FINAL REPORT

FOR INTEGRATED NETWORK PLANNING IN EUROPE

A DELIVERABLE OF THE STEERS-PROJECT

JUNE 2023

CBS DEPARTMENT OF ECONOMICS
COPENHAGEN BUSINESS SCHOOL

CSEI Copenhagen School of Energy Infrastructure

DEPARTMENT OF ECONOMICS
COPENHAGEN BUSINESS SCHOOL

PREPARED BY:

COPENHAGEN SCHOOL OF ENERGY INFRASTRUCTURE
COPENHAGEN BUSINESS SCHOOL

MAIN AUTHORS:

CHRISTINE BRANDSTÄTT

ALEXANDRA LÜTH

BASED ON CONTRIBUTIONS FROM:

THEODOROS BECHLIVANIS

PETER GEORGE

LEONARD GÖKE

TOORAJ JAMASB

MANUEL LLORCA

JULIUS MEIER

JENS WEIBEZAHN

30. JUNE 2023

Funded by
the European Union

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CONTENTS

ACRONYMS

ACER	Agency for the Cooperation of Energy Regulators
EE1st	Energy Efficiency First
ESI	Energy System Integration
EV	Electric Vehicle
FAIR	Findable, accessible, interoperable, reusable
GHG	Greenhouse gases
STEERS	SmarT and Efficient EneRrgy System integration
TEN-E	Trans-European Networks for Energy
TSO	Transmission System Operator
TYNDP	Ten-year Network Development Plan

EXECUTIVE SUMMARY

This report sums up the findings of the STEERS project, which aims at aiding the implementation of system integration, the energy efficiency first principle, as well as the improvement of transparency and openness in the planning of energy networks in the European Union, and specifically in the Ten-Year Network Development Plan (TYNDP) process.

In the project, the Copenhagen School of Energy Infrastructure (CSEI) has first assessed the planning of cross-border network infrastructure in Europe against the current state of knowledge. Subsequently, with the STEERS methodology (Brandstätt et al., 2023) the project team has proposed incremental changes to the TYNDP process in view of the requirements from the TEN-E regulation recast. Lastly, the feasibility of the altered methodology is assessed in this report. The suggestions and findings have been discussed throughout the project with and among stakeholders from the modelling community, the European network industry, policy makers and societal actors, to ensure their relevance and viability in practice.

The methodology applied for the TYNDP evolves with each new edition along with the regulatory pressures and with the state of knowledge. This is particularly evident regarding the integration of gas and electricity systems and with respect to the representation of flexible and cross-sectoral technologies. While aknowledging this, the STEERS methodology outlines potential further improvements. It highlights the need for varied scenario storylines to address uncertainties regarding the future development of the energy system. Moreover, the methodology 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. As a central improvement, the STEERS methodology also focuses on openness and traceability of data, assumptions and methods, and promotes the use of publicly available, non-commercial tools.

As a next step, the project validated the feasibility of the improvements outlined in the STEERS methodology. To facilitate the verification of future TYNDP versions in view of the STEERS methodology, the project provides a comprehensive checklist with specific questions related to the critical aspects of each step in the TYNDP process.

The final assessment in this report distinguishes improvements of the TYNDP methodology which seem more relevant to comply with the TEN-E criteria and with transparency objectives and that require relatively low, maybe only a one-off effort. Basic improvements regarding transparency and stakeholder involvement along with some basic implementation of open data and open modelling seem particularly attainable at medium effort but have a high relevance according to this framework. Also the use of more varied storylines to reflect the impact of flexibility better seems highly relevant, and can at least to some degree also be realized with moderate effort.

A concrete example of 'low-hanging-fruit' with respect to transparency, is the improvement of data publication. To showcase the shortcomings of the current procedure in detail, we have compiled a list of all input data and assumption variables for the scenario building. This exercise points out precisely what kind of data is not yet published as accessibly and transparent as it is common practice in energy system modelling.

To provide further inspiration, this report includes a list of good practices that have provided valuable insights for the project and cover all different steps of the TYNDP process. The list includes a number of open models and tools which can either be employed directly in the TYNDP process or can inspire open solutions to be used in the future. We also feature promising instances of stakeholder engagement and some references of indicators included in cost-benefit analysis.

While the STEERS assessment sees the TYNDP process tackling many of the necessary improvements, the project also still identifies shortcomings with respect to transparency and openness. The material provided in this report and the input provided throughout countless discussions and consultations throughout the project ideally help to bring the process closer to the state of knowledge and common good practices in those dimensions as well.

1 CONTEXT & OBJECTIVES

In the STEERS[1] project, Copenhagen School of Energy Infrastructure has assessed potential developments and improvements of network planning process in Europe. This final report sums up the findings of the project.

The Ten-Year Network Development Plan (TYNDP) is developed biannually by the European networks of transmission system operators (ENTSOs). It assesses planned infrastructure projects, and the overall infrastructure needs between European countries over a time span of 10 years. Due to the long lifespan of this infrastructure and the long lead times of commissioning it, the scenarios and modelling horizon cover a timeframe of 20 to 30 years, i.e., until 2040 and 2050.

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 (PCI). 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.

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.

The recent exercises raised concerns among stakeholders on the level of joint planning between electricity and gas, the incorporation of the energy efficiency first principle, and the lack of transparency along the process and in the outputs. The STEERS project developed a modified

[1] Methodology for implementing SmarT and Efficient EneRgy System integration

methodology for the TYNDP process. This STEERS methodology draws from the state of knowledge regarding energy system modelling and planning and has a close link to the current methodology established by the ENTSOs for the TYNDP. It is subsequently validated in a proof of concept and supplemented by a checklist to aid the assessment of future TYNDPs. This report furthermore illustrates the methodology with examples of good practices and assesses the current state of data publishing within the TYNDP.

The report is organized as follows: Section 2 provides a background, Section 3 summarizes the STEERS methodology, and Section 4 delivers a proof of concept. Support material for working with the methodology is explained in Section 5, and we conclude on the project in Section 6.

2 BACKGROUND

The objectives of the TYNDP comprise streamlining the planning of network interconnections in Europe, assessing planned projects, and pointing out remaining infrastructure gaps as per the current planning. The TYNDP also provides a cost-benefit analysis (CBA) of planned projects which forms the basis for the selection of so-called projects of common interest (PCIs). Based on their European relevance, PCIs are eligible for additional support and some even for funding from the Connecting Europe Facility (CEF). The new TEN-E regulation appears to strengthen the aspect of a future-proof system within the framework of the European Green Deal, suitable for energy systems integration (ESI) and in line with the energy efficiency first (EE1st) principle.

Beyond the mandate of streamlining the planning of network interconnections, the TYNDP 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.[2] Although ENTSOs declare that it is not their intention to promote a political agenda the TYNDP may have this effect. Additionally, 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.

According to the recently recast TEN-E regulation:

- ENTSOs develop, consult, and publish draft scenarios, get opinions from the Agency for the Cooperation of Energy Regulators (ACER) and from the Commission, revise the draft, get the Commission's approval, and publish the final scenario report (including relevant input data) (Art 12.2-8, TEN-E).
- ENTSOs develop, consult, and publish a draft for the infrastructure gaps report, get ACER's and the Commission's opinions, revise the draft, and publish the final report (without requiring final approval from the Commission and not necessarily including the relevant data) (Art 13, TEN-E).

[2] This aspect has been brought forward by several stakeholders and is discussed for example by Göke et al. (2021).

- ENTSOs develop, consult, and publish the methodologies (i.e., regarding network & market modelling) for a harmonized energy system-wide CBA, get ACER's and the Commission's opinions, revise their draft accordingly (including a justification in case of only incremental revision), get the Commission's approval, and publish the final methodology (Art 11.1-9, TEN-E).
- ACER publishes indicators and reference values for unit investment costs of comparable electricity and hydrogen projects every three years and ENTSOs are to use those for subsequent CBAs (Art 11.10, TEN-E).

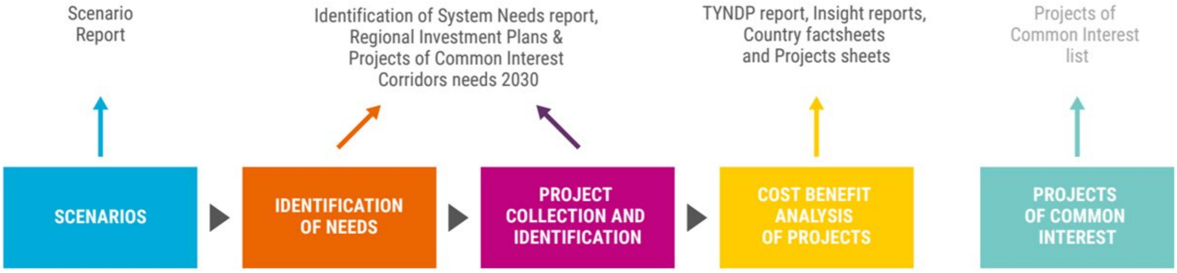

Figure 1: TYNDP process and PCI selection according to TEN-E (adapted from ENTSO-E, 2021)

As shown in Figure 1, the analytical steps of the TYNDP are the scenario building, the identification of system needs and infrastructure gaps, and the CBA. For this project, we assess all the depicted steps.

The project follows the workflow shown in Figure 2. We thoroughly assessed the state of knowledge regarding scenario development and energy systems modelling in view of the current state of the TYNDP exercise. The assessment focuses on the reflection of energy systems integration and EE1st, as well as on stakeholder participation and transparency. These features greatly affect main outcomes regarding infrastructure gaps and cost-benefit evaluation, as well as the usability and acceptancy by the manyfold stakeholders. The recast of the TEN-E regulation has strengthened the mission to adequately and ambitiously reflect energy systems integration and the EE1st principle in this process and thus underlines its ongoing challenges of incorporating the integration of renewable energies and flexibilities from demands at distribution levels and from sectors beyond the core infrastructure captured in the TYNDP.

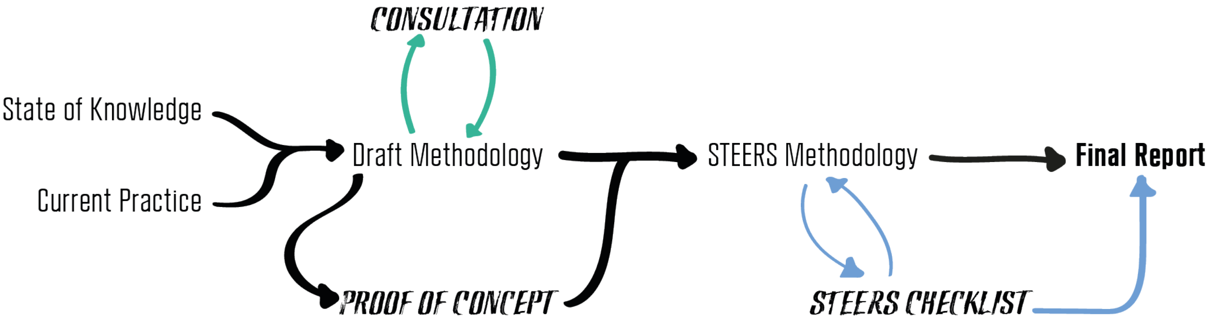

Figure 2: Workflow of the STEERS project

Table 1 summarizes central features of an energy system modelling exercise and locates the TYNDP process within this descriptive account of scenario frameworks based on Witt et al. (2018). Given the current challenges it seems worthwhile to revisit, whether and to what extend the process is positioned appropriately in all dimensions.

Having assessed the state of knowledge and aligned with the current practice, we develop and present our TYNDP draft methodology in *deliverable D2-3* (Brandstätt et al., 2022). The draft methodology focuses particularly on the reflection of energy systems integration, the EE1st principle, and on stakeholder participation and transparency. In a consultation process and with the help of a proof of concept, the draft methodology advanced into the STEERS methodology which we publish in Brandstätt et al. (2023), summarise in this final report, and accompany with a checklist.

Table 1: Morphological assessment of the TYNDP framework based on Witt et al. (2018)

Energy Scenarios						
Orientation	predictive	explorative	normative			
Purpose	policy effect of external conditions	exploration of future circumstances	advocacy of particular actions	representative sample of future states		
Type of Information	mainly quantitative	mainly qualitative	combined (storyline + simulation)			
Domain of Results / Impacts	technical	economic	social	climate impact	environmental	
Temporal Scope	short term	medium term	long term			
Geographical Scope	local	regional	national	international	global	
Economic Sector	overall economy	electricity	heat	transport		
Model Properties						
Analytical Approach	top down	bottom up				
Geographical Scope	local	regional	national	international	global	
Temporal Resolution	minutes	hours	days	years		
Number of Models	one	multiple				
Coupling of Models	soft link	hard link	no link			
Scientific Practice						
Transparency of Decision Support	explicit evaluation of scenario (e.g., multi-criteria analysis)	implicit data driven analysis				
Rationale for Assumption and Constraints	based on literature	based on own assumptions	not provided			
Consistency of Constraints & Assumptions	demonstrated	not demonstrated				
Communication of Uncertainties	critical assumptions are marked explicitly	assumptions are not distinguished				
Ease of Model Validation	glass box	grey box	black box			
Institutional Setting						
Commissioner	public institution	private institution	non-governmental organization	no commissioner		
Affiliation of Commissioner	political	technical	economic	social	environmental	no commissioner
Involvement of Stakeholders	regulatory stakeholders	political stakeholders	commercial stakeholder	societal stakeholder		

3 THE STEERS METHODOLOGY

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 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 EE1st 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. 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 current exercise can improve by enhancing its traceability, openness, and sector integrated activity. The existing toolchain approach (as in Figure 3) with (soft-)linking of different purpose models along the subsequent steps of the exercise is well established but needs further development. Most tasks can be fulfilled with open methodologies given the availability and reusability of data.

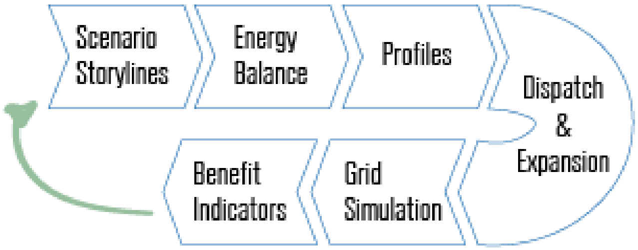

Figure 3: Stylised workflow of the STEERS/TYNDP methodology.

The STEERS methodology sees a need for varied scenario storylines to address uncertainties regarding the future development of the energy system. Furthermore, it is based solely on energy balances that comply with politically agreed CO_2 budgets. The methodology also proposes targeted improvements for constructing demand profiles for flexible demands and renewable generation. Regarding energy system modelling, there have been several advances in methodology including full-fledged sector coupled models that are useful for the TYNDP analysis. The methodology focuses on openness and traceability for both modelling and stakeholder engagement, suggesting using publicly available, non-commercial tools while ensuring an increased level of integration and a higher level of detail on flexibility and endusers. We suggest a set of open-source models that can already live up to commercial solutions A comprehensive list of relevant tools and good practices is available in Section 5.2. For data and assumptions, the FAIR data principles (Wilkinson et al., 2016) are a widely established open standard. 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. The deliverable *D3-2 Draft Methodology* (Brandstätt et al., 2022) of this project discusses the relevance and practice of transparency and openness in more detail.

Table 9 presents an overview of the developments: it summarises the suggested approach, explains the delta to the current TYNDP methodology in each section and lists options for even further development. This lays out the path for a more detailed analysis of further development of the TYNDP 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: Overview of STEERS methodology and list of deltas to the current practice.

	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 CO_2 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 in between 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 aspect of the TEN-E recast, evaluated, and discussed for all scenarios and time horizons, see details in Brandstätt et al. (2023)	see details in Brandstätt et al. (2023)	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

4 PROOF OF CONCEPT

The STEERS methodology, as described in the *STEERS Methodology* (Brandstätt et al., 2023) and summarised above, needs to meet specific requirements. To verify that this holds, the methodology, also referred to as the concept below, undergoes a proof of concept. We present this exercise in the following.

A proof of concept in general can be defined as "[…] ***a demonstration, the purpose of which is to verify that certain concepts or theories have the potential for real-world application. […] The proof of concept provides evidence that demonstrates that a business model, product, service, system, or idea is feasible and will function as intended.*** " ***(Harrington and Voehl, 2016)***

Following this definition and in accordance with Prasanna (2021), the proof of concept includes four steps:

a) definition of success criteria,
b) engineering of a proposed solution,
c) evaluation of proposed solution against success criteria,
d) decision to proceed.

The proposed solution is presented in detail in the deliverable *D2-3 Draft Methodology* (Brandstätt et al., 2022). The remaining steps are covered in the following. This proof of concept is a qualitative exercise and uses predefined criteria to verify that the methodology is feasible in terms of effort and technical requirements and compliant with regulatory boundaries. Section 4.1 defines and explains these criteria. Section 4.2 revisits each step of the STEERS methodology and evaluates them against the criteria. The analysis is followed by an overview of the relevance and feasibility of the improvements in Section 4.3.

The presented analysis has led to improve details in our STEERS methodology. It is essentially a quality and compliance exercise which can be applied to future TYNDP processes using the criteria and guiding questions presented in this report.

4.1 Evaluation Criteria

We evaluate the methodology based on its general feasibility and its compliance with the TEN-E regulation. The following criteria are relevant to evaluate and validate the methodology.

a) Feasibility

Feasibility describes the capability of the method to deliver a TYNDP **within reasonable time** and with **reasonable effort and resources**. In this context, the primary benchmark is the current practice, and we describe **changes** from this practice and evaluate their associated efforts.

b) TEN-E compliance

i. Transparency

Transparency improves processes that are relevant to society and increases their accessibility. This can be ensured through (1) easily accessible information, (2) comprehensive presentation and discussion of results and conclusions, and (3) justification of assumptions which may evidence the inclusion of different positions. Transparency can empower non-academic and less affluent stakeholders to take part in and contribute to the process.

ii. Openness

For welfare impacting exercises such as the TYNDP, it is important to allow for a validation of processes. Openness may imply reproducibility which can improve productivity and quality, transparency, and may even enhance trust (Morrison, 2018). Openness can allow **for reiterating the process.** Transparency is a necessary condition for openness. In addition, it often requires (1) the **use of openly available tools** as this ensures a sufficient degree of reproducibility (Pfenninger et al., 2017), (2) **adequate licensing**, and (3) c**ompliance with the FAIR data principles.**

iii. Integration of energy systems (ESI)

Energy system integration describes the connection and combined development of **energy carriers, infrastructures, and consumption** across sectors. Assessing and planning such integrated systems requires a **holistic approach beyond individual sectors**. It also addresses the decarbonisation needs of the hard to abate sectors, such as parts of industry or certain modes of transport, where direct electrification is, currently technically, or economically challenging. It includes hydrogen and electrolysers, which are progressing towards commercial large-scale deployment (paraphrased from (13) of the TEN-E regulation).

iv. Adherence to energy efficient first principle (EE1st)

The EE1st principle "[…] means to consider, before taking energy planning, policy, and investment decisions, whether cost-efficient, technically, economically and environmentally sound alternative energy efficiency measures could replace in whole or in part the envisaged planning, policy and investment measures, whilst still achieving the objectives of the respective decisions. This includes, in particular, the treatment of energy efficiency as a crucial element and a key consideration in future investment decisions on energy infrastructure [...]. Such cost-efficient alternatives include measures to make energy demand and energy supply more efficient, in particular by means of cost-effective energy end-use savings, demand-side response initiatives and more efficient conversion, transmission, and distribution of energy." (EU 2021/1749, Annex 2.1)

4.2 The Proof

The proof of concept is a qualitative exercise along the abovementioned criteria to evaluate a) feasibility and b) TEN-E compliance. The structure of this proof follows the stylised workflow of the TYNDP methodology as pictured in Figure 2 above. For each step of the methodology, we summarise the key characteristics, highlight the changes to the current TYNDP practice along Table 2, and explain how the steps meet the criteria. For this, we use a framework for examining feasibility and a standardised table format to verify TEN-E compliance for each of the four criteria. The methodology can be compliant due to explicit requirements, methodological choices, or previous steps that transfer the compliance.

Scenario storylines

The STEERS methodology pledges for varied storylines, interpreted in the context of descriptive and normative aspects. These need to be compliant with climate targets and cover a time horizon of the required ten years and beyond. The development of the scenario storylines shall also include:

1. Stakeholder consultations from across all sectors,
2. Open publishing and licensing of data, assumptions, and tools,
3. Broad discussion and streamlining across scenarios, and consideration of ESI, EE1st and interconnection targets.

The STEERS methodology includes more storylines than the current methodology to capture different strategies for climate target compliant storylines, for example capturing electrification or flexibility separately.

The scenario storyline development suggested in the STEERS methodology is evaluated against the defined criteria for a comprehensive methodology:

a) Feasibility
The variation in storylines can be implemented by merely rearranging the storylines and separating specific aspects into individual scenarios which can thus be analysed individually. This would mean only a small deviation from the current practice.[3]

More fundamentally distinct storylines on the other hand may at least initially require significant additional resources. The related effort will reduce subsequently with new iterations of the TYNDP when the initially new, distinct storylines are mostly just updated.

[3] Currently, ENTSOs discuss extrapolating the National Trends scenario into two storylines, i.e., Global Ambition and Distributed Energy. In parallel ACER's scenario-building guidelines require at least two scenarios representing low and high economic growth futures. A small variation would for example differentiate the distributed energy scenario into variants with high and with ceteris paribus lower decentrally sourced flexibility.

The proposed changes regarding storylines can likely be implemented in a stepwise manner, in order to spread the one-off efforts over time.

Improvements to the stakeholder process related to the storylines represent some additional effort for interacting with stakeholders early on and for planning and communicating the interaction process with more advance. This effort however will possibly be offset later on when stakeholders that have been involved early on pose less clarification questions and have fewer comments throughout in the process.

b) **TEN-E compliance**

Compliance of the storyline with the criteria in the TEN-E regulation is mostly ensured as an explicit requirement to comply, as well as by stakeholder interactions as a control loop. Table 3 below sums this up for the four core aspects of the TEN-E.

Table 3: TEN-E compliance of storylines in STEERS methodology

	explicitly required	given by methodological approach	implicit due to previous steps
Transparency	stakeholder process, open publishing required (2. above)	–	–
Openness	Open publishing of data, assumptions, and tools required (2. above)	–	–
ESI	streamlined scenarios across sectors and for different infrastructures required (3. above)	–	–
EE1st	streamlined scenarios including EE1st, including implementation of decentral flexibility and grid-enhancing technology required (3. above)	–	–

Note that the updated scenario guidelines require the scenario storylines to focus largely on changes in economic activity. The STEERS methodology is concerned with the broader implementation of the TEN-E recast, i.e. transparency, openness, energy systems integration and the energy efficiency fist principle and therefore considers more varied storylines. Hence, this report presents the perspective of a scenario building approach including various storylines.

Inspiration: Seeds stakeholder engagement project

The Seeds project will (1) develop an automated approach to generate a wide range of alternative energy system scenarios that go beyond an economically optimal solution; (2) integrate the computation of social and environmental impacts into these alternatives; and (3) build a web-based interface with experts and members of the public, in which they can interactively visualise scenarios and feed their preferences into the generation of refined alternatives in a human-computer co-creation loop.

This project presents a great example of stakeholder engagement as it allows for co-creation, adjustments by the stakeholders that feed back into the pool of feasible solutions, and access to increase awareness.

See: https://seeds-project.org/

Energy balance

The STEERS methodology suggests basing the energy balance on sectoral demands, supply potential across technologies, and a carbon budget in line with climate and energy targets. In addition, it is key to the suggested methodology to disclose all relevant assumptions and input modifications at the level of the FAIR data principle. Further, the tool used shall be accessible to other non-commercial users.

The STEERS methodology deviates from the current one by applying the same methodology to derive all energy balances across scenarios. It also requires comprehensively revealing assumptions and input modifications.

The energy balance development suggested in the STEERS methodology is evaluated against the defined criteria for a comprehensive methodology:

a) **Feasibility**
Initial adaptation of the tools for all scenarios leads to a one-off effort. In the long-term, the reduced number of methods used to derive the balance lowers the number of tools and processes to maintain. Comprehensive documentation may alter current processes but is likely to represent a low effort change.

b) **TEN-E Compliance**
Compliance of the energy balance with the criteria in the TEN-E regulation is ensured as an explicit requirement to comply, by stakeholder interactions as a control loop and to some extent via the previous steps and the modelling approach. Table 4 below sums this up for the four core aspects of the TEN-E.

Table 4: TEN-E compliance of deriving the energy balance in STEERS methodology

	explicitly required	implicit due to previous steps	given by methodological approach
Transparency	disclosure of relevant assumptions and input modifications	–	–
Openness	publication of data and assumptions, use of non-commercial software	–	–
ESI	shall cover all sectoral activity and have a joint emissions target	–	joint sector modelling
EE1st	–	as embedded in the storyline	–

Profiles

Profiling distributes the aggregate yearly quantities obtained in ***Step 2 Energy balance*** across the time horizon. This can be done by (i) deriving fixed profiles that serve as exogenous input, or (ii) engineering methods to endogenize profiles into the model.

For the TYNDP, it is relevant to include generation profiles for wind and solar, hydro reservoirs, district heating, and demand ones for electric vehicles and Power-to-X. The presented methodology suggests to

- collect exogenous profiles for the weather-dependent renewables,
- model hydro power as storage systems with exogenous charging profiles,
- dispatch CHP and heat pumps for district heating to reduce residual load and include an energy balance,
- optimise charging of electric vehicles based on exogenous grid-connection profiles, and
- endogenously determine the power demand for different electrolyzer types.

As with all previous steps, it is particularly relevant for the input data to be openly available and well-documented as described precisely in *D2-3 Draft Methodology* (Brandstätt et al., 2022). For this data-related step, the methodology requires compliance with the ***FAIR*** data principles, i.e., findable, accessible, interoperable, and reusable data. To assess the current availability of data and scope for improvement regarding data transparency, we have conducted an extensive review of the current data provision. This work is documented in deliverable *D3-1 List of required Data* (CSEI, 2023).

FAIR-compliant data and adjustments in the profiling approaches allow for more endogenous decisions (regarding district heating and electric vehicles), improve the transparency of hydro power modelling, and shift the impact of less favourable sites for renewables from costs to lower full-load hours.

The profile and data collection approach in the STEERS methodology is evaluated against the defined criteria for a comprehensive methodology:

a) **Feasibility**
The methodology requires limited altering of the current practice regarding some assumptions. This is likely not a substantial increase of efforts. Compliance with the FAIR data principles may have some start-up cost with short-term increased effort.

b) **TEN-E Compliance**
Compliance of the energy profiles with the criteria in the TEN-E regulation is ensured partly as an explicit requirement by the methodology to comply and to some extent via the compliance of the energy balance and of the modelling approach. Table 5 below sums this up for the four core aspects of the TEN-E.

Table 5: TEN-E compliance of the profile development in STEERS methodology

	explicitly required	implicit due to previous steps	given by methodological approach
Transparency	availability of data and assumptions, publication of documentation	–	–
Openness	compliance with FAIR data principles	–	–
ESI	–	–	endogenous dispatch modelling
EE1st	–	via energy balance	–

Best Practice: Open Power System Data

Open Power System Data is a free-of-charge data platform dedicated to electricity system researchers. It collects, checks, processes, documents, and publishes data that are publicly available but currently inconvenient to use. The project provides a service to the modelling community by collecting data in a clear structure. The database complies with the FAIR data principle and provides users with well-structured information about available data sets.

See: https://open-power-system-data.org/

Dispatch & expansion

The dispatch and expansion modelling combines the previous steps and feeds the demand and supply profiles into an energy system model. In line with the storylines, the modelling needs to include a series of policy specific constraints. As of current development, these comprise details on prosumers, storage, multi-temporal planning, and sectoral scope. In future development, these constraints can be complemented with new arising policy reflections. All mentioned constraints, assumptions and modelling approach must be presented and communicated. The dispatch and capacity expansion model shall be open-source and transparent.

The STEERS methodology includes a transparent and exogenous assumption for ***prosumer*** modelling to better reflect the social planner perspective. ***Storage*** shall be reflected in high granularity by differentiating between capacity and energy expansion cost to capture short- and medium-term and seasonal storage, which also requires a long modelling horizon. The ***multi-temporal planning*** is approached by a two-step procedure that ensures better foresight and rolling horizon: the first step covers the entire time horizon but only considers a few spotlight years, and the second step covers the years in between and expands the system based on the bounds given by the spotlight years. The ***sectoral scope*** is set to integrate all relevant sectors by exogenous assumptions for the separate ones and an endogenous joint expansion planning. This ensures joint planning with electricity, gas, hydrogen, district heating and ideally also flexibility.

The presented methodology differs from current practice by modelling prosumers from a social planner's approach. Further, storage is here reflected in different granularity. STEERS also includes a requirement to integrate sectors by joint endogenous optimisation and suggests improving the multi-period planning to account for path dependencies.

The reflection of policy specific constraints in the STEERS methodology is evaluated against the defined criteria for a comprehensive methodology:

a) Feasibility
The proposed methodology is common practice in research, and it is therefore reasonable to assume that the suggested methodological changes are implementable with open access and well-supported software, e.g., PyPSA (Brown et al., 2018). Processes may need to adjust, but not at substantial increase of effort/resources and time, as documented in an open-access proof of concept by de Felice (2023)[4]. The transformation can be broken down in several phases and sub steps and could start with a knowledge exchange from system operators that have experience with open access software such as TransnetBW (PyPSA)[5] and RTE (Antares)[6].

b) TEN-E Compliance
Compliance of the dispatch and expansion modelling with the criteria in the TEN-E regulation is ensured as an explicit requirement in the STEERS methodology and to some extent via the compliance of the energy balance and scenarios, as well as due to integrated modelling. Table 6 below sums this up for the four core aspects of the TEN-E.

Table 6: TEN-E compliance of the dispatch and expansion modelling in STEERS methodology

	explicitly required	implicit due to previous steps	given by methodological approach
Transparency	publication of documentation, communication of data, assumptions, and constraints	–	–
Openness	compliance with FAIR data and use of open tools	–	–
ESI	–	joint balance and scenarios	integrated modelling

[4] See Open modelling of European power systems with Python http://www.matteodefelice.name/post/pypsa-entsoe/.
[5] See TransnetBW Energy System 2050: https://www.energysystem2050.net/
[6] See Antares Simulator: https://antares-simulator.org/pages/etudes/4/

EE1st	–	scenarios, balances, and profiles enhance it	integrated modelling

Inspiration: PyPSA for European Energy System Study

The TSO TransnetBW conducted an energy system study for a decarbonised Europe in 2050. For the study, they deployed the open-source model PyPSA (Brown et al., 2018) and extended this with features needed for the analysis. The full report is available including a description of the relevant model features and adaptations.

See: PyPSA (2023) and TransnetBW (2022)

Grid simulation

The results of the dispatch and expansion modelling are used to evaluate the grid impact of specific expansion projects. To do this, a grid simulation using the same method is performed for all scenarios. This requires a transparent allocation of the zonal dispatch of capacities obtained from the previous step to a nodal power system. All necessary information, tools and details on the allocation mechanism for this step must be made available. For the electricity grid in Central and Western Europe, flow-based market coupling can be considered to reflect cross-border capacity use more accurately. Finally, the grid simulation needs to be performed for all scenarios in the process.

This differs from the current practice by simulating all scenarios and thus basing consequent decisions on all scenarios not disregarding the broader view on the use of flexibility, storage, and sector integration assets considered in the other scenarios.

The grid simulation is evaluated against the defined criteria for a comprehensive methodology:

a) **Feasibility**
No change in methodological approach. However, there is increased effort to publish information on the transfer of results from the previous step and to realise additional simulations and evaluations for additional scenarios.

b) **TEN-E compliance**
Compliance of the grid simulation with the criteria in the TEN-E regulation is ensured as an explicit requirement as well as via the compliance of the previous steps. Table 7 below sums this up for the four core aspects of the TEN-E.

Table 7: TEN-E compliance of the grid simulation in STEERS methodology

	explicitly required	implicit due to previous steps	given by methodological approach
Transparency	revealing the methodology and the allocation mechanism	–	–
Openness	compliance with transparency criteria	–	–
ESI	–	all previous steps	–
EE1st	–	all previous steps	–

Inspiration: Transparency checklist

This project develops criteria to reach transparency in energy scenarios and modelling. The checklist is a supportive tool for improving transparency. The work targets experts who author and read energy scenarios. By making use of the transparency checklist, the developers of energy scenario studies show their commitment to a high degree of transparency. The checklist is provided as downloadable file with brief and concise documentation.

See: Cao et al. (2016)

Benefit indicators

The benefit indicators serve to weigh potential benefits of projects in the TYNDP against their cost. The STEERS methodology proposes a set of streamlined indicators for electricity and gas that cover all aspects of the TEN-E recast. In short, the indicators cover renewable energy integration, societal cost of CO2-equivalent, non-direct GHG-emissions & environmental impacts, welfare & supply cost, diversification & integration of energy supply, balancing, adequacy and selected other benefits. For more detail see *D2-3 Draft Methodology* (Brandstätt et al., 2022). The methodology also requires that they should be evaluated and discussed for all scenarios and time horizons of the TYNDP.

The indicators in the proposed methodology differ from the practice for the TYNDP of 2022 in that they

- analyse overall RE in final energy supply as opposed to differentiating between RE capacity and production or between RE in gas and electricity,
  (This would replace the assessment of a difference in electricity curtailed or respectively in hydrogen capacity connected.)
- capture cost of avoided GHG emission in addition to the valuation captured by emission trading,
  (This would replace the choice between the two in the gas methodology of 2022.)
- capture welfare beyond mere cost minimization, which is especially relevant for demand flexibilities and energy savings,
- assess the difference in dominance of a single source or technology as a complement to the dimensions of competition and supply security, and that they
- add purposeful variations to the random Monte-Carlo approach currently employed for the assessment of system adequacy.

Prospectively, the methodology also suggests to

- add an assessment of cybersecurity as the state-of- knowledge on this evolves,
- revise the set of indicators recurringly to capture emerging aspects such as hydrogen leakage or innovative types of flexibility,
- deploy more sophisticated stochastic analysis (instead of analysis with or without the project) to capture interrelations between the proposed projects, and to
- streamline the assessment with that of other PCI categories as far as possible.

The benefit indicators suggested in the STEERS methodology are evaluated against the defined criteria for a comprehensive methodology:

a) **Feasibility**
The suggested alterations of the indicators do not structurally increase the effort required for the analysis. For the changes to the indicators themselves, we identify merely a one-off effort to establish the changes in the methodology.

With respect to evaluating and discussing the indicators for all scenarios and time horizons, we acknowledge some additional effort as compared to current practice. However, since the employed methodology remains the same, this is likely no substantial feat. Comparing the results between the different scenarios can be considered a main outcome for project developers and other stakeholders alike, so that the effort would be easily justified.

b) TEN-E Compliance
Compliance of the benefit indicators with the criteria in the TEN-E regulation is ensured as an explicit requirement and via the compliance of the previous steps and of the modelling approach. Table 8 below sums this up for the four core aspects of the TEN-E.

Table 8: TEN-E compliance of the benefit indicators in STEERS methodology

	explicitly required	implicit due to previous steps	given by methodological approach
Transparency	Indicators evaluated and discussed for all scenarios and time horizons	–	–
Openness	–	all previous steps	–
ESI	assessing RE in final overall energy supply	based on integrated dispatch for electricity & gases	–
EE1st	–	–	capture welfare beyond mere cost-minimization

4.3 Feasibility and Illustrations

For this proof of concept, feasibility is a major measure to evaluate the adequacy of the STEERS methodology. Feasibility in this context is defined as the capability of the method to deliver a TYNDP **within reasonable time** and with **reasonable effort and resources**. The primary benchmark is the current practice, and we describe the **changes** and evaluate their associated efforts**.**

This section reflects on the relevance of specific improvements and their feasibility, summarises specific data needs and illustrates good practice of open and transparent data.

Relevance of improvements

The suggested improvements impact the process in different ways. The following explains the relevance and summarises the insights in Table 9. The table lists the improvements in descending order of relevance.

Improving the transparency of the whole TYNDP process is very relevant in view of TEN-E compliance and stakeholder inclusion. This concerns the presentation of data and assumptions and the processes to involve stakeholders and communicate results. Better transparency is beneficial for processes with a high societal impact. As an important follow up to achieving better transparency, openness in modelling can elevate this exercise further.

Adoption of suggested endogenous modelling of heat pumps for district heating and EVs improves the coherence of the process with high relevance to the results and representation of flexibility provision. Combined with a change of assumptions on these suggestions lead to a consistent social planner's perspective. Improvements regarding the exploitation of flexibility (heat pumps, EVs and reservoir/storage modelling) may be the most influential and crucial aspect; adjusting the assumptions on prosumers and cost of renewables are minor but lead to achieving a much more concise process.

EE1st is largely only considered in the narrow sense of energy savings limiting the growth of energy demands. The broader dimension of behavioural and systemic changes that mitigate or postpone infrastructure still needs to be implemented further. Additional storylines allow for more distinct analyses of specific strategies, for example, electrification and representation of flexibility. Therefore, the required scenarios based on economic activity should be extended for flexibility related storylines or sensitivities as far as possible.

A stringent joint assessment of the systems for electricity and gases is essential and energy systems integration is largely well under way with the improvements the ENTSOs have made and have outlined to implement in their methodology.

Table 9: Overview of the improvements and their impact.

relevance (↑)	Suggested Development	Relevance
Transparency	Improvement of the current presentation of modelling inputs and output as well as stakeholder involvement and communication to make the process more accessible	Influential and crucial for a process with high societal impact
Benefit indicators	Analysis and discussion of benefit indicators based on all scenarios in comparison	Critical for project promoters, other stakeholders, and evaluators to fully assess the proposed projects
Modelling improvements	Implementation of endogenous decision-making on district heating use and EVs; improved modelling of storage and reservoirs	Relevant to manage coherence and streamline the approach, and to improve exploitation of flexible resources to their full potential
EE1st	Expansion beyond the narrow sense of energy savings, particularly covering flexibility in varied storylines	Can be slowly and continuously adjusted based on advancing research
Openness	Use of more open tools and databases	Adaptable as a follow up to improving transparency
Storylines	Varied storylines to reflect, for example, direct electrification, flexibility	Critical to account for uncertainties regarding the future development of the energy system

Feasibility of improvements

The suggested improvements are linked to different extents of workload. Section 4.2 elaborates on the feasibility of the STEERS methodology and the following groups these improvements into three categories: (i) considerable one-off efforts with lasting benefits, (ii) larger effort that can follow a stepwise implementation, (iii) continuous but smaller to medium efforts.

(i) Considerable one-off effort

Improving **transparency** requires an initial effort but is largely related to restructuring the current process and therefore rather feasible.
The **modelling related changes** require a one-off effort and are less work-intensive once implemented.

(ii) Larger effort with stepwise implementation.

Compliance with all **open modelling** criteria throughout the whole process is a large effort. This can, however, follow a stepwise and tool by tool implementation schedule to improve **openness** continuously.

Varied **storylines** as well as more distinct ones require a substantial one-off effort which can, however, be spread the efforts over time.

(iii) Continuous but small to medium efforts

Representation of **energy efficiency** beyond sole energy saving is feasible when research advances and requires continuous and stepwise but small efforts.

Evaluating the **benefit indicators** for all scenarios and time horizons requires additional and continuous effort but using the same employed methodology.

This clustering is based on a more detailed analysis of required additions and developments compared to today's practice. We base this on seven sub indicators that range from tool modification to continuous needs for human resources. For each suggested development, we consider the resources needed and indicate the level to which they are used in Table 10. For openness and storylines, we acknowledge two pathways, one that creates full fetched changes and another one that covers the easy to grasp variations. These are evaluated in sub columns. Columns and rows are both sorted by level of effort as indicated by the arrows on the side.

Table 10: Resource and effort needed for the development according to the STEERS methodology.

level of effort →

level of effort ↓

	Transparency	Modelling improvements	EE1st	benefit indicator evaluation	Openness		Storylines	
					low	high	mod.	add.
tool modification		x	x					
tool extension			x			x		
introduction of a new tool	(x)					xx		
one off human resource		x	x	x	x	xx		
additional/extended runs				x			x	xx
further analysis			x	x			x	xx
continuous human	x			x		x	x	xx

mod. – modifications; add. – additional

Based on the two elements above, in Figure 4 we derive a summary of the suggested developments and link them based on relevance and effort needed for implementation. Due to the differing pathways for open modelling and varied storylines, the bubbles stretch along the graph to cover the variety in effort.

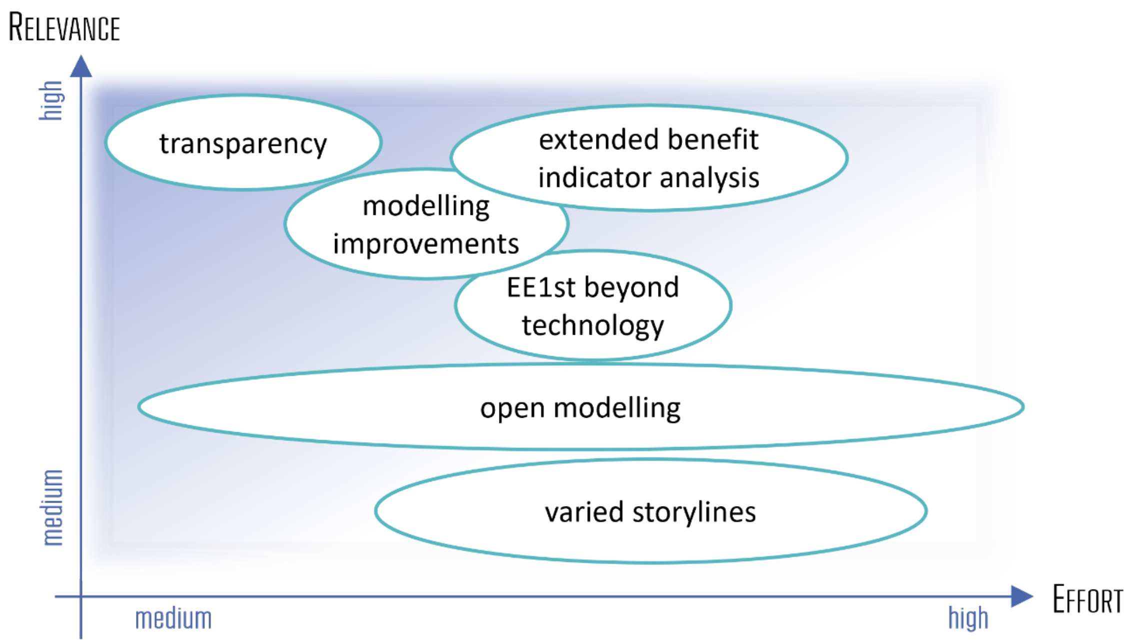

Figure 4: Summary of the feasibility analysis for future developments.

Additional data needs

We identify some methodological improvements in the generation of profiles and the dispatch modelling. Changes in the approach require a few additional datasets but at the same time make the collection of some of the current data redundant. Deliverable *D3-1* lists the currently used data and adds the following:

- share of full load hours at less favourable sites
  needed to replace cost assumptions in renewables profiling
- charging profiles of hydro power reservoirs
  needed to improve the representation of water availability in the dispatch model
- demand profiles for residential heating
  needed to endogenize the use of heating plants and heat pumps
- demand profiles EVs
  needed to endogenize charging of EVs to exploit flexibility
- trajectory of prosumer expansion
  needed as an assumption to reconcile with the social planner approach
- cost data for energy storage and (dis)charging capacity of stores
  to distinguish expansion in different storage types

Examples of open access datasets for these are listed in the deliverable *D3-1 List of required Data* (CSEI, 2023). Instead of being based on existing datasets, the generation of demand profiles for residential heating and EVs can become an integrated part of the profiling step. The renewable energy profiles can be based on weather data and the current aggregated heat spread across regions according to weather, population, and housing data.

Illustrating open and transparent data

Processes that are relevant for society such as the TYNDP benefit from the open availability of data and modelling tools. We set up an illustrative example of a modelling exercise that complies with the FAIR data principles and best practice in open-source modelling. The example is available online at https://csei-eu.github.io/steers-test/intro.html. This webpage illustrates the provision of background information, data documentation, and an integrated model description and its code. It also collects all public deliverables. The deliverable *D3-1 List of required Data* (CSEI, 2023) is extensively documented on this page. The main contribution of this data list is to highlight the accessibility of TYNDP data, and we find that many data points are solely listed in flow text which lowers findability, accessibility, interoperability, and reusability. Based on the provided excel spreadsheet it is possible to identify gaps in transparency of data and assumptions.

5 GUIDANCE FOR STEERS COMPLIANCE

The proof of concept presented above has helped to improve the STEERS methodology. It can be complemented with the checklists presented in Section 5.1. They support the verification of whether a process complies with the STEERS methodology. Section 5.2 outlines examples of tools and good practices beyond the selected examples featured in the proof of concept.

5.1 Checklists for STEERS Compliance

The following checklists support the development of a TYNDP that complies with today's TEN-E regulations and transparency criteria. We present a dedicated checklist for each of the six steps analysed above. The subcategories are derived from the proof of concept and the necessary TEN-E criteria concerning the distinct steps. The questions arise from the explicit and methodological requirements of the STEERS methodology. This is closely linked to the STEERS methodology and its deviations from the TYNDP as summed up in Table 2.

Scenario storylines

Scenario storylines

☐ **Energy system integration**
- Do the same scenarios apply to all relevant sectors?
- Are hard-to-abate sectors and modes of transport represented across sectors?
- Are electrolysers, hydrogen, and derived fuels reflected in the scenarios?

☐ **EE1st principle**
- Are policies and technologies to induce the energy efficiency first principle, such as for demand flexibility and grid-enhancing technologies, part of the storylines?
- Is energy efficiency represented beyond its technical aspects, e.g., via behavioural changes and sufficiency?

☐ **Plausibility and comprehensiveness**
- Can stakeholders interact or are they merely consulted?
- Is the stakeholder process outlined clearly and reliably, early-on in the scenario building, i.e., dates, deadlines, and type of interactions?

☐ **Transparency**
- Are all assumptions and sources named explicitly and justified comprehensively?
- Is the version history of documents presented clearly?

☐ **Consistency and coherence**
- Can changes and updates be traced?
- Is the process comparable to other existing scenario building processes, such as the EU reference scenarios?

☐ **Accessibility**
- Is the scenario report published openly and is the related data FAIR compliant?
- Are the tools used open access? If not, is the reason evident?

Energy Balance

Energy Balance

☐ **Sectoral scope**

- Does the energy balance include demands for all relevant sectors, i.e., electricity, gas, heating, transport and hydrogen?
- Are the sectoral demands assigned to different energy carriers?

☐ **Supply potentials across technologies**

- Is there a supply potential for all renewable sources?
- Are the assumptions regarding the realisation of this potential ambitious?

☐ **Energy imports and greenhouse gases**

- Are all energy imports clearly outlined?
- Does the energy balance account for imported and produced greenhouse gases?
- Is the greenhouse gas budget transparent and does it comply with current climate and energy targets?

☐ **Transparency**

- Are all input modifications disclosed?
- Is it possible to trace any adjustments of the energy balance, e.g., those that are necessary to reconcile targets and demand projections?
- Is there an overview of all assumptions? And are they explained and justified?
- Can stakeholders find and access all related data?

☐ **Accessibility**

- Is the energy balance published openly and is data FAIR compliant?
- Are the tools used open access? If not, is the reason evident?

Profiles

Profiles

☐ **Weather dependent potentials**

- Are solar and wind production based on exogenous timeseries?
- Are favourable sites represented with higher full load hours rather than lower investment cost?
- Are hydropower reservoirs charging profiles collected empirically?

☐ **Asset flexibility**

- Is the flexibility of assets in district heating, such as heat pumps and CHPs, based on an overall heat profile for the network?
- Is charging of EVs optimised based on grid-connection profiles rather than fixed time series?
- Is the demand for Power-to-X derived endogenously?

☐ **Transparency**

- Are all data sources listed?
- Is there a comprehensive overview of sources and data needed?
- Are the generated profiles published?

☐ **Accessibility**

- Is the collected and generated data openly available?
- Are all data series FAIR compliant?

Dispatch & expansion	
Dispatch & expansion	☐ **Energy systems integration** - Does the model optimise all energy carriers in an integrated manner? - Is there a clear link in the model between heat, gas, electricity, and transport?
	☐ **Transparency** - Are the tools that are used open source or is all information required for reproducibility presented? - Are the tools documented according to common standards? - Can the optimization be solved using free solvers? - Were stakeholders involved in updating the dispatch and expansion modelling?
	☐ **Coherence** - Do the constraints coherently reflect the social planner's perspective, i.e., maximising social welfare? - Are expansion decisions for technology, which depend on personal preferences and incentives, such as heat pumps, EVs etc, and self-generation given by exogenous projections?
	☐ **Flexibility and efficiency** - Does the expansion of storage consider different storage capacities as well as (dis)charging rates (i.e., energy and power) for different storage types? - Are hydropower reservoirs modelled as storage systems? - Are synergies, for example from enhanced system integration, reflected in the models? - Can the model consider pipeline repurposing?
	☐ **Path dependencies** - Does the model consider a two-step optimisation rolling horizon approach?

Grid simulation	
Grid simulation	☐ **Transparency** - Are all mechanisms to allocate the zonal dispatch to individual nodes disclosed and explained? - Does the allocation follow the same procedure for all scenarios? - Are all modifications to the dispatch from the previous step disclosed and justified? - Is the method for grid simulation well-described and documented? - Are the results from using different models to perform the same simulation compared comprehensively?
	☐ **Comparative scenarios** - Are there different scenario simulations? - Does the simulation build on the same method for all zones and scenarios?
	☐ **EE1st principle** - Are batteries and peak units included as partial alternatives to grid expansion?

Benefit Indicators	
Benefit Indicators	☐ **TEN-E criteria** - Do the benefit indicators cover all criteria named in the TEN-E, i.e., sustainability, security of supply and market integration/competition? - Do the benefit indicators include an assessment of dominance of a single supplier, source or technology? - Does the set of indicators include considerations on cybersecurity?
	☐ **Energy system integration** - Do the benefit indicators consider changes in overall renewable energy and GHG, rather than per sector? - Are the criteria suitable to assess hydrogen infrastructure? - Are the criteria suitable in the context of repurposing natural gas infrastructure for hydrogen? - Is the methodology for this step streamlined with the CBA process for other infrastructure categories in the TEN-E? If not, is this justified?
	☐ **Flexibility** - Do the benefit indicators include changes in utility for users and particularly consumers, rather than merely changes in the cost of supply?
	☐ **Security of Supply** - Are the adequacy indicators based on purposeful variations of the scenario in addition to Monte-Carlo-Simulations? - Are project promoters, who provide (parts of the) benefit assessments themselves, required to disclose and justify the tools, input data and assumptions they use?
	☐ **Transparency & Robustness** - Are the benefits assessed and discussed across different scenarios? - Are their sensitivities to certain assumptions assessed and discussed? - Is there a process to revise the set of indicators in order to adjust to new business and technology frameworks, for example regarding hydrogen leakage and innovative types of flexibility?

5.2 Tools, Good Practices, and Experts

A range of material and current practices inspired the development of the STEERS methodology. The most insightful tools and good practices are listed in Table 11. Besides a description and keywords for categorisation, the table provides an indication for where the tool or practice can be useful or inspirational in the work for the TYNDP. For some of the tools and practices, we list reference experts who have been driving the development and have valuable expertise for TYNDP exercises.

Table 11: Tools and Good Practices

Relevance for TYNDP	Name	Description	Keywords	Reference/Weblink
All	Seeds Project	The Seeds project (1) develops an automated approach to generate a wide range of alternative energy system scenarios that go beyond an economically optimal solution; (2) integrates the computation of social and environmental impacts into these alternatives; and (3) builds a web-based interface with experts and members of the public, in which they can interactively visualise scenarios and feed their preferences into the generation of refined alternatives in a human-computer co-creation loop. This project presents a great example of stakeholder engagement as it allows for co-creation, adjustments by the stakeholders that feed back into the pool of feasible solutions, and access to increase awareness.	Stakeholder engagement, consultations	https://seeds-project.org/ **Contact**: Stefan Pfenniger, TU Delft
All	Transparency checklist	The work by Cao et al. (2016) develops a checklist with six different groups of criteria to allow authors for improving the level of transparency of their work.	Transparency	Cao et al. (2016) **Contact**: Karl-Kiên Cao, DLR
All	National Grid Operational Transparency Forum	It is a weekly open forum to report important actions and offer an opportunity to stakeholders to consult the grid operator	Stakeholder involvement, Consultation, Transparency	https://www.nationalgrideso.com/what-we-do/electricity-national-control-centre/operational-transparency-forum

Relevance for TYNDP	Name	Description	Keywords	Reference/Weblink
Scenario storylines	IAMC Scenario Explorer	The Scenario Explorer allows access to a web-based user interface that manages scenario data. The interface allows users to follow intuitive visualizations and it can display timeseries and allow for data download in multiple formats.	Visualisation, Transparency, Openness, Engagement	https://data.ece.iiasa.ac.at/ar6/ **Contact**: Daniel Huppmann, IIASA
Scenario storylines	EU Reference Scenario	The EU Reference Scenario is an European Commission analysis tools in the areas of energy, transport, and climate action. It allows for the long-term economic, energy, climate and transport outlook based on the policy framework in place in 2020. It is a comprehensive basis against which new proposals can be assessed	Visualisation, Data, Transparency	https://e3modelling.com/modelling-tools/primes/
Energy balance	Energy union indicators webtool	Energy union indicators webtool is a set of interactive graphs and tables that allow for exploring the union's key indicators. It consists of a scoreboard, a datamapper, factsheets, and a database.	Energy demand	https://energy.ec.europa.eu/data-and-analysis/energy-union-indicators-webtool_en
Energy balance	JRC POTEnCIA	POTEnCIA is a modelling tool for the EU energy system and follows a hybrid partial equilibrium approach. It combines behavioural decisions with detailed techno-economic data, therefore allowing for an analysis of both technology-oriented policies and of those addressing behavioural change. Its output consists of detailed energy balances, among others.	Energy demand, Transparency	https://joint-research-centre.ec.europa.eu/potencia_en
Profile/data collection	PyPSA ENTSO-E	PyPSA ENTSO-E is a proof of concept for open modelling. This includes all relevant information that is needed to replicate the exercise.	Openness	https://github.com/matteodefelice/pypsa-entsoe
Profile/data collection	Open Power System Data	Open Power System Data is a free-of-charge data platform dedicated to electricity system researchers. It collects, checks, processes, documents, and publishes data that are publicly available but currently inconvenient to use. The project is a service provider to the modelling community: a supplier of a public good.	Data, Openness, Transparency	https://open-power-system-data.org/
Dispatch modelling	PyPSA	Power system analysis toolbox built in Python with an extension for capacity planning of integrated energy systems (PyPSA-Eur-Sec). It includes the heating, transport, and industry sectors and hydrogen infrastructure. There are functionalities to pre-process input data, analyse results, and create plots. PyPSA and PyPSA-Eur-Sec have been used by numerous academic and non-academic institutions for power and energy system analyses	Data, Modelling, Openness	https://github.com/PyPSA, Brown et al. (2018); **Contact**: Tom Brown, TU Berlin

Relevance for TYNDP	Name	Description	Keywords	Reference/Weblink
Dispatch modelling	AnyMOD	Expansion planning tool written in Julia and developed for integrated energy systems with large shares of fluctuating renewables. It implements several methodological innovations to model systems with options to configure to the application's needs. 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.	Modelling, Openness	https://leonardgoeke.github.io/AnyMOD.jl/stable/; **Contact**: Leonard Göke, ETH Zurich
Dispatch modelling	Antares	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	Modelling, Openness	https://github.com/AntaresSimulatorTeam/Antares_Simulator
Dispatch modelling	Calliope	Capacity planning tool for multi-scale energy systems, meaning it is suited for analyses of large and small-scale systems. 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.	Modelling, Openness	Pfenninger and Pickering (2018)
Dispatch modelling	SCIP and HiGHS	SCIP and HiGHS are both solvers and 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	Modelling, Openness	https://www.scipopt.org/ https://highs.dev/
Dispatch modelling	SpineOPT	SpineOPT 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 manage and use data and execute models in a graphical user interface.	Modelling, Openness	https://spine-tools.github.io/SpineOpt.jl/latest/index.html
Grid simulation	PowerSimulationsDynamics.jl	The tool is a part of the Scalable Integrated Infrastructure Planning (SIIP) modelling framework developed by NREL that allows for simulation of power system dynamics.	Simulation, Openness	https://github.com/nrel-siip/powersimulationsdynamics.jl
Grid simulation	PowerDynamics.jl	PowerDynamics is a package that provides all the tools to create a dynamic power grid model and analyse it.	Simulation, Openness	https://juliaenergy.github.io/PowerDynamics.jl/latest/
Grid simulation	PowerModels.jl	PowerModels.jl is a Julia/JuMP package for Steady-State Power Network Optimization which is community developed and hosted at advanced network science initiative.	Simulation, Openness	https://lanl-ansi.github.io/PowerModels.jl/stable/

Relevance for TYNDP	Name	Description	Keywords	Reference/Weblink
Grid simulation	GasModels.jl	GasModels.jl provides simulation and optimization methods for steady-state natural gas transmission networks.	Simulation, Openness	https://lanl-ansi.github.io/GasModels.jl/latest/
Grid simulation	SciGrid	SciGrid is a framework to build gas and electricity network models.	Simulation, Openness	https://www.scigrid.de/
Grid simulation, Dispatch Modelling	Static Grid model	The Core Static Grid Model is a list of relevant grid elements of the transmission system, including their electrical properties, that is published every six months by the Core TSOs in accordance with Article 25(2)(f) of the Day-ahead capacity calculation methodology of the Core capacity calculation region.	Transparency, Data, Openness	https://www.jao.eu/static-grid-model
Benefit indicators	Indicators on import dependency and supplier diversification	A comprehensive set of indicators to assess benefits of energy efficiency including a methodological overview, list of data, and limitations.	Cost-Benefit-Analysis, Transparency	Reuter et al. (2020)
Cost Benefit Analysis	Electrolysers, CO_2 networks and energy storage CBAs	A comprehensive assessment framework of energy infrastructure outside electricity and gas grids as defined by the TEN-E and consulted by the European Commission.	Cost-Benefit-Analysis, Transparency	https://energy.ec.europa.eu/consultations/targeted-consultation-methodologies-assessing-costs-and-benefits-candidate-projects-under-revised_en
Cost Benefit Analysis	Smart Grid CBA	A comprehensive assessment framework of energy infrastructure (smart grids) that was tested on a real project. It includes set of 10 guidelines to tailor the CBA to local conditions.	Cost-Benefit-Analysis, Assessment	https://ses.jrc.ec.europa.eu/smart-grid-cost-benefit-analysis

6 CONCLUSIONS

The STEERS project aimed at aiding the implementation of system integration, the energy efficiency first principle, as well as the improvement of transparency and openness in the planning of energy networks in the European Union, and specifically in the TYNDP process.

Over the course of the project, CSEI has assessed the current process against the state of knowledge, proposed incremental changes to the TYNDP process in view of the requirements from the TEN-E regulation recast and assessed the feasibility of the altered methodology. Throughout the project we have kept in close contact with stakeholders from the modelling community, the European network industry, policy makers and societal actors to continuously discuss the implications of our suggestions and findings in practice.

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 the modelling features. The methodology applied for the TYNDP evolves with each new edition along with the state of knowledge. This is particularly evident regarding the integration of gas and electricity systems and with respect to the representation of flexible and cross-sectoral technologies.

The STEERS methodology outlines potential improvements. It highlights the need for varied scenario storylines to address uncertainties regarding the future development of the energy system. The methodology 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. And furthermore, the STEERS methodology focuses on openness and traceability and promotes the use of publicly available, non-commercial tools.

Subsequently, the project validated the feasibility of these improvements. To facilitate the verification of future TYNDP versions in view of the STEERS methodology, the project provides a comprehensive checklist with specific questions related to the critical aspects of each step in the TYNDP process.

In a final assessment, we distinguish improvements of the TYNDP methodology which seem more relevant to comply with the TEN-E criteria and with transparency objectives from others that constitute relatively minor improvements. We also acknowledge that some changes require relatively low, maybe only a one-off effort, whereas other entail substantial and recurring additional efforts. Particularly some basic improvements regarding transparency and stakeholder involvement along with some basic implementation of open data and open modelling come at medium effort but have a high relevance according to this framework. The use of more varied storylines to reflect the impact of flexibility better seems highly relevant, and at least to some degree can be realized at moderate effort.

A concrete example of 'low-hanging-fruit' with respect to transparency, is the improvement of data publication. To showcase the shortcomings of the current procedure in detail, we have compiled a list of all input data and assumption variables for the scenario building. This exercise points out precisely what kind of data is not yet published as accessibly and transparent as it is common practice in energy system modelling.

To provide further inspiration, this report includes a list of good practices that have provided valuable insights for the project and cover all different steps of the TYNDP process. The list includes a number of open models and tools which can either be employed directly in the TYNDP process or can inspire open solutions to be used in the future. We also feature promising instances of stakeholder engagement and some references of indicators included in cost-benefit analysis.

While the STEERS assessment sees the TYNDP process tackling many of the improvements necessary in view of energy system integration, the project also still identifies shortcomings with respect to transparency and openness. The material provided in this report and the input provided throughout countless discussions and consultations throughout the project ideally help to bring the process closer to the state of knowledge and common good practices in those dimensions as well.

Improving the TYNDP process is a continuous and ongoing task. For several desirable improvements, such as reconciling long- and short-term perspectives better in the modelling or assessing additional dimensions like cybersecurity, we have not been able to identify relevant references in the current state of knowledge. Ideally, these aspects will be covered better in subsequent assessments. In the future, the TYNDP process might grow closer to the planning and assessment of other infrastructures covered by the TEN-E regulation. For this it will be very desirable to streamline the methodologies for gas and electricity networks as far as possible with those assessing electrolysers, smart grids, and CO_2 networks. As the energy system and its regulatory framework evolve further, the STEERS methodology and the conclusions from the project will merit revision and updating in the future.

7 REFERENCES

Artelys. (2022). *Does phasing-out Russian gas require new gas infrastructure?* (p. 17). https://www.artelys.com/wp-content/uploads/2022/05/Artelys-Russian-gas-phase-out-Briefing-note.pdf

Brandstätt, C., Göke, L., Llorca, M., Lüth, A., & Weibezahn, J. (2022). *Draft Methodology for Integrated Network Planning in Europe*. Zenodo. https://doi.org/10.5281/zenodo.7356933

Brandstätt, C., Göke, L., Llorca, M., Lüth, A., & Weibezahn, J. (2023). *Methodology for Integrated Network Planning in Europe*.

Brown, T., Hörsch, J., & Schlachtberger, D. (2018). PyPSA: Python for Power System Analysis. *Journal of Open Research Software*, *6*(1), 1. https://doi.org/10.5334/jors.188

Cao, K.-K., Cebulla, F., Gómez Vilchez, J. J., Mousavi, B., & Prehofer, S. (2016). Raising awareness in model-based energy scenario studies—A transparency checklist. *Energy, Sustainability and Society*, *6*(1), 28. https://doi.org/10.1186/s13705-016-0090-z

CSEI. (2023). *TYNDP 2022 data* [Data set]. https://csei-eu.github.io/steers-test/pages/tyndp_data_matrix.html

Eriksrud, A. L., Hentschel, J., Paredes, S., & von Schemde, A. (2022). *The Value of Hybrid Offshore Assets – Findings from the Integration Study* (p. 65).

Göke, L., & Weibezahn, J. (2022). *How Flexible Electrification Can Integrate Fluctuating Renewables* (SSRN Scholarly Paper No. 4105876). https://doi.org/10.2139/ssrn.4105876

Göke, L., Weibezahn, J., & von Hirschhausen, C. (2021). *Fictional expectations in energy scenarios and implications for bottom-up planning models* (arXiv:2112.04821). arXiv. https://doi.org/10.48550/arXiv.2112.04821

Morrison, R. (2018). Energy system modeling: Public transparency, scientific reproducibility, and open development. *Energy Strategy Reviews*, *20*, 49–63. https://doi.org/10.1016/j.esr.2017.12.010

Pfenninger, S., DeCarolis, J., Hirth, L., Quoilin, S., & Staffell, I. (2017). The importance of open data and software: Is energy research lagging behind? *Energy Policy*, *101*, 211–215. https://doi.org/10.1016/j.enpol.2016.11.046

Pfenninger, S., & Pickering, B. (2018). Calliope: A multi-scale energy systems modelling framework. *Journal of Open Source Software*, *3*(29), 825. https://doi.org/10.21105/joss.00825

Prasanna, K., Ramana, K., Dhiman, G., Kautish, S., & Chakravarthy, V. D. (2021). PoC Design: A Methodology for Proof-of-Concept (PoC) Development on Internet of

Things Connected Dynamic Environments. *Security and Communication Networks*, *2021*, 1–12. https://doi.org/10.1155/2021/7185827

Reuter, M., Patel, M. K., Eichhammer, W., Lapillonne, B., & Pollier, K. (2020). A comprehensive indicator set for measuring multiple benefits of energy efficiency. *Energy Policy*, *139*, 111284. https://doi.org/10.1016/j.enpol.2020.111284

Victoria, M., Zhu, K., Brown, T., Andresen, G. B., & Greiner, M. (2020). Early decarbonisation of the European energy system pays off. *Nature Communications*, *11*(1), 1. https://doi.org/10.1038/s41467-020-20015-4

Wilkinson, M. D., Dumontier, M., Aalbersberg, Ij. J., Appleton, G., Axton, M., Baak, A., Blomberg, N., Boiten, J.-W., da Silva Santos, L. B., Bourne, P. E., Bouwman, J., Brookes, A. J., Clark, T., Crosas, M., Dillo, I., Dumon, O., Edmunds, S., Evelo, C. T., Finkers, R., … Mons, B. (2016). The FAIR Guiding Principles for scientific data management and stewardship. *Scientific Data*, *3*(1), 1. https://doi.org/10.1038/sdata.2016.18

Witt, T., Stahlecker, K., & Geldermann, J. (2018). Morphological analysis of energy scenarios. *International Journal of Energy Sector Management*, *12*(4), 525–546. https://doi.org/10.1108/IJESM-09-2017-0003

CONTACT

Christine Brandstätt
Assistant Professor

Email: cbr.eco@cbs.dk
Phone: +45 4185 2645

Copenhagen School of Energy Infrastructure
Copenhagen Business School
Department of Economics

Porcelænshaven 16A
2000 Frederiksberg
Denmark