Energy Transition Pathways to a Low-carbon Europe in 2050: the Degree of Cooperation and the Level of Decentralization

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ABSTRACT

In the framework of the Paris Agreement, the European Union (EU) will have to firmly set decarbonization targets to 2050. However, the viability on these targets is an ongoing discussion. The European Commission has made several propositions for energy and climate "roadmaps". In this regard, this paper contributes by analyzing alternative pathways derived in a unique modelling process. As part of the SET-Nav project, we defined four pathways to a clean, secure and efficient energy system—taking different routes. Two key uncertainties shape the SET-Nav pathways: the level of cooperation (i.e. cooperation versus entrenchment) and the level of decentralization (i.e. decentralization versus path dependency). All four pathways achieve an 85–95% emissions reduction by 2050. We include a broad portfolio of options under distinct framework conditions by comprehensively analyzing all energy-consuming and energy-providing sectors as well as the general economic conditions. We do this by applying a unique suite of linked models developed in the SET-Nav project. By linking more than ten models, we overcome the traditional limitation of models that cover one single sector while at the same time having access to detail sectoral data and expertise. In this paper, we focus on the implications for the energy demand sectors (buildings, transport, and industry) and the electricity supply mix in Europe and compare our insights of the electricity sector to the scenarios of the recent European Commission (2018a) report "A clean Planet for all".

Keywords: Energy transition, Model linkage, Pathways, Renewables, EU decarbonization policy, Cooperation

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1. INTRODUCTION

The 2018 Intergovernmental Panel on Climate Change report (IPCC 2018) raised the question ever more urgently, how a sustainable reduction of greenhouse gas emissions can be

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achieved worldwide and at a European level. In the European Union, we are now in the midst of a debate on firm emission reduction targets for the year 2050. The SET-Nav research project (2016-2019) brought together a large European consortium of energy and climate modelers that looked in this question. It started from the technological focus of the SET-Plan and developed several comprehensive, cross-sectoral scenarios—the SET-Nav pathways (Crespo del Granado et. al. 2019). The pathways show that—while several options are still at hand—the next years' decisions on the European energy system are critical in order to achieve a low-carbon energy future.

The European Union currently has legally fixed climate targets for the year 2030. They encompass an EU-wide greenhouse gas emission reduction target of 40 % (compared to 1990 emission levels), a greater importance of renewable energies with a share of at least 32% of gross final energy, and an improvement of energy efficiency with 32.5 % less energy consumption compared to a no-policy baseline. For several years now, European policy makers, stakeholders and academics have discussed 2050 targets and how to get there from 2030 onwards. It is essential to set long-term goals for 2050 and outline the path to achieve emission reductions compatible with the global 1.5°C climate target.

Scenarios and pathways of the European energy sector are important tools in this debate that help evaluating the feasibility and costs of the potential options for decarbonization. A scenario, in general, includes specific assumptions on the costs and availability of technologies as well as on the policy framework. These assumptions should be part of a consistent narrative (storyline) which gives a better idea of the scenario's meaning for decision makers in businesses and politics. A number of actors, including the European Commission, academia and the Intergovernmental Panel on Climate Change (IPCC), have proposed scenarios for the development of the (EU) energy system. These scenarios generally have a focus on the electricity sector and, thereby, ignore the role of other energy consuming sectors such as transport, buildings and industry. While some scenarios include the totality of energy demand by all sectors, their spatial and sectoral aggregation is quite high.

In the SET-Nav project[1], we developed four new and comprehensive scenarios on how the EU can reduce its greenhouse gas emissions by 85 to 95 % (compared to 1990 levels) by 2050. We call these scenarios "pathways" because a low-carbon year 2050 is as important as the (path)way to get there. Our pathways include the electricity, heat, transport, and industry sectors with very detailed temporal, spatial and technological disaggregation. We started the pathway development (see Figure 1) by designing consistent—qualitative—narratives on the socio-political development, with a particular focus on the degree of cooperation in Europe, the level of (de-) centralization, and the availability (development and deployment) of certain (disputed) technologies. The qualitative narratives gave input to the quantitative assumptions for further modelling, which included assumptions on technology costs and availability as well as CO2 budget and price. A suite of detailed sectoral models that were linked in an ambitious modelling process used these assumptions across all models. The modelling process gives a very large range of results that quantify the pathway narratives from today until 2050. They include the electricity mix, the modal split in transportation, the heat mix and energy consumption by industry among others. Hence, we obtain an all-inclusive picture, which allows comparing several development paths and their limits and challenges of the politico-technology-energy system.

1. More information on the SET-Nav project: http://www.set-nav.eu/.

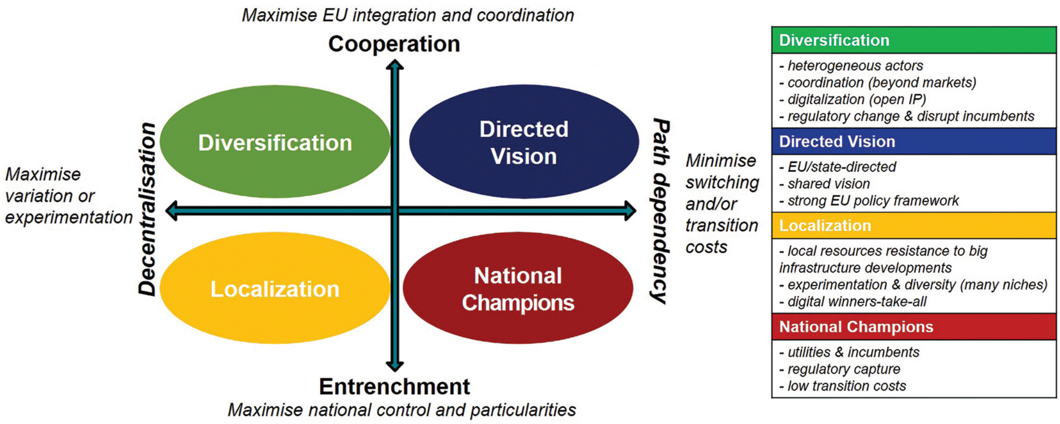

FIGURE 1

Proposed 2x2 scenario typology = cooperation-boundaries x decentralization-path dependency.

2. THE SET-NAV PATHWAYS

The SET-Nav consortium developed four novel and holistic scenarios on the decarbonization of the European energy supply and demand until 2050 (Crespo del Granado et. al. 2019). Each of the four scenarios ("pathways" because we are mainly interested in the path to 2050) presents an alternative world. However, we assume that in all of them a decarbonization target of 85 to 95% is realized by 2050 (compared to 1990 levels). As we discuss in detail in the following chapter, the pathway analysis is done by a unique configuration of models representing various energy sectors that supply or demand energy (e.g., electricity, transportation) in order to allow for a comprehensive analysis of the challenges to decarbonization in Europe.

The pathways were defined along two major axes of uncertainty on the economic and political development in the European energy sector and beyond (Figure 1):

- Cooperation vs. entrenchment
- Decentralization vs. traditionally centralized ("path dependency").

Figure 1 shows the four pathways and their classification along the two axes of uncertainty. Clearly, in contrast to other traditional scenario exercises there is no "best case", no "business as usual" and no "worst case" scenario in our scenario matrix. Rather, we describe four alternative development paths, which all fulfil the same decarbonization target but happen in different policy environments and have different options of technologies. At a glance, the main features of the pathways are as follows:

- The "Diversification" pathway describes a decentralized, yet cooperative world where heterogeneous and new actors dominate the energy market. Smart technologies and appliances, prosumage and regulatory openness to new forms of cooperation and to new technologies characterize this pathway.
- The "Directed Vision" pathway envisions a strong path dependency and strict EU regulations. This helps to create a common vision for the European energy system, which is implemented top-down in the member states. There is a strong role for large actors in this pathway.

- The "Localisation" pathway is based on the use of local (domestic) resources. Given the differences in resource endowments, the national energy strategies of the EU member states vary strongly. Moreover, there is little exchange between member states because of the focus on domestic resources. Large, new infrastructure projects face public resistance. Instead, more and smaller niche markets are created, as well as smart technologies and smart appliances emerge as key actors.
- The "National Champions" pathway rests on a strong role for traditional energy companies. It is characterized by strong path dependency and a preference for large-scale projects. Here too, national strategies for decarbonization are preferred. With very little cross-border electricity trade, many countries use gas-fired power plants and/or CCS as flexible back-up to integrate renewable energy sources.

Developing these pathways had two main objectives: i) identifying the central drivers and key uncertainties for successful energy transition and decarbonization; ii) discerning the consequences of the particular technological and political decisions that characterize each pathway. While the first objective is largely answered by a careful analysis of the inputs to the models, the second objective more strongly relates to the modelling results. The four pathways are very diverse, to some extent even extreme, and therefore allow us to investigate a large number of drivers and uncertainties for the decarbonization of Europe.

In addition to the emissions reduction target for 2050, we assume that all EU member states fulfil their 2020 climate targets and that the legally binding EU-wide 2030 target, namely 40% lower emissions than 1990, is achieved. All sectors may contribute to the emissions reduction and we do not prescribe a sectoral allocation of the emission reductions. Each sector's contribution is endogenously determined in the modelling and varies by pathway.

After having thoroughly assessed the SET Plan technologies and potential developments towards 2050, we vary the technologies deployment by pathway. For example, we exogenously assume that the Carbon Capture and Storage (CCS) technology can be used only in the two pathways with an important role for large energy market players (Directed Vision and National Champions). In addition, we vary some assumptions related to the cost digression and the improvement of efficiency of individual technologies by pathway, for example for battery electric storage. More details on the main features for each pathway refer to Crespo del Granado et. al. (2019).

3. A UNIQUE CROSS-MODELLING AND MULTI-SECTOR REPRESENTATION OF ENERGY MODELS

The four overarching SET-Nav pathways are quantified by applying a cross-modelling and multi-sector combination of energy models. Thus, instead of applying a single large energy system model (Löffler et al. 2017), our approach links several detailed sectoral models to provide an unprecedented level of insights for the pathway analysis. This unique methodological framework (combining several models) allows delivering consistent and coherent quantitative results and data across all models. In short, as part of the overall assessment of the SET-Nav pathways, twelve models are combined (i.e. two macro-economic models, nine sector models and one risk/robustness assessment tool) to have a holistic representation and analysis of the entire energy system. In this paper, we focus on the demand and supply sector for electricity, hydrogen and heat and thus on the interplay between the models[2]: i) Invert, ii) Forecast-Industry, iii) Astra, iv) Enertile, v) Green-X and vi) TEPES. Figure 2 and Table 1 describe these models' features, implementation and overall interaction.

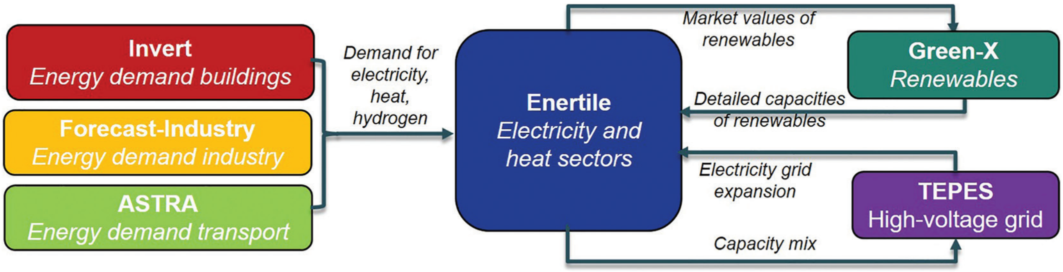

FIGURE 2

SET-NAV Modelling Framework representing key energy demand and supply sector perspectives.

In a first step, the demand for energy carriers such as electricity, heat, and hydrogen in the four different pathways is calculated with the models *Forecast* for the industry sector, *Invert* for the building sector, and *ASTRA* for the transport sector. The modelled demand is given as exogenous input parameter to a first optimization of the energy supply with *Enertile*. The total electricity demand and the resulting market values for renewable energy technologies are then passed over to the *Green-X* model. The rationale of linking *Green-X* and *Enertile* is their different modelling approach regarding deployment of renewables. *Green-X* simulates deployment of renewables while incorporating the impact of policy interventions such as RES targets or corresponding support schemes dedicated to renewables. Thus, within the pathway analysis *Green-X* is used to calculate the capacity and generation of renewables in the period up to 2030, considering the recently agreed overall 2030 EU RES target. The resulting renewable electricity capacity values from the year 2030 are then used as minimum conditions to a second optimization with *Enertile*. In 2030, the renewable generation in the *Enertile* optimization has to be equal to the *Green-X* values. In the years 2040 and 2050 renewable expansion is optimized in *Enertile*. The results from the second Enertile optimization serve as an input for the *TEPES* model, which recalculates the expansion of the transmission grid. The *Enertile* model contains a transport model of interconnectors between countries. This representation is improved by the detailed calculations in the grid model *TEPES*. The revised grid is then fixed in the third and last optimization with *Enertile* based on the results of the *TEPES* model.

These six models thus strongly complement each other as they combine several perspectives with different sectoral priorities but also by integrating the energy consuming sectors—buildings (heating and cooling), transport, and industry—with the power producing sector thus reflecting the increasing sector coupling within the future energy system. In addition, the central point of connection among the models is that all interpreted the pathways storylines for their respective sector and hence some common data inputs were harmonized (e.g. fossil fuel prices).

2. For a detailed model description please refer to SET-Nav project results (http://www.set-nav.eu/content/pages/results): Reports D5.8 (INVERT, FORECAST, ASTRA), D6.9 (ENERTILE, GREEN-X) and D7.8(TEPES).

TABLE 1
SET-Nav models overall details.

Model	Sector representation	Method	Short description and objective	More info
Enertile	Electricity supply	optimization	Minimizing the energy system cost (investment and operation)	https://www.enertile.eu
FORECAST Industry	Industry sector	simulation	Modelling of investment decisions under constraints	http://www.forecast-model.eu/
TEPES	Power Grids	optimization	Minimizing the power system cost (investment and operation of the transmission grids)	http://www.iit.comillas.edu/technology-offer/tepes
ASTRA	Transport sector	simulation	Modelling of modal and technology shares based on total costs and further influencing factors for choice	www.astra-model.eu
Invert	Building sector	optimization	Modelling of the RES share, the total energy investments	Kranzl, L. 2013 Müller, A., 2015
Green-X	Renewable energy	simulation	Total costs while maximizing the proportion of EE	https://green-x.at/

4. PATHWAYS ANALYSIS AND RESULTS

As noted earlier, in this paper we present the SET-Nav pathways results[3] focused on demand and supply sectors, for a more comprehensive overview of other results (e.g., Macroeconomics or gas models) refer to Crespo del Granado et. al. (2019).

4.1 Energy Systems: Demand Perspective

The demand side was the beginning of the modelling sequence and provided input data on energy demand from buildings, industry and transport sectors on the energy supply models. As a first step, the SET Nav pathway narratives were translated into assumptions for demand side scenarios and consequential model inputs accompanied by harmonized assumptions on energy prices, population growth, economic developments and ranges of emission reduction targets.

For the building sector the pathway specific scenario design varies from focus on a decentralized technology mix (heat pumps, biomass, solar thermal, smart heating), concerted approaches for thermal renovation and district heating uptake, focus on local resources to completely country specific approaches. These assumptions translate into a variety of country specific regimes on subsidies and obligations for renewable heating and thermal renovation, obligatory building standards and restrictions for fossil energy carriers.

For the industry sector, the pathways were interpreted into a scenario strongly focusing on the use of CCS in industry and scenario using a portfolio of many different mitigation options including low-carbon innovations, ambitious material efficiency and circular economy, hydrogen as an energy carrier and feedstock as well as electricity for process heating. In all pathways, any remaining energy efficiency potentials are almost completely exploited. The scenario narratives are reflected in financial support schemes for RES and RES based electricity, CO2 price paths, assumptions on technology development and branch-specific economic developments.

For the transport sector various technology options are considered comprising conventional drives, electricity-, hybrid- and fuel cell powered vehicles, as well as trolley truck systems

3. The SET-Nav decarbonization pathway datasets are accessible through the SET-NAV Scenario explorer https://data.ene.iiasa.ac.at/set-nav/#/workspaces or the SET-Nav community on Zenodo https://zenodo.org/communities/set-nav/?page=1&size=20.

TABLE 2
Interpretation of pathway narratives into assumptions for the demand perspective.

	Diversification	Directed vision	Localization	National Champions
building	• Decentralized technology mix, smart heating • Fossil fuel phase out (2030)	• Concerted thermal renovation and district heating uptake • Fossil fuel phase out (2030)	• National resources • Higher diffusion of Solar thermal/PV • Biomass • Fossil fuel phase out	• Different strategies per country • No concerted fossil fuel phase out (option for biogas)
industry	• Industrial processes change • Power-to-X • Increased material efficiency	• No radical process improvements • Use of CCS • Fuel switch to biomass	• Industrial processes change • Power-to-X • Increased material efficiency	• No radical process improvements • Use of CCS • Fuel switch to biomass
transport	• Mobility as a service, autonomous driving • Various technologies	• Joint infrastructure • Electrification of road traffic (incl. freight) • Fossil fuel phase out	• Car sharing, public transport, walking, cycling • Electrification triggered by decentral electricity generation • Biofuels	• Different strategies per country • Large scale biofuels

for freight transport. Complemented by autonomous driving and shared economy scenarios, the worlds of "vehicle ownership" versus "mobility services" are outlined. Furthermore, changes in technology choice behavior as well as acceptance levels for car sharing, public transport and active modes are taken into account. Different measures regarding the support and the phase out of vehicle drive technologies, the infrastructure deployment, and the share of biofuels were assumed.

The total energy demand (Table 3) is reduced by 2050 by 20% to 25% (compared to 6% in a reference scenario), because of different efficiency increases in each sector. In addition, the final energy carrier mix is altered significantly. Final energy covered by fossil fuels is reduced by 76% to 59%, with remaining shares of fossil fuels in 2050 originating mainly from the transport sector, respectively from CCS usage in the industry sector and remaining gas demand for buildings. Electricity demand increases significantly in all scenarios (up to 52%), strongly driven by increased electrification in the industry or transport sector. CCS in the industry sector, higher gas shares in the building sector and the substantial increase in the use of biofuels in the transport sector however can lead to lower increases. Ambient heat utilized through installations of heat pumps in the building and industry sector makes up for 5% to 8% of the total final energy demand in 2050.

While the share of district heating in total final energy supply increases in all pathways, absolute final energy demand for district heating in 2050 compared to 2015 only increases in the Directed Vision pathway. Final energy demand for biomass related energy carriers (biomass, biofuel, biogas) increases strongly from 69% to 138%, mainly as a results of changes in the demand for biofuels in the transport sector and fuel switch in the industry. Hydrogen is assumed to play a critical role in the industrial sector. In the transport sector it can occupy a niche role only in heavy traffic, especially in the technology open scenario Diversification.

While the share of the building sector on the total final energy demand is expected to remain similar, the share of the transport sector is expected to decrease, the expected share of the industry sector strongly depends on the deployment of CCS technology. Overall, the pathway calculations on the demand side in SET-Nav show that decarbonization until 2050 is possible. However, the analysis and model runs in each sector show that the necessary changes would

TABLE 3

Overall total final energy demand per energy carrier for EU28 in all pathways in 2050, change from 2015 to 2050 by energy carrier, share of the respective energy carrier in 2050.

	Diversification			Directed vision			Localization			National champions		
Energy demand	TWh	(%) 2050 comp. to 2015	(%) Share 2050	TWh	(%) 2050 comp. to 2015	(%) Share 2050	TWh	(%) 2050 comp. to 2015	(%) Share 2050	TWh	(%) 2050 comp. to 2015	(%) Share 2050
Gas	750	–76	7	995	–64	9	748	–76	7	1516	–59	14
Coal	101		1	212		2	101		1	229		2
Oil	1200		12	1830		17	1197		12	1756		16
Other fossil	135		1	198		2	135		1	198		2
Waste non RES	31	–17	0	66	77	1	31	–17	0	66	77	1
Electricity	4096	52	40	3950	47	38	4088	52	40	3430	27	32
District heating	495	–21	5	733	17	7	571	–9	6	519	–17	5
Biomass	850	86	8	1089	69	10	767	92	7	1005	137	9
Biofuel	839		8	529		5	904		9	1141		11
Biogas	104		1	9		0	179		2	139		1
Ambient heat	758	0	7	580	0	6	784	0	8	517	0	5
Solar	234	0	2	233	0	2	262	0	3	244	0	2
Hydrogen	554	0	5	57	0	1	483	0	5	2	0	0
Other RES	0	0	0	1	0	0	0	0	0	1	0	0
Total	10148	–25	100	10482	–22	100	10249	–24	100	10765	–20	100

be very hard to achieve as each pathway implies huge challenges and significant transitions accompanied by strong policy interventions in each sector.

4.2 Supply

In all SET-Nav pathways, renewable energy plays a central role. Wind power covers up to 57% of the production while PV takes up to 18%. Altogether, in 2050, renewables with biomass, power-to-X, Geothermal and hydropower reach 75-98%. This has important implications for the entire European decarbonization strategy. For example, the decarbonized (renewable based) power generation supports other sectors such as heat or the power supply in the industrial sector which can be CO2-neutral (sector coupling). That is, the direct use of electricity for a secondary carrier such as hydrogen (“Power-to-X”). Overall, results show that strong electrification is efficient and central for the high decarbonization targets.

FIGURE 3

SET-Nav Modelling Framework representing key energy demand and supply sector perspectives.

As mentioned before, the “Diversification” and “Directed vision” pathways have strong coordination efforts at European level. This translates into sharing and managing surplus (balancing) of wind and solar throughout the European continent. Substantial European transmission network would therefore be necessary in the medium and long term.

“Localization” and “National Champions” in contrast, have a less grid expansion needs. The “Localization” pathway assumes that the EU Member States mainly use their own resources to cover their needs. Thus, the cross-border exchange of electricity will rise less. In other words, traditional, large current market players develop their climate strategies on their national markets and taking into account their national resources. This may lead to a strong role of nuclear power and keep some conventional power plants (combined with CCS to reduce their CO2 emissions) as part of the supply mix.

The expansion of the pan-European electricity grid, in particular in "Diversification" and "Directed Vision" would lead to three key challenges: 1) The introduction of an appropriate institutional framework for the regulation of cross-border networks; 2) an efficient yet fair distribution of costs of cross-border investment projects; 3) the creation of favorable financing conditions.

The development of distribution grids is, except in the "National Champions", in all scenarios relevant. Most importantly, this expansion is, however, in scenarios that rely heavily on distributed generation, especially in the "Localization" pathway. In order to achieve the expansion of distribution networks, it is extremely important to introduce an adequate compensation scheme for distribution network operators. For example, system operators might need compensation (or define new business models) for the increased costs of feed-in a high shares of decentralized energy sources.

CCS plays a role in "Directed vision" of where this technology learns the cost reductions through generous financial and regulatory support within a few years that have not been achieved in the past 15 years. In this scenario, CCS serves as a technology to control emissions in coal and natural gas power plants. These power plants act as a fall back option in supporting wind and solar variable generation while other backup options such as battery storage and power grid expansion are less necessary in this pathway.

In "National Champions", CCS also comes into play, but at a higher cost because the technology development is less based on EU-wide Community research and development efforts. CCS can achieve a market share of up to 10% of total electricity generation in both scenarios. Also in the industrial sector with CCS up to two thirds of CO2 emissions could be captured in 2050. In contrast, "Diversification" and "Localization" achieve the same emissions target without CCS. Hence, renewable energy sources in conjunction with alternative flexible options such as battery storage, network expansion and demand management emerge as the optimal supply mix for these Pathways.

5. SET-NAV PATHWAYS TAKEAWAYS RELATED TO "A CLEAN PLANET FOR ALL"

In this section, we discuss some of the SET-Nav analyses results and insights in line with the European Commission's (EC) long-term strategy "A Clean Planet for all" (European Commission 2018a). After a brief introduction to the underlying EC modelling works, we start with a brief comparison of quantitative outcomes focusing on the electricity sector. Then we conclude in the final section by placing SET-Nav Pathways specific findings and recommendations next to the EC's headline conclusions.

5.1 European Commission's modelling on "A Clean Planet for all"

The European Commission long-term strategy "A Clean Planet for all" (European Commission 2018a) present the EC's long-term vision on how "Europe can lead the way to climate neutrality by investing into realistic technological solutions, empowering citizens, and aligning action in key areas such as industrial policy, finance, or research—while ensuring social fairness for a just transition." (European Commission 2018b). In this report, nine scenarios assess and consider different action areas and technologies. Apart from a Baseline scenario where

GHG targets are not met, the set of ambitious decarbonization scenarios differ in technology development and others as well as in the overall GHG ambition, this is summarized as follows:

- An 80% GHG emission reduction (compared to 1990 levels) is prescribed for five scenarios, including three scenarios where decarbonization efforts are largely driven by decarbonized energy carriers and examining the impacts of switching from the direct use of fossil fuels to zero/carbon-neutral carbon carriers, namely electricity (ELEC), hydrogen (H2) and e-fuels (P2X). Other two scenarios examine how stronger energy efficiency measures (EE) or the transition to a more circular economy (CIRC) can deliver the emissions reduction target.
- The COMBO scenario pursues a 90% GHG reduction through a cost-efficient combination of the options outlined above.
- The third category of scenarios achieves even stronger emissions reduction, reaching net zero GHG emissions by 2050 and thus pursuing efforts to achieve a 1.5°C temperature change. In this scenario category, remaining emissions that cannot be abated by 2050 need to be balanced out with negative emissions, including from the LULUCF sink. The 1.5TECH scenario aims to increase the contribution of all the technology options, and relies more heavily on the deployment of biomass associated with significant amounts of carbon capture and storage (BECCS) in order to reach net zero emissions in 2050. The 1.5LIFE scenario relies less on the technology options of 1.5TECH, but assumes a drive by EU business and consumption patterns towards a more circular economy and (strong) lifestyle changes.

5.2 Comparison of Key Results on Decarbonizing the EU's Electricity Sector

As outlined in (European Commission 2018c), "there is a consensus across studies that electricity consumption will further grow in Europe." "In line with earlier analyses of the Commission, electricity demand increases significantly by 2050 in all decarbonization scenarios." The findings of the SET-Nav pathways corroborates both EC statements: the need for decarbonization comes along with an increase in electricity demand. According to the SET-Nav pathways analysis, this implies an increase in electricity demand and supply by 31% to 81% compared to current (2015) levels (see Figure 3). The EC analysis goes even well above these levels, specifically in those scenarios where either hydrogen (H2) or P2X is emphasized, or, if a full decarbonization (i.e. 100%) is defined as GHG target—cf. scenario 1.5TECH where electricity demand is projected to increase by 146% until 2050, or 1.5LIFE with an increase of 102% (both compared to 2015).

A closer look on the corresponding supply to match these increased demand projection for electricity is provided in Figure 4. The illustration shows a comparison of the shares (in total electricity generation) of all key supply options by 2050 at EU28 level, according to assessed pathways and scenarios of SET-Nav and from the EC's own work related to "A Clean Planet for all". Thus, the shares of renewables, nuclear and fossil fuels sum up to 100% in all scenarios. Please note further that for the EC's analysis the data underlying "Decarbon" are the averages across all decarbonization scenarios per category. According to their analysis, these (decarbonization) scenarios provide very similar power mix in 2050, with renewables ranging from to 81% to 85%, nuclear from 12% to 15% and fossil fuels from 2% to 6%. Within the SET-Nav pathways, we see a broader variety across all three categories: RES shares range here from 73% to 97%, and for example nuclear from 0.5% to 17%. This illustrates the fundamental differ-

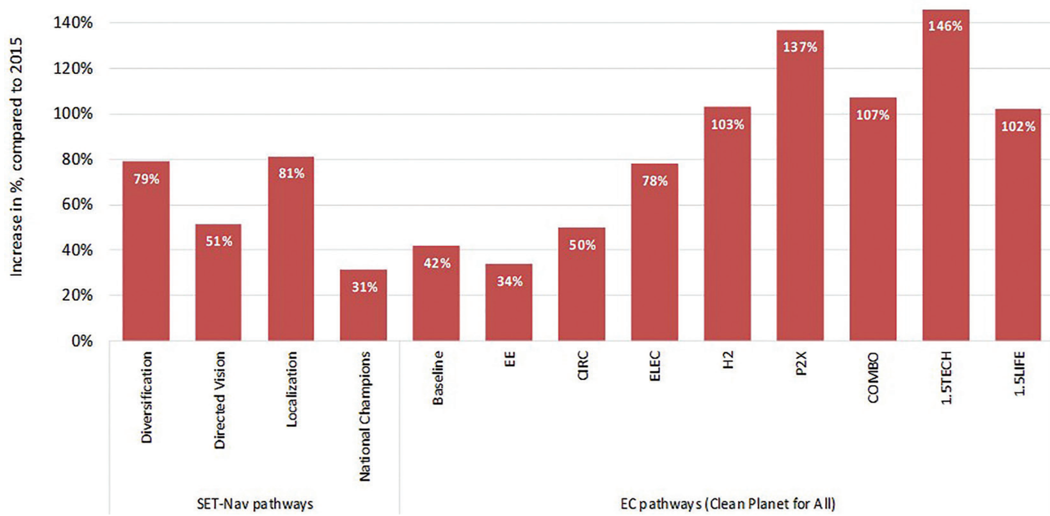

FIGURE 4
Comparison of increase in electricity generation by 2050 (compared to 2015) at EU28 level according to assessed pathways and scenarios (SET-Nav and "A Clean Planet for all").

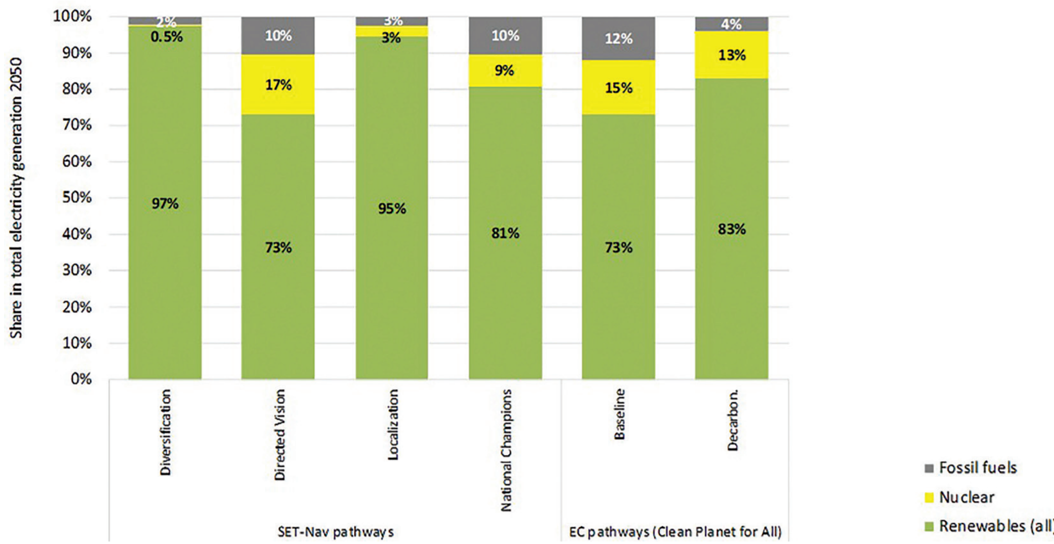

FIGURE 5
Comparison of shares in total electricity generation by 2050 at EU28 level for key supply options according to assessed pathways and scenarios (SET-Nav and "A Clean Planet for all").

ences in our pathway conception across assessed options, and these affect finally the selection of decarbonization options used in electricity supply.

Further insights on the decomposition of power supply is provided by Figure 6, illustrating the cumulative installed capacities of distinct generation technologies at EU28 level by 2050. The strong deployment of renewables is visible as wind and solar dominate the power sector by 2050 within all cases. Within the EC study one can observe that the highest increase of renewables capacity takes place in scenarios deploying hydrogen and e-fuels—this statement is also confirmed by our own analysis where "Localisation" and "Diversification" show the highest numbers on the renewables side. On the renewables side we show generally higher numbers for onshore wind whereas EC scenarios indicate a more balanced mix, involving offshore wind and possibly also a higher contribution to come from bioenergy. Common across all scenarios is moreover that the weight of fossil fuel-fired capacity in the total power mix decreases strongly over time. In accordance with generation data, EC scenarios show higher nuclear capacities by 2050—these are then only slightly lower than current level (99-121 GW versus 122 GW in 2015).

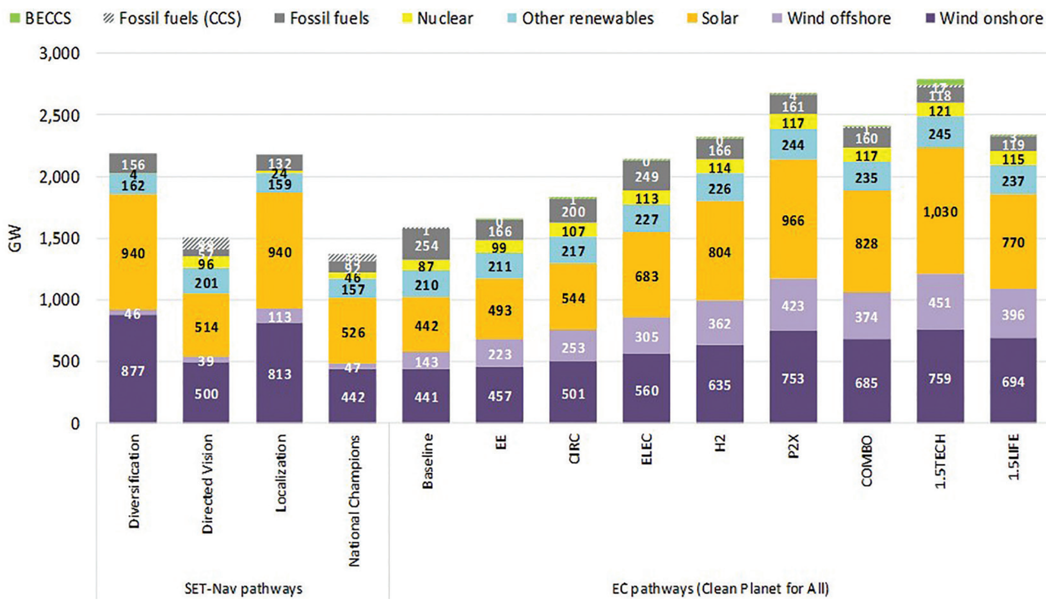

FIGURE 6

Comparison of cumulative installed capacities of power generation technologies by 2050 at EU28 level according to assessed pathways and scenarios (SET-Nav and "A Clean Planet for all").

6. CONCLUSIONS AND RECOMMENDATIONS

In this paper, we analyzed unique EU climate and energy scenarios that take into account a variety of possible paths on the way to a low carbon energy production and its use. Each pathway exploration of decarbonization options (under different circumstances) provided an understanding of the effect of different policies in reducing greenhouse gases. Such as the prohibition of conventional transport (internal combustion engine), the power system expansion, re-configuration of distribution grids, and others. An interesting insight is that debated technologies such as CCS, nuclear energy and coal can be dispensed for other effective decarbonization alternatives. Moreover, all the pathways envision a decisive reduction of emissions by 2030 and the successful expansion of renewable energy sources (in particular wind power) as a main driver. Hence, new technologies (batteries, hydrogen or bio-gas) will be crucial for the decarbonization of non-electricity sectors or providing balancing options for variable renewable energy sources in the power sector. In other words, efficient decarbonization via direct or indirect (e.g. via the transformation and use of hydrogen) electrification requires efficient linkages between the energy markets by monitoring close to real-time carbon content of energy carriers and emissions.

To summarize the main recommendations of the SET-Nav pathways, Table 4 details a tabular comparison extracting key quotes and conclusions noted in pages 22-25 in the EC's Communication "A Clean Planet for all" (EC, 2018a) and puts them side-by-side with key insights from the SET-Nav pathways for demand sectors (buildings, transport, and industry) and the electricity supply mix.

TABLE 4
SET-Nav pathways recommendations next to the EC's headline conclusions.

EC communication 773 "A clean planet for all"	Key insights from the SET-Nav pathways
"Accelerate the clean energy transition, ramping up renewable energy production, high energy-efficiency and improved security of supply, with increased focus on reducing cyber security threats, while ensuring competitive energy prices, all of which power the modernisation of our economy;"	A stable electricity & heat grid system with 96% decarbonization is possible Foreseeable CO_2 prices well above 100-150 €/t CO_2 are needed in 2050 In order to keep cost as low as possible: 1) Strengthen the electricity grid, 2) Create a competitive market environment for the direct use of electricity in other sectors such as heat grids Heat pumps play a crucial role in all scenarios—in very ambitious mitigation targets electricity demand from heating and cooling increases significantly Thermal renovation and efficient new construction in buildings help to conserve biomass and limit the impact of electricity demand for heat pumps
"Roll out carbon-free, connected and automated road-transport mobility; promote multi-modality and shifts towards low-carbon modes such as rail and waterborne transport; restructure transport charges and taxes to reflect infrastructure and external costs; "	SET-Nav pathways takeaways for transport: Shift to more efficient transport modes is important, for both freight and passengers. However, the potential is limited due to infrastructure capacity restrictions, logistics effort for multi-modal transport and required behavior change. Diffusion of low/zero-emission vehicles for road transport contributes substantially: BEV/PHEV soon competitive prices—range anxieties to be resolved, FCEV & trolley trucks as options for freight to be further evaluated Alternative fuels play an important role, in particular for non-road modes—to be covered either by biomass or by synthetic PtX-fuels Decarbonizing transport by -65% is possible, but requires strong measures like emission based taxes and charges and investments in infrastructure deployment for alternative technologies
"Boost the EU's industrial competitiveness through research and innovation towards a digitalised and circular economy that limits the rise of new material dependencies; start testing at scale breakthrough technologies; monitor the implications on the EU's terms of trade, in particular for the energy intensive industries and suppliers of low carbon solutions, ensure competitive markets that attracts low carbon industries… "	SET-Nav pathways takeaways for industry: Currently available technologies not sufficient for decarbonization of EU industry >80% decarbonization is possible—even without CCS, but requires policies to boost: 1) Process innovations, 2) CO_2-free secondary energy carriers, and 3) strong innovations in material efficiency and circular economy Extending the ETS with a minimum price path to provide long-term certainty CO_2 tax to provide incentives for companies outside the ETS
"Strengthen infrastructure and make it climate proof. Adapt through smart digital and cyber-secure solutions to the future needs of electricity, gas, heating and other grids allowing for sectoral integration starting at local level and with the main industrial/energy clusters;"	Significant investment in the transmission network will be needed in all pathways. This investment however only amounts to a fraction of the investments needed for additional generation infrastructure. System development that goes in a decentralized direction needs substantially more network improvements to back renewable generation New transmission technologies will be very relevant (between 40 and 50% of the new capacity in 2030 is built using HVDC lines, percentage increased with time horizon). R&D investment in new technologies could result in improved solutions If we want to keep requirements for generation infrastructure low: Prefer direct use of electricity over hydrogen/"synthetic hydrocarbons" wherever possible and economically feasible

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