shah Deniz Stage 2 adds further 16 bcma to the export gas production. Of the Shah Deniz Stage 2 production, 6 bcma are contracted to Turkey (open end contract) and 10 bcma to the EU market via the route known as the Southern Gas Corridor.

The Southern Gas Corridor consist of the Trans Anatolian Pipeline (TANAP) and Trans Adriatic Pipeline (TAP) projects, in combination with the extension of the South Caucasus Pipeline (SCPX), which are planned to initiate export of gas to Europe in 2020 (10 bcma from Shah Deniz 2).

The potential for Azerbaijan export gas is correlated with infrastructure projects, and with the possible expansion of the Southern Gas Corridor (e.g. SCPFX, 2025), the export potential from Azerbaijan are projected to include additional 5 bcma from either the current exporting fields or the remaining Azerbaijani fields.

The potential exports of gas from Turkmenistan to EU in the TYNDP 2020 are linked to the infrastructure projects provided for the TYNDP 2018. The project list includes a Trans-Caspian pipeline (TCP) project with a capacity of 30 bcma crossing the Caspian Sea to Azerbaijan with objective to transport Turkmenistan gas to EU. This project will further need an expansion of the Southern Gas Corridor and additional pipeline project crossing the Black Sea to reach Europe.

Turkey imports gas from a variety of supply sources i.e. Russia, Iran, Azerbaijan and the global LNG market (with gas from Russia as the main supplier). As EU, Turkey is looking to diversify its supply portfolio, and with that objective, BOTAS are looking to expand its infrastructure[28]. Furthermore, BOTAS has a vision of creating a Southern Gas Hub for the South East European gas market, which potentially then can supply EU with gas in the future.

Today, the EU gas market is supplied at the Greek border by 0.5 bcma from Turkey. An assessment of the Turkish gas market and infrastructure shows, that Turkey in 2030 can have entry capacity to the Turkish market well above[29] (>25 bcma) the domestic demand, thereby able to supply the EU market with large amount of gas in theory. This is of course closely related to the infrastructure projects expanding the entry capacity to EU from Turkey.

The Turkish maximum supply potential is assumed to be 6 bcma in 2030, which can be redirected gas from the Azerbaijan, Russia or LNG. In the TYNDP 2018, this was assessed to be 8 bcma. The projection of the Caspian and Turkish supply potential for the EU is illustrated in Figure 44.
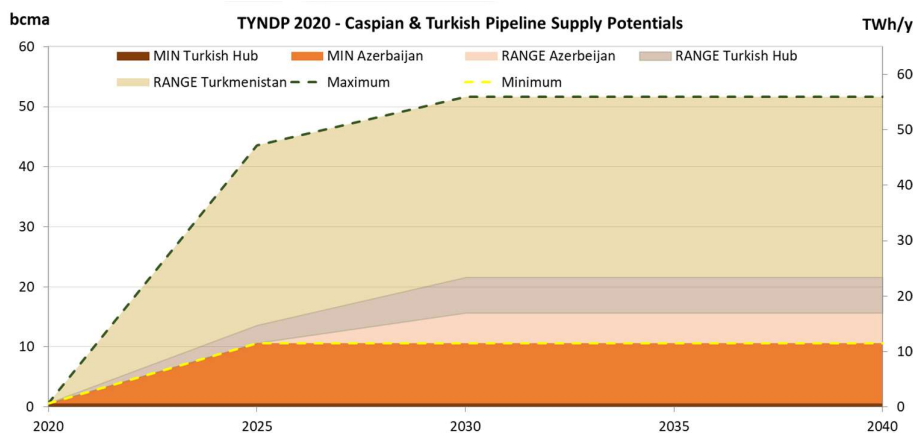
FIGURE 44: CASPIAN AND TURKISH PIPELINE SUPPLY POTENTIAL FOR EU

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[28] Gas Supply Changes in Turkey (OIES, 2018), Turkeys gas demand decline reasons and consequences (OIES, 2017)
[29] Including Turkstream

7.4.2.6   LNG Supply Potential

In recent past, the market share of LNG supply has been around 8%. This might be changing, as the supply for the first half of 2019 is equal to the supply in 2011 with a market share of 15%[30] .

LNG is expected in various studies to play an increasingly important role in Europe[31]. This is partly expected because of the decreasing indigenous EU production and the increasing in liquefication capacity in the world.

For the TYNDP 2020, the projection of the supply to EU is based on IEA's WEO, which is similar to TYNDP 2018. The difference from the last TYNDP is, that a specific projection of the supply potential for **EU** (WEO 2018) is used compared to the last TYNDP, where a projection of the LNG for the **global** market was used (WEO 2017). For the TYNDP 2018, the assessment of the global LNG potential for the EU market was included in the market assumptions. A consequence of this change, the LNG market is represented by different basins than in the TYNDP 2018.

The projection of the maximum potential is approximately constant after 2025 and account for 34% of EU demand (2016). The load factor of utilised capacity is approx. 0.67. Due to the EU perspective in the TYNDP 2020 compared to the global perspective in TYNDP 2018, the maximum potentials are less in the TYNDP 2020 than TYNDP 2018. The projection for the LNG supply potential for EU is illustrated in Figure 45. The Long-term LNG contracts related to the minimum potentials are projected to slowly start expiring from 2030 onwards to 2040.
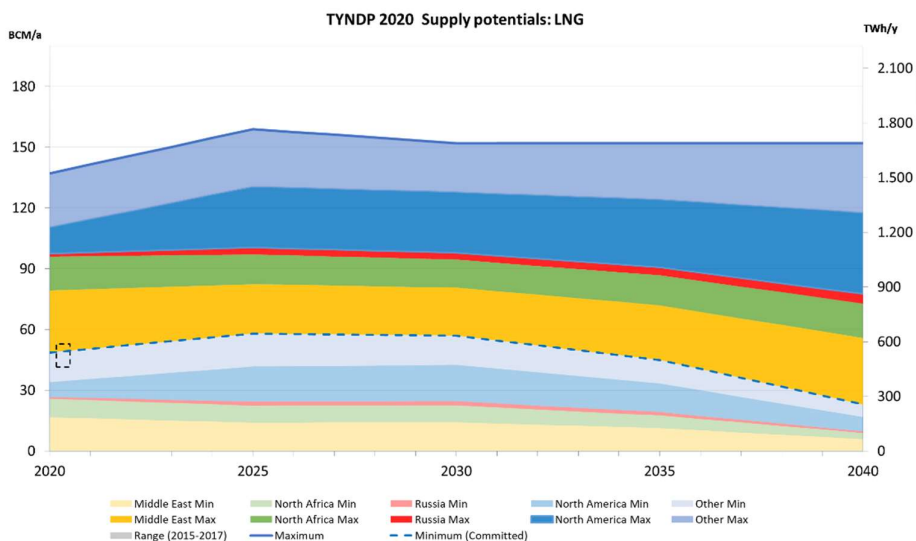
FIGURE 45: LNG SUPPLY POTENTIAL FOR EU

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[30] New energy market reports covering the second quarter of 2019
[31] ENTSOG Workshop: LNG Supply Potential in Europe (IOGP)

7.4.2.7 Hydrogen and Decarbonised Methane Import in a carbon neutral gas system

The Hydrogen and decarbonised methane Import are a review of the feasible technical import potential, which could be available on the EU gas market in a future going towards a carbon neutral energy system in 2050. The review includes both gases produced with known established technologies and technologies in the research and development phase.

For imports to the methane demand both decarbonised natural gas with post-combustive CCU/S or direct green gas can be considered [Fortum Oslo Varme's CCS project, Norcem and Heidelberg Cement CCS project, Gas for Climate (Navigant, 2019)].

For imports to the hydrogen demand, natural gas converted to hydrogen at import point/city gate and direct hydrogen imports are considered [H21-project, H2M-Magnum project, Yorkshire and Humber CCS project, P2X Study 2019 (Frontier), European Commission, Case Study Report - Hydrogen Society (Japan)(2018), Hydrogen from Natural Gas (PÖYRY, 2019)].

For current projects that illustrates the supply feasibility have a look at the ENTSOG Workshop[32] on Low Carbon Supply Potential or ENTSOG's Innovative Projects Platform[33].

7.4.2.8 Export of Supply Potentials

In the period from 2014-18, the EU export or transit to Kaliningrad (Russia) and Turkey have been respectively about 2 bcma (23 TWh/year) and 11 bcma (125 TWh/year) according to ENTSOG transparency platform[34].

The export to Turkey has significantly been reduced the first half of 2019 to about 2 bcm. If this trend continues, the yearly transit will be reduced to approximately 4-5 bcma. This indicated, that the long-term strategical changes in the Turkish supply chain report by the Oxford Institute for Energy Studies[35] among others are starting to show in the gas balance. Another explanation could be a strategical move in the supply route made by Gazprom from the Ukraine-Romania-Bulgaria route to the more direct Russia-Turkey export pipelines. Both explanations, indicate a long-term change in the supply route to Turkey.

For TYNDP 2020, we assume that the recent changes in the supply routes from Gazprom to Turkey is permanent, thereby the transit to Turkey by Ukraine-Romania-Bulgaria will be 5 bcma (155 GWh/d)[36]. For Kaliningrad, a transit of 2 bcma (60 GWh/d) is assumed. This is a reduction in transit compared to the TYNDP 2018, as the transits were assumed to be 104 GWh/d (3.4 bcma) and 461 GWh/d (14.9 bcma) for Kaliningrad and Turkey respectively.

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[32] ENTSOG Workshop: Low Carbon Supply Potential (Equinor)

[33] Innovative Projects Platform

[34] https://transparency.entsog.eu

[35] Gas Supply Changes in Turkey (OIES, 2018), Turkeys gas demand decline reasons and consequences (OIES, 2017)

[36] Turkstream is not included in the assessment.

7.4.3 Extra-EU Import prices

Within the modelling tool, each supply source is described as a supply curve reflecting the supply potential and the gas price in the respective scenario for the given year. The final merit order among the supply sources will consider also transportation costs as well as regasification costs in all European countries. Those elements are not included in the Scenario Report, but in dedicated Annexes that will be published together with the Draft TYNDP 2020 System Assessment Report.

Additionally, it is important to underline that ENTSOG models supply curves with variability around the reference price to allow more competition among sources and avoid "*all or nothing*" situations where cheapest sources are used fully first. Given a certain price the model will therefore take as much gas as it can from each source before moving to more expensive quantities (again from each source).

The way ENTSOG defines the reference price for each of the extra-EU supply sources is described in the following paragraphs.

7.4.3.1 LNG prices

The LNG reference price is determined by ENTSOG through the so-called netback approach. This approach is built under the assumption that Asia will remain the main driver of LNG demand also in the future. A reference price is calculated for each of the LNG basins considered in TYNDP 2020 as follows:

TABLE 19: NETBACK ASIA APPROACH

	Asian LNG price, based on IEA WEO (a)
-	Shipping cost LNG basin to Asia (b)
=	LNG basin price at which the supplier will be indifferent to sell gas to Asia or Europe (c)
+	Shipping cost LNG basin to Europe (d)
=	LNG price in Europe (e)

Below the table of the shipping costs used by ENTSOG.

TABLE 20: SHIPPING COSTS FROM LNG TO RECEIVING REGIONS

$/MMBtu					
LNG Basin \ Receiving Region	**Asia**	**Atlantic**	**Baltic**	**Med. 1**	**Med. 2**
LNG North America	0,70	0,60	0,70	0,65	0,75
LNG Middle East	0,75	0,90	1,00	0,75	0,70
LNG North Africa	1,30	0,25	0,35	0,10	0,20
LNG South Sahara	1,20	0,55	0,65	0,55	0,75
LNG Australia & SE Asia	0,60	1,35	1,45	1,15	1,15
LNG South America 1	1,00	1,00	1,10	1,05	1,15
LNG South America 2	1,35	0,50	0,60	0,55	0,65
LNG Norway	1,50	0,20	0,15	0,35	0,45
LNG Russia	0,60	0,20	0,15	0,35	0,45

With regards to the shipping costs to Europe, in line with TYNDP 2018 and stakeholders feedback, ENTSOG considers four different receiving areas (Atlantic, Baltic, Mediterranean 1 and Mediterranean 2). From one LNG basin, countries belonging to the same receiving area will have the same shipping cost. This simplified approach allows in fact to avoid that significantly small differences among shipping costs will overly influence gas flows results.

It is currently under investigation whether to consider a different approach for US LNG and based on Henry Hub indexation. If so, this will be reflected in the final version of this report.

7.4.3.2 Pipeline gas prices
Below the assumptions used to build the reference prices for pipeline gas.

- Norway pipe: Norway pipe assumption that the Norwegian gas pipe price will be competitive with LNG reaching Atlantic countries taking into account regassification costs and long-term capacity booking contracts. The final price of Norwegian LNG and pipe gas in Europe will also take into account, respectively, the different country regasification costs and transportation costs;

- Russia for North-West Europe: assumption that Russian gas is as competitive as Norwegian gas in Germany;

- Russia for East Europe: other countries have direct import routes from Russia or through other extra-EU countries like Ukraine or Belarus. In those countries the price of Russian gas is defined taking into account the average spread (versus Germany) observed in the European Commission Quarterly Reports [37] (from 2016 to 2018) plus additional assumptions when this value is not available (see Table 21: Spread Russian gas between Germany and other countries);

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[37] https://ec.europa.eu/energy/en/data-analysis/market-analysis

- Algeria pipe: assumption that the Algerian supplier will be indifferent whether to sell its gas via LNG or pipe. The final price of Algerian LNG and pipe gas in Europe will also take into account, respectively, the different country regasification costs and transportation costs. Additionally, it is currently under consideration to split Algerian pipe price between Italy and Spain;

- Libya pipe: considered as expensive as Algeria pipe gas in Italy, the only European country directly connected to Libya;

- Azerbaijan gas: being Italy the exit point of the South Gas Corridor projects (from Azerbaijan production fields to the Trans Adriatic Pipeline), Azerbaijan gas is considered being as expensive as Algerian gas and Libyan gas in Italy, factoring long-term capacity booking contracts;
  Turkmenistan gas: at the Turkmenistan border it is considered being as expensive as Azeri gas at Azeri border. The difference in the final prices of the two sources reaching Europe will be defined by the transportation costs among the possible routes.

Differently from TYNDP 2018 no reference price for the gas flowing to Europe though Turkey is defined. As explained in Section 7.4.2.5 of this report, the gas that Europe could import from Turkey could be from different sources such as Azerbaijan, Russia and LNG. Given the reference costs of those supplies and the related transportation costs, the model will try to minimize the cost for Europe.
=> no specific price since AZ, RU and LNG can flow through Turkey

TABLE 21: SPREAD RUSSIAN GAS BETWEEN GERMANY AND OTHER COUNTRIES

Country	Route to	From	TYNDP 2020 (average from last 3 years)
DE	Germany	Russia	0.00
BG	Bulgaria	Romanian transit system	0.29
CZ	Czech Republic	Czech transit system	0.98
EE	Estonia	Russia	3.62
FI	Finland	Russia	2.37
GR	Greece	Bulgarian transit system	-0.83
HU	Hungary	Ukraine	1.24
LT	Lithuania	Belarus	2.07
LV	Latvia	Estonian transit system	1.41
MK	North Macedonia	Bulgarian transit system	0.29
PL	Poland	Belarus, Yaml-Europe pipeline, Ukraine	2.07
RO	Romania	Ukraine	1.51
SK	Slovakia	Ukraine	1.46
FI	Average of spread for Blatic states		
MK	Bulgarian spread		
PL	Lithuatian spread		

7.5 Biomethane tool – Input assumptions & methodology

This section describes the input assumptions and methodology used to develop the estimations for biomethane potentials in 2050 in ENTSOG's biomethane tool. The Global and Scenario input parameters and the Original Feedstock Raw data used in the calculations can be find in Annex A. A S-curve approach has been applied to compute values for 2030 and 2040. For 2030, it is assumed that 30% of the potentials in 2050 will be produced. For 2045, it is assumed that 95% of the potentials in 2050 will be produced.

7.5.1 Global Inputs and Scenario Inputs

Global Inputs contains all general inputs used throughout the tool impacting the calculations of all feedstock types. In *Global Inputs,* inputs such as the country list, the feedstock categories and feedstock types used throughout the tool are specified.

Other general input assumptions used throughout the calculations are also specified in Annex A. These assumptions refer to the following:

- Natural gas low calorific heating value, later converted into gross calorific value by applying a conversion factor of 110%
- Biomethane low calorific heating value and density, later converted into gross calorific value by applying a conversion factor of 110%
- Biogas and biomethane yields per feedstock type and per technology
- Average shares of biomethane and carbon dioxide in biogas from anaerobic digestion
- Average share of carbon dioxide in biomethane from thermal gasification

Scenario Inputs gathers all inputs specific to each feedstock type included in the tool. In *Scenario Inputs,* an overview of the input assumptions specific to each feedstock type is given. The common parameters for almost all feedstock types are:

- Moisture content (%)
- Allocation share of [*feedstock type*] to biomethane use (%)
- Yield increase to 2050 (%)

With respect to input parameters specific to a feedstock type, please check the relevant *Scenario Inputs section* in Annex A.

7.5.2 Original Feedstock Raw Data

Original Feedstock Raw Data contains the raw data per feedstock type that are used as a basis to calculate the feedstock potentials in 2050. Feedstock potentials are calculated in ktonnes (DM) and 1000 hectares, per feedstock type in the respective data year. Data years vary per feedstock type as follows:

- 2010: Manure
- 2015: Branches & tops
- 2016: Waste wood, Thinnings
- 2017: Sequential cropping, MSW
- 2030: Agricultural residues, Food waste, Sewage sludge, Landscape care wood and roadside verge grass

In the following subsections, a more detailed step by step explanation is given on the methodology used per feedstock type to calculate the feedstock potentials that will lead to the estimated biomethane potentials per Member State by 2050.

7.5.3 Sequential cropping

The sequential cropping concept is based on cultivating a second crop (or winter crop) to produce biomethane in addition to the production of the main crop. No agricultural crops that are produced as the main crop would be used for biomethane production. Sequential cropping is estimated to represent a significant share of the feedstock potential in the EU by 2050. To estimate this potential raw data from Eurostat has been used to extract the utilised agricultural area (UAA) per Member State in 2017.

A share of this utilised agricultural land is assumed to have the potential to be used for sequential cropping. By default, the same share has been assumed for each Member State. However, this can vary significantly per country and it is at the user's discretion to define the most appropriate share for a given country.

$$\text{Land for sequential cropping in 2017 (1000 ha)}$$
$$= \text{UAA per MS (1000 ha)} \textbf{ x } \text{Share of UAA for sequential cropping (\%)}$$

On the other hand, crop yield estimations for sequential crops (winter crops) are calculated as a share of the average summer silage crop yields. The share of summer silage crop yield that would reflect the average sequential crop yield differs per region in Europe. Climatological conditions in southern European countries are more favourable compared to Northern countries where the average yield for sequential crops is assumed to be zero. Table 22 shows the three regions defined, i.e. North, Centre and South, that capture the different climatological conditions in Europe impacting the introduction of sequential cropping.

$$\text{Sequential crop yield in 2050} \left(\frac{\text{tonne DM}}{\text{ha}}\right)$$
$$= \text{Average summer silage crop yield in 2050} \left(\frac{\text{tonne DM}}{\text{ha}}\right) \textbf{ x } \text{Sequential crop yield (\% of average summer silage crop yield)}$$

TABLE 22 REGIONS IN EUROPE WITH VARYING CLIMATOLOGICAL CONDITIONS IMPACTING THE INTRODUCTION OF SEQUENTIAL CROPPING.

Member State region	Member States
North	Denmark, Estonia, Finland, Latvia, Lithuania, Sweden
Centre	Austria, Belgium, Bulgaria, Croatia, Czech Republic, Germany, Hungary, Ireland, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, UK
South	Cyprus, France, Greece, Italy, Spain

Next to that, the average summer silage crop yield in 2050 is calculated by applying a yield increase to the average summer silage crop yield assumed in 2017. Subject to the Member State in question and the region it falls under, different average summer silage crop yields have been estimated, being these higher in Southern countries than in Northern ones due to more favourable climatological conditions.

$$\text{Average summer silage crop yield in 2050} \left(\frac{\text{tonne DM}}{\text{ha}}\right)$$
$$= \text{Average summer silage crop yield in 2017} \left(\frac{\text{tonne DM}}{\text{ha}}\right) \mathbf{x} \left(1 + \text{Yield increase to 2050 (\%)}\right)$$

Finally, the actual sequential crop harvested in 2050 is calculated taking into account the sequential crop yield calculated for 2050 and the available land for sequential cropping in 2017, which is assumed to remain approximately the same as in 2050.

$$\text{Harvested sequential crop in 2050 (ktonnes DM)}$$
$$= \text{Land for sequential cropping in 2017 (1000 ha)} \mathbf{x} \text{ Sequential crop yield in 2050} \left(\frac{\text{tonne DM}}{\text{ha}}\right)$$

Table 23 gives an overview of the input assumptions considered for all intermediate calculation steps to derive the feedstock potential from sequential crops in 2050.

TABLE 23 INPUT ASSUMPTIONS USED FOR FEEDSTOCK POTENTIAL IN 2050 FROM SEQUENTIAL CROPPING.

Parameter	Units	Default value
Share of UAA for sequential cropping	%	10%[38]
Average summer silage crop yield in 2017 - North	tonne/ha DM	10[38]
Average summer silage crop yield in 2017 - Centre	tonne/ha DM	14[38]
Average summer silage crop yield in 2017 - South	tonne/ha DM	20[39]
Yield increase to 2050	%	20%[38]
Average summer silage crop yield in 2050 - North	tonne/ha DM	12
Average summer silage crop yield in 2050 - Centre	tonne/ha DM	17
Average summer silage crop yield in 2050 - South	tonne/ha DM	24
Sequential crop yield as % share of summer crop yield - North	%	0%[38]
Sequential crop yield as % share of summer crop yield – Centre	%	30%[38]
Sequential crop yield as % share of summer crop yield - South	%	60%[38]

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[38] Navigant expert opinion
[39] CIB input

7.5.4 Agricultural residues

Elbersen et al. (2016), in his study "Outlook of spatial biomass value chains in EU-28" assessed the feedstock potential from a set of different agricultural residues that include: cereal straw, grain maize stover, rapeseed and sunflower stubbles, rice straw and sugarbeet leaves, and prunings. Raw data on the estimated sustainable potential per type of agricultural residue and Member State in 2030 is extracted from this study. However, only a share of this sustainable potential will be allocated to the production of biomethane.

Sustainable potential allocated to biomethane use in 2030 (ktonne DM)
= Sustainable potential per agricultural residue type in 2030 (ktonne DM) **x** Allocation share to biomethane use (%)

The percentage share of cereal straw available for energy production is expected to be low. Cereal straw is of high quality, so it finds numerous non-energy uses such as animal bedding and feed. On the other hand, the percentage share of rapeseed & sunflower stubbles available for energy production is expected to be relatively high. Oil crop residues are of low quality so more potential can be allocated for energy production. With regards to prunings, alternative uses of the pruning material other than for nutrient and soil conservation are scarce. The source used assumes that high mobilisation rates are possible to arrive at the estimated potential.

Finally, a yield increase is applied to the sustainable potential allocated to biomethane use in 2030 to estimate that of 2050. In the default scenario, for straw and stubble no major changes are foreseen in the total potential towards 2050. For prunings, figures for 2030 from the high biomass sustainability scenario in the Elbersen et al. study are taken. However, after 2030 no major changes in potentials are expected as there is a limit to the mobilisation of biomass that is currently burned on the field. Olive pits potential is expected to stay the same towards 2050.

Sustainable potential allocated to biomethane use in 2050 (ktonne DM)
= Sustainable potential allocated to biomethane use in 2030 (ktonne DM) **x** (1
+ Yield increase to 2050 (%))

Following table shows the input assumptions related to the calculation steps followed to estimate the feedstock potential from agricultural residues in 2050.

TABLE 24: INPUT ASSUMPTIONS USED FOR FEEDSTOCK POTENTIAL IN 2050 FROM AGRICULTURAL RESIDUES.

Parameter	Units	Default value
Allocation share of agricultural residues to biomethane use - Cereal straw	%	30%[40]
Allocation share of agricultural residues to biomethane use – Grain maize stover	%	50%[38]
Allocation share of agricultural residues to biomethane use – Rapeseed & sunflower stubbles, rice, straw and sugarbeet leaves	%	50%[38]
Allocation share of agricultural residues to biomethane use – Prunings (including apples, peers, cherries, vineyards, olive pits and citrus)	%	100%[41]
Yield increase to 2050	%	0%[42]

7.5.5 Food waste

In the case of food waste feedstock, raw data on the total technical potential of animal and mixed food waste plus vegetable waste in 2030 is extracted from Elbersen et al. (2016). An additional share needs to be considered on top of the estimated technical potential to derive the sustainable potential. This share is referred to in the calculations as *additional share from technical to sustainable potential*.

Sustainable potential of food waste in 2030 (ktonne as received)
$=$ Total technical potential of animal & mixed food waste plus vegetable waste in 2030 (ktonne as received) x (1
$+$ Additional share from technical to sustainable potential (%))

Since the raw data on the total technical potential of animal and mixed food waste plus vegetable waste is given in ktonnes of fresh matter, a moisture content factor needs to be applied to calculate the remaining dry matter available for production of biomethane.

Sustainable potential of food waste in 2030 (ktonne DM)
$=$ Sustainable potential of food waste in 2030 (ktonne as received) $\mathbf{x}$ (1 – Moisture content (%))

Finally, a yield increase is applied to derive the sustainable potential of food waste in 2050, in case it becomes relevant. By default, this factor has been set to zero since no major changes are expected in the feedstock amounts for food waste. Table 25 gives an overview of the input assumptions related to the calculation steps followed to estimate the feedstock potential from food waste in 2050.

Sustainable potential of food waste in 2050 (ktonne DM)
$= $ Sustainable potential of food waste in 2030 (ktonne DM)$\mathbf{x} \left(1 + \text{Yield increase to 2050 } (\%)\right)$

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[40] Spottle et al., 2013, "Low ILUC potential of wastes and residues for biofuels: Straw, forestry residues, UCO, corn cobs", http://www.mvak.eu/test5674213467/Ecofys_2013_low_ILUC.pdf

[41] Elbersen et al., 2016, "Outlook of spatial biomass value chains in EU-28"

[42] Navigant expert opinion considering the EU Agricultural Outlook for 2030, https://ec.europa.eu/info/sites/info/files/food-farming-fisheries/farming/documents/medium-term-outlook-2018-report_en.pdf

TABLE 25: INPUT ASSUMPTIONS USED FOR FEEDSTOCK POTENTIAL IN 2050 FROM FOOD WASTE.

Parameter	Units	Default value
Additional share from technical to sustainable potential	%	10%[38]
Moisture content	%	40%[41]
Yield increase to 2050	%	0%[38]

7.5.6 Manure

The Elbersen et al. study was also used to extract the raw data on the technical potential of manure produced in stables in dry matter basis for the year 2010 throughout Europe. Different solid (cattle, pig, poultry, sheep/goat) and liquid (cattle, pig) manure types are considered and different sustainable shares per manure type and per Member State are applied to estimate the sustainable potential of this feedstock.

$$\text{Sustainable potential of manure produced in stables in 2010 (ktonne DM)}$$
$$= \text{Technical potential of manure produced in stables in 2010 (ktonne DM) } \mathbf{x}$$
$$\text{Sustainable potential share per manure type in 2010 (\%)}$$

As with other feedstock types, a yield increase factor is applied to estimate the potential in 2050 compared to 2010. However, no major changes are expected in the total manure potential towards 2050 as EU livestock heads would remain approximately the same as suggested by the EU Agricultural Outlook for 2030.

$$\text{Sustainable potential of manure produced in stables in 2050 (ktonne DM)}$$
$$= \text{Sustainable potential of manure produced in stables in sustainable scenario in 2010 (ktonne DM) } \mathbf{x} \, (1$$
$$+ \text{ Yield increase to 2050 (\%))}$$

TABLE 26: INPUT ASSUMPTIONS USED FOR FEEDSTOCK POTENTIAL IN 2050 FROM MANURE.

Parameter	Units	Default value
Sustainable potential shares per manure types	%	*See Table 19*
Yield increase to 2050	%	0%[42]

TABLE 27: SUSTAINABLE POTENTIAL SHARES TO CALCULATE THE SUSTAINABLE POTENTIAL FOR DIFFERENT MANURE TYPES AND PER MEMBER STATE.

Member State	Solid				Liquid	
	Cattle	Pig	Poultry	Sheep/Goat	Cattle	Pig
Austria	3%	30%	30%	1%	5%	61%
Belgium	9%	33%	26%	2%	18%	66%
Bulgaria	34%	49%	46%	13%	67%	98%
Croatia	0%	0%	0%	0%	0%	0%
Cyprus	47%	49%	44%	12%	93%	99%
Czech Republic	44%	0%	42%	9%	85%	96%
Denmark	39%	50%	49%	18%	91%	99%
Estonia	38%	48%	1%	7%	73%	97%
Finland	13%	41%	42%	2%	22%	82%
France	30%	49%	45%	13%	61%	97%
Germany	30%	44%	45%	18%	60%	88%
Greece	16%	33%	28%	2%	33%	67%
Hungary	37%	36%	34%	11%	70%	72%
Ireland	19%	0%	47%	11%	45%	99%
Italy	29%	0%	47%	6%	57%	94%
Latvia	38%	47%	33%	17%	75%	95%
Lithuania	13%	38%	41%	7%	26%	75%
Luxembourg	0%	0%	0%	0%	0%	0%
Malta	16%	38%	29%	1%	32%	76%
Netherlands	28%	0%	33%	1%	0%	53%
Poland	37%	0%	49%	19%	73%	98%
Portugal	5%	18%	40%	2%	11%	36%
Romania	27%	44%	39%	9%	44%	88%
Slovakia	45%	44%	40%	30%	90%	88%
Slovenia	28%	46%	46%	7%	65%	92%
Spain	21%	46%	47%	19%	40%	93%
Sweden	4%	0%	17%	6%	9%	32%
UK	38%	41%	39%	35%	84%	81%

7.5.7 Sewage sludge

Raw data was extracted from the Elbersen et al. study, where they assessed the potential of common sludges produced in households and in other sectors in 2030 in dry matter basis. In addition, a yield increase was applied to estimate the 2050 potential. However, as Table 28 shows, the potential is estimated to remain the same as in 2030.

Total potential of common sludges produced in households and in other sectors in 2050 (ktonne DM)
= Total potential of common sludges produced in households and in other sectors in 2030 (ktonne DM) **x** (1 + Yield increase to 2050 (%))

TABLE 28: INPUT ASSUMPTION USED FOR FEEDSTOCK POTENTIAL IN 2050 FROM SEWAGE SLUDGE.

Parameter	Units	Default value
Yield increase to 2050	%	0%[41]

7.5.8 Municipal Solid Waste (MSW)

Eurostat provided raw data on the municipal waste generated in 2017 in fresh matter basis. However, only the dry organic fraction of it is suitable for biomethane production. Therefore, a share representing the organic fraction and a share for the moisture content are applied.

Organic municipal waste generated in 2017 (ktonne as received)
= Municipal waste generated in 2017 (ktonne as received) **x** Share of organic fraction in MSW (%)

Organic municipal waste generated in 2017 (ktonne DM)
= Organic municipal waste generated in 2017 (ktonne as received) **x** (1 – Moisture content (%))

Additionally, it is assumed that only a share of the dry organic municipal waste generated will be allocated to biomethane use.

Organic municipal waste generated allocated to biomethane use in 2017 (ktonne DM)
= Organic municipal waste generated in 2017 (ktonne DM)**x** Allocation share of organic volume to biomethane use (%)

Finally, a yield increase of -30% is assumed in this case to estimate the potential in 2050. A reduction in municipal waste is expected towards 2050 due to increased separation and recycling.

Organic municipal waste generated allocated to biomethane use in 2050 (ktonne DM)
= Organic municipal waste generated allocated to biomethane use in 2017 (ktonne DM) **x** (1 + Yield increase to 2050 (%))

Following table shows the input assumptions related to the calculation steps followed to estimate the feedstock potential from municipal solid waste in 2050.

TABLE 29: INPUT ASSUMPTIONS USED FOR FEEDSTOCK POTENTIAL IN 2050 FROM MUNICIPAL SOLID WASTE (MSW).

Parameter	Units	Default value
Share of organic fraction in MSW	%	60%[38]
Moisture content	%	40%[38]
Allocation share of organic volume to biomethane use	%	30%[38]
Yield increase to 2050	%	-30%[38]

7.5.9 Waste wood

Raw data from Eurostat was collected on wood waste generated in fresh matter basis for 2016. A moisture content factor was applied as well as a share to account for the part that will be allocated to biomethane use. Finally, a yield increase was applied to derive the 2050 potential of waste wood. Overall, waste wood will stabilize, so same figures as in 2016 apply for 2050.

$$\text{Wood waste generated in 2016 (ktonne DM)}$$
$$= \text{Wood waste generated in 2016 (ktonne as received)} \times (1 - \text{Moisture content (\%)})$$

$$\text{Wood waste generated allocated to biomethane use in 2016 (ktonne DM)}$$
$$= \text{Wood waste generated in 2016 (ktonne DM)} \times \text{Allocation share of waste wood to biomethane use (\%)}$$

$$\text{Wood waste generated allocated to biomethane use in 2050 (ktonne DM)}$$
$$= \text{Wood waste generated allocated to biomethane use in 2016 (ktonne DM)} \times (1 + \text{Yield increase to 2050 (\%)})$$

Table 30 shows the input assumptions related to the calculation steps followed to estimate the feedstock potential from waste wood in 2050.

TABLE 30: INPUT ASSUMPTIONS USED FOR FEEDSTOCK POTENTIAL IN 2050 FROM WASTE WOOD.

Parameter	Units	Default value
Moisture content	%	20%[43]
Allocation share of waste wood to biomethane use	%	50%[43]
Yield increase to 2050	%	0%[43]

7.5.10 Landscape care wood & roadside verge grass

Landscape care wood and roadside verge grass potentials for 2030 are estimated in Elbersen et al. study in fresh matter basis. Again, this source is used for the raw data of this feedstock type. Next to that, by applying a moisture content factor, an allocation share to biomethane use and a yield increase share, the potential allocated to biomethane use in dry matter basis and for 2050 is estimated. The Elbersen et al. study does not expect major changes in the total potential in 2050. It is assumed that it will remain stable.

$$\text{Landscape care wood in 2030 (ktonne DM)}$$
$$= \text{Landscape care wood in 2030 (ktonne as received)} \times (1 - \text{Moisture content (\%)})$$

$$\text{Roadside verge grass in 2030 (ktonne DM)}$$
$$= \text{Roadside verge grass in 2030 (ktonne as received)} \times (1 - \text{Moisture content (\%)})$$

$$\text{Landscape care wood allocated to biomethane use in 2030 (ktonne DM)}$$
$$= \text{Landscape care wood in 2030 (ktonne DM)} \times$$
$$\text{Allocation share of landscape care wood and roadside verge grass to biomethane use (\%)}$$

$$\text{Roadside verge grass allocated to biomethane use in 2030 (ktonne DM)}$$
$$= \text{Roadside verge grass in 2030 (ktonne DM)} \times$$
$$\text{Allocation share of landscape care wood and roadside verge grass to biomethane use (\%)}$$

$$\text{Landscape care wood allocated to biomethane use in 2050 (ktonne DM)}$$
$$= \text{Landscape care wood allocated to biomethane use in 2030 (ktonne DM)} \times (1 + \text{Yield increase to 2050 (\%)})$$

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[43] Ecofys, 2018, "Mobilising woody residues to produce biomethane"

Roadside verge grass allocated to biomethane use in 2050 (ktonne DM)
$$= \text{Roadside verge grass allocated to biomethane use in 2030 (ktonne DM)} \times (1 + \text{Yield increase to 2050 (\%))}$$

Table 31 gives an overview of the input assumptions in relation to the calculation steps followed to estimate the feedstock potential from waste wood in 2050.

TABLE 31: INPUT ASSUMPTIONS USED FOR FEEDSTOCK POTENTIAL IN 2050 FROM LANDSCAPE CARE WOOD & ROADSIDE VERGE GRASS

Parameter	Units	Default value
Moisture content	%	25%[38]
Allocation share of landscape care wood and roadside verge grass to biomethane use	%	90%[43]
Yield increase to 2050	%	0%[41,43]

7.5.11 Thinnings

Eurostat is used as the source for raw data on the harvest of roundwood removal, for both coniferous and non-coniferous species, per Member State in fresh matter basis and in 1000 m^3. In order to calculate the total potential of primary thinnings in seasoned wood allocated to biomethane use, the following parameters need to be applied:

- Mass density of thinnings (tonnes/m^3) – this allows to calculate the raw potential in ktonnes
- Moisture content (%) – this allows to calculate the share of the potential that is dry wood and hence suitable for energy use
- Harvest increase to 2050 – this accounts for the expected increase in the harvest of wood growth
- Yield increase to 2050 – to estimate the increase in the yield of wood growth
- Share of primary thinnings as % of roundwood removal – this accounts for the part of roundwood removal that is actually primary thinnings
- Allocation share of primary thinnings to biomethane use – finally, this accounts for the share of primary thinnings that will be allocated to biomethane production

The formulas below reflect each of the calculation steps when applying each and every of the parameters above.

Roundwood removal − seasoned wood in 2016 (ktonne as received)
$$= \text{Roundwood removal} - \text{all species (over bark) in 2016 (1000 m3)} \times \text{Mass density of thinnings (tonnes/m3)}$$

Roundwood removal − seasoned wood in 2016 (ktonne DM)
$$= \text{Roundwood removal} - \text{seasoned wood in 2016 (ktonne as received)} \times (1 - \text{Moisture content (\%))}$$

Roundwood removal − seasoned wood in 2050 (ktonne DM)
$$= \text{Roundwood removal} - \text{seasoned wood in 2016 (ktonne DM)} \times (1 + \text{Harvest increase to 2050 (\%)} + \text{Yield increase to 2050 (\%))}$$

Primary thinnings in seasoned wood in 2050 (ktonne DM)
= Roundwood removal
− seasoned wood in 2050 (ktonne DM) **x** Share of primary thinnings from roundwood removal (%)

Primary thinnings in seasoned wood allocated to biomethane use in 2050 (ktonne DM)
= Primary thinnings in seasoned wood in 2050 (ktonne DM)**x**
Allocation share of primary thinnings to biomethane use (%)

Table 32 shows the input assumptions used in each calculation step to derive the feedstock potential from thinnings in 2050.

TABLE 32: INPUT ASSUMPTIONS USED FOR FEEDSTOCK POTENTIAL IN 2050 FROM THINNINGS

Parameter	Units	Default value
Mass density of thinnings	tonnes/m^3	0.50[44]
Moisture content	%	20%[44]
Harvest increase to 2050	%	20%[38]
Yield increase to 2050	%	10%[38]
Share of primary thinnings as % of roundwood removal	%	5%[38]
Allocation share of primary thinnings to biomethane use	%	100%[38]

7.5.12 Branches & tops

Similarly, as with thinning, raw data from Eurostat was collected on the roundwood (wood in the rough) for over bark for coniferous and non-coniferous species (1000 m^3) for the year 2015 per Member State.

In order to calculate the total potential of branches and tops from roundwood, the following parameters are applied:

- Average BEFs for coniferous and non-coniferous species in EU – these factors allow to estimate the amount of crown mass for different species groups according to the climatic zone. Member States are categorised by climatic zone. Within the EU-27, Member States are predominantly located in the temperate climatic zone
- Sustainable removal rate of branches & tops (%) – this accounts for the rate at which branches & tops are sustainably removed from trees. This estimate already includes sustainable potential
- Mass density of branches & tops (tonnes/m^3) - this allows to calculate the potential in ktonnes
- Moisture content (%) – this allows to calculate the share of the potential that is dry wood and hence suitable for energy use
- Yield increase to 2050 – to account for the increase in the yield of forestry residues assumed towards 2050

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[44] Engineering toolbox: https://www.engineeringtoolbox.com/wood-density-d_40.html

The formulas below guide the calculation steps applied with each parameter above.

Sustainably removed roundwood in 2015 – coniferous species (1000 m3)
$$= \text{Roundwood for over bark for coniferous species in 2015 (1000 m3)} \times \text{Average BEFs}$$
$$- \text{Coniferous species in EU} \times \text{Sustainable removal rate of branches \& tops (\%)}$$

Sustainably removed roundwood in 2015 – non − coniferous species (1000 m3)
$$= \text{Roundwood for over bark for non}$$
$$- \text{coniferous species in 2015 (1000 m3)} \times \text{Average BEFs} - \text{Non}$$
$$- \text{coniferous species in EU} \times \text{Sustainable removal rate of branches \& tops (\%)}$$

Sustainably removed roundwood in 2015 – coniferous & non − coniferous species (ktonne DM)
$$= \text{Sustainably removed roundwood in 2015 – coniferous \& non}$$
$$- \text{coniferous species (1000 m3)} \times \text{Mass density of branches \& tops (tonnes}$$
$$/\text{m3)} \times (1 - \text{Moisture content (\%)})$$

Sustainably removed roundwood in 2050 – coniferous & non − coniferous species (ktonne DM)
$$= \text{Sustainably removed roundwood in 2015 – coniferous \& non}$$
$$- \text{coniferous species (ktonne DM)} \times (1 + \text{Yield increase to 2050 (\%)})$$

Table 33 shows the input assumptions used in each calculation step to derive the feedstock potential from branches and tops in 2050.

TABLE 33: INPUT ASSUMPTIONS USED FOR FEEDSTOCK POTENTIAL IN 2050 FROM BRANCHES & TOPS

Parameter	Units	Default value
Average Biomass Expansion Factors (BEFs) - Coniferous species in EU temperate climate zone	-	0.30[40]
Average Biomass Expansion Factors (BEFs) - Non-coniferous species in EU temperate climate zone	-	0.40[40]
Sustainable removal rate of branches & tops	%	20%[40]
Moisture content	%	20%[44]
Mass density of branches & tops	tonnes/m³	0.50[44]
Yield increase to 2050	%	10%[38]

Power-to-Gas Development

8 Power-to-Gas

With increasing climate ambitions and progressing energy transition both the electricity and gas sector face challenges to further decarbonise. Electricity generation by wind turbines and PV does not match the demand at all hours and, even nowadays, in some regions the electricity grid is stretched to its limits in integrating further installations of variable renewables (e.g. northern Germany). The gas sector, on the contrary, needs to decarbonise to be an option in a highly or even fully decarbonised energy system.

Power-to-gas (P2G) provides the solution for both challenges. It can be used to convert excess electricity into carbon-neutral hydrogen and/or methane and also produce these gaseous fuels from dedicated renewables.
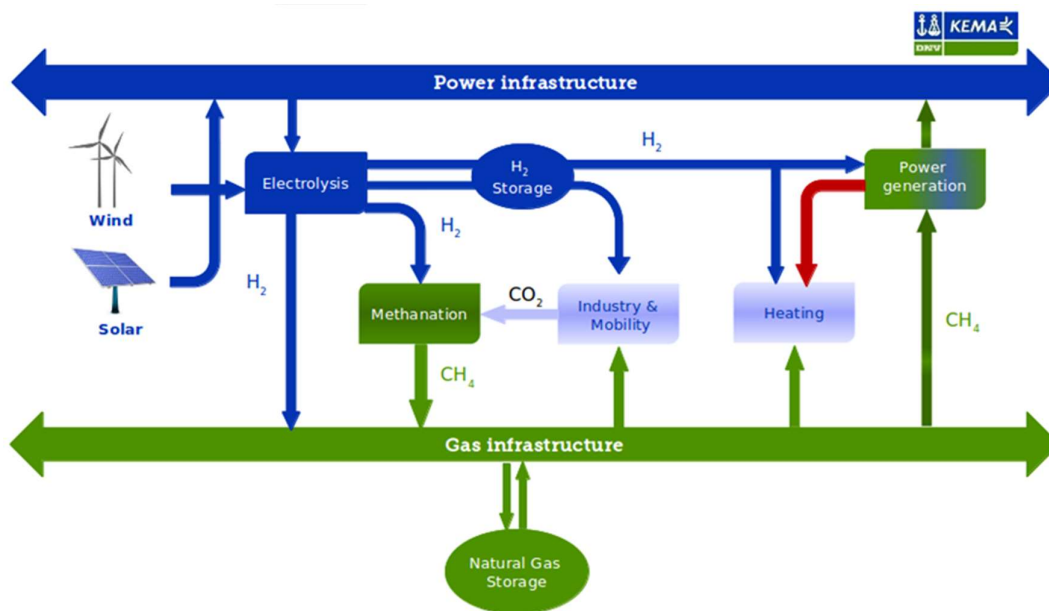

FIGURE 46: P2G PROCESS CHAIN

Following their assessment on P2G made in the TYNDP 2018 Scenario Report, ENTSOs further improved their assumptions and methodologies on the quantification, distribution and optimisation of P2G in the EU28.

8.1 Introduction to P2G

P2G processes involve the production of gaseous fuels from mostly low-cost renewable electricity. There are two main P2G processes. The first one involves the production of hydrogen via electrolysis of water using electricity. Today, there are three technological options to produce hydrogen via electrolysis: alkaline water electrolysis, polymer electrolyte membrane electrolysis and solid oxide electrolysis. Each technology has its own characteristics and differentiating factors and are at different technology readiness levels. The second type of process (methanation), involves producing synthetic methane through hydrogenation of carbon dioxide as an additional step to electrolysis or as a coupled process to anaerobic digestion in

biogas plants. Synthetic methane can be injected into the gas grid without any new requirements or modifications to the existing infrastructure, but further efficiency losses during the methanation process need to be taken into account.

If renewable energy cannot be integrated in the electricity infrastructure, P2G does offer the possibility to store renewable energy, to transport it over long distances by using the gas infrastructure or directly use it as a feedstock in industry. At this moment in time, hydrogen injection in the gas grid is in a pilot stage whereas synthetic methane can be fully injected. The permissible levels of hydrogen [injection in to the gas grid] are typically set by national legislation and are currently up to 10 % (Germany). This source of green gas can be used to decarbonise sectors that will struggle to move to direct electrification. It also has the potential to provide a demand side balancing mechanism to the power system. In addition, it could enable the installed capacity of renewable power generation to increase, along with the overall usage of renewable sources in the energy mix. P2G is a technology that enables the convergence of the electricity and gas systems, utilising the respective strengths of each.

8.2   Technology Review

8.2.1   Alkaline Water Electrolysis

Alkaline water electrolysis (ALK) has been used for almost a century in the industrial sector. The process involves an electrolyser that uses two electrodes operating in a liquid alkaline solution. A porous foil, typically referred to as diaphragm, keeps both the electrodes and the gases produced in the reaction separate. Hydroxide ions are transported from one electrode to the other through the diaphragm thanks to the ionic conductivity of the aqueous alkaline solution.

Electricity (e.g. produced from variable renewable sources) can be used to feed the electrolyser. The hydrogen is produced at atmospheric pressure or up to 15 bar. Output pressures lower than this would translate into a higher cost downstream to pressurize the hydrogen for end uses. A compressor can also be used, and a constant flow of hydrogen could be guaranteed by installing a gaseous storage at 30 bar and oversizing the electrolyser. Currently the lifetime of the alkaline water electrolyser is twice as long as the other electrolyser technologies available and it is expected to remain significantly longer in the next decade.[45]

From a technical perspective, the operation of the alkaline water electrolyser is optimised at a constant lower load than the nominal and is in general less flexible for supporting grid services compared to other electrolyser technologies. It can handle lower load ranges and have longer start up and shut down response times. However, existing models are being improved in this respect. On the other hand, short timescale grid services such as Frequency Restoration Reserve

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[45] ASSET, Sectoral integration- long-term perspective in the EU Energy System; pages 33, 118; 2018

(FRR) and Replacement Reserves (RR) could be adequately addressed by alkaline water electrolysers.[46]

Current efficiencies are around 67 – 82 %[47] with the potential to increase up to 85 %[48] in the long-term (2040 – 2050).

8.2.2 Polymer Electrolyte Membrane electrolysis

The polymer electrolyte membrane (PEM) electrolyser was first developed in the 1960s. It was developed to overcome the drawbacks of the alkaline electrolysis technology, namely partial load issues, low current density and low-pressure operation. An electrolyser of this type uses a solid polymer electrolyte that conducts protons, separates the product gases and provides electrical insulation to the electrodes. The hydrogen is produced at a higher pressure compared to alkaline electrolysers, typically at around 30 bar. This means that the compression required downstream to reach end-use pressures is lower. In mobility applications (e.g. fuel stations) PEM electrolysers are, therefore, very relevant.

This technology is already commercially available and one of its key selling points is its higher levels of flexibility, making it suitable for a wider range of grid services, mainly primary reserve services. The PEM electrolyser can capture sudden spikes of power production coming from renewable energy sources. The feasibility of using central large-scale PEM electrolysers to supply both grid services and hydrogen for high-value markets, such as in the industry and mobility sectors, was proven by the HyBalance project.[49] This flexibility in operation allows it to capture different revenue streams from multiple markets.

In technical terms, the PEM electrolyser can be operated with minimum electricity consumption and it can ramp up to up to 160 % or 200 % of its nominal load for around 10 minutes. As with alkaline electrolysers, the PEM electrolysers also operate with higher efficiency below their nominal load. PEM electrolysers currently have a shorter lifetime than alkaline electrolysers.[50]

PEM electrolysers that are connected to the grid are the most competitive since they enable the operator to fully optimise the electricity purchases and the plant's utilisation rate. The plant's business case could be improved by not only supplying hydrogen to the industry or mobility sectors, or the gas grid, but also by providing ancillary services to the grid. This revenue stream can be considered as a reduction in the cost of electricity.[51]

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[46] FCH JU, Study on early business cases for H2 in energy storage and more broadly power to H2 applications, pages 2, 47, 48; 2017.

[47] DENA, 2015, Efficiency based on Gross Calorific Value. Specific energy consumption: 4 - 5 kWh/Nm3 H2

[48] ASSET, 2018

[49] FCH JU, Fuel cell and hydrogen technology: Europe's journey to a greener world, pages 57, 65; 2017

[50] FCH JU, Study on early business cases for H2 in energy storage and more broadly power to H2 applications, pages 2, 47, 48; 2017

[51] DENA, Power to Gas - Opportunities, challenges and parameters on the way to marketability, page 10; 2015.

Current efficiencies are around 44 – 86 %[52] with the further potentials in the long-term.

As in the case of ALK electrolysers, driving technology scale-up and achieving further cost reductions from this scale-up is the most critical challenge now. While R&D investments are still needed for further efficiency and lifetime improvements, [53] the 20 MW capacity PEM electrolysers envisioned in the short-term are already unlocking the potential and availability of large scale green hydrogen production.[54]

8.2.3 Solid Oxide Electrolysis

Solid oxide electrolysers (SOEC) are a less mature technology, still in the development phase and only demonstrated in the laboratory on a small demonstration scale. However, 1 MW capacity SOEC electrolysers will be realised in the medium-term. These electrolysers are made of predominantly of ceramic and use only limited rare materials for their catalyst layers.[55] They operate in high temperatures, contrary to the ALK and PEM technologies, and are highly efficient, with up to 90 % efficiency according to Helmeth project (co-funded by the Fuel Cells and Hydrogen Joint Undertaking/FCH JU).

SOEC electrolysis is a promising technology that offers the potential of greater energy efficiencies of up to 90 % in the medium- and long-term and the possibility to produce a synthesised gas directly from steam and carbon dioxide that can be used in many applications. A factor that might limit the long-term economic variability of this technology is the requirement of high-temperature heat sources close by. Leveraging on industrial processes that deliver heat as a by-product or on synergies with renewable sources like geothermal energy or concentrated solar power (CSP), which produces both electricity and steam on-site, would ensure that all energy inputs are renewable.[56]

8.2.4 Methanation

Methanation is the process of producing synthetic methane with almost identical properties to fossil natural gas from carbon dioxide through hydrogenation. It can be implemented as an additional step to electrolysis in the power-to-gas process, entailing additional efficiency losses.[57] A methanation reactor unit would then be required in addition to the electrolyser unit. Synthetic natural gas (SNG) can be then integrated in the gas grid without any other restrictions.

Catalytic methanation is a thermochemical process that operates at high temperatures, around 450°C on the catalyst, and pressures up to 10 bar. The methanation reaction is highly exothermic and controlling the temperature inside the reactor can be challenging. The variable operation

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[52] DENA, 2015, Efficiency based on HHV. Specific energy consumption: 4 - 5 kWh/Nm3 H2

[53] IRENA, Hydrogen from Renewable Power - Technology outlook for the energy transition, pages 19-21, 23; 2018.

[54] FCH JU, Fuel cell and hydrogen technology: Europe's journey to a greener world, pages 57, 65; 2017.

[55] FCH JU, Fuel cell and hydrogen technology: Europe's journey to a greener world, pages 57, 65; 2017.

[56] IRENA, Hydrogen from Renewable Power - Technology outlook for the energy transition, pages 19-21, 23; 2018.

[57] DENA, Power to Gas - Opportunities, challenges and parameters on the way to marketability, page 10; 2015.

characteristic of power-to-gas processes gradually undermines the performance of catalysts. For this reason, isothermal reactors in the order of magnitude of 1 - 10 MW for power-to-gas processes are best suited. Currently R&D efforts are focused on improving the design of the reactor to boost the performance of the cooling system through the recovery of the reactor's heat.[58]

Investment costs for methanation reactors are currently high and the overall efficiency of the reaction reaches 80 %. According to estimates by the Helmeth project, an integrated power-to-methane system based on high temperature SOEC electrolyser modules and thermal integration with the methanation module could bring the overall efficiency of the power-to-gas process to 85 %.

8.2.5 Technology assumptions for the TYNDP Scenarios

As mentioned above, different types of electrolysers could be applied for P2G. Due to the long-term character of the TYNDP Scenarios and the uncertainty of technological improvements, no explicit "winner" is chosen. For the electrolysis process an average efficiency of 80 % for 2030 and 85 % for 2040 is considered[59] (based on higher calorific value). A further efficiency loss is given during the methanation process, when converting hydrogen to methane. For this process a general efficiency of 80 % is considered.

Overall Efficiencies	2030	2040
Power-to-Hydrogen	80 %	85 %
Power-to-Methane	64 %	68 %

TABLE 34: GAS EFFICIENCIES

Since National Trends does not differ between the gas types, an average efficiency of 72 % for 2030 and 77 % for 2040 is used.

8.3 P2G Methodologies

ENTSOs have improved their methodologies for the quantification, distribution and optimization of P2G. Following the scenario storylines, different methodologies were applied to bottom-up and top-down scenarios.

General methodologies for bottom-up Scenarios

For National Trends, as it is a bottom-up scenario, only excess electricity from the electricity market simulations was taken into account. To quantify the economic viable P2G production necessary FLH of P2G facilities are calculated. NT2030 requires 1622 FLR, NT2040 required 910 full load hours. The ENTSOs assume that P2G is economic viable, provided that hydrogen can be produced at the same or at a lower price than natural gas including a given CO_2-price in the scenario year. Following this equation minimum yearly full load hours for P2G facilities can be calculated. The intersection of aforementioned minimum full load hours and the duration curve

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[58] Enea Consulting, The potential of power-to-gas; pages 12, 38; 2016.

[59] Asset, Sectoral integration - Long-term perspective in the EU Energy System, https://ec.europa.eu/energy/sites/ener/files/documents/final_draft_asset_study_12.05.pdf, p. 19

for excess electricity gives a first potential for economic viable P2G production in a country. The real P2G production can be higher or lower, depending on the distance of RES facilities to the grid, the local excess electricity duration curve etc.

For National Trends, an average efficiency for P2G for methane and hydrogen of 72 % in 2030 and 77 % in 2040 is considered.

General methodology for top-down scenarios

In the top-down scenarios, P2G is not only considered for excess-electricity, but also as an option to decarbonize the gas supply in compliance with the climate targets of the scenarios Distributed Energy and Global Ambition.

ENTSOs have applied a multi-step approach, starting from EU-wide annual demand figures (demand expresses the need for renewable gas production via P2G) to the distribution of such annual figures to member states and, finally, the optimisation of dedicated RES and P2G facilities per country. The figures are shown in Figure 47 and further explained in following sections.
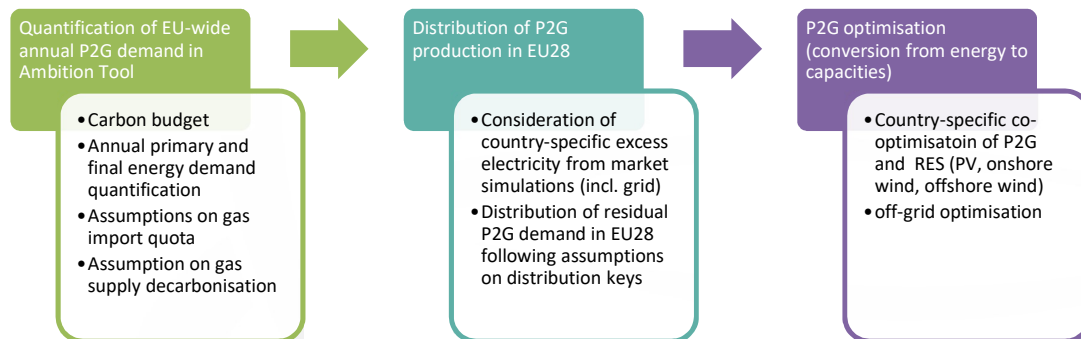
Quantification of EU-wide annual P2G demand in Ambition Tool	Distribution of P2G production in EU28	P2G optimisation (conversion from energy to capacities)
• Carbon budget • Annual primary and final energy demand quantification • Assumptions on gas import quota • Assumption on gas supply decarbonisation	• Consideration of country-specific excess electricity from market simulations (incl. grid) • Distribution of residual P2G demand in EU28 following assumptions on distribution keys	• Country-specific co-optimisatoin of P2G and RES (PV, onshore wind, offshore wind) • off-grid optimisation

FIGURE 47: P2G METHODOLOGY FOR TOP-DOWN SCENARIOS

8.3.1 Calculating Power-to-Gas Annual Energy Volumes

For the quantification of the production of synthetic hydrogen and methane via P2G, a two-step approach is used.

In National Trends, the production of renewable gas via P2G depends only on the amount of excess electricity as a result of the electricity market studies.

For the two top-down scenarios GA and DE, the overall need for synthetic gases via P2G is given by the Ambition Tool as an equation of the decarbonization target of the gas mix and the import quota.

For the decarbonisation of the gas supply, both the EU and most of the EU member states lack long-term targets. Therefore, ENTSOs have based their assumptions on the the decarbonisation pathway shown in European Commission's study "The role of trans-European gas infrastructure

in the light of the 2050 decarbonisation targets"[60]. As a reference the "Methane Scenario" was chosen.

As for the decarbonisation of the gas supply, also for self-sufficiency or, the other way round, for the reduction of the import quota for gas currently no targets are in place. ENTSOs assume that the reduction of import quota will be driven rather by policies and national quotas than by economics. To have differing scenarios in terms of import needs (imports are a main driver for gas transmission infrastructure needs), the selected storylines include assumptions on import shares of 35 % for Distributed Energy and 70 % for Global Ambition by 2050. Further information are shown in Table 35.

TABLE 35: P2G ANNUAL DEMAND QUANTIFICATION

	Explanation	Distributed Energy	Global Ambition
Quantification of P2G demand			
Gas Demand	Annual demand in TWh	Demand for methane and hydrogen from Ambition Tool	
Gas Decarbonisation	Target for renewable gases (biomethane, P2G, Blue Hydrogen) in % share of total gas supply	- Increasing renewable gas share in compliance with Methane Scenario of EC's "Gas Infrastructure 2050 Study" - 14 % in 2030, 54 % in 2040, full decarbonisation of gas supply by 2050	
EU28 Import Quota	- Target for imported gases in % share of total gas supply - Current value: 75 – 80 %	halving import dependency until 2050	Stable import share (Business as usual)
Power Demand for P2G	Ambition Tool output	(Total Gas Demand *(1-Import Quota) – Biomethane Production – Indigenous Natural Gas Production)/Efficiency of P2G	

8.3.2   Renewable electricity generation as source for P2G

In a first step and as for National Trends 2040, the amount of synthetic gases was assessed using the amount of excess electricity from the market studies.

In a second step and explicitly for the top-down scenarios, the need for synthetic gases as quantified by the Ambition Tool and the production already given by market based excess electricity were compared. If the demand quantified by the Ambition Tool could not be satisfied by the market based excess electricity, the residual production of synthetic gases via P2G is

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[60] Trinomics, The role of trans-European gas infrastructure in the light of the 2050 decarbonisation targets, 2018

assumed to be done in dedicated and off-grid P2G facilities including the installation of on-/offshore wind parks and photovoltaic plants.

First step: Excess electricity as a result from electricity market simulations

The electricity market simulations also quantify the hourly amount of so-called excess electricity. Excess electricity is the amount of generated electricity in a market node at a specific time, which cannot be utilised due to the lack of electricity grid and/or storage and/or demand side response. The amount of excess electricity usually correlates with additional variable renewable electricity production, such as wind or solar. Excess electricity has a zero or even negative price.

For Distributed Energy and Global Ambition, the excess electricity is split into the production of hydrogen and methane based on the proportions of the scenario-specific synthetic hydrogen and methane demand. The time series for the excess electricity generation output are then fed into the dedicated P2G model as a based generation.

Second step: Dedicated RES electricity generation as source for P2G

As described above, the electricity demand to produce synthetic gases in the top-down scenarios was higher than market based excess electricity.

8.3.3 Where to distribute P2G facilities in Europe

Dedicated and off-grid P2G including respective RES capacities need to be allocated to EU member states. Therefore, ENTSOs have developed distributions keys and weighting factors taking into account scenario- and country-specific parameters.

Assumptions on Power-to-Gas Distribution Keys

The residual electricity demand is given on an EU28-level and needs to be distributed among the countries. The distribution is done for hydrogen and methane separately. This is done by ranking each country based on two variables:

1. Scenario-specific hydrogen and methane demand
2. Natural resources for onshore/offshore wind and solar (best locations due to their capacity factor)

In the calculation of the country scores, specific weights are given to the different variables. The weighting factors are given in the table below. The weighting factors were chosen in such a way that:

- P2G production facilities can be operated with high load factors to keep costs down. As a result, most weight is given to offshore wind (50 %). Because offshore wind has the highest full load hours (up to 4.300 hours per year), it shows the highest potential for P2G. Followed by onshore wind and then (to a lesser extent and where off-shore wind is limited) solar PV.

- Gas can be produced relatively close to the electricity production areas. Therefore, unnecessary transport of energy can be avoided.

TABLE 36: P2G DISTRIBUTION KEY WEIGHTING

Criteria	Distribution key weight
Hydrogen/Methane Consumption	30 %
Offshore Wind	50 %
Onshore Wind	15 %
Solar	5 %

Based on the calculated scores each country will be given a percentage of contribution to P2G. In the determination of the final P2G demand, the following constraints are being considered:

- Max new RES capacity installations per country
- Countries with no gas consumption will be ruled out

8.3.4 Power-to-Gas Optimization

For the top down scenarios, a dedicated P2G optimization tool is used to convert energy from electrolysis to capacities of electrolysis plants, wind and solar. This is because there is a specific demand for hydrogen in the top down scenarios, which must be met internally and by green sources.

Hourly solar and wind load factors are imported for a specific climate year (1984). The scenario specific curtailed energy is also used as an input for each country's generation. The power to gas plants are assumed to have an overload capacity of 300 %, which can be used only to convert curtailed energy to hydrogen for short periods of time (30 minutes) and a for a limited amount of hours per year. The optimization of power to gas builds capacities for electrolysers, Wind Onshore, Wind Offshore and Solar PV in order to meet the demand for green hydrogen and methane. The boundary conditions used for the renewable capacities are a result of the distribution keys, and the renewables installed in the optimization of the electricity market. Whatever capacity is left after the electricity market simulations have been performed, can be used in the power to gas optimization process.

An important consideration is that the grid will not be used in the power to gas optimization, for several reasons, e.g. the electricity supplied to the electricity plant should only be applied through green sources. Therefore, the power to gas facility will be operated in an isolated location void of grid connections to the electricity market (except for curtailed renewables coming from the market). To reinforce this consideration, the starting capacities for Onshore Wind and Solar must be divided by the number of zones in the country, this is done in simplified manner, where the zones are taken from the E-highways. The full remaining capacity for Offshore Wind can be used in the simulation. If the renewable capacity in one area is not high enough to meet the hydrogen demand, multiple power to gas facilities will have to be built in a country, enabling the use of more onshore wind and solar.

For the bottom up scenarios, the methodology is different. There is no target for EU produced green hydrogen. Therefore, the target is to build electrolysers in order to capture some of the curtailed energy, where economic and competitive with natural gas. This competitiveness is based on the Capex and Opex cost of the electrolysers, gas price and CO_2 price (total annual cost is the net present value of Capex and Opex (25 years, 4 % discount rate)). The minimum electrolyser running hours are used to ensure the plants is profitable against natural gas can be deduced from the equation below;

$$Electrolyser\ Running\ Hours\ = \frac{Total\ Annual\ Cost}{CO_2\ Price\ \times (Natural\ Gas\ Production\ factor) + Gas\ Price} + VO\&M\ Costs$$

The equation takes into account the number of hours an electrolyser should be run in order to cover its Capex and Opex cost and a price that is competitive with natural gas.