EERA
European Energy Research Alliance

Vision paper

Towards a more collaborative energy system modelling

for addressing Europe's energy transition challenges

About EERA
The European Energy Research Alliance (EERA) is the association of European public research centres and universities active in low-carbon energy research. EERA pursues the mission of catalysing European energy research for a climate-neutral society by 2050. Bringing together more than 250 organisations from 30 countries, EERA is Europe's largest energy research community. EERA coordinates its research activities through 18 Joint Programmes and is a key player in the European Union's Strategic Energy Technology (SET) Plan.

ISBN: 978-2-931174-05-0

Citation: Vingerhoets et al., 2023, EERA vision paper - Towards a more collaborative energy system modelling for addressing Europe's energy transition challenges.

Available for download: www.eera-set.eu

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Date: December 2023

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Executive summary

This paper was written by the EERA Center of Excellence on Energy Transition Models, an organisation of research teams across Europe which not only develop energy system models, but also perform studies for industries, utilities and policymakers. The paper addresses how energy system models can play a larger role in the energy transition, de-risking investments for industries and utilities and supporting European and national policymakers. The main takeaways for the reader are the following:

The modelling toolbox which is currently used for determining European energy policy should be expanded

To assess the impact of the current set of national and EU policies, energy system models are used to explore possible outcomes of the energy system on short-, medium- and long-term [1]. The outcome of this modelling provides the basis for the climate targets and other ambitions in the REPowerEU plan, the Net Zero Industry Act etc. [2]. The modelling, performed by the PRIMES – GAINS – GLOBIOM – POLES modelling toolset [1], optimises the energy system under a certain set of policies (climate targets etc.). It features a link with land use models; links with industrial, buildings sector and transport sector are built in the modelling. National policies are represented in a high-level way through discussion with member states. All relevant types of energy vectors and EU member states are covered.

To support a complex societal transition such as the energy transition, the EERA system modelling community believes the current toolbox needs to be significantly expanded:

- A wider variety of policy and energy system scenarios should be investigated. Typically, only one or a few policy scenarios are modelled in support of policies. For instance, there is one main scenario behind the REPowerEU plan [2], in the context of the Renewable Energy Directive update, additional sensitivities are modelled [3]. Large amounts of hydrogen are modelled in sectors such as mobility and industrial heating. Potentially more cost-effective solutions involving higher electrification, and/or varying a larger scope of uncertain parameters, should be explored.
- The link with security of electricity supply models and energy infrastructure scenarios should be expanded. Currently, the scenarios and process where ENTSO-E and ENTSO-G build their scenarios is independent from the ambitions formulated in REPowerEU [4]. The latest energy infrastructure plans published by ENTSO-E are not sufficient to reach the renewable ambitions in REPowerEU [5]. Aligning the modelling of the transmission system operators with the REPowerEU policy modelling will allow investigating the dimensioning of energy infrastructure challenges.
- Potential supply chain issues regarding critical materials, critical equipment, permitting times, refining capacity or manufacturing capacity should be integrated into the modelling scenarios. Some illustrations of this are given in the text:
    - Wind Europe already discussed potential problems for reaching the Fit-for-55 targets regarding manufacturing capacity, workforce and long permitting times. Recently, a report was published involving serious barriers for wind energy to reach the ambitions of REPowerEU [6]. The Inflation Reduction Act in USA presents competition for certain aspects of the supply chain for installing wind turbines.

- Permitting times are assumed to be drastically reduced. While this may be the ambition of the European Commission, in practice projects may still face delay due to permitting uncertainties. The impact of permitting delays should be reflected in model scenarios.
- Geopolitical aspects of the energy transition should be adequately addressed. For these parameters, political – societal discussions are needed as input to simulations. For instance, the dependency of future pipelines/electricity grid connection with North Africa, or the dependency of critical raw materials – including their supply chains – need to be weighed against system cost efficiency.
- Some parts of the supply chain may be in danger of relocating to other parts of the world with higher production of renewables. For instance, ammonia production, steel production, other base chemicals are subject to strong international competition and are at risk of re-locating to regions with higher renewable potentials or more favorable investment regulation. While the European Carbon Border Adjustment Mechanism (CBAM) may address the emission component, for some processes a structural energy cost handicap exists. The Net-Zero Industry Act does not yet cover these issues for all industries. As an example, the ambition is formulated to anchor the production of wind turbines in Europe, but the steel to build these wind turbines needs to be secured as well.

- The social impact of the energy transition can be further detailed using collabouration between European level and national level models. A high-level discussion with member states and implementation of (the impact of) a selection of national policies is incorporated in the EU model. However, the impact on different consumer groups in different member states, the functioning of the market and the financing of the plan is not worked out in full detail. Also national energy and climate plans (NECP) often read as a set of ambitions, and lack a well-modelled section on financing of the plan and social impact [7].

From a much wider perspective, there is limited knowledge in the wider decision analysis community on how to co-design system modelling, uncertainty treatment and use in decision support for these very complex decision environments. Typically, there is a trade-off between model complexity, and the ability to perform uncertainty treatment associated with the model – thus adding greater model detail can degrade the ability to deduce what the model is able to say about the real-world system of interest.

More extensive energy system modelling results could reduce investment uncertainty

As we discuss in the first chapter of this document, a lot of different scenario outcomes are needed, capturing uncertainties in the evolution of the energy system. For industries, a lack of credible long-term scenarios translates in uncertainties for the future cost of electricity, hydrogen, and other energy carriers. The lack of social impact detail presents a challenge for national policy makers to support the energy transition. The uncertainty on the industrial demand investments translates into uncertainties regarding energy infrastructure needs, and vice versa. Scenarios with a decrease in industrial activity in Europe are currently not modelled. In general, more energy system scenarios exploring possible outcomes of the energy transition, can to a certain extent reduce this investment uncertainty.

Efforts are needed to complement the modelling behind the European energy policies with insights of other models

As we show extensively in Chapter 2 of this paper, a wide variety of energy system models exist, each with their own functionalities.

There are a variety of techno-economic investment models,on which can add more European scenarios other than the few existing, outlining more possible pathways for the energy transition and reducing investment uncertainty. In addition, such scenarios can shed light on other possible policy choices and their impact on the energy system. More specialised models on security of supply, policy projections and market models can incorporate details that are currently unavailable at the EU level. For instance, the EU scenarios could be assessed in terms of energy security and electricity market efficiency. In addition, the EU scenarios can be translated into national studies where details on security of supply, national energy infrastructure plans, local social impact can be added and linked with the EU scenarios.

Energy modelling communities of practice should be set up to have modellers discuss optimal outcomes with other stakeholders

Energy system model outcomes should not be focused on one or two optimal results, more attention needs to be paid to uncertainty in modelling outcomes. There should be a broad community where modellers discuss the results with policymakers, industries and other stakeholders. These communities of practice should:

- Train the non-modelling experts to interpret the modelling results,
- Explore the assumptions and the boundary conditions of the energy system models. For instance, below the cost-optimal Scenario X can be a slightly less cost-efficient Scenario Y which is more easily acceptable from a societal or political point of view. These discussions should deliver input to the energy system model scenarios.
- Involve pragmatic discussions on how to translate the model results into practice, i.e. into impact on investment decisions by industries or to relevance for policy makers.

To a certain extent, the European Climate and Energy Modelling Forum[1] is taking up part of these objectives in their core mission. However, the scope of this initiative should be expanded, and its relevance for policy makers should be increased, the conclusions directly feeding into the decision process.

The need for open-source models to mobilize the experience of the energy system modelling community

The energy system modelling community recommends making the source code of core models for policy recommendations open-source, and publishing all assumptions, data results of the model in full detail. This recommendation extends primarily to the energy system models, the open-source availability of solvers is considered to be less critical.

Firstly, open-source modelling communities will benefit the development of the model, and it will have a positive impact on the training of young researchers in energy system modelling. In addition, this would enable to translate the EU scenarios to national level, or adding the impact of national investment decisions in a dynamic way to the EU scenarios.

[1] https://www.ecemf.eu/about/

In general, it is recommended that all EU modelling exercises using public EU funding should be performed with open-source models or with a clear trajectory to be open-source available after the project. A good example of these practices is the Mopo project[2], which has a growing community around its SpineOpt model thanks to the EU funding. Nevertheless, this is not always the case; for instance, a recent tender of DG Clima to model 2040 targets did not have such an open-source requirement.

More generally, while there may not be the same moral imperative for modelling in the private sector to use open-source models, many commercial tools do not provide a full model specification – there is also a pragmatic issue that without a model specification it can be difficult or impossible for a user to determine the relevance of a modelling tool to a given decision support question.

Data harmonisation

Other recommendations in this paper include further efforts of data harmonisation, and public data, which can be easily accessed and used by several modellers and modelling communities. Efforts are being made in this field, for instance the Open Energy Ontology (OEO) or the Spine Toolbox in the Mopo project are also working on this aspect.

[2] The Mopo project: https://www.tools-for-energy-system-modelling.org/

1. Introduction and overview of this paper

In this paper, we argue that the current modelling toolbox behind the REPowerEU plan and national energy and climate plans should be expanded.

In a second chapter, we illustrate how energy system research institutes can step in to provide model scenarios which feed in the European planning process, and to further develop and align different types of energy system models. We provide a non-exhaustive overview of how the research community can support the energy transition for industries, policy makers, and utilities.

For each type of modelling, we:

- Address the knowledge gaps related to the European target-setting process and to investment support for industries, policy makers and utilities.
- We present a non-exhaustive overview of the current modelling toolbox, and address how the research community can support the energy transition by further developing energy system models and energy databases.

1.1 Context

After the full-scale Russian invasion of Ukraine, the European Commission responded to the energy crisis by putting forward the REPowerEU plan [2] as an update to the Fit-for-55 package [8]. The plan, which was published in May 2022, featured even higher ambitions for the deployment of PV and wind, but most remarkably pushed for a rapid increase of green hydrogen production and demand. Up to 10 Mt of green hydrogen should be produced in Europe, and another 10 Mt (of which 4 Mt in the form of ammonia) to be imported.

Although the gas prices have sharply decreased by early 2023 [9], electricity and gas forward prices remain high in Europe. However, despite continued high gas prices renewables are struggling to respond to the investment signals. The deployment speed of wind energy should at least double to reach the targets set out in REPowerEU, nevertheless 2022 saw investments stalling due to high financing costs and permitting times.

Material supply chains of clean energy technologies such as batteries, electric vehicles and renewable energy are under pressure, with the worldwide mining industry struggling to deliver on the increased needs for metals such as lithium, nickel and rare earth materials [10] [11]. Meanwhile, the Inflation Reduction Act [12] sets out insourcing industrial activity in the United States with an aggressive set of subsidies and tax levies for industry.

As a response, the European Commission proposed the Critical Raw Materials Act [13], and the Net Zero Industry Act [14], which both have the ambition to retain critical industrial activities such as mining and refining of critical materials, and manufacturing of solar panels, wind turbines, electrolysers and batteries on the European continent. However, in terms of financing, there is no concrete mechanism yet to support the ambitions set out in these documents. The Net Zero Industry Act explicitly mentions the possibility of innovation funds to support the manufacturing ambitions for clean energy technologies, which could have negative consequences for the innovation leadership of Europe.

In terms of hydrogen, the Commission set out plans to support green hydrogen demand by setting up auctions to cover the difference between the green hydrogen production cost and the willingness-to-pay on the demand side [15]. The document mentions different financing mechanisms to attract private financing, under which the first auction will have an indicative budget of 800 M€. The communication mentions an estimate of up to 90-115 bn€ support for both local production and import of 20 Mt of hydrogen, without referring to calculations to support these figures. It is unclear how much public funding will finally be allocated to the European Hydrogen Bank.

In the coming years, an enormous number of crucial investment decisions will be taken by European industries. The result of the investment decisions in the different sectors will determine the location of energy-intensive industries, the technology rolled out, and the energy infrastructure requirements for the decades to come.

In this context, energy system modelling is critical to understanding the uncertainties and opportunities on long-term investments. However, conventional energy system models should be extended by macroeconomic considerations and social acceptance integration. Energy scenarios that provide estimations on future wholesale prices, sector specific labour demand, material specific resource demand, hydrogen or other molecule costs, renewable energy availability, security of supply, etc., are a crucial input to business case assessments of energy-intensive companies.

1.2 Short summary of the knowledge gaps in European modelling

The modelling that underlies the REPowerEU plan, and more generally the climate targets and some other key policies, is performed with the PRIMES model [1]. The PRIMES-GAINS-GLOBIOM-POLES modelling toolset features specialised models that work on land use, transport, and agriculture, and allows assessment of a number of European policies. The PRIMES model itself is not open-source available and only a selection of the data that are used in the model runs is published. The output of the PRIMES model includes a range of data per member state, aggregated results on European level are published, and some of the results per member state are available on request.

The modeling captures well the interaction between the energy system and land use changes, and provides the major techno-economic indicators per member state as an output. However, there is significant room to enhance the scope of the modelling and improve the results. An overview is given in Figure 1.

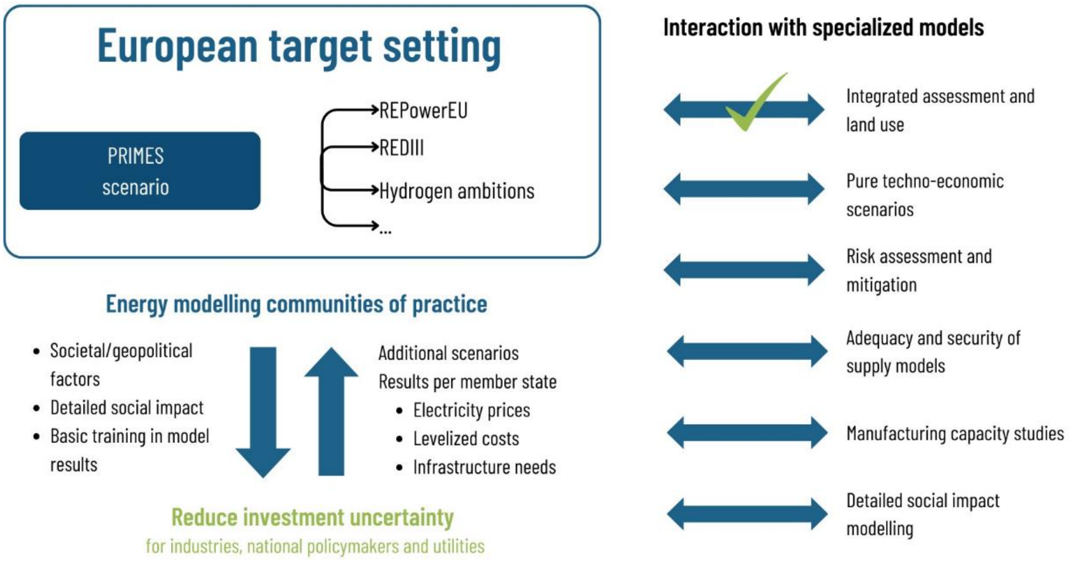

Figure 1: The European target setting process needs to expand its scope and (i) interact with more specialised models, (ii) add more specialised and detailed national data sources and (iii) better discuss the boundary conditions behind the model runs in communities between modellers and policy makers.

The modelling results of the REPowerEU plan can still be significantly improved in several ways to reduce investment uncertainty[3]:

- The PRIMES model provides a simultaneous policy projection/optimisation, where some policy driven choices are made together with a techno-economic optimisation in a hybrid approach. As we argue in Chapter 2, an example is the hydrogen targets which are most probably not an optimal outcome of the model, but an assumption/choice given to the model.
- Many **more (extended) techno-economic scenarios are needed** to explore different outcomes of the energy system. Chapter 2 will discuss the state of play of techno-economic and policy projection models separately. National policies and their socio-economic impact are taken into account in a high-level way. Still, the modelling between the National Energy and Climate Plans and the European modelling is high-level only and offers much room for improvement.
- Better alignment is needed between the modelling behind REPowerEU and the required **energy infrastructure** or critical materials needed to realize the REPowerEU plan. The scenarios should be aligned with the ENTSO-E/G analysis, and a reflection should be made towards the manufacturing capacity for supporting technologies such as electricity grids to achieve the ambitious uptake of renewables.
- On **flexibility and market models**, much work is left on a transparent and effective functioning of the pan-European energy market. Chapter 4 discusses how the research community can fill the gaps.

[3] The suggested improvements made in this document concern the European policy modelling process and the unavailability of the model and its results. None of the comments below should be interpreted as critique on the PRIMES model from a technical perspective, nor on the skilled modellers operation of the PRIMES model.

- On the **social impact modelling**, work is needed to detail the effects of the transition policies on the different social groups in society. The financial planning of the REPowerEU plan to secure the necessary funding for investments needs to be improved, according to a recent report of the European Court of Auditors [7]. In addition, while high-level policies of the member states are taken into account in the PRIMES modelling, the **national policy analysis** of the member states themselves is not sufficient to provide the necessary confidence to reach the targets with the current set of actions.
- In general, every plan should have a risk assessment and mitigation plan. This concept should be present in the modelling behind policy documents such as the REPowerEU plan.

Inadequately addressing the abovementioned factors results in increased investment uncertainty for industries, policy makers and utilities. The research modelling community has the expertise and the knowledge to support these stakeholders and reduce investment uncertainty. Opening up the modelling behind the European energy policy process and making the model, the assumptions and the results available would enable the academic community to enforce the results with new modelling insights, translate the impact to the national level and reduce investment uncertainty for local stakeholders.

In the remainder of this document, we systematically discuss how the energy system modelling community can improve state-of-the-art knowledge. We will discuss the following models:

- Techno-economic scenarios,
- Manufacturing capacity,
- Risk assessment and mitigation,
- Adequacy and security of supply models,
- Flexibility and market models,
- Detailed social impact modelling,
- Policy projections behind local energy and climate plans of member states.

For every type of model, we highlight the experience of the energy system modelling community to address these issues.

1.3 Illustration of investment uncertainty

Before we discuss the technical aspects of energy system modelling, we give a concrete example of investment uncertainty. We take the example of the European steel sector. Today, primary steel production still relies heavily on fossil fuels, mainly coal products to reduce iron ore and natural gas for heating and finishing processes [16]. Several technologies exist to decarbonize the steel sector:

- Direct reduction of iron oxide, coal products can be replaced by hydrogen or natural gas, for which significant investments are required. Direct reduction of natural gas can be combined with carbon capture and storage in case hydrogen is not available at low cost.
- Capturing-based technologies can lower emissions as well. For instance, the Steelanol project at Arcelor Mittal uses bio-cokes to replace the coal products, and captures the blast furnace gases and processes them via the Lanzatech technology into bio-ethanol [17]. This pathway would also increase the need for electricity at the site, in addition to the electricity needed to produce green hydrogen.

- On a lower technology readiness level, direct electric technologies such as molten electrolysis are developed, these technologies would need only electricity, but are not expected to reach commercial maturity in the coming decade.

Where to get hydrogen?

In many studies, the hydrogen pathway is put forward as the most readily developed way to reduce vast quantities of emissions in a relatively short term. The REPowerEU plan does set out ambitions for green hydrogen deployment in Europe. However, it is unclear how this will translate to the cost of green hydrogen in the coming decade and the associated uncertainties are very significant. Primarily, the uncertainty to the cost of electricity is notably high (see next paragraph).

Blue hydrogen could be a commercially viable interesting transition technology, especially autothermal reforming where capture rates of +95% can be reached. The main uncertainty is the inherent dependency on the natural gas price, and the remaining non-captured emissions.

Transporting hydrogen via shipping will certainly not be commercially viable in the next decade. For transporting liquid hydrogen, liquefaction losses, boiloff losses, the absence of an existing fleet and the four times lower volumetric density will make it inherently more expensive than the transport of natural gas. Transporting hydrogen in the form of ammonia might be more cost effective, and from a technological perspective, can rely on an existing fleet. However, the high-temperature ammonia-to-hydrogen conversion process, requiring ~30% of the energy content of the hydrogen [18], is detrimental for the commercial viability of the cost of hydrogen from shipping. Other hydrogen carriers face similar problems.

Where to get electricity?

Whereas the deployment of electrolysers is pushed by the REPowerEU ambitions, the most significant factor in the cost of green hydrogen is the cost of electricity as an input to the electrolysis process. The REPowerEU ambitions are met with double installation speed of wind energy with respect to recent years, adding up to more than 500 GW installed in 2030. To reach these ambitions, the deployment of new wind energy parks needs to count on a complete collapse of the permitting times for new wind energy projects, decreasing from 7-8 years in the past decade to within a single year.

Also the supply chain of new clean energy projects is under pressure. For instance, in addition to the challenge of getting the required materials for the wind turbine manufacturing, the transmission grid plans fall short for delivering a pre-2030 massive rollout of offshore wind energy [5].

The uncertainty on energy infrastructure requirements

The uncertainty faced by the end user - in this case the steel sector – equally holds for chemical sector, refineries, non-ferrous and other energy-intensive industries, even if the technological pathways are different. In addition, the uncertainty at the demand side translates into uncertainty for the deployment of energy infrastructure. In the coming years large infrastructure investment decisions need to be taken by electricity and gas transmission system operators, supervised by regulators. Any investment at the industrial cluster side, for instance electric steam crackers in the chemical sector, but also the electrification of heating in smaller industrial facilities through industrial heat pumps and other electric heating technologies, result in a dramatic increase in required grid connection capacity in the coming years. In addition, the deployment of 10 Mt of hydrogen requires around 500 TWh of electricity, which is roughly a fifth of the current electricity demand in Europe.

For hydrogen infrastructure, network rollout is being planned in some parts of Europe, such as Belgium and the Netherlands. Market inquiries are set out by the gas transmission network operators to probe for market interest for offtaking hydrogen, including pipelines to the North Sea for offshore electrolysis. However, as the cost of hydrogen from different sources is still unclear, the offtake, injection volumes and locations are still uncertain. Hydrogen from the south of Europe or North Africa will probably be more cost effective, however projects that cover with such an extent will certainly take time. A discussion on geopolitical dependency of North Africa can be another factor, but this discussion is beyond the scope of this paper.

In addition to the abovementioned sources of uncertainty, permitting procedures have proven in the past to be tedious and lengthy, further driving up the cost and implementation time of sustainable investments.

In the following chapters we will illustrate the existing gaps in the development of the models with some concrete examples and show the alternatives through which the research community is capable of developing the modelling toolbox of the future. Energy system modelling will not be able to reduce all investment uncertainty but can improve the vision on several of the abovementioned practical challenges for industries and utilities. While the research community is extensive, this paper does not aim to give an exhaustive overview of all ongoing initiatives. Instead, its goal is to illustrate how the research community can offer support.

2. Current models overview: knowledge gaps and research community's role

Before we start, we define the concept of investment optimisation models and policy projection models, and make the difference between the two:

Investment optimisation models calculate cost-optimal transition pathways to achieve certain climate goals. Over the time horizon, this type of model will identify how much investment in certain technologies is needed to reach the climate objective. This type of model typically includes all sectors, energy supply, transformation (e.g. electricity production or storage technologies), residential & commercial sectors, transport, agriculture and possibly land use. This type of model typically performs a cost minimisation across the time horizon. Examples are JRC-EU-TIMES, GENeSYS-MOD, REMix, Calliope, etc.

Policy projection models focus on the policies needed to reach those climate targets and the impact of those policies on the energy system, emissions, the economy and the social implications. Whereas techno-economic models focus mostly on the cost of the energy system, this type of exercise offers more detail to e.g. the distribution of the investment effort on the different stakeholders, the social impact of certain policies etc.

Hybrid approaches are possible, where the energy system is optimised under a set of specific policy constraints.

2.1 Economic investment models

Current knowledge gap regarding economic investment models

The modelling behind the current REPowerEU plan does perform an economic investment and policy projection model at the same time. This is in itself not a problem; however it may cloud where decision makers made an explicit political choice and which model results are an outcome of techno-economic optimisation.

It is very insightful to look at the pure techno-economic outcome of the system, taking into account many different boundary conditions.

An example is given below. The main difference in terms of technology uptake between REPowerEU and Fit-for-55 is the uptake of green hydrogen (10 Mt in Europe, 6 Mt imported, 4 Mt imported in the form of Ammonia). However, it is not at all clear to which extent the hydrogen uptake is result of the optimisation modelling or inspired by political motivations. In the table below, the difference between REPowerEU and Fit-for-55 are shown. Use cases like blending of hydrogen in the gas grid are usually not a result of a techno-economic optimisation. Also for industrial heat and transport, the electricity driven alternatives should be more cost efficient. In addition, where the imported 6 Mt of hydrogen will come from is an open question. A recent study estimated that less than one fifth of the renewable hydrogen volumes in the REPowerEU plan are needed to reach the REPowerEU goals [19].

Sector	RePowerEU	Fit-for-55
Bunker fuels	0	0
Refineries	2273	613
Industrial Heat	3629	756
Transport	2319	882
Petrochemicals (Ammonia)	3232	1306
Blast furnaces	1520	1152
Synthetic fuels	1788	1870
Power generation	105	0
Blending	1335	0
Total	**16200**	**6579**

Table 1: Hydrogen use by sector in 2030 (kt hydrogen). Source: [3]. Processes such as industrial heat, road transport and especially hydrogen blending in the gas grid are not a result of a cost optimisation, as electric alternatives are more cost efficient.

Where the research community supports and develops economic investment models

Economic investment optimisation models are used to derive cost-effective pathways to climate neutrality. The main strength of this type of model lies in its clear mathematical formulation, enabling the integration of the entire energy system into the optimisation, including all sectors such as industry, power sector, residential, commercial, agriculture and transport. In many of the model scenario exercises, all energy carriers such as electricity, gases, liquid fuels, biomass streams, heat flows, CO_2 capture, etc., are included, and the analysis is not limited to, for example, electricity alone.

Usually, the analysis of this type of models includes a basic dispatch as well (we discuss dispatch models further in this chapter).

Some of the well-used models are:

- JRC – TIMES [20][21][22]. The JRC-TIMES model was developed within the ETSAP (Energy Technology Systems Analysis Program), one of the longest-running Technology Collabouration Programmes of the IEA.
- GENeSYS-MOD (The Global Energy System Model) is an open-source energy system model, originally based on the Open-Source Energy Modeling System (OSeMOSYS) framework. GENeSYS-MOD is a linear program, minimising total system costs. Energy demands are exogenously predefined and the model needs to provide the necessary capacities to meet them. The modeling framework is very flexible in its use cases. Based on research questions and input data, calculations can be done from a household-basis to a global aggregation of regions.
- SpineOpt is an open-source optimisation model generator for planning as well as scheduling written in Julia. It has a rich set of features, such as unit-commitment with optional integer variables, ramping and reserve constraints, inertia constraints, piece-wise linear efficiencies, investment planning, sector coupling and possibilities to reduce model complexity through rolling horizon, representative periods, and decomposition. It can represent DC power flows, pressure-driven gas flows, heat diffusion, delayed energy transfers and material flows. The temporal and stochastic structures are highly flexible – different parts of the same model can have differing temporalities. It uses Spine Toolbox as a graphical user interface and allows connections to other tools. There is a high granularity open access dataset under development in EU project Mopo – the dataset can be configured to produce model instances at user-defined resolutions.
- PyPSA (Python for Power System Analysis) is an open-source framework designed for energy system modeling. It facilitates economic investment and policy projection analysis of energy systems. With a scale-agnostic approach, PyPSA offers high flexibility in defining energy system models, allowing customization of sector coverage, geospatial representation, time resolution, and technological aspects [22]. This framework has been utilized to build various energy models, among which PyPSA-Eur-Sec (PyPSA Europe Sector Coupled Model) stands out as a crucial one. PyPSA-Eur-Sec is an openly accessible dataset that provides a comprehensive representation of the European energy system, specifically focusing on the transmission network level and encompassing the entirety of the ENTSO-E area [23].
- Calliope is a free and open-source (Apache 2.0 licensed) tool that makes building energy system models at scales ranging from urban districts to entire continents easy. The Calliope code is tested with a comprehensive suite of automated software tests and has been used in a large range of peer-reviewed publications. Two versions of Euro-Calliope exist. Firstly, a fully sector-coupled version includes, besides the electricity system, the transport, heat, and industry sectors (including the use of non-energy feedstocks). Secondly, the power-sector-only model (upon which the sector-coupled version is built) retains interesting features, such as –a more flexible spatial resolution.
- REMix (Renewable Energy Mix) is an open-source framework including various sectors and diverse energy conversion, storage and transport technologies. In the case of energy conversion, in addition to electricity and heat generation from renewable and fossil sources, the electricity-based production of synthetic fuels (hydrogen, methane, liquid hydrocarbons) is also mapped – this makes it suitable for considering sector integration. For the temporal decoupling of generation and demand, the framework includes electricity storage, heat storage, fuel storage, load management in households, commerce and industry, as well as the controlled charging and grid feed-in of electric vehicles. In addition, energy transport

between the model regions via the AC and high-voltage DC transmission lines and international fuel trades are considered in a simplified way [24].

- AMIRIS (Agent-based Market model for the Investigation of Renewable and Integrated energy Systems) is an open-source, agent-based model for energy markets. It aims at enabling scientists to dissect the complex questions arising with respect to future energy markets, their market design, and energy-related policy instruments. The model computes electricity prices endogenously based on the simulation of strategic bidding behavior of prototyped market actors. This bidding behavior does not only reflect marginal prices, but can also consider effects of support instruments like market premia, uncertainties and limited information, or market power [25].

In Annex: energy system model overview.

Economic models work at both European and national scales. Whether on a national or regional level, it is useful and insightful to examine techno-economic investment models to assess the cost-effective pathways for policymakers. For instance the TIMES model has an EU variant but also several national based models, such as in Belgium [26], Finland, the Netherlands, Spain, Portugal [28] and Ireland.

Also at a national scale, it is useful to address investment models and policy projection models, as we discuss further below.

On several different fields, the research community performs relevant work to expand the scope of soptimisation-based equilibrium models:

- Optimisation models such as the ones described above, usually do not model structural societal transformations such as a large-scale behavior change. The economic decision making is often based on simple and rational behavior, which does not always reflect the behavior of consumers or companies. New modelling approaches expand on the typical equilibrium-based theory models to include more complex societal dynamics. A recent overview and collection of recent case studies were made by EEIST [27].
- In addition to the cost-optimal scenario, there may be scenarios that are not cost-optimal but are nevertheless more desirable from a societal or political point of view.
- Cost of technologies are often modelled in a fixed declining way, e.g. PV and wind turbine costs. Breakthrough innovations at low technology readiness level are hard to represent.
- The level of detail of the private and public funding sector is only represented in a high-level way.
- Agent-based models are used to reflect the dynamics of the consumers and market systems, which are not part of a central planner but involve complex systems of actors with each different objectives and strategies.
- Investment scenario results do not deal with disruptive events such as industry relocating to other regions in the world with higher potential for renewables.
- The way required ressources and circularity is represented in energy system models should still improve [28].

It is important to note that the above ongoing work on energy system models does not imply that the 'pure' techno-economic optimum is not useful. On the contrary, the pure techno-economic insights of a central planner with perfect foresight can serve as a benchmark for more detailed scenarios or agent-based approaches. In addition, it has to be noted that agent-based approaches, reflecting more complex interactions between different stakeholders in the system, usually have to make other simplifications due to computational limitations.

2.2 Policy projection exercises

Current knowledge gaps

The use of models within policy development can provide a robust, consistent and comparable check on recommendations. However, models are not merely neutral tools for generating evidence [29]. Particular interests and agendas often shape the framing of models. These interests can steer the process through the questions asked, the way findings are presented or through the data used. For instance, national member states may pursue different ways to reach climate neutrality based on the local political climate (e.g., some member states may be more willing to accommodate nuclear power projects than others, favour different policy instruments to promote the uptake of heat pumps, renovation or electric vehicles, etc.).

For generating societally relevant results, it would be imperative to vastly increase the number of implementation constraints that the models consider or to use models in parallel to cover different constraints and gain a better understanding of the whole system. That includes, but is not limited to, workforce constraints, financial constraints (lack of capital among stakeholders), material flows (e.g., rare earths), environmental constraints (e.g., recycling), social acceptance and social justice constraints (e.g., geographically varying degree of opposition to wind power), political and security risks and many more. There are well-documented cases where the boundaries used to define scenarios, or the parameters used to set the scope of a model, limit the full range of available policy advice (see for example [30]).

An example of a failure due to a lack of properly weighted multi-objective planning was the Desertec project [31]. This Sahara electrical cable connection was from a technical perspective entirely reasonable, but from a geopolitical and risk perspective was less than ideal.

In addition, for policy projection models the following elements still require work:

- National policy projection exercises can make use of the parameters and insights coming out from the EU modelling process, however the main link today is limited to the climate target for non-ETS emissions. Electricity prices, fuel costs etc. are for most national energy and climate plans not related to the REPowerEU scenario.
- A key aspect of policy projection studies is data on how policies have worked in the past, but this topic is still receiving too little attention. The challenging aspect of ex-post evaluation lies in building a counterfactual or reference scenario that depicts what would have happened without the policy ([27]). Policy is often built on ex ante estimations only, however ex post studies are very important to assess the potential of future policies.
- Energy policy impact assessments in NECPs often miss the detailed social impact modelling, both with respect to macro-economic impact as to consumer groups.
- To make the energy system model results more compatible with society at large, it would be desirable to integrate multi-objective approaches and consider aspects such as energy security, political stability, manufacturing and workforce ramp-up capabilities, among many others.

Exploring the research community's role in supporting and developing policy projection models

Also here, the research community can help by building policy projection models that assess national energy and climate plans clearly and transparently identifying the boundaries of all models being used. The research institutes have excellent knowledge of model capabilities, technology possibilities, and an extensive portfolio of modelling alternatives. They can also assist policymakers in drafting realistic climate pathways.

In several member states, modelling results are used as an inspiration for a realistic energy mix.

One of the best case studies is found in the Netherlands, where research institutes (TNO, Universiteit Wageningen), the Planning Bureau (PBL) and administrations performed an 'exploration' of the current boundary conditions and energy system evolutions, as an input to the policy makers who make up the national energy and climate plan [32]. Similarly, the Leitstudie is used as a basis for many political decisions [33]. The regularly updated study combines some impact assessment modelling with input from various stakeholders.

2.3 Energy infrastructure and security of supply

Current knowledge gaps between the European target-setting process and energy infrastructure

Another important point is the deployment of energy infrastructure. Are the pathways proposed realistic in terms of manufacturing capacity and deployment rate?

This type of consideration is still to be integrated into the input for modelling behind the REPowerEU plan. For instance, with respect to the Fit-for-55 plan, the ambitions for wind energy by 2030 are increased.

In a recent report [6], the wind energy sector identified critical elements in the supply chain, regarding turbine manufacturing capacity, which presents a major barrier to achieving the doubling of the deployment rate as stipulated by the REPowerEU plan. In addition, IEA confirms the worldwide gap in manufacturing capacity for wind energy projects [34], where competition by wind energy projects outside Europe may negatively influence the delivery of European projects.

To start with, constraints in expanding the power grid are a key factor. When comparing the latest ENTSO-E ten-year network development plans (TYNDPs) with the REPowerEU plan, an investment gap in grid infrastructure is apparent, as concluded in a recent study [5]. In general, the infrastructure planning procedure followed by ENTSO-E and ENTSO-G is a completely independent exercise from a methodological point of view. More interaction is needed between the investment and policy modelling behind the political targets and the ENTSO-E and ENTSO-G scenarios that need to ensure generation adequacy, security of supply, and make plans for energy infrastructure investments of national TSOs. However, models exist that are able to take into account a – simplified – energy infrastructure planning together with investment and policies, as we will detail in the next chapter.

Moreover, for several energy technologies, materials are needed as input to manufacturing clean energy technologies. Here too, challenges arise that could pose bottlenecks, especially concerning materials such as lithium for batteries, copper for electricity grids or rare earth elements for electric motors [35]. It is clear that a robust plan should incorporate a check which looks at supply chains to support technology uptake. A plan should then incorporate a 'what if' scenario based on the possible outcomes. This identifies the no-regret investments under a range of external circumstances. As a practical example, when a shortage occurs with respect to the foreseen renewable electricity capacity, the green hydrogen targets may have to be revised, as the electricity used in electrolysers will then cannibalize on electricity needed for transport and heating sectors.

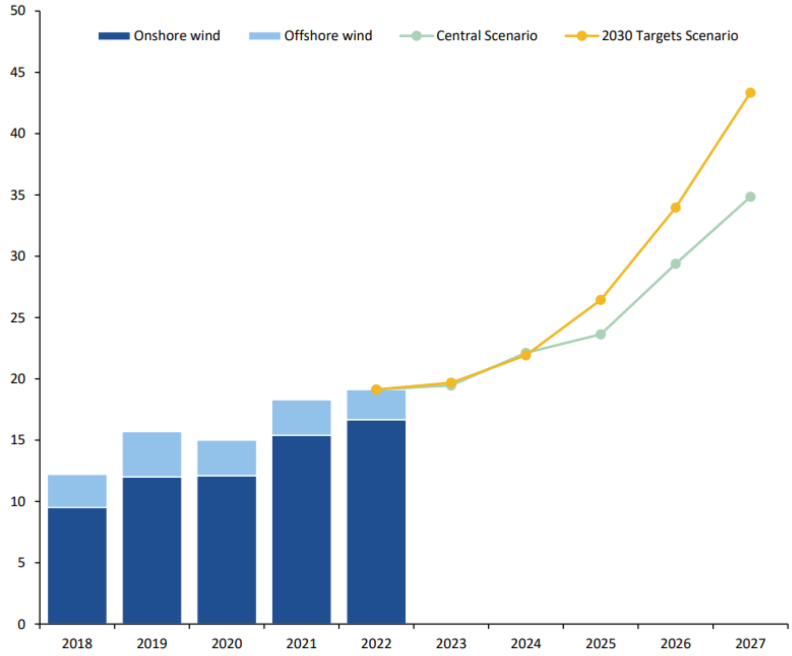

Figure 2: source [6]: Annual wind installed capacity in Europe by a Wind Europe scenario: 2018 -2027

In conclusion, considerations on the energy infrastructure value chain being able to deliver on the aspired targets per technology, the robustness of the scenarios in terms of security of supply, and a 'what if' risk analysis if one of the aspired ambitions for a certain technology would not be met, should be an integral part of an overall energy system plan. In general, every project of a certain size should have a risk assessment and mitigation plan at the very start of the process.

How the research community supports modelling security of supply and energy infrastructure decisions

Generation adequacy and security of supply models are typically used by TSOs to assess the adequacy of the power mix and future energy infrastructure needs. This category broadly includes unit commitment and dispatch models, capacity expansion planning models, optimal power flow models which are able to take into account the possibility of component outages, etc.

The European Resource Adequacy Assessment (ERAA) is a pan-European assessment of power system resource adequacy of up to 10 years ahead, based on state-of-the-art methodologies [4].

Research institutes work on expanding the mathematical scope of those type of models with more advanced probabilistic tools, machine learning approaches for forecasting of outage risks, etc.

Examples are the following:

- Improving the mathematical treatment of operating reserves in generation expansion planning models [36][37],
- Studying different ways to operate short term and long-term storage and its impact resource adequacy indicators [38][39],
- Assessing the benefits of coordinating between different market zones the sizing, allocation and activation of reserves [40].
- Improved forecasting techniques in power systems, using advanced algorithms such as machine learning [41].
- VITO – EnergyVille calculated a net-zero emission pathway study end of last year. Concrete and very recent investment plans of local industrial clusters were taken along [42].
- In a recent study for the Flemish cities and communities, the potential for district heating in Flanders was determined. The analysis method included a combination of regional building kadaster data, satellite data for the building envelopes and renewable potential, energy consumption data from the DSO on sub-street level for the entire territory of Flanders. Building stock models and district heating routing tools were combined. Such detail is not available in EU exercises.
- A team of mathematical scientists in GB has provided support on risk modelling and decision analysis methodology to the Capacity Assessment and Capacity Market studies since 2011. A general description of this work is available in case studies for the national Research Excellence Framework studies of 2014 and 2021 [43] [44]. This is underpinned by a number of research papers, including on integration of storage [45] and decision analysis [46]. Incorporating the Modeling to Generate Alternatives (MGA) technique into high-resolution models to provide a range of near optimal solutions that can be used to balance techno-economic feasibility of energy systems with social and political goals.

In this way, the research community is exploring different techniques and methodologies to improve security of supply assessments, and there is a discussion between the research community and the transmission system operators and regulators.

Also for energy infrastructure, the research community supports TSO's and DSO's with the rollout of their implementation.

- In many countries, load flow simulations are performed by research institutes as a contract support for utilities.
- The AID-RES project [47] determined the impact of industrial decarbonization pathways on energy and electricity demand in Europe on a NUTS-2 regional level. This gives utilities input for their infrastructure assessment.
- On a regional level, research institutes combine building stock models, GIS based models and various data sources such as building cadaster data, satellite data and energy consumption data, to assess where and with which technology the gas grid can be replaced in time. An example is where VITO-EnergyVille supports local communities with 'heat zoning maps', identifying least cost renovation pathways and interesting locations for district heating infrastructure [48].

As we discussed above, there is still a gap in infrastructure for the energy transition, and the challenges are enormous. Currently, knowledge gaps still exist. Recently, ACER published an opinion on shortcomings of existing

CBA methodologies, where the lack of harmonised and transparent models for conducting high level market studies and power flow studies has been highlighted [49]. This was also the conclusion of a study for the European Commission on improved methodologies for CBA analysis of AC/DC grids [50].

In addition, there is still a manufacturing capacity gap, as determined in recent projects [34] , also hydrogen and CO_2 infrastructure is lacking.

The energy research community can support here with energy system scenarios to project industrial transformation. This involves techno-economic models, industrial process models, and GIS based models for determining spatial constraints for infrastructure deployment.

2.4 Flexibility and market models

Knowledge gaps in market and flexibility models

The market model was a heavily debated subject to the energy crisis, and at the time of writing electricity market reforms are being discussed by the European Council.

The knowledge gap arises from the fact that the conventional market curves (supply and demand curves) are deterministic and static whereas the flexibility of e.g., a supermarket is stochastic and dynamic. The need for a dynamic formulation arises from the fact that if the market has been flexible during this hour, then the flexibility might not be available for the coming hour.

In some recent smart grid and power market projects, this is solved by using the concepts of a Flexibility Function [49][50], which establish an interoperability between the static market principles which must exist in large scale considerations, and the local flexibility in buildings, supermarkets, etc. The Flexibility Function is suggested as one of the essential Minimum Interoperability Mechanisms (MIMs) for the use of flexibility for providing grid and balancing services [51]. This is for instance implemented in the Smart Energy OS framework for digitalization of the energy grids and for activating flexibility by a massive deployment of demand-response solutions for buildings, etc. [52].

The open-source Frigg modeling framework [53] includes such methods for considering short-term flexibility in energy systems modeling. Another example is the AMIRIS model, which allows to simulate the future day-ahead market with regard to business-oriented actors' behavior and respective uncertainties. AMIRIS is currently being extended to simulate investment decisions.

How the research community addresses the knowledge gap

Similar to the adequacy and security of supply, the research community explores different market mechanisms and their impact, a few examples are added below:

- Forecasting algorithms to better predict the renewable generation, responses of the market to outages etc. [54], [55], [56].
- Agent-based modelling and different strategies for market participants and their impact on the market [57],
- New market products and algorithms for operation of market bids, [58]

- Capacity mechanisms in future electricity markets, the options and quantitative impact [59].
- Scarcity pricing mechanisms [60].

2.5 Social and macro-economic impact assessment models

Knowledge gap in national and European target setting process

Any energy transition plan should involve a detailed social impact analysis, involving different categories of consumers, their future behavior, reflections to energy poverty, etc. In addition, macro-economic consequences of the scenario, such as jobs and created, governmental budget balances, and changes in commodity prices should be worked out. Here, data availability is key, as well as calculation power. Social and macro-economic impact are taken along in a very high-level way in the current analysis. For these topics, a lot of the relevant data are found on a national level; the current policy mix, consumer categories, macro-economic parameters, building stock data etc. This is one of the examples why it is important for European modelling exercises to take input from member states along. We discuss this point further in the next subchapter.

However, while impact is important models often ignore the feedback from consumers to energy infrastructure. Consumers, consumer choice and consumer preferences will often impact energy infrastructure far more than most (all) models allow. For example, planning processes can be considerably lengthened through citizen engagement with many issues that are not considered within modelling to be important. Also consumer uptake of new technology is often vastly underestimated by traditional economic modelling. Therefore, qualitative data, consumer surveys and citizen engagement activities are important aspects to be run alongside modelling and early on in policy development cycles.

Another question is the following: what is the impact of certain energy-intensive processes shutting down or re-investing in other regions with more aggressive subsidy policies such as USA? This question is currently unaddressed because it investigates the impact of an outcome which is as such undesirable. However, being unprepared for such an undesirable outcome can have even more drastic consequences. The Net Zero Industry Act formulates ambitions, but does not provide investment certainty in terms of funding. The Carbon Border Adjustment Mechanism (CBAM) should cover the emission price, but is not expected to cover the entire cost gap for every process, as certain electricity driven processes will be structurally cheaper in certain parts of the world where renewable capacity factors are high. In the NZIA, a manufacturing process such as wind turbine manufacturing capacity is assumed to be remain in Europe, however it is not clear if steel, base chemicals or other processes are targeted to remain in Europe and which funding sources will be needed to cover the cost gap. Also on a national level, national energy and climate plans do not take into account energy-intensive industrial processes relocating to regions in the world with higher potential for renewables.

How the research community is supporting the knowledge gap

Also here, the research community has substantially developed its knowledge and modelling expertise in integration social and macro-economic aspects into policy design and national energy and climate planning.

These models have the potential to significantly equip the policy makers with a tool to rethink and restructure the policy scenarios on a European level by integrating the insights and feedbacks received from the social and macro-economic impact assessments. However, the effective application of these models by policymakers has been very limited by policymakers within European scale. On a national or regional level, however much more detail is added with respect to the European exercise, as also the impact of national policies is included and more data on consumer segmentation is available.

3. Operational digitalization

Operational technical models are needed for instance to make industrial processes more flexible, or to digitise and improve the operation of the electricity grid. In such a scenario, digitalisation is perceived as a key enabler [61] and, thus, it must be exploited to achieve a common and continental energy system model, which could even end in a digital twin of the electricity market.

This goal presents several challenges that must be addressed holistically. Even when different methodologies were implemented (analytical models, evolutionary algorithms, artificial intelligence, etc.), the inputs and the outputs should follow a common principle in order to make the models interoperable.

Some of the advances that can work towards the interoperation among systems are:

- Digital workflows: Codes should be integrated in a continuous data-driven workflow that will allow their coupling under a modular basis.
- sDockerised models: in order to facilitate the previous item, codes and applications should be integrated into dockers containing the necessary computing dependencies.
- The European Open Science Cloud (EOSC) offers a valid platform for executing the workflow and the sdockerised models. However, traditional clusters and High Performance Computing (HPC) could also be exploited, if needed.
- Cybersecurity: One of the risks that the sdigitalisation of the energy sector will bring is the security of the data, so cybersecurity capacities must be provided in order to preserve the value of data.
- Blockchain: It will allow, for example, the tracing of the renewable aspect of the consumed energy or will facilitate secure transactions.

Last but not least, under this digital transformation, it is mandatory to count on the citizen and even the prosumer as key actors in the process. A human-centred approach is a driving force that must guide digital developments to allow final users to be an active part of the system and, simultaneously, avoid the digital gap. Thus, different developments must be associated with designing easy-to-use apps and webs, integrating decision-making capabilities, providing clear information, etc.

4. Energy data

Overview of available data sources and knowledge gap

Energy data should adhere to FAIR principles; none of the aforementioned alternatives to support the existing modelling gaps will be possible if data are not Findable, Accessible, Interoperable, and Reusable. The implementation of these principles relies on trustworthy sources, which further necessitates the adoption of standards, persistent identifiers, and ontologies to ensure the production of accurate metadata.

Several databases already exist. However, the data landscape is still too fragmented. Some of the available databases are:

- ENTSO-E,
- EUROSTAT,
- BPIE - Buildings Performance Institute Europe,
- IEA,
- IRENA,
- JRC - European Commission,
- IPCC emissions inventories,
- national statistical offices,
- PLATTS database,
- national TSOs and DSOs,
- energy companies,
- national and European manufacturing industry associations (e.g. CEMBUREAU, EUROFER, Glass Alliance Europe, CERAMIE UNIE, etc.),
- EURELETRIC,
- EUROHEAT & Power,
- DG Energy, DG Clima, DG Environment,
- national energy and environment authorities,
- Energy Cities,
- Center Denmark (a European Digital Innovation Hub for Smart Energy)
- Etc.

A lot of data related to buildings, consumers, and social aspects of the energy transition are found on regional or member state level but not publicly available. In addition, data of the DSO regarding the local electricity and gas grid is usually not public information. For improving the data quality across all levels of detail and across all regions of Europe, one possible approach would be to set up a collabourative database that unifies the current, fragmented data landscape, where every energy system model uses different values from different sources for different times, from different macro-economic scenarios and different technology development estimations. In other words, a unified, collabourative, database of energy generation, potentials, and demands, including their uncertainties, for both past and future with both a high temporal and spatial resolution would yield the biggest benefit, but also the biggest challenge.

How the research community can address the knowledge gap

Recently, there have been initiatives aimed at enhancing data structure and availability, and we have identified some best practices.

- The European Climate Advisory Board Scenario Explorer[4], a new entity set up in the context of the Climate Law (i.e., 2040 GHG targets) to validate that the European Commission projections are in line with the most recent scientific developments.
- The IIASA platform contains PRIMES model outputs in the open database for the EU.
- The Spine project works towards sharmonisation of data and interoperability of databases [62], not only collecting the data but also building a data structure so that the data can easily be used by a variety of energy system models.
- A similar approach is developed by the Open Energy Ontology (OEO), which assures that modelers use the same data formats which will simplify model coupling and the usage of unique data samples.

While multiple actions are ongoing to improve the accessibility and the interoperability of data, significant work is still needed. For instance, not all data behind the PRIMES model exercises or their results are publicly available. The underlying data and models supporting the National Energy and Climate Plans are not publicly available.

An international research agenda plays a pivotal role in many areas, necessitating data identification, acquisition, and analysis spanning multiple countries. However, additional reasons support the adoption of an international approach beyond the fact that the phenomena being investigated transcend national borders. Combining datasets from various countries enables the investigation of rare groups, occurrences, or combinations of characteristics that would remain inaccessible when relying solely on data from a single country. Furthermore, the proliferation of multinational sorganisations diminishes the significance of national boundaries in data production, particularly in cases involving data generated through or associated with global communication networks.

A foundational step in research and analysis is ensuring that the data used is fit for purpose, supports the research objectives, and is collected and managed efficiently. The following fundamental data prerequisites are necessary to be identified:

- Micro-data, providing information pertaining to individuals and/or organisations, need to be generated for research purposes
- Repeated observations on the same unit of observation are required to study change processes.
- Data need to be up-to-date. In a changing world, and with the new capacity to collaborate across nations and in multidisciplinary teams, there is an imperative to study phenomena as they emerge.
- Data must be comparable across cultures and environments. The concepts used to implement and communicate data at the international level should derive from universally srecognised methods and standards. The complementarity of data from different sources still has to be explored.

The internet transcends national borders, as do numerous transactions and communications, and often, the major organisations/authorities responsible for collecting this data operate on a global scale. However, legal regulations governing property rights, usage rights, privacy, and confidentiality are typically rooted in national jurisdictions.

[4] European Climate Advisory Board Scenario Explorer (iiasa.ac.at).

This contradiction can cause uncertainty and complexity for individuals and entities involved in data collection, storage, and utilisation.

- Social science data infrastructure significantly extends the capacity to accumulate knowledge from existing sources and extend its relevance. Still, it will also increase the potential impact on the knowledge base from well sorganised new sources through identifying the most relevant areas for harmonisation.
- Digital data formats are significantly more intricate and diverse compared to the conventional structure of a dataset, which typically comprises a set of attributes representing various units within a specific population. When it comes to communication and transactions, there's often the involvement of two or more units, and these interactions can be depicted through networks or even more intricate structural arrangements. Consequently, this complexity underscores the requirement for employing unconventional approaches in data management and analysis. This particular field calls for substantial methodological and skill development to effectively tackle the multifaceted challenges it presents.

The establishment of a new data infrastructure will foster equal and easy access to official microdata across the European Research area. This kind of initiative must operate within a well-sorganised framework where responsibilities and accountability are evenly distributed. **Europe is in need of an inclusive and user-friendly research data infrastructure to sustain the creation of pioneering research and trustworthy policy assessments**. Consequently, enhancing the accessibility to official statistical microdata by creating a remote access network connecting established research data centres as well as ensuring sstandardised metadata integrated into official datasets will enable energy data to be utilised more easilysfor modelling and research purposes.

In addition, a forum dedicated to the advancement of energy data and related data sources promises to yield significant benefits by fostering enhanced coordination and communication among various stakeholders. This forum can facilitate the interaction between scientists, data producers (including national statistical agencies, government departments, major private sector enterprises, and academic research institutions), as well as individuals engaged in data curation.

5. Energy modelling communities of practice

First, we recommend that European and national policy makers accept and embrace plurality in expectations of appropriate energy model use. This means creating policy processes where multiple modelling voices are heard (and multiple models used). This must allow for the differences between outputs to exist and inform fruitful multi-stakeholder dialogue processes that do not advantage particular approaches.

Secondly, Communities of Practice with diverse modelling and policy expertise should be set up. The challenges of access and exclusion can sometimes be addressed through the power of cross-sectoral relationships and coalitions. The building of such communities needs to be based on shared understandings of what models can and cannot do, as well as the recognition that no model is perfect, so multiple assumptions and projections should be challenged and explored.

Building relationships of mutual understanding is an integral part of embedding transparency, access and participation throughout the modelling and policymaking process. Crucially, it will enable the integration of the knowledge of different actors such as modellers, policy workers and NGO experts. The bridging expertise offered by policy intermediaries should be prioritised. Funding for model development often requires engagement with the community (especially under funding through European Horizon programmes), and therefore, knowledge exchange exist on both sides. However, the institutional systems established for policy appraisal are not structured to make the best use of this range of expertise. A more open and transparent dialogue should be set up much earlier in the policy design process.. In particular, while we do not suggest that policymakers need to understand the specific nuance of model features, they need to be able to grapple with modelling boundaries and their inherent limitations. Therefore, some form of overall training and/or an open space for dialogue should be supported to bring together the two communities, including the intermediaries on both sides.

The use of models within policy development can provide a robust, consistent and comparable check on recommendations. However, models are not simply neutral tools for producing evidence [29]. The framing of models is often shaped by particular interests and agendas. These interests can steer the process, through the questions that are asked of models, the way findings are presented or through the data that are used.

There are well-documented cases where the boundaries used to define scenarios, or the parameters used to set the scope of a model, limit the full range of policy advice that is available (see for example [30]). Key technical issues also provide areas of concern in current modelling and advice, including assumptions on the cost of capital or technology cost curves, or the structural assumptions of the economic system modelled (especially around an economy in equilibrium). The limited availability of data used to inform models, means that data associated with new technologies and alternative approaches are often less robust or even completely unavailable.

There is an inertia within policy development where the models currently used for appraisal are preferred over time by virtue of providing comparable results (in the same format) from policy to policy. Many of these current models struggle with interactions, feedback loops, tipping points and behaviours. Even where models have offered influential policy advice over many years, such as the PRIMES model which has played a major role in energy policy in the European Union, there is an increasing critical social science challenge emerging around the need to understand better the diverse and complex ways in which evidence and policy shape each other. We need to understand better how political dynamics shape a model's development, design and outputs. This includes the framing of the problem and questions, and the choice of scenarios and solutions.

Sometimes policy makers are given the modelling results and have no space to actually pose questions about model selection or use. Sometimes they also do not know how to put forward such questions. Often policy makers will say "*we trust modellers*" and are led by "*what they want to highlight*". Occasionally model inputs (and the framing of outputs) are repeatedly manipulated in order to generate the specific outcomes desired by policymakers (who in many cases are contracting the modellers). Therefore, it can be said that models are not "*shaping*" policies, but are instead frequently used to "*confirm assumptions*".

In response to these issues, policy makers should consider opening up processes of engagement to include a range of voices, to facilitate open discussion around model choice, construction and assumptions [63], and try to break any lock-ins or model monopolies that may exist.

An overarching recommendation is the need to build structured communities and coalitions, where issues of access and exclusion can be addressed, and where models can be developed with a shared understanding of what they can and cannot do. Such Communities of Practice [29] would involve diverse stakeholders, and multiple model teams, to co-develop a suite of evidence generation tools that supports policy cycles. These Communities of Practice should champion a systems view of both the model-policy cycle, and the economy as a whole. In this way, modelling can support real innovation and emergent policy solutions for an energy transition at scale and at speed.

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Annex: energy system model overview

Below a comparison on functionality on a non-exhaustive list of techno-economic energy system optimisation models is given.

Characteristic	Alternative	GENeSYS-MOD	PyPSA	JRC-EU-TIMES	SpineOpt	REMix	AMIRIS
Methodology	Simulation		X				X
	Dispatch optimisation		X		X	X	
	Single objective investment optimisation	X	X	X	X	X	
	Multi objective optimisation			X			
Programming techniques	Linear	X	X	X	X	X	
	Non-linear					x	
	Dynamic						X
	Mixed-integer		X		X	X	
	Heuristic						X
	Other						X
Foresight approach	Perfect	X	X	X	X	X	
	Myopic		X	X	X	X	X
Accounting of uncertainty	Deterministic	X	X	X	X	X	X
	Stochastic		X	X	X	x	(x)
Code	Open	X	X	X	X	X	x
	Not open						
	Other (partially open)			X			
License	Reuse and modification allowed	X	X	X	X	X	X
	Reuse and modification not allowed						
Energy sectors	Electricity	X	X	X	X	x	X
	Gas	X	X	X	X	x	
	Buildings	X	X	X	X		
	Heat	X	X	X	X	x	(x)
	Industry	X	X	X	X	x	(x)
	Transport	X	X	X	X	x	(x)
Techno-economic detail level*	Low						
	Medium		X	X		X	(X)
	High				X		
Geographical coverage	Single-node						X
	Multi-node	X	X	X	X	x	
Time resolution	Low (1-32 time slices)			X	X		
	Medium (36 – 288 time slices)	X			X		
	High (8760 time slices)		X		X	x	X

* Techno- economic detail level: Low: fully flexible power plants, tank model without self-discharging for electric storage), Medium: (start-up costs for power plants, tank model with self-discharging for electric storage, primary reserves): High: (Time-dependent start-up costs for power and delay of efficiency for power plants, tank model with self-discharging for electric storage, primary, secondary and tertiary reserves).

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