IMPULSE

Designing energy infrastructure for a climate-neutral Europe

Solutions for cost-effective system development

Agora Energiewende

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Designing energy infrastructure for a climate-neutral Europe. Solutions for cost-effective system development.

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Preface

Dear reader,

Europe's energy transition is in a critical phase. Today's infrastructure decisions are essential to achieving climate neutrality and delivering secure, affordable energy. As both the Draghi and Letta reports stressed, a well-functional single energy market is pivotal. In this context, the European Commission's forthcoming Grids Package is a key chance to shape Europe's energy infrastructure. Planning must keep pace with the transition to avoid costly bottlenecks and stranded assets and to align national priorities with European interest.

To address this, Agora Energiewende together with Forum Energii, IDDRI, ECCO and the Energy Policy Group commissioned Fraunhofer IEG, Fraunhofer ISI and d-fine to carry out a comprehensive modelling of Europe's energy infrastructure needs. Using conservative parameters to ensure robust insights, the modelling identifies where to prioritise investment for an efficient, coordinated and cost-effective energy transition.

Building on the Fraunhofer and d-fine study, our Impulse paper sets out priorities, planning approaches and concrete recommendations to guide infrastructure development across Europe. It aims to inform ongoing discussions among policymakers, stakeholders and planners on how best to deliver the infrastructure underpinning Europe's climate, security and competitiveness goals.

I wish you an interesting read,

Frauke Thies
Co-Director Europe, Agora Energiewende

Key findings at a glance

1 **Infrastructure underpins Europe's transition to climate neutrality and a competitive economy.** As the energy system shifts to variable renewables, flexibility and clean molecules, the supporting networks must also evolve. The power grid needs to expand in length and capacity, with interconnection becoming increasingly crucial. The need for fossil gas pipelines will rapidly decline, while new infrastructure is needed for hydrogen and carbon dioxide. Planning must keep pace to deliver timely, efficient buildout for a modern energy system.

2 **Europe can reduce its energy system costs – by over an estimated 560 billion euros between 2030 and 2050 – and make itself more resilient and secure by optimising its infrastructure investment.** Without forward-looking planning, there is a risk of inefficient investments or bottlenecks that could slow the energy transition and create stranded assets. At the same time, an integrated approach will unlock efficiency gains, direct investments to where they are most needed and maximise the benefits of a flexible and secure energy system.

3 **To ensure that the requisite infrastructure is developed as a cohesive and connected network, the first step would be to task an existing European entity to undertake system-wide modelling.** Energy modelling across Europe and across sectors can identify efficiencies and solutions to meet energy needs effectively, at the lowest cost and in line with policy priorities. This high-level framework can align bottom-up planning processes, ensuring that energy system plans function together seamlessly.

4 **To align with climate neutrality and the shifting energy system, Europe's infrastructure-planning governance needs updating.** This means prioritising electricity grids and end-use efficiency, and limiting hydrogen, methane and CO_2 networks to clearly defined industrial and regional clusters. EU-level coordination, for example through an independent agency, could enhance transparency and accountability across the energy system.

Content

1 Planning infrastructure for the energy transition in a time of turbulence

As Europe stands in the middle not only of an energy transition, but also in the throes of dramatic geopolitical shifts that are further altering the energy landscape, it must act to ensure that it has the energy infrastructure necessary to meet policy goals of increased competitiveness, improved security and climate neutrality (IMF, 2024). Europe's energy infrastructure serves not only as the backbone of Europe's internal energy market, but also as a precondition of Europe's global competitiveness through efficient energy delivery, as a safeguard of Europe's security by making the most of European energy supply, and as a critical link to accessing energy efficiency, system flexibility, and renewable energy resources.

The infrastructure behind Europe's current energy system will need to be adapted to support our future energy mix. The European Climate Law greenhouse gas reduction targets – which stipulate that greenhouse gas emissions should be reduced by 55 percent between 1990 and 2030 and that net zero is achieved by 2050 – require the energy system to move away from reliance on fossil fuels to an energy system based on renewable energy resources. Overall, a net-zero Europe will reduce primary energy demand through energy efficiency. It will meet energy needs mainly with renewable and decarbonised electricity, with a supporting role for other clean fuels (European Commission, 2020). The power grid will need to expand in length, capacity and interconnectivity, while the need for fossil fuel infrastructure will decrease significantly, if not entirely by 2050. In parallel, new infrastructure systems will need to be developed for hydrogen and carbon dioxide. This transition cannot be achieved simply by switching one-for-one from fossil to renewable resources but will require the development of a much more nimble and dynamic system to allow for the integration of variable renewable resources and flexible demand. Without stronger, more forward-looking planning, infrastructure could become a serious bottleneck — slowing progress, raising costs and undermining Europe's competitiveness. Moreover, poor planning could lead to stranded assets and inefficient investments that divert resources away from the clean technologies needed for the transition.

The need for a better approach to infrastructure planning is reflected in calls for change. The European Commission states in its Action Plan for Affordable Energy that it will put forward a European Grids Package that will address improvements to grid planning. Notably, the Commission explains that its proposal will follow "a top-down planning approach, integrating regional and EU interests and develop effective cost sharing mechanism . . . for an optimised energy system." (European Commission, 2025a). Similarly, the Enrico Letta and Mario Draghi reports stress the need for change to enable connectivity and coordination across Europe and across energy sectors for an affordable and diversified energy system (Letta, E., 2024; Draghi, M., 2024). Similar calls for change have come from actors across the system, with Transmission System Operators highlighting the need for greater alignment between European, national and regional level planning, industry actors expressing the need for increased integration across sectors and geographies and civil society entities noting the importance of a top-down perspective to guide system development.[1]

Recognising the importance of infrastructure does not necessarily mean it will be effectively developed, however. The Ten-Year Network Development Plan (TYNDP) process, which is currently the most comprehensive European infrastructure planning process, is driven by bottom-up, national and sector-isolated data (Artelys, 2025; ACER, 2025a).

1 See, e.g., Responses, European Commission Grids Package consultation, https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/14672-European-grid-package_en

Although joint scenarios underpinning the TYNDP reflect an attempt to develop more integrated approaches, the national plans remain the foundation for these scenarios. In many cases, these plans do not reflect sectoral integration at the national level and therefore limit the ability of the TYNDP to identify geographic and sector-integrated system efficiencies for Europe and for Member States (Fraunhofer IEG et al., 2025; ACER, 2025a).

Energy and infrastructure planning processes need to be developed that identify areas where the system can become more efficient – including through flexible demand, storage, and by coordinating and optimising the utilisation of renewable resources across the system and between regions (Fraunhofer IEG et al., 2025). Planning processes must ensure that the power grid is designed to meet the anticipated increase in demand for electricity to prevent infrastructure from becoming a limiting factor for system transformation, while reflecting the fact that the need for fossil gas infrastructure will rapidly decline on the path to a net-zero system. Planning processes should also provide a check to ensure that time and money are not invested in unnecessary infrastructure, or worse in infrastructure that could hamper the transition by diverting resources away from solutions geared towards a sustainable energy transition. Instead, infrastructure planning should create a self-reinforcing loop: system plans that foresee an integrated and efficient system will serve as a signal to private sector investors that it is wise to put time and money into the clean technologies anticipated in such a system.

The planning process must also account for the multiple uncertainties facing the development of a modern energy system. A successful approach will address the tensions inherent in the transition: enabling shifts away from fossil fuels while simultaneously maintaining those parts of the infrastructure still needed for remaining fossil fuel applications today; balancing anticipatory investments to cover expected shifts in energy demand and supply against the risk that the consumer will have to bear the costs of stranded assets; recognising that pathways to climate neutrality may incorporate different national strategies, while seeking to align those approaches to benefit from a geographically integrated system; and realising and rewarding the benefits of investing in a European single market while ensuring that benefits are shared across Member States.

To address these challenges, Agora Energiewende together with Forum Energii, IDDRI, ECCO and the Energy Policy Group (EPG) developed a project to support ongoing discussions about how best to plan infrastructure for the decarbonisation of the energy system and design governance for efficient planning processes to develop infrastructure to support that system. We commissioned Fraunhofer IEG, Fraunhofer ISI and d-fine to model the impacts of different approaches to infrastructure planning on energy system development and infrastructure requirements at the European transmission level.[2] This impulse paper is based on that open-source modelling exercise, which has been published in a separate technical report, to develop recommendations for changes to energy system planning and governance (Fraunhofer IEG et al., 2025).

Our recommendations advance the design of infrastructure planning processes to robustly identify the trans-European infrastructure needed to enable the transition of the energy system to one that can meet European goals of affordability, competitiveness, security, and climate neutrality – while addressing the challenges of doing so in the midst of transition. This project is intended to provide a basis for further discussions and modelling to determine how to accelerate the development of necessary infrastructure and plan for those aspects around which uncertainty remains.

2 In this paper, the term infrastructure includes electricity infrastructure, gas infrastructure (including both natural gas and future hydrogen infrastructures), infrastructure related to carbon dioxide (CO_2) transport, heat infrastructure and its contribution to sector coupling. The modelling does not cover oil infrastructure.

2 Developing an energy and infrastructure system model integrated across sectors and across Europe

2.1 An integrated approach to infrastructure modelling

The energy system is becoming more and more geographically interdependent, requiring generation and demand to be balanced far beyond national borders. It is also increasingly intertwined across sectors: there is growing potential to meet energy demand through electrification instead of with fossil fuels, with system-wide demand for electricity expected to triple between 2020 and 2050 (Fraunhofer IEG et al., 2025). However, most planning processes still take place in geographic and/or sectoral silos and thus risk underestimating the benefits of a more integrated system (Artelys, 2025; ACER, 2025a).

The integrated modelling approach developed in this project co-optimises European energy supply, storage and infrastructure to meet the demand for energy and industrial feedstocks. The modelling framework reflects a sectorally and geographically integrated energy system and tests how the different approaches to and degrees of integrated planning affect system outcomes, such as energy system costs and energy infrastructure requirements.

The model takes a novel approach to modelling the energy system holistically and illustrates the possibilities that can be revealed by adopting a co-optimisation approach. This project is unique because it integrates multiple energy vectors and geographies

What does 'integrated' mean when we talk about 'integrated planning'?

The definition of the term 'integrated planning' can vary depending on the context or perspective. It may refer to planning across geographies, sectors or transmission and distribution systems, or a combination of these dimensions. It may also indicate planning processes at various levels of integration, from planning processes that are adjacent but are not substantively integrated, to planning that is based on modelling intended to co-optimise the system across sectors and geographies.

Given that the term 'integrated planning' has various meanings, it is important to define it clearly, especially in policy discussions where it is critical to have a shared understanding of proposed solutions. In addition, different 'levels' of integration may be appropriate in specific situations. For example, a transmission system operator planning electrical grids within its service area may want to integrate planning regionally and across the transmission and distribution systems – and will need to ensure appropriate input about interactions with molecules especially with respect to electrolysers and hydrogen system (Agora, 2024) – but may not need to coordinate with gas system operators at all stages of the planning process.

For the purposes of this paper, 'integrated planning' refers to a planning process that incorporates co-optimisation energy system modelling that can endogenously determine the best way to meet a given energy demand by co-optimising supply, storage, demand-side flexibility and transport solutions across Europe and across energy vectors (specifically, in this study, electricity, fossil gas, hydrogen and its derivatives, and CO_2). This paper explains the benefits of this type of holistic, co-optimised modelling.

within a single framework, enabling the identification of cross-sectoral synergies and efficiencies that are often missed in more fragmented approaches. By applying a top-down analytical perspective, the model ensures that assumptions and data are assessed across Europe and energy vectors, capturing interactions between sectors and regions that bottom-up models often overlook. In contrast, processes such as the TYNDP may involve a joint scenario, yet the underlying modelling is still performed separately by the European Network Transmission System Operator for Electricity (ENTSO-E) and for gas (ENTSOG). Finally, unlike the proprietary modelling used in the TYNDP and in most national modelling work, the open-source nature of the modelling allows for results to be tested, reproduced and built upon.

Built on the open-source PyPSA-Eur energy-system model,[3] the model in this project includes the relevant energy vectors – electricity, fossil gas, hydrogen and its derivatives, including methanol, ammonia, synthetic oils and synthetic methane, as well as CO_2 – and covers the European Union (excluding Cyprus and Malta), the United Kingdom, Norway, Switzerland and the Western Balkan countries. These areas are represented by 62 regional clusters ("nodes") across Europe, with each country having at least one node and larger countries having up to eight. The model optimises investment and operation across the entire energy system, covering generation, storage, conversion and transmission infrastructure, solving for minimum total system costs[4] for the energy supply to meet energy demand on a nodal level, while reaching climate neutrality in Europe by 2050. The energy demand inputs are based on the PyPSA-Eur-Sec provided data – the inputs are publicly available for which can be reviewed – which are then configured and validated based on other studies (Fraunhofer IEG et al., 2025). To meet demand, the model can choose among various technologies: wind, solar, biomass, hydropower, fossil and nuclear fuels are available as primary energy sources. The model optimises the energy supply based on the main conversion technologies (including heat pumps, combined heat and power plants (CHP), thermal storage, electric vehicles, batteries, power-to-X processes and hydrogen fuel cells) and considers the transmission-level infrastructure required by these technologies. Imports of energy carriers are also included in the model. Hard coal, oil products and fossil gas via pipeline or liquefied natural gas (LNG) terminals are available for the current energy system, with imports of hydrogen and its derivatives becoming more important in a future system.

Transmission grid buildout is considered at five-year milestone intervals from 2025 to 2050, both within each country and across Europe. Given the model's broad reach across Europe and across sectors, the project design includes limits to the temporal and geographic resolution to strike a balance between finding solutions that are as granular as possible and ensuring that the time needed to run the model does not make it too unwieldly. Specifically, based on existing electricity and gas transmission infrastructure, the model optimisation determines grid expansion and new construction needs, including repurposing gas pipelines for hydrogen. Carbon flows, which include carbon capture, utilisation, transport, sequestration, removal and emissions into the atmosphere, are also mapped.

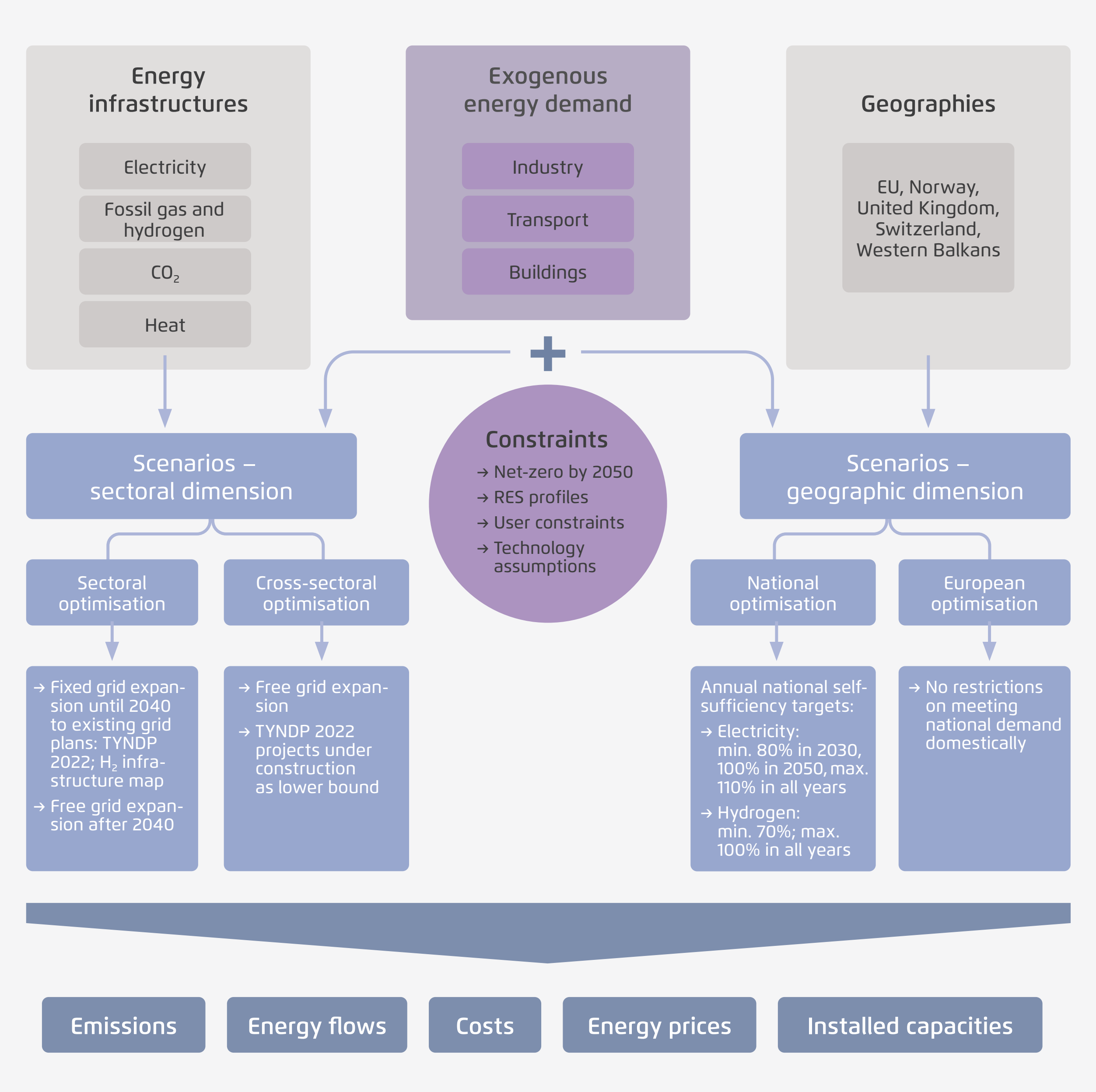
It is important to note that this specific modelling exercise does not propose or deliver a blueprint for a net-zero energy system. As we discuss in our recommendations below, such specificity around solutions is achieved by finding common ground across various scenarios and sensitivities to test uncertainty around assumptions such as costs and technical characteristics. Instead, this project sets out a modelling approach that can be used to strengthen the process of finding economic solutions, and in so doing provides an illustrative view of a net-zero energy system – which also serves as a solid basis for discussing and further refining the identified solutions (e.g. in terms of regional biomass potentials and costs).

3 Python for Power System Analysis (PyPSA), https://pypsa.org/.
4 Total system costs include capital costs, operational costs, and fuel costs, and cumulated investment in infrastructure and technology, including electricity and heat generation as well as transformation processes such as H_2 electrolysis (Fraunhofer IEG et al., 2025).

As illustrated in the figure below, the project considered four scenarios across two dimensions: a cross-sectoral versus a sectoral silo approach, and a European optimisation versus greater national self-sufficiency approach. By combining the different aspects of these dimensions into four scenarios, the modelling can consider the impacts of each dimension on system optimisation and costs. The assumptions for energy demand have been set to follow conservative trajectories – that is to say demand projections are compared to other modelling activities and fall within the middle and upper demand ranges to allow solid conclusions to be drawn about infrastructure needs. The model identifies solutions for electricity, hydrogen, gas and CO_2 transmission level infrastructure within the scenario optimisations.

Illustration of the modelling approach for the co-optimisation of energy and infrastructure systems

→ Fig. 1



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The first dimension is designed to allow an analysis of whether co-optimising across energy sectors arrives at different outcomes for infrastructure needs. This aspect is incorporated into the scenarios either by constraining the infrastructure planned on the basis of existing infrastructure planning processes (sectoral optimisation) or by allowing the model to freely optimise the system across sectors (cross-sectoral optimisation). To reflect this dimension, the sectoral scenarios include fixed grid capacities up to 2040, with expansion allowed for TYNDP projects that are at the planning or more advanced stages and hydrogen network expansion designed to mimic the proposed European hydrogen backbone.[5] From 2040, which marks the end point of the TYNDP planning processes, endogenous expansion is allowed. For the cross-sectoral scenarios, endogenous optimisation is allowed for all years, with only advanced TYNDP projects for electricity and fossil gas under construction included as lower boundaries.[6]

The second dimension considers the impacts of planning based on a predominantly national perspective oriented towards self-sufficiency as compared to an approach in which the energy supply would be optimised Europe-wide. In the nationally focused scenarios, the model introduces partial self-sufficiency constraints that require a minimum share of domestic generation to meet average annual demand in each country – 80 percent for electricity and 70 percent for hydrogen in 2030; 100 percent for electricity and still 70 percent for hydrogen by 2050.[7] These calculations are made by defining a minimum share of domestic generation relative to gross consumption on an annual basis; the constraint is therefore eased by the fact that a country can still take advantage of imports and exports within a year as long as the annual calculation meets the constraint. The model does not impose self-sufficiency constraints on the cross-European scenarios and can therefore freely optimise the imported versus domestically generated electricity and hydrogen.

5 The European Hydrogen Backbone (EHB) initiative, *European Hydrogen Backbone*, available online at: https://ehb.eu/.
6 In the cross-sectoral scenarios, there is no exogenous lower boundary for H_2 infrastructure, while the model fully optimises the hydrogen transmission grid buildout.

7 As such, "national" scenarios represent self-sufficiency – or net imports – considered on an annual basis. Countries still engage in hourly trading of electricity across borders to optimise costs and ensure system stability in the national scenarios.

How current infrastructure planning differs from top-down modelling

Current modelling and planning processes do not entail any independent, high-level vision for a net-zero EU energy system. The Ten-Year Network Development Plan (TYNDP) process – which was put in place to identify priority European cross-border projects – brings information together across European countries but is not designed to provide an independent co-optimisation of the energy system that would inform the coordinated infrastructure planning to meet European policy goals. The TYNDP process is organised around joint scenarios, but because it is not designed to present a co-optimised view of the energy system, it cannot for various reasons identify system efficiencies in a manner similar to the top-down, independent and integrated modelling described above (Fraunhofer IEG et al., 2025).

First, the TYNDP process is designed to reflect Member State planning processes by basing scenarios on Member States' National Energy and Climate Plans (NECPs). The process includes Member States' perspectives regarding infrastructure investments but thereby constrains the freedom necessary for European optimization. Furthermore, although the approach seeks to attain alignment with NECPs, it lacks any cohesive and consistent set of data to underpin this process because the NECPs are developed on different timelines (every five years compared to the two-year TYNDP cycle) and because the data needed for the TYNDP scenarios and modelling is not always available in the NECPs. Instead, the Transmission System Operators (TSOs) – which take a national view of the energy system and may have a vested interest in the outcome of the planning exercise – translate the NECPs into data to inform the TYNDP process and fill gaps where data is not available. In the absence of a standard method for turning NECP policies into analytical data for use in the TYNDP process, and without requirements that all data be made uniformly available in the NECPs, inputs to the TYNDP can vary widely across Member States (Artelys, 2025; ACER, 2025a).

Second, the TYNDP process currently lacks a systematic mechanism to verify and cross-validate the data supplied by the TSOs against independent analyses or evolving policy developments. The Stakeholder Reference Group (SRG) provides an opportunity for expert stakeholders to review some of the methodology and data being used; given that it is often conducted under time constraints and relies on voluntary input, however, it is not sufficient to make up for the structural lack of a more consistent data review.[1]

Third, although data and assumptions about the electricity and gas sectors sit together in a 'joint scenario,' electricity and gas TSOs provide data for many inputs into the TYNDP process separately and the data is not necessarily checked for cross-sector consistency. For example, although demand projections are supplied jointly by gas and electricity TSOs, there is a lack of transparency about these inputs, especially as TSOs often do not rely on data within the NECPs for these numbers (Artelys, 2025; ACER, 2025a). Without any high-level consistency check, the joint scenarios effectively compile sector-specific data and assumptions rather than reflect fully integrated assumptions. Furthermore, because modelling and cost-benefit analyses are performed independently by ENTSO-E and ENTSOG, the resulting analysis does not necessarily capture cross-sector co-optimisation. To address this deficiency, the TEN-E regulation requires the ENTSOs to develop a "consistent and progressively integrated model that will provide consistency between single sector methodologies based on common assumptions."[2] Although the regulation calls for an "integrated model", the ENTSOs' latest Interlinked Modelling Report discusses an "integrated modelling framework" and explains that it is a strategic process to "harmonise and progressively integrate electricity, hydrogen, and gas datasets, assumptions, methodologies, and computational workflows" within the existing TYNDP processes (ENTSO-E, ENTSOG 2025). It therefore seems unlikely that a model will be developed that will optimise across sectors or provide a high-level overview of the interactions across Europe and energy sectors from a top-down perspective.

In short, there is a lack of complementary top-down optimisation of the European energy system to ameliorate the constraints of the TYNDP and to serve as guidance for national planning processes. Among others, the European Union Agency for the Cooperation of European Regulators (ACER) and the Council of European Energy Regulators (CEER) have therefore called for single-sector planning to be discontinued in favour of a European, multi-sectoral plan (ACER, CEER, 2024). The work in this project illustrates how such an approach can work and the benefits that can be realised by adding top-down, independent, integrated and transparent modelling to infrastructure planning governance.

1 Information about and inputs from the Scenarios Stakeholder Reference Group are available at: https://www.entsos-tyndp-scenarios.eu/stakeholder-reference-group/
2 REGULATION (EU) 2022/869 (TEN-E Regulation) (May 30, 2022); see also REGULATON (EU) 2024/1789 (amending the deadline for the model to 31 October 2025).

2.2 How an integrated approach can shed light on new solutions

In contrast to modelling and planning that consider geographies or sectors side-by-side, the modelling exemplified by this project co-optimises across these dimensions for energy supply, storage and transmission investment. The model can therefore consider the interactions across these dimensions, finding solutions that might otherwise be overlooked.

The modelling in this project reveals, for example, ways to reduce system costs in a pan-European and cross-sectoral scenario. Overall energy supply and sector-coupling capacity can be reduced in several areas: based on the model, it is estimated that 505 GW less back-up capacity, 15 percent less onshore wind capacity and 9 percent less hydrogen electrolyser capacity will be required in the integrated scenario than in a more nationally-focused and sectoral approach (Fraunhofer IEG et al., 2025). It is, however, important to note that all of the scenarios in the modelling show an acceleration of renewable energy buildout to achieve climate neutrality. In addition, the modelling demonstrates that infrastructure requirements could be decreased, with substantially reduced need for hydrogen and carbon dioxide infrastructure, and utilization rates increased for the infrastructure that is projected. Planning in sectoral silos or from a national perspective does not reveal these savings and therefore does not allow them to be realised. As discussed above, the scenarios in this project do not offer an exact solution for a 2050 energy system. They do, however, demonstrate that looking at the energy system from a more integrated perspective enables the discovery of efficiencies, synergies and solutions that simply do not show up in more fragmented approaches.

In addition, with such an open, high-level model in place, further questions can be explored both to guide infrastructure planning and to inform discussions about different pathways to achieve policy objectives. Some examples of questions for which the model could provide insight include:

- → how generation and transmission requirements change when considered from a European perspective versus an approach in which Member States meet self-sufficiency targets, taking into account for instance the best locations for renewables and electrolytic hydrogen production versus the cost of transporting that energy;
- → how hydrogen infrastructure is built when considered across sectors as compared to a scenario where gas and hydrogen are planned independently from the electricity sector;
- → under what conditions the model opts for production of synthetic fuels with carbon dioxide rather than transporting that carbon dioxide for storage;
- → how different supply options might change optimal choices for hydrogen and its derivatives;
- → where the model identifies optimal 'coupling points', i.e. where the gas and electricity system most effectively meet to produce hydrogen by electrolysis, for example.

The outcomes of this model, like all models, depend upon the assumptions that go into it. Those assumptions can be modified and may move in one direction or the other. This project uses the open-source PyPSA-Eur model, which benefits from previous analyses that underpin the assumptions of the PyPSA-Eur database. In addition, the model and dataset are publicly available, thus ensuring that the assumptions can be subjected to constructive and critical analysis – PyPSA-Eur for example has already been 'battle-tested' in various settings (Brown, T. 2022; Pfenninger, S., et al (2018).[8] Moreover, those wishing to build upon the model can do so to test outcomes based on different assumptions.

The strict scrutiny of the assumptions upon which the four scenarios in this project are based has allowed for robust findings about infrastructure needs. At the same time, these scenarios can be modified and thus serve as a point of reference that can be considered alongside other modelling results – from other modelling approaches or from the scenarios

8 See also, Open Energy Transition, *Tools*, https://openenergytransition.org/tools.html.

used in this project. One key finding of this work is that integrated models such as the one used here – which can provide opportunities for many additional model runs based on different assumptions and sensitivity analyses – are critical in order to determine where outcomes overlap, and thus where solutions that will remain viable under various conditions. We discuss a role for this type of modelling in our recommendations below.

3 Energy infrastructure governance that reflects energy policy

To efficiently build the infrastructure required to support a secure, competitive and climate-neutral Europe, changes to Europe's energy and infrastructure system planning are needed. As noted above, current planning processes do not define or follow a shared vision for Europe's energy system and therefore leave a gap in the realization of effective system planning. Recent recommendations from ACER to amend these existing processes, including the addition of a scenario methodology and review of scenario inputs (ACER, 2025a), would improve the current situation. However, such changes would not address the inherent structural deficiency, namely the lack of any means to visualise the kind of integrated energy system needed to meet Europe's long-term policy goals. That deficiency can be addressed by carrying out top-down system modelling that can provide a tool to enable policymakers, Member States, system operators and regulators to align their efforts to build the energy system required.

High-level co-optimisation of the infrastructure and energy system can serve three purposes: first, it can provide a visualisation of a co-optimised system capable of guiding bottom-up planning processes; second, it can inform policy by providing a check regarding the feasibility or consequences of various policy goals; and third, the outcomes of the modelling can inform energy planning governance by revealing priority needs or areas where decreased demand may necessitate decommissioning rather than development. The modelling exercise conducted in this project illustrates the benefit of including high-level modelling in infrastructure planning governance. First, the modelling provides a vision of a potential pan-European, cross-sector, net-zero energy system that can show the direction of travel for bottom-up planning processes. Second, the exercise tests whether current policies are in line with a co-optimised scenario: the model demonstrates a consistent need for electricity infrastructure buildout across Europe, while revealing that current plans for hydrogen infrastructure are around two and a half times greater than a co-optimised solution - with fossil gas, hydrogen and carbon dioxide transport needed in clusters to serve specific demands, rather than a widespread backbone. Third, these outcomes show that rather than requirements for sector-integrated planning at all levels, governance for infrastructure planning should reflect the changing importance of the electricity and gas sectors (Fraunhofer IEG et al., 2025).

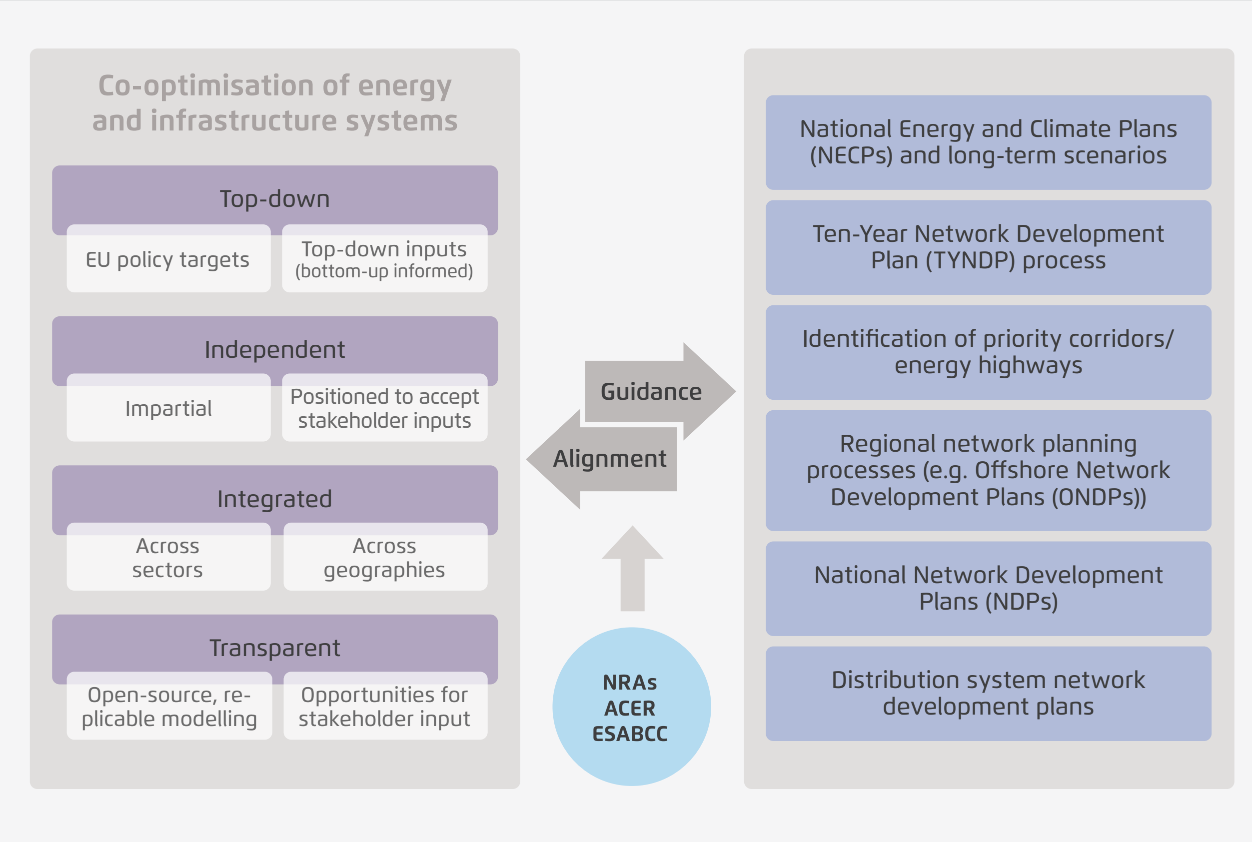
A more transparent approach to energy system modelling could also provide greater insights into the costs and benefits of investments in cross-border projects and thereby inform discussions about cost allocation. This information could in turn provide Member States with a high-level perspective about the relative importance of cross-border projects to facilitate market integration.

Our proposal for adding high-level infrastructure and energy system co-optimisation to guide bottom-up planning processes is discussed in more detail below and illustrated in Figure 2.

1. Top-down, integrated, independent and transparent energy system modelling is needed to provide guidance for infrastructure planning.

To build an energy system that is in line with policy goals – including prioritization of energy efficiency and electrification – guidance is needed to steer the construction of the energy infrastructure that is the physical backbone for that system. Not only does such guidance not yet exist, the means to develop it is also missing. Our first recommendation is therefore to conduct high-level, integrated, independent and transparent co-optimisation energy system

Including system-wide modelling in infrastructure planning → Fig. 2



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modelling in order to obtain a vision of the energy system that can inform bottom-up infrastructure planning. This recommendation can be broken down into several component parts, each of which will help to ensure that the top-down modelling is effective.

1a. Top-down modelling adds perspective about the system as a whole.

Critical bottom-up energy system modelling is already being carried out in numerous forums: in distribution level planning, national grid development plans, regional planning efforts and the TYNDPs. These processes are guided by data and assumptions based on particular knowledge of a system or area and can enable a granular analysis of the energy system critical for making specific infrastructure decisions in a timely manner. By contrast, a top-down modelling approach can add the big-picture perspective, informed by inputs that have been tested against high-level market and policy direction: analysis of projected system-wide demand and supply inputs (such as demand for and availability of green hydrogen), industry trends (such as decisions about the location or extent of future industry demand) and solution prioritisation (such as prioritising electrification).

Modelling based on these top-down inputs can reveal solutions across or between parts of the whole system, thereby adding a range of perspectives and solutions. These counterpoints to bottom-up analysis can offer insights and evidence for changes to enable system efficiencies, delivering input to policymakers about how a decision in one direction or the other might facilitate or hinder the desired policy outcomes.

1b. Integrated modelling can provide solutions across the energy system.

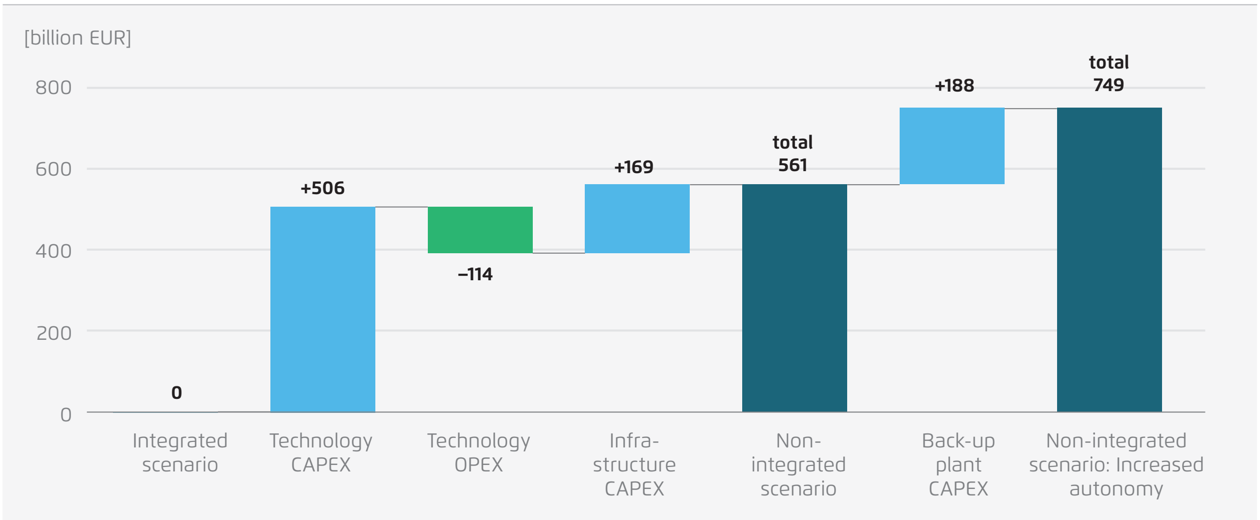
As explained above, the term 'integrated' can refer to various types and degrees of modelling and planning. With this recommendation, we mean that a high-level energy system visualisation will be most useful if it is supported by modelling that can determine the best way to meet a given energy demand by co-optimising solutions across Europe and across energy carriers (electricity, fossil gas, hydrogen and derivatives, CO_2), storage and demand-side flexibility.

The efficiencies that can be identified by utilising a top-down, integrated view of the system are illustrated by the modelling done in our project: taking a high-integration approach that co-optimises infrastructure buildout across Europe and across sectors reduces total system costs – compared to a low-integration approach – by up to **561 billion euros between 2030 and 2050,** or by up to **750 billion euros** if the savings from avoided back-up generation are considered (Fraunhofer IEG et al., 2025).[9]

The benefits of a high-level, integrated perspective are not limited to monetary savings. Modelling the system across geographies and sectors allows policymakers, regulators and system planners to see different paths for the energy system and determine their relative costs and benefits. For example, European priority corridors may be identified based on an overlap across iterative model runs that test various scenarios or sensitivities. More granular prioritization could come from including one priority corridor or project over another in order to test impacts to the system. Areas of commonality can serve as the basis for a European energy infrastructure system visualization to guide bottom-up planning exercises.

9 Higher European and cross-sectoral integration reduces technology capital expenditure (CAPEX), i.e. the investments needed in power generation, storage and other flexibility options, and infrastructure CAPEX, i.e. the investments required in transport level infrastructure. Moreover, an increased focus on autonomy of national energy policy making would further increase costs of less integrated approaches as a result of the additional investment costs for domestic back-up plants, as shown in Figure 3.

Overall findings in system cost differences between the low-integration and high-integration scenarios for Europe, 2030–2050 → Fig. 3



Agora Energiewende (2025) based on Fraunhofer IEG, Fraunhofer ISI and d-fine (2025)

While integrated, co-optimised modelling is crucial when it comes to developing guidance for the energy infrastructure system, this recommendation is not intended to imply that integrated modelling and planning is necessary or even useful at all stages of planning. On the contrary, the modelling is designed to show a possible direction of travel for the energy system and its overarching infrastructural needs, which can provide guidance and coordination of sectoral and more geographically discrete planning processes. For example, the modelling in this project demonstrates that current – and not sufficiently integrated – planning processes are greatly over-estimating the need for a hydrogen transport network. Even based on hydrogen demand assumptions similar to those in the Commission 2040 Impact Assessment, the integrated modelling in this project[10] shows that current plans would result in a hydrogen network capacity that is more than 2.5 times higher than in an integrated, endogenously co-optimised scenario (see right section of Figure 4) (Fraunhofer IEG et al., 2025). At the same time, the project modelling indicates a robust need for investments in electricity infrastructure across all scenarios (see left section of Figure 4). This high-level finding can guide bottom-up processes to ensure that hydrogen infrastructure investments are focused on specific needs and are not overemphasised relative to electricity. At the same time, given the robust finding of a need to invest in electricity infrastructure, planning should focus on efficiently expanding the necessary electricity infrastructure taking into account sector coupling needs.

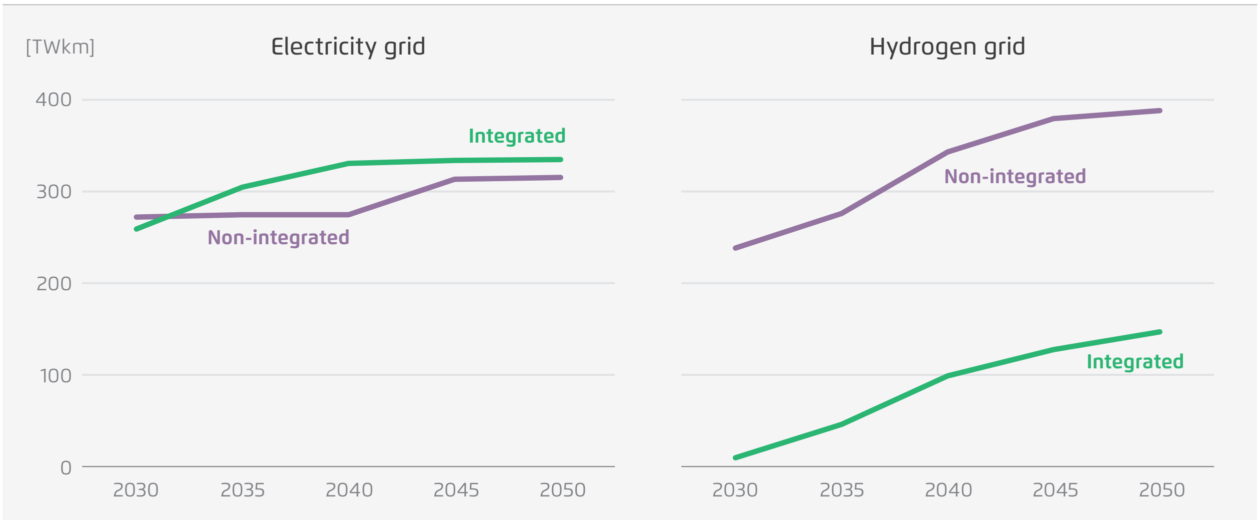
10 The EU-wide demand for pure hydrogen molecules in the scenarios is set between 1900 and 2600 TWh in 2050.

1c. Having an independent entity conduct the top-down modelling can ensure non-biased outcomes.

System modelling and planning has typically been carried out by system operators, with significant deference given to those entities based on their deep understanding of their systems. The deference, however, has also led to scepticism of the process as system operators can have a vested interest in continued investment into the system – an issue particularly problematic when, for example, it is in the interests of consumers for gas grids to be decommissioned rather than further expanded (Öko, RAP, 2024).

Trans-European transmission infrastructure for electricity and hydrogen in integrated and non-integrated scenarios

→ Fig. 4



Agora Energiewende (2025) based on Fraunhofer IEG, Fraunhofer ISI and d-fine (2025)

By contrast, top-down, integrated and independent system modelling requires an entity that possesses different attributes. The entity needs to be independent from vested interests to ensure that modelling outcomes are trusted. It must be in a position to design opportunities for stakeholders to meaningfully review, test and challenge modelling assumptions to ensure that the model is informed by the best available data, and to provide a basis for trust in the objectivity of the process. Specifically, the modelling entity must make its work open and available to stakeholders, allow sufficient time before decisions are taken for stakeholders to supply informed and considered inputs, as well as enough time for the modelling entity to address or incorporate those inputs, and must explain its reasoning for taking a different approach. The entity must have the capacity and expertise to conduct such modelling, or the ability to engage and work with consultants to work through the modelling exercises.

Several entities exist that could take on the task of top-down, integrated and independent system modelling:

→ The European Commission itself would be well positioned either to engage its own experts to conduct this modelling or to engage and lead consultants to perform the modelling. The Commission has the expertise to act in either capacity as well as the political weight to stand behind the modelling outputs.[11] Further, the Commission is accustomed to accepting public input and could therefore easily develop processes to invite stakeholder input about assumptions and methodology to inform the modelling activities. Finally, the Commission would be able to easily share findings with policymakers and the public.
→ The Joint Research Centre (JRC) of the European Commission[12] is in a similarly good position to lead such a modelling exercise. Already the JRC is tasked with conducting independent, scientific research and could utilise and build upon its existing expertise to conduct this modelling. The JRC's mandate as an independent entity could complement the European Commission's policymaking role.
→ The European Union Agency for the Cooperation of Energy Regulators (ACER), another entity with significant expertise in infrastructure modelling and planning, could also host the modelling work. However, one downside to having ACER act in this capacity is that it then – being the representative agency for energy regulators – would not be able to supervise the process as an external observer, a key role for reviewing and guiding the TYNDP process, in particular by developing framework guidelines for the joint scenarios.
→ Giving the growing importance of the electric power system, another option would be to create an independent arm of the ENTSO-E – given the increasing importance of the electric power system – which has traditionally been in the role of system planner. This approach would require safeguards, such as restrictions on communication with constituent TSOs, to ensure sufficient independence and to build in sufficient perspective from its current role.
→ Alternatively, a newly-formed independent energy agency would be well placed to conduct this modelling, and has been recommended by various entities (Letta, E., 2024). An independent entity of this kind could take various forms. One option would be a European entity that performs the modelling outlined above, provides coordination between European, regional, Member State and local planning processes and serves as a clearinghouse for data and information to ensure shared starting points and understanding of modelling and planning processes. As setting up such an entity would require some time and resources before it could become operational, this option may be best in combination with a shorter-term option to accelerate the implementation of modelling for a top-down systems vision.

11 Although the Commission's political legitimacy would allow it to back the modelling outputs, there are arguments that this modelling should be done by a more politically independent entity.
12 Joint Research Centre, https://commission.europa.eu/about/departments-and-executive-agencies/joint-research-centre_en

→ Another approach – already implemented in the United Kingdom in the form of the National Energy System Operator (NESO),[13] and recommended by several civil society organisations (e.g. E3G, 2025; RAP, BFF, 2025), would be the development of Independent System Operator and Planners (ISOPs) at the national level. Stemming from this approach is the idea of a European Independent System Operator (EU ISO), which would be responsible for central planning and operation of and supply for the electricity network, with ownership of the grids and backup operation retained at the national level (Bruegel, 2025). Incorporating such a high-level approach to planning and operation – which would be a significant addition to the co-optimised modelling recommended above – would need to be balanced with the important role and understanding of national system operators in managing their systems.

Regardless of which entity is chosen to lead the modelling process, it should develop and publish terms of reference that outline its modelling methodology, its interactions with other entities, how it will maintain its independence and opportunities for stakeholder input to ensure transparency in the process. These terms of reference should be subject to review by the European Commission, the European Scientific Advisory Board on Climate Change (ESABCC) and stakeholders, including stakeholder groups such as the TYNDP Scenario Reference Group (SRG), and to approval by ACER.[14]

1d. Using open-source modelling can augment transparency and provide opportunities for further analysis.

Related, but in addition to independence, deriving a European energy system and infrastructure would be strengthened by open-source modelling that allows for a greater degree of transparency about the model design, how it is allowed to optimize, and the assumptions underpinning the analysis. Such models not only enhance transparency in the work of energy system planners, but also enable others to use the model to reproduce scenario runs, test additional or varying scenarios, sensitivities or assumptions, and collaborate around work being done.[15] The open-source modelling platform thus facilitates discussion around inputs, assumptions, and consequences of changes to different parameters, allowing for iterative analysis of scenarios and sensitivities. Although there have been concerns that open-source models could be exposed to external influence, their broad usage has demonstrated that any manipulation of data or assumptions can be identified and understood (Brown, T. 2022).

High-level modelling to inform an energy infrastructure visualisation would achieve the greatest transparency if it were based on open-source tools. Ongoing iteration would allow the modelling entity to continually refine the system vision to provide guidance even in the face of high uncertainty and rapidly changing circumstances. In this way, the modelling would serve as a means to test ideas and inform the more detailed planning processes that are led by national and regional entities, Member States and their ministries or by system operators.

2. Infrastructure planning needs to reflect the direction of the energy system: an increased focus on electricity infrastructure is needed to support Europe's future energy system; a cluster-based infrastructure approach should be developed for molecules (methane, hydrogen and CO_2).

Current policy, including the EU Energy System Integration Strategy, Fit for 55 package and Action Plan for Affordable Energy, as well as high-level modelling place efficiency and electrification at the core

13 National Energy System Operator (NESO), see https://www.neso.energy/about-neso
14 The list of reviewers would change if one of those entities were chosen to lead or perform the modelling.
15 In addition, and in contrast to open-source models that are essentially available for free, proprietary software can also involve prohibitive costs for those who may wish to engage in further analysis.

of a decarbonised energy system. The modelling in this project supports this prioritisation with investments in the electricity system showing up consistently across scenarios, whereas molecules will play a declining role, largely needed in clusters to serve specific demands.

Despite the expanding importance of the electricity system to support increases in electrification, and attendant decline in the need for ubiquitous gas infrastructure, energy system planning continues to treat these sectors as equal players. The TYNDP process, for example, includes ENTSO-E, ENTSOG, and the newly-created European Network of Network Operators for Hydrogen (ENNOH). We recommend ensuring that planning exercises reflect the relative roles of the solutions that they represent.

Practically speaking, this recommendation could be implemented by facilitating approval and permitting for projects that are aligned with top-down system modelling. Projects consistent with the top-down guidance could receive priority and benefit from a streamlined regulatory review process, similar to the current treatment of Projects of Common Interest and Projects of Mutual Interest (PCI/PMI).[16] At the same time, molecule-based planning could be reoriented towards cluster-based needs, and away from investments that would perpetuate a widespread network of pipelines. Incentives could be provided for infrastructure serving certain priority areas, whereas investments to maintain or augment more extensive networks would face a higher level of scrutiny.

These shifts would require an expanded role for National Regulatory Authorities (NRAs). Currently, NRAs generally have the ability to approve or request amendments to electricity National Development Plans (NDPs), but NRAs are only empowered to do so for gas NDPs in eleven Member States (ACER, 2025b; ACER, 2024a). With top-down modelling in place, it would become even more important for the NRAs' role to include review and approval of sector-specific plans for consistency with the high-level energy system modelling. In the absence of such consistency, NRAs should then be able to require system operators to justify any deviations. The heightened transparency of the high-level modelling – a requirement which could also be imposed on bottom-up processes – would be a critical precondition for NRAs to be able to play a more active role in energy system planning.

3. **Using the energy system modelling to identify priority corridors for infrastructure investments, especially for the electricity grid, could increase the benefits of participating in European energy markets. Identifying these benefits could incentivise greater coordination between regions and Member States to accelerate build-out of the energy system needed to realize those benefits.**

A top-down modelling process would facilitate identification of areas in need of additional investment, including infrastructure projects required to enable greater participation in European energy markets and maximise shared European benefits. With a more transparent, open, and iterative process in place, Member States would have improved access to information about costs and benefits and timing of needed projects. This information may empower Member States to consider increased coordination within regions or across the European Union as a whole. At the same time, top-down modelling could also inform regional planning efforts,[17] including priority projects within regional groups pursuant to the TEN-E regulation, and the High-Level infrastructure

16 European Commission, Projects of Common Interest and Projects of Mutual Interest, https://energy.ec.europa.eu/topics/infrastructure/projects-common-interest-and-projects-mutual-interest_en

17 The European Council has already called for coordinated planning noting the importance of regional planning. Council of the EU, Sustainable electricity grids: Council approves conclusions (May 30, 2024), available at: https://www.consilium.europa.eu/en/press/press-releases/2024/05/30/sustainable-electricity-grids-council-approves-conclusions/; see also, Pentalateral Energy Forum, Statement by Ministers of the Pentalateral Energy Forum on a joint vision for a decarbonized electricity system (Dec. 18, 2023), available at: https://www.benelux.int/wp-content/uploads/2023/12/Statement-by-Penta-Ministers-on-a-joint-vision-for-a-decarbonized-electricity-system-short.pdf

groups.[18] This modelling would also help to inform stakeholder input into discussion around PCI projects within those groups – in line with a recommendation to focus stakeholder input into PCIs within the regional groups (Sikow-Magny, C., 2025).

Ultimately, however, greater coordination across Member States will require cost-benefit sharing mechanisms that provide equitable outcomes. As noted above, an integrated approach to planning can identify system efficiencies, resulting from both European integration and cross-sector integration, that bring about overall system savings. It also demonstrates – at a high level – that savings are not shared equally by all Member States, and indeed some Member States may see greater costs than benefits. For a European approach to work, all Member States must come out ahead. Cost-allocation mechanisms will therefore need to be designed and implemented to ensure that the savings are shared. ACER has noted that the three existing mechanisms that enable cost sharing – cross-border cost allocation (CBCA), inter-TSO compensation (ITC) and congestion income distribution (CID) – are fragmented and do not ensure an equitable allocation of infrastructure costs and benefits arising from cost-border trade (ACER, 2025a; ACER 2024b). Innovative methods such as grouping projects for cost-benefit sharing should be explored to enhance regional coordination and efficiency. In addition, the proposal in sources including the Draghi report to leverage a considerably larger Connecting Europe Facility (CEF), and the tailored financial instruments from the EIB recommended in a recent paper by the European University Institute, could help manage the high costs and risks of complex cross-border projects, supporting affordability, cost effectiveness and timely implementation (Draghi, M., 2024; Sikow-Magny, C., 2025). In sum, integrated modelling can provide additional information about system priorities, but an approach to cost allocation that reflects Member State concerns, alongside increased EU-level financial support, will need to be defined to overcome delays and deadlocks (FSR, 2020).

Europe's energy system can enable a secure, competitive and climate-neutral Europe, but only if it is designed to do so. To arrive at the energy system required, and the infrastructure necessary to create it, a shared vision is needed to guide its development. Significant investments are needed to adapt our infrastructure to changing supply and demand. System operators are already having to make these investments. Co-optimisation of the infrastructure and energy system is needed to ensure that investments are aligned with the energy system required to support European goals of climate neutrality, security and competitiveness.

18 These groups include the North Seas Energy Cooperation, the Baltic Energy Interconnection Plan, the Interconnections for South-West Europe, and Central and South-Eastern Europe Energy Connectivity. https://energy.ec.europa.eu/topics/infrastructure/high-level-groups_en

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Agora Energiewende develops scientifically sound and politically feasible strategies for a successful pathway to climate neutrality – in Germany, Europe and internationally. The organisation which is part of the Agora Think Tanks works independently of economic and partisan interests. Its only commitment is to climate action.

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