METHODOLOGY FOR INTEGRATED NETWORK PLANNING IN EUROPE

A DELIVERABLE OF THE STEERS-PROJECT

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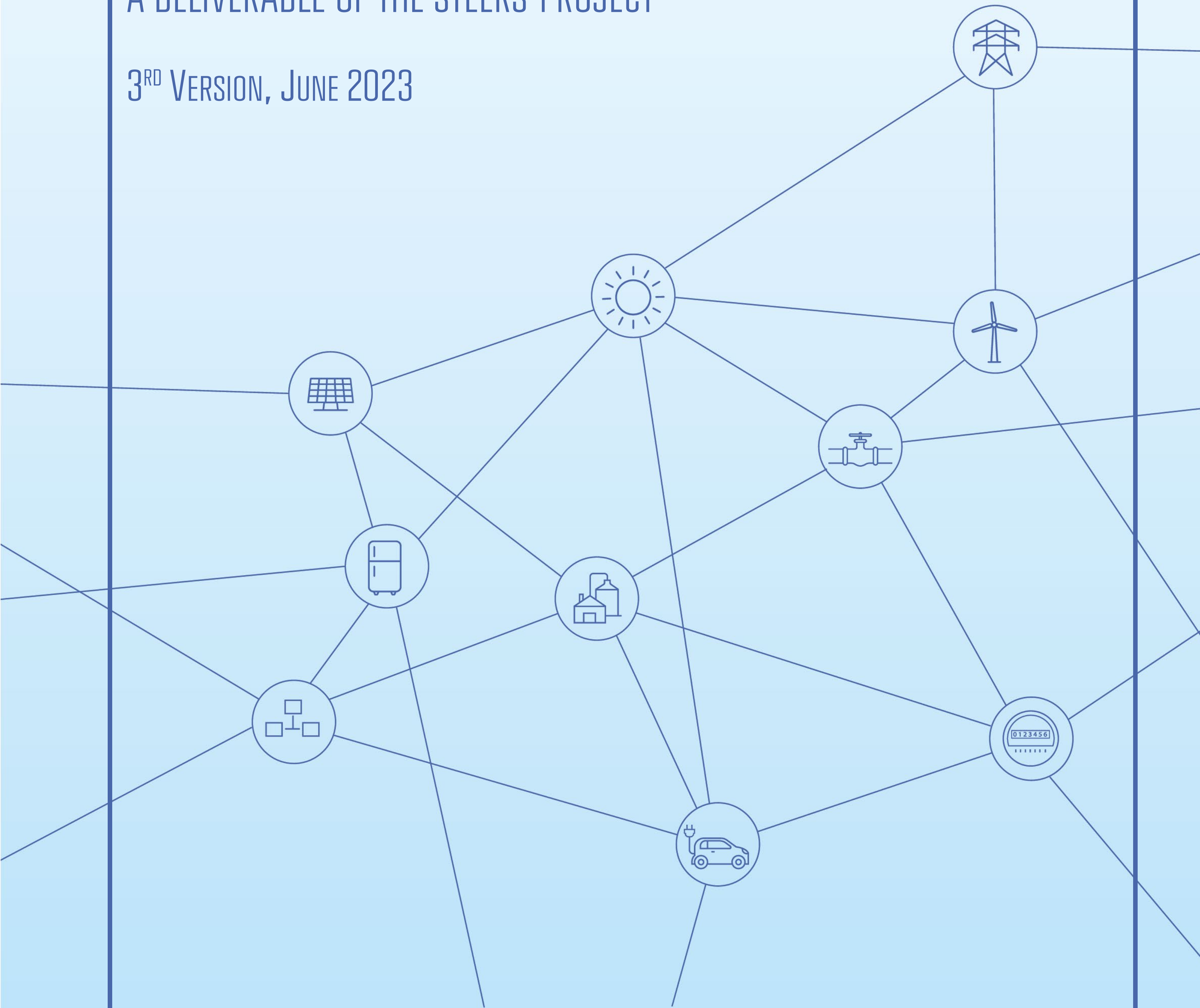

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1 CONTEXT & OBJECTIVES

Regulations EC 714/2009 and EC 715/2009 cover the community-wide planning of “viable [electricity/gas] transmission networks and necessary regional interconnections, relevant from a commercial or security of supply point of view” in connection with a generation-respective supply adequacy outlook. Regulation EC 347/2013 (TEN-E) links this to the selection of Projects of Common Interest. The new TEN-E regulation underlines the aspect of a future-proof system that supports and is viable within the framework of the European Green Deal, is suitable for Energy Systems Integration, and in line with the Energy Efficiency First principle.

By and large, the aim of the planning exercise is streamlining the planning of network interconnections in Europe and specifically:

- assessing planned projects;
- pointing out remaining infrastructure gaps as per the current planning and providing a Cost-Benefit Analysis of planned projects as a basis for the selection of Projects of Common Interest.

This document presents the STEERS methodology for improving the current network planning process. This methodology draws from the state of knowledge regarding energy system modelling and planning and discusses the link to the current methodology established by the European Networks of Transmission System Operators for the Ten-Year Network Development Plan (TYNDP) where applicable. Our methodology focuses particularly on the reflection of energy systems integration and the Energy Efficiency First principle, as well as on stakeholder participation and transparency.

Beyond the initial and immediate mandate, European network planning arguably has a larger political significance, as the scenarios and system needs can easily be perceived by both policymakers and the public as an account of what is a likely or possible future energy system.[1]

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[1] Although ENTSOs declare that it is not their intention to promote a political agenda, the TYNDP may have this effect. Additionally, and in line with this, the data sets and assumptions form the basis for many other modelling exercises and assessments by commercial (e.g., Eriksrud et al., 2022), societal (e.g. Artelys, 2022) and academic stakeholders (e.g., Göke & Weibezahn, 2022; Victoria et al., 2020) as well as for planning processes at national level or of other infrastructures within the realm of the TEN-E regulation.

2 MODELLING & SIMULATION

2.1 Scenario Storylines

The uncertainty of the future development of the energy system needs to be reflected in the TYNDP scenarios. European regulation prescribes a time horizon of ten years for network planning. Yet, given that investments are recovered over a significantly longer time span, it seems reasonable to additionally consider a longer outlook of 15 or 20 years, despite the increasing uncertainty linked to a longer scenario horizon.

It seems intuitive to base infrastructure investment decisions on a realistic, best guess of the likely future system development, such as the current National Trends scenario (ENTSO-E & ENTSO-G, 2022). More contrasting scenario storylines complement this by exploring the robustness of investment decisions with respect to an uncertain future. For European network planning such uncertainties may concern for example:

- the development towards central vs. decentral systems, such as the current Distributed Generation and Global Ambition (ENTSO-E & ENTSO-G, 2022),
- a focus on direct electrification vs. hydrogen and e-fuels, or
- the effects and effectiveness of flexibility and Energy Efficiency First policies[2].

Variations of storylines may manifest as substantially different scenarios that subsequently entail an entirely separate simulation and analysis. However, it is also possible to explore some variations as minor changes in only some or a group of parameters and thus explore alternative pathways without the effort of a full-fledged additional scenario. This is the case if the variation can be defined in a way that does not affect the energy balance and target compliance in one of the initial, main scenarios.

Importantly, the relevant outcomes, i.e., system needs and benefit indicators, need to be compared and discussed between those different scenarios to really assess the viability and

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[2] The latter two are currently lacking as distinct storylines.

robustness of alternative investment decisions.[3] It is vital to interpret the results of descriptive scenarios differently from those of normative ones:

- Descriptive scenarios: necessary infrastructure to remain operational in a likely future, feasibility of the near-term planning.
- Normative scenarios: necessary infrastructure to achieve the climate goals, feasibility of the planning beyond specified expected investments.

Normative and descriptive scenarios lend themselves to stakeholder communication, particularly for policy-relevant contexts and where non-expert groups are among the stakeholders of the analysis.

Underlying storylines bear regular verification regarding their plausibility given the advancement of green transition policies and regulation and their relevance to capturing the differences in infrastructure needs.

Criteria for individual scenarios are:

- **plausibility, comprehensibility, and transparency,**

  ensured via the stakeholder process that requires representatives from all sectors and reinforced by the subsequent communication of the scenarios and the results from the analysis in a way that is suitable for non-expert stakeholders;

- **traceability and openness,**

  enforced via the open publication and licensing of data, assumptions, and relevant tools; enables validation and thus reduces scepticism and creates acceptance of the analysis and its outcomes;

- **consistency and coherence within the scenario and with other scenario exercises,**

  achieved via the scenario building process, the discussion of data and assumptions, and the coherence with TEN-E pillars, i.e., ESI, EE1st and interconnection targets.

The preparation and presentation of the storylines shall include a discussion of how and to what extent these criteria are met.

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[3] If time and capacity constraints prevent all scenarios and results from being available within the tight schedule outlined by the TEN-E, missing scenario results and their discussion should be amended later and the automation or staffing of the process should be improved to streamline the process in the future.

2.2 Energy Balance

For consistency and comparability of the analysis between different scenarios it is important that they follow similar intrinsic logic and are constructed of the same building blocks:

- Determining demands per sector and energy carrier:
  - Determining sectoral activity as a basis for energy demand based on possible levels of economic activity or on projections within the national planning.[4]
  - Assigning sectoral demands to energy carriers based on assumptions on sectoral energy use.
- Determining supply potentials, e.g., for wind, photovoltaics, and biomass, based on data and assumptions, e.g., from JRC POTEnCIA and other relevant sources.
- Accounting of imports and greenhouse gas emissions, i.e., CO_2 and equivalents:
  - Deriving the levels of imports to balance out supply and demand from the previous two steps.
  - Deriving overall greenhouse gas emissions as a function of the energy carriers and technologies in the energy balance.
- Feedback loop for the verification of the greenhouse gas budget:
  - Employing a transparent carbon budget based on population or equity and including the use of carbon capture and storage in line with European policies.

Adjustments to the assumptions and projections entering these steps might be necessary to ensure the comprehensiveness of the storyline or as a result of the feedback loop for CO_2 equivalent. Importantly, such adjustments need to be justified and made transparent as part of the process.

2.3 Profiles

Profiling collectively refers to all methods that distribute the total quantities of supply and demand across the timesteps of the year. Intermittent supply and flexible demands are set to increase in future energy systems. These changes are relevant for the integration of renewables and the resulting need for grid expansion. To reflect them adequately, two general approaches can be distinguished:

- deriving fixed profiles as exogenous inputs to the dispatch and planning models, or

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[4] This should include a sensitivity analysis on economic growth as a driver of sectoral activity.

- implementing methods for endogenous decisions on profiles within the models.

Endogenous methods are generally more difficult to implement but potentially able to capture the dynamics of supply and demand within the energy system. In the following, we discuss how to improve the different profiling methods deployed in the TYNDP.

Supply from wind and solar

Generation profiles for fluctuating renewables like wind and solar are exogenous to the models since wind and solar generation are in fact exogenous to the energy system. The data for this can build on the Pan-European Climate Database covering different climatic years and capturing the difference between existing and newly installed wind turbines for each country. This is in line with the current approach in the TYNDP.

To reflect that not all conceivable sites for the installation of renewables have the same quality, the available potential of wind and solar is grouped into different sub-categories. Different full load hours should be assigned to less favourable sites. This means an improvement from the current methodology of merely assigning different investment costs to each category. Different generation profiles for each category, i.e., for less favourable sites, can be derived based on geodata (see for instance McKenna et al., 2022).

In addition, the dataset of generation profiles and ideally also the tool to derive them should be openly available. For the future, it is recommended to consider how climate change will impact the profiles of wind and solar generation and if historical data is still a valid foundation for future planning. However, it should be noted that despite its relevance, so far this question is not thoroughly discussed in academic research either.

Supply from hydro reservoirs

In contrast to wind and solar, hydro reservoirs can be dispatched but are restricted by the storage level that is again determined by exogenous inflows. Hydro reservoirs are an important source of flexibility for the European system. To capture this flexibility, reservoirs should be modelled as storage systems, but with an exogenous charging profile reflecting inflow (for an in-depth discussion on storage modelling see the following section).

Currently, the documentation of the TYNDP lacks a description of how supply from reservoirs is modelled. The deployed methods should be made transparent. This includes the level of aggregation meaning to what degree distinct but connected dams and reservoirs are treated as one system within the planning and dispatch model.

Supply from CHP plants and demand from heat pumps in district heating

The supply from CHP plants and demand from heat pumps in district heating networks create close interdependencies between this sector and the power system. It is important to capture how district heating networks can facilitate the integration of fluctuating renewables and improve the security of supply. The operation should aim to reduce residual load, for instance by utilizing CHP plants instead of heat pumps, when the residual load is high. For the deployed models this requires including an additional energy balance for district heat.

This is an improvement from the current TYNDP methodology, where the supply and demand profiles for these units are based on exogenous assumptions that include backup boilers to mitigate load peaks from heat pumps for district heating. A similar approach is employed for the representation of hydrogen added in the latest TYNDP.

Besides the additional computational effort, there is regulatory uncertainty about whether district heating network operators have incentives for system-friendly operation.

Demand from individual electric heating

Individual electric heating will increase in the future and is in principle also flexible. However, research shows that the flexibility of local heating systems not embedded into a network is limited. To reflect the flexibility and as an improvement to the current exogenous profiles[5] based merely on climatic data, endogenous profiles can be applied, similar to those discussed for district heating above.

This method is particularly relevant to capturing the effect of flexibility in the presence of price-based or contractual incentives for consumers. It is therefore particularly relevant for scenario storylines featuring policy commitments for flexibility as mentioned in 2.1. In the absence of such storylines, however, it may be reasonable to focus efforts and computational resources on other issues.

Demand from electric vehicles

Profiles of electric vehicles are determined endogenously and represent vehicles as storage that must match the predefined demand. The vehicles can only be charged while plugged in, which is an exogenous assumption. In the future, profiles of demand from electric vehicles could be subject to more extensive sensitivity analysis regarding the roll-out and grid integration of electric vehicles. In addition to system-friendly loading or vehicle-to-grid charging, the impact

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[5] Ruhnau et al. (2019) present an open methodology providing exogenous heat demand time series that can be used as the baseline demand to be matched.

of inflexible load profiles on system development could be analysed as well. Moreover, other developments, like battery swapping or the balance between individual and fleet vehicles, could be assessed regarding their impact on load profiles as well.

Similar to flexibility from individual electric heating, this approach is particularly relevant to scenario storylines featuring policy commitments for flexibility as mentioned in 2.1.

Demand from P2X

The electricity demand for electrolysis is a substantial source of flexibility. Hydrogen and subsequently produced e-fuels can typically be stored much easier than electricity, especially over longer periods. The newest iteration of the TYNDP implemented a novel and highly detailed representation of hydrogen that determines the corresponding electricity demand endogenously and considers differences among consumers, for instance regarding access to a potential transmission grid for hydrogen.

Overall, the methodology does not require substantial improvements. Potential shortcomings related to modelling for storage systems will be discussed in detail in the next section.

2.4 Dispatch & Expansion

Dispatch and expansion follow an optimisation from a social planner perspective. The respective models determine the expansion and operation of power plants and other infrastructure, like electrolysers or transmission networks, to satisfy a predefined demand at the lowest system costs. The optimisation is subject to various boundary constraints, for instance reflecting an emission limit or the technical potential of renewable energies. Since expansion planning includes decisions on plant operation, dispatch modelling is a subset of expansion planning. The main purpose of dispatch modelling is to identify the security of supply issues early on and it, therefore, neglects technical details which are included in the grid simulation discussed in section 2.5. Subsequent to the expansion model itself, the current TYNDP methodology includes a separate script that adds additional peak-load capacities where needed to ensure security of supply.

The potential expansion options stem from the scenario storyline. Some storylines, such as currently National Trends, base capacities on national projections, consider expansion only in the mid and long term and only optimise dispatch in the short term. To truly assess infrastructure gaps, however, expansion planning needs to start in the short term, like currently in the COP21 scenarios, and utilise a rolling horizon approach to account for path dependencies.

Expansion planning can be based on open-source tools, such as Antares, currently used for National Trends, and as a transparent alternative to commercial software, like Plexos, which is currently deployed for the COP21 scenarios.

Prosumers

Increasing local combination of demand and supply by prosumers affects grid expansion and the dispatch of flexible resources. Since it is often driven by factors that escape the techno-economic logic of cost minimisation it can be captured by exogenous assumptions on the development of residential photovoltaic in line with a specific scenario storyline. Although these assumptions will inevitably exhibit some degree of arbitrariness, this can be implemented in a transparent manner and in line with the overall social planner approach.

Expansion planning in the TYNDP currently represents prosumers by adding the electricity price paid by consumers for power from the grid to the overall objective function. To reduce these costs, the model can expand residential photovoltaic systems that cover a share of residential demand instead. However, a social planner approach for expansion planning should not account for transfer payments between actors within the system, like the power price paid by consumers to generators, grid operators, and the government. At the same time, its parametrisation related to current power prices seems arbitrary and not robust for a modelling horizon until 2050.

Storage modelling

Storage of electricity but also of hydrogen is key for the integration of fluctuating renewables into the power systems and its representation will impact the investment in other flexibility options, like transmission infrastructure. At the same time, the representation of storage in planning models can be complex and the existing approaches are heterogeneous. One approach is to optimise the operation of storage systems across the entire year under perfect foresight. However, this approach is computationally expensive and as a result other approaches only model storage operation across shorter timeframes, for instance, a week. These approaches, on the other hand, cannot capture the operation of seasonal storage.

Generally, capturing the full flexibility of short- or medium-term electricity storage, like batteries or pumped storage, but also seasonal storage, like hydrogen caverns, should be a priority in the expansion planning. In addition, it is beneficial to differentiate investments between energy and power capacity of storage, so expansion can adapt to the system needs.

To fully capture the benefits of seasonal storage, especially if these technologies play a bigger role in future energy systems, adjustments will be required regarding the current simulation of only a few representative weeks from a data set spanning several years of climatic data.

Multi-temporal planning

Expansion planning over a long timeframe is challenging because of the path-dependencies that arise. Since infrastructure has a long lifetime, decisions in the near future should already consider the long-term development of the energy system. Often, this is prevented by computational limitations. As a compromise, longer timeframes can be combined with fewer timesteps and combined with a subsequent myopic foresight approach. Thus, a first optimisation covers the entire timeframe until 2050 but only considers every fifth or tenth year to reduce the computational load. In the second step, expansion for the years in-between is determined with the previous results as boundary conditions at the beginning and end of the period.

This exhibits an improvement upon modelling with a reduced foresight and a rolling horizon, as in the current expansion planning within the TYNDP. The current myopic planning method based on 5-year steps might result in stranded assets. For instance, investment into new gas power plants could appear viable when limiting the scope to the years 2025 to 2030, although expansion is not cost efficient and leads to stranded assets as soon as the tightening of emissions constraints after 2030 is considered (see Gerbaulet et al., 2019). Alternative to perfect foresight, reduced foresight with a longer time horizon, for instance ten years, could be deployed. This approach could capture long-term planning by market participants but avoid “over-optimizing” and mimic imperfect decision making by real world investors.

In this regard, the TYNDP should adequately represent the lifetime of assets beyond the scenario horizon. To avoid stranded assets, the optimization needs to reflect that their utility might change if the asset is not as useful in the future as it is during the modelling period. Initially, it might be sufficient to qualitatively analyse what conceivable developments after 2050 could incur major changes of asset values. In the future, an extension of the modelling horizon or a dedicated effect in residual valuation or the annualization of investment cost should be considered.

Sectoral scope

Sector integration introduces various novel kinds of electricity demands, including hydrogen and e-fuels to provide seasonal flexibility. Thus, the interaction of the power sector with the rest of the energy system becomes increasingly important. As discussed in sections 2.2 and 2.3, it is important that other sectors are captured by exogenous assumptions or endogenously in the model, thereby partially expanding the sectoral scope of capacity planning to other sectors.

The novel representation of the hydrogen sector and electric vehicles constitute substantial improvements in the TYNDP. As discussed earlier in section 2.3, the sectoral scope needs to be extended at least to district heating networks and ideally also to individual flexibility.

Beyond that, the TYNDP for electricity and gas infrastructure should deploy a shared expansion planning to capture the increasing interdependencies between the sectors, for instance by considering the potential repurposing of methane pipelines for hydrogen.[6]

2.5 Grid Simulation

The actual grid simulation occurs after the initial dispatch modelling for expansion planning. This is largely due to computational limits, as the dispatch modelling that supports the expansion planning as part of the scenario process is not sufficiently detailed to also evaluate the grid impact of expansion projects. In the dispatch modelling, the transmission grid is only represented on a country level and modelled as a transport instead of a load flow problem. To evaluate the grid impact of specific expansion projects, a comprehensive grid simulation using a larger number of nodes and a flow representation is performed subsequently. This grid simulation builds on the previous market simulation that determines dispatch decisions on a spatial resolution of about one hundred nodes for all of Europe. The grid simulation itself applies different models separately for each synchronous grid area. For the TYNDP itself, it does not yet consider redispatch within the market zones.

The grid simulation and corresponding identification of system needs should be performed for all scenarios and evaluated subsequently as elaborated in section 2.6. This constitutes an expansion of the analysis compared to the current TYNDP process where this step is limited to the National Trends scenario. The two COP21 scenarios complying with long-term climate targets are not analysed for all scenarios and time horizons although the scenario building process dedicates significant effort to them.

To fully capture potential benefits from battery storage and peak units as substitutes for grid expansion, the identification of system needs should not be limited to the expansion of the power grid. This is a considerable improvement already implemented in the latest TYNDP.

The grid simulation is performed separately for specific hours and dispatch is based on results from the previous step. The transfer of dispatch is one of the most critical aspects of the grid simulation. Inputs regarding demand or generation that are initially computed at national or zonal level must be allocated to each network node in a plausible and transparent way. Making the scripts and methodology of this step available supports further studies and subsequent improvements on the topic. The TYNDP methodology thoroughly describes this process for

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[6] This approach also enables to assess offshore energy hubs more closely within the planning process. On artificial islands such hubs could combine offshore generation of electricity with on-site electrolysis and provide both electricity and hydrogen. Implementing these hubs as distinct nodes in an integrated electricity and gas model can assess to what degree such hubs should deploy gas or electricity transmission to transport energy to consumers.

the transfer from scenarios to expansion and dispatch simulation but lacks corresponding information for the grid simulation.

For a future improvement of the grid simulation methodology, the introduction of flow-based market coupling (FBMC) in central and western Europe could be taken into consideration in order to more accurately depict cross-border capacity use and allocation.

2.6 Benefit Indicators

The recast of the TEN-E (Art. 4, 3. a & d) specifies sustainability in combination with security of supply or market integration and competition as criteria to assess the benefits of electricity and hydrogen transmission infrastructure.

- **Sustainability** refers to the transport of electricity or hydrogen from renewable sources and the support of variable renewable power generation via flexibility and storage.
- **Security of supply** captures the benefit of appropriate connections and facilitating secure and reliable system operation, interoperability, system flexibility, and cybersecurity.
- **Market integration** and **competition** encompass connecting hydrogen networks and contributing to a Union-wide network, lifting the electrical isolation of Member States and reducing bottlenecks, as well as enabling access to multiple supply sources and network users on a transparent and non-discriminatory basis.

In line with the above modelling and simulation these criteria are captured by a set of indicators discussed in the following.

For an individual project these criteria are often assessed as a delta between the simulation outcome with or without the project. Without significant interrelations between the proposed projects, it is valid to assess the simulation outcome against a baseline with only the project in question or alternatively with all proposed projects except the one to be assessed (+project / -project). For circumstances where the subset of proposed projects is highly interrelated, a more sophisticated stochastic analysis might be appropriate.

All indicators can in principle and with slight adaptations apply to both electricity and gas. In view of increasing system integration an integrated model is used to assess both electricity and gas projects for their effects in both sectors. Hence, a new transmission line or pipeline is assessed for its effect on welfare or greenhouse gas (GHG) emissions related in electricity and gas supply.

Table 1: Benefit Indicators

Indicator	Method / Approach	Δ to current TYNDP	Potential sensitivities	Criteria
Renewable energy (RE) integration	difference in energy supplied (sum of electricity & gases) from renewable sources (absolute values & shares) from simulated dispatch	analyse overall RE in final energy supply as opposed to differentiating between capacity and production or gas and electricity (to replace difference in electricity curtailed / in hydrogen capacity connected)	hydrogen production types (electrolyser matrix), climate years & RE potential	sustainability
Societal cost of CO_2-equvalent	difference in GHG emissions (additional to emission trading value) per multiplication of dispatch	capture cost in addition to emission trading valuation, which is accounted for in welfare (to replace the choice between the two in the current gas methodology)	CO_2 price path, additional societal cost	sustainability
Non-direct GHG-emissions & env. impacts	difference in non-direct emissions & impacts per multiplication of dispatch	based on integrated dispatch for electricity & gas to capture system interdependencies	emission & impact factors	sustainability
Welfare & supply cost	difference in maximum welfare from energy supply from simulation	evolved from simple cost minimisation - especially relevant for demand flexibilities and energy savings, integrated analysis of electricity and gases to capture sector integration	cost paths for energy, GHG & technologies, shares of prosumers, heat pumps & electric vehicles	market integration, competition, sustainability
Diversification & integration	difference in dominance (largest market share in x consecutive time steps) of a single source (incl. imports) or technology, incl. through access to storage per concerned country	summarises the indicators on supply source diversification & access and market diversification for the gas system and adds this dimension for the assessment in electricity	cost paths for energy, GHG & technologies, climate years & RE potential	competition, market integration, security of supply
Balancing	difference in capacity requirement and cost for balancing	--		security of supply, flexibility
Adequacy	difference in expected unsupplied demand (energy and valuation) in Monte-Carlo varied scenario & for extreme cases (extreme weather, infrastructure disruptions, demand synchronisation)	addition of purposeful variations to random Monte-Carlo approach	VOLL & CODG/H, demand flexibility, storage & peak capacity	security of supply
Other Benefits	such as system stability, impact on capacity or price for black start	addition of cybersecurity as required in the TEN-E		security of supply

	reserves and reactive power or cybersecurity, if applicable consider acceptance and stakeholder engagement as benefit dimensions	

The indicators need to be compared and discussed between diverse scenarios and in view of their main sensitivities. This is important to explore the robustness of a project's assessment and to assess its contribution to the long-term flexibility of the energy system. Thus, for example, a project that adds significantly to overall welfare in only one scenario can be assessed justly against another one adding slightly less welfare but does so robustly in all possible futures considered within the analysis.

Furthermore, these indicators should be subject to regular revision in view of new developments, business models and technologies. Moving forward the process should involve a recurring evaluation of whether aspects such as hydrogen leakage or innovative types of flexibility are reflected in line with the state of knowledge. Wherever assessments are provided by the project promoter, they should have access to the initial model and scenario parameters to ensure consistency with the remaining assessment. Ideally this applies also for promoters of projects in other categories of projects of common interest.[7]

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[7] As the TYNDP is the most developed effort among the categories of projects of common interest, the modelling and scenario framework should be made available to other project promoters - as well as to all other stakeholders.

3 STAKEHOLDER ENGAGEMENT & TRANSPARENCY

Positive stakeholder engagement is shaped and fostered by adequate and suitable stakeholder processes and via transparency and documentation of data, assumptions, and methods used in network planning. The process needs to cater both to experts and to stakeholders with cursory involvement in the process.

3.1 Stakeholder Process

In addition to the existing stakeholder process, consisting of a sequence of webinars and written consultations of advanced draft documents, the stakeholder process should involve a consensus- and dialogue-based expert consultation and a feedback loop to reiterate central parts of the scenario building. The former is instrumental for capturing disruptive events in the scenario design. The latter gives especially non-expert stakeholders the opportunity to fully grasp the effects of individual scenario aspects as well as their interactions. The SEEDS project[8] represents an attempt to let stakeholders iterate the scenario building itself rather than merely consulting the consecutive steps.

Furthermore, diverse storylines potentially streamline the stakeholder interaction, as conflicting or contradicting inputs from different stakeholders can be reflected in separate storylines. This shifts the discussions and stakeholder involvement from the scenario building phase to the results, i.e., system needs and project assessment, where it can more immediately foster the acceptance of infrastructure planning.

To interpret and utilise the consulted scenarios, stakeholders need to be able to navigate the (intermediary) results easily. The presentation and visualisation of the scenario data for network planning should therefore follow best practices for user-friendliness as established for comparable data by Eurostat or the visualisation of the PRIMES scenarios[9] as well as the IAMC 1.5º Scenario Explorer[10] for reports of the Intergovernmental Panel on Climate Change.

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[8] https://seeds-project.org/

[9] https://e3modelling.com/modelling-tools/primes/

[10] https://data.ene.iiasa.ac.at/iamc-1.5c-explorer/

3.2 Openness of Data, Code, and Publications

Especially when it comes to an infrastructure planning process affecting many stakeholders like the TYNDP, the grade of openness of the process in terms of data and models used, but also publications (see Figure 1), are important.

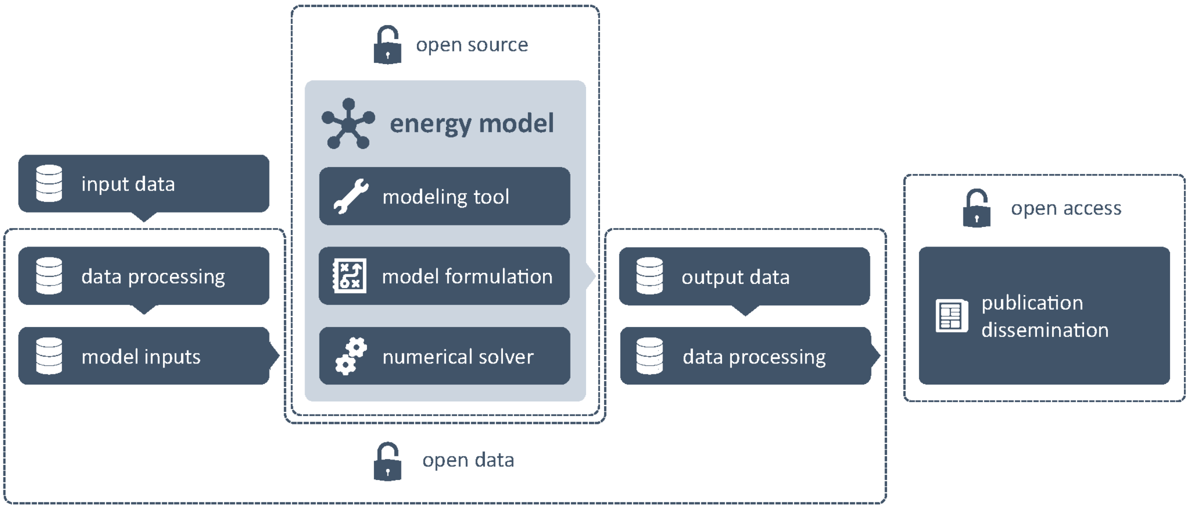

Figure 1: Workflow and dimensions of openness in the energy modelling process (adapted from Weibezahn & Kendziorski, 2019)

There are ample benefits connected to open data and open-source modelling tools and frameworks. Using ‘black-box’ models prevents stakeholders like the scientific community or non-governmental organizations from replicating and validating the results. This essentially means a forgone opportunity to create and propel acceptance. Another aspect is the quality of the modelling. Checks and balances for the results and also for the tools and process improve the quality and therefore significance of the information that is generated. Relying on a decentralised community of collaborators may also improve and speed up the adaptation of the modelling to new developments and technologies.

Ideally, not only the model formulation itself but also the entire modelling tools are available open source and therefore usable for others with as little friction as possible. Aside from these practical matters, transparency may be perceived by consumers as a quality dimension of network use. In the absence of competition to make it available, monopoly regulation of network operation might foster that tools developed and data obtained enter the public domain or are at least openly licensed.

In the future and when available, also open-source solvers should be considered to empower also non-academic and less affluent stakeholders to fully reproduce the process.

Open data

A central aspect is the open provision of data used in the TYNDP process. This applies to input data, processed and intermediate data, as well as to output data. For data to be truly open and therefore ultimately reusable, the process should follow the generally recognised standards for data re-use. One now widely established open standard are the FAIR data principles (Wilkinson et al., 2016). The acronym stands for:

- **findable,**
  i.e., described by rich metadata and indexed in searchable resources;
- **accessible,**
  i.e., via a standardised communication protocol;
- **interoperable,**
  i.e., using a standardised language for knowledge representation and the FAIR vocabulary; and
- **reusable,**
  i.e., licensed and with detailed provenance (see above).

FAIR contains 15 principles in total. Ideally, the TYNDP should adhere to all of them. Yet, some are more important than others in this context:

- A first step is to publish the *full* data set (including input, processed, and output data).
- Data is published including rich and metadata[11]. Metadata help the user and machines to understand and use the available data. They are essentially a documentation of the data set and should be as rich as possible describing exactly the scope and limitations, the type of data (e.g., raw/processed), what the content of each table is, where the data come from[12], what the variables exactly contain including, e.g., the use of self-explanatory of thoroughly explained variable names, the used units, etc. It also contains a thorough versioning of data sets. A commonly accepted language and a good data model are prerequisites for the documentation[13].

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[11] Principles F2 and R1: Data are described with rich metadata and (meta)data are richly described with a plurality of accurate and relevant attributes.

[12] Principle R1.2.: (Meta)data are associated with detailed provenance.

[13] Principle I1: (Meta)data use a formal, accessible, shared, and broadly applicable language for knowledge representation.

- Data is adequately licensed[14]. Only properly licensed data can be legally reused by others than the data owner. An open licensing model should be used. Morrison (2018) and Hirth (2020) both discuss the issue of license selection. A commonly used license is the CC-BY 4.0 license. Yet, this depends on the provenance and prior licensing of the data that became part of the TYNDP. Ball (2014) provides a guide to license selection. A final decision requires legal consultation.
- Data are made available with an adequate identifier[15]. In addition to uploading the data sets to the TYNDP website, they should be made available at a place where a unique and persistent identifier can be appropriated. This could, for example, be a repository on Zenodo or comparable resources. This helps in finding and accessing the data sets but also in versioning them properly and keeping track of changes.
- Further principles should be implemented to ease automated and machine-readable access to data.

The GO FAIR initiative provides details, examples, and guidelines, for example, the FAIRification Process and framework in how to go FAIR.

Open tools

The availability of open tools has been addressed in the previous section where applicable. Open-source alternatives should be preferred over proprietary software. If tools are specifically developed for the TYNDP they need to be made available on a code repository like, for example, GitHub. The models used for the TYNDP, including the specific versions of the modelling frameworks used and all the code in that context, should also be made available. In addition to that, the code needs to be properly documented in comments or a separate documentation file and, just as described above with the data sets, an open license like the MIT License needs to be applied in order to allow for the reuse of this code. Again, Morrison (2018) and Hirth (2020) provide insightful discussions on the choice of the right license.

Open-source alternatives for dispatch & expansion modelling

Implementing the improvements in a closed commercial tool, like currently employed for the COP21 scenarios, appears challenging and limits transparency. Since changing the tools used for an extensive analysis like the TYNDP is difficult and subject to considerable risk, a first step of transitioning to open-source could be to use current and open-source tools in parallel

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[14] Principle R1.1: (Meta)data are released with a clear and accessible data usage license.

[15] Principle F1: (Meta)data are assigned a globally unique and persistent identifier.

for some time, also to support cross-validation. There are several open-source alternatives available for capacity planning based on linear optimisation:

- *PyPSA/PyPSA-Eur-Sec* (Brown et al., 2018) originated as a power system analysis toolbox but has been extended to a capacity planning tool for integrated energy systems. This extension is called *PyPSA-Eur-Sec* and includes the heating, transport, and industry sectors and hydrogen infrastructure. For the operation of storage, the tool considers the entire year under perfect foresight implying suitability to model both short- and long-term storage of any energy carrier. It is implemented in Python and includes a wide range of functionalities to pre-process input data, analyse results, and create plots. The power sector tool *PyPSA* supports optimisation of pathways under perfect foresight, but *PyPSA-Eur-Sec* is currently limited to myopic foresight. *PyPSA* and *PyPSA-Eur-Sec* have been used by numerous academic and non-academic institutions for power and energy system analyses.[16]
- *Calliope* (Pfenninger & Pickering, 2018) is a capacity planning tool for multi-scale energy systems, meaning it is equally suited for analyses of large and small-scale systems. Operation of storage can either be modelled based on a continuous time-series or selected representative periods that are interlinked to enable seasonal storage as well. The tool does not support planning over several years. Data inputs for the tool are provided by easily accessible YAML files and built-in functionalities facilitate the analysis and visualisation of results.
- *AnyMOD.jl* (Göke, 2021a, 2021b) is an expansion planning tool written in Julia and developed for integrated energy systems with large shares of fluctuating renewables. The tool implements several methodological innovations to model systems at great scope and detail without exceeding computational limitations. Temporal resolution can be adjusted individually per energy carrier, meaning electricity can be modelled hourly while hydrogen is represented daily. This maintains the representation of flexibility but reduces computational complexity. Operation of storage and expansion modelling assume perfect foresight within a single year. *AnyMOD.jl* promotes accessibility by using CSV files as a standard in- and output format and requires only few lines of standard code to run.
- *SpineOpt* (Ihlemann et al., 2022) is an energy system modelling framework with high level of flexible temporal, spatial, and technological adaptability including stochasticity. It is part of the larger Spine Toolbox enabling users to comfortably

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[16] see https://pypsa.readthedocs.io/en/latest/users.html

manage and use data and execute models in a graphical user interface. In the upcoming HORIZON Europe project "Mopo"[17], the Spine Toolbox will be further developed with regard to time series and sector-specific data acquisition tools.

- *Antares-Simulator*[18], originally developed by RTE, is a power system simulation software currently used in the TYNDP process. The special feature is the possibility of representing stochastic features in short- and long-term adequacy studies using Monte Carlo simulations. Antares does not have any expansion features but soft-linking options with TIMES and OSeMOSYS/GENeSYS-MOD.
- *SCIP*[19] and *HiGHS*[20] are both solvers suitable for the process available under open licenses with HiGHS also being fully open-source. Yet, they still need to reach the potential of proprietary and commercial solvers.

Open-source alternatives for grid modeling

Currently, different (proprietary) tools for the simulation of different grid areas are being used. Several open-source tools for grid simulations in the power and gas transmission grids have been developed over the last years and can be used to replace the proprietary ones:

- For power grids, the following tools are available: PowerSimulationsDynamics.jl (NREL), PowerDynamics.jl (ELENA), PowerModels.jl (ANSI).
- For gas (and hydrogen) grids, the tool GasModels.jl (ANSI) is available. Potentially, pure transportation models could suffice the needs in the process already.

In any case, it is of high importance to make the underlying grid data for electricity and gas networks openly available in a well-documented and machine-readable form.

Roadmap to openness

Acknowledging the limited resources allocated to the TYNDP process additional tasks connected to openness might be difficult to accommodate. Yet, the process can be broken down into several steps of gradual improvement:

1) Versioning and assigning a doi for different versions of the documents involved

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[17] Call HORIZON-CL5-2022-D3-01-13: "Energy system modelling, optimisation and planning tools"

[18] https://github.com/AntaresSimulatorTeam/Antares_Simulator

[19] https://www.scipopt.org/

[20] https://highs.dev/

2) FAIR data: As a first step, all (a) output data and (b) input data should be made available following the principles described above. This includes the use of meta data, adequate licensing, and interoperability. The availability of data involved in the scenario building process can be initially improved to develop a best-practice which could then be extended to the rest of the process, including grid simulations and the cost-benefit analysis.
3) Dispatch & expansion planning: In a second step, the tools used for the dispatch and expansion modelling can be replaced by open-source tools as far as possible (or proprietary tools can be transferred under an open license). This process can be based, first on (a) an assessment of existing tools for their potential to replace proprietary tools. This includes formulating a list of requirements and checking it against those candidates. As a next step, (b) the currently used and the proposed open-source tool would be compared. Lastly, (c) for those tools developed as part of the TYNDP process, the model code used can be made openly available under an adequate license.
4) Further tools: The same approach should be followed in the third step for further tools used in the generation of profiles.
5) Grid simulation: In a last step, this process should be performed for the used grid simulation tools.

Ideally, such a roadmap to full openness should be supported by the regulation, concretely outlining the requirements of the process and at the same time endowing the responsible parties with sufficient resources, in the different dimensions laid out in the sections above.

4 SUMMARY

The scenario building and energy system modelling are at the core of the TYNDP process. The main outcomes regarding infrastructure gaps and cost-benefit evaluation, as well as the usability and acceptance by the manifold stakeholders rely heavily on a suitable design of these features. The recast of the TEN-E regulation has strengthened the mission to reflect energy systems integration and the Energy Efficiency First principle adequately and ambitiously in this process.

In view of these challenges, the TYNDP methodology is set to advance along with the state of knowledge on scenario building and energy system modelling. This document presents the STEERS methodology for improving the network planning process. We present a set of building blocks to enhance streamlined European energy infrastructure development. These are based on academic literature on scenario development and state-of-the art energy system modelling.

The objectives of the exercise are to assess planned projects, point out infrastructure gaps, and to provide a cost-benefit analysis for the selection of projects of common interest. In light of these objectives, the current exercise can improve by enhancing in traceability, openness, and sector integrated activity. The most promising approach is still a toolchain with (soft-)links of different purpose models. Most tasks can be fulfilled with open methodologies given the availability and reusability of data.

This STEERS methodology highlights the need for varied scenario storylines to address uncertainties regarding the future development of the energy system. It is based solely on energy balances that comply with politically agreed greenhouse gas budgets and proposes targeted improvements for constructing demand profiles for flexible demands and renewable generation. The methodology focuses on openness and traceability suggesting using publicly available, non-commercial tools while ensuring an increased level of integration and a higher level of detail on flexibility and end-users.

Regarding energy system modelling, there have been several advances in methodology including full-fledged sector coupled models that are useful for the TYNDP analysis. We suggest a set of open-source models that can already live up to commercial solutions.

This lays out the path for a more detailed analysis of tangible improvements of the methodology regarding selected use cases of sector integration, energy efficiency, and stakeholder involvement, which we will tackle in a next step as a proof of concept.

Table 2: Methodology Overview

	STEERS Methodology	Δ to Current TYNDP	Options for Future Improvements
Scenario Storylines	varied storylines, interpreted in the context of descriptive and normative aspects	additional storylines (direct electrification, flexibility) all compliant with climate targets, compared and interpreted thoroughly, time horizon of ten years and beyond	Improvements and increased automation/interoperability in tool chain to streamline the analysis of varied storylines and sensitivities
Energy Balance	scenarios build on sectoral activity, supply potentials in line with common studies and emissions targets	base all scenarios on the same methodology, disclose all relevant assumptions and input modifications	explore and communicate sensitivities in a structured manner
Profiles			
Wind & Solar	exogenous profiles for weather dependent renewables	lower full load hours instead of higher investment cost for less favourable sites	reflect climate change in input weather data
Hydro Reservoir	modelled as storage systems with exogenous charging profile	currently modelling and its aggregation somewhat unclear	reflect climate change in input weather data
District Heating	dispatch CHP and heat pumps to reduce residual load and include an energy balance for district heat	endogenous dispatch instead of exogenous assumptions	reflect regulatory uncertainty regarding incentives for system-friendly operation of district heating
Electric Vehicles	optimisation of charging based on exogenous grid-connection profiles	endogenous charging instead of exogenous assumptions	reflect system-friendly charging, vehicle-to-grid options, battery swapping and individual vs. fleet vehicles
Power to X	endogenously determined demand for different consumer types	--	--
Dispatch & Expansion			
Prosumers	transparent, exogenous assumptions for expansion	exogenous assumptions instead of endogenous expansion based on consumer prices and deviating from the social planner perspective	reflect regulatory uncertainty regarding incentives for prosumers
Storage	capture the full flexibility of short- or medium-term but also seasonal storage for capacity expansion	differentiate investments between energy and power capacity of storage, simulate more than a few representative weeks	--

	STEERS Methodology	Δ to Current TYNDP	Options for Future Improvements
Multi-temporal Planning	combine a first optimisation covering the entire timeframe but only few years with a second step expanding the system inbetween those years with the previous results as boundary conditions	improvement from reduced foresight and rolling horizon, preventing stranded assets	reflect disruptions in assets' lifetime beyond the scenario horizon, initially qualitatively and eventually via extended modelling horizon or a dedicated effect in residual valuation or annualization of investment cost
Sectoral Scope	capture other sectors by exogenous assumptions and ideally endogenously via shared expansion planning	extension of the sectoral scope, e.g., following the example of hydrogen, at least to district heating and ideally also to individual flexibility	--
Grid Simulation	employ open modelling tool uniformly across the entire area	transparent methodology for transfer of zonal dispatch to grid nodes (similar as for transfer from scenarios to market simulation), publication and discussion of results for all scenarios and time horizons	include potential effects on redispatch within zones, depict flow-based market coupling in CWE region
Benefit Indicators	streamlined indicators for electricity and gas (as far as possible) cover all aspects of the TEN-E recast, evaluated and discussed for all scenarios and time horizons, see details in Table 1	see details in Table 1	recurring revision to capture emerging aspects such as hydrogen leakage or innovative types of flexibility, deployment of more sophisticated stochastic analysis (instead of analysis +/- project) to capture interrelations between the proposed projects, links to assessment of other PCI categories
Transparency			
Stakeholder Process	Targeted communication along the process, expert consultation, feedback loops	broader exploration space to reflect stakeholders' positions in the analysis	--
Openness of Data, Code, and Publications	complete and easy access to data and tools for reuse and validation	complete input, intermediary and output data in line with FAIR principles, use of open tools as far as possible, stepwise improvement of transparency	recurring structured comparison of open tools for process steps that are still closed, use of open-source and openly licensed solvers

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