



MANOEUVRE

**Energy System Modelling for Transition to a net-Zero 2050 for EU via
REPowerEU**

D4.1 - NECP Man0EUvRE vision: Analyses of the NECPs of the considered countries

A project in the CET partnership



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List of Acronyms and Abbreviations

Table 1: List of acronyms and abbreviations

Term	Explanation
CETP	Clean Energy Transition Partnership
CDR	Carbon Dioxide Removal
CfD	Contract for Differences
CSP	Concentrated Solar Power
DSR	Demand side response
ENS	Energy Not Served
EU	European Union
NECP	National Energy and Climate Plan
PPA	Power Purchase Agreement
REPowerEU	European Commission plan to phase out Russian fossil fuel imports
SSP	Socioeconomic Pathways
vRES	variable renewable energy sources
WP	Work Package



Executive Summary

The development of the energy system at both national and European levels requires effective coordination between national and European energy transition plans, to ensure consistency. The overall aim of this project is to improve and coordinate energy system modelling across Europe and provide open scientific evidence and research-based results that facilitate ambitious emissions reductions for a clean energy transition (CET), while incorporating the measures suggested in REPowerEU and recent policy suggestions of the Fit for 55 package and the Net Zero Industrial act. The objectives of ManOEUVRE are:

1. To develop robust pathways for the European energy system that meet climate targets towards net-zero greenhouse gas (GHG) emissions and consider current policies like the REPowerEU plan.
2. To provide feedback and advice to the National Energy and Climate Plans (NECPs) of the individual EU countries.
3. To improve a set of models for conducting energy transition studies at both European and national level, which can support NECP generation, evaluation and future updates.
4. To publish consistent energy system modelling datasets and scenario projections at both European and national level.
5. To strengthen the coordination between national energy plans and EU-wide transition goals.

As part of the Clean Energy for all Europeans package, the EU member states have submitted national energy and climate plans (NECP) covering the period 2021-2030 and addressing how the country will work towards the binding targets common for the EU. NECPs are conducted in each member state individually, each one having its own representation of European strategies and pathways. One objective of ManOEUVRE was then to evaluate the current available NECPs or equivalent for countries included in ManOEUVRE, to develop a methodology for how ManOEUVRE models can be used in NECP analyses and how national results could be replicated to other countries, to communicate with stakeholders and to develop advice and recommendations to the NECP responsible in each country.

The current deliverable consists of the first step towards recommendations for the NECP process. It includes analyses about the NECPs for Spain, Norway, Sweden, Germany, Turkey, Greece, France, Portugal, and Hungary. A section is devoted to each country, and is composed of the following subsections:

- A summary of the NECP of the country
- A comparison of the NECP with the NECP Essentials scenario
- Lessons and recommendations from the case study conducted on the country in WP3
- Feedback from stakeholders

The main highlights per countries are summarised below:

Spain:

Case study 1 focused on a detailed comparison between the Spanish National Energy and Climate Plan (NECP) and the NECP Essentials scenario developed with the European energy system model GENeSYS-Mod, with the objective of assessing the robustness and feasibility of Spain's decarbonisation pathway towards 2030. The analysis covered key energy system indicators, including electricity generation and installed capacity, cross-border electricity trade, final and primary energy consumption, and CO₂



emissions. The results highlighted that, while both scenarios converge towards a highly decarbonised energy system, the Spanish NECP assumes a more ambitious and faster transition, characterised by higher renewable electricity generation, stronger electrification of end-use sectors, larger deployment of storage and renewable hydrogen, and a greater role for Spain as a net electricity exporter. In contrast, GENeSYS-Mod projects a more gradual transition pathway, with lower overall energy demand, reduced emissions, greater system efficiency, and stronger reliance on European integration and cross-border flexibility mechanisms. Key findings also include the critical role of modelling scope and assumptions in shaping transition pathways, the importance of storage and system flexibility in highly renewable systems, and the need to carefully assess industrial and transport decarbonisation strategies. The study was complemented by a national stakeholder workshop, which confirmed the relevance of combining national and pan-European modelling perspectives to improve the transparency, robustness, and policy relevance of long-term energy transition planning

Norway and Sweden:

Case study 2 consisted of two parallel studies: Case study 2a considered decarbonisation of Norway and Sweden's energy systems combined with contributions to the European energy transition as exporter of electricity and hydrogen, across four scenarios based on two of ManOEUVRE's EU EnVis-2060 scenarios. Case study 2b considered the influence of different flexibility options implemented in Norway on the northern European power system dynamics, including the resulting power price level and volatility.

Case study 2 provides a short overview of the decarbonisation and energy exports of the Norwegian and Swedish energy plans, as well as insights and outcomes of an early-stage assessment of the GENeSYS-MOD results for the NECP Essentials v1.0 scenario, compared to existing Norwegian and Swedish energy system plans from the transmission system operators and the Norwegian Water Resources and Energy Directorate (NVE). This assessment led to a revised version (v1.0.1) of the scenario that was used in the work performed in case study 2b. It is pointed out that the NECP does not capture the full contribution to global reduction of greenhouse gas emission, as export also contributes to this. Another point is that cross-border collaboration can contribute to achieving national NECP targets. Key findings from the assessment of the early NECP Essentials scenario were that the GENeSYS-MOD electricity demand was too low and had to be adjusted upward. The annual hydropower from Norway had to be adjusted downward. Take-aways from the key findings and policy relevance of case study 2b include that there is strong weather-dependent interannual variability in the power system dynamics that is not captured in average-year results, and that Norwegian power prices represent a substantial electricity surplus that can be exported given enough cross-border export capacity.

Germany:

Case study 3-5 analysed impact factors for the German NECP. Case study 3 examined the impacts of changing structures in the energy costs on industrial applications. So far, the German NECP assumes a stable industrial structure driven by efficiency gains, overlooking the potentiality of intra-European industrial restructuring due to uneven renewable energy potential and resulting systematic energy cost differentials. Such spatial shifts introduce structural uncertainty that undermines the coherence of demand forecasts. Future NECPs should therefore include cross-border coordinated demand projections and respective sensitivity scenarios.



Case study 4 examined the perspectives for market-based cost recovery for renewable electricity generators and flexibility options in the European Energy Vision 2060 scenarios. The assessment reveals that growing flexible demand increases the market values of renewables but still cannot ensure their refinancing. In addition, the flexibility options themselves are exposed to self-cannibalisation effects. Therefore, future NECP iterations should integrate detailed assessments of investment incentives and support mechanisms – both for renewables and flexibilities.

In case study 5, the German NECP was analysed using the extended bioenergy optimization model, with a particular focus on renewable energy. To this end, the German NECP was compared with the NECP Essentials scenario which was provided by coupling the GENeSYS-MOD and BENOPTex models. The complementary role of biomass to variable renewable technologies was investigated. Biomass will be mostly used in the heating sector. Electricity will be generated by variable renewable technologies in addition to a small share of biogas from BECCS technologies.

Turkey:

Case study 6 analysed the Turkish National Energy Plan (NECP) using the GENeSYS-MOD framework to evaluate ambitious renewable energy expansion, decarbonization trajectories, and green hydrogen export potentials. The analysis compared Turkey's policy-driven, security-oriented transition with cost-optimal scenarios, highlighting that while aggressive capacity targets for solar and wind successfully cut fossil fuel use and establish a viable green hydrogen export hub to the EU, they also introduce substantial infrastructure bottlenecks, supply chain friction, and land availability challenges.

Greece:

Case study 7 examined different possible configurations of infrastructure, domestic production, imports and (re)exports of multiple renewable energy carriers which could render Greece a renewable energy hub within the European-MENA regions. An initial comparison of version 1.3 of GENeSYS-MOD's outputs for the "NECP Essentials" EU EnVis-2060 scenario to the Greek NECP showcased some divergences between them for specific sectoral consumptions and energy carriers; for electricity specifically, while final energy consumption was at a very close level to the NECP, generation and capacities were lower, possibly because the Greek NECP also accounts for electricity exports and renewable fuels of non-biological origin (RFNBO) production for domestic decarbonization.

With the aim of enhancing the NECP by furthering its ambition towards elevating Greece to the level of a renewable energy hub, four scenarios were conceived and evaluated using the PRIMES energy system model and the Go RES ENVIS scenario as the basis of energy demand and prices input to the model. The first (S1) focused on reproducing Greece's NECP, without any additional infrastructure investments focused on imports and exports, serving as the basis of the analysis. Three more were subsequently developed, simulating different levels of infrastructure availability and demand. S2 examined the possibility of Greece being a regional exporter of hydrogen in South-Eastern Europe, S3 examined a higher infrastructure availability scenario which could facilitate larger export amounts of hydrogen towards Central Europe, and S4 evaluated the potential of Greece exporting electricity towards Central Europe instead; both S3 and S4's needs for electricity were supported with an HVDC interconnection with Egypt, while S4 assumed also an interconnection with Germany. The relevant KPIs taken into account were among others electricity and hydrogen balances for Greece, capacity expansion for the power system, electrolyzers, storage and RES plants and associated investment expenditures; findings showed that, while all scenarios have their merits, S3 showed the most



pronounced beneficial effects for the total of the energy system, given that demand and willingness-to-pay for hydrogen justified the investments needed.

France:

Case study 8 was focused on the power system in France. We established that the version 4 of the ENVIS NECP Essentials scenario is reasonably consistent with the French NECP for 2030, as most deviations can be explained by either the difficulty to separate captive and non-captive electricity uses, in particular for the industry sector, for which the ENVIS scenario underestimates the use of electricity, and the different ways of redressing consumptions from meteorological dependencies.

The case study assessed the feasibility of the NECP scenario by running a stochastic power system model, using ensemble scenarios for representing the meteorological uncertainties in 2030. The main results are that the flexibility needs of the system is under revaluated in the scenario, which is easily explained by the fact that GENeSYS-MOD is a deterministic model, and that the renewable generation potential, demand and inflows profiles used represent the year 2018 and do thus not account for climate change, while the case study used projected timeseries.

Portugal:

Case study 9 highlights three main lessons across optimal power mix design, operational validation, and market and system dynamics. First, differences in detail and transparency between the Portuguese NECP and GENeSYS-MOD limit direct comparability, highlighting the need for more harmonised and standardised reporting frameworks. Second, optimal power mix results are highly sensitive to modelling assumptions and system boundaries. Early GENeSYS-MOD versions exhibited excessive solar PV deployment and the decommissioning of onshore wind, associated with the pan-European scale optimisation, underscoring the need of robust national calibration of technology costs and capacity factors. Third, operational and system analysis shows that flexibility and network constraints are critical for future renewable-based power systems. Results from a unit commitment model indicate that system adequacy depends strongly on storage duration and demand-side response, requiring the inclusion of multiple competing flexibility options. In parallel, market simulations show higher price volatility and persistent transmission bottlenecks between Portugal and Spain under high shares of renewable energy. These findings suggest that technology-specific discount rates could better represent investment risk and support more realistic and robust energy mixes. In addition, strengthening interconnection capacity between Portugal and Spain (and potentially with other countries in the future) will play an important role in reducing congestion and may significantly change the observed market dynamics.

Hungary:

The last chapter presents decarbonisation targets and targets related to energy efficiency, energy security and market integration for Hungary. This study was performed in the course of case study 5 and resulted in a comparison of the Hungarian NECP with simulation results.



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Introduction

The development of the energy system at both national and European levels requires effective coordination between national and European energy transition plans, to ensure consistency. The overall aim of ManOeuvre is to improve and coordinate energy system modelling across Europe and provide open scientific evidence and research-based results that facilitate ambitious emissions reductions for a clean energy transition (CET), while incorporating the measures suggested in REPowerEU and recent policy suggestions of the Fit for 55 package and the Net Zero Industrial act. The detailed objectives of this project are:

- To develop robust pathways for the European energy system that meet climate targets towards net-zero greenhouse gas (GHG) emissions and consider current policies like the REPowerEU plan.
- To provide feedback and advice to the National Energy and Climate Plans (NECPs) of the individual EU countries.
- To improve a set of models for conducting energy transition studies at both European and national level, which can support NECP generation, evaluation and future updates.
- To publish consistent energy system modelling datasets and scenario projections at both European and national level.
- To strengthen the coordination between national energy plans and EU-wide transition goals.

The current deliverable is part of WP4, which is focused on the NECPs of the considered countries, namely: Spain, Portugal, Greece, Sweden, Germany, France, as well as Norway and Turkey even though those countries, as non-EU members, do not have an NECP, but do have national plans that are analysed as if they were NECPs.

As the different NECPs, were developed separately by each member state, for a duration of only 10 years (2021 to 2030), the following main question is considered in WP4: **Is the time perspective a limitation, what will be the cost of the individual way of thinking in the NECPs?** The main objectives of WP4 are:

- Evaluate the current available NECPs or equivalent for countries included in ManOEUVRE
- Develop a methodology for how ManOEUVRE models can be used in NECP analyses and how national results could be replicated to other countries.
- Communicate with stakeholders, national decision makers and European decision makers involved in the NECP process to co-create the above process.
- Develop advice and recommendations to the NECP responsible in each country.

For this, WP4 is implemented along the following steps:

- First, an analyses and comparison of each NECP is conducted towards the NECP Essentials scenario produced in WP2 (T4.1)
- Second, the outputs of each case study will be analysed as to find out which of their results could be used in the creation of the NECPs. These results will be fed back to the European analyses, allowing ManOEUVRE to conduct a second iteration of the pan-European study including the updates of the NECPs from the case studies.
- Finally, the replication potential of each case study will be analysed and will serve as a basis to develop advice to the NECP construction, regarding how the ManOeuvre models could be used to complement the NECPs.



The aim of the current deliverable is to present the results of the first step.

This deliverable is organized into 8 chapters, each one devoted to one of the countries in Man0EUvRE consortium.



Methodology

The comparison of the NECPs with the NECP Essentials scenario produced by WP2 has been conducted in steps during the first 2 ½ years of the project:

First, an initial dataset for the model GENeSYS-MOD was created by gathering diverse public databases. This input dataset, covering the transport, industry, buildings and power sectors, includes a description of all available technologies with their availabilities, efficiencies, costs, installed capacities and productions in the base year, assumptions for development or phasing out, emissions budgets for the coming years, and final energy and service demands and their future developments, for all sectors. Based on this dataset, a run of the GENeSYS-MOD model was conducted to create the first version of the EnVis pathways, describing the evolution of the energy system (i.e. installed capacities and dispatch, as well as final energies per fuel) in the coming years. These parameters and pathways were published on Zenodo (see <https://zenodo.org/records/13710869>) as version 1.0 in September 2024.

Following this, analyses were conducted for each of the focus countries, including in particular comparisons with the NECPs and analyses of the deviations. An iterative process conducted to new versions of the input parameters and resulting pathways:

- Version 2 of the input parameters was published in February 2025, together with version 1.0 of the resulting pathways, including mainly corrections of data and scripts.
- Version 3 of the input parameters was published in July 2025, together with version 1.2 of the pathways, including feedback from partners, as well as an update of the cost assumptions in particular for wind and PV
- Version 4 was published in February 2026, together with version 1.3 of the pathways, including partner feedback, updated availability factors of nuclear power plants per region, natural gas pipeline connections to outside EU, technology costs, residual capacities...
- Version 5 was published in April 2026 together with version 1.4 of the pathways, with additional partners feedback as well as updated input data for hydrogen from SMRs, trade parameters, freight road technologies characteristics, district heat losses and recalibration of industrial sector

This process allowed to reach a better level of consistency between the NECP Essentials scenario and the real NECPs. It is to be noted that the year 2025 is considered as the ‘future’ by the GENeSYS-MOD model (as the starting year, named ‘Base year’ in 2018), meaning that the energy system data for 2025 are the result of an optimization and not collected past data. As a linear optimization model, GENeSYS-MOD relies on assumptions about future data points, which inevitably introduces uncertainty into the results. Moreover, since 2030 lies in the near future, some differences between the modelled results and what has already been achieved or is currently planned at the national level are to be expected. This should be kept in mind throughout the comparisons presented in the following chapters.

All versions of the input parameters can be found here <https://zenodo.org/records/19796827>, while all corresponding versions of the resulting pathways can be found here: <https://zenodo.org/records/19796965>.



1 Spain (Case Study 1)

1.1 The Spanish NECP

The updated Spanish National Energy and Climate Plan (NECP) is driven by the objective of accelerating the transition to climate neutrality by 2050, while strengthening energy security, affordability, and industrial competitiveness. It establishes a comprehensive policy framework structured along the five dimensions of the Energy Union, with clear quantitative targets for 2030.

1.1.1 Decarbonisation

Decarbonisation is the core driver of the NECP, with strengthened ambition compared to previous versions.

Key targets:

- GHG emissions reduction: ~32% by 2030 compared to 1990 (non-ETS sectors aligned with EU targets).
- Renewables in final energy consumption: 48% by 2030.
- Renewables in electricity generation: ~81% by 2030.
- Installed renewable capacity: ~160 GW total, including:
 - ~62 GW solar PV
 - ~50 GW wind (onshore + offshore initial deployment)
- Electrification rate of final energy demand: ~34%.

Policy drivers:

- Large-scale deployment of solar PV and wind.
- Electrification of transport (EV uptake) and heating (heat pumps).
- Development of renewable hydrogen (electrolyser capacity targets around 11 GW by 2030).
- Enhancement of carbon sinks (LULUCF sector).

1.1.2 Energy Efficiency

Energy efficiency is a key lever to reduce demand, emissions, and system costs.

Key targets:

- Primary energy consumption reduction: ~39.5% compared to baseline projections.
- Final energy consumption reduction: ~43% compared to baseline.
- Annual energy savings obligation reinforced under EU directives.

Policy drivers:

- Building renovation wave, targeting large-scale improvement of residential and public buildings.
- Deployment of high-efficiency heating and cooling systems (notably heat pumps).
- Improved industrial energy efficiency and waste heat recovery.
- Sustainable mobility policies, including modal shift and efficiency improvements.

1.1.3 Energy Security

Reducing external dependency is a central driver, particularly after recent energy crises.

Key targets:

- Reduction of energy import dependency from ~70% to around 50% by 2030.



- Significant decrease in fossil fuel consumption across all sectors.

Policy drivers:

- Massive expansion of domestic renewable generation.
- Deployment of energy storage capacity (target ~22 GW storage including pumped hydro and batteries).
- Development of renewable gases (biogas/biomethane and hydrogen).
- Strengthening electricity interconnections with France and the EU system.

1.1.4 Internal Energy Market

The NECP promotes a flexible, integrated, and consumer-driven energy system.

Key targets:

- Increased interconnection capacity (towards EU target of 15%¹).
- Strong growth in self-consumption (several GW expected, especially distributed PV).

Policy drivers:

- Grid modernisation and digitalisation to integrate high RES penetration.
- Deployment of flexibility solutions: storage, demand response, aggregation.
- Promotion of energy communities and prosumers.
- Market reforms to accommodate high shares of variable renewables.

1.1.5 Research, Innovation and Competitiveness

Innovation is positioned as a strategic driver for both decarbonisation and economic growth.

Key targets and priorities:

- Scaling up renewable hydrogen industry (~11 GW electrolyzers).
- Development of strategic value chains (batteries, renewables, hydrogen).
- Increased R&D investment in clean energy technologies.

Policy drivers:

- Public-private partnerships and innovation programmes.
- Industrial policy to position Spain as a clean energy hub in Europe.
- Measures for a just transition, including reskilling and regional support.

Cross-cutting drivers

- Investment needs: estimated at over €300 billion (2021–2030).
- Strong focus on job creation and economic transformation.
- Policies addressing energy poverty and social inclusion.
- Alignment with EU climate governance and regulatory framework.

1.2 Comparison of the Spanish NECP with the NECP Essentials scenario

This section summarizes the comparison between the Spanish National Energy and Climate Plan (PNIEC) and the NECP Essentials scenario developed with GENESYS-Mod within the MANOUVRE project. The analysis focuses on the main energy system indicators, including electricity generation

¹ Each country should have electricity infrastructure in place that would allow it to import, from its neighbouring EU countries, an equivalent of at least 15% of the electricity production capacity on its territory



and installed capacity, energy trade balances, final and primary energy consumption, and CO₂ emissions. The objective of the intercomparison is to identify the main similarities and divergences between both modelling approaches, highlighting the influence of methodological assumptions, geographical scope, sectoral transition pathways, and system integration aspects on the resulting decarbonisation trajectories for Spain.

1.2.1 Electricity production and installed capacity

Figure 1 compares the electricity generation mix obtained with GENESYS-Mod (“NECP Essentials 1.4.0”) against the official Spanish PNIEC projections for 2025 and 2030.

Overall, both scenarios show a strong increase in renewable electricity generation over time, particularly from solar PV and wind technologies. However, the PNIEC scenario projects a significantly higher total electricity production than the GENESYS-Mod results, especially in 2030.

In 2025, total electricity generation in the PNIEC scenario reaches approximately 300 TWh, compared to around 260 TWh in the GENESYS-Mod scenario. The difference is mainly explained by higher contributions from solar PV, onshore wind and gas-fired generation in the PNIEC projections. Nuclear and hydropower generation remain relatively similar in both cases, although GENESYS-Mod maintains a slightly larger share of hydroelectricity.

By 2030, the divergence between both scenarios becomes more pronounced. The PNIEC projects electricity generation close to 400 TWh, while GENESYS-Mod estimates around 310 TWh. The increase in the PNIEC scenario is driven primarily by a substantial expansion of solar PV and wind generation. In contrast, the GENESYS-Mod results show a more moderate deployment of variable renewable technologies and a lower overall electricity demand and/or production requirement.

The higher electricity generation levels projected in the PNIEC scenario may also be related to the expected deployment of renewable hydrogen production through electrolysis. The Spanish PNIEC includes electrolysis capacity targets of around 4 GW in 2025 and 12 GW in 2030, implying a significant increase in electricity demand. Consequently, the larger renewable electricity production observed in the PNIEC pathway could be partially driven by the need to supply electricity for hydrogen generation, particularly from solar PV and wind technologies. Although the full generation gap cannot be attributed exclusively to hydrogen production, the expected deployment of electrolyzers could explain a significant part of the difference. With 12 GW of electrolysis capacity operating at a 40–50% capacity factor, electricity demand for hydrogen production would be in the order of 42–53 TWh/year by 2030.

Another relevant difference concerns the role of thermal generation technologies. The PNIEC scenario still includes noticeable contributions from gas-fired generation in 2030, whereas the GENESYS-Mod pathway shows a more limited use of gas technologies. Coal generation is almost completely phased out in both scenarios by 2030.

Overall, the comparison indicates that while both approaches follow the same decarbonisation trend, the PNIEC assumes a faster and larger-scale expansion of renewable electricity generation capacities, leading to a substantially higher total electricity output by 2030.

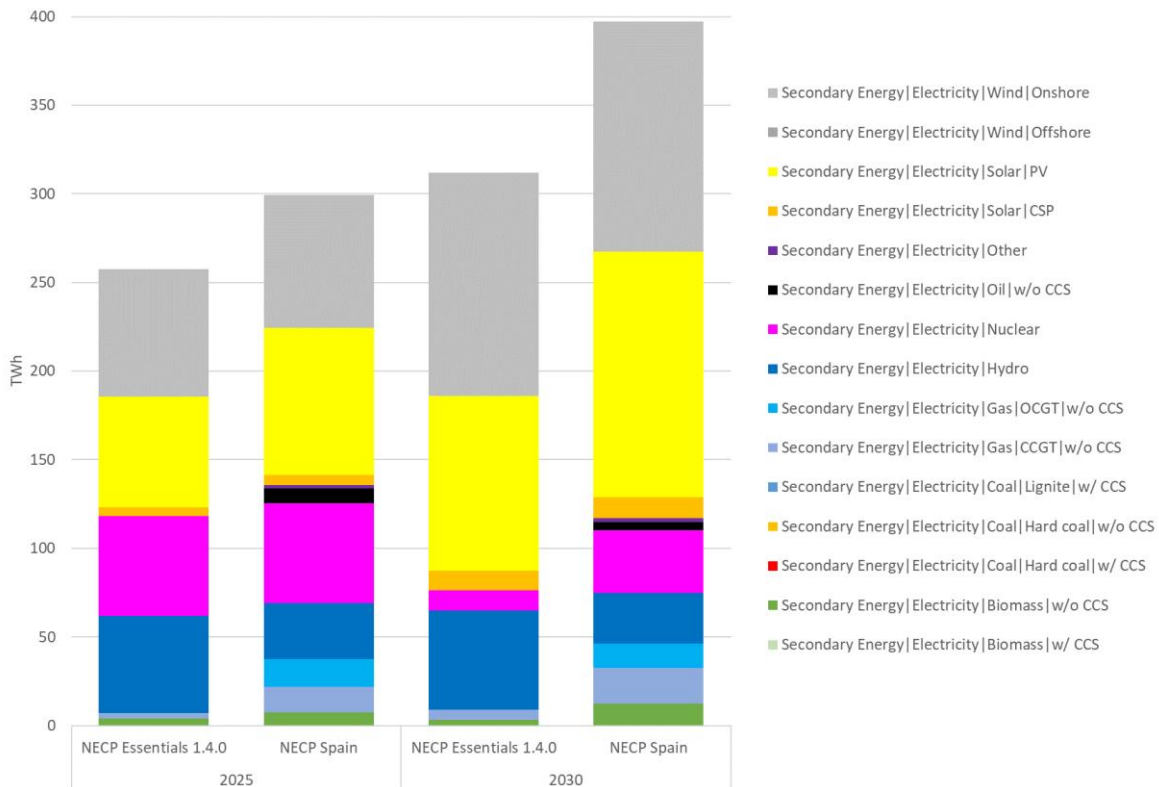


Figure 1: Electricity generation mix obtained with GENESYS-Mod (“NECP Essentials 1.4.0”) against the official Spanish PNIEC projections for 2025 and 2030

Figure 2 presents the comparison of installed electricity generation capacities between the GENESYS-Mod results (“NECP Essentials 1.4.0”) and the official Spanish PNIEC projections for 2025 and 2030.

Both scenarios show a clear transition towards a renewable-based electricity system, with significant increases in solar PV and wind capacities over time. However, important differences can be observed regarding the pace of renewable deployment, the role of storage technologies, and the evolution of conventional generation capacities.

In 2025, the GENESYS-Mod scenario reaches a slightly higher total installed capacity than the PNIEC scenario. This difference is mainly associated with larger onshore wind and gas capacities in GENESYS-Mod, while the PNIEC projects somewhat higher solar PV deployment. In both cases, hydropower and nuclear capacities remain relatively stable, reflecting the existing structure of the Spanish power system during the transition period.

By 2030, both scenarios foresee a substantial increase in total installed capacity, although the PNIEC projects a more ambitious expansion, exceeding 210 GW, compared to approximately 195 GW in GENESYS-Mod. The increase is largely driven by the rapid deployment of solar PV and onshore wind technologies. Solar PV becomes the dominant technology in both scenarios, although the PNIEC assumes a higher installed capacity than GENESYS-Mod.

Another notable difference concerns energy storage deployment. The PNIEC scenario incorporates a significantly larger amount of storage capacity by 2030, highlighting the increasing importance attributed to system flexibility and renewable integration. In contrast, the GENESYS-Mod scenario shows a more moderate storage expansion.



A relevant difference concerns the role of conventional thermal technologies. While GENESYS-Mod retains part of the gas and coal installed capacity by 2030, these technologies are barely dispatched, indicating that they mainly act as backup or firm capacity to ensure system adequacy and flexibility under high shares of variable renewable energy. In the PNIEC, however, gas-fired generation remains visibly present in the electricity mix, suggesting a more active operational role for gas in balancing the system and supporting renewable integration, whereas coal generation is practically phased out. Therefore, the two scenarios differ not only in installed capacity levels, but also in the utilisation rate and function assigned to conventional thermal technologies within the future power system.

Overall, the comparison suggests that both scenarios are aligned with the long-term decarbonisation objectives of the Spanish electricity sector, but the PNIEC assumes a faster deployment of renewable and storage capacities, resulting in a more highly electrified and flexibility-oriented system by 2030.

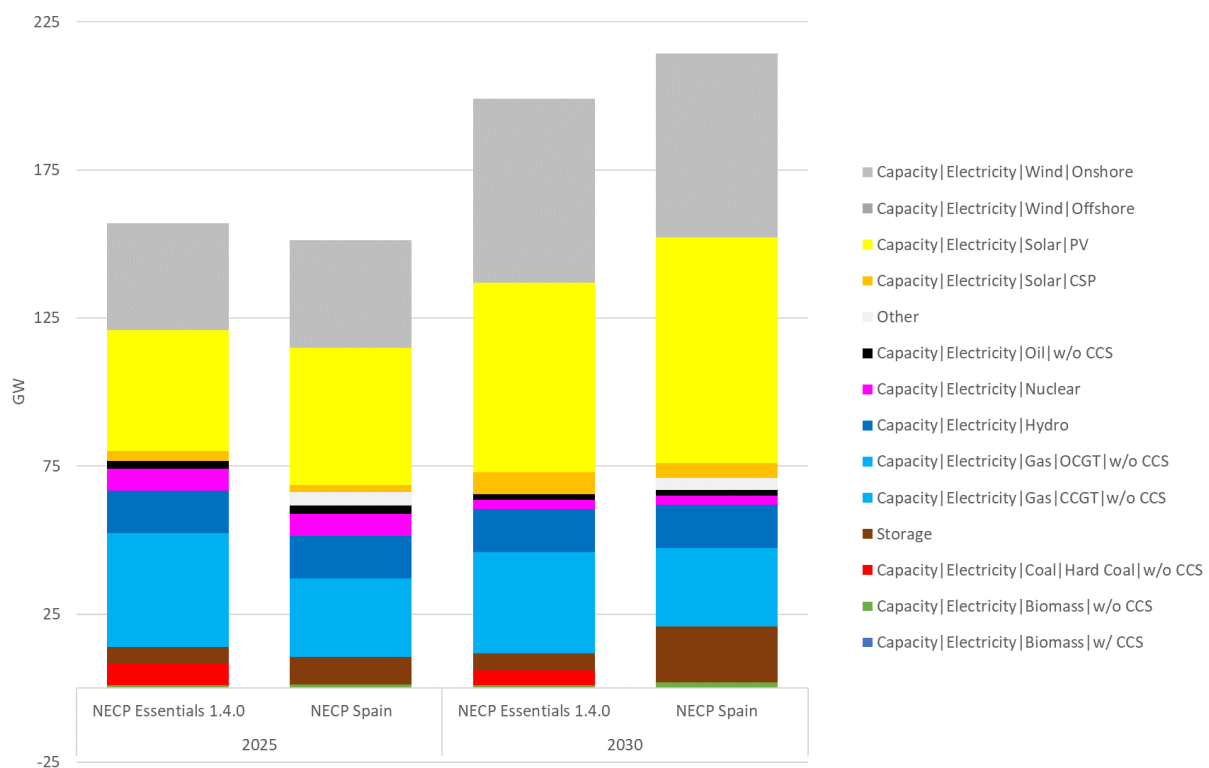


Figure 2: Installed electricity generation capacities obtained with GENESYS-Mod (“NECP Essentials 1.4.0”) and the official Spanish PNIEC projections for 2025 and 2030.

Electricity trade

Figure 3 compares the electricity import and export balances obtained with GENESYS-Mod (“NECP Essentials 1.4.0”) and the Spanish PNIEC projections for 2025 and 2030.

An important aspect to consider when interpreting these results is the different modelling scope of both approaches. GENESYS-Mod is a pan-European energy system model that explicitly represents cross-border electricity exchanges and interconnections between European countries. Therefore, trade flows are determined endogenously according to system-wide optimisation at the European



level. In contrast, the model used for the PNIEC is mainly national in scope and does not fully capture the dynamics of the integrated European electricity market.

Overall, both scenarios project Spain as a net electricity exporter in 2025 and 2030. However, the PNIEC assumes a significantly larger export surplus, particularly by 2030. These differences may indicate that the PNIEC adopts a more optimistic assumption regarding Spain's future role as a major renewable electricity exporter within Europe. From the perspective of GENESYS-Mod, which considers simultaneous developments in neighbouring countries and competition among renewable electricity producers across Europe, such high export levels may be more difficult to achieve in practice.

Therefore, the comparison highlights the added value of using a European-scale modelling framework for assessing national energy transition pathways. By explicitly accounting for international market interactions and cross-border competition, GENESYS-Mod provides additional insights into the feasibility and realism of future electricity trade balances projected at the national level.

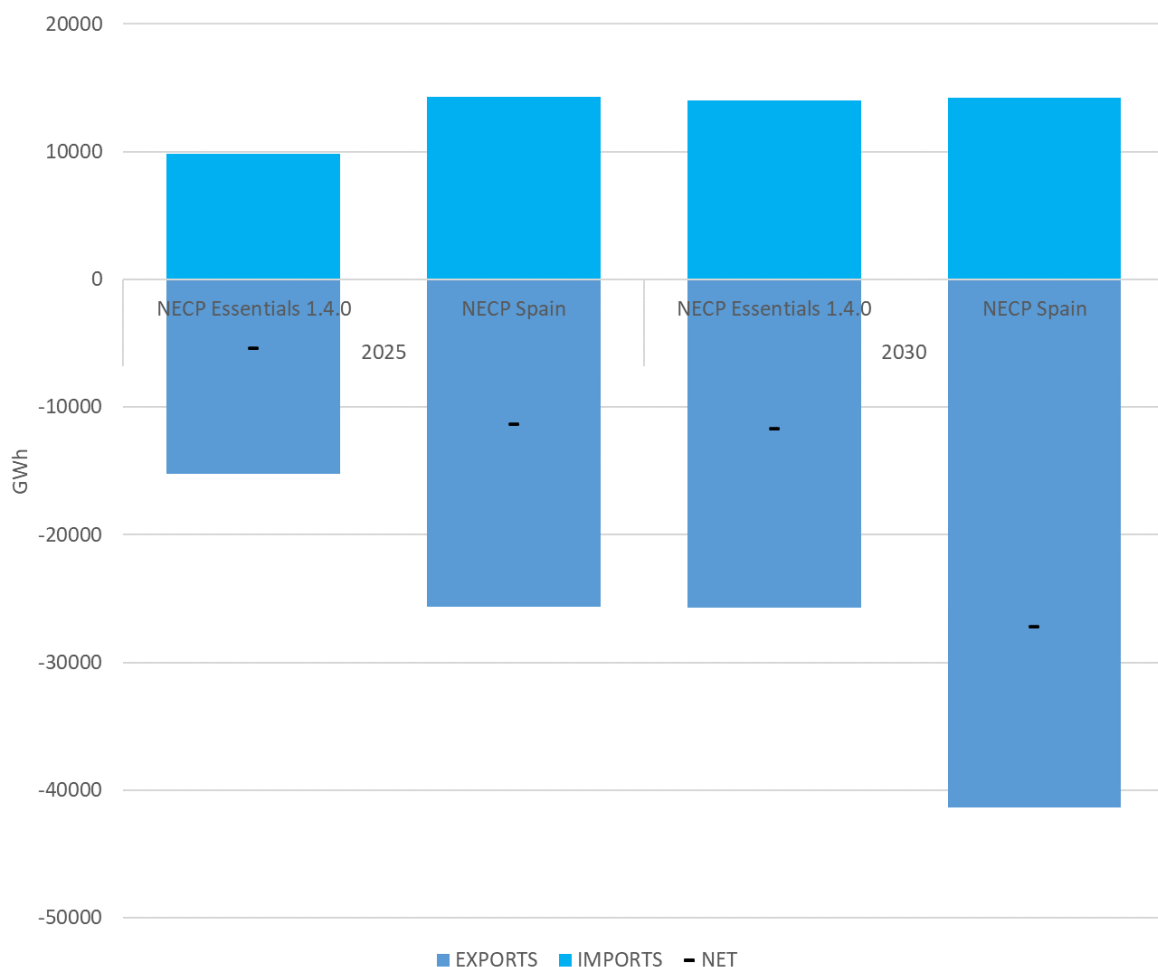


Figure 3: Electricity import and export balances obtained with GENESYS-Mod (‘NECP Essentials 1.4.0’) and the Spanish PNIEC projections for 2025 and 2030.

Final energy

Figure 4 compares the final energy consumption structure projected by GENESYS-Mod (‘NECP Essentials 1.4.0’) and the Spanish PNIEC for 2025 and 2030.



Overall, both scenarios show a progressive reduction in total final energy consumption between 2025 and 2030, reflecting improvements in energy efficiency and the gradual transition towards a more electrified and decarbonised energy system. In both cases, electricity and liquid fuels remain the dominant final energy carriers, although their relative shares evolve differently across the two scenarios.

One of the main differences concerns the role of gaseous fuels. GENESYS-Mod projects a substantially higher final consumption of gases in both 2025 and 2030 compared to the PNIEC scenario. This suggests a more gradual reduction of gaseous energy carriers within the GENESYS-Mod pathway, whereas the PNIEC assumes a faster decline in gas consumption, likely associated with stronger electrification and efficiency measures in end-use sectors.

Electricity consumption increases its relative importance in both scenarios by 2030, reflecting the electrification of transport, buildings and industry. However, the increase appears more pronounced in the PNIEC scenario, which is consistent with its higher deployment of renewable electricity generation and electrolysis capacities.

Another relevant difference is observed in biomass consumption. The PNIEC projects a larger contribution of biomass to final energy demand by 2030, while GENESYS-Mod shows a more moderate increase. This may reflect different assumptions regarding the availability and utilisation of bioenergy resources in hard-to-abate sectors.

A notable divergence concerns coal consumption trends. While the PNIEC projects a rapid decline in final coal consumption towards almost negligible levels by 2030, GENESYS-Mod shows a slight increase in coal use over the same period. Although coal remains a relatively small share of total final energy demand, this result may reflect the persistence of coal consumption in specific industrial or hard-to-abate sectors within the European modelling framework, possibly linked to cost-optimisation dynamics or slower substitution rates for certain end uses. Consequently, GENESYS-Mod depicts a more conservative transition pathway regarding the phase-out of solid fossil fuels compared to the PNIEC assumptions.

Overall, the comparison indicates that both scenarios follow similar long-term decarbonisation trends but differ in the speed and structure of the transition. The PNIEC assumes a stronger shift towards electrification and biomass use, whereas GENESYS-Mod maintains a relatively larger role for gaseous fuels and residual coal consumption during the transition period.

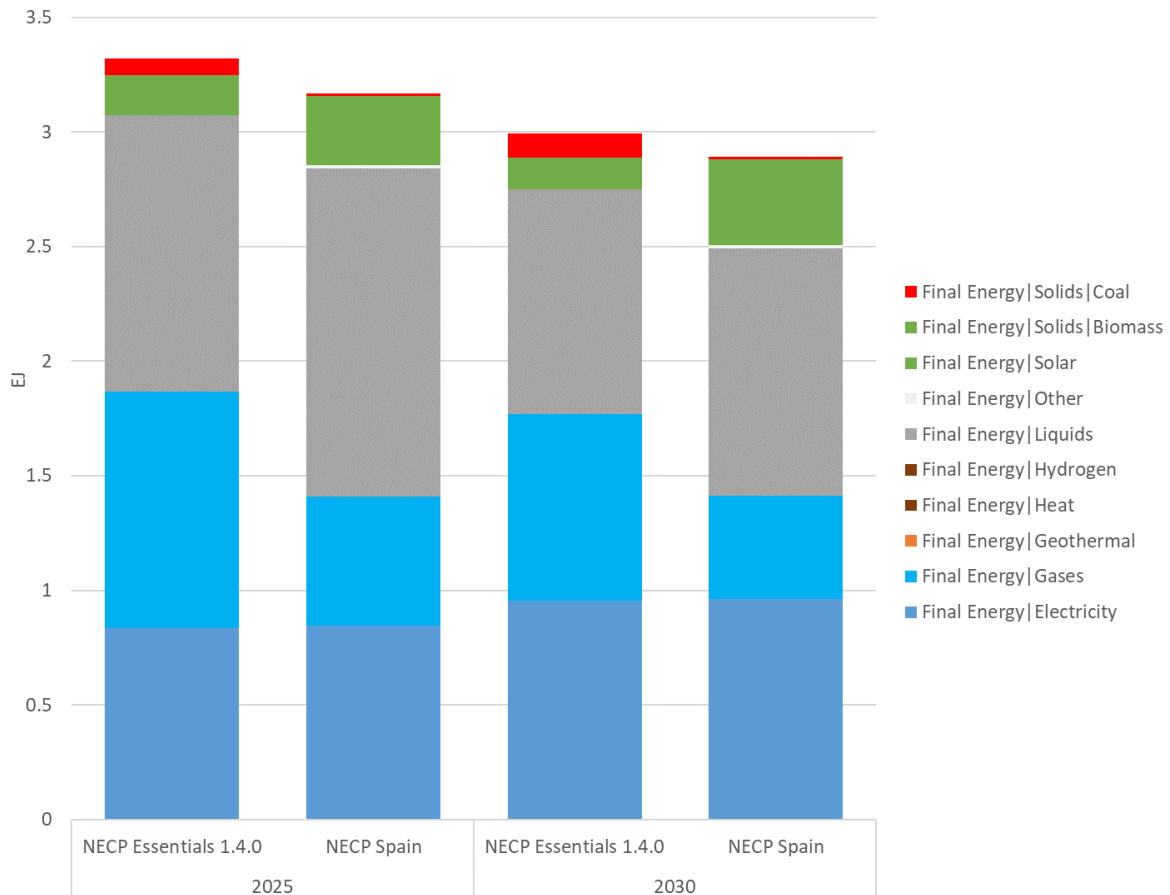


Figure 4: Final energy consumption structure projected by GENESYS-Mod (“NECP Essentials 1.4.0”) and the Spanish PNIEC for 2025 and 2030.

Final energy in industry

Figure 5 compares the industrial final energy consumption projected by GENESYS-Mod (“NECP Essentials 1.4.0”) and the Spanish PNIEC for 2025 and 2030.

The two scenarios show different trends regarding the evolution of total industrial final energy demand. While GENESYS-Mod projects a noticeable reduction in industrial energy consumption between 2025 and 2030, the PNIEC maintains relatively stable industrial final energy demand over the same period. This difference may reflect distinct assumptions regarding industrial activity growth, energy efficiency improvements, and the pace of technological transformation within the industrial sector.

The most significant divergence concerns the role of electricity and gaseous fuels. In the GENESYS-Mod scenario, industrial energy demand continues to be dominated by gaseous fuels in both 2025 and 2030, while electricity represents a relatively smaller share of total consumption. In contrast, the PNIEC projects a much stronger electrification of industry, with electricity consumption increasing substantially by 2030 and becoming one of the dominant industrial energy carriers.

Consequently, gas consumption decreases more rapidly in the PNIEC scenario, whereas GENESYS-Mod maintains a larger role for gaseous fuels during the transition period. This difference may reflect more



conservative assumptions within the European optimisation framework regarding the speed of industrial electrification.

Another relevant difference concerns solid fuels. While the PNIEC projects an almost complete phase-out of coal use in industry by 2030, GENESYS-Mod maintains industrial coal consumption over time. Although coal represents a relatively limited share of total industrial final energy demand, this result may indicate the persistence of coal use in specific hard-to-abate industrial applications within the model framework.

Biomass consumption increases in both scenarios, although the PNIEC projects a larger contribution by 2030. This suggests a stronger reliance on bioenergy as a decarbonisation option for industrial heat and process demand in the national strategy.

Overall, the comparison indicates that the PNIEC assumes a faster transformation of the industrial energy mix, characterised by stronger electrification and a quicker phase-out of fossil fuels, while maintaining overall industrial energy demand at relatively constant levels. In contrast, GENESYS-Mod depicts a more gradual transition pathway, combining lower total industrial energy demand with a larger role for gaseous fuels and residual coal consumption during the transition period.

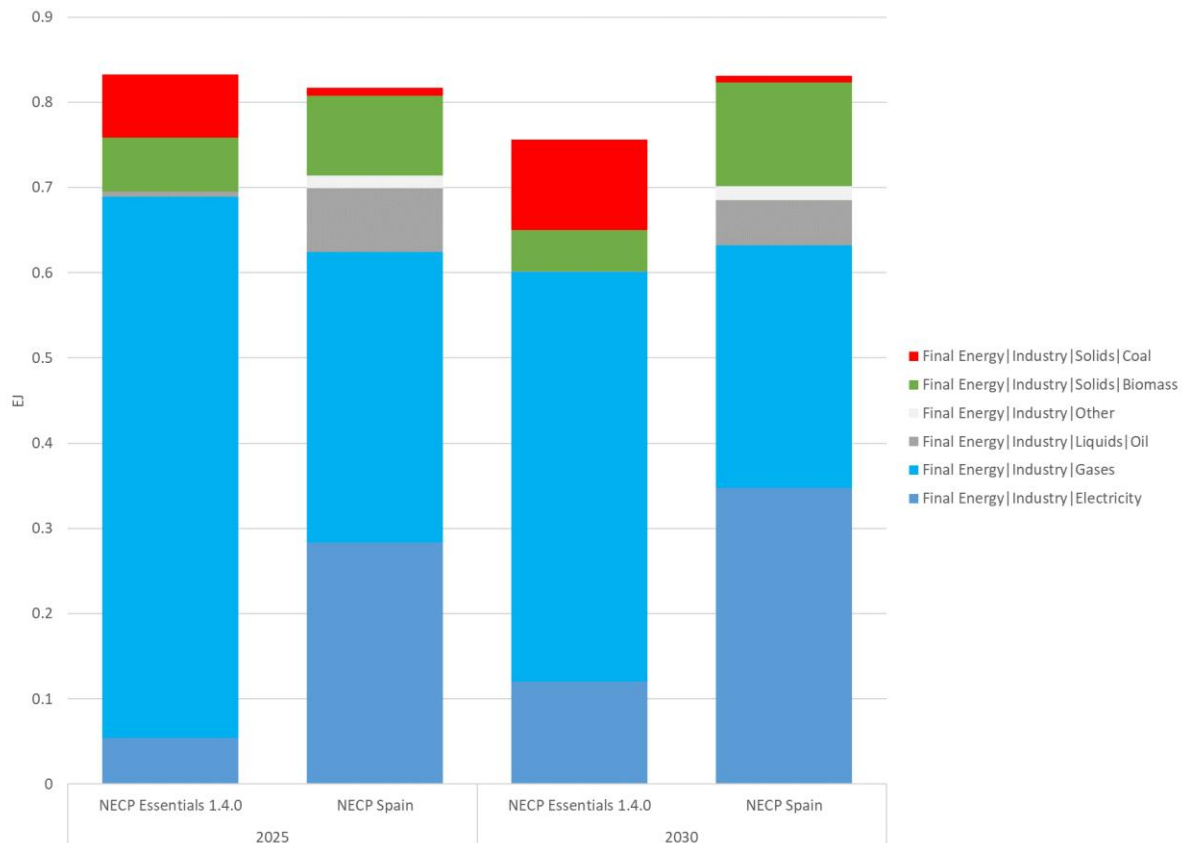


Figure 5: Industrial final energy consumption projected by GENESYS-Mod (“NECP Essentials 1.4.0”) and the Spanish PNIEC for 2025 and 2030.

Final energy in transport

Figure 6 compares the final energy consumption in the transportation sector projected by GENESYS-Mod (“NECP Essentials 1.4.0”) and the Spanish PNIEC for 2025 and 2030.



Both scenarios project a gradual reduction in total final energy demand in transport between 2025 and 2030, reflecting efficiency improvements and the progressive transition towards alternative low-carbon energy carriers. However, the PNIEC maintains a higher total transport final energy demand than GENESYS-Mod in both years.

In both scenarios, liquid fossil fuels continue to dominate the transport sector by 2030, although their contribution decreases over time. Nevertheless, the reduction of oil products is more pronounced in GENESYS-Mod, which projects lower overall liquid fuel consumption than the PNIEC pathway.

A major difference between the two scenarios concerns the deployment of alternative energy carriers. The PNIEC projects a stronger penetration of electricity and biofuels in transport, particularly by 2030. Electricity consumption in transport increases more significantly in the PNIEC scenario, indicating a faster electrification of road transport and greater adoption of electric mobility technologies. Similarly, biomass-based liquid fuels play a larger role in the PNIEC projections, suggesting a stronger reliance on biofuels to support transport decarbonisation targets.

In contrast, GENESYS-Mod depicts a more moderate transition in the transport sector, with lower electrification levels and a smaller contribution from biofuels. The model therefore maintains a larger dependence on conventional liquid fuels during the transition period.

Hydrogen and gaseous fuels remain marginal in both scenarios, indicating a limited penetration of these technologies in transport up to 2030 under the analysed pathways.

Overall, the comparison suggests that the PNIEC assumes a faster transformation of the transport sector through stronger electrification and biofuel deployment, whereas GENESYS-Mod projects a more gradual decarbonisation pathway with a slower reduction of fossil fuel dependence.

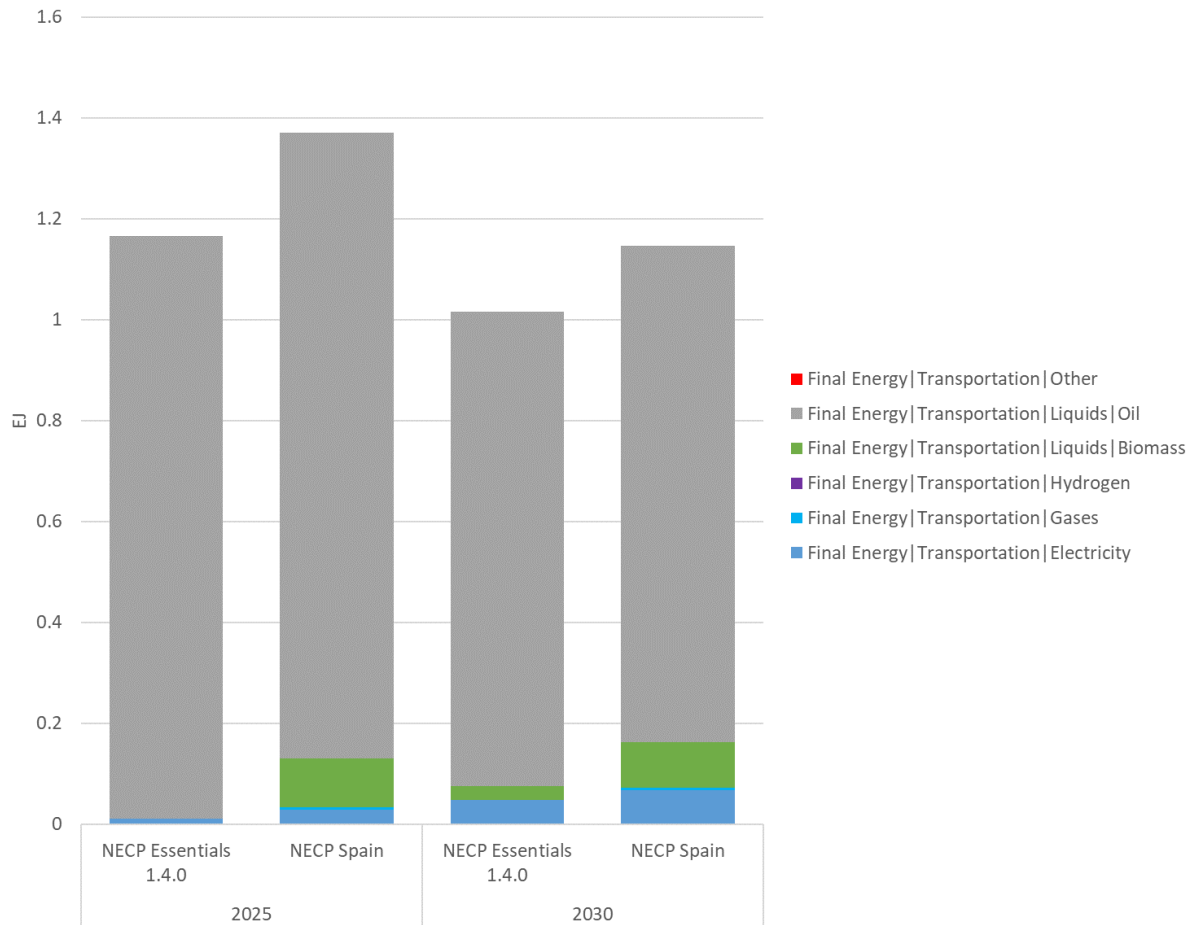


Figure 6: Final energy consumption in the transportation sector projected by GENESYS-Mod (“NECP Essentials 1.4.0”) and the Spanish PNIEC for 2025 and 2030.

Primary energy

Figure 7 compares the primary energy consumption projected by GENESYS-Mod (“NECP Essentials 1.4.0”) and the Spanish PNIEC for 2025 and 2030.

A significant difference can be observed between the two scenarios regarding total primary energy demand. While GENESYS-Mod projects primary energy consumption levels around 2 EJ in both 2025 and 2030, the PNIEC estimates substantially higher values, exceeding 4 EJ. This large divergence is likely driven by a combination of methodological and structural factors.

One important difference concerns the role of oil products. The PNIEC scenario maintains substantially higher oil consumption in both 2025 and 2030, particularly linked to the transport sector. Since oil-based energy uses are associated with relatively low conversion efficiencies, they contribute significantly to higher primary energy demand. By contrast, GENESYS-Mod projects a stronger reduction in oil dependence, leading to lower overall primary energy requirements.

Biomass also plays a much larger role in the PNIEC scenario, especially by 2030, where it becomes one of the dominant primary energy sources. In addition, the PNIEC maintains higher contributions from nuclear energy and gas consumption compared to GENESYS-Mod. These differences are consistent with the higher electricity generation levels and the more active role of gas-fired technologies previously observed in the PNIEC pathway.



The higher electricity demand associated with renewable hydrogen production through electrolysis in the PNIEC may also contribute to the observed differences. The deployment targets for electrolyzers increase electricity consumption requirements and may indirectly raise total primary energy demand within the national scenario.

Overall, the comparison indicates that the PNIEC depicts a more energy-intensive pathway with higher fossil fuel and biomass consumption, whereas GENESYS-Mod projects a more energy-efficient transition characterised by lower primary energy requirements and reduced dependence on conventional fuels.

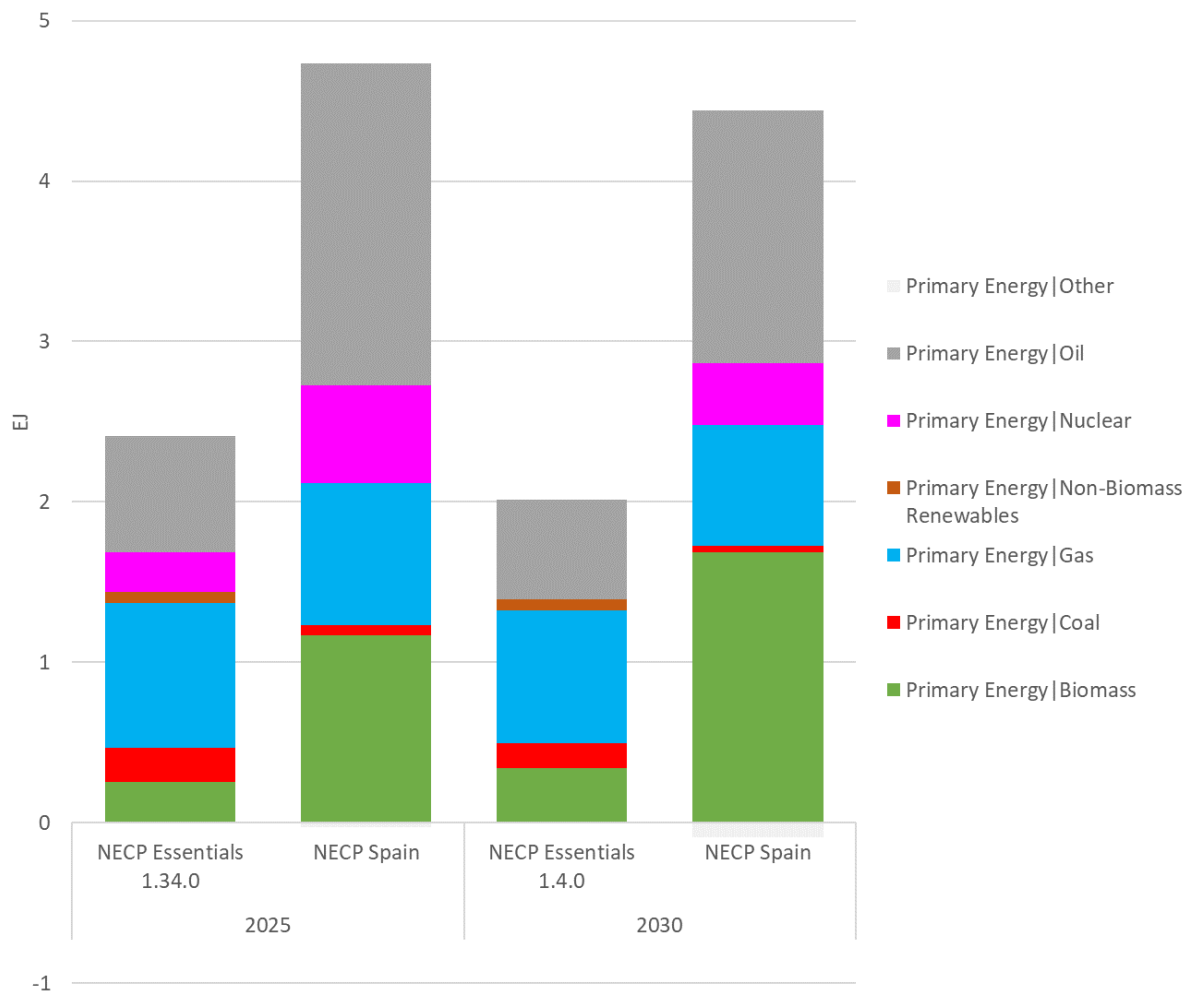


Figure 7: Primary energy consumption projected by GENESYS-Mod (“NECP Essentials 1.4.0”) and the Spanish PNIEC for 2025 and 2030.

Emissions

Figure 8 compares the CO₂ emissions projected by GENESYS-Mod (“NECP Essentials 1.4.0”) and the Spanish PNIEC for 2025 and 2030, distinguishing emissions from industry, residential and commercial sectors, transportation, and electricity supply.



Both scenarios project a substantial reduction in CO₂ emissions between 2025 and 2030, reflecting the progressive decarbonisation of the Spanish energy system. However, the PNIEC consistently shows higher total emissions than GENESYS-Mod in both years, despite the stronger electrification trends observed in some sectors.

Transportation remains the largest source of emissions in both scenarios. Nevertheless, GENESYS-Mod projects significantly lower transport emissions compared to the PNIEC, particularly in 2030. This result is consistent with the lower oil consumption and lower overall final energy demand previously observed in the GENESYS-Mod transport pathway.

Industrial emissions also remain substantial in both scenarios. The PNIEC shows noticeably higher industrial CO₂ emissions, which is coherent with the relatively stable industrial final energy demand and the continued use of fossil fuels within the sector. In contrast, GENESYS-Mod projects lower industrial emissions, partly associated with reduced total industrial energy demand.

Emissions from the residential and commercial sectors decrease in both scenarios over time, although the reduction is more pronounced in the PNIEC. This behaviour is consistent with the stronger electrification and lower gas consumption previously identified in the PNIEC final energy mix for buildings and services.

A relevant difference can also be observed in electricity supply emissions. GENESYS-Mod projects almost negligible emissions from electricity generation by 2030, reflecting the very limited use of fossil fuel power plants. In contrast, the PNIEC still shows residual emissions from electricity supply in both 2025 and 2030, mainly due to the continued operational role of gas-fired generation technologies within the electricity mix.

Overall, the comparison indicates that GENESYS-Mod projects a lower-carbon transition pathway than the PNIEC, particularly due to lower emissions in transportation, industry, and electricity generation. The differences are closely linked to the lower fossil fuel consumption and higher overall system efficiency projected by the European optimisation framework.

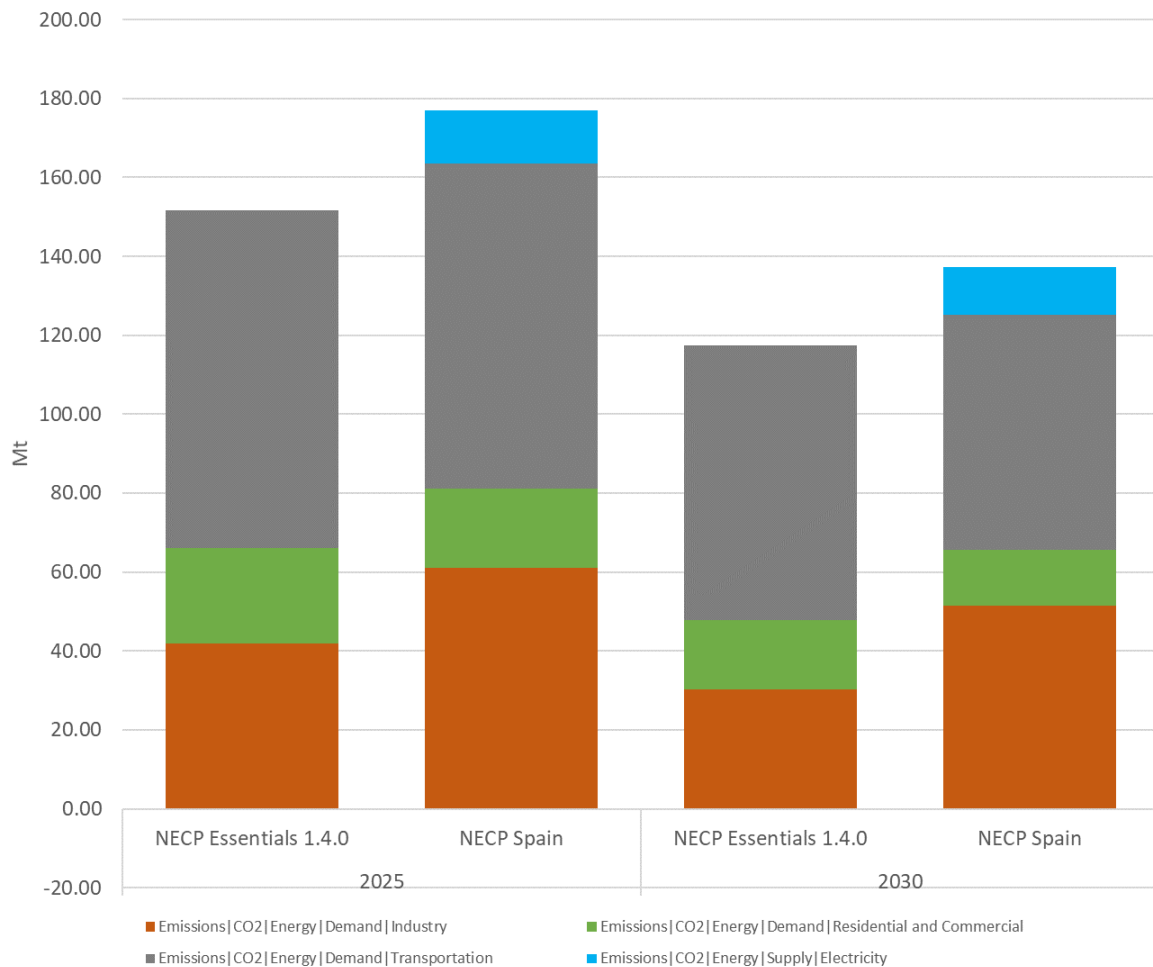


Figure 8: CO₂ emissions projected by GENESYS-Mod (“NECP Essentials 1.4.0”) and the Spanish PNIEC for 2025 and 2030, distinguishing emissions from industry, residential and commercial sectors, transportation, and electricity supply.

1.3 Lessons learnt in Case study 1

The comparison between GENESYS-Mod and the Spanish PNIEC highlights the importance of modelling assumptions, methodological approaches, and system boundaries when assessing energy transition pathways. Although both scenarios are aligned with the long-term objective of decarbonising the Spanish energy system, significant differences emerge regarding the pace and structure of the transition.

One of the main lessons learned is the strong influence of the modelling scope on the results. As a European-scale optimisation model, GENESYS-Mod explicitly accounts for cross-border electricity exchanges, competition among neighbouring energy systems, and system-wide optimisation across interconnected countries. This provides additional insights into the feasibility of national assumptions related to electricity exports, system adequacy, and resource allocation. In contrast, nationally focused models such as those supporting the PNIEC may project more optimistic assumptions regarding domestic renewable deployment and export potential.

Another relevant lesson concerns the uncertainty associated with sectoral transformation pathways, particularly in industry and transport. The comparison reveals different assumptions regarding



electrification rates, fossil fuel substitution, biomass deployment, and the persistence of gaseous fuels or coal in hard-to-abate sectors. These differences highlight the need for careful assessment of technological feasibility, infrastructure requirements, and sector-specific transition barriers.

The comparison also underlines the growing importance of energy storage technologies in highly renewable energy systems. The PNIEC projects a significantly larger deployment of storage capacities by 2030, reflecting a stronger reliance on flexibility solutions to integrate large shares of variable renewable electricity generation and support electrolysis demand. In contrast, GENESYS-Mod depicts a more moderate storage expansion, partly supported by the flexibility provided through European interconnections and cross-border exchanges. This highlights the strong interdependence between storage needs, system integration, and geographical modelling scope.

Furthermore, the analysis shows that retaining thermal generation capacity does not necessarily imply high fossil fuel use. GENESYS-Mod maintains part of the gas and coal capacities for adequacy and flexibility purposes, while their actual utilisation remains very limited. This underlines the importance of distinguishing between installed capacity requirements and real operational dispatch in highly renewable electricity systems.

Overall, the intercomparison exercise demonstrates the value of combining national and European modelling perspectives to better understand the robustness, uncertainties, and sensitivities of energy transition scenarios. Such comparisons contribute to improving transparency, identifying critical assumptions, and strengthening the credibility of long-term energy planning exercises.

1.4 Feedback from stakeholders

The Spanish national stakeholder workshop for Case Study 1 was held online on 25 March 2026, in the framework of a RedMENTES meeting, and gathered 23 participants from universities, research centres, technology centres, companies and the Ministry for the Ecological Transition and the Demographic Challenge (MITECO). The session combined a presentation of the ManOEUVRE scenarios for Spain with a participatory exercise using an interactive whiteboard, where stakeholders provided comments, improvement proposals and links to other projects along several thematic blocks aligned with the case study analysis. Overall, the discussion confirmed the relevance of the ManOEUVRE results for the Spanish energy-modelling community, industry representatives and policy actors, while also highlighting several aspects that could be strengthened in future iterations of the work.

Stakeholders emphasised that one of the main strengths of the work lies in the systematic comparison between the GENeSYS-Mod NECP Essentials scenario and the official PNIEC projections, across electricity generation and capacity, energy balances, final and primary energy demand, and emissions indicators. They considered this model-to-plan intercomparison a useful way to test the robustness and realism of national assumptions, and to identify where pan-European cost-optimal results point to alternative transition pathways or different timings of technology deployment.

A recurring point in the discussion concerned the influence of the modelling scope and system boundaries on the results. Stakeholders recognised that GENeSYS-Mod, as a European-scale optimisation model with endogenous cross-border trade, often delivers lower electricity generation levels, different export balances and a more moderate deployment of storage and conventional thermal plants than the PNIEC, which is built from a national planning perspective. This contrast was seen as valuable to reassess assumptions on renewable build-out rates, security-of-supply margins and the role of interconnections, and to better understand how competition with neighbouring



systems may limit the extent to which a country can act as a large net exporter of renewable electricity.

Stakeholders also highlighted that the comparison reveals different views on sectoral transformation, in particular in industry and transport, where the PNIEC often assumes faster electrification, stronger bioenergy deployment and a more rapid phase-out of fossil fuels than the GENeSYS-Mod pathway. From their perspective, these discrepancies underline the need to scrutinise technological and infrastructural feasibility, as well as to complement the quantitative results with life-cycle and criticality assessments, social and environmental indicators, and a more explicit treatment of uncertainty.

Overall, participants agreed that confronting GENeSYS-Mod results with the PNIEC delivers actionable insights for future updates of the national plan, provided that the reasons behind divergences are clearly explained and communicated. They encouraged the project to further exploit this comparative framework in subsequent iterations, both by deepening the analysis of key drivers (such as hydrogen deployment, storage and flexibility, or industrial heat demand) and by extending the dialogue with policymakers and other stakeholders involved in the NECP process.



2 Norway and Sweden (Case studies 2a and 2b)

Originally, Case study 2 was designed as an integrated analysis combining energy system modelling using TIMES-NOSE with power system modelling using FanSi. During the project, this approach was revised, and the work was divided into two complementary parts in order to better leverage the respective strengths of the two models without requiring extensive model integration. Case study 2a focuses on the broader energy system, including sectors such as hydrogen and industry, while Case study 2b provides a more detailed assessment of the electricity system and power market dynamics. Together, the two parts offer complementary insights into potential Nordic roles in the European energy transition.

Case study 2a examines how Norway and Sweden can decarbonise their closely connected energy systems while contributing to the broader European energy transition. In particular, it explores their potential roles as suppliers of low-carbon energy commodities, such as electricity and hydrogen, as well as energy-intensive green industrial products, including iron, steel, and aluminium.

The results show that Norway and Sweden can make substantial contributions to the European energy transition beyond their own borders. However, their respective roles differ depending on future industrial developments, the evolution of the European energy system, and technological learning, particularly for green hydrogen production.

Case study 2b combines results from the pan-European energy system model GENeSYS-MOD with the stochastic power market model FanSi to analyse flexibility in the Norwegian and Northern European power system in 2050. Using the NECP Essentials 2050 scenario results from GENeSYS-MOD as the underlying system configuration, four stylized flexibility variants are assessed relative to the baseline case: enhanced hydropower flexibility, elastic demand, time-shiftable demand, and expanded cross-border transmission.

The results show that Norway experiences lower electricity prices than continental Europe and the United Kingdom due to a substantial electricity surplus, while extensive hydropower resources contribute to comparatively low price volatility in the NECP Essentials 2050 configuration. The analysis also reveals substantial interannual variation in prices and other system indicators across weather years, underscoring the importance of multi-year analysis for power system planning. The investigation of stylized flexibility expansions indicate that different flexibility mechanisms address complementary dimensions of variability: Hydropower flexibility and time-shiftable demand expansions are particularly effective in reducing solar-driven intraday variability, while elastic demand expansion is more effective in mitigating wind-related variability. Expanded transmission primarily reduces regional differences in prices and volatility.

2.1 The Norwegian and Swedish energy plans

Decarbonisation

In Norway and Sweden, most CO₂ emissions come from industry, petroleum and the transport sector. From 2030 to 2050, total emissions decline strongly in the analysis, with the largest reductions coming from transport due to electrification and the use of biofuels and synthetic fuels.

Industrial emissions are reduced mainly by replacing fossil fuels with electricity and hydrogen. However, some emissions are difficult to eliminate, especially in cement production and in metals and



minerals industries. These remaining emissions highlight the need for additional solutions, such as carbon capture and storage (CCS), alongside electrification and hydrogen use.

Energy exports

Norway and Sweden play different roles in Europe's low-carbon energy system, mainly depending on how much energy they use at home. With limited industrial growth, both can export large amounts of low-carbon electricity and hydrogen. With higher industrial activity, Norway remains a net energy exporter, mainly of green hydrogen, while Sweden uses more energy domestically and instead exports energy-intensive green products such as steel and batteries.

2.2 Comparison of the Norwegian “NECP” with the NECP Essentials scenario

As discussed in section 2A.4.2 in ManOEUVRE Deliverable 3.1 (“Executive Summaries of Case Studies”, ref. [5]), Norway does not have a formal National Energy and Climate Plan (NECP) equivalent to those prepared by EU member states under the EU Energy Union Governance Regulation. Instead, Norwegian climate and energy policy is set out across several policy documents and strategies. The closest equivalent to an NECP is the Norwegian Climate Plan for 2021–2030, which outlines emission reduction targets, sectoral measures, and policy instruments for achieving Norway's 2030 climate goals.

In the remainder of this section, we report the main insights and outcomes from an early-stage assessment of the GENeSYS-MOD results for NECP Essentials v1.1. This assessment informed subsequent updates to the GENeSYS-MOD model run underpinning Case Study 2b.

The most important updates were increases in total electricity demand in Norway and Sweden, to better align with national scenarios published by the respective transmission system operators (Statnett and Svenska Kraftnät) and the Norwegian Water Resources and Energy Directorate (NVE) for the year 2050. In the revised modelling and results used as a basis for Case study 2b, the total annual electricity demand in 2050 is 172 TWh and 186 TWh for Norway and Sweden, respectively. Another update was a downward adjustment of annual hydropower production in Norway to 149 TWh, which approximately aligns with the most recent long-term power market scenario from NVE.

Regarding wind and solar generation levels in Norway in 2050, the revised GENeSYS-MOD NECP Essentials v1.0.1 model run used for Case study 2b contains 35 TWh offshore wind, 16 TWh onshore wind and 13 TWh solar. By comparison, the most recent long-term power market scenario from NVE contains 17 TWh offshore wind, 33 TWh onshore wind and 10 TWh solar. Finally, we note that while the GENeSYS-MOD NECP Essentials results for Case study 2b have zero hydrogen production from electrolysis in Norway in 2050, the most recent baseline scenarios from NVE and Statnett, respectively, include 9 TWh and 27 TWh annual electricity demand for hydrogen production.

2.3 Lessons learnt in Case study 2a

Focusing on national NECPs alone captures only part of a country's contribution to reducing global greenhouse gas emissions. Countries can also contribute beyond their borders through energy and product exports. Norway and Sweden are clear examples of this, given their large potential to export low-carbon energy carriers such as hydrogen and renewable-based electricity, as well as energy-intensive green industrial products, including steel and aluminium.



Cross-border collaboration can play an important role in achieving national NECP targets. Coordinated planning of electricity and hydrogen trade allows energy carriers to be produced where renewable resources are most abundant and cost-efficient and consumed where demand is highest. Such cooperation can lower overall system costs, improve resource use, and support more effective decarbonisation across countries.

Industry is one of the hardest sectors to decarbonise, as many emissions are linked to industrial processes rather than energy use. Reaching net-zero therefore requires further development and deployment of new technologies.

2.4 Lessons learnt in Case study 2b

Here we present a short summary of the key findings and policy relevance of Case study 2b. For a full analysis, please see [5].

Key findings:

- The analysis shows strong interannual variability beyond average-year outcomes, with extreme events and system stress occurring only in certain weather years and therefore not captured in average-year results.
- Average electricity prices in Norway are considerably lower than in continental Europe and the United Kingdom. The lower Norwegian prices reflect a substantial electricity surplus for Norway combined with limited cross-border export capacity in NECP Essentials.
- Cross-border interconnections are frequently used in both directions on daily and weekly timescales, reflecting dynamic trade patterns even in a surplus system.
- Different flexibility options address variability in different ways, suggesting benefits of combining different flexibility solutions in future high-wind-solar systems.
- Hydropower plays a significant role in balancing variability, particularly by offsetting intraday fluctuations in solar generation. As such, Norwegian hydropower provides valuable flexibility in the European energy system.
- Expanded transmission improves overall system efficiency and reduces regional price differences but may increase exposure to high-price periods in Norway.

Policy relevance:

- Robust power system planning requires going beyond average-year analysis and explicitly accounting for variability and extreme conditions.
- Diversified approaches to mitigating variability are operationally beneficial, as different measures address different types of variability.
- Hydropower may play a stronger role in future intraday balancing than historically, with implications for hydropower plant operation.
- Cross-border transmission should be assessed with a nuanced perspective, recognising both system-wide efficiency gains and distributional impacts.



- A domestic electricity surplus for Norway can support electrification as an emissions reduction strategy by enabling relatively low domestic electricity prices.

2.5 Feedback from stakeholders

The Norway-Sweden national stakeholder workshop on 12 May 2026 brought together research and industry participants to discuss modelling results from Case Study 2a and 2b.

Stakeholders noted that the case studies address strategic dilemmas they face in practice, notably the role of the Nordic region in the European energy transition. This includes the balance between exporting energy versus exporting energy-intensive products. Some participants acknowledged the analytical value of scenarios with expanded cross-border transmission from Norway, while also emphasizing that such developments are currently socially and politically controversial. For some stakeholders, increased transmission capacity between Norway and continental Europe remains highly controversial.

A central theme in the discussion was uncertainty. Stakeholders pointed to significant uncertainties related to technology development, future demand, and policy frameworks. There was concern that the current set of scenarios may not fully capture the breadth of possible outcomes, and participants stressed the importance of systematic sensitivity analyses together with transparency regarding key assumptions and parameter choices.

Stakeholders also provided feedback on model representation of system flexibility. While acknowledging that the FanSi model includes relatively detailed hydropower modelling, participants noted that important operational constraints, such as ramping limitations, are not fully represented. This could affect the results of flexibility assessments in the Nordic power system. A similar argument may be made for other technologies, including battery energy storage.

In addition, stakeholders expressed a need for clearer insight into how system-level efficiency varies across scenario model runs. For example, how much more efficient does the system get with given expansions in flexibility? The absence of reported CO₂ emissions was also noted as a limitation, as emissions outcomes are central to evaluating transition pathways.



3 Germany (Case studies 3, 4, 5)

3.1 The German NECP

The German NECP is also developed to cover the five dimensions of the EU-Energy Union: Reduction in CO₂ emissions, energy efficiency, security of supply, internal energy market, and research and innovation.

The German NECP is structured into two parts: a political-strategic part and a second analytical part. Germany's targets are more ambitious than EU targets. Germany attempts to reach climate-neutrality in 2045, emissions shall be reduced by at least 65% until 2030 and by 88% until 2040 compared to 1990 levels.

Laws and regulations contributing to the NECP are the update to the Climate Protection Law from 2024, the legally defined national coal phase-out until 2038, and the nuclear phase-out completed in April 2023. Germany plans a technology-neutral approach to not restrict any future technology options and to avoid foreseeable increases in costs during the transformation process. The Energy Efficiency Law and German Climate Protection Plan support the planned extension of renewable installations in Germany. The Building Modernisation Act regulates the national strategy and the decarbonisation in the heating sector.

3.1.1 Decarbonization

Decarbonization will be established through emission reductions and the installation of renewable energy sources.

Reduction goals:

- -65% emission in 2030 compared to 1990. -88% emissions in 2040 and climate-neutrality in 2045.
- ETS I goal: EU-wide target of -62% until 2030 compared to 2005
- LULUCF goal: increase carbon sink by about 3.8Mt compared to 2016-2018
- Increased extension of natural sinks in accordance with German climate law
- Climate-neutral federal administration until 2030

Renewable energy targets:

- Share of renewable energies on gross final energy consumption in 2030 by at least 42.5%
- Generation of at least 600TWh renewable power in 2030, at least 80% of gross electricity consumption.
- Provision of 50% of grid-based heat from renewable sources or unavoidable waste heat
- Technology-specific targets:
 - Installed PV capacity in 2030: 215GW, 400 GW by 2040
 - Installed wind onshore capacity in 2030: 115GW, 160 GW by 2040
 - Installed wind offshore capacity in 2030: 30GW, 70 GW by 2040

Energy Efficiency



- In accordance with the new Energy Efficiency Act: reduction of total energy consumption in 2030 about 26.5% in comparison to 2008 to 1867 TWh. Reduction in primary energy consumption about 39.9% to 2252 TWh.

Energy security

- Meet energy demand at all times.
- Maintain resilience
- Have precautionary measures and reserves ready

Energy market

- Expansion and modernisation of electricity networks - building of new interconnectors and faster power grid expansion
- Stable grid operations under 100% renewables
- Cross-border cooperation
- Sector coupling
- Coal phase-out.
- Energy and Heat Storage Strategy: Battery

Innovation and Competitiveness

Germany plans to further support research in energy and climate protection through public research institutions and the business sector. Furthermore, it wants to maintain a competitive base for industry in Germany and to stop carbon leakage by industry moving to countries with lower environmental standards as well as keeping and expanding jobs in Germany.

- National bioeconomy strategy
- New innovations in buildings and construction sector (wood buildings)
- Research in carbon dioxide removal
- Skilled Immigration Act
- Clean hydrogen strategy: Green hydrogen

3.2 Comparison of the German NECP with the NECP Essentials scenario

The comparison of the NECP Essentials scenario (v1.4.0) with the German NECP reveals a mostly consistent picture for several variables, while some differences remain. Regarding installed renewable electricity capacities, the scenario was aligned with the NECP targets for solar PV (215 GW), onshore wind (115 GW), and offshore wind (30 GW) in 2030. Minor differences are observed for biomass (7.64 vs. 8.4 GW) and hydropower (5.3 vs. 6 GW) as can be seen in Table 2.

Table 2: Comparison of installed capacities of renewables in 2030 in the NECP Essentials scenario v1.4.0 and the German NECP.

Variable in GW	NECP Essentials v1.4 2030	Real NECP 2030
Capacity Electricity Biomass	7.64	8.4
Capacity Electricity Hydro	5.3	6
Capacity Electricity Solar	215	215



Capacity Electricity Wind onshore	115	115
Capacity Electricity Wind offshore	30	30

Total final energy consumption shows strong alignment between the scenario and the NECP (1813 vs. 1809 TWh), suggesting that the overall demand trajectory is well captured by the model. Unfortunately, a more detailed comparison cannot be made in regard to the final energy consumption, as the model and NECP use different sectoral disaggregation methods. The final energy consumption as well as RE shares in different sectors, and GHG reductions can be found in Table 3. The renewable energy shares projected by the model exceed those of the NECP across the available sectors: electricity (88.8% vs. 80%) and heating and cooling (38% vs. 32%), reflecting a more ambitious deployment of renewables in the model. Consequently, the GHG emission reductions achieved in the scenario (–56.6% vs. 2005; –67.5% vs. 1990) also exceed the NECP projections (–50% vs. 2005; –65% vs. 1990), indicating that the NECP Essentials scenario follows a more ambitious decarbonisation pathway than the German NECP's projection for 2030.

Table 3: Comparison of RE share in different sectors, GHG reductions and total final energy consumption between the NECP Essentials scenario v.1.4.0 and the German NECP

Variable	NECP Essential v1.4 2030	Real NECP 2030
RE share in electricity sector	88.8	80.0
RE share in heating and cooling	38	32
GHG reductions compared to 2005	-56.6%	-50%
GHG reductions compared to 1990	-67.5%	-65%
Total final energy consumption in TWh	1813	1809

Table 4 displays the comparison of primary energy consumption by energy carrier, showing differences, especially in the consumption of petroleum. Petroleum (2140 vs. 3632 TWh) shows considerably lower values in the model compared to the German NECP. This discrepancy has two components. The first is structural: a significant share of the NECP's petroleum consumption reflects aspects outside the model's design, namely the non-energy use of petroleum as industrial feedstocks, international maritime bunker fuels, and refinery own consumption and losses. The second component reflects a difference in transport sector assumptions. In the NECP, transport final energy consumption declines by only 5.5% between 2024 and 2030 as the projection assumes stable transport activity. By contrast, the model projects a more substantial decline in transport energy consumption. Petroleum consumption in the transport sector falls around 20% from 2018 to 2030, reflecting a more aggressive electrification trajectory and a greater reduction in fossil fuel use in the transport sector than the NECP foresees by 2030. Nevertheless, overall renewable energy is closely aligned, highlighting that both the model scenario and the German NECP are moving in the same direction regarding the decarbonisation of the energy system.

**Table 4: Comparison of primary energy consumption between the NECP Essentials scenario v.1.4.0 and the German NECP**

Variable in PJ	NECP Essential v1.4 2030	Real NECP 2030
Hard coal	314	244
Lignite	11	45
Coal combined	325	289
Petroleum	2,140	3,632
Gases	2,315	2,513
Nuclear energy	0	0
Renewable energy	3,290	3,275
Other energy sources	72	349
Total	8,142	10,058

It should be noted that the modelling results presented here stem from a European model run, from which the German results were extracted. As results from a linear optimisation model, the NECP Essentials scenario is subject to data assumptions, particularly for future years, introducing a degree of uncertainty into the results. Furthermore, the base year of the model at the time of modelling was 2018, with 2025 as the first modelled year. Although steps were taken to align certain parameters for 2025 with observed data, the proximity of the 2030 horizon means that the model results may differ in some respects from what has already been achieved or is currently planned at the national level, including deviations from the underlying projection data used in the preparation of the German NECP itself. These limitations should be kept in mind when interpreting the comparisons above.

3.3 Lessons and Recommendations for German NECP

In general, we would like to point out that only 4 years are left until 2030 to accomplish targets from the NECP. However, the Case studies focus on long-term targets until the years 2050, respectively 2060.

3.3.1 Lessons learnt in Case study 3

The German NECP projects a steady decline in industrial energy consumption towards 2030, derived from a scenario in which sectoral structural change is treated as an exogenously given process driven primarily by efficiency improvements and technological substitution within existing production sites. While the NECP explicitly recognises the risk of carbon leakage and addresses it through compensatory instruments, this framework is implicitly oriented towards leakage to non-EU countries with lower environmental standards. The possibility of systematic intra-European industrial restructuring driven by differential renewable resource endowments is not considered.

Case study 3 suggests that this framing omits a structurally important mechanism. As the transition to renewable energy progresses, countries differ substantially in their long-run renewable electricity



generation potential, creating persistent and systematic cost differentials that may alter where energy-intensive - and, through supply-chain propagation, also downstream - manufacturing activity takes place within Europe. The resulting industrial restructuring does not simply determine which countries retain or lose existing production; it triggers more complex processes of specialisation within Europe's integrated production network, with implications for regional employment, for the sectoral composition of national industrial bases, and consequently for national energy demand trajectories. To explore these dynamics, Case Study 3 developed an agent-based simulation model of a multi-regional production network, calibrated to empirical data on industrial structure and trade flows. Models of this kind are inherently complex, and their results depend on assumptions about firm behaviour, adjustment frictions, and the transmission of cost signals through supply chains - assumptions that are difficult to validate against observed data and that introduce substantial parameter uncertainty. Nevertheless, such frameworks serve a valuable function even in their current, exploratory form: they make explicit the mechanisms through which energy cost differentials could translate into structural economic change, and they provide a concrete analytical basis for asking whether and how these mechanisms are reflected in existing planning frameworks. In this sense, the model functions as a structured way of interrogating the assumptions that underlie conventional demand projections.

The central lesson for the NECP process is therefore not primarily about the magnitude of demand changes that such restructuring might produce, but about the nature of the uncertainty it introduces. A demand trajectory that appears plausible in aggregate may rest on causal assumptions - efficiency-driven decline, stable sectoral composition - that do not hold if industrial location decisions respond endogenously to changing energy cost conditions across Europe. Instruments designed to improve on-site efficiency or to compensate for energy cost burdens will not prevent the underlying structural shift if comparative disadvantages in renewable resource endowment are sufficiently persistent.

This has consequences that extend beyond the national planning context. Energy infrastructure planning in Europe - including grid expansion, hydrogen network development, and cross-border interconnector investment - depends critically on projections of where industrial demand will be located in the medium and long run. If industrial activity gradually concentrates in regions with favourable renewable endowments while contracting elsewhere, the spatial distribution of demand may diverge from trajectories projected under the assumption of stable industrial structures. Since NECP demand projections are currently prepared largely in national silos, such cross-border redistribution of industrial activity is systematically underrepresented at the European level, creating the risk of individually plausible but collectively inconsistent aggregate assumptions.

Against this background, two recommendations emerge for the German NECP and its European coordination context. First, future iterations of national energy plans should include sensitivity variants that explicitly consider industrial demand restructuring as a possible adjustment channel - alongside efficiency improvements and fuel switching - and assess its implications for the sectoral and regional composition of projected demand. Second, and more fundamentally, the coordination of NECP demand projections across Member States should be deepened to account for the spatial heterogeneity of renewable resource endowments. A European planning process that treats national demand trajectories as independent inputs risks missing the redistributive dynamics that the energy transition itself may set in motion.



3.3.2 Lessons learnt in Case study 4

The German NECP stresses the importance of the ambitious expansion of renewable generation sources and accompanying flexibility, both, within the power sector and cross-sectoral. It also describes financial support mechanisms currently in place to support renewable electricity generation and sketches their future development towards Contracts for Difference (CfD), alongside with an expected increase in market-based power purchasing agreements (PPAs). However, it falls short on incorporating the actors' perspective and their exposure to financial risks, as investments into renewable resources and flexibility technologies will only happen if the revenue perspective is sufficiently high. Beyond the NECP, there are ongoing policy debates on when and how to phase out financial support mechanisms for renewable electricity generators ([13], [14], [15]). In the following, we build on the analyses presented in [5]. Parts of the subchapter on the NECP for case study 4 are taken over in the following and extended by some more insights.

We took the question about sufficient investment incentives as a motivation to dive into the market-based cost recovery perspectives for renewable electricity generators and flexibility technologies in case study 4. Therefore, we applied the agent-based power market model AMIRIS and used the installed capacities from the EU EnVis-2060 scenarios in version 1.3 while we analysed the cost recovery perspective of the system in place for every scenario and year. One central limitation is that we have not yet accounted for important flexibility sources, such as power imports and exports or flexible electrolysis which do have quite a positive effect on cost recovery perspectives for renewable energy sources. However, the major findings we derive build on general trends observed.

For most scenarios and variants, we find market-based cost recovery rates of well below 100% in our analyses for both, renewable generators as well as flexibility technologies, due to declining market values as well as price spreads with increasing deployment rates. Besides the already mentioned model limitations, another explanation is the scenario assumptions, such as rather low fuel prices. However, future fuel prices are highly uncertain, and it is not given for granted that they ensure sufficient situations with high electricity prices. On the contrary, there rather is an interest in cheap fuel prices, such as the hydrogen price.

For variable renewable generators, there are some measures to potentially cope with the low-cost recovery levels that are out of scope in our analysis. They can conclude PPAs with buyers on the demand side. However, if there is an expectation of rather low electricity prices, it will be hard to find counterparties on the demand side willing to conclude PPAs at considerably higher prices.

However, we find quite a stark cross-scenario and cross-year variation of cost recovery levels, also with cases, where a completely market-based cost recovery is achieved for renewable generators. Ultimately, this stark variation stresses the vast uncertainty concerning future price developments and the needs for adequate investment de-risking.

The low price and cost recovery levels observed raise the question for adequate de-risking or policy support of renewables to ensure the necessary renewable capacity expansion to meet Germany's NECP targets. As future support is to come from CfDs pursuant to Article 19d of the European electricity market regulation ([16]), those mechanisms need to be designed in such a way that they foster sufficient investments and balance the risk distribution among the power plant producer and the broader public. Similarly, the low-cost recovery rates for flexibility technologies raise the question about how these investments can be de-risked and whether they should be supported. Again, there are potential countermeasures to tackle low-cost recovery rates, such as a multi-market dispatch strategy which we do not account for. However, market volumes of other markets, such as intraday



and balancing markets, are ultimately limited, which restricts additional revenue potential. There is the obligation for member states to analyse flexibility needs and establish indicative targets, according to Articles 19e and 19f of the EU electricity market regulation ([16]). In this context, the possibility to establish support mechanisms for flexibility within capacity mechanisms or even as additional regimes is addressed in Article 19g ([16]). As of now, no flexibility assessment, target or support mechanism is established for Germany.

In summary, the low-cost recovery rates observed in most variants of case study 4 as well as a stark variation of cost-recovery levels underscore significant uncertainty and raise concerns regarding the feasibility of achieving a climate-neutral power system without targeted de-risking mechanisms for variable renewable generators and flexibility technologies. This subject should be covered in more depth in future versions of the German NECP.

3.3.3 Lessons learnt in Case study 5

The German NECP has a focus on expanding renewable energy sources, such as wind power and PV. The results of Case study 5 show that the stated expansion targets for renewable energy technologies, like wind onshore, offshore and PV will neither be reached in 2030 nor 2040. However, enough power will be produced to satisfy the demand with clean energy technologies even in times of low availabilities of wind and solar power and to not rely on fossil technologies anymore. The results from Case study 5 also show, that it is important to acknowledge biomass, as it can complement variable renewable energy sources in times of low availability. While the NECP is referring to the national biomass strategy (NABIS) to create a framework for climate-friendly and resource-efficient production and use of biomass, this strategy has not been published yet.

Our work also shows that biomass will be mostly used in the heating sector. Regulations besides an expansion target for large-scale heat pumps are missing in the NECP. Furthermore, the defined measures in the NECP are not enough to reach climate targets without buying external carbon credits.

3.4 Feedback from stakeholders

The German national stakeholder workshop took place on May 12. The participating stakeholders have backgrounds in German government agencies, federations and scientific advisory boards.

Feedback on the findings with regards to the NECP presented from the case studies included a closer examination of the LULUCF sector, the distinction between short- and long-term sinks in our calculations, and the integration of the agricultural sector. The consideration of sustainability aspects regarding biomass, varying biomass potentials, and imports across sectors was raised. Additionally, there were inquiries regarding the inclusion of water-source heat pumps for electricity generation. Furthermore, there were inquiries regarding the mapping of future CO₂ and H₂ infrastructure as well as of carbon dioxide removal (CDR) technologies.

Concerning case study 4, a stakeholder raised doubts concerning the low market-based cost recovery levels observed, especially for renewable generators. Also, EU-EniVS 2060 scenario results showing a rather low battery deployment were criticised. The authors think that the critic relates to the communication of the results. Obviously, the model limitations and scenario setting should have been made more transparent. Also, the aspect of uncertainty and cross-scenario variations should have been stressed even more as this underpins the general findings and NECP implications. Furthermore, it is planned to incorporate further flexibility sources in upcoming analyses which will have an implication on the magnitude of the quantitative results. Another participant raised the question as



to whether the AgNes grid reform (procedure for determining the general grid fee system for electricity, [17]) was considered in the analyses and if marketing at several marketplaces (e.g., intraday market) was considered.

Regarding case study 5, high interest was expressed in detailed potentials of biomass and the discussion of its import rates. Additionally, inquiries about the level of detail of wood and wood products in the model were raised. The authors refer to a different project using BENOPT working on the integration of the wood sector. Hence, for future research, the wood sector could be investigated. Questions with regards to current political debates about heating technologies and the use of biogas in Germany are not reflected in the model. It was requested how uncertainty is considered in Case study 5. The presented model results rely on a model version using perfect foresight. Due to time constraints the stochastic model version was not presented, however results using the stochastic BENOPT model will be presented at the EEM.



4 Turkey (Case study 6)

4.1 The Turkish National Energy Plan (NECP)

The latest Turkish National Energy Plan, published in early 2022, represents a pivotal shift in Turkey's climate and energy policy, culminating in the ratification of the Paris Agreement and a commitment to achieve net-zero emissions by 2053. Its development was based on thorough modelling of Turkey's energy demand, supply security, and economic growth targets, utilizing the TIMES energy system optimization model. Three distinct time periods of energy transition are envisioned: a) 2023-2030: Maximizing renewable energy penetration, particularly solar and wind, commissioning the first nuclear power plant, and improving energy efficiency; b) 2030-2040: Deeper electrification of final energy consumption, scaling up energy storage, and introducing green hydrogen and advanced nuclear technologies; c) 2040-2053: Widespread use of green hydrogen, synthetic fuels, and Carbon Capture and Storage (CCS) to eliminate residual emissions in hard-to-abate sectors. The underlying strategy emphasizes energy security, reducing foreign energy dependency, and utilizing all domestic resources (including coal and renewables) in the short term, while pivoting heavily toward mature renewables and nuclear for long-term decarbonisation.

A detailed description of Turkey's strategy under the five main dimensions is as follows:

Decarbonisation: Achieve net-zero emissions by 2053, with an updated NDC target of up to 21% reduction in greenhouse gas emissions by 2030 compared to the Business-As-Usual (BAU) scenario. Unlike the EU, Turkey's 2030 target is relative to BAU rather than a baseline year, but its long-term 2053 target aligns with global climate goals. Electricity generation decarbonisation is central to Turkey's plan, to be achieved by:

- Continued but optimized use of domestic coal: Unlike other countries, Turkey does not have a coal phase-out date. Instead, it prioritizes utilizing domestic lignite resources to reduce import dependency, while imposing emission limits and planning for Carbon Capture and Storage (CCS) retrofits in the long term.
- Massive expansion of installed electrical capacity, driven by solar and wind. Turkey aims to increase its total installed capacity from around 100 GW today to 189.7 GW by 2035. Solar capacity is targeted to reach 52.9 GW and wind 29.6 GW by 2035. Offshore wind is slated for initial development, with 5 GW targeted by 2035.
- Introduction of Nuclear Power. Turkey is diversifying its zero-carbon baseload power through nuclear. The Akkuyu Nuclear Power Plant (4.8 GW) is expected to be fully operational by the mid-2020s, with a target of 10 GW total nuclear capacity by 2053, potentially including Small Modular Reactors (SMRs).
- Investment in storage and flexibility solutions. Turkey aims to install 7.5 GW of battery storage and 5 GW of pumped hydro storage by 2035 to support the intermittent nature of its massive RES expansion.

While the power sector leads the transition, final energy consumption is also targeted:

- Turkey aims to increase the share of renewable energy in its gross final energy consumption, targeting a RES share of approximately 23% by 2030 and 69.1% by 2053.



- Fossil fuel consumption is projected to plateau and then gradually decline, though natural gas usage is expected to grow in the medium term as a transition fuel and to replace heavy fuel oil in industry and heating.
- Industrial emissions are targeted for reduction via electrification, fuel switching, and the deployment of CCS in hard-to-abate sectors (particularly cement and steel) post-2040.
- Green hydrogen is expected to play a critical role post-2030, particularly for industrial feedstock and heavy transport, with blending in the natural gas network also under research.

Energy efficiency: Energy efficiency is considered the "first fuel" in Turkey's transition, aiming to limit the rapid growth of final energy demand driven by economic and population growth.

- The National Energy Efficiency Action Plan targets a 16% reduction in primary energy consumption by 2035 compared to the BAU scenario.
- Renovation initiatives and subsidies focus on improving the thermal performance of residential and public buildings, promoting efficient heating systems (including heat pumps), and widespread adoption of smart meters and smart home technologies.
- Vehicle efficiency is targeted through the promotion of electric vehicles (EVs). Turkey aims for 1 million EVs on the roads by 2030 and is heavily promoting domestic EV manufacturing (e.g., Togg). Rail freight and public transportation are also prioritized to reduce road transport emissions.

Energy security: Ensuring Turkey has a sturdy, reliable, and self-sufficient energy system is the core driving force of its NECP, as the country currently imports nearly 70% of its energy. To that end:

- Electricity security is ensured by maximizing domestic resources (renewables, domestic lignite, and nuclear), adding storage, and maintaining flexible natural gas capacity.
- Reducing reliance on imported fossil fuels (specifically natural gas and imported coal) is a primary economic and security objective, achieved by scaling up domestic RES.
- Diversification of supply routes remains critical. Turkey acts as an energy transit hub (hosting pipelines like TANAP and TurkStream) and is expanding its LNG floating storage regasification units (FSRUs) to ensure gas supply flexibility.
- Climate change risks, particularly droughts impacting hydropower (which traditionally makes up ~20% of Turkey's electricity mix), are addressed by diversifying the RES mix heavily toward solar and wind, as well as investing in battery/pumped storage.

Energy market: The NECP includes structural market reforms to incentivize participants and align the market with the transition:

- Turkey has adopted the "Unlicensed Electricity Generation" regulation, allowing consumers (and small businesses) to install rooftop solar up to their consumption limits, democratizing energy generation.
- Power purchase agreements (PPAs) are increasingly promoted, with the transition away from the state-guaranteed Renewable Energy Resources Support Mechanism YEKDEM feed-in-



tariffs (which expired for new applicants in 2021) toward market-based bilateral PPAs to facilitate corporate investment in renewables.

- Smart grid investments and the deployment of smart meters are underway to modernize the distribution network and allow consumers to react to price signals.
- A capacity mechanism is being structured to ensure that flexible natural gas and hydropower plants remain financially viable to provide backup for the renewables-dominated system.

Research, innovation and Competitiveness: The research and innovation dimension is mostly associated with scaling up new technologies and fostering domestic industry. Priority areas include:

- Developing a domestic supply chain for solar PV, wind turbines, and battery storage to capture the economic value of the energy transition.
- Offshore wind and floating solar technologies, with dedicated mapping and licensing of maritime zones already underway.
- Green hydrogen and synthetic fuels development, with pilot projects planned for blending hydrogen into the natural gas network and industrial use.
- Carbon capture, utilization, and storage (CCUS), which is deemed essential for the continued use of Turkey's domestic lignite fleet and cement industry beyond 2040.

4.2 Comparison of the Turkish NECP with the NECP Essentials scenario

4.2.1 Comparisons of electricity capacities, generation, and consumption

The TR NECP projects a gradual expansion of Turkey's electricity system between 2025 and 2035, with balanced growth across solar PV, wind, hydropower, natural gas, and nuclear power. Nuclear capacity reaches 7.2 GW by 2035 following the planned deployment of the Akkuyu nuclear power plant. Natural gas capacity also remains significant to support system flexibility and energy security. (Figure 9)

In contrast, the EnVis scenario shows a much stronger expansion of renewable technologies, particularly wind power, which increases sharply to nearly 140 GW by 2035. Solar PV also grows considerably, while nuclear deployment remains limited. Gas capacity in ENVIS increases substantially by 2035, indicating the continued need for flexible backup generation to support high renewable penetration.

These differences arise mainly from the modelling approaches. The TR NECP reflects policy targets, implementation feasibility, and energy security priorities, whereas GENeSYS-MOD optimizes the system under cost-minimization and decarbonization assumptions, favouring large-scale renewable deployment due to declining renewable technology costs.

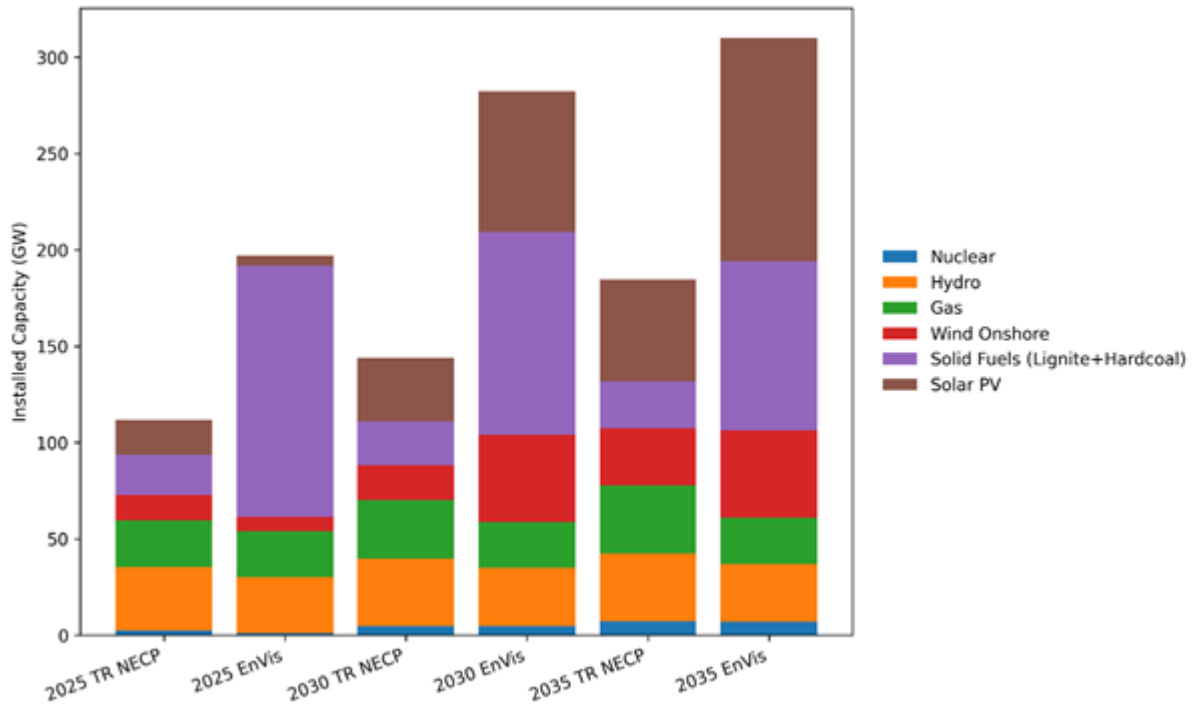


Figure 9: Comparison of TR NECP and ENVIS in terms of electricity capacity in Turkey

The TR NECP maintains a diversified electricity generation mix through 2035, with thermal generation from coal and natural gas still playing a dominant role despite increasing renewable shares. This reflects a gradual transition strategy that prioritizes supply reliability and domestic resource utilization.

The ENVIS scenario projects a much faster shift toward renewable electricity generation. By 2035, wind and solar become major contributors, while thermal generation declines substantially. Hydropower remains relatively stable in both scenarios due to limited additional hydro potential (Figure 10).

The lower thermal generation in ENVIS is consistent with the strong renewable capacity expansion observed in the optimization model. In contrast, the TR NECP maintains fossil-based generation to ensure grid stability and system flexibility during the transition period.

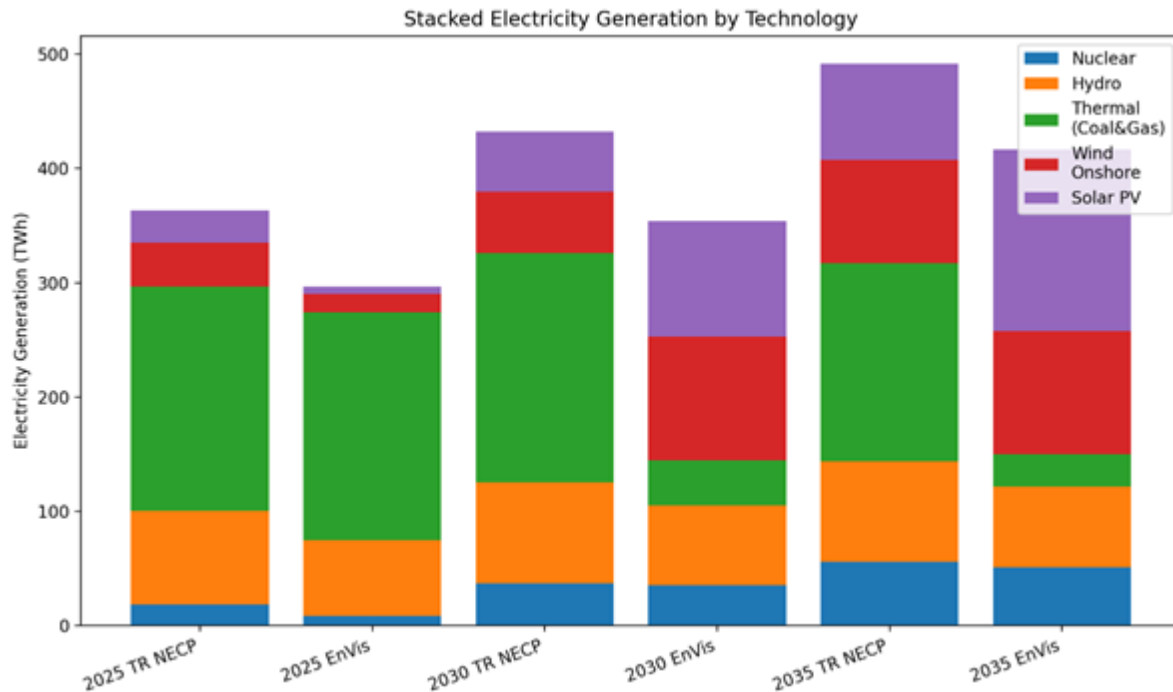


Figure 10: Comparison of TR NECP and ENVIS in terms of electricity generation in Turkey

Electricity consumption increases across all sectors in both scenarios, driven by electrification and economic growth. In the TR NECP, industry remains the largest electricity-consuming sector, reflecting continued industrial expansion and gradual electrification.

The ENVIS scenario projects significantly lower industrial electricity demand compared to the TR NECP, especially before 2035. This likely reflects stronger efficiency improvements, technological optimization, and structural changes in industrial energy use (Figure 11).

Buildings electricity demand remains relatively high in ENVIS, possibly due to increased deployment of electric heating technologies such as heat pumps. Transport electricity demand grows steadily in both scenarios due to vehicle electrification, although ENVIS projects lower transport electricity consumption by 2035.

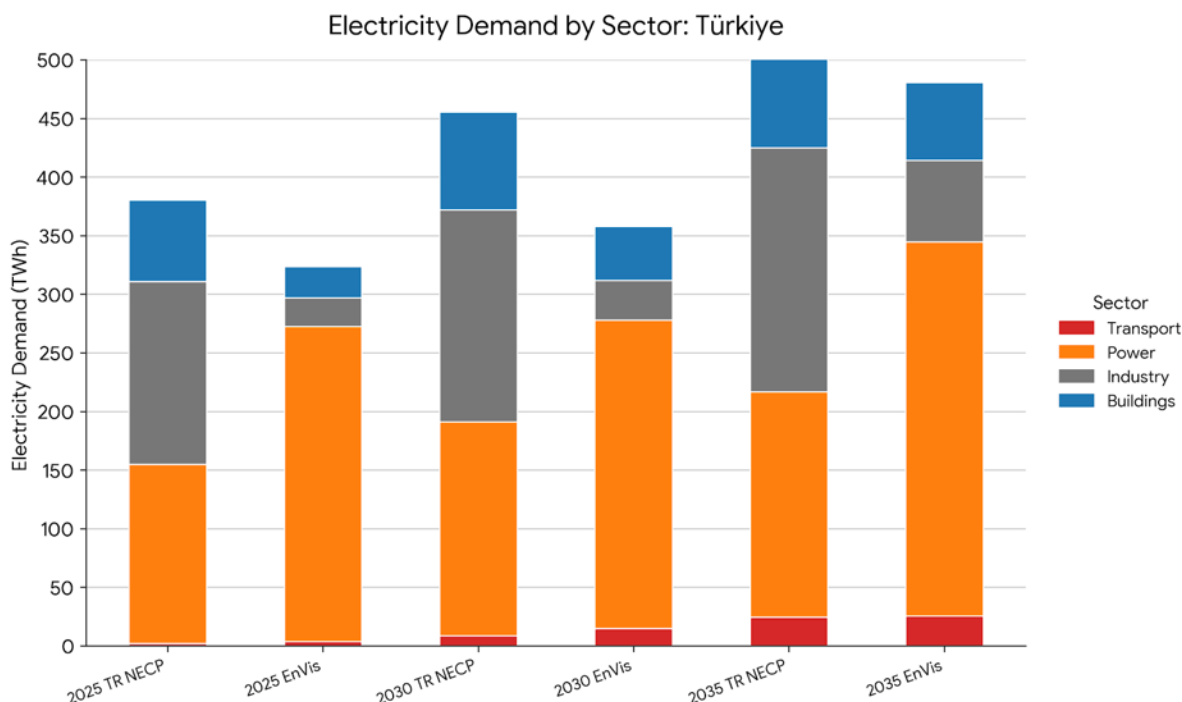


Figure 11: Comparison of TR NECP and ENVIS in terms of electricity consumption by sector in Turkey

4.2.2 Comparisons of primary and final energy consumption

The TR NECP maintains relatively high consumption of oil, natural gas, and solid fuels through 2035. Oil remains the dominant energy source due to continued transport demand, while coal and gas continue to support electricity generation and industrial activities.

The ENVIS scenario shows a much faster reduction in fossil fuel use. Solid fuel consumption declines sharply by 2035, indicating accelerated coal phase-out and renewable substitution. Oil demand also decreases significantly due to transport electrification and efficiency improvements.

Renewable energy consumption increases strongly in ENVIS, consistent with the large expansion of wind and solar capacities. Natural gas consumption also declines gradually as renewable electricity replaces gas-fired generation.

The absence of significant nuclear energy in ENVIS before 2035 reflects different assumptions regarding nuclear deployment and competitiveness relative to renewable technologies.

Moreover, ENVIS represents a faster structural transition toward a renewable-based energy system, whereas the TR NECP adopts a more gradual transition pathway balancing decarbonization with energy security considerations.

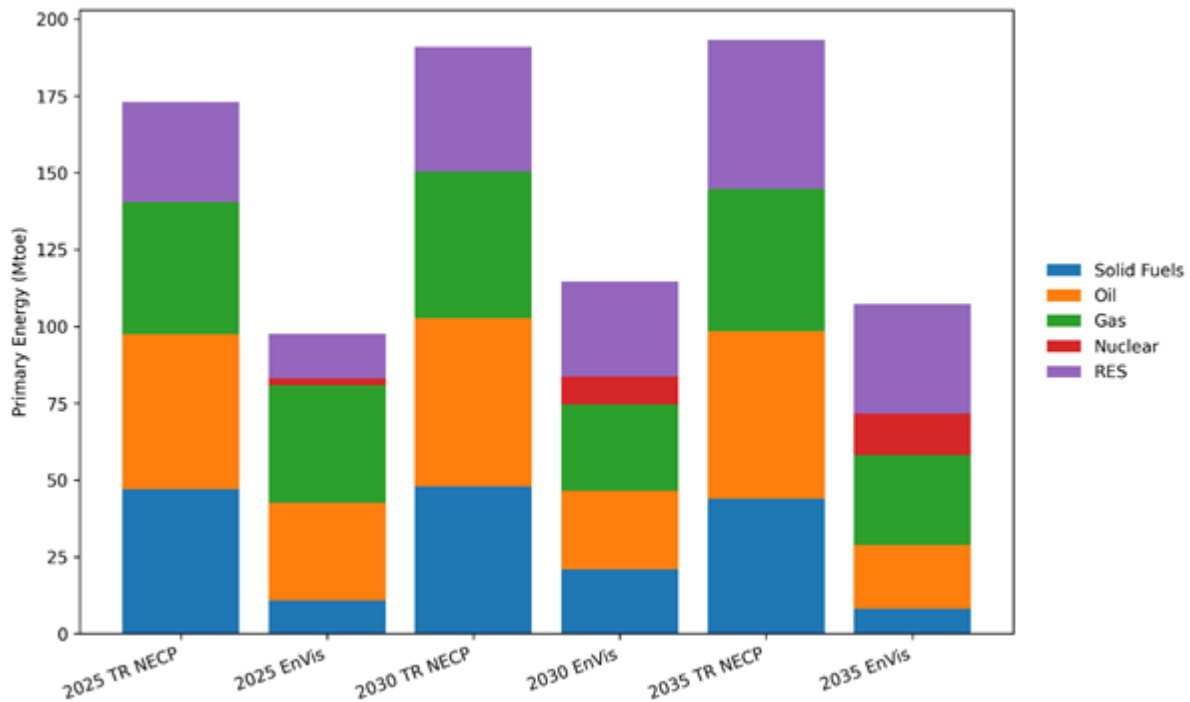


Figure 12: Comparison of Primary energy consumption between NECP and ENVIS in Turkey

The comparison across these two requires careful interpretive framing: TR NECP values for primary energy reflect consumption, while EnVis values reflect production — a methodologically important distinction, as consumption incorporates import dependencies and conversion losses, whereas production represents domestically generated supply before distribution.

On the primary energy side, TR NECP's consumption figures for coal remain persistently high (47–48 Mtoe through 2030 before easing to 43.9 Mtoe by 2035), indicating continued heavy reliance on coal in the consumption mix, likely sustained through imports. EnVis's production figures for coal, by contrast, decline sharply from 10.8 Mtoe to 8.07 Mtoe, suggesting domestic coal output is being deliberately wound down. For oil and gas, TR NECP consumption grows steadily — oil reaching 54.5 Mtoe and gas 46.2 Mtoe by 2035 — reinforcing Turkey's well-documented import dependence in these fuels. EnVis domestic production of both falls considerably short of these consumption levels, underscoring that a decarbonized production portfolio cannot independently satisfy fossil fuel demand without significant import substitution or demand destruction. The EnVis nuclear production trajectory (0 to 13.37 Mtoe) signals Akkuyu-type capacity coming online, contributing meaningfully to domestic supply diversification. RES production under EnVis grows from 14.48 to 35.76 Mtoe, while TR NECP's RES consumption reaches 48.7 Mtoe — the gap implying that renewable consumption in



the NECP pathway depends partly on system-level accounting differences or imported renewable energy carriers.

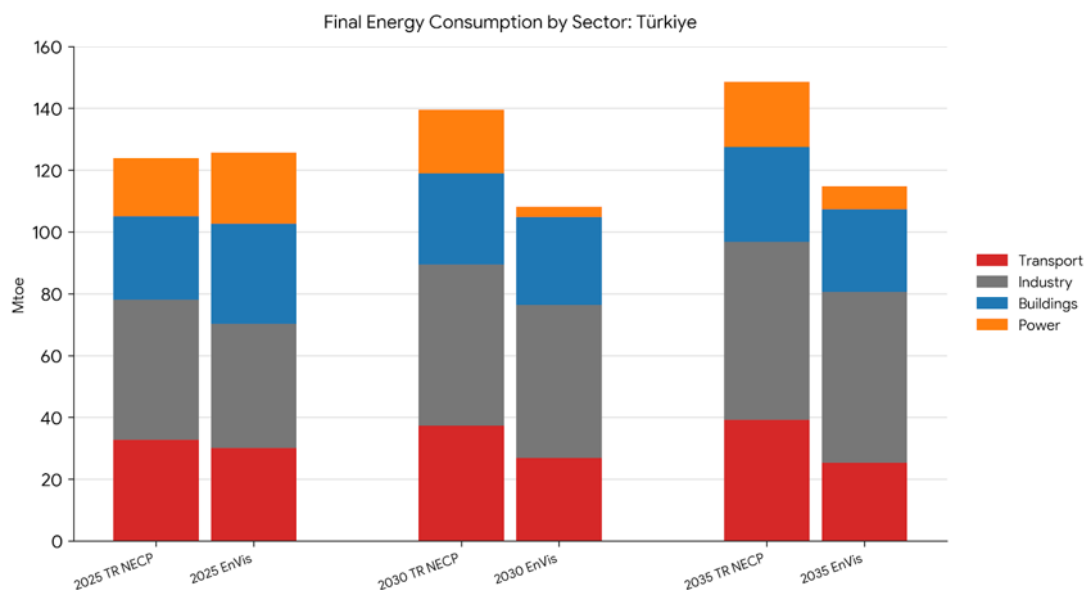


Figure 13: Comparison of Final energy between NECP and ENVIS for Turkey

On the final energy consumption side, the sectoral divergence is most acute in industry, where TR NECP projects consumption climbing to 57.6 Mtoe against EnVis's near-static ~11 Mtoe — a gap too large to attribute solely to efficiency gains, likely reflecting fundamentally different industrial structure or electrification assumptions embedded in each scenario.

4.2.3 Comparisons of CO₂ emission

The CO₂ emissions comparison highlights major differences in the decarbonization pathways of the two scenarios. In the TR NECP, emissions remain relatively high in 2030, particularly in the power and transport sectors. Power sector emissions remain significant because coal and natural gas continue to play important roles in electricity generation. Transport emissions also stay high due to ongoing dependence on oil-based fuels. The ENVIS scenario achieves substantially lower emissions, especially in the power sector, due to rapid renewable electricity expansion and reduced thermal generation. Industrial emissions are also lower in ENVIS because of lower fossil fuel consumption, electrification, and higher efficiency improvements. By 2050, ENVIS approaches near-zero emissions in most sectors, with power sector emissions fully eliminated. In contrast, the TR NECP still retains residual emissions in industry, transport, and power generation. These results indicate that accelerated renewable deployment, electrification, and energy efficiency are essential for achieving deep decarbonization. While the TR NECP reflects a more conservative and implementation-oriented transition pathway, ENVIS represents a more ambitious optimization-driven pathway aligned more closely with long-term net-zero objectives.

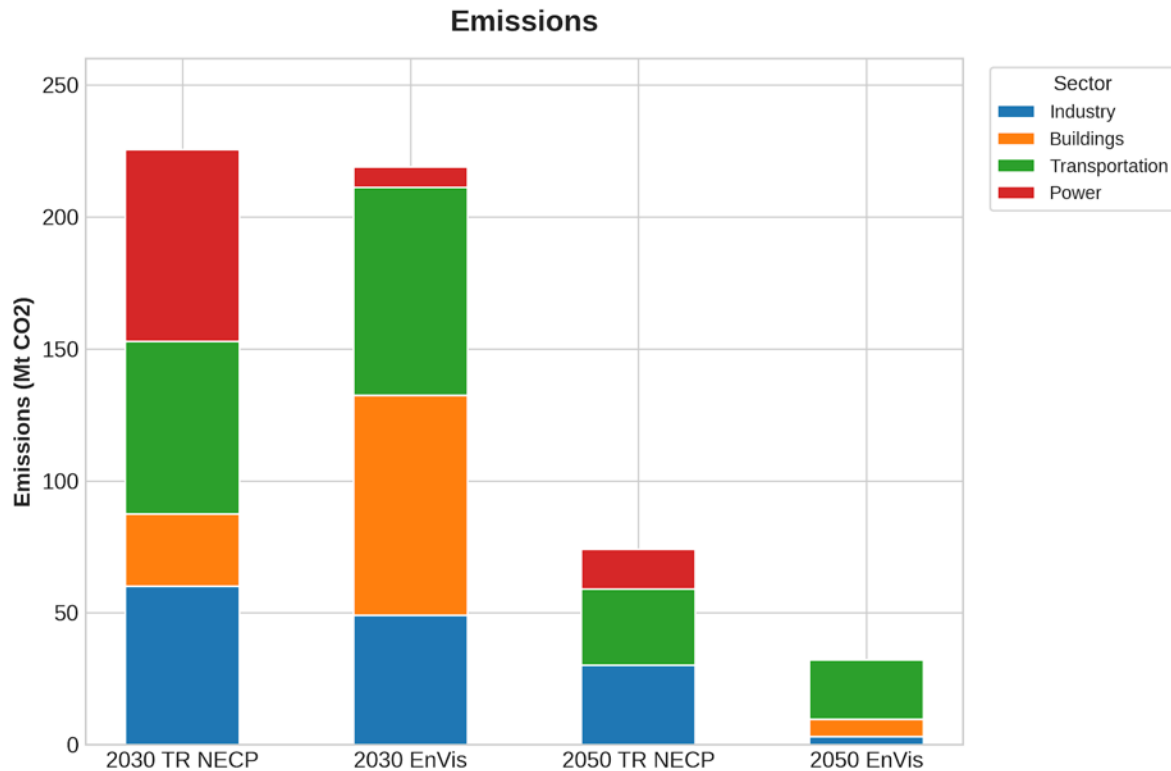


Figure 14: Comparison of emissions between NECP and ENVIS for Turkey

4.3 Lessons learnt in Case study 6

In Case study 6, we analyzed Turkey's long-term energy transition pathway by soft-linking the national optimization framework with GENESYS-MOD, focusing heavily on renewable energy targets, sectoral decarbonization, and the economic viability of green hydrogen production. The major findings detailed below elaborate on the interaction between national policy goals and cost-optimal modelling outcomes

- **Validation of Export Potential:** The GENESYS-MOD analysis demonstrates that fulfilling Turkey's aggressive capacity targets not only secures domestic decarbonization (cutting fossil fuel use by ~35%) but also successfully establishes the country as a vital export hub, capable of supplying up to 0.5 million tonnes of annual green hydrogen exports to the EU.[3]
- **Implementation and Supply Chain Friction:** While the transition pathways are mathematically cost-optimal, the scale of expansion implies unprecedented annual deployment rates. Scaling electrolyzers to 70 GW by 2053 and deploying massive VRE parks will place immense pressure on manufacturing supply chains, grid integration, land availability, and permitting procedures.
- **Infrastructure Bottlenecks:** The analysis reveals that while cross-border hydrogen trade is economically viable, fully capturing and validating these flows requires endogenous modelling. Beyond these mathematical and modelling requirements, actualizing such trade volumes presents significant practical challenges. It would demand massive capital investment into physical infrastructure, including pipeline routing, port facilities, and international financing arrangements extending far beyond mere generation capacity.



4.4 Feedback from stakeholders

We have shared the results of NECP scenario with responsible persons in Turkish government agencies, federations and scientific advisory boards.

Feedback on the findings with regards to the NECP included high electrolyser deployment and hydrogen production. They have asked if we can share the model assumptions and settings in GENeSYS-MOD with them. They have also planned an in-house study and said they can benefit from the results of this study.



5 Greece (Case study 7)

5.1 The Greek NECP

The latest version of the Greek NECP is the most ambitious yet, building upon the targets set in its previous iterations and EU climate legislation (Fit for 55, EU Climate Law, Greek Climate Law, etc). Its development was based on the TIMES energy model, using a methodology of system cost minimisation under emissions constraints and employing detailed simulations of the Greek power generation sector. Three distinct time periods of energy transition are described: **a) 2025-2030:** Rapid RES penetration and decarbonisation of the power generation sector accompanied by the development of suitable supply chain infrastructure and increasing the rate of demand sector electrification; **b) 2030-2040:** Deeper electrification of Greece's final energy consumption and usage of biofuels and, to a lesser degree, hydrogen in hard-to-abate sectors; **c) 2040-2050:** Development of green hydrogen and synthetic fuels production to cover domestic demand. As such, the underlying strategy for the transformation of the energy system emphasises renewable energy and electrification rather than focusing on just sector specific targets, prioritising mature technologies and cost-effective solutions in the short term and more complex ones for the later stages of the transition. A more detailed description of the incorporation of the five main dimensions of the EU underlying the NECP is as follows.

5.1.1 Decarbonisation: reduce greenhouse gas emissions by at least 55% by 2030 compared to 1990 achieving carbon neutrality by 2050

Greece's NECP is more ambitious than the EU target for 55% emissions reduction by 2030, projecting a 58% reduction on 1990's emissions, ascending to 69% in 2035 and 80% in 2040 accordingly.

Electricity generation decarbonisation is the central aspect of Greece's NECP. This is to be achieved by:

- Complete lignite phaseout by 2028. Greece will completely stop using lignite for power generation by the end of 2028, becoming one of the first EU countries to do so.
- Rapid expansion of installed electrical capacity, mainly driven by solar and wind capacity expansion. Greece expects a total installed capacity of 35.5 GW by 2030, 53 GW by 2040, and 70.7 GW by 2050. Projections of solar and wind (onshore and offshore) account for 24.3 GW in 2030, 42.8 GW in 2040 and 59.9 GW in 2050. About 2 GW of offshore wind projects are expected to have launched by 2030, ascending to almost 12 GW by 2050.
- A gradual reduction in Greece's natural gas power plant capacity, expected to be reduced to 5.9 GW in 2050 from the current 7 GW, with this technology being used mainly as backup capacity to support a renewable-dominated power system.
- Investment in storage and flexibility solutions. Greece aims to have 1.9 GW of pumped storage and 4.3 GW of battery storage by 2030 and 5.5 GW and 12 GW, respectively, by 2050.
- Demand-side measures and enhancements in interconnections with neighbouring countries, including a reinforced to up to 2 GW capacity interconnection with Albania and a second planned interconnection with Turkey offering an additional 600 MW capacity by 2031, as well as an additional planned capacity of 1.7 GW with Bulgaria.



While the decarbonisation of its power sector is the main driver of Greece's energy transition, a significant effort is also to be done made from the side of final energy consumption.

- Greece aims for a significant increase in the share of renewable energy in its gross final energy consumption, as shown in the following table.

Table 5: Evolution of the RES share in gross final energy consumption according with the latest version of the Greek NECP.

	2030	2035	2040	2045	2050
RES share in Gross Final Energy Consumption	43.0%	60.6%	77.2%	88.6%	95.8%

- Oil consumption is projected to decrease to a great degree, mainly due to the decarbonisation of the transport sector, from a currently estimated net consumption of 8646 ktoe to a projected 615 ktoe by 2050. Natural gas usage is also expected to gradually decrease from a currently estimated consumption of 1288 ktoe to 266 by 2050.
- Solid fossil fuels are expected to have been completely phased out of use by 2040.
- Industrial emissions are expected to be reduced through electrification where possible and energy efficiency improvements.
- Carbon capture and storage is considered as a decarbonisation solution mainly for hard-to-abate sectors such as cement production and refineries, until better alternatives can be employed.
- Green hydrogen's role is expected to rise in the longer term, mainly for the production of synthetic fuels for aviation and maritime.
- Direct air capture (DAC) is also considered post 2045 as an additional measure to mitigate remaining emissions.

5.1.2 Energy efficiency

Energy efficiency measures to limit final energy demand are an important part of Greece's NECP.

- Renovation initiatives, subsidies and incentives are focused on the least efficient households and service buildings focused particularly on thermal efficiency through insulation, efficient heating systems, and smart controls. The increase in heat pump usage and solar thermal technologies is at the centre of that effort.
- Vehicle efficiency is expected to improve significantly as electric vehicles become more widespread. Public transportation and shared mobility are also promoted to contribute to transport's energy efficiency.

5.1.3 Energy security

Ensuring that Greece has a sturdy, reliable, and self-sufficient to the greatest extent possible energy system is another core dimension of the energy transition envisioned in the Greek NECP. To that end:

- Electricity security is ensured through a mix of domestic renewable generation, storage, flexible gas power plants and demand response.



- Interconnections with most of the Greek islands are expected to have been launched by 2030, replacing expensive and emissive oil-based generation.
- Reliance on imported fossil fuels is reduced, following their gradual drop in final energy consumption and power generation usage.
- Growing risks brought upon electricity networks and hydropower by climate change phenomena such as extreme heatwaves and droughts are addressed.

5.1.4 Energy market

The NECP includes measures aiming to help incentivise participators in the energy market to support the transition, wherever those incentives are not already a natural market outcome. A case of the latter is the stabilisation and reduction of the average electricity prices expected to be the result of the dominance of renewables in power generation, due to their low operating costs.

- Smart meters are projected to have been fully deployed by 2030, modernising the distribution network's operation and allowing consumers to react to price signals.
- Power purchase agreements (PPAs) are promoted to facilitate investment in renewable projects and ensure industrial growth.

5.1.5 Research, innovation and Competitiveness

The research and innovation dimension is mostly associated with the latter stage of decarbonisation in Greece. Priority areas include:

- The ambitious energy storage, offshore and floating wind expansion
- Hydrogen and synthetic fuels production development, with a special interest in methanol
- Carbon capture and removal technologies, with DAC also having a specific target capacity by 2045.

5.2 Comparison of the Greek NECP with the NECP Essentials EnVis scenario

5.2.1 Comparisons of final energy consumption

The comparison of the final energy consumption assumed in the Greek NECP and the NECP Essentials EnVis scenario v.1.3 shows significant divergence, though not equally distributed across vectors or sectors (Figure 15 - Figure 17). The total final energy consumption comparison results can be seen in Figure 15.

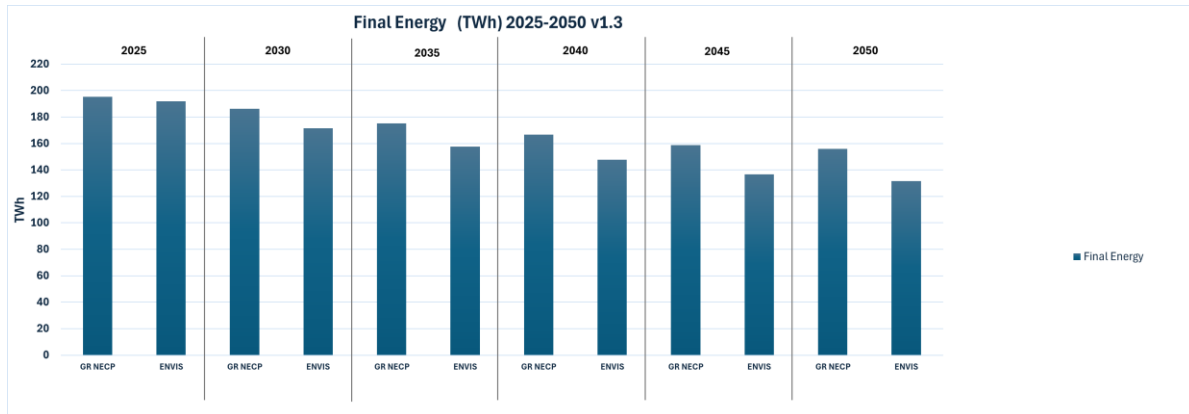


Figure 15: Final Energy Consumption Comparison in Greece

In general, the total final energy consumption reduction accounted for in NECP Essentials represents a more ambitious reduction compared to the Greek NECP. Thus, despite the values for 2025 are similar, the trajectories diverge thereafter.

The sectoral final energy consumption allocation comparison is depicted in Figure 16.

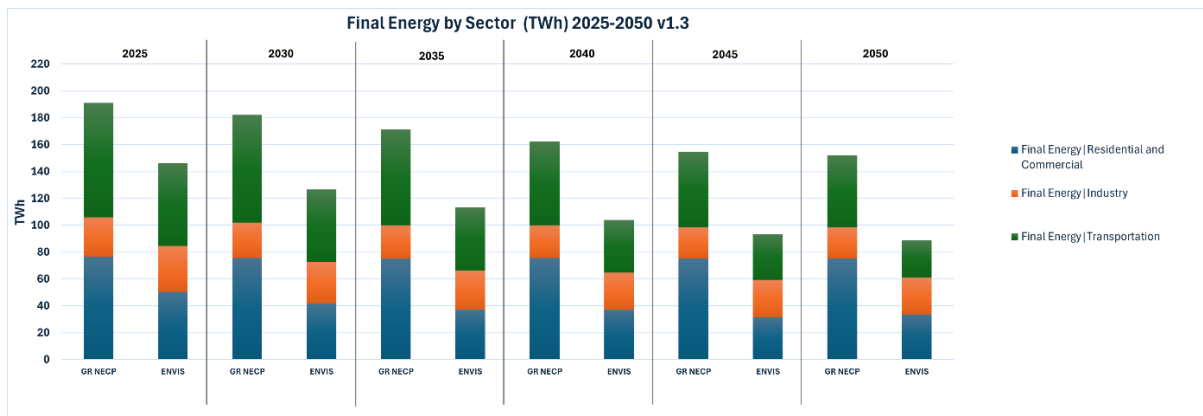


Figure 16: Final Energy Consumption by Sector in Greece

For the Greek NECP, the approach that was followed was to aggregate the Residential sector, which only accounts for households, with the Tertiary sector, accounting for services which is understandably a significant sector in Greece and comparing the total of the two with GENeSYS-MOD's "Residential and Commercial" category. This might explain the divergence to a certain degree, if the Tertiary sector is not accounted for in NECP Essentials or is underestimated, but a comparison between households only in the NECP and the aforementioned category would again result in an underestimation of the sector's consumption in NECP Essentials.

In Figure 17 , a sectoral breakdown of some important energy vectors for the energy transition is shown.

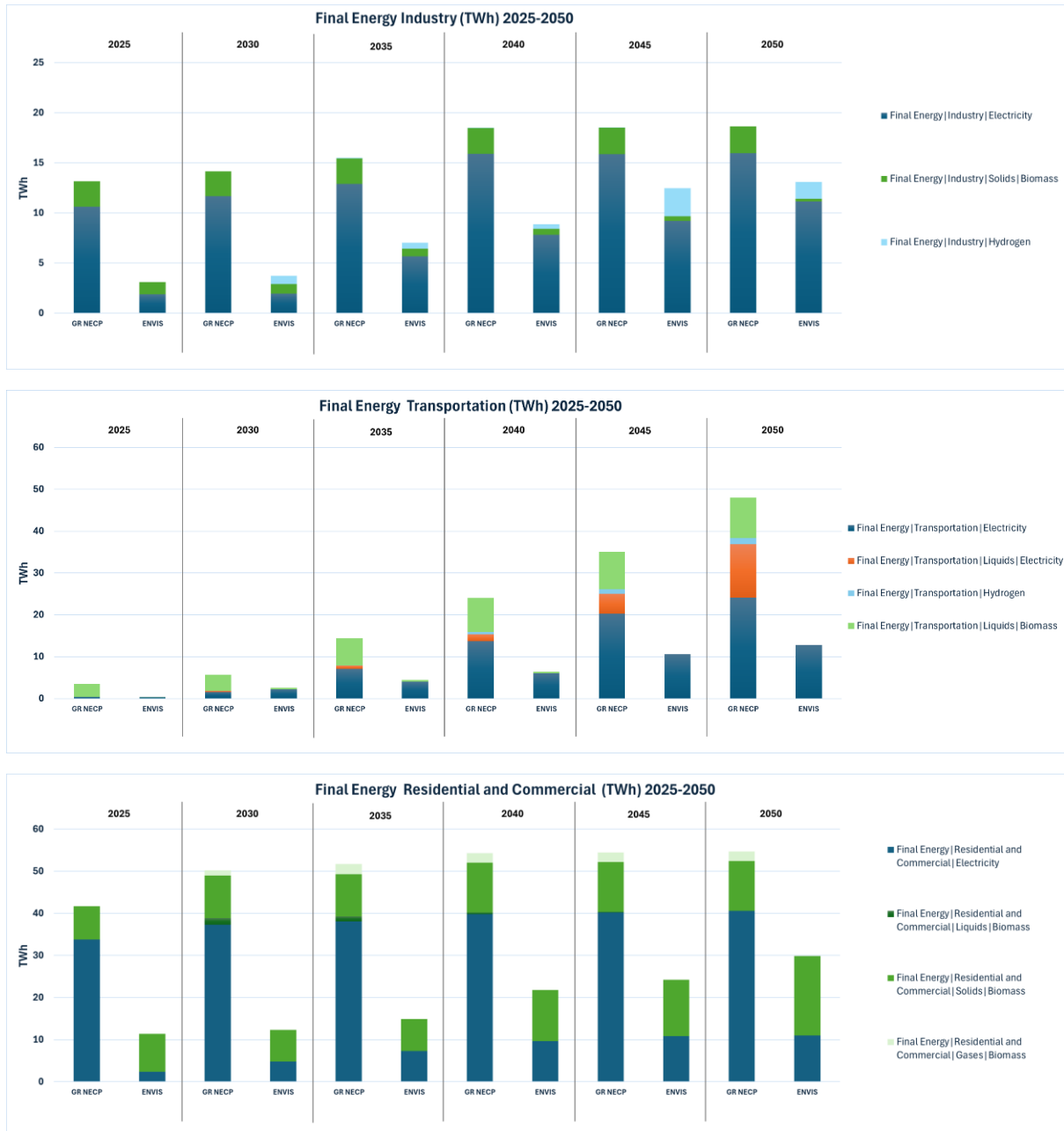


Figure 17: Comparison of energy transition related vectors per sector in Greece

For all sectors, there seems to be a lower level of electrification in the NECP essentials EnVis scenario. In the case of industry, this can be partially explained by the fact that a quantity of hydrogen that is larger than the NECP seems to be used but given that the total quantities of final energy consumption are close, it is an indicator that less electrification is assumed in the industrial sector in the NECP Essentials scenario. Similarly, the NECP Essentials scenario underestimates the penetration of electric vehicles in the whole timeseries, while the Greek NECP projects also an increase in the use of biofuels and synthetic fuels in the long run. Finally, other than the potential discrepancy mentioned before on the total final energy consumption in the Residential and Commercial sector, electrification seems again reduced compared to the Greek NECP, while solid biomass usage is projected to be increasing compared to the relatively stable amounts in the Greek NECP.



5.2.2 Comparisons of electricity generation and capacities

The comparison of electricity generation projected in the Greek NECP and the NECP Essentials EnVis scenario is shown in Figure 18.

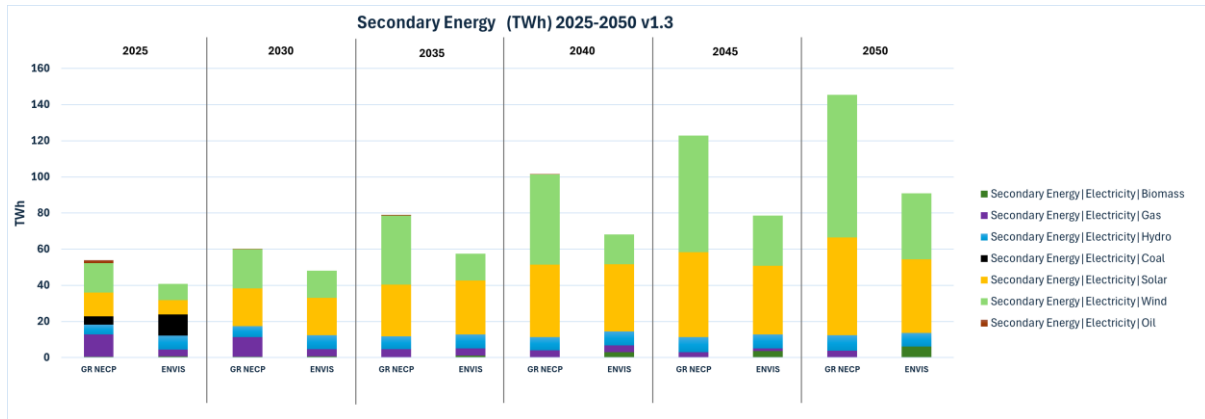


Figure 18: Electricity Production Comparison in Greece

The total generation projections in the NECP Essentials scenario seems significantly lower than the Greek NECP's. This can be explained by three factors: a) The differences in final energy consumption indicated by the sectoral analysis; b) The fact that the Greek NECP projections take into account that Greece is expected to be a net exporter of electricity; c) Projections related to hydrogen and synthetic fuels present in the Greek NECP in the later stage of the transition. As such, both total and renewable capacities also differ.

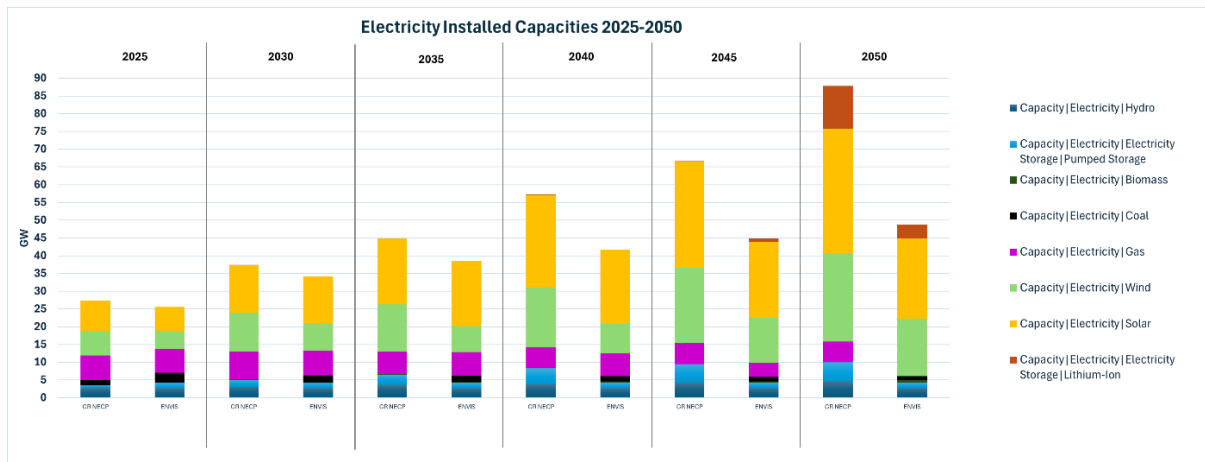


Figure 19: Electricity Capacities Comparison in Greece

The most notable differences are, as expected, in renewable capacities, since these technologies are expected to dominate the energy mix in the future and these differences tend to get more pronounced as the years pass. Notably, coal capacity still remains in the future for the NECP Essentials scenario, though unused, and natural gas capacities are absent in the year 2050. Finally, the Greek NECP expects an expansion in hydro capacities as well; in the NECP Essentials scenario they remain the same through the whole time series.



5.3 Lessons learnt in Case study 7

Greece's NECP sets quite ambitious targets, using electrification of demand and renewable capacity expansion as the main drivers of the energy transition up to 2050. These are accompanied by suitable considerations on infrastructure reinforcement, interconnections, and the introduction of new energy vectors, such as hydrogen and synthetic fuels in the later years of the transition. While accounting for Greece's geographical advantage in RES production and, as such, some exporting potential on renewable energy carriers, especially electricity, synthetic methanol and ammonia, Greece's NECP remains focused on domestic decarbonisation first and foremost. As such, the scenarios of Case Study 7 were conceived as complementary to the NECP for the same timeframe the NECP explores, meaning 2050, exploring routes where decarbonisation was not only domestically achieved in Greece, but the country also functioned as a renewable energy hub in the longer term, either at the regional level or as an interconnector between the wider South-Eastern European, MENA and Central European countries. The results of the scenarios are presented in deliverable *D3.1 - Executive Summaries of Case Studies* ([5]) of the project.

A scenario simulating Greece as a regional hydrogen exporter in the South-Eastern European area (S2), mainly through a planned Greece-Bulgaria hydrogen pipeline, shows less divergence compared to the NECP, driving a higher, but not to a large extent, renewable capacity expansion (3.7 additional GW in 2040 and 2 additional GW in 2050) to support the increased hydrogen production. Other than renewable and electrolyser capacities, no other significant fundamental changes to the system's behaviour were observed, showcasing this scenario's proximity to the actual NECP, in the case where only a regional uptake of hydrogen demand arises in the mid to long term.

The scenario exploring Greece's potential as an electricity exporter to the South-East and Central Europe (S4), through a large increase in grid-connected renewable capacity expansion and enhanced HVDC interconnections with Egypt and Germany, while technically feasible, would require significant additional investments than the current NECP, seeing as the uptake in renewable electricity production would add significant stress to the grid. As such, the effect of grid congestions, storage needs and rising curtailments would have to be taken into account as infrastructure investments, if this route is to be pursued.

The scenario where Greece becomes a major hydrogen exporter to the Central and Northern Europe (S3), through a fully-fledged European Hydrogen Backbone, is the most ambitious of the three but, at the same time, the one showing the greatest potential for Greece to become a renewable energy hub. Much more sizable investments in renewable capacity expansion would be needed, in part supported by additional renewable electricity imports through new interconnections with Egypt, but the effect on electricity prices would be less pronounced, since the capacity expansion would be mostly integrated in the hydrogen supply chain. At the same time, less curtailment and storage needs would have to be considered in such an updated plan than one pursuing an electricity exporter route, with hydrogen serving also as a flexibility option. Provided that the uptake of hydrogen in markets with higher willingness to pay is high enough, this complementary route to the current NECP could provide a more robust pathway of capitalising on Greece's renewable energy sources and its potential of serving as a renewable energy hub on a large scale.



6 France (Case study 8)

6.1 The French NECP

As all NECPs, the French plan is structured around the five key dimensions of the EU: decarbonization, energy efficiency, security of supply, energy markets, and research, innovation, and competitiveness. It is based on French national strategic frameworks such as the Multiannual Energy Programme (PPE) — the PPE is the law about energy, to be noted that the 3rd PPE has been validated by the French government in February 2026 — and the National Low-Carbon Strategy. The main objectives in the plan are described below.

6.1.1 Decarbonization: reduce emissions of greenhouse gases by at least 50% by 2030 compared to 1990 and reach carbon neutrality in 2050.

- Use of CCS technologies in the industry sector from 2027 with an objective of 6.6 MtCO₂/yr in 2030 and between 30 and 50 MtCO₂/yr in 2050,
- Increase the share of renewable energy in the final energy from 23% in 2023 to 58% in 2030 and 71% in 2035, with an objective of 570 TWh of final energy from renewable in 2030, by deploying 54 to 60 (75 to 100) GW of PV, 33 to 35 (40 to 45) GW of onshore wind power, 3.6 (18) GW of offshore wind power and 26.3 (28.5) GW of hydropower (including pumped storage) in 2030 (2035),
- Move away from fossil fuels with the objective of reaching 42% of fossil energy in final energy in 2030 and further reducing it to 29% in 2035. In particular, the use of coal in primary energy should be reduced by 70% in 2030 and 75% in 2035 compared to 2012, and the use of oil products by 50% in 2030 and 70% in 2035,
- Increase the share of renewable cold and heat to 45% in 2030 and 55% in 2035, and the share of renewable energy in buildings to 49% in 2030,
- Engage the construction of 9.9 GW of new renewable generation by 2026 and start the decision process for a second share of 13 GW, with an objective of 400 TWh produced,
- Reduce greenhouse gas emissions in the transport sector by 14.5% and 25% in 2030 and 2035, respectively,
- Increase the flexibility capacity to 6.5 GW of demand response in 2028, and additional flexibility capacities between 28 and 68 GW by 2050.

6.1.2 Energy Efficiency: reduce the final energy consumption by 30% in 2030 (50% in 2050) compared to 2012, with an objective of 1243 TWh of final energy and 1844 TWh of primary energy demand in 2030 via:

- Energy savings via sobriety,
- Building renovation and decarbonization with an objective of reducing energy consumption in commercial buildings of 40% in 2030 and 60% in 2050,
- Electrification of transport with an objective of 66%/51%/50% of the new vehicles being powered by 2030 for cars/commercial vehicles/trucks,
- Increase electricity production by 10% until 2030 and 55% until 2050 to allow electrification of uses



6.1.3 Energy Security: secure fuel supplies

- For the electricity sector: either turn fossil fuel plants to biomass, biogas, biofuels or hydrogen, or use CCS,
- Re-examine the relevance of gas storage infrastructure in light of the demand evolution and the new context of natural gas supply,
- Develop flexible solutions in the power mix (i.e., thermal generation, batteries, pumped storage, demand response and interconnections).

6.1.4 Energy Market:

- Adaptation of the infrastructure, in particular the power grids
- Develop infrastructures for transport of hydrogen and CO2

6.1.5 Innovation and competitiveness:

- Reindustrialization
- Electrification

6.2 Comparison of the French NECP with the NECP Essentials scenario

The comparison will focus on EU EnVis-2060 NECP Essentials v1.4. Comparisons made with the previous versions (v1.1, v1.2 and v1.3) showed high deviations, enabling us to better adjust the NECP Essentials scenario's assumptions related to:

- the sectoral demands (especially Industry and captive power uses),
- The policy decisions in France about fossil fuels (in particular coal and gas),
- the level of electrification in the industry sector and the residential heating sector (which in terms of primary energy resulted in an over representation of natural gas in the French energy mix compared to the NECP).

The comparisons regarding 2050 are not based on the NECP itself (as the NECP targets are only set up to 2035), but on the NECP appendix, which provides a first idea of what 2050 could look like. Therefore, it must be considered with caution. The following graphs show a comparison of EU EnVis-2060 NECP Essentials v1.4 with the French NECP as published in 2024.



6.2.1 Electricity demand

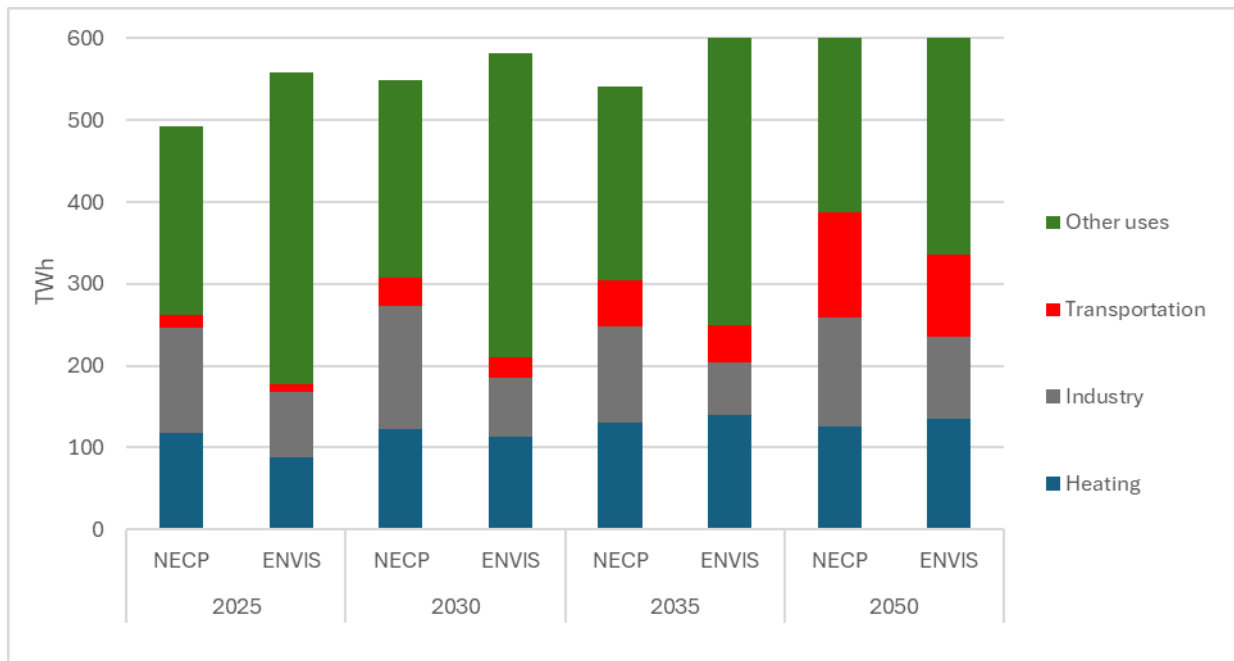


Figure 20: Comparison of electricity demand in France (NECP vs EU EnVis-2060 NECP Essentials v1.4)

The electricity demand (see Figure 20) in EU EnVis-2060 is significantly higher than the 2025 NECP, with lower numbers regarding heating and industry that could be aggregated in the much higher “other uses” number. The gap is then reduced in 2030 and 2035 as the numbers for heating become closer. Industry and Transportation shares are still lower for EU EnVis-2060, but the overall demand gap between NECP and EU EnVis-2060 closes down in 2050.

6.2.2 Electricity installed capacities

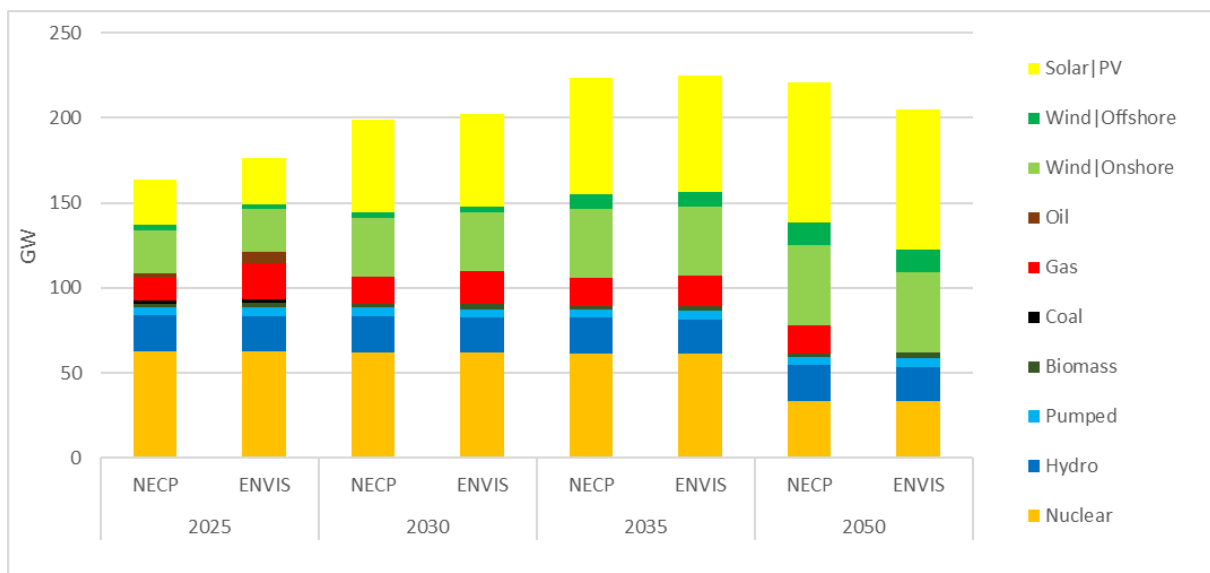


Figure 21: Comparison of Electricity Installed Capacity in France (NECP vs EU EnVis-2060 NECP Essentials 1.4)



The installed capacities (see Figure 21) in EU EnVis-2060 are reasonably close to the NECP from 2025 to 2035. The main difference in 2050 lies on the gas power plants, which are kept in the NECP in order to ensure an adequate level of flexibility while EU EnVis-2060 phases gas power out.

6.2.3 Electricity production

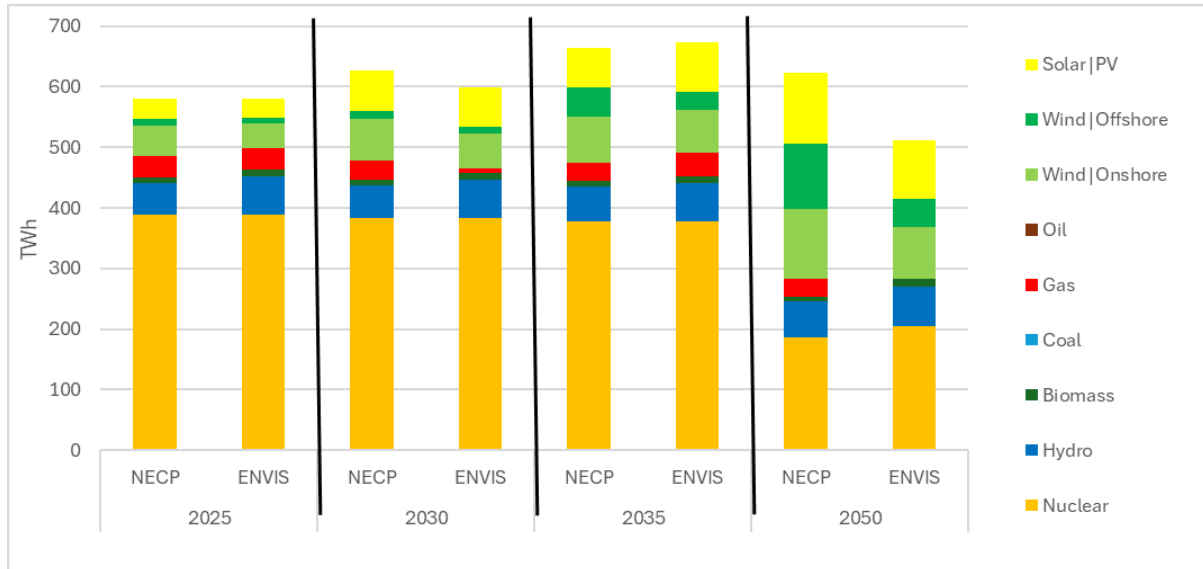


Figure 22: Comparison of Electricity Production in France (NECP vs EU EnVis-2060 NECP Essentials 1.4)

The electricity production per energy vector is nearly identical from 2025 to 2035. The main differences lie in the capacity factors for PV and Wind Power, which are different in the assumptions taken in the NECP and in EU EnVis-2060 (e.g., 45% for the offshore wind in the NECP, whereas 34% in EU EnVis-2060 in 2025). In 2035 and 2050, the assumption in the NECP for the capacity factor of the offshore wind power seems to be very optimistic (65% in 2035, 90% in 2050) while in EU EnVis-2060 it remains stable (40% for all years). In 2050, the power production from gas plants is assumed to be zero in EU EnVis-2060, similar to their installed capacities. The different assumptions in the capacity factors as well as the gas power phasing out explain all deviations.



6.2.4 Final energy per sector

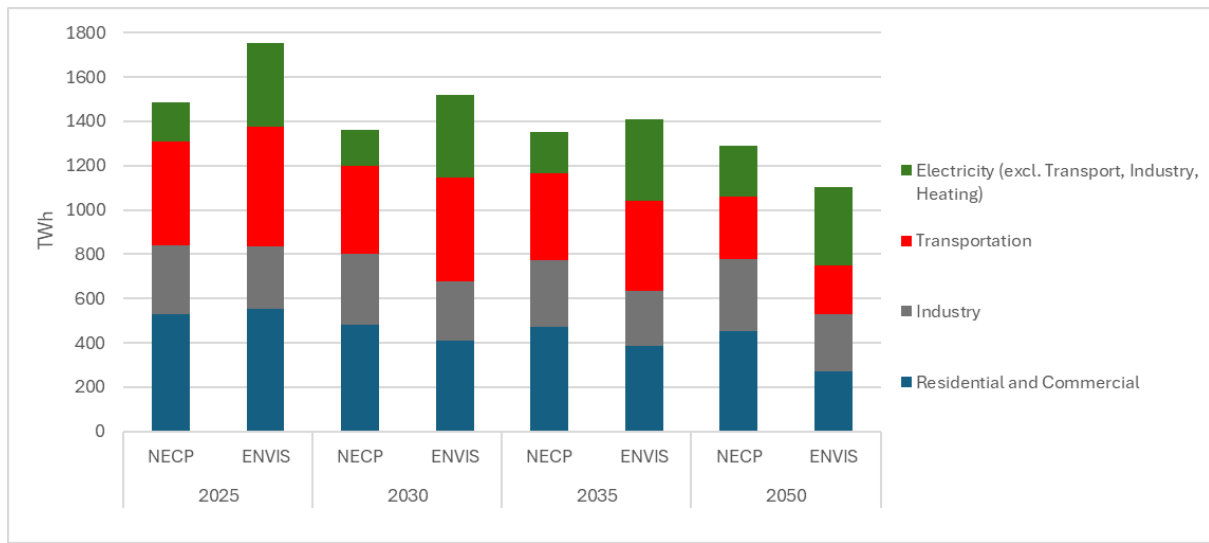


Figure 23: Comparison of Final Energy per sector in France (NECP vs EU EnVis-2060 NECP Essentials 1.4)

Final energy demand is higher in EU EnVis-2060 from 2025 to 2035, the gap slowly closing down, to become lower in 2050 with a significant decrease in buildings and transport, which could be linked to energy efficiency and electrification. The main deviations between NECP and EU EnVis-2060 lie in the power demand, which corresponds to the captive uses of electricity for everything that cannot be substituted by other energy vectors, which seems overestimated in the scenario, while the demand for the buildings sector (residential and commercial) seems underestimated. It is highly probable that there is a compensation there as it is very difficult to isolate the heating from all uses of electricity. The consumption of the industry sector is also slightly lower in EU EnVis-2060.

6.2.5 Industry

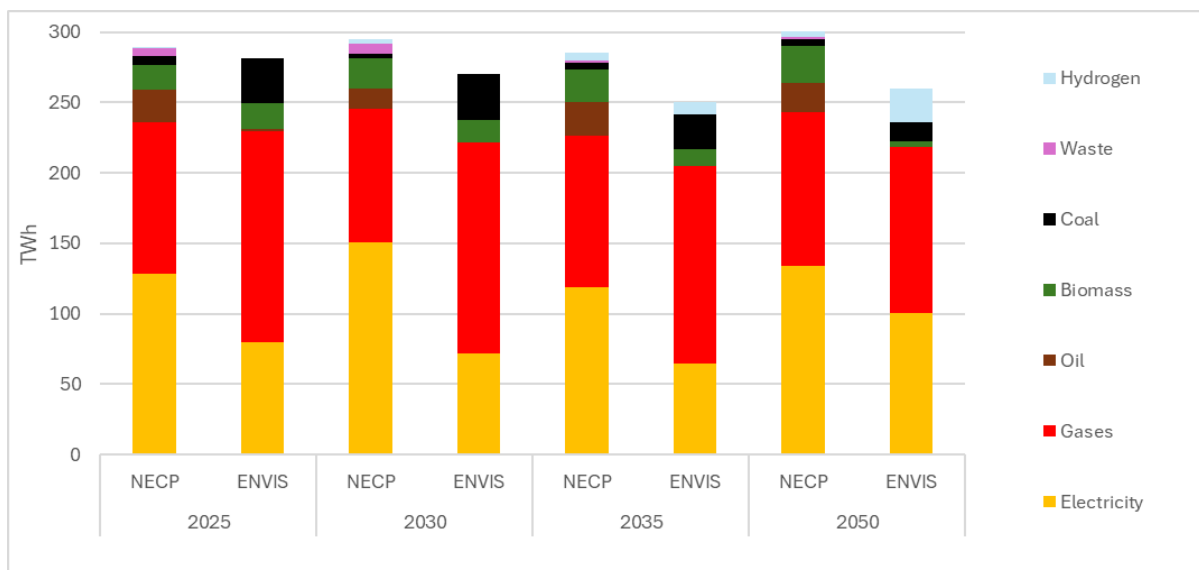


Figure 24: Comparison of Industry consumption in France (NECP vs EU EnVis-2060 NECP Essentials 1.4)



The main deviations in the industry sector lay on the level of electrification which is more optimistic in the NECP than in the EU EnVis-2060 scenario. On the contrary, the scenario nearly erases the oil uses in industrial process while it remains in the NECP until 2050, with 20 TWh, which may represent processes that are difficult to convert. The NECP includes a small share of industrial process using waste (which in the EU EnVis-2060 scenario is included in biomass). The scenario is more optimistic than the NECP regarding the hydrogen use (with 20 TWh in 2050 compared to only 5 TWh in the NECP); however, it keeps a significant share of coal use up to 2050 compared with the very little share kept in NECP since 2025.

6.2.6 Transport

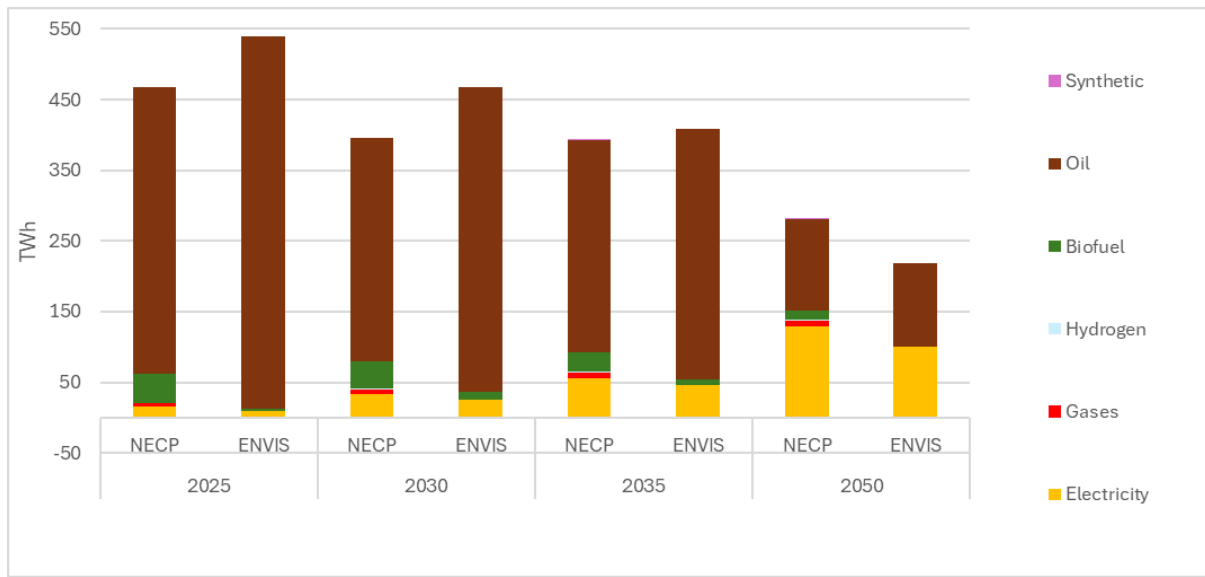


Figure 25: Comparison of transport consumption in France (NECP vs EU EnVis-2060 NECP Essentials 1.4)

The deviations in the transport sector mainly lie in a much slower electrification rate in the scenario compared to the NECP, associated with a less optimistic share of biofuel in the scenario and no gas or synthetic fuel. These are compensated by more oil, which decreases in 2050 probably due to sobriety. The deviations remain reasonable.



6.2.7 Heating (residential and commercial)

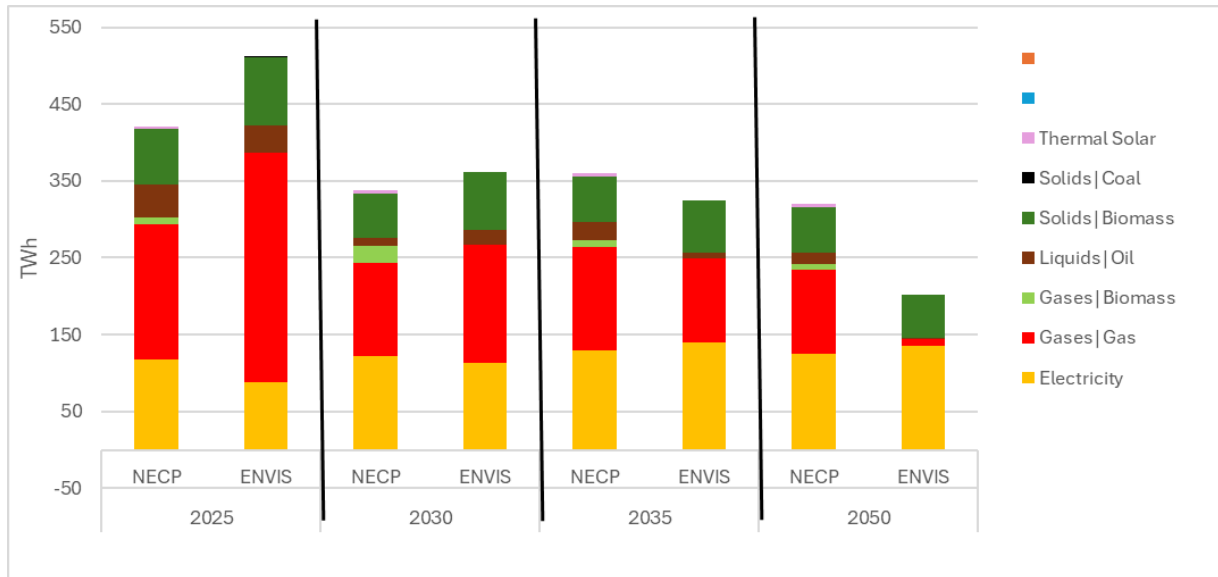


Figure 26: Comparison of the heating consumption in France (NECP vs EU EnVis-2060 NECP Essentials 1.4)

This sector is difficult to compare, given the fact the energy demand for heating is highly dependent on the temperature, and the methodology to account for this correlation are extremely different in the NECP and the EU EnVis-2060 scenario. Nevertheless, the scenario and the NECP present similarities, regarding the electricity and biomass consumption as well as the oil consumption. However, the main deviation is the gas consumption that starts much higher in EU EnVis-2060 in 2025, slowly decreasing in 2030/2035 and next to disappearing in 2050. The overall energy for heating demand in 2050 is one third lower in EU EnVis-2060, which relies on much more optimistic assumptions regarding energy efficiency in the scenario compared to the NECP, as well as different assumptions concerning the impact of temperature uncertainties.



6.2.8 Use of primary energy

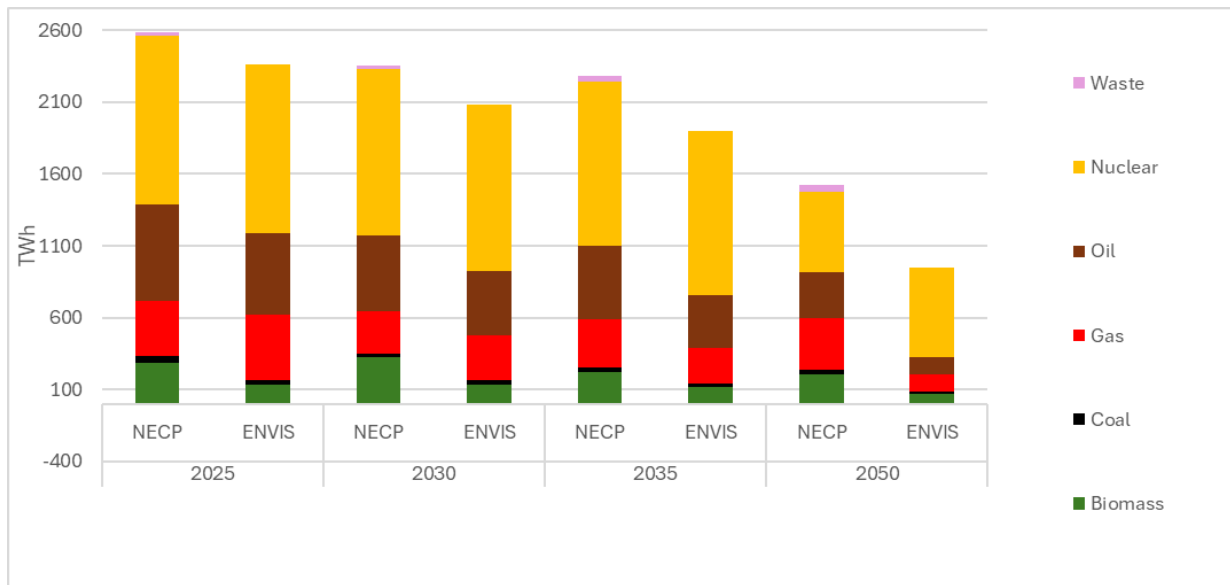


Figure 27: Comparison of Primary energy in France (NECP vs EU EnVis-2060 NECP Essentials 1.4)

The deviations rely on each of the sectoral deviations below. Nevertheless, the numbers are comparable except for 2050 with much lower numbers for oil, gas and biomass in 2050. One main deviation for all the years considered is the use of biomass which is much higher in the NECP.

6.3 Lessons learnt in Case study 8

In Case study 8, we analysed the power system derived from the NECP Essentials scenario, for the year 2030, using the plan4res model.

6.3.1 Plan4res Model short description

Plan4res is an electricity system optimization and simulation tool, composed of three following models:

- A Capacity Expansion Model (**CEM**) aimed at adapting the electricity mix.
- A Seasonal Storage Valuation model (**SSV**) aimed at optimizing the management of seasonal storage. It computes the Bellman values (= cost-to-go functions) that represent the future expected economic value of the seasonal storage levels at time stages. This is necessary to know when to best use a “free” but limited and uncertain resource such as water inflows to large hydropower reservoirs: should the hydropower plant produce now and discharge part of its stored water, for example to avoid starting up a costly coal plant to meet demand, or should water be kept for a latter use, for example because present demand is low and RES generation is sufficient?
- A Simulation Model (**SIM**), aimed at optimizing the short-term operation of the system. The simulation is run on every scenario one after the other using a Unit Commitment model (UC) sequentially on the whole time period. The cost-to-go functions computed by the SSV are used as a variable cost for the generation of seasonal storage.



All models share the exact same set of data, as summarized in Figure 28.

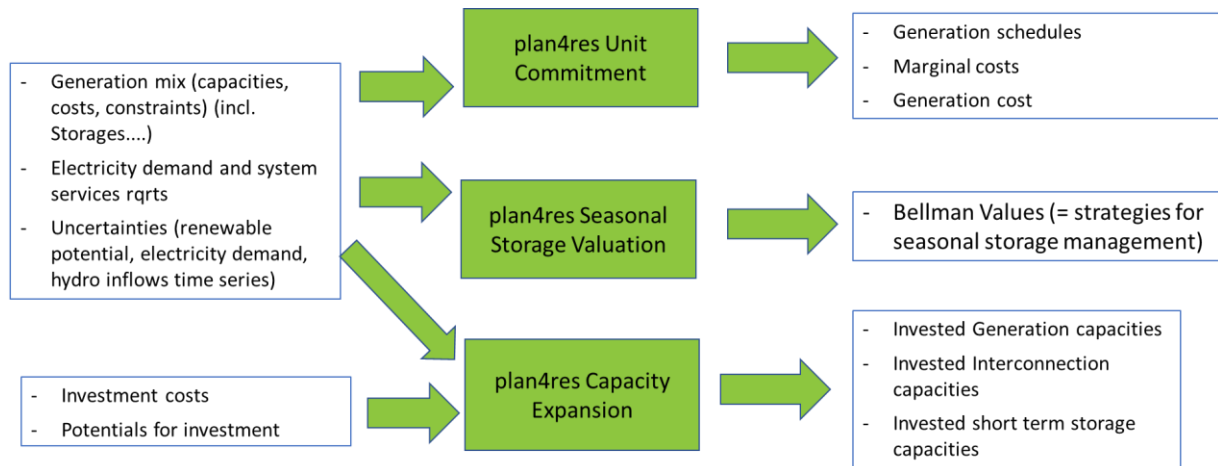


Figure 28: the plan4res model, inputs and outputs

More details about the model can be found in [18], [22], [23], [24], [25].

6.3.2 Scenarized timeseries for climate uncertainties

Plan4res being a stochastic model, the dataset produced by GENeSYS-MOD is complemented by scenarized timeseries for:

- The power demand
- The hydraulic inflows
- The capacity factors of renewable generation (Windpower, PV, run-of-river)

Those timeseries are calculated by using results of the CROSSEU project (see [19]).

CROSSEU provided timeseries for the following energy variables (see [21]), aggregated at country resolution over the whole Europe:

- Wind Power Onshore capacity factor at hourly resolution,
- Wind Power Offshore capacity factor at hourly resolution,
- Solar generation capacity factor at hourly resolution,
- Hydropower reservoirs inflow energy at weekly resolution,
- Hydropower run-of-river inflow energy at weekly resolution,
- Electricity demand at hourly resolution.

Hydro inflows, run-of-river and demand are rescaled to the annual energy from the ENVIS datasets.

The CROSSEU timeseries are based on data from ERA5 and CMIP6 (see [20] [21]). ERA5 consists in reanalysis of historic data while CMIP6 consists in future projections, computed by a serie of climatic models, based on different Socioeconomic Pathways (SSP).

Within CMIP6, CROSSEU selected the following SSPs (see [27]):



- SSP2-4.5 is a high-emissions climate scenario combining the SSP2 socioeconomic pathway (**Middle of the road - (medium challenges to mitigation and adaptation)**) with a radiative forcing level of about 4.5 W/m² by 2100 relative to pre-industrial conditions.
- SSP3-7 is a high-emissions climate scenario combining the SSP3 socioeconomic pathway (**Regional rivalry - A rocky road (high challenges to mitigation and adaptation)**) with a radiative forcing level of about 7.0 W/m² by 2100 relative to pre-industrial conditions.
- SSP5-8.5 is a very high emissions climate scenario combining the SSP5 socioeconomic pathway (**Fossil-fuelled development - Taking the highway (high challenges to mitigation, low challenges to adaptation)**) with a radiative forcing level of about 8.5 W/m² by 2100 relative to pre-industrial conditions.

Emissions foreseen on the different SSPs are shown on Figure 29.

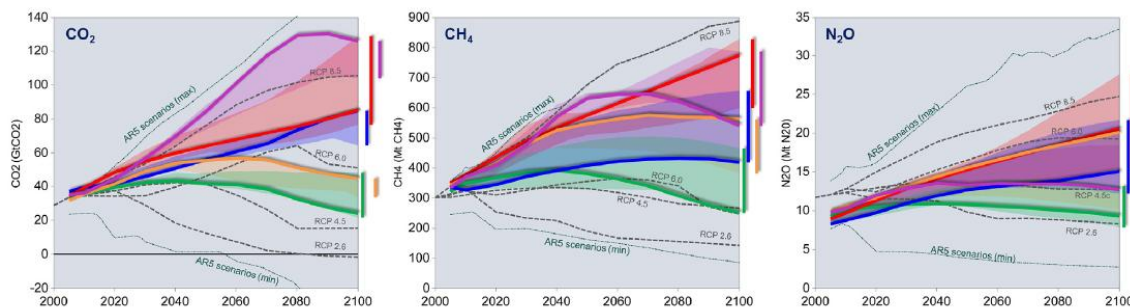


Figure 29: SSPs emissions (1: green, 2: blue, 3: red, 4: orange, 5: purple), source [28]

Within CMIP6, CROSSEU selected the following 5 models:

- AWI-CM-1-1-MR (AWCM) - Alfred Wegener Institute (Germany)
- BCC-CSM2-MR (BCCS) - Beijing Climate Center (China)
- CMCC-CM2-SR5 (CMR5) - CMCC Foundation (Italy)
- EC-Earth3 (ECE3) - EC-Earth Consortium (Europe)
- MPI-ESM1-2-HR (MEHR) - Max Planck Institute (Germany)
- MRI-ESM2-0 (MRM2) - Meteorological Research Institute (Japan)

In the end, we created the following sets of timeseries:

- ERA5: 30 “scenarios” by using timeseries for the years 1991 to 2020
- CMIP6: 105 scenarios for each of the SSP by selecting the years 2020 to 2040 for plan4res runs for 2030, and 2040 to 2060 for plan4res runs on 2050. (for each case we then are using 21 years, 5 models which gives 105 scenarios)

6.3.3 Analysis on the year 2030

We ran plan4res on 4 different datasets, each sharing the same installed capacity, as well as yearly demands and hydro inflows, extracted from the ENVIS2060 scenario NECP Essentials for 2030. The uncertainties for the power demand, hydro inflows, generation potential of PV, wind power and run-of river are computed by using the scenarized timeseries from:

- ERA5: 30 scenarized timeseries for each variable and region
- CMIP6 SSP2-4.5 for 2020 to 2040, 5 models: 105 scenarized timeseries for each variable and region



- CMIP6 SSP3-7.0 for 2020 to 2040, 5 models: 105 scenarized timeseries for each variable and region
- CMIP6 SSP5-8.5 for 2020 to 2040, 5 models: 105 scenarized timeseries for each variable and region

We start from the installed capacity in ENVIS60 NECP Essentials v1.4, 2030, as shown in Figure 30.

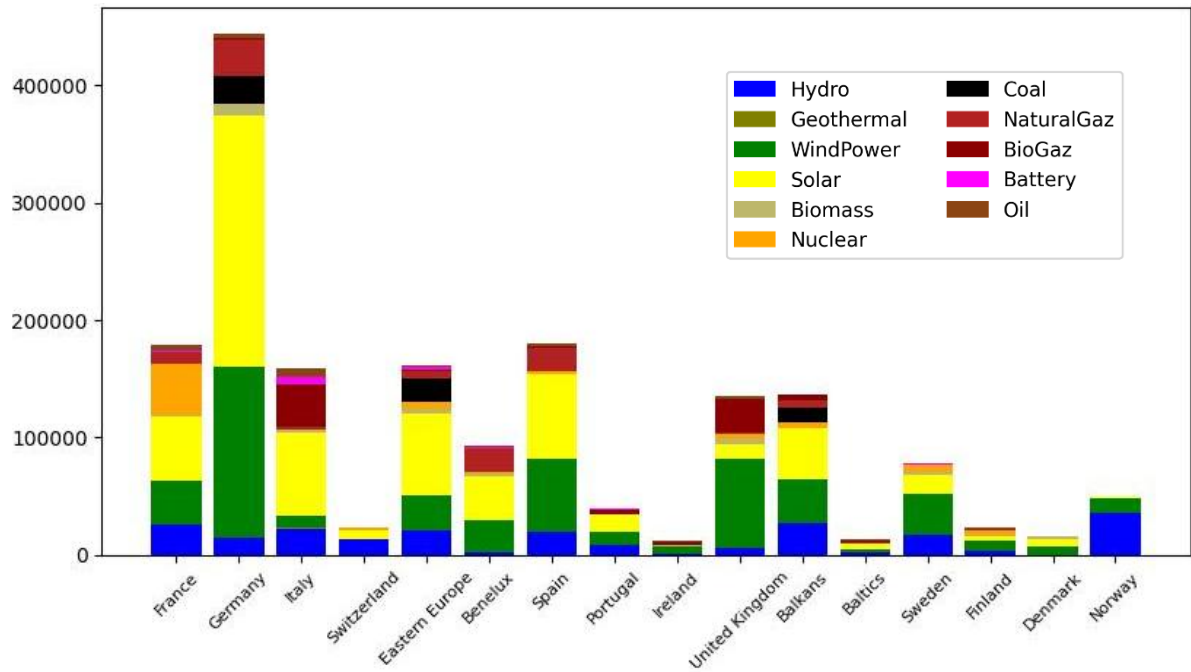


Figure 30: Installed Capacity ENVIS60 NECP Essentials 2030 (in MW)

Figure 31 shows the variability of the power demand in the case of SSP2-4.5 data.

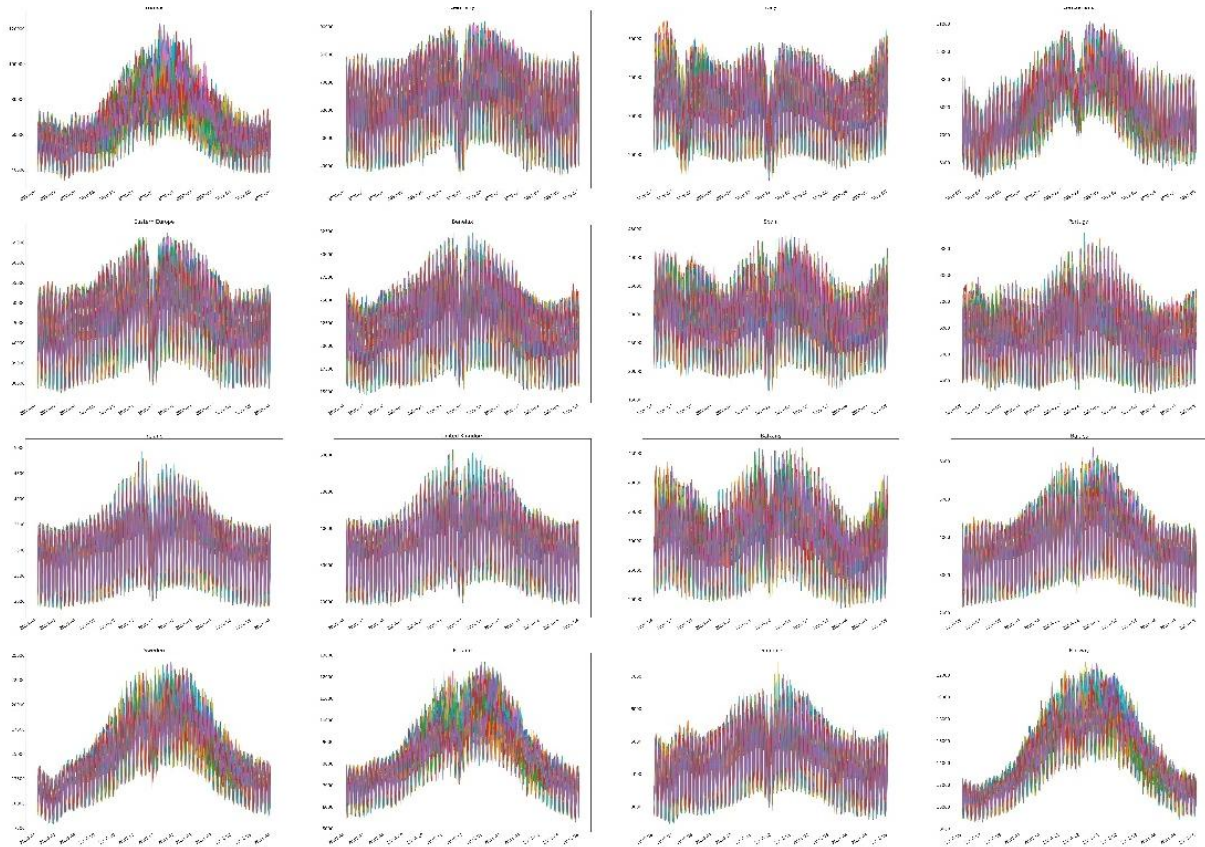


Figure 31: Power demand hourly scenarized timeseries for each region (MWh), from July to the next year's June, computed from SP2-4.5 and ENVIS NECP Essentials 1.4 yearly power demand in 2030

From the results of a plan4res simulation, we compute the maximum and average (over all uncertainty scenarios) and number of hours with non-served electricity, which are shown in Figure 32.

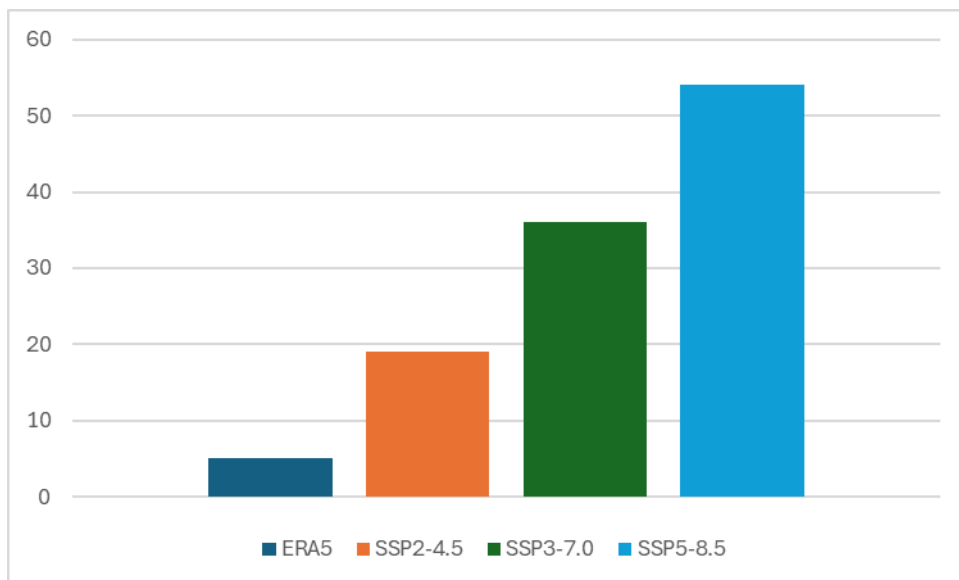


Figure 32: Maximum number of hours with non-served electricity in the NECP Essentials v1.4 scenario for 2030 in France

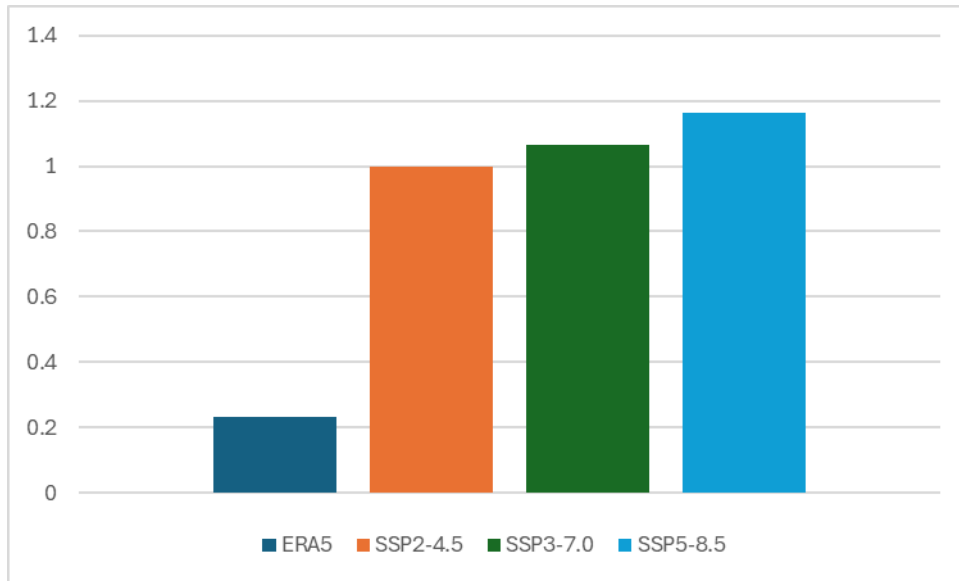


Figure 33: Average number of hours with non-served electricity in the NECP Essentials v1.4 scenario for 2030 in France

We can see that the number of hours with non-served electricity becomes higher with the projected data and is higher in harder SSPs. This confirms that the climate change will make the conditions for the operation of the power system harder in the future.

Plan4res computes the marginal costs of electricity (as the dual of the production-demand constraint) for each of the scenarios. Figure 34 shows the histograms of marginal costs in each case. Those histograms are “cut” at 60€/MWh for visibility reasons. Figure 35 shows the global average and standard deviation computed on all scenarios and all hours, in each case. We can see that the variability of the marginal costs increases with the hardness of the assumptions (ERA5 being the “easier”, and SSP5 the harder).

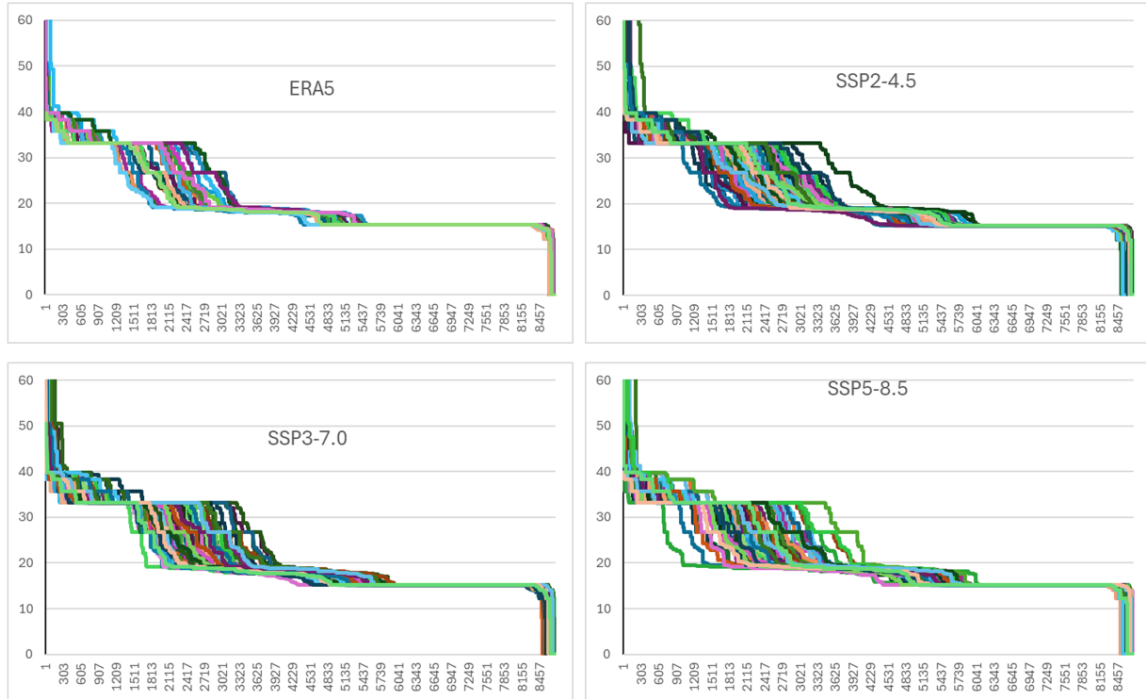


Figure 34: scenarized histograms of electricity marginal costs in France in 2030 (€/MWh)

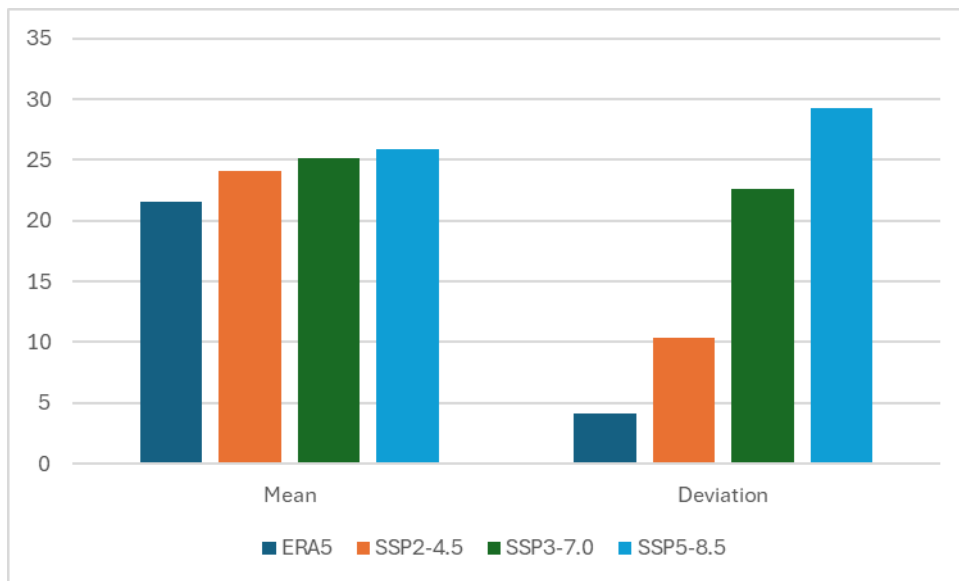


Figure 35: Mean and deviation of the marginal costs on all hours all scenarios for 2030 in France (€/MWh)

In terms of production, Figure 36 shows the differences in the energy produced by the main carrier. We can see that SSP2 and SSP5 seem dryer. All SSPs seem to be more sunny and less windy than ERA5. The need for flexible electricity is increased in all SSPs compared to ERA5.

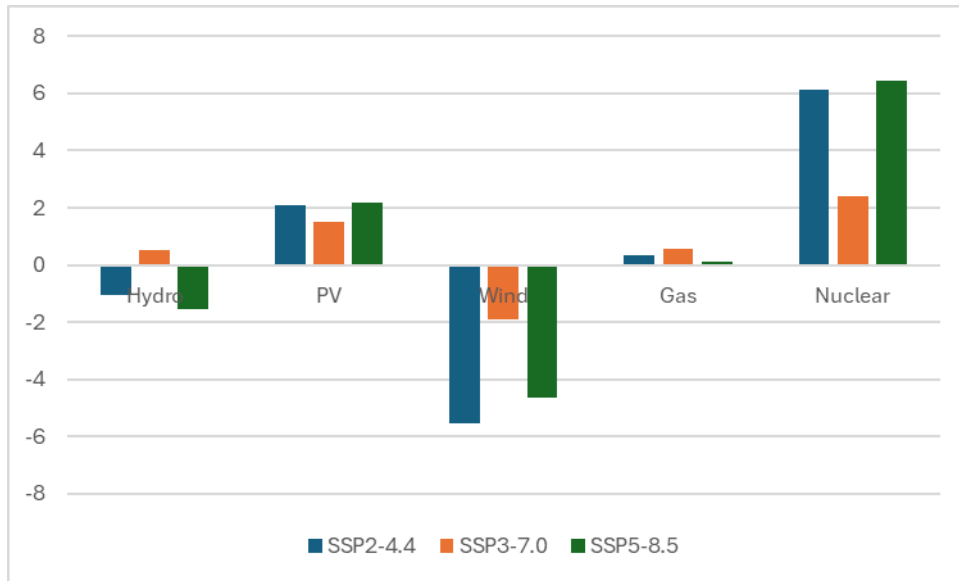


Figure 36: Differences in yearly generation per carrier (France 2030, TWh)

6.3.4 Analysis for 2050

We ran plan4res on 4 different datasets, each sharing the same installed capacity, as well as yearly demands and hydro inflows, extracted from the ENVIS2060 scenario NECP Essentials for 2050. The uncertainties for the power demand, hydro inflows, generation potential of PV, wind power and run-of river are computed by using the scenarized timeseries from:

- ERA5: 30 scenarized timeseries for each variable and region
- CMIP6 SSP2-4.5 for 2040 to 2060, 5 models: 105 scenarized timeseries for each variable and region
- CMIP6 SSP3-7.0 for 2040 to 2060, 5 models: 105 scenarized timeseries for each variable and region
- CMIP6 SSP5-8.5 for 2040 to 2060, 5 models: 105 scenarized timeseries for each variable and region

We start from the installed capacity and yearly demand in ENVIS60 NECP Essentials v1.4, 2030, as shown in Figure 37.

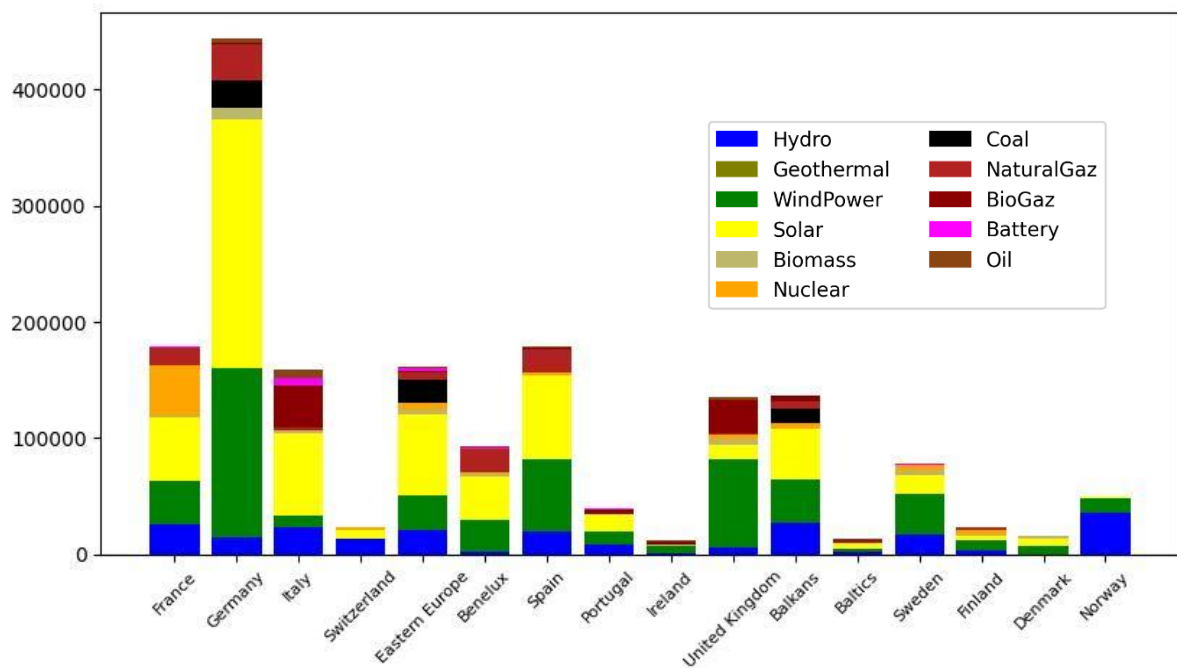


Figure 37: Installed Capacity ENVIS60 NECP Essentials 2050 (in MW)

This power mix presents a high level of infeasibility, with very high numbers of hours with non-served electricity, as shown in Figure 38.

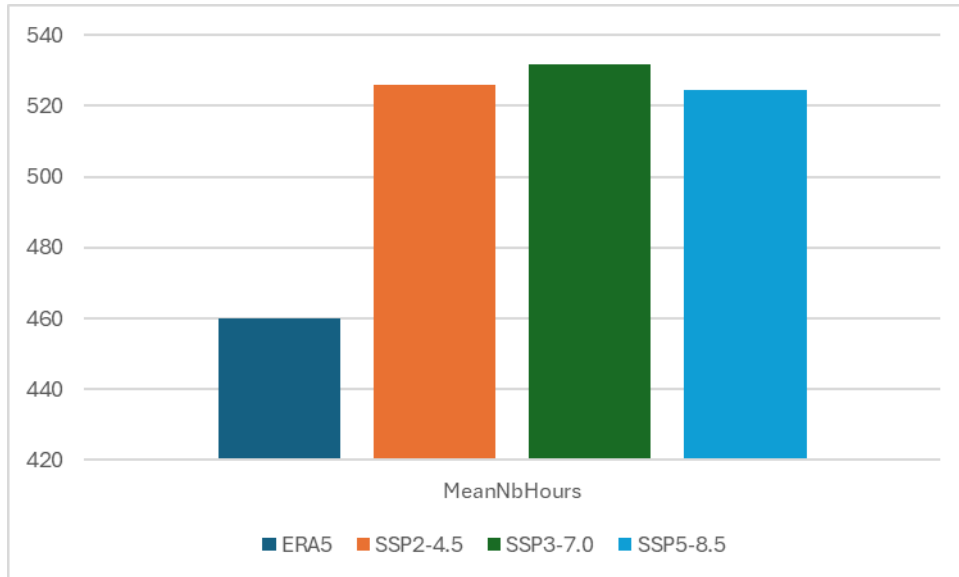


Figure 38: Average number of hours with non-served electricity, France 2050

6.3.5 Conclusion

As a result of our calculations, we can say that the power system mix is not fully robust to the uncertainty of the meteorological conditions, mainly in late years.

We also showed that a model such as plan4res can give an estimate of the missing flexibility in each area, and therefore where capacities should be developed.



7 Portugal (Case study 9)

7.1 The Portuguese NECP

The updated Portuguese National Energy and Climate Plan (PNEC 2030), released in 2024 [29] is driven by the objective of anticipating the transition to climate neutrality to 2045, positioning decarbonization as a strategic opportunity for the country. The plan establishes a comprehensive policy framework structured along the different dimensions, with revised and more ambitious quantitative targets for 2030 designed to align the national economy with its accelerated climate goals. The key dimensions are outlined below.

7.1.1 Decarbonisation of the national economy

Decarbonisation is a central pillar of the plan, with increased ambition to meet European targets under the "Fit-for-55" package.

- Key Targets:
 - **GHG Emissions Reduction:** -55% by 2030 compared to 2005 levels (excluding LULUCF).
 - Renewables in Final Energy Consumption: 51% by 2030.
 - Renewables in Electricity Sector: Approximately 93% by 2030.
 - **Installed Renewable Capacity:** Estimated at 48 GW total by 2030, including: 20.8 GW Solar PV (15.1 GW centralized + 5.7 GW decentralized) and 12.4 GW Wind (10.4 GW onshore + 2.0 GW offshore).
 - Renewables in Transport: 29% by 2030.
 - Interconnections: 15% by 2030.
- Policy Drivers:
 - **Electrification** of the economy, particularly in transport, industry, and residential buildings.
 - **Large-scale deployment of solar PV** and reinforcement of onshore wind capacity. Production costs and the abundance of the primary resource make solar PV technology more competitive compared with fossil or renewable alternatives. However, environmental impacts need to be addressed, so distributed production, the use of unconventional areas (e.g. water plans, berms), and combination with other activities (e.g., agrivoltaics) should be promoted. Onshore wind production will also be expected to grow mainly through hybridisation, overpowering and repowering, three ways to increase renewable electricity generation while minimising environmental impacts, as already realised grid investments are optimised. New locations for this technology are still possible, but with limited capacity. It is expected the launch of offshore wind auctions will aim to reach 2 GW of installed capacity.
 - **Active consumers** in the transition to a carbon-neutral society promoted through distributed generation, aiming to reach 5.7 GW of decentralized solar capacity by 2030, and self-consumption of energy from renewable energy sources supported by storage solutions. A critical enabler for active consumers is the deployment of smart meters, with a target of 100% coverage for all low-voltage clients in Mainland Portugal by late 2024 and full integration into smart grids by 2025.



- **Boosting sustainable mobility** fostering modal shift and a better functioning of collective transport networks, promoting electric and active mobility and the use of clean alternative fuels. The active mobility includes targets as i) increase the pedestrian modal share from 16% to 35% by 2030 and ii) construct 1,000 km of new bike lanes by 2030. The plan aims to achieve 29% of renewable energy in the transport sector by 2030.
- **Renewable gases:** Replacing natural gas consumption with biomethane and renewable hydrogen (green hydrogen), particularly in industrial processes and heavy transport where electrification is difficult. The plan foresees the progressive incorporation of renewable gases into the existing natural gas infrastructure. Portugal has very favourable conditions for exploring green hydrogen production industry with potential exporter due to the low costs of producing renewable electricity. Consequently, renewable gases have the potential to promote a reversal of the Portuguese energy importing paradigm. A strategic electrolyser capacity target of 3 GW (output) by 2030 is foreseen in the NECP. The development of a green hydrogen production industry in Portugal thus has the potential to drive a new economy, complemented by the significant potential for reducing CO2 emissions associated with hard-to-decarbonise industrial activities.

7.1.2 Putting Energy Efficiency First

Portugal applies this principle to its energy sector investment decisions, aiming to optimize the use of endogenous resources, reduce systemic costs, and minimize environmental impact.

- Key Targets:
 - **Primary Energy Consumption:** Limit of 16,711 ktep by 2030.
 - **Final Energy Consumption:** Limit of 14,371 ktep by 2030.
 - **Annual Energy Savings:** A cumulative final energy saving obligation of 10,484 ktep between 2021 and 2030.
- Policy Drivers:
 - **Long-Term Strategy for Building Renovation (ELPRE):** Improving the thermal performance and comfort of residential and public buildings.
 - **Public Sector Leadership:** The ECO.AP 2030 program targets a 1.9% annual reduction in final energy consumption for public organisations.
 - **Industrial Efficiency:** Promoting electrification and high-efficiency renewable cogeneration.
 - **Sustainable Mobility:** Shifting towards public transport and active mobility (walking and cycling).

7.1.3 Energy Security

Reducing external dependency through the diversification and expansion of renewable-based technologies is a central objective.

- Key Targets:
 - **Energy Import Dependency:** Portugal aims to reduce its external energy dependency to 65% by 2030, continuing a steady downward trajectory from 88.8% in 2005 and 71.2% in 2022.
 - **Coal Phase-out:** Successfully completed in 2021 with the closure of the Pego and Sines power plants.



- **Natural Gas:** The role of fossil natural gas is set to decline gradually, with its use for power generation banned by 2040. Until then, it remains a critical backup source to ensure system flexibility and energy security.
- Policy Drivers:
 - **Renewable Expansion:** Significant growth in renewable capacity solar, wind, and the use of biomass.
 - **Energy Storage:** Target of 3.9 GW in pumped hydro storage and 2 GW in battery storage by 2030.
 - **Renewable Gases:** National Biomethane Action Plan and Hydrogen Strategy to replace fossil imports.
 - **H2Med:** Developing the green hydrogen corridor linking the Iberian Peninsula to Central Europe. This also requires the reinforcement of the internal transport grid.

7.1.4 Internal Energy Market

Promotion of a flexible, decentralised, and digitalised energy system.

- Key Targets:
 - **Interconnection Capacity:** Reach the EU target of 15% by 2030.
 - **Smart Meters:** 100% coverage for low-voltage clients in Mainland Portugal by late 2024/2025.
- Policy Drivers:
 - **Self-Consumption and Communities:** Encouraging individual/collective self-consumption and Renewable Energy Communities.
 - **Grid Digitalisation:** Investment in smart grids to integrate variable renewable energy sources (vRES).
 - **Market Reforms:** Implementing the "aggregator" figure and demand response mechanisms to increase system flexibility.

7.1.5 Research, Innovation and Competitiveness

Innovation is viewed as the driver for green industrialisation and economic value creation.

- Key Targets and Priorities:
 - **Global R&D Investment:** Reach 3% of GDP by 2030.
 - **Global R&D in energy sector:** Reach 0.2% of GDP by 2030.
 - **Hydrogen Industry:** Positioning Portugal as an exporter through the Sines industrial hub.
 - **Value Chains:** Developing clusters for batteries, offshore wind, and bioeconomy.
- Policy Drivers:
 - **“Zonas livres tecnológicas (ZLT)” - Free Technology Zones:** Testing innovative renewable and storage technologies in real environments, e.g., “ZLT VIANA DO CASTELO” dedicated to offshore renewable energies.
 - **Green Industrial Strategy:** Supporting industrial transition and competitiveness through decarbonization.



- **Collaborative Laboratories:** Specific research agendas for energy, sustainability, and materials.

Cross-cutting Drivers

- **Investment:** Significant funding supported by the Recovery and Resilience Plan (PRR).
- **Job Creation:** The "Green Skills & Jobs" program focuses on professional retraining for the green economy.
- **Social Inclusion:** Combating energy poverty via the Long-Term National Strategy to Combat Energy Poverty, aiming to reduce the population unable to keep homes i) warm from 17.5% in 2020 to 10% by 2030, 5% by 2040 and less than 1% by 2050 and ii) cool during the summer from 35.7% in 2012 to 20% by 2030, 10% by 2040 and less than 5% in 2050.

7.2 Comparison of the Portuguese NECP with the NECP Essentials scenario

To support its 2030 targets, the 2024 revision of Portugal's NECP uses two modelling scenarios to assess how climate and energy policies may affect the national economy:

1. *With Existing Measures (WEM):* This baseline scenario includes all policies and measures approved or published up to 30 June 2022. Under WEM, Portugal is projected to reduce greenhouse gas (GHG) emissions by 50% by 2030 and 67% by 2040, compared to 2005 levels. These reductions rely largely on the completed phase-out of coal and a moderate expansion of renewable energy.
2. *With Additional Measures (WAM):* This is the core scenario of the revised NECP. It incorporates planned measures and strategic updates adopted after mid-2022. WAM targets a more ambitious reduction in emissions by 2030, aligning Portugal with its objective of achieving climate neutrality by 2045.

The Portuguese NECP is not presented with the same level of detail as the project results, which limits direct comparison. Therefore, the analysis focuses on key power system indicators, particularly installed capacity.

The comparison between the different scenarios i) Portuguese NECP (WEM and WAM) and ii) the NECP Essentials (NECP-E) version 1.3 obtained with GENeSYS-MOD, obtained within the scope of the project, highlights differences in the projected evolution of the power system to 2030, including renewable deployment, system flexibility, and the role of fossil fuels. These differences are illustrated in Figure 39, which compares installed capacity across scenarios and highlights their contrasting trajectories in terms of decarbonisation and system transformation.

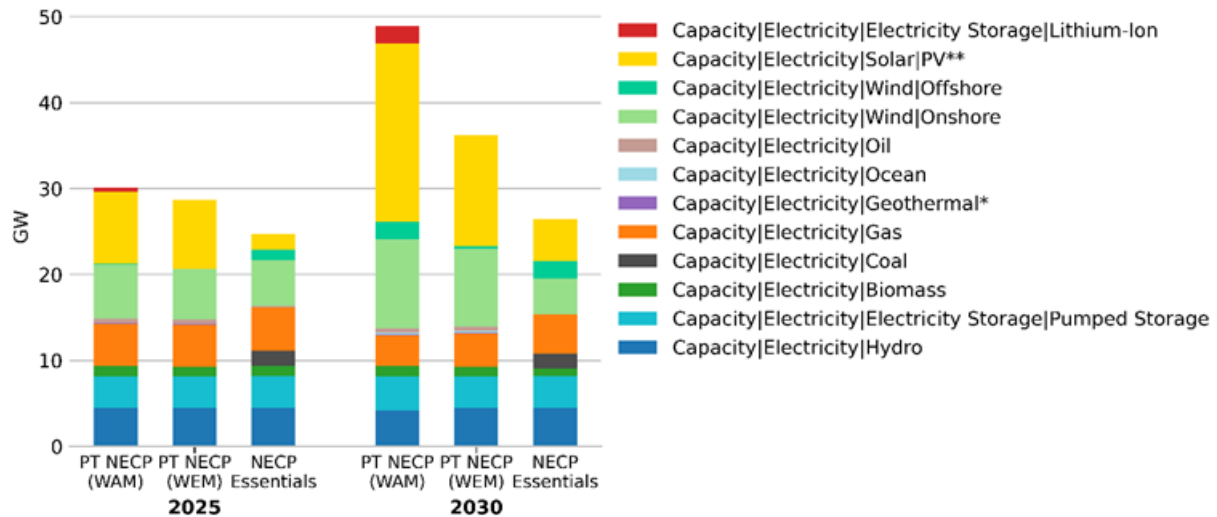


Figure 39: Comparison of installed capacity in the Portuguese 2030 NECP scenarios and NECP Essentials version 1.3 (* Geothermal only in Azores Island, ** centralised and decentralised solar PV).

The WAM scenario represents the most ambitious decarbonisation pathway, driven by the rapid expansion of renewable energy capacity and a corresponding transformation in system flexibility. By 2030, solar PV is projected to account for approximately 43% of total installed capacity, supported by strong growth in wind power, while gas capacity declines to around 7%, indicating a markedly reduced role in the power system. This accelerated renewable uptake is complemented by the deployment of new flexibility solutions, most notably lithium-ion battery storage, which enables higher integration of variable generation. The WEM scenario reflects a moderate progress in renewable deployment and system transformation, broadly aligned with existing policy measures and without the accelerated flexibility enhancements anticipated in WAM. Coal is fully phased out in both the WAM and WEM scenarios consistent with Portugal's current energy transition trajectory. Despite that no generation is observed, the NECP-E scenario still considers coal capacity, reflecting less updated policy assumptions.

Compared with WAM, NECP-E scenario follows a more conservative transition pathway, characterised by slower renewable deployment and a more limited evolution of system flexibility. Gas remains a significant component of the system, accounting for approximately 17% of total installed capacity in 2030. Renewable expansion is more restrained, with solar PV reaching only 18% of capacity and onshore wind declining by roughly 22% over the period. Unlike WAM, no new large-scale storage technologies are introduced, and system balancing continues to rely primarily on existing hydro and pumped-storage resources. Consequently, the renewable-based installed capacity represents 62% of the capacity mix, reflecting a slower structural transformation of the power system. Overall, the comparison indicates that while all scenarios are aligned in their decarbonisation trajectory, differences emerge in the pace and extent of transformation, particularly in renewable capacity expansion and the deployment of flexibility options.

At the end of March, a new version of the GENeSYS-MOD was released (version 1.4). Figure 40 compares installed capacity in Portugal across the NECP scenarios (WAM, WEM, and NECP-E v1.4) for 2025 and 2030, highlighting the evolution of the generation mix and system flexibility.

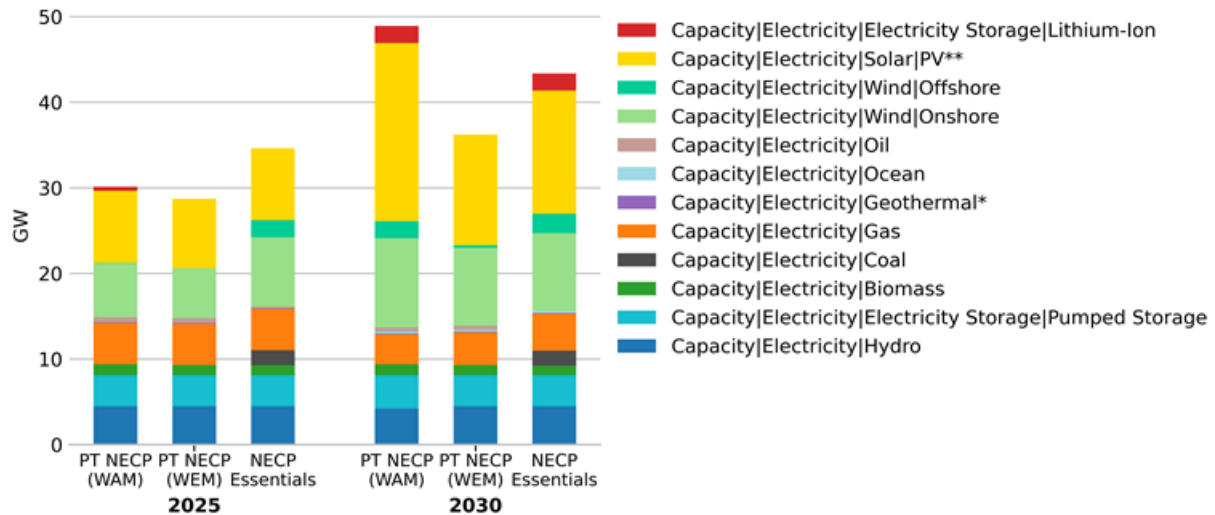


Figure 40: Comparison of installed capacity in the Portuguese 2030 NCEP scenarios and NECP Essentials version 1.4 (* Geothermal only in Azores Island, ** centralised and decentralised solar PV).

Overall, the updated NECP-E v1.4 shows a closer alignment with the WAM scenario than earlier versions, particularly in renewable capacity expansion and the inclusion of battery storage. By 2030, the gap between NECP-E and WAM narrows significantly, especially for solar PV, onshore wind, and storage capacity. This convergence is partly driven by modelling constraints in GENeSYS-MOD, which enforce minimum installed capacities from the WAM scenario and higher electricity demand assumptions, including 3 GW of electrolyzers and 2 GW of battery storage. As a result, NECP-E v1.4 follows a more ambitious trajectory comparing with the previous versions. Despite this convergence, some differences remain, partly explained using interconnections. The NECP-Essentials scenario assumes the use of interconnections, whereas the Portuguese NECP considers an isolated power system. As a result, a higher installed capacity is required in the Portuguese NECP case to meet demand.

The evolution of the GENeSYS-MOD scenarios and their alignment with the Portuguese NECP are illustrated in Figure 41.

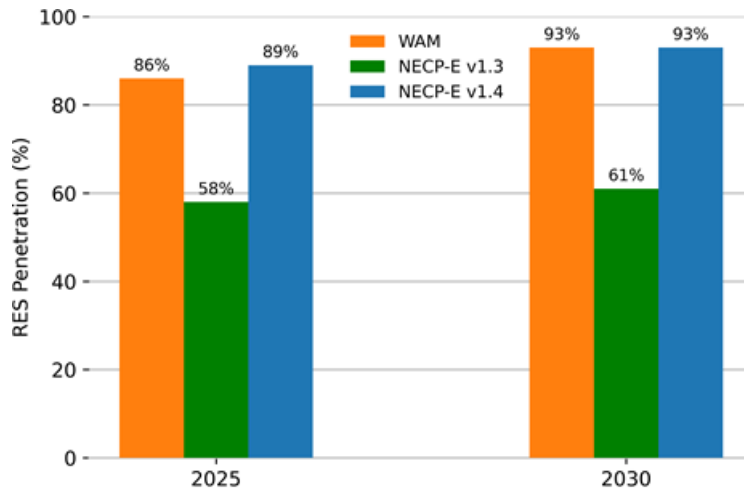


Figure 41: Renewable energy source (RES) shares in the electricity consumption across the Portuguese NECP WAM scenario, and the NECP Essentials (NECP-E) versions 1.3 and 1.4.

From Figure 41, it is possible to observe that NECP-E v1.4 is closely aligned with the WAM scenario, achieving a renewable energy source (RES) share of 89% in 2025 and 93% in 2030, which is consistent with the ambition of moving towards a fully renewable-based power system.

7.3 Lessons learnt in Case study 9

Below a summary of the main lessons learned, structured across three key dimensions: optimal power mix design, operational validation using a dispatch model, and electricity market dynamics, are provided.

A first key lesson from comparing the Portuguese NECP with GENeSYS-MOD results is that the NECP presents less detailed information than the model outputs. This difference in transparency and level of detail limits direct comparison between scenarios and model results, highlighting the need for more harmonised reporting frameworks to enable consistent inter-model comparison.

Optimal power mixes: Similarly to Case Study 1, the comparison between GENeSYS-MOD and the Portuguese NECP highlights the importance of modelling assumptions, methodological approaches, and system boundaries when assessing energy transition pathways.

The pan-European optimisation framework implemented in GENeSYS-MOD explicitly accounts for cross-border electricity exchanges, competition among neighbouring energy systems, and system-wide optimisation across interconnected countries. Since GENeSYS-MOD minimises total system costs at the European level, the first results (version 1.1 to 1.3) resulted in excessive solar PV deployment in Portugal and Spain, together with a reduction or decommissioning of onshore wind capacity. This behaviour underscores the **importance of constraining the feasible range of capacity expansion and calibrating national assumptions so that optimisation model outputs remain aligned with national energy and climate strategies. The results also highlight the need for careful parameterisation of GENeSYS-MOD inputs, including capacity factors, temporal generation profiles, technical potentials, and technology cost trajectories, to improve the robustness and policy relevance of optimisation outcomes.** The representation of dispatchable renewable technologies, such as Concentrated Solar Power (CSP) with thermal energy storage, also requires further improvement in order to capture their full operational and system value. Inadequate representation of these parameters and technologies may lead to unrealistic deployment pathways, distort the perceived competitiveness of technologies



resulting in sub-optimal investment decisions that do not provide relevant results for supporting the national NECP objectives.

Importance of operational power system validation: As described in the deliverable *D3.1 - Executive Summaries of Case Studies* ([5]) of the project, installed capacities and projected electricity demand from the Portuguese NECP version 2024 were used to perform sensitivity analyses of key flexibility solutions, including battery storage capacity, electrolyser installed capacity, and demand flexibility, for the Portuguese power system using the JRC Dispa-SET model [30].

One of the most critical bottlenecks identified in this analysis was that “...all Energy Not Served (ENS) events occur between 19:00 and 20:00, coinciding with the evening peak in domestic electricity consumption.” [5]. This result highlights the importance of adequately representing flexibility resources capable of supporting the power system during peak demand periods.

The simulations showed that, for the same installed electrochemical battery capacity, 2-hour storage systems provide limited support during evening peak periods, whereas 4-hour and 8-hour storage systems significantly reduce Energy Not Served (ENS). GENESYS-MOD currently assumes a maximum storage duration of 3 hours for the most economically competitive electrochemical storage technology. **One key lesson learned is therefore that optimisation models should include multiple and economically competitive battery storage duration options in order to better reflect the diversity of real-world storage capabilities and their expected different contribution to system adequacy.** This requirement also applies to other storage-based technologies, including CSP with thermal energy storage, which shows significant potential in several Southern European countries and can play an important role in future energy mixes.

In addition, the Dispa-SET simulations highlighted that Demand Side Response (DSR) is a critical flexibility resource for reducing ENS, supporting system adequacy during peak demand periods, and reducing curtailment of variable renewable energy sources. Consequently, DSR should be explicitly represented in optimisation models such as GENESYS-MOD.

Electricity market dynamics under high shares of renewable energy sources: Market simulations performed using PyMIBEL-DAM², a day-ahead market simulator developed within the scope of the project and fed with GENESYS-MOD v1.2 outputs (which are similar to version 1.3 for Portugal), provided important insights into electricity market behaviour under scenarios with a large-scale integration of vRES. The results confirm several expected trends: increasing renewable penetration reduces average wholesale electricity prices; price volatility increases; and the merit-order effect becomes more pronounced, leading to “price cannibalisation” effects in technologies such as solar PV.

These findings highlight the importance of incorporating market revenue risk into long-term investment modelling, reflecting the different levels of market exposure and revenue uncertainty across technologies, rather than relying solely on CAPEX-driven optimisation assumptions. One way to represent this is through **technology-specific discount rates, which better capture investment risk and avoid applying uniform values across all technologies and time periods.**

The 2024 Portuguese NECP does not explicitly account for interconnection capacity in its system optimisation framework. In contrast, **GENESYS-MOD explicitly represents cross-border electricity exchanges and shows that interconnection can reduce the required installed capacity within**

2 Available at: <https://github.com/AntCouto/PyMIBEL-DAMSimulator> (accessed on 25 May 2026).



Portugal, which is an important insight from the project. However, since both the Portuguese and Spanish power systems are expected to rely heavily on solar PV with similar generation profiles, and the planned interconnection capacity remains limited, a significant number of market-splitting events is still observed in the modelling results. This indicates that **transmission constraints are likely to become a systemic bottleneck in a fully integrated Iberian electricity market.** Increasing **interconnection capacity** between Portugal and Spain is therefore essential to reduce congestion, mitigate price divergences, and improve overall system efficiency. **In the short term, this can be achieved by:** i) **ensuring convergence and consistency of Portugal-Spain interconnection capacity** assumptions, as current values differ depending on the direction of power flows, for example, for 2030 the Portuguese NECP assumes 3.5 GW from Portugal to Spain, while from Spain to Portugal the value increases to 4.2 GW, and ii) **adopting approaches such as Dynamic Line Rating for overhead transmission lines**, which can enable to increase the transfer capacity during periods of favourable meteorological conditions.



8 Hungary

8.1 The Hungarian NECP

8.1.1 Decarbonisation Targets: Act XLIV of 2020 on climate protection: achieving climate neutrality by 2050

- By 2030: reduce gross GHG emissions by at least 50% compared to 1990, to 47,5 Mt CO₂e. Net GHG emissions reduction: 55% compared to 1990, to 41,2 Mt CO₂e.
- ESR-emissions reduction of at least 18,7% compared to 2005.
- Phasing-out coal and lignite by 2029 from domestic electricity generation.
- Expand Nuclear Power Plant: extend the lifetime of existing units Paks I. with 2 GW, add units Paks II. with 2,4 GW.

Renewable Energy:

- RED III: by 2030/2035 replace 42%/60% of H₂ used in industry by RFNBO.
- National Hydrogen Strategy: produce 16 kt carbon-free and 20 kt low-carbon H₂ (240 MW water-dissolving capacity), plus significant imports. Main industrial sectors: ammonia production, petroleum refining, petrochemicals, steel industry.
- Share of renewables in gross final energy consumption: 30% by 2030. Sub-targets: Power sector: 32%, Heating and cooling: 32%, Transport: 25%.
- *Expected* generation capacities: 12 GW PV, 1 GW wind. Besides: increase hydro- and geothermal electricity generation capacities, while reduce biomass.
- In the heating and cooling sector, the share of renewables should increase at least by 1 percentage point per year between 2021 and 2025, and by 1,3 percentage point per year between 2026 and 2030, by increasing the use of biomass, geothermal heat, renewable electricity, heat pumps and waste heat.

In district heating, reduce the share of natural gas by 50% by 2030, by using biomass, geothermal, heat pumps. The share of renewables and waste heat in district heating network should be increased by an average of 2,2 percentage point per year until 2030.

- In Transport sector, increase second generation biofuels and biogas to at least 4,5%, RFNBO to at least 1% in the final energy consumption of transport by 2030. The share of first-generation food and feed crop-based biofuels will not increase beyond 2020 levels (2030: 3%). The rest to reach 25% renewable share: electricity and hydrogen.

8.1.2 LULUCF Regulation on natural CO₂-sinks

- By 2030: 5,724Mt CO₂e removal per year in the LULUCF sector.
- National Forest Strategy: **increase the share of forest and other woodland cover to 27% by 2030**, where it does not cause adverse impacts in other directions, such as water balance, soil strength and biodiversity.

8.2 Negative Emissions Target

- While there are no plans concerning CCUS until 2030, by 2050, 8 Mt CO₂ *could be neutralized* out of 23 Mt CO₂e rest emissions.
- However, clear targets and policy measures are missing.



8.2.1 Energy Efficiency:

- Final energy consumption by 2030: max 740 PJ (in 2021: 787 PJ). In cumulative terms: 336,3 PJ end-use energy savings between 2021 and 2030. This falls short of the target 484,6 PJ set in Energy Efficiency Directive (EU) 2023/1791.
- Long-term Renovation Strategy, building sector: 20% energy savings by 2030 compared to the average of 2018-2020. Targets need to be updated in line with the Energy Performance of Buildings Directive (EPBD, 2010/31/EU).

8.2.2 Energy Security and Market Integration:

- Decrease electricity import from 30% in 2019 to 20% in 2030.
- Increase share of interconnected electricity systems to 60% high-voltage cross-border capacity.
- Increase electricity storage: 500-600 MW by 2026, *potentially* 1 GW by 2030.
- Reducing import dependency of natural gas from 87% (2021) to 80% (2030) and of oil from 87% (2021) to 85% (2030). Diversification strategies include establishing new import connections, enhancing Hungary's role in regional natural gas transit, and establishing a regional transit function for the supply of hydrogen.

8.3 Comparison of the Hungarian NECP with the HU-BENOPT scenario with CO2-price

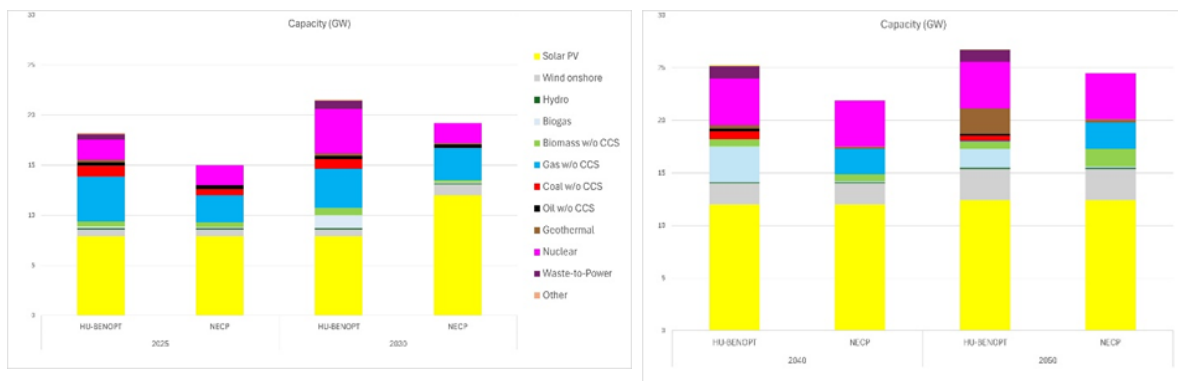


Figure 42: Comparison of Installed Capacity in Hungary



Figure 43: Comparison of Generation in Hungary



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