Energy and climate plans in energy system modelling scenarios

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***Abstract*—The national energy and climate plans were introduced as a means to explain how each EU country will reach its energy-related goals, among others, to achieve the EU targets for 2030 and climate neutrality by 2050. Because the plans state each country's individualistic plan, they propose an uncoordinated solution. Energy system modelling can give us an overview of the integrated energy system in an area. In this paper, we compare the energy system modelling results from European energy transition scenarios and investigate the consequences of approved policies and their impact on a longer horizon, compared to an ideal energy transition and compared to a scenario with less effort spent on a clean energy transition. The results provide insight into the value of cooperation across member states compared to an individualistic mindset, which can lead to barriers and protectionism that make the clean energy transition more expensive than necessary.**

***Index Terms*—Clean energy transition, energy policy, energy system modelling, energy scenarios**

I. INTRODUCTION

Since the launch of REPowerEU [1], the EU has made significant strides in promoting the transition to Renewable energy sources (RES). This progress is driven by the urgent need to tackle climate change, enhance energy security, and reduce dependence on fossil fuels. Given the current energy crisis and supply chain disruptions caused by geopolitical tensions, it is even more pressing that this development continues and accelerates. The European Green Deal [2], translated into the European Climate Law in 2021, established a comprehensive roadmap in 2020 for achieving climate neutrality by 2050. It legally binds all member states to work towards limiting the global average temperature increase to 1.5 degrees Celsius or lower.

Several important policies support the focus on decarbonization, competitiveness, and autonomy. Most recently, these were addressed in the Competitiveness Compass [3], released in January 2025 in response to the Draghi report [4]. Following the Net Zero Industry Act [5] in 2024, a Clean Industrial Deal is planned for launch in February 2025, along with an action plan for affordable energy and a roadmap to completely end energy imports from Russia. These policies address various aspects of the energy sector, including energy security and prices, financing, recycling, critical raw materials, and labour and skills.

One of the tools for implementing and measuring the progress of the policies is the National Energy and Climate Plans (NECPs), which are a key component of the Clean Energy for all Europeans package [6]. The NECPs describe how each EU country will reach its energy-related goals, among others, the decarbonisation goal [7]. The first round of NECPs with 10-year plans was submitted at the end of 2019, and updates were due to be submitted in mid-2024, including descriptions of how the member states plan to comply with more ambitious targets defined in the recent policies. Although the plans describe how the respective countries contribute to the EU-wide energy-related targets, the collective assessment based on the first drafts of the 2024 NECPs submitted in 2023 showed that the combined plans do not reach the binding targets and that many drafts were not submitted in time for the deadline [8]. Because the NECPs state each country's individual plan to achieve the EU targets for 2030 and climate neutrality by 2050, they propose an uncoordinated solution. The question we ask is whether the plans could benefit from a more holistic approach, including synergies between the countries, to find faster and cheaper solutions if the individual member states work together. The value of cooperation across member states was also discussed in [9–11], considering the role of cooperation between the Nordic countries in their respective NECPs or equivalents, and how Nordic cooperation could benefit the plans. For the electricity sector, [9] states that the intended development of the transmission grid would be a natural candidate for cooperation between the Nordic countries

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in their plans. In the industrial sector and building sector, collaboration on demand-side management will contribute to a less strained electricity sector. For the bioenergy, land use and forestry perspective [10], it would also be natural to investigate how biomass could contribute to the energy security of supply in a Nordic context.

Energy system modelling can give us an overview of the integrated energy system in an area, including different sectors, energy technologies and fuels, and conversions between them. The geographical and temporal scopes of energy system models can vary. In this paper, we concentrate on the long-term development of the European energy transition, where energy system models can be used to explore various types of scenarios for the future [12]. Along such a pathway, the costs of the energy system can be calculated for an optimal set of investment decisions for the optimisation horizon, given a set of system constraints that describe the system. In an optimisation-based energy system model, the optimal solution is found for the system as a whole, without considering what is the optimal solution for either sectors in the energy system or for geographical areas like states. Therefore, the output of an energy system model is not necessarily representative of a protectionist strategy unless explicitly described.

As different research scopes demand different future visions to be made, there already exist a number of scenarios describing the European energy system intended for research purposes (see an overview of energy transition scenarios in [13] and European decarbonisation scenarios provided in [14]) and for governmental planning purposes (e.g. the European Commission (EC)'s EU Reference Scenario [15]), many of which are also openly available. They are characteristic of the surroundings in which they were made, i.e. more recent scenarios are more likely to consider relevant key uncertainties than earlier scenarios. The recently developed European Energy Vision 2060 (EU EnVis-2060) scenarios exemplify this by incorporating the latest European plans and policy frameworks—including the NECPs and REPowerEU—and emphasizing geopolitical instabilities in response to recent global events. Developed under the Clean Energy Transition Partnership project Man0EUvRE and the Horizon Europe project iDesignRES, the EU EnVis-2060 [13, 16] comprise four qualitative scenarios for the European energy system until 2060, which are discussed in more detail in the next section.

In this paper, we compare the results from the *NECP Essentials* scenario with the other EU-EnVis-2060 scenarios and try to answer the following questions: What are the consequences of approved policies and their projections on a longer horizon on the European energy system? What is the value of a unified clean energy transition with cooperation among the EU member states compared to an individualistic mindset? How do these two futures compare to a scenario with less effort spent on a clean energy transition, and to a scenario describing an optimistic and idealistic energy transition? This paper provides insights on the benefits of cooperation, and on the difference in technology investments and energy system costs of different energy transition scenarios.

II. SCENARIOS

EU EnVis-2060, developed in 2024, presents four long-term energy transition scenarios for Europe's energy system until 2060. These scenarios integrate both qualitative and quantitative elements, with the quantitative aspects derived from the qualitative inputs using the energy system modelling tool GENeSYS-MOD. The scenarios are constructed by considering five overarching uncertainties: Social, Technological, Economic, Political, and Geopolitical (STEP+G). Initially, three of these uncertainties (i.e., social, Technological, and geopolitical) are analyzed, and their potential future developments are projected. Through expert discussions and consensus, the status of each scenario is determined for these uncertainties. Based on these projections, detailed narratives are developed for each scenario. A condensed version of these narratives is provided below:

EU Trinity: In the *EU Trinity* scenario, Europe's energy transition is marked by public indifference, low technological innovation, and significant geopolitical instability. Energy policies prioritise short-term stability over transformative change, leading to the slow adoption of clean technologies like EVs and heat pumps. National priorities take precedence over collective action, resulting in fragmented EU policies that hinder the energy transition. This disjointed strategy weakens Europe's energy resilience, and with fragmented energy policies, Europe is unlikely to meet its goal of net zero greenhouse gas emissions by 2050.

NECP Essentials: In the *NECP Essentials* scenario, the focus is on aligning with NECP under the With Existing Measures (WEM) scenario up to 2040, with extensions toward 2060 relying on NECP policies and ambitions, with minimal additional measures. Beyond 2040, the extension is driven by trends like positive public sentiment, moderate political will for GHG reductions, modest innovation in existing technologies, and unchanged geopolitical stability, resulting in an ambivalent approach to energy independence within the EU.

REPowerEU++: In the *REPowerEU++* scenario, the EU embarks on an ambitious path toward energy security and sustainability amid escalating global geopolitical tensions. Despite external pressures, the EU remains united. This unity is reinforced by strong public support for transformative energy policies and advanced technological innovations, which drives renewable integration and cost reductions. By 2050, the EU sets a global benchmark in renewable energy adoption, achieving both climate targets and robust energy independence despite global instability.

Go RES: In the *Go RES* scenario, Europe makes a transformative shift toward a fully decarbonised energy system, driven by strong public support and political determination. Innovations in technologies and digitalisation accelerate decarbonisation, improving efficiency and reducing energy use. The widespread adoption of climate-friendly solutions like heat pumps and EVs reinforces this transition. A stable geopolitical landscape, both inside and outside Europe, alongside global cooperation, facilitates the transition, positioning Europe as a leading model for global energy transformation.

Once the scenario narratives are defined, policy and economic factors are incorporated to further expand the uncertainty of the scenarios. Based on these uncertainties, a detailed table, the Qualitative-to-Quantitative (Q2Q) matrix, is developed to qualitatively outline key energy model parameters such as technology cost and efficiency projections, CO_2 emission budgets, and resource availability. The Q2Q matrix use citable data sources to provide entries for each data point, but also ensuring that they respect the scenarios' narratives.

III. METHODOLOGY

The European energy transition pathways described by the EU EnVis-2060 scenarios are quantified and analysed with the open-source Global Energy System Model (GENeSYS-MOD) [17, 18], a linear optimization model which provides cost-optimal transition pathways for the entire energy system and all its sub-sectors including industry, electricity, transportation, and buildings. The model (available in GAMS and Julia), alongside all data used for this study, can be found on its public GitHub page [19]. To fulfil the projected final energy demands outlined in the EU EnVis-2060 scenarios, GENeSYS-MOD chooses from over 160 different technologies spanning the supply, transformation, trade, and storage of a multitude of energy carriers (see Fig. 1). With 2018 taken as the historical base year, GENeSYS-MOD then tries to find the cost-optimal allocation of investments over time, considering the requirements for flexibility in the resulting highly renewable system configurations, and upholding the constraints set by the scenarios, e.g. on the available emission budget. The emission budgets used come from the *Global Carbon Budget 2021* [20], and are: 73.98 Gt $CO_2$for *EU Trinity*, 45.67 Gt CO_2 for *REPowerEU++*, 45.67 Gt CO_2 for *NECP Essentials* and 25.86 Gt CO_2 for *Go RES*, which corresponds to 2°C increase, 1.8°C increase, and 1.5°C increase.

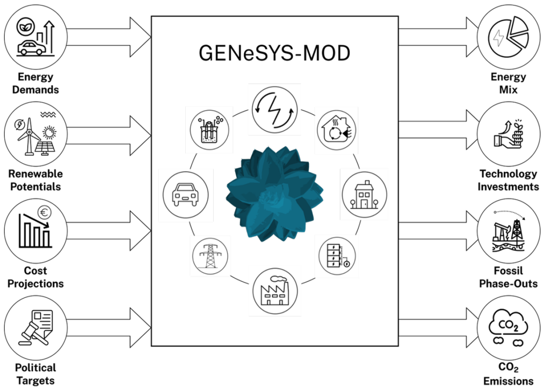

Fig. 1. Inputs and outputs of the energy system model GENeSYS-MOD.

The model setup for the EU EnVis-2060 scenarios consists of 30 regions (the EU27 without Malta and Cyprus, Switzerland, Norway, the UK, as well as an aggregated Balkan region). The newly developed model version used for the quantification of the EU EnVis-2060 scenarios features a completely overhauled European data set, including a new native data structure that is both more user-friendly, as well as more flexible regarding modularity of data, allowing a quick set-up of multiple regional aggregation levels, time horizons, data sensitivities, or modelled regions.

In this first iteration, the qualitative storylines outlined in the EU EnVis-2060 scenarios have been quantified by GENeSYS-MOD at the country level. Upcoming research will now apply the GENeSYS-MOD results in ten case studies by coupling GENeSYS-MOD with other sectoral or national models, including feedback loops back to the Pan-European GENeSYS-MOD application. By doing so, insights from the more detailed sectoral or regional models can be integrated in the holistic planning process of GENeSYS-MOD.

IV. RESULTS

A. Development of technology choices

The development of primary energy consumption is shown in Fig. 2. Though the consumption is decreasing over time for all scenarios, the *EU Trinity* scenario stands out with lower consumption in the end year (2060) than the rest of the scenarios. This scenario has a higher share of coal than the other scenarios throughout the time horizon, and less Photovoltaics (PV). *NECP Essentials* shows the highest total primary energy consumption for the start year (2018) and for 2025, but shows approximately the same consumption as *REPowerEU++* in 2030, and slightly higher than *Go RES*.

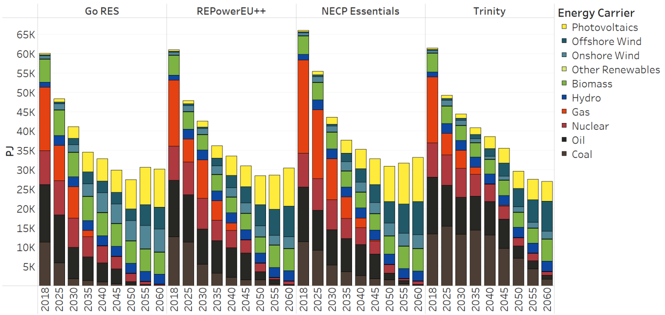

Fig. 2. Development of primary energy consumption from 2018 - 2060.

The development of electricity generation and consumption is shown in Fig. 3. Both values increase fastest for *Go RES* until 2045, when the *NECP Essentials* scenario catches up and moves beyond until 2060, mainly due to offshore wind and PV on the generation side and electrolysis on the consumption side. *REPowerEU++* does not have the same steep development as *Go RES* and *NECP Essentials*, and reaches approximately the same consumption and generation as *Go RES* in 2060, though with more offshore wind where *Go RES* has more onshore wind. The final electricity demand of *REPowerEU++* decreases over time until 2060, much more so than for *NECP Essentials*. *EU Trinity* has the lowest increase in consumption and generation reaches an end year level that is lower than the other scenarios. We do not see the same levels of PV in *Trinity* as in the other scenarios, and the level of electricity generation using fossil gas compensates for less wind and PV until the end year. Besides, *EU Trinity* sees much less electrolysis than the other three scenarios, a smaller industry demand, and an almost constant final electricity demand.

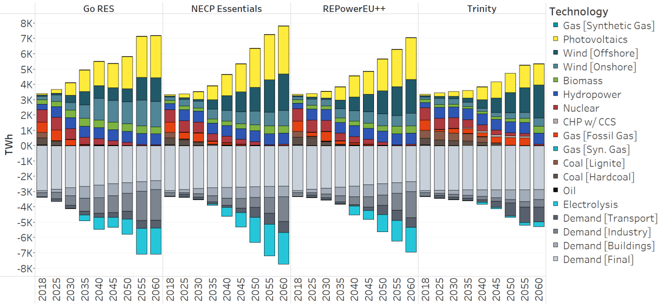

Fig. 3. Development of electricity generation (positive) and consumption (negative) in Europe.

The development of building heat supply in Europe is shown in Fig. 4. *Go RES*, *NECP Essentials* and *REPowerEU++* show a gradual decline in total building heat supply - steepest for *Go RES*, then gradually less decline for *REPowerEU++* and *NECP Essentials* with corresponding decline in use of natural gas, hardcoal and oil, and in total level for the end year (2060). The *NECP Essentials* is the only scenario that has a considerable share of hydrogen used for building heat, although *Go RES* and *REPowerEU++* both utilize the technology, and it has a higher share of district heat than the other two. The *EU Trinity* scenario has the highest total heat generation of the scenarios already from 2025. In 2060, district heat constitutes close to half of the supply, there are insignificant amounts of biogas and approximately the same amount of heat pump use as the other three scenarios. *EU Trinity* maintains a high share of natural gas and hard coal in the heat supply mix until 2050.

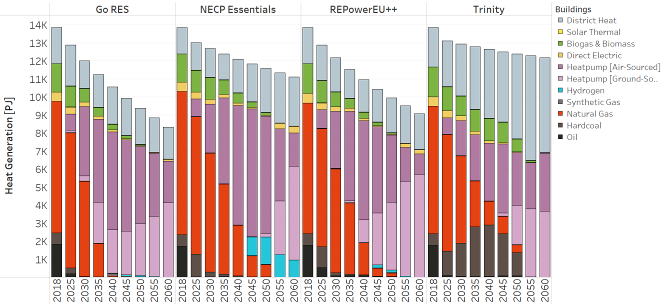

Fig. 4. Development of building heat supply in Europe.

The development of technology choices and modal types for passenger and freight mobility can be seen in Fig. 5 and 6. The total passenger travel activity declines for *Go RES* and slightly for *REPowerEU++*, though the freight travel activity decreases only for *Go RES*. For all other scenarios, the activity increases, and more so for the *EU Trinity* scenario and *NECP Essetials* than for *REPowerEU++*. A high share of this increase is covered by electric rail transport. For passenger as well as freight transport, combustion engines (Road[ICE] and Road[ICE|Bio]) have a high share in all scenarios, for gradually being replaced with Battery-powered electric vehicle (BEV). All scenarios also see a gradual increase in ship freight transport, which is then to some degree replaced by road transport with BEV.

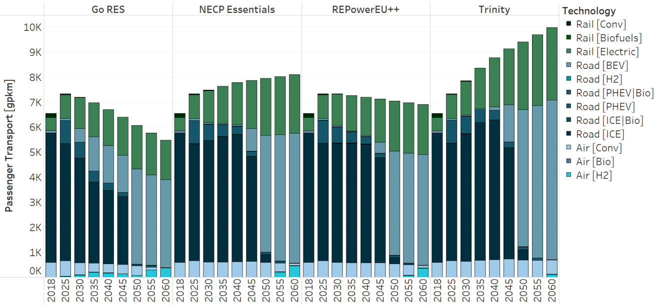

Fig. 5. Development of technology choices and modal types for passenger mobility.

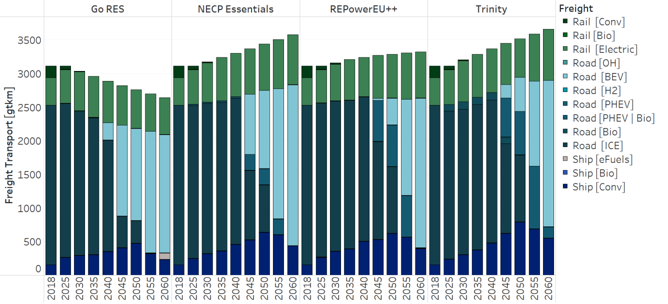

Fig. 6. Development of technology choices and modal types for freight mobility.

In Fig. 7, the development of industrial process heat generation sources is shown. The most noticeable is that the industrial activity is declining significantly more in *EU Trinity* than in *Go RES*, with *REPowerE++* and *NECP Essentials* in between in declining order. The share of direct electric heat is also noticeably smaller for *EU Trinity* than for the others, which is also reflected in the lower increase of electricity generation and consumption in Fig. 3. The share of fossil gas and hard coal is also high in *EU Trinity*, though with CCS. *REPowerEU++* has more direct electricity and district heating in the end year than *NECP Essentials*, but the development in the use of fossil fuels is approximately the same for *NECP Essentials* and *REPowerEU++*, which is higher than for *Go RES*. *Go RES* has a steep decline in fossil fuels already before 2035, and no fossil fuels in the technology mix in 2060.

B. *Economic results*

According to Table I, *EU Trinity* has highest energy system costs for the time horizon and for the end year, followed by *NECP Essentials*, *REPowerEU++* and *Go RES*. The difference between the scenarios is more evident for the end year than for the entire time horizon, leading to assume that the difference

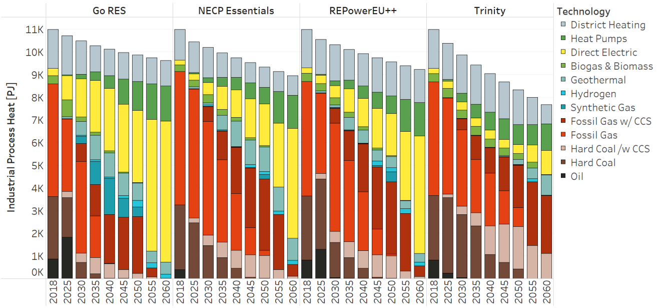

Fig. 7. Development of industrial process heat generation sources from 2018 - 2060.

TABLE I
ENERGY SYSTEM COSTS

Scenario	Type	Value	Relative
EU Trinity	Time Horizon 2018-2060	61735000[a]	105.8%
REPowerEU++	Time 2018-2061	58395836[a]	100.1%
Go RES	Time Horizon 2018-2062	58351807[a]	100.0%
NECP Essentials	Time Horizon 2018-2063	58976699[a]	101.1%
EU Trinity	End Year (2060)	254016	140.4%
REPowerEU++	End Year (2060)	202727[b]	112.1%
Go RES	End Year (2060)	180913[b]	100.0%
NECP Essentials	End Year (2060)	225521[b]	124.7%
EU Trinity	End Year (2060)	1971567.424[c]	140.4%
REPowerEU++	End Year (2060)	1573483.36[c]	112.1%
Go RES	End Year (2060)	1404172.089[c]	100.0%
NECP Essentials	End Year (2060)	1750400.987[c]	124.7%

[a] Unit: M€/2018
[b] Discounted. Unit: M€/2018 [c] Absolute. Unit: M€/2060

will increase over time, as the more expensive investments were made in the beginning. Indeed, the discounted energy system cost of 2060 for the *Go RES* scenario amounts to 0.310% of the total energy system costs for the entire time horizon, whereas the costs for *REPowerEU++*, *NECP Essentials* and *EU Trinity* are 0.347%, 0.382% and 0.411%, respectively.

V. DISCUSSION

Relating the results to the research questions, we want to find the consequences of approved policies on the European energy system and the value of a unified clean energy transition with a high degree of cooperation. Therefore, we sum up the resulting differences between the scenario representing an individualistic mindset, *NECP Essentials*, which aims to represent the NECPs for the European countries, and the scenario representing a unified Europe working together in the energy transition. We see that *REPowerEU++* has a slightly less costly energy system than *NECP Essentials* with slightly less primary energy consumption, noticeably less total building heat supply and less transport activity, introducing BEV later in the freight transport technology mix, and with slightly more total industrial process heat generation. The difference in transport activity will be a direct consequence of the assumptions for the scenarios, where the *REPowerEU++* scenario presents strong public support for innovations, policies and a shared effort. The same can be said about the building heat demand: With a higher inclination to utilize new technologies and energy conservation measures, the heat demand decreases. Both scenarios have a high degree of electrification in their industry and a decreasing building heat demand, and both scenarios have a high share (approximately two-thirds) of the primary energy consumption coming from variable renewable energy sources. The value of the unified approach is therefore a reduced energy system cost and a reduced primary energy consumption. One difficulty in the creation of *NECP Essentials* is to use the latest, updated NECPs, as they are not always available.

Comparing *REPowerEU++* and *NECP Essentials* to the pessimistic low-effort *EU Trinity* scenario and to the idealistic and optimistic *Go RES* scenario, they lie somewhere in between the optimistic and the pessimistic scenario. *EU Trinity* is more costly, less electrified and has less industrial process heat generation than *NECP Essentials* and *REPowerEU++*, though with slightly more freight and much more passenger mobility. It is interesting that the more costly scenario with less industrial activity can support more passenger travel activity. The low electricity generation and consumption in the *EU Trinity* scenario is reflected in the low electrification of the industry, and that a high share of the increased building heat demand is covered by district heating. *Go RES* is the scenario with the lowest total energy system costs for the entire time horizon and for the end year, with the highest industrial process heat demand (though closely followed by *REPowerEU++*), lowest building heat supply and a declining passenger and freight mobility. A high degree of electrification of the industry calls for increasing electricity generation and consumption. However, *NECP Essentials* has the highest electricity generation in 2060, which is used for an electrified industrial sector and also an electrified and growing transport sector.

The emission budgets are overall budgets calculated over the entire time period. For now, we allow the model to overshoot if necessary, so it can decide to offset emissions in earlier years by having net negative emissions in later years. This is something that could be analysed via sensitivity analyses (although 1.5°C is technically impossible without overshoot at this point in time).

VI. CONCLUDING REMARKS

To conclude, there is value in a unified, clean energy transition with cooperation among the EU member states, compared to an individualistic mindset, measured in a reduced cost for the energy system and an increase in industrial activity. These scenarios are better than a pessimistic scenario and worse than an idealistic scenario for the clean energy transition. A deeper knowledge of your neighbouring country's energy situation and policy will influence your own energy and climate plan to facilitate further cooperation.

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