# Flexibility in Energy System Models - Gap Analysis

**An explorative study by the Kenniscoalitie energietransitie (KCET)**

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# Contents

# 1 Introduction

Flexibility becomes increasingly important in our energy system: with the growing share of variable renewable energy production (sun and wind), the system - particularly the electricity system - becomes supply-driven and more decentralised, which makes balancing over time and space of increasing importance.

We observe that in our public knowledge, this challenge is not represented well. Flexibility is not well represented in the main energy system models, monitors, and plans that underpin energy policymaking in the Netherlands, e.g., the Nationaal Plan Energie Systeem (NPE), the Monitor Leveringszekerheid, and the Klimaat en Energie Verkenning (KEV). The partners of the Kenniscoalitie Energietransitie (KCET) see this as an important topic and are developing a program line to address this.

As a first step in assessing what a program line should focus on, multiple assessments have been conducted to determine where the program's focus should lie. The focus of this particular gap analysis is to identify where the energy system models fall short.
The objective of this study is to identify the current gaps in existing energy models that are necessary to better understand the flexibility and market dynamics between 2025 and 2050. The conclusions and recommendations will inform the further development of the KCET program line on flexibility.

The scope of this assessment is defined in Chapter 2. Chapter 3 describes the methodology used to carry out the gap assessment. The actual assessment and the identified gaps are described in Chapter 4. Based on the gaps identifies, possible further developments of the models are discussed in Chapter 5. Finally, Chapter 6 finishes the report with recommendations. Detailed descriptions of the models, capabilities and the details of the gap analysis are provided in the Annexes.

# 2 Scope

This report evaluates the capability of energy system optimisation and market models for analysing flexibility in the Netherlands' power sector. We define flexibility as follows:

> *"the power system's ability to cope with variability and uncertainty. In power systems, these can be found in demand, generation and power flows resulting from their geographical spread. This implies that flexibility is required for both key tasks of a system operator: matching generation with demand and ensuring that power flows do not exceed network thermal and voltage limits."*[1]

The assessments include the models currently used by KCET partners, along with the main publicly available commercial models. Rather than performing the flexibility analysis itself, the report assesses the extent to which these models can support such analysis (a gap analysis) and identifies desired enhancements.

The report focuses on questions about flexibility that can be addressed through the optimisation and simulation of energy systems, including energy supply and demand, system costs, and $CO_2$ emissions. Excluded from the assessment are topics such as power system stability, spatial and environmental impacts, critical materials & life cycle, and safety or resilience in response to rare, high-impact events, as these fall outside the models' capabilities.

The capabilities that the models have are only one puzzle piece. There can be multiple reasons, e.g., because the right analysis is not done, even though the model's capabilities suffice. Or detailed data of e.g. energy infrastructure (low and medium voltage grids and energy assets) is lacking to assess flexibility at a higher spatial and temporal granularity. Data availability to run the analysis is not examined in detail, as it is typically specific to the policy or research question at hand.

Finally, it is crucial to emphasise that the assessment in this document was an exploration conducted with limited time and budget and therefore relies significantly on available expertise and expert judgement.

[1] Heggarty, T., Bourmaud, J., Girard, R., & Kariniotakis, G. (2020). Quantifying power system flexibility provision. Applied Energy, 115852.

# 3 Methodology

In this assignment, we first made an inventory of important questions that address several topics essential to the energy sector. To develop an inventory of questions that can test the models against open-ended questions, there is a need for legitimate questions from governmental bodies that look into the future and seek to make changes in the present. The questions in this assignment, used to test the models, were developed based on conversations with senior scientists and consultants working with these governmental bodies. While finalising them, attention was paid to preserving the open-ended nature and system perspective observed in conversations with scientists and consultants.

Models, as a means to answer a question, may fall short in their ability to answer one question but may be equipped enough to answer another. In the energy transition sector, which is complex and involves many moving pieces in the realisation of a green future, the capabilities of multiple models may be necessary to evaluate solutions and scenarios. To do so, it is essential to evaluate the models individually and, in addition, see if the set of models as a whole (integrating multiple models to answer questions on different levels of insights and complexities) is capable of answering open-ended questions. This is taken into account in the assessment with the formulation of a specific question (research question no. 8).

It is challenging to judge a model on an abstract question. Hence, each question was broken down in terms of ‘capabilities required from the model to answer the question’. This allowed us to create a method to analyse the abstract questions specific enough to assess them against the model capabilities. Based on how the models score on different capabilities and how those capabilities relate to the questions, we can determine a model's ability to answer the question and identify its strengths and gaps.

The following section of the chapter presents the research questions devised and the capabilities associated with them. The definition of the modelling capabilities needed to answer the research questions is provided in Appendix A – Models Capabilities Description. Figure 1 shows a general overview of the methodology in this report.

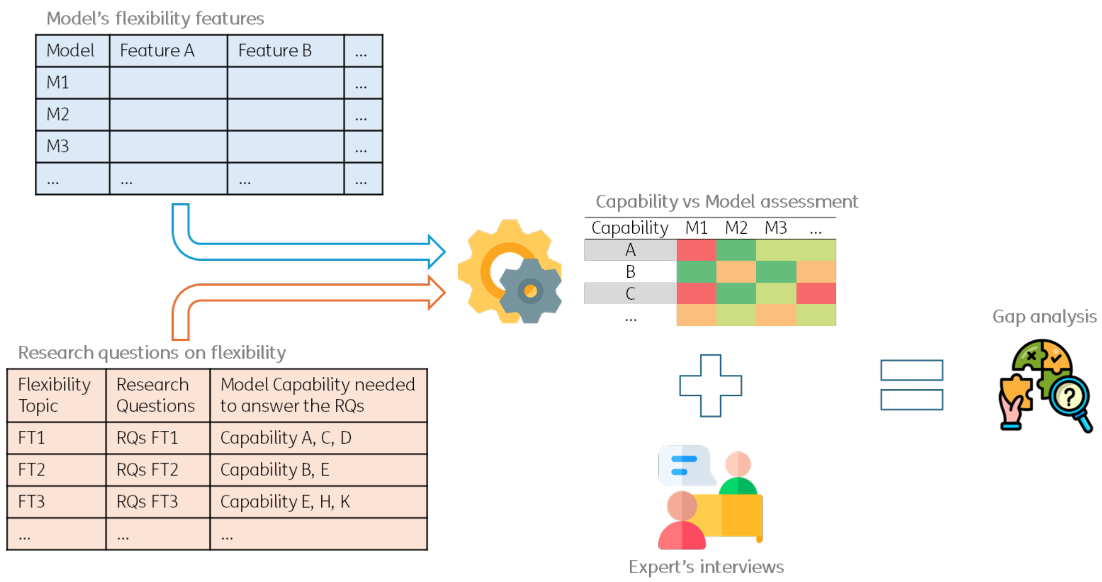


**Figure 3.1:** Methodology for the gap analysis

# 3.1 Modelling topics for flexibility assessment

Based on consultants' experience and the nature of questions from various government agencies about the Netherlands' future in the energy landscape, its challenges, and what needs to be done, the following questions were formulated. The model’s capabilities were judged by its ability to answer such broad, open-ended questions.

### Research question 1

**How much flexibility (in power and energy) will be required in 2030, 2035, 2040, and 2050 to maintain energy and system balance, and to mitigate grid congestion?**

*Which modelling topic for flexibility assessment is associated with the RQ?*
- Demand for flexibility

*What types of model capabilities will be required?*
- Optimise system dimensioning and its evaluation
- Model flexible dispatch characteristics from supply
- Model network congestion with power flow and its potential solutions
- Uncertainty analysis

### Research question 2

**Which sectors and technologies (e.g., EVs, heat pumps, batteries, industry) have the potential to deliver this flexibility at different time horizons and locations (e.g., Western Europe, NL, regional, local)? What are the associated investment, operational, and emissions impacts?**

*Which modelling topic for flexibility assessment is associated with the RQ?*
- Supply of flexibility needs (technical potential)

*What types of model capabilities will be required?*
- Optimise system dimensioning and its evaluation
- Model flexible dispatch characteristics from supply

- Model network congestion with power flow and its potential solutions
- Sector-wise modelling
- Output financial information
- $CO_2$ emissions calculation and reduction analysis
- Detailed market modelling

### Research question 3

**Can the impact of incentive policies be modelled? Consider examples like subsidising a technology or implementing taxes. This involves addressing and modelling policy questions such as:**

1) Adjusting network transport tariffs to promote flexibility options like batteries and e-boilers
2) Implementing time-dependent transport tariffs for households
3) Eliminating double energy taxes for small consumers

*Which modelling topic for flexibility assessment is associated with the RQ?*

- Policies for incentives/tariffs

*What types of model capabilities will be required?*

- Output financial information
- $CO_2$ emissions calculation and reduction analysis
- Detailed market modelling
- Detailed market party behaviour modelling
- Modelling the impact of market changes on existing markets
- Modelling policies
- Business cases

### Research question 4

How sensitive are system outcomes to uncertainties in key technologies or adoption rates (e.g., V2G, heat networks, industrial electrification)?

*Which modelling topic for flexibility assessment is associated with the RQ?*

- Robustness

*What types of model capabilities will be required?*

- Optimise system dimensioning and its evaluation
- Model flexible dispatch characteristics from supply
- Uncertainty analysis
- Sector-wise modelling

### Research question 5

Can different scenarios or transition pathways be modelled? This includes system pathway dynamics with critical interdependencies and tipping points?

*Which modelling topic for flexibility assessment is associated with the RQ?*

- Pathway analysis

*What types of model capabilities will be required?*

- Optimise system dimensioning and its evaluation
- Uncertainty analysis
- Sector-wise modelling

- $CO_2$ emissions calculation and reduction analysis
- Modelling policies

### Research question 6

Are the networks (electricity, gas, heat) prepared for the flexibility needs? How will limitations (e.g. congestion) affect system outcomes?

*Which modelling topic for flexibility assessment is associated with the RQ?*
- System physics constraints

*What types of model capabilities will be required?*
- Sector-wise modelling
- Model the detailed physical constraints of the electricity system (e.g., power flow constraints)

### Research question 7

**On the one hand, what are the economic, reliability, and climate impacts of delaying the implementation of key flexibility solutions, such as increased system costs, electricity price volatility and its distribution across different consumer types, curtailment of renewables, unserved demand, or even power outages? On the other hand, what are the advantages of early implementation of flexibility?**

*Which modelling topic for flexibility assessment is associated with the RQ?*
- Societal effects

*What types of model capabilities will be required?*
- Optimise system dimensioning and its evaluation
- Model flexible dispatch characteristics from supply
- Model network congestion with power flow and its potential solutions
- Sector-wise modelling
- $CO_2$ emissions calculation and reduction analysis
- Detailed market modelling
- Detailed market party behaviour modelling
- Modelling the impact of market changes on existing markets
- Modelling policies

### Research question 8

**How robust are the results, and can they be compared with other methods or model results to validate and potentially yield new insights? Can combining multiple models address gaps that a single model might have? Cross-validation could also enhance the robustness of the results.**

*Which modelling topic for flexibility assessment is associated with the RQ?*
- Integration of models

*What types of model capabilities will be required?*
- Interoperability with other models

## 3.2 Evaluation matrix

The capabilities mentioned in the previous section are not an exhaustive list. It is possible that, in the future, additional model capabilities will be required to answer the abstract/umbrella questions about the energy transition. To ensure the method is replicable in the future. That model evaluation is not tied to a specific question, an evaluation matrix is developed in which models are scored on a 0-3 scale, with 0 indicating 0% of the specified capability. Three indicates the model has 100% of the said capability. The scores in the matrix are based on experts' knowledge of the models and their features and capabilities. A complete overview of the model's features is available in the file "KCET Flex Gap analysis Annex.xlsx", see Appendix B.

# 4 Model evaluation and gap analysis

To evaluate the models, it is essential to understand their technical and administrative features. The current features and technical capabilities will help in answering whether the model has the needed capability to answer the research question (for example, if the model can function at different time granularities and also model energy markets, then it has the capability of market modelling and thus can answer research questions that are around energy markets). Administrative features help users navigate the model. For example, if the model has documentation, making its link accessible helps users perform basic troubleshooting or understand how the model works.

## 4.1 Overview of existing energy models

Several energy models have been developed to address various policy questions. This document primarily focuses on models developed within the KCET coalition (predominantly by TNO and PBL), but we have also included a few main external models. Here is the list of analysed models:

| Model name | The main purpose of the model | Ownership | Contact person | Link |
|---|---|---|---|---|
| TIAM ECN | Integrated energy system analysis for investment and operation in a global context | TNO (TES) | Francesco Dalla Longa | https://www.iamcdocumentation.eu/index.php/TIAM-ECN |
| TIMES Europe | Integrated energy system analysis for investment and operation in Europe | TNO (TES) | Francesco Dalla Longa | https://link.springer.com/article/10.1007/s10666-024-09976-8 |
| OPERA-TNO | Integrated energy system analysis for investment and operation in the Netherlands | TNO (TES) | Joost van Stralen | https://www.pbl.nl/modellen/opera |
| OPERA-PBL | Integrated energy system analysis for investment and operation in the Netherlands | PBL | Bert Daniels (PBL) | https://www.pbl.nl/modellen/opera |
| IESA-Opt | Integrated energy system analysis for investment and operation | TNO (TES) | Amir Fattahi | https://www.sciencedirect.com/science/article/pii/S266679242100072X |
| COMPETES-TNO | Sector coupling gas and electricity for investment and operation analysis in Europe | TNO (TES) | German Morales Espana | https://topsectorenergie.nl/documents/837/2017-FLEXNET-phase-2_kYVchtZ.pdf |
| I-ELGAS | Sector coupling gas and electricity for operation analysis in the Netherlands | TNO (TES) | Sebastiaan Hers | https://www.sciencedirect.com/science/article/pii/S0306261921002336 |
| Tulipa | Integrated energy system analysis of investment and operation with focus on the power sector | TNO (TES), eScience, TU Delft, University of Utrecht | German Morales Espana | https://tulipaenergy.github.io/TulipaEnergyModel.jl/stable/ |

| Model name | The main purpose of the model | Ownership | Contact person | Link |
|---|---|---|---|---|
| REPOWERS | Power system market optimization | TNO (TES) | Sebastiaan Hers | - |
| EYE | Simulating scenarios and impacts on energy markets. | TNO (ICSE) | Aliene, Wester, Peter | - |
| EYE-FLEX | Electricity balancing market model | TNO (ICSE) | Aliene, Wester, Peter | - |
| ESSIM | System dimensioning | TNO (ICSE) | Edwin, Ewoud | https://essim-documentation.readthedocs.io/en/latest/introduction/index.html |
| Ruimtelijke Energie Verkenner | Regional scenario builder (view on the supply/demand and infrastructure) for municipalities and regions | TNO (TES and ICSE) | Richard Westerga, Edwin, Ewoud | https://www.esdl.nl/wp-content/uploads/2025/02/Ruimtelijke-Energie-Verkenner-TNO.pdf |
| Energy Transition Model ETM | System dimensioning and scenario evaluation | Quintel | Quintel | https://energytransitionmodel.com/ |
| Tool voor Integraal Programmeren (TIP) | Start from National Scenarios and then regionalise that information for municipalities (similar to REV) | Witteveen + Bos | Witteveen + Bos | https://www.witteveenbos.com/nl/digital-solutions/tool-for-integrated-programming |
| METIS | Sector coupling gas and electricity for investment and operation analysis in Europe | Co-ownership (EU & third parties) | Tijs Langeveld (RVO) | https://energy.ec.europa.eu/data-and-analysis/energy-modelling/metis_en |
| PLEXOS | Sector coupling gas, water, and electricity for investment and operation analysis | Energy Exemplar | DNV | https://www.energyexemplar.com/plexos |

A complete overview of the main model features is available in the file "KCET Flex Model Gap analysis Annex.xlsx", see Appendix B.

Here is a summary of the main findings from the model overview:

**Core Similarities Among Models:** Most models use energy system analysis tools, focusing on optimisation and scenario development, or simulation and policy assessment. They typically integrate multiple energy sectors (electricity, heat, and transport) and support long-term planning. Many are designed for European or national-level applications and emphasise flexibility to accommodate various policy or technology assumptions.

**Key Differences in Scope and Methodology:** Models differ in their geographic scope (pan-European vs. national or regional), temporal resolution (hourly, daily, time slices), and methodological approach (bottom-up optimisation, simulation, or hybrid). Some, like TIMES Europe and TIAM ECN, are comprehensive and multi-regional, while others, such as the Ruimtelijke Energie Verkenner or Tulipa, focus on spatial or sectoral details. Proprietary versus open-source status and user accessibility also vary.

**Distinctive Features and Specialisations:** Certain models offer unique capabilities: OPERA-TNO and OPERA-PBL emphasise the optimisation of the energy system in the Netherlands; EYE and EYE-FLEX focus on electricity market dynamics using simulations; COMPETES, METIS and PLEXOS are known for detailed power system simulations; and tools like Energy Transition Model ETM and Tool voor Integraal Programmeren (TIP) provide user-friendly interfaces for stakeholder engagement with simulations of the energy and power sector in the Netherlands. Some models are tailored for policy support, while others are research-oriented.

## 4.2 Mapping model capabilities to the current models

To conduct the gap analysis, we map the model's features and capabilities to answer questions derived from the modelling topics to assess flexibility. The following table shows the overview of this capability and models mapping, where:

| | |
|---|---|
| (red) | The model doesn't have the capability. |
| (orange) | The model has the minimum capability. |
| (light green) | The model is partially capable. |
| (green) | The model is fully capable. |

At first glance, there is a solid stance on long-term system dimensioning, sector coupling, $CO_2$ analysis, and high-level policy evaluation. However, no model fits all. This is expected, since models have been developed for specific purposes in the past (e.g., representing electricity markets, integrated energy assessment, simulation, etc.), and flexibility analysis goes across several time scales, technologies, supply, and spatial dimensions, making it difficult for one model with all the capabilities to answer the policy questions. The following section describes the identified structural gaps and links them to the research questions proposed in previous sections.

⚠ **Caveats**

- The scoring in the following matrix is the result of an attempt to translate TNO's expert knowledge and the model's features, i.e., **qualitative analysis**, into a **quantitative scoring** in an attempt to identify patterns that can shed light on the main gaps to address flexibility with energy system models. As such, these values should be taken as a general overview rather than as an exhaustive assessment for a particular case, where some of the scores here may differ.
- **Modelling choices can affect the results and the assessment of flexibility:**
    - **Selection of temporal resolution**: for instance, to evaluate flexibility in the day-ahead markets, the analysis should be done with a model with at least hourly resolution. Models like OPERA can run analyses at hourly resolution; however, the computational burden makes this impractical. A common approach is to use time slices to reduce the computational burden, but that modelling choice will affect the results. So, although the model can run hourly, its typical use is with time-slice aggregation. Therefore, the evaluation in the matrix uses the model's most common use as a reference, rather than its actual capabilities.
    - **System dimensioning**: Although two models can determine the investment decisions, both are capable of doing system dimensioning; a model with hourly constraints for storage can lead to a totally different investment result from a model that works with time slices. Once again, the modelling choice affects the result, even when the model has the capacity and the features.

  - Depending on the flexibility assessment for an analysis, the first question to answer is not only if the model has the capability or feature for the analysis, but also **which modelling choices suit the flexibility analysis**. For instance, analysis of short-term flexibility needs would require hourly temporal resolutions, while seasonal flexibility analysis needs would require analysis across months or even years.
- Working towards **more interoperable models** is an option to get the best from each model, but the **soft-coupling of models has its challenges and consequences** and shouldn't be seen as an easy solution; it needs to be used in the right way and assumptions to guarantee that relevant results from the models are aligned with the research questions.
- **Validation of the models is not addressed in this gap analysis.** Although reproducing behaviour from the past year can be considered a way to validate the models, that practice carries the risk of overfitting the models, i.e., models that can reproduce the past but don't work for future conditions that haven't been seen before. Therefore, the focus should be on the quality of the models (i.e., their fundamental representation of the energy system), and validation with historical data is only part of that quality.

| The capability needed to answer the question | TIAM ECN | TIMES Europe | OPERA-TNO | OPERA-PBL | IESA-Opt | COMPETES-TNO | I-ELGAS | Tulipa | REPOWERS | EYE | EYE-FLEX | ESSIM | Ruimtelijke Energie Verkenner | Energy Transition Model ETM | Tool voor Integraal Programmeren (TIP) | METIS | PLEXOS |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Optimise system dimensioning and its evaluation | | | | | | | | | | | | | | | | | |
| Model flexible dispatch characteristics from the supply | | | | | | | | | | | | | | | | | |
| Model network congestion with power flow and its potential solutions | | | | | | | | | | | | | | | | | |
| Uncertainty analysis | | | | | | | | | | | | | | | | | |
| Sector-wise modelling | | | | | | | | | | | | | | | | | |
| Output financial information | | | | | | | | | | | | | | | | | |
| $CO_2$ emissions calculation and reduction analysis | | | | | | | | | | | | | | | | | |
| Detailed market modelling | | | | | | | | | | | | | | | | | |
| Detailed market party behaviour modelling | | | | | | | | | | | | | | | | | |
| Modelling the impact of market changes on existing markets | | | | | | | | | | | | | | | | | |
| Modelling policies | | | | | | | | | | | | | | | | | |
| Business cases | | | | | | | | | | | | | | | | | |
| Model the detailed physical constraints of the energy system | | | | | | | | | | | | | | | | | |
| Interoperability with other models | | | | | | | | | | | | | | | | | |

## 4.3 Gap analysis

This section provides the actual gap analysis. It is structured around the research questions, as they formed the basis for the analysis. The following steps were taken for each question:

1) Look at each research question and the capabilities needed to answer it.
2) Look at those capabilities in the matrix and identify how many models are present with those capabilities.
3) Identify which capabilities are not well covered.
4) Relate this to the research question and conclude the existing gap.

### Research question 1

**How much flexibility (in power and energy) will be required in 2030, 2035, 2040, and 2050 to maintain energy and system balance, and to mitigate grid congestion?**

To answer this research question, multiple capabilities are required of a model, as presented in Section 3.1. From the evaluation matrix, it is noted that although there are many models for system modelling, there is a lack of models to model network congestion in power flow and its potential solutions. The model capable of doing so lacks reliable data. Since congestion is local and nodal, it is important to note that congestion simulation data should have high spatial resolution (not a single data set for an entire province) and high temporal resolution. It is easier to aggregate data from 5-minute intervals into 1-hour intervals than the other way around. When modelling network congestion and potential solutions, it will be necessary to run multiple scenarios and perform uncertainty analysis. From the matrix, it is clear that most models are not fully capable of performing them. This illustrates the importance of high-quality data and model integration, leveraging the strengths of two models to answer such research questions.

### Research question 2

**Which sectors and technologies (e.g., EVs, heat pumps, batteries, industry)  Which sectors and technologies (e.g., EVs, heat pumps, batteries, industry) have the potential to deliver this flexibility at different time horizons and locations (e.g., Western Europe, NL, regional, local)? What are the associated investment, operational, and emissions impacts?**

Such a research question touches upon multiple avenues. It seeks technical, economic, operational, environmental, and social insights into technologies and sectors, in the context of providing flexibility to the energy system. There are many models capable of performing technical simulations of technologies (covering flexibility) and sector modelling, but, again, for an accurate depiction, quality data is needed that represents the required temporal and spatial granularity not only for supply sources but also for demand. Activating this flexibility is necessary to meet the needs of the energy market, hence the need for detailed market modelling. There are very few models in the matrix that can capture the energy market. Still, none of them cover all energy markets or their intricacies, such as price formation, market-to-market interrelations, and market participants' behaviour, which affect the need for flexibility. Regarding environmental impact, models are limited to calculating $CO_2$ emissions and reductions alone. None of the models in the matrix addresses the social impact of the technologies and sectors.

### Research question 3

**Can the impact of incentive policies be modelled? Consider examples like subsidising a technology or implementing taxes. This involves addressing policy questions such as:**

1) Adjusting network transport tariffs to promote flexibility options like batteries and e-boilers
2) Implementing time-dependent transport tariffs for households
3) Eliminating double energy taxes for small consumers

To model policies, it is essential to run stochastic simulations to evaluate multiple scenarios. Simulating the changes resulting from subsidising a technology would require a technoeconomic analysis. Some of the policies would also require modelling energy markets and market participants' behaviour to understand how a particular policy could change the market. In the matrix, it can be observed that very few models have the partial capability to perform such simulations.

### Research question 4

**How sensitive are system outcomes to uncertainties in key technologies or adoption rates (e.g., V2G, heat networks, industrial electrification)?**

To simulate future systems with variables such as technology adoption rates, realised capacities, etc., the model should be able to run multiple scenarios in a shorter timeframe, allowing analysis of differences within that period and then running more scenarios if needed. The time difference can be substantial. The runtime of some models will be limited to having 2-3 scenarios in a day, while other models allow you to run 2-3 scenarios within an hour. The matrix shows that very few models have the partial capability to provide this capability, while many allow you to design scenarios or systems and optimise system dimensioning. These questions also require modelling flexibility of the systems and the capability to model different sectors. While there are a limited number of models for flexibility, there are plenty that can model different sectors.

### Research question 5

**Can different scenarios or transition pathways be modelled? This includes system pathway dynamics with critical interdependencies and tipping points?**

Modelling and analysing system pathways is essential for exploring future scenarios that would enable climate agreements and reduce $CO_2$ emissions. This would mean scenario generation with optimal dimensioning for specific objective functions, modelling different sectors, running multiple scenarios, performing uncertainty analysis, calculating $CO_2$ emissions for each scenario, and modelling potential policies to assess their impact on $CO_2$ reduction. Looking at the matrix, it is clear that a significant number of models are present to create scenarios, perform $CO_2$ calculations, and also model different sectors. Fewer models are available for uncertainty analysis, and even fewer for modelling policies. Models that can do so have some restrictions. In addition, model integration and interoperability are needed to ensure that the strengths of different models can be utilised to answer such questions.

### Research question 6

**Are the networks (electricity, gas, heat) prepared for the flexibility needs? How will limitations (e.g. congestion) affect system outcomes?**

With the increasing demand for renewables and the influx of renewables, there is a greater need for flexibility. To assess whether the existing network can support this flexibility in the future, it is essential to model different sectors that provide the flexibility and to simulate the physics of the physical system, such as power-flow constraints. Looking at the capabilities matrix, it is evident that few models can simulate the network's physical constraints, while many can simulate different sectors.

### Research question 7

**On the one hand, what are the economic, reliability, and climate impacts of delaying the implementation of key flexibility solutions, such as increased system costs, electricity price volatility and its distribution across different consumer types, curtailment of renewables, unserved demand, or even power outages? On the other hand, what are the advantages of early implementation of flexibility?**

Such a research question covers a broad range of topics, so models will need different capabilities to answer it. Section 3.1 presents this research question, along with a long list of capabilities needed to answer it. Having a long list makes it clear that no single model can answer this question, so multiple models are needed. To answer some parts of the question, there might be a need for interactions between two models, using the output of one as input for another, while for others. This again underscores the importance of having interoperable models, such as those based on the ESDL language, which are interoperable to some extent. There are plenty of models in the matrix that can answer questions about optimal system dimensioning, model different sectors, perform $CO_2$ emission calculations, and model the flexibility characteristics of supply. There are a few models that have sufficient capability to answer questions about energy markets, but need further development to simulate the coupling and interrelations among different markets and the behaviour of market participants. There are very few, but capable, models to simulate congestion and its possible solutions.

### Research question 8

**How robust are the results, and can they be compared with other methods or model results to validate and potentially yield new insights? Can combining multiple models address gaps that a single model might have? Cross-validation could also enhance the robustness of the results.**

In the previously answered research questions, it was noted that no single model can answer a question in its entirety. Using more than one model that complements each other's capabilities to answer a question would be optimal. Still, it would require integration among models, with the output of one used as input to the other. For example, questions related to simulating policy effects on energy markets and congestion, a model which can simulate congestion and its solutions, simulate policy and the effects it will have on the energy market, market party behaviour, etc., will require multiple models to come together and complement each other.

# 5 Further developments

Based on the identified gaps, we formulate possible further developments of the models. This chapter outlines several model development tracks that can be executed in stages. We have grouped them in technical development tracks and policy-facing tracks.

## 5.1 Technical development tracks

**T1. Grid & (intraday, multi-day up to seasonal) storage:** Enhance network-resolution (regional/local) and multi-timescale storage modules, including stacked revenue streams and market-consistent pricing, to credibly measure the location-dependent value of flexibility.

**T2. Integrated multi-vector market modelling:** Tighten coupling among electricity, gas, and hydrogen (and heat where relevant), standardise market design features (bidding zones, reserves/imbalance), and align profit-seeking behaviour across models to ensure consistent price formation.

**T3. Operationalised robustness analysis:** Build scenario ensembles and stochastic analyses into standard workflows. Provide analysis that speaks about policy robustness rather than single-trajectory forecasts.

**T4. Cross-model validations:** Institutionalise benchmarks, feature mapping and comparison, documentation, and “model switch” transparent workflows to build trust and reproducibility across platforms.

**T5. Open-access input/output platform/tool for stakeholders:** Provide ETM-like views to compare inputs and results across models and scenarios, improving public transparency and comparability.

**T6. Alignment with EU Integrated Assessment Models (IAMs):** Closer linkage to TIMES Europe and similar IAMs helps ensure NL power flex insights are consistent with wider EU pathways, connecting national market behaviour with integrated planning families like OPERA.

**T7. Include macro - energy–economy coupling:** Coupling (e.g., OPERA ↔ WorldScan) allows economy-wide impacts of flexibility to be assessed, thereby improving the policy relevance of outcomes.

**T8. Coordinated scenarios & shared assumptions:** Harmonise scenario definitions across models and scales (global/EU ↔ NL ↔ regional) to support consistent cross-model integration and clear policy narratives.

**T9. Data access enablement:** Pursue standard, shareable data (especially for medium- and low-voltage networks) to unlock congestion analysis use cases that current public datasets cannot support.

## 5.2 Policy-facing priorities

**A) Establish the public value of flexibility and storage:** Offer clear proof of the benefits of flexibility—particularly storage—by using market-consistent pricing, an extensive geographic scope (northwest Europe), and multi-vector coupling (electricity, gas, hydrogen). This helps fill a key information gap in policymaking and aids decisions on wind and nuclear development strategies.

**B) Enable robust policy programming:** Implement robust scenarios, stochastic analysis, and critical path assessments within integrated frameworks like OPERA and TIMES-Europe. This approach supports sustainable policy packages rather than isolated plans.

**C) Integrate and explain:** Present integrated model workflows and clear visuals, such as ETM-style dashboards, enabling non-technical audiences to compare options, trade-offs easily, and co-benefits at a glance, thereby increasing trust and adoption.

# 6 Recommendations

In this short explorative study, we have identified gaps in the main energy system models used to better understand flexibility and market dynamics between 2025 and 2050. These gaps have led to the formulation of desired improvements to the model. In this chapter, we provide recommendations on the model improvements that we think should be prioritised.

**1. Work towards model integration & interoperability:** Today's models each effectively address different aspects of the problem; the logical next step is to enable interoperability. This involves sharing harmonised assumptions, scenarios, and out-puts across models (e.g., system planning, market dispatch, grid analysis). Such integration allows for cross-validation, capitalises on each model's strengths, and helps mitigate the limitations of relying on a single model. There are models in the matrix based on the ESDL language, and they are interoperable to some extent; they can be improved to increase interoperability.

**2. Increase grid & spatial representation for flexibility valuation:** Two directions are needed in parallel:
- **Regional/local resolution** to analyse congestion and the value of flexibility as an alternative to or complement to grid reinforcement.
- **Northwest Europe (NWE) system context** to reflect NL's transit role, cross-border exchanges, and corridor developments. Together, these im-prove location-specific price signals and the valuation of flexibility.

**3. Enhance the representation of storage across time scales (e.g., intraday → multi day → seasonal):** Represent stacked revenues and operational constraints for storage across time scales, with market-consistent pricing and price duration statistics. This is a natural frontier given the increasing share of variable renewable energy and congestion patterns.

**4. Operationalise uncertainty analysis:** Shift from single or ad hoc Monte Carlo sensitivity runs to structured uncertainty analysis, which prepares flexible solutions for multiple potential future scenarios instead of optimising for just one. Promising re-search areas to accomplish this include modelling to generate alternatives (MGA), stochastic optimisation, and robust optimisation.

**5. Synchronise market design & pricing fidelity:** Harmonise the representation of bidding zones, reserve/imbalance pricing, and profit-seeking vs cost-minimising behaviour across coupled markets (electricity, gas, hydrogen) so that flexibility options are priced consistently in analysis.

**6. Improve policy instruments representation:** Strengthen encoding of key policy instruments and their interactions—e.g., EU Emissions Trading System (ETS), Energy Performance of Buildings Directive (EPBD), and the Dutch Klimaat- en Energieverkenning (KEV) assumptions—so demand side, efficiency, and storage incentives can be assessed within the models.

**Furthermore..**
Given current societal challenges and unstable geopolitical developments, we recognise that a broader analysis of the Dutch energy system is needed beyond the flexibility requirements assessed in this study. Such an analysis could consider factors including dependence on critical materials, environmental impact, security (robustness and resilience), strategic autonomy, and economic impacts. The energy system models used in this study are not developed for such analysis. Most likely, other models exist that can support such analysis on specific aspects. In addition to the above-listed improvements, it is recommended to further explore the need for such wider assessments, with what (combination of) models and data these analyses could be carried out, and what is required in terms of further developments.

# Appendix A
# Models Capabilities Description

This annex describes the capabilities that are used in this study to assess the models.

- **Optimise system dimensioning and its evaluation**

The model's ability to optimise the sizing (investments) of energy systems for specific objectives (such as minimising costs or maximising welfare) and assess its performance through dispatch optimisation or simulation. For instance, modelling an energy system comprising a mix of renewables and no fossil fuel plants, then sizing it to fully balance the energy system, followed by simulation at a defined time granularity.

- **Model flexible dispatch characteristics from the supply**

Performing a simulation that dispatches assets flexibly to adjust their production or demand, maintaining system balance and avoiding congestion. The model also calculates the energy volume (MWh) and capacity (i.e., power) (MW) of flexibility required to keep the system balanced. Adjusting dispatch timing and volume allows for controlled ramping rates of assets, considering operational limits and constraints.

- **Model network congestion with power flow and its potential solutions**

Modelling congestion in the energy system at the nodal or regional level involves using various options, such as special markets, flexible production and consumption assets, and improved forecasting, to support better resource planning. Solving this may also require power flow calculations at finer time resolutions, leading to high spatial and temporal granularity in simulation and optimisation.

- **Uncertainty analysis**

How the model manages uncertainty in future energy system scenarios: through sensitivity and scenario analysis, Monte Carlo methods, and stochastic optimisation.

- **Sector-wise modelling**

The model should be capable of individually representing different sectors and their characteristics. Additionally, sector-specific interactions can be incorporated later. For instance, the mobility sector can support the grid during critical periods through demand response and feed-in mechanisms. Industries such as chemicals and steel operate with steady loads, and delaying production by an hour might benefit the grid without causing significant losses, as earnings from demand response could outweigh the potential costs of the delay.

- **Output financial information**

The model's ability to generate financial figures based on CAPEX and OPEX—such as revenues, costs, NPV, IRR, and Levelized Cost—helps evaluate different solutions. Access to this financial data supports comparisons of options and helps understand the investor's perspective in business cases.

- **$CO_2$ emissions calculation and reduction analysis**

The amount of $CO_2$ reduction resulting from the implementation of a specific technology, process, or policy.

- **Detailed market modelling**

This detailed energy market model replicates its functioning, dynamics, and behaviour, which depend on factors such as fluctuating demand and supply, influences from other markets, international trade volumes, and other variables. For example, suppose forecasted supply, including renewables and imports, is sufficient to meet demand. In that case, energy prices might remain low because there's no need to procure additional energy to avoid load loss. Imbalanced prices are highly dynamic, constantly changing in response to real-time market behaviour, such as demand versus supply. In a scenario with 100% renewables and conversion technologies, if the minimum renewable demand isn't met, energy prices could spike significantly. Similarly, sudden changes in demand and supply forecasts on the day of operation can cause imbalance or Frequency Control Regulation (FCR) market prices to soar. International trade can also influence these market outcomes.

- **Detailed market party behaviour modelling**

Having predefined or customizable market party behaviour for different types of consumers (e.g., households, industries, commercial areas) to simulate real-life conditions of how people (re)act on the energy market while responding to energy prices. For example, market participants exhibit ever-changing behaviour to keep up with shifts in the energy market and maximise profits. Their strategies change constantly, such as to curtail and ensure they have a dynamic strike price based on asset health, SDE subsidies, GVOs, etc. These strategies continually evolve as the market changes.

- **Modelling the impact of market changes on existing markets**

Introducing a new energy market will influence existing markets, or market changes, e.g., the day-ahead market MTU time from 1 hour to 15 minutes. The model should be capable of delivering either a preliminary or detailed analysis of these effects.

- **Modelling policies**

Policies influence how technologies are deployed and how energy producers and consumers behave. Modelling this can help anticipate its effects.

- **Business cases**

Analysis of various revenue streams—including Day Ahead (DA), balancing, Power Purchase Agreement (PPA), capacity, and flexibility revenues—along with the impact of policy changes on revenues and costs, as this will impact both the investments in new assets as well as their operational behaviour.

- **Model the detailed physical constraints of the energy system**

To understand the dynamics of the energy infrastructure, including asset tipping points, system imbalances, and frequency deviations, it is necessary to model the system's detailed physics.

- **Interoperability with other models**

The ability of a model to accept output from another model as input. Since the input and output may operate at different time granularities, the model receiving the input or providing the output must be adaptable to support cross-model interaction. This also applies to the input and output formats.

# Appendix B
# Detailed model description and gap analysis

A more detailed overview of the model, their features and the gap analysis can be found in the separate spreadsheet KCET Flex Model gap analysis Annex.xlsx.

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