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European energy infrastructure for 100% renewables

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Executive summary

The EU faces critical decisions on energy infrastructure planning and deployment to meet its climate goals, aiming for a 55% emissions reduction by 2030 and net-zero by 2050. A 100% renewable energy system, eliminating fossil fuels and nuclear energy is seen as the most viable solution. However, current EU energy infrastructure policy and planning are insufficient, risking lock-in to outdated technologies. Instead, building towards a decentralised and a 100% renewable energy system should not only support successful decarbonisation but also enhance energy security and citizen involvement. It is recommended to align EU infrastructure planning with a fully renewable future, avoiding investments in nuclear- and fossil-dependent technologies, and improving grid infrastructure for a successful energy system transformation.

Abbreviations

ACER – Agency for the Cooperation of Energy Regulators
CEF – Connecting Europe Facility
CCS – Carbon Capture and Storage
CCTS – Carbon Capture Transportation and Storage
CRCF – Carbon Removals and Certification Framework
DE – Distributed Energy
ECA – European Court of Auditors
ENTSO-E – European Network of Transmission System Operators for Electricity
ENTSOG – European Network of Transmission System Operators for Gas
ENNOH – European Network of Network Operators for Hydrogen
EU – European Union
GA – Global Ambition
ICMS – Industrial Carbon Management Strategy
ISO – Independent System Operator
LNG – Liquefied natural gas
NECP – National Energy and Climate Plan
NRA – National Regulatory Authority
NT+ – National Trends+
PCI – Project of Common Interest
PMI – Project of Mutual Interest
PPP – Public-Private Partnership
PtX – Power-to-X
TEN-E – Trans-European Networks for Energy
TOS – Transmission System Operator
TYNDP – Ten-Year Network Development Plan

1 Introduction

The European Union (EU) and its Member States stand at a crucial juncture, facing fundamental decisions on energy infrastructure design and deployment that are important for the success of their climate ambitions and ultimately achieving the 1.5°C target agreed upon under the Paris Agreement.[1] The EU aims to reduce its net emissions by 55% by 2030 and achieve net-zero emissions by 2050, as outlined in the EU Green Deal (European Commission 2019) and legally enforced by the European Climate Law.[2]

Despite these commitments, current efforts are considered insufficient to achieve the 1.5°C target (CAN Europe 2024). The urgency to mitigate climate change, particularly as the continent already faces its visible impacts, such as heatwaves, droughts, wildfires and floods, underscores the need for the EU to drastically cut emissions across all sectors and transform its energy system. Given the long-term impact of today's decisions and potential path dependencies – where past choices influence the development of current and future energy systems – careful planning is essential (Unruh 2000; Mattauch, Creutzig and Edenhofer 2015; Fouquet 2016).

The realisation of a 100% renewable energy system in the EU,[3] and thus eliminating any reliance on fossil fuels and nuclear energy, is increasingly being considered as the most attractive route for the transformation, as it is technologically feasible, environmentally sustainable and cost effective (Schwartzkopff and Ott 2024; Hainsch et al. 2020; Göke et al. 2023; Präger et al. 2024). As energy infrastructure development can be seen as a subordinated technical system with a 'serving' function emerging from the requirements of the energy system rather than being the vehicle shaping it, planning, construction and operation should align accordingly.

European infrastructure development should avoid repeating past mistakes of overestimating network expansion and adhering to fossil- and nuclear-fuel trajectories, leading to technology lock-ins (Holz et al. 2018). The network development for integrating large-scale nuclear power during the 1970s and 1980s, for example, proved inefficient and unsustainable for the energy system towards decarbonisation (Christian von Hirschhausen et al. 2018). Renewable energy development also requires appropriate infrastructure (Eitan and Hekkert 2023). The EU should be cautious in its energy infrastructure planning, as simply increasing infrastructure does not necessarily lead to a better supply.

1 Council decision (EU) 2016/1841, 5 October 2016 (last accessed: July 8, 2024; this applies to all other internet accesses unless otherwise noted).

2 Regulation (EU) 2021/1119 establishing the European Climate Law, 30 June 2021.

3 Here, the term '100% renewable energy system' is introduced as a definition for the target energy system. The term 'system' encompasses not only the generation facilities (such as PV systems, wind turbines, biomass power plants, hydroelectric plants and geothermal power plants, among others) but also the various system services and flexibility options necessary to ensure a reliable supply of renewable energy in all sectors and areas of life.

Why a 100% renewable energy system?

A 100% renewable energy system entails using solar, wind, hydro and other renewable sources to meet all energy needs, eliminating any reliance on fossil fuels and nuclear power. Since the 1970s, the benefits of moving from a centralised fossil-nuclear energy system to a largely decentralised renewable system has been advocated (Schumacher 1973; Lovins 1975; 1976). In fact, the increasing scholarship on 100% renewable energy system argues that it is feasible and cost effective, enhancing energy security and meeting climate targets more efficiently than net-zero approaches, as well as promoting greater citizen involvement (Bogdanov et al. 2019; Löffler et al. 2019; Auer et al. 2020; Jacobsen 2020; Kendziorski et al. 2022; Wiese, Thema and Cordroch 2022; Schwartzkopff and Ott 2024).

'Net-zero' or 'climate-neutral' scenarios, in contrast, too often just balance residual greenhouse gas emissions with removals by employing CCTS technologies, an approach which can be observed to widely be adopted to justify the continued use of fossil fuels. Even with a CCTS-optimistic approach (Haszeldine et al. 2018), the projected build-out and capture rate is too slow for sufficient climate protection with the CCTS route. In fact, emissions savings are largely negated by persisting upstream emissions of fossil fuels, including extraction, processing and transportation (IEA 2020). Additionally, the technical, environmental and economic difficulties of CO_2 storage are largely underrepresented (CIEL 2023). 'Net-zero' or 'climate-neutral' scenarios often also bet on a continued or increased use of nuclear power, aiming to reach climate targets by overestimating the future role of nuclear energy. The continued operation and new construction of nuclear power plants, however, face significant challenges in contributing to a sustainable energy system, for safety, economic and transformational reasons (Präger et al. 2024).

Centralised vs decentralised approaches

In distinguishing between decentralised and centralised energy supply structures, several technical-economic dimensions can be considered. However, the distinction mainly addresses the spatial arrangement of generation facilities, such as for electricity, gas or hydrogen. Their supply structures integrate a variety of elements that can align with either centralised or decentralised approaches. The term 'centralised' encompasses both the placement of individual large power plants and other energy facilities (such as industrial appliances, electrolysers or battery storage) and the related ownership and organisational structures of these types of infrastructure, which are operated by private, primarily profit-driven energy supply companies. In contrast, 'decentralised', community-based renewable energy plants are typically owned and operated by citizens or cooperatively organised energy companies. These plants can be either non-profit or profit oriented, as well as more equitably organised, thus competing with traditional energy supply companies.

2 Disentangling EU energy infrastructure policy

It is important that infrastructure planning at the European level avoids the danger of fossil-nuclear path dependency, and favours renewable deployment, through a combination of decentral (e.g. national or regional) and central (cross-border or European-wide) approaches. Generally, since the late 1990s, the EU's energy and energy infrastructure policies have evolved significantly. Initially focused on liberalising, harmonising and interconnecting nationally secluded energy systems, with an emphasis on electricity and fossil gas, the policies have progressively expanded in line with the EU's emission-reduction and climate ambitions.

Following the First Energy Packages in 1996/1998, which initiated market liberalisation, and the Second Energy Package in 2003, which introduced further integration measures, the Third Energy Package in 2009 furthered this process through the establishment of network codes and the Agency for the Cooperation of Energy Regulators (ACER).[4] The European Network of Transmission System Operators for Electricity (ENTSO-E)[5] and the European Network of Transmission System Operators for Gas (ENTSOG)[6] were also introduced to coordinate between Member States' National Regulatory Authorities (NRAs) and Transmission System Operators (TSOs). However, this has not focused on abandoning the fossil-nuclear centralised energy system.

More recently, policies have aimed to align climate and energy targets, emphasising the expansion of renewable energy, while maintaining large shares of fossil and nuclear (uranium) sources. The Fit for 55 package under the European Green Deal, introduced in 2021, includes provisions for renewable energy, decarbonised gas and hydrogen markets, and infrastructure development, amongst others. The REPowerEU plan,[7] established in 2022, further aims to phase out dependency on Russian fossil fuels.

However, both policies still rely on nuclear energy, imported uranium, and optimistic assumptions about hydrogen imports and CCTS technologies, which are not available at scale and risk locking in the old system. Focusing on the EU's renewable energy ambitions, the Renewable Energy Directive targets a share of 42.5% renewable energy in gross final energy consumption, including solar power, wind, ocean and hydropower, biomass, and biofuels, by 2030.

4 Regulation (EC) 713/2009 establishing an Agency for the Cooperation of Energy Regulators, 13 July 2009.
5 See: https://www.entsoe.eu
6 See: https://entsog.eu
7 Communication COM(2022) 230 from the Commission 'REPowerEU Plan', 18 May 2022.

In terms of infrastructure, the Trans-European Networks for Energy (TEN-E) Regulation takes centre stage. Established in 2013 and revised in 2022,[8] it builds a pillar of EU infrastructure policy, especially optimising cross-border infrastructure. However, the priority corridors still plan for a large share of fossil and nuclear energy production, be it corridors for electricity, hydrogen infrastructure across various regions or a cross-border CO_2 network.

2.1 Ten-Year Network Development Plan

The Ten-Year Network Development Plans (TYNDPs) for gas and for electricity, developed by ENTSO-E and ENTSOG with ACER oversight, try to streamline European network planning, integrating the latest developments in national energy and climate policies and seeking to ensure alignment with EU targets (ENTSO-E and ENTSOG 2023). Published every two years, they assess projects, identify infrastructure gaps and provide cost-benefit analyses for selecting Projects of Common Interest (PCIs), eligible for funding from the Connecting Europe Facility (CEF). TYNDP scenarios include data on future energy demands, resources, import potentials, energy prices and current infrastructure. TYNDPs are also considered to hold political significance as they shape perceptions of future energy systems and influence various stakeholders' modelling and planning processes (Brandstätt et al. 2023).

The planning process is guided by scenario frameworks,[9] which are supposed to align with EU energy efficiency and climate targets. The scenario building, on the other hand, draws on EU and Member State data, such as the National Energy and Climate Plans (NECPs), to project energy demand and supply, considering factors and uncertainties impacting gas and electricity infrastructure.

The 2024 TYNDP cycle includes six scenarios, including National Trends+ (NT+) scenarios, based on NECPs for 2030 and 2040, as well as more ambitious scenario pathways in the Distributed Energy (DE) and Global Ambition (GA) scenarios, which aim for 2040 and 2050 horizons (ENTSO-E and ENTSOG 2023). The scenarios' assumptions differ significantly in a number of different areas: European autonomy; energy savings (decarbonisation through imports vs circularity and consumption behaviour); digitalisation (EU business competitiveness vs an active role for renewable self-consumption and management of variable renewable energy sources); and technology choices (large-scale and molecule-based technologies vs renewable energies and an electrified energy system). The DE scenario pursues a decentralised approach for greater European autonomy, while the GA scenario focuses on a globalised energy trade and centralised energy technologies. Whilst the GA scenario puts an emphasis on so-called low-carbon technologies like nuclear and CCTS, the DE scenario gets closer to a fully renewable energy system and considers some of the systemic requirements, but still significantly falls short of the 100% renewable energies goal.

8 Regulation (EU) 2022/869 on guidelines for trans-European energy infrastructure, 30 May 2022.
9 Regulation (EU) 2022/869 on guidelines for trans-European energy infrastructure, 30 May 2022.

2.2 EU Action Plan for Grids

To accelerate progress in EU energy infrastructure development, the EU Action Plan for Grids,[10] published in late November 2023, seeks to improve grid efficiency and rollout following a 14-point strategy. Overall, it aims to modernise and expand Europe's electricity infrastructure to support the energy system transformation and accommodate growing electricity demand, projected to increase by 60% by 2030. Key actions include accelerating the implementation of PCIs and Projects of Mutual Interest (PMIs)[11] with enhanced support and funding starting from 2024 and improving access to finance, as well as incentivising grid usage and rollout. This is in response to projections that cross-border transmission capacity will need to double by 2030, adding approximately 87 GW.

Given this call to action, EU policy makers seem to have realised the urgency of the transformation; however, accelerated action is only meaningful if aligned with the correct principles.

Main EU energy infrastructure actors and roles

National Regulatory Authorities: Regulate national energy markets, ensure compliance with EU laws, protect consumers and prevent anti-competitive practices. They collaborate with ACER to ensure a cohesive approach across the EU, addressing both national and European energy market needs.

Transmission System Operators: Manage electricity and gas transmission at the national level, maintain infrastructure, ensure reliable energy flow and contribute to network development plans.

Agency for the Cooperation of Energy Regulators: Coordinates and monitors NRAs, drafts and implements network codes, oversees energy markets, and advises EU institutions. It also advises EU institutions and oversees the development of the TYNDP by ENTSO-E and ENTSO-G.

European Network of Transmission System Operators for Electricity and Gas: Umbrella organisations of national TSOs with legal mandates in view of supporting energy markets and infrastructure management. They develop, consult and publish draft TYNDP scenarios in coordination with ACER and the Commission, and publish final scenario reports.

European Network of Network Operators for Hydrogen (ENNOH): Nascent umbrella organisation, established under the reform of EU gas markets in 2024. It develops hydrogen infrastructure, integrating it into the gas network and managing EU hydrogen transport, while considering both centralized and decentralized approaches.

10 Communication COM/2023/757 from the Commission 'Grids, the missing link – An EU Action Plan for Grids', 28 November 2023.

11 PMIs were introduced with the 2022 reform of the guidelines for trans-European energy infrastructure. In contrast to PCIs, these projects do not span across intra-EU borders but engage with neighbouring non-EU countries.

2.3 Improving the EU's energy infrastructure planning

Achieving a 100% renewable energy system requires not only a shift of the generation mix but also system flexibility, comprehensive planning and well-functioning governance. This is why there are increasing calls for reforms of the current energy infrastructure setup in the EU (Schwartzkopff and Ott 2024; Cremona and Rosslowe 2024; Meeus et al. 2023). Critics have highlighted several areas for improvement, emphasising the necessity for a comprehensive approach to energy planning and implementation.

Starting with streamlining the planning processes to ensure better integration across various sectors, an independent EU body could help to better coordinate and oversee more consistent and top-down planning efforts (Meeus et al. 2023). Additionally, enhancing demand-side flexibility, increasing transparency and improving data access are crucial steps towards effective and responsive infrastructure planning (Cremona und Rosslowe 2024), provided that they be compatible with the 100% renewable energy system target.

Aiming at further organisational effectiveness, measures such as merging ENTSO-E and ENTSOG to create a more cohesive framework, strengthening ACER, and transitioning towards an Independent System Operator (ISO) model could aid to streamline operations (Meeus et al. 2023; Cremona and Rosslowe 2024).

Of course, effective financing is pivotal too. Introducing Green Bonds and fostering Public-Private Partnerships (PPPs) could attract investment into energy networks (Cremona and Rosslowe 2024). Reforming network tariff designs to allow for anticipatory grid investments could ensure that the grid evolves to meet future demands better. Additionally, more efficient use of existing EU funds and increased future allocations for energy infrastructure investments are essential to support a successful transformation (Schwartzkopff and Ott 2024; Meeus et al. 2023).

Modelling a 100% renewable energy system

Within the increasing research on 100% renewable energy systems, there are various scenarios at national and regional, as well as global, levels.[12] The EU, however, has not yet presented a 100% renewable energy scenario. Instead, other publications have taken up the job and proposed potential scenarios and pathways for achieving a fully renewable energy system, adopting differing levels of ambition and approaches to assessing future uncertainties (Breyer et al. 2020; Goeke et al. 2023; Kendziorski et al. 2022; Schwartzkopff and Ott 2024).

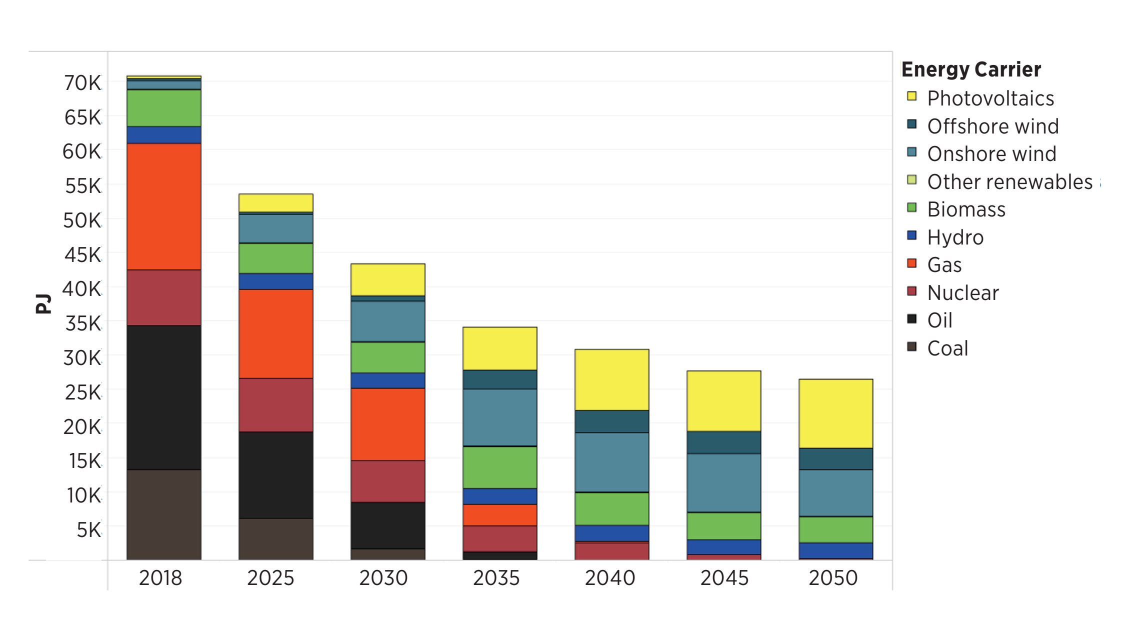
Studies differ in assumptions such as the composition between wind and solar photovoltaic energy, the importance of power grids and batteries, and development of the final energy demand. Nevertheless, there is a broad consensus regarding two areas across all these studies. First, the massive expansion of solar and wind is key for the energy transformation, through which renewable energy sources can entirely substitute fossil and nuclear fuels. Second, substituting fossil fuels in the heating, transport and industry sectors requires direct electrification. Synthetic fuels produced from biomass or electricity, like hydrogen, are limited to specific applications due to costs and other limitations.

The Societal Commitment scenario by Hans Auer (2022) outlines such a possible pathway. Their model projects an overall reduction in energy consumption, high levels of local renewable generation and strong policy support for renewable technologies. In this scenario, energy use decreases significantly across all sectors, with a shift in demand patterns aligning with peak renewable energy production. The power sector sees a rapid phase-out of coal, lignite and oil by 2030, followed by a decline in fossil gas and nuclear power by 2040.[13] A strengthened and decentralised power grid is essential to support this transformation, emphasising local generation and reducing dependence on large power plants. Accordingly, solar photovoltaic, onshore wind and offshore wind become the primary energy sources, supported by high public investment and policy measures. **Figure 1** shows the shifting primary energy demand in the EU until 2050, whilst **Figure 2** provides an overview of the projected electricity generation per country by 2050, highlighting the energy mix within each Member State. The residential sector is assumed to move to heat pumps for heating, phasing out fossil fuels, while the industrial sector adopts electricity-based technologies and biofuels. In transportation, battery electric vehicles replace combustion engines by 2040, with freight transport increasingly relying on hydrogen and biofuels.

12 For a comprehensive meta-analysis of 100% renewable energy scenarios, see Khalili and Breyer (2022).

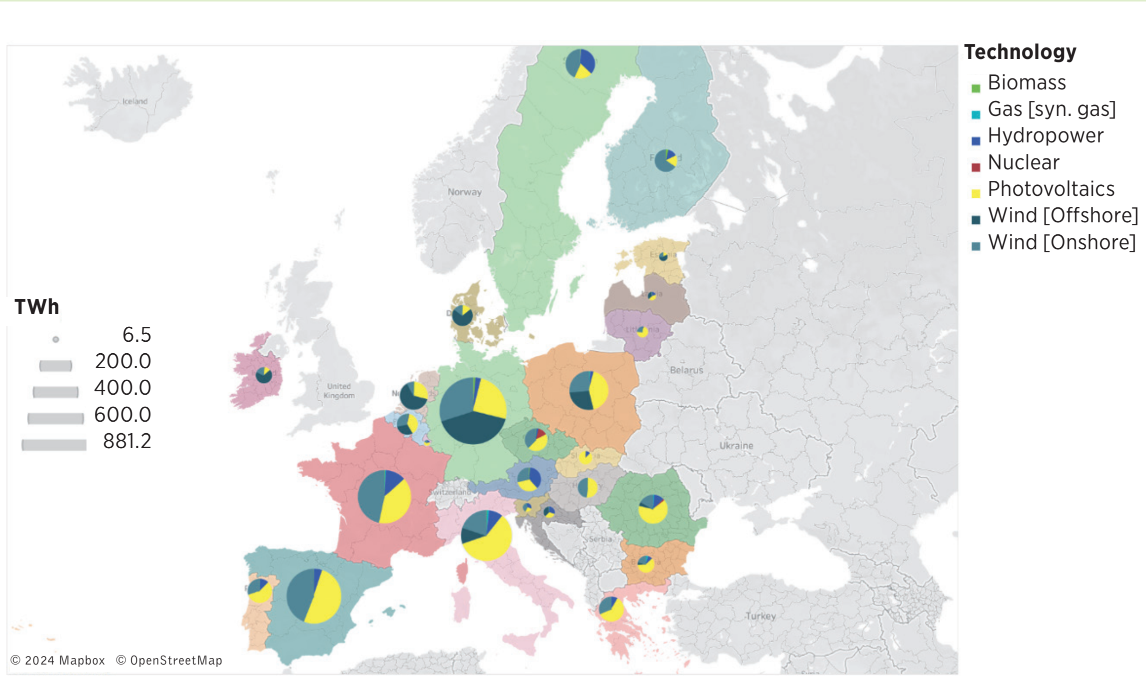
13 Whilst no new nuclear power plant capacities are being considered in the scenario, a very low share of nuclear power remains in the Czech Republic.

Figure 1: Primary energy demand in the EU until 2050 (in Petajoule, PJ).



Source: Based on data from Hans Auer et al. 2022, updated.

Figure 2: Electricity generation per country by 2050 (in Terawatt hour, TWh).



Source: Based on data from Hans Auer et al. 2022, updated.

3 How to prepare EU energy infrastructure for 100% renewables

3.1 Electricity networks – a new system paradigm

Electricity networks, both at the transmission and distribution level, play an important role in the decarbonisation of the EU energy system until 2030 and beyond. However, when developing a network for a 100% renewable energy system, it must be taken into account that its function and design fundamentally differ from the traditional fossil-nuclear energy system. A new system paradigm, shifting from a fossil-centric to a flexible and more decentralised 100% renewable energy system, must be implemented. A decentralised 100% renewable energy system is supply oriented, meaning that demand is organised according to the availability of renewable energy. To ensure security of supply, particularly for the industry and economic sectors, and to meet society needs (housing, mobility, etc.), the expansion of renewable energy must be secured. This necessitates flexibility options such as demand management, digital solutions, smart grids, energy storage and indirect electrification through Power-to-X (PtX) options (Child et al. 2019; Hans Auer et al. 2022). In a 100% renewable energy system, the concept of baseload, previously provided by large, central fossil and nuclear power plants, is replaced by decentralised and intelligently networked renewable energy systems. Consequently, the proportion of baseload generation will decrease, and a smart grid will exhibit significantly more variable load patterns.

In 2023, 44% of Europe's electricity came from renewables, with solar and wind producing a record 721 TWh, surpassing fossil gas at 452 TWh (Brown and Jones 2024). As solar and wind shares grow, power systems need to adapt accordingly, requiring the modernisation of distribution grids, as well as becoming more flexible.

Trans-national electricity grids have been significantly developed over the last decades, thus strengthening the European internal electricity market. A few bottlenecks remain (Cremona and Rosslowe 2024). In addition to network development, a more efficient use of existing infrastructure can also relieve congestion significantly (Neuhoff et al. 2013), which is also the preferred option from a cost and planning perspective.

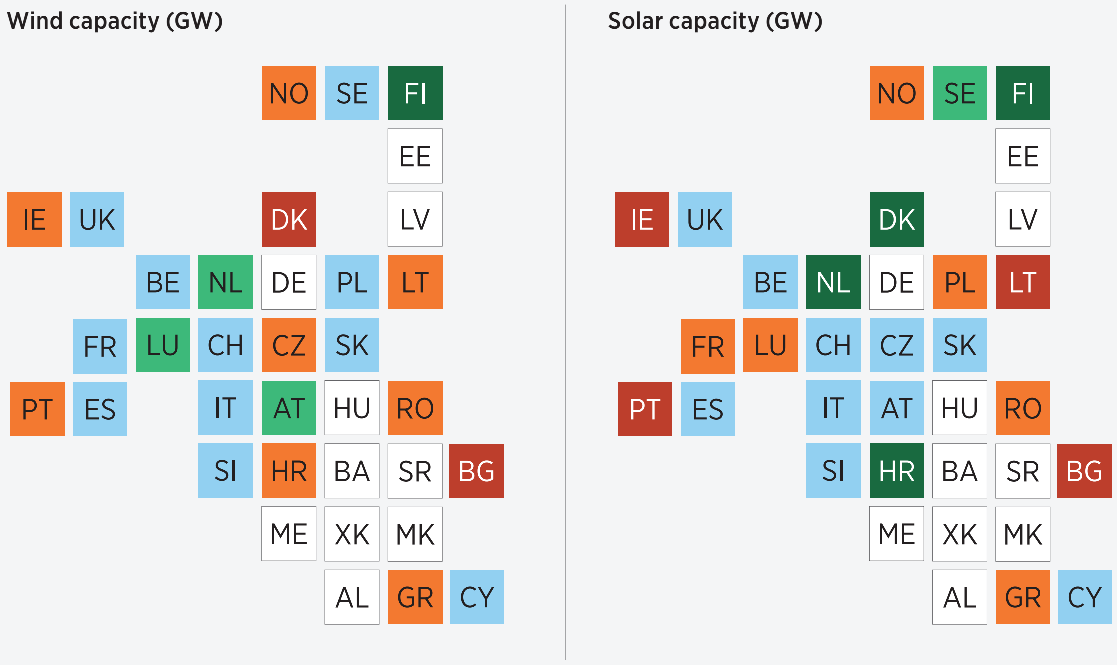
The crucial step to develop a 100% renewable energy system is to accelerate the extension of solar, wind and other renewable resources as well as to phase out fossil and nuclear fuels. With this in mind, a recent analysis by Cremona and Rosslowe (2024) highlights a lack of ambition of national TSOs in the system change in many Member States, both with respect to solar and to wind capacities. In many countries, the current plans of grid operators would not add sufficient grid capacity to integrate the – often very modest – growth foreseen by national governments. Only in Finland and the Netherlands do the national TSOs have sufficiently ambitious plans for grid expansion to accommodate a further increase of solar and wind capacities (see **Figure 3**). Solar capacity is more frequently underestimated, with a total shortfall of 60 GW across 11 countries, compared to a 27 GW shortfall for wind.

Figure 3: Comparing TSO grid plans to national policy targets reveals cases of misalignment.

Comparing TSO grid plans to national policy targets reveals cases of misalignment, risking insufficient network development

TSO grid plans vs. 2030 national targets

- **Exceptionally ambitious –** TSO grid plan is **over 50% more** than 2030 national target
- **Moderately ambitious** – TSO grid plan is **10-50% more** than 2030 national target
- **Neutral** – TSO grid plan is **10% less to 10% more** than 2030 national target
- **Slightly falling behind** – TSO grid plan is **10-50% less** than 2030 national target
- **Significantly falling behind** – TSO grid plan is **over 50% less** than 2030 national target
- Assessment not possible due to lack of data



Source: Ember analysis of Transmission System Operator (TSO) plans,
Draft updated NECPs, 2030 Global Renewable Target Tracker.
Certain countries could not be assessed due to lack of data or, in case of Germany,
because the data corresponds to the grid plan's target years 2037 and 2045, and not 2030.
Countries examined in this report include EU27, Norway, Switzerland, UK and the Western Balkans,
Kosovo (XK): This designation is without prejudice to positions on status, and is in line with
UNSCR 1244/1999 and the ICJ Opinion on the Kosovo declaration of independence.

Source: Cremona and Rosslowe 2024.

Further challenges include insufficient energy storage capacity, inadequate network infrastructure and the need for flexibility capacities such as a strengthened grid, advancements in battery technology and hydrogen infrastructure.

With the increasing integration of renewables like solar and wind, and their associated variability in demand and production, flexibility in energy systems is considered essential for addressing seasonal, medium-term, and short-term supply and demand mismatches (OSMOSE 2019). Key flexibility aspects, such as adequacy, power transmission, reactive power control, frequency stability and voltage stability, can be achieved through options such as dispatchable generation, demand response, energy storage and network interconnections (Schill 2020). Whilst presently flexibility is primarily provided by thermal power plants and network interconnections, the importance of storage technologies like batteries is rising with the increasing use of renewable energy (Schill and Zerrahn 2018). Further, flexible demand-side options can also enhance the integration of non-dispatchable renewables, reduce curtailment and thus boost overall energy system efficiency (Moura and de Almeida 2010; Zerrahn and Schill 2015).

With regards to infrastructure, power grid expansion is considered to aid renewable integration as it helps balance local supply and demand fluctuations and can reduce overall system costs (Schaber, Steinke, and Hamacher 2012; Brown et al. 2018; Göke et al. 2023; Neumann and Brown 2021). However, alternatives such as battery storage and positioning renewables closer to demand centres can potentially reduce the need for extensive grid expansion (Tröndle et al. 2020; Göke et al. 2022).

One element that contributes to the democratisation and decentralisation of the energy system is the integration of energy-sharing concepts, which are already enabled by an EU regulation and must be implemented by the Member States (European Commission 2024). Energy sharing allows citizens to form communities that produce, consume, store and trade their own electricity. This organisational form increases and diversifies the supply of renewable energy and reduces electricity prices. A study in the German context shows that up to 90% of households in Germany could benefit from these approaches (IÖW 2022). For network and infrastructure development, these concepts should be considered important elements. Better aligning local, decentralised production and consumption can reduce overall system costs and diminish the need for grid expansion. Additionally, other community energy concepts, such as cooperative participation in renewable energy plants, neighbourhood solutions, community energy parks and e-car sharing, should be consistently integrated into network and infrastructure development to facilitate the implementation of such projects.

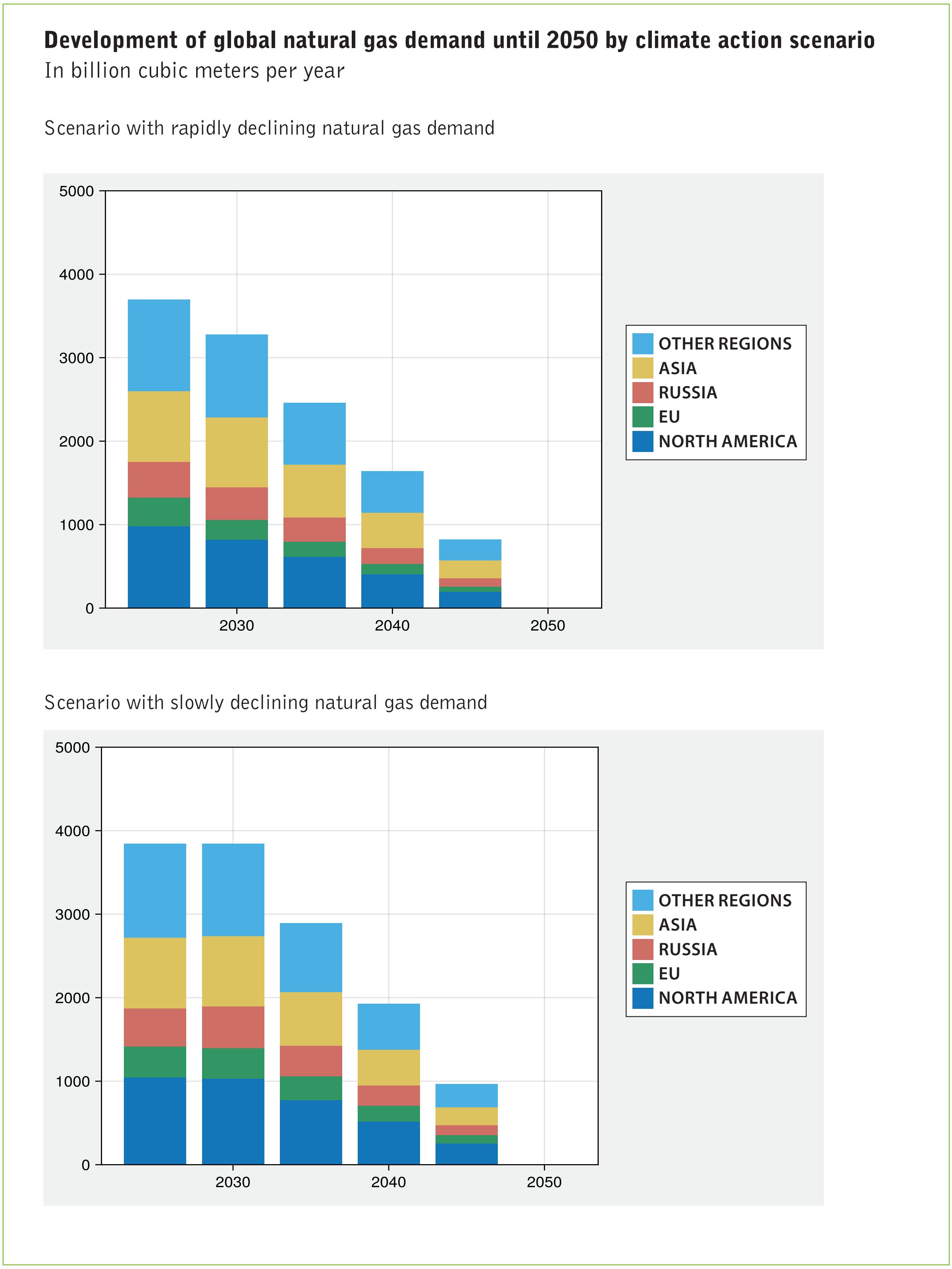
3.2 Gas infrastructure – fossil gas exit is imperative

The globally declining gas demands amidst a consistent decarbonisation of energy systems in the coming years (see **Figure 4**) imply that the fossil gas infrastructure will become largely obsolete. Clearly, a fossil gas exit is a necessary step towards a more sustainable European energy supply system and fossil gas as a 'bridge' is a myth (von Hirschhausen, Kemfert and Präger 2021). This was clearly demonstrated with the Russian invasion of Ukraine on 24 February 2022, which disrupted supply perspectives, while the view of fossil gas as a 'bridge technology' has disappeared due to its climate impact, similar to coal, necessitating a rapid phase-out (Kemfert et al. 2022).

Overall, the current infrastructure for fossil gas is considered as sufficiently expanded, making large-scale expansions unnecessary (Kemfert et al. 2022). This also applies in terms of security of supply. Holz et al. (2024) show that EU countries could compensate for a disruption of Russian gas imports across different demand scenarios. Even with high demand until 2030, EU gas needs could be met through other pipeline imports and liquefied natural gas (LNG) – without expanding infrastructure. According to their analysis, increased energy savings and a timely gas phase-out would reduce dependency on Russia, as well as supporting the EU's climate goals. Given that even under moderate climate ambitions, fossil gas exit will occur in the 2040s at the latest, the demand for new LNG and pipeline infrastructure is very modest, in particular with respect to firm LNG import terminals (Holz et al. 2024).

Instead of expanding fossil gas infrastructure, the conversation should focus on preventing stranded assets and mechanisms for repurposing and decommissioning fossil gas networks, at the local distribution and the cross-border transmission level. Decommissioning gas grids, however, presents several challenges, requiring integrated long-term infrastructure planning that considers both gas and electricity grids. As gas demand declines, the costs of maintaining gas infrastructure and amortizing the existing network investments will be spread across a decreasing number of customers. Regulators must address these amortisation and other social impacts, including costs that arise from disconnecting from the gas network, while identifying priorities for remaining gas consumption and potential repurposing for renewable hydrogen (Rosenow, Lowes, and Kemfert 2024). Crucial steps include accelerating depreciation rates, defining decommissioning criteria and minimizing further investments. Generally, early prevention strategies for asset stranding will lower risks for taxpayers as well as the climate (Rosenow, Lowes, and Kemfert 2024).

Figure 4: Development of global fossil gas demand until 2050 (bcm/year).



Source: Holz et al. 2024.

3.3 Hydrogen – remaining high uncertainty

Hydrogen is a typical case of extreme uncertainty about future quantities and qualities, and the level of decentralisation. In the current REPowerEU plan, the European Union has set ambitious targets for hydrogen production and imports. Hydrogen takes centre stage for the EU's climate strategy, especially in industrial processes such as steel and chemistry (Griffiths et al. 2021).[14]

Initial indications suggest that these extensive expansion plans were not based on actual needs and appear to be oversized, as progress on planned hydrogen supply in Europe is minimal (Lambert et al. 2024). As of 7 May 2024, only 3.6% of the planned supply for 2030 is operational or has reached final investment decision. Despite significant targets and funding, most of the committed supply (over 60%) relies on fossil fuels with CCTS, primarily from retrofitted fossil hydrogen plants. Committed electrolysis projects are projected to produce only 0.2 million metric tons of hydrogen per year.

There are significant divergences regarding the technical design, economic viability and future infrastructural support. A report by the European Court of Auditors (ECA) suggests that the European Commission has set overly ambitious hydrogen production and import targets for 2030, driven more 'by political will rather than being based on robust analyses' (ECA 2024). Specifically, no member states have set import targets in their NECPs, except for Germany. The level and competitiveness of large scale imports from overseas also remains widely uncertain (Goeke et al. 2023). The ECA (2024) calls for thorough planning and assessment to ensure realistic targets and strategic alignment.

Therefore, the development of hydrogen infrastructure should consider a comprehensive evaluation of centralized and decentralized approaches:

- The decentralised approach ensures regional consistency between renewable hydrogen production and consumption, leading to demand-oriented infrastructure development.
- The centralised approach requires large-scale infrastructural expansion, connecting high-capacity central plants with geographically distant consumers, which may involve both domestic and large-scale foreign production.

Imported hydrogen is typically more expensive than local production, with transport costs constituting 30-60% of the total, making imports economically unattractive in most cases (Galimova et al. 2023). Domestic and more decentralised production will likely dominate, as it reduces import dependency and enhances energy security (Galimova et al. 2023).

Apart from the fact that the use of fossil hydrogen has little or no advantage over the direct use of fossil gas in terms of emissions, even if CCTS is implemented (Howarth and

14 The REPowerEU Plan aims for 10 million tonnes of domestic renewable hydrogen and another 10 million tonnes of imports by 2030, necessitating significant infrastructure for production, storage, and transport (European Comission 2022). The European Court of Auditors in 2024 has called for a 'reality check' in view of the feasibility of these targets.

Jacobson 2021; Bauer et al. 2022), this will lead to an extension of emission-intensive fossil gas use and a large-scale development of CCTS. These are all technologies that are not developed, available or affordable on a large scale to date. If this infrastructure and associated business models are not available, investment in fossil-based hydrogen production will become stranded or continue without CCTS, which is an even bigger risk for EU climate targets.

In terms of infrastructure planning, the revised EU gas market design foresees that ENNOH will function as an umbrella organisation for hydrogen network operators. In similar terms, it is suggested that integrated cross-sectoral infrastructure planning by an ISO could ensure more coordinated and efficient build-out (Schwartzkopff and Ott 2024).

Today's planning should also consider the emergence of new global supply chain patterns as production might relocate, following the 'renewables pull effect', describing the tendency of industries to move to regions with abundant and relatively low-cost renewable energy sources compared to other countries (Verpoort et al. 2024). Clear assessment is needed for checking if the hydrogen infrastructure is needed for all targeted processes.

Localised hydrogen production aligned with regional consumption is more cost efficient than extensive infrastructure (Braunger, Grüter and Präger 2021; Galimova et al. 2023). Planning should integrate hydrogen with electricity and gas systems, prioritising long-term sustainability.

3.4 Carbon Capture, Transport and Storage – largely incompatible with a 100% renewable energy system

Clearly, CCTS[15] is a typical case of central vs decentral approaches, and over the past two decades, it has failed to provide significant support for decarbonisation through either approach (von Hirschhausen, Herold and Oei 2012; Watari et al. 2023). Most attempts deployed thus far on CCTS have been motivated by the hope of keeping fossil fuel infrastructure alive, and few emissions remain that require CCTS explicitly (Jacobsen 2020).

Yet, the EU's CCTS strategy is spread across different policies and directives. The 2024 Industrial Carbon Management Strategy (ICMS)[16] focuses on promoting and implementing carbon management practices across various industries to reduce carbon emissions. The CCS Directive[17] establishes the comprehensive legal framework necessary for the geological storage of CO_2.

15 We use the term CCTS because transportation of the CO_2 is of crucial importance, and it is often neglected in the techno-economical analyses as well as the common concept use of Carbon Capture and Storage (CCS).

16 Communication COM(2024) 62 from the Commission 'Towards an ambitious Industrial Carbon Management for the EU', 6 February 2024.

17 Directive 2009/31/EC on the geological storage of carbon dioxide, 23 April 2009.

Further, in 2024, the European Parliament adopted the provisional agreement on the Carbon Removals and Certification Framework (CRCF) Regulation.[18] This regulation created the first EU-wide voluntary framework for certifying carbon removals, carbon farming and carbon storage in products across Europe.

On the planning side, the TYNDP's GA scenario, aligning with the Industrial Carbon Management Strategy, forecasts an increased application of CCTS, predicting up to 400 Mt of CO_2 captured per year by 2050. In contrast, the DE scenario limits the use of CCTS technology, projecting a maximum of 150 Mt of CO_2 captured per year by 2050. Given the failure of CCTS thus far to support decarbonisation at scale, it is implausible that anything close to these figures will be attained. Thus, infrastructure planning must not rely on these exaggerated figures.

Capturing CO_2 emissions is a costly endeavour. It is generally more cost effective and environmentally efficient to prevent emissions rather than capture them. The EU must be cautious to ensure that CCTS does not become an excuse for continued emissions. CCTS should be employed where emissions are unavoidable, such as in cement production processes. Decentral capture and domestic transportation may be an option. While the EU has made significant strides in establishing frameworks and strategies for CCTS, the actual deployment and effectiveness of these technologies have been limited. Future efforts must balance technological feasibility, economic viability and environmental impact to ensure sustainable progress in carbon management.

18 Legislative proposal for a Regulation establishing a Union certification framework for carbon removals, 30 November 2022.

4 Policy recommendations

- **Infrastructure development is an important element of decarbonisation, but it needs to be aligned with a strategy for a 100% renewable energy system at the European level, which is still missing.** For building towards a 100% renewable energy system and an economy that contribute to limiting the global temperature increase to 1.5°C, the EU should not only set more ambitious decarbonisation targets but invest in and scale up renewable energy technologies. A 100% renewable energy system stands out as cost effective, highly secure in terms of supply and capable of achieving a sustainable energy future.
- **However, current EU infrastructure planning, as reflected in the TYNDPs and the Grid Action Plan, is not aligned with a 100% renewable energy system development and needs to be adapted.** Current scenarios still include large shares of fossil fuels and nuclear power, which are not part of a sustainable energy future. The GA scenario is clearly too expensive and not sustainable. Even the DE scenario is not fully aligned with a fully renewables-based infrastructure.
- **Infrastructure development needs to balance between more centralised, cross-border approaches and decentralised approaches.** Current planning favours centralised infrastructure, including fossil and nuclear capacities. Building LNG terminals and fossil gas plants, however, reinforces dependence on fossil fuels, reducing momentum towards a 100% renewable energy system and favouring outdated fossil fuel industries. Similarly, pursuing fossil hydrogen production, even with CCTS technologies, extends reliance on fossil fuel infrastructure, offering minimal emissions benefits over fossil gas. Such investments risk becoming stranded, as the required technologies for large-scale CCTS are neither developed nor affordable. Therefore, so-called 'bridge-technologies' need to be critically assessed to avoid any lock-in effects.
- The European Commission and the Council of EU energy ministers as well as grid operators repeatedly have pleaded for increased investments into the EU's energy networks. The urgency and the volume of these investments make it even more imperative to plan and build our pipes and pylons in the most effective way. **Independent System Operators have less incentives to over-invest in infrastructure and could ensure a coherent and integrated planning process**, provided they have a 100% renewable energy system target and balance between centralised and decentral solutions.
- **The revision of the TEN-E Regulation during the new legislative term from 2024 to 2029 should abandon the silos of separated planning for electricity and gas**. It gives EU institutions and grid operators the opportunity to prepare processes that align more consistently the many different national grid plans with an overarching EU-wide scenario for a fully renewable energy system.

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ECOLOGY

European energy infrastructure for 100% renewables

The EU faces critical decisions on energy infrastructure planning and deployment to meet its climate goals, aiming for a 55% emissions reduction by 2030 and net-zero by 2050. A 100% renewable energy system, eliminating fossil fuels and nuclear energy is seen as the most viable solution. However, current EU energy infrastructure policy and planning are insufficient, risking lock-in to outdated technologies. Instead, building towards a decentralised and a 100% renewable energy system should not only support successful decarbonisation but also enhance energy security and citizen involvement. It is recommended to align EU infrastructure planning with a fully renewable future, avoiding investments in nuclear- and fossil-dependent technologies, and improving grid infrastructure for a successful energy system transformation.

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