International PtX Hub

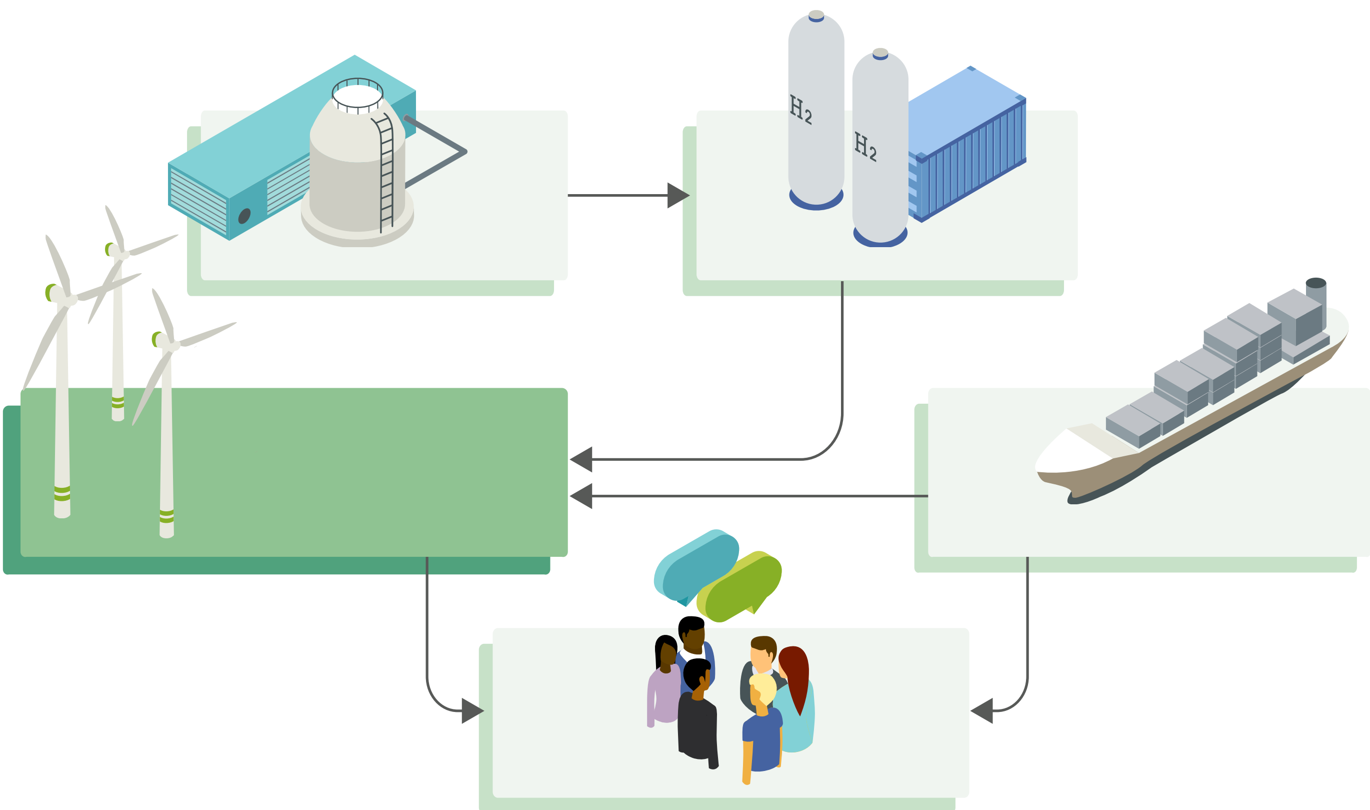
On behalf of:
Federal Ministry for the Environment, Climate Action, Nature Conservation and Nuclear Safety
of the Federal Republic of Germany

IKI International Climate Initiative

Implemented by
giz Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH

A Guide to PtX Modelling and Allocation in Long Term Energy Planning

Lessons Learnt



Agora Industry

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INTERNATIONAL CLIMATE INITIATIVE

Implemented by

Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH

IMPRINT

As a federally owned enterprise, GIZ supports the German Government in achieving its objectives in the field of international cooperation for sustainable development.

Published by:
Deutsche Gesellschaft für
Internationale Zusammenarbeit (GIZ) GmbH

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Bonn and Eschborn, Germany

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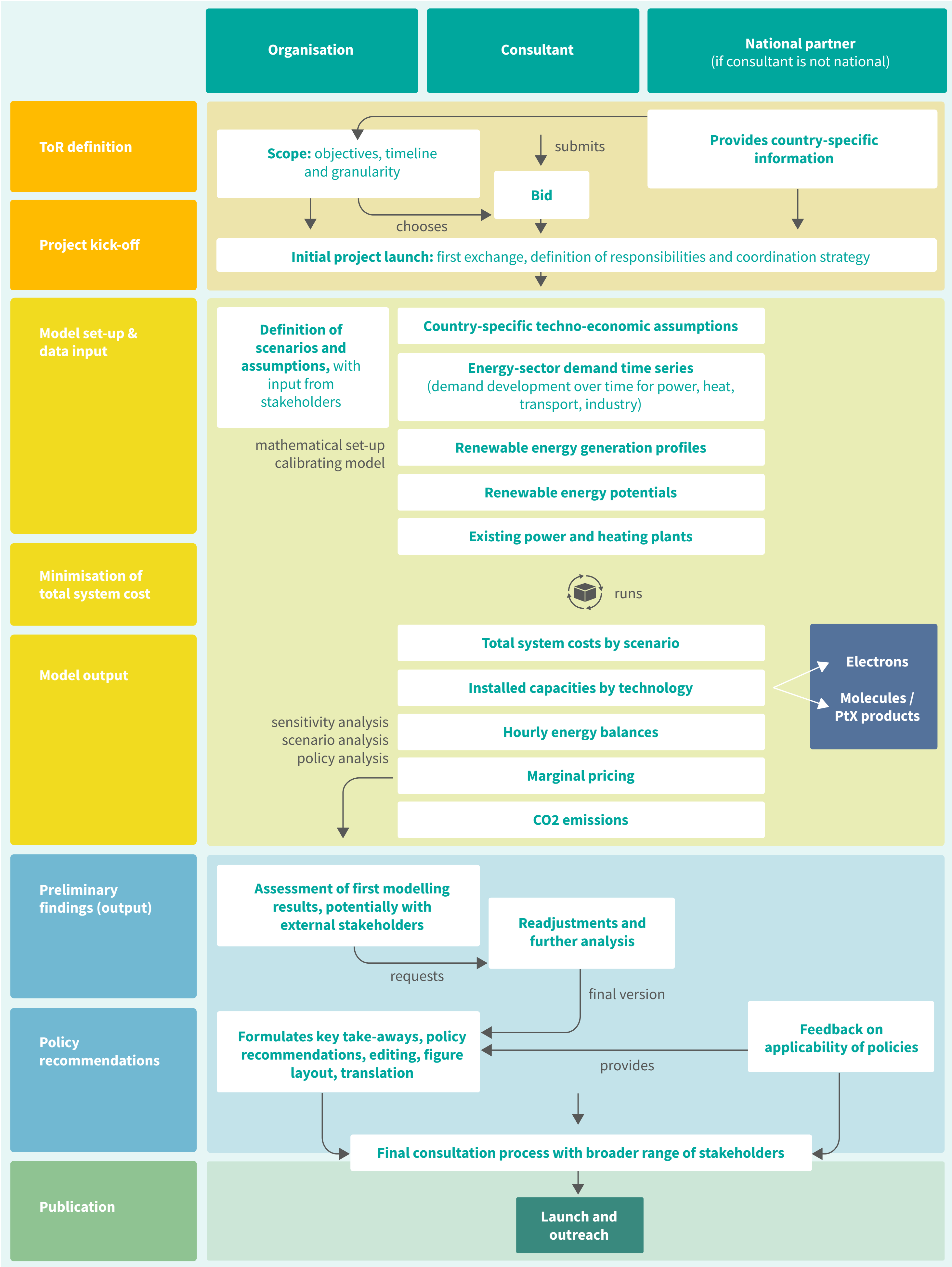
The International PtX Hub is implemented by the Deutsche Gesellschaft fur Internationale Zusammenarbeit (GIZ) GmbH on behalf of the German Federal Ministry for the Environment, Climate Action, Nature Conservation and Nuclear Safety (BMUKN). Financed by the International Climate Initiative (Internationale Klimaschutzinitiative, IKI), the International PtX Hub is a contribution to the German National Hydrogen Strategy of 2020 and represents one of the four pillars of the BMUV's PtX action programme initiated in 2019.

December 2025

Agora Industry

Content

Overview: The PtX Allocation Modelling Process



1 Background and Context

To reach the goal of the Paris Agreement and be in line with a 1.5°C pathway, the global energy system needs to be transformed towards climate neutrality over the next three decades. Green hydrogen and green hydrogen-based synthetic products generated from renewable electricity (Power-to-X, PtX) can replace fossil products in industry, transport (where direct electrification is not feasible, such as long-range aviation and shipping), and other sectors, with the relevant PtX products including green ammonia, methane, methanol, synthetic liquid fuels and even plastic. The technology will be a key element of global energy transformation.

Countries and regions with favorable conditions for renewable energy (RE) generation are suited to become global players in PtX production. However, the scarce and expensive resources need to be allocated to those applications that depend on PtX to become climate-neutral (see table below).

Need for molecules in addiction to green electrons

Green molecules needed for climate neutrality by 2050?	Industry	Transport	Power sector	Buildings
No-regret	Non-energy use[1]: • Feedstock: ammonia, chemicals, fertilisers • Reaction agents: DRI steel	• Long-haul aviation • Maritime shipping	• Renewable energy back-up, depending on wind and photovoltaic share and seasonal demand structure	• Heating grids (residual heat load[2])
Controversial	• High-temperature heat	• Trucks and buses[3] • Short-haul aviation and shipping • Trains[4] • Non-road mobile machinery	• Absolute size of need given other flexibility and storage options	–
Bad idea	• Low-temperature heat	• Cars • Light-duty vehicles • Two- and three-wheelers	–	• Building-level heating

Agora Energiewende and Agora Industry (2021).
[1] Hydrogen may also be used as a reaction agent and/or feedstock in bio-refineries.
[2] After using renewable energy, ambient and waste heat as much as possible. Especially relevant for large, existing district heating systems with high flow temperatures. Note that according to the UNFCCC Common Reporting Format, district heating is classified as being part of the power sector.
[3] Series production currently more advanced on electric than on hydrogen for heavy-duty vehicles and buses. Hydrogen heavy-duty to be deployed currently in time only in locations with synergies (ports, mines, industry clusters).
[4] Depending on distance, frequency and energy supply options.

Source: Agora Industry, ICCT and RAP (2025)

As several countries in the Global North, e.g. Germany, are not well positioned to cover their hydrogen demand fully by exploiting their own renewables, new ways of trading and energy partnerships are being discussed. Thus, many countries in the Global South pursue the strategy of becoming exporters of green hydrogen and PtX products. However, such export plans may to some extent conflict with domestic energy transformation ambitions. The PtX Hub therefore aims to support countries in developing their own country-specific concepts and approach for PtX, considering their different starting situations, individual motivations and various potentials for PtX production and application. In this regard, the methodology for so-called "allocation studies" described in this paper aims to identify national PtX allocation pathways and cost-optimal distribution of PtX products among applications – while potentially also considering export. This is done by performing cost-optimisation modelling for the energy system of a given country (long-term energy planning). Practically, this implies minimising the total energy system costs while staying within the limits of a certain greenhouse gas emissions cap of a given target year. **The optimisation then informs the user about the cost-optimal applications for PtX – and, vice versa, about the applications for which PtX products should not be used from an economic perspective.** The modelling proposed here covers different scenarios, e.g. (1) business as usual, (2) current NDC (Nationally Determined Contributions) and long-term policy goals and (3) carbon neutrality. However, these scenarios are tailored to each country's context in order to obtain results closer to the national reality. Indeed, the consultation process conducted in each country contributes to the scenario development, and hence the variation in scenario definitions across countries for which this methodology is applied.

Taking into account the experience from PtX allocation studies previously conducted for Argentina and South Africa, this guideline provides a framework for setting up and conducting future PtX allocation studies, while highlighting the lessons learnt, best practices and common pitfalls identified during past experiences. In the annex, the reader finds sample Terms of Reference for tendering PtX allocation studies.

2 Objective of the PtX Allocation Studies

The aim for PtX allocation studies is to develop a range of detailed energy transition pathways/scenarios for a respective country up to 2050 to better inform ongoing and upcoming policy and expert discussions on this topic.

The pathways to be produced should demonstrate how and which PtX products can contribute to the defossilisation of power, heat, transport and industrial systems in the country. The study should also consider off-grid solutions as well as assess the necessary renewable energy sources to be integrated into the power system for the implementation of PtX applications in the country. Importantly, the studies should analyse the total system costs of the pathways in detail, based on in-depth economic and technical assessments.

Particular attention should be given to the **short-term 2030 horizon**, to understand how long-term decarbonisation commitments (2050) translate into short and mid-term priorities (2040), including its strong link to climate action. A focus should be to understand which mid-term priorities are 'no regrets' for all PtX technology options, and which technologies are essential to demonstrate feasibility in the 2020s. This approach aims to provide guidelines for investors and developers on the times for the development of supply chains and future demand loads – especially for green hydrogen production and use – that will need to be ready to scale up after 2030.

Obtaining these results will require a detailed **modelling** of a country's energy system with high spatial and temporal resolution. The flow chart at the beginning of this paper provides an overview of the necessary steps. The modelling should be developed by a consortium including a national partner, or by a consultant in exchange with a group of national experts. The modelling of the power system and its interaction with the heating and transport systems will be crucial, together with the required PtX products as feedstock in the industrial sector. The study should also model flexibility provision (and requirements) in the power sector considering renewable-based integration between the evaluated sectors, with a focus on the system needs to successfully implement PtX applications. Additionally, the consultant should consider existing relevant work developed in the country related to energy scenarios, hydrogen roadmaps, flexibility studies as well as mid- and long-term energy and climate targets.

By developing the PtX allocation pathways, all elements of the **green hydrogen/PtX supply chain** for different sources, technologies, products (e.g. hydrogen feedstock for national industry, for transport in existing gas pipeline, hydrogen as energy carrier and end use, Power-to-Liquid, ammonia) as well as market opportunities and needs (national use and export) for the time until 2050 will be analysed. The design of country scenarios is among other factors based on supply and demand (national and for export) assessed through detailed modelling of various sectors and linked to overall energy and decarbonisation scenarios.

This shall provide a **strategic long-term perspective** for policy makers and allow for respective regulations, agenda setting and identification of early no-regret strategies. The overarching goal is to inform stakeholder processes on potential market development and to utilise those results to support the development of long-term strategies for 2050 and beyond and highlight the role of green hydrogen in climate commitments such as the NDCs.

The allocation modelling will not solve all questions around PtX products, mainly because the future is fundamentally uncertain and any model output will inevitably reflect the uncertainties in model inputs, in addition to the peculiarities in model scope, structure and granularity. But the optimisation brings in a clear focus on costs, which should be of interest to most if not all policy makers. Based on those insights, they will be better equipped to weigh other decision criteria explicitly against those costs and lead to a more transparent and informed discussion on PtX products. In particular, the insights should contribute to strategic discussions on the issue of domestic use versus export of PtX products.

3 Scope and Considerations

The pathways produced should demonstrate how very large shares of renewables can be integrated into the power system, and how renewables-based electrification and PtX products can contribute to the defossilisation of power, heat, industries and transport systems. The total system costs of the pathways are analysed in detail, based on an in-depth economic and technical assessment. While modelling the system up to 2050, particular attention should be paid to the 2030 horizon, in order to understand how long-term decarbonisation commitments (2050) translate into short and mid-term priorities (2030).

The following considerations for the framing of the analysis have proven useful to reach meaningful results with the modelling process:

- **Technologies** to be considered for the country defossilisation pathways in each of the demand sectors (power, transport, industry and buildings)
- Possible and needed amount of **renewable electricity integration** in the country's energy system for the achievement of decarbonisation goals, including PtX needs
- **Financial impact:** Total system costs and respective investment needs
- Requirements for increased generation capacity and energy **system flexibility**
- **Infrastructure** development requirements at the regional level for the achievement of high levels of electrification and PtX production

4 Project Implementation: Lessons Learned from First PtX Allocation Studies

The following sections summarise the experience from allocation studies conducted for **Argentina** and **South Africa** to highlight lessons learnt and best practices.

4.1 Approaching Energy System Modelling

Lessons learned:

- A project consortium with a national partner ensures better outcomes, enhancing data access, stakeholder engagement, and model applicability
- Regular consultation with national experts is crucial, especially for international consultants, to align assumptions with national energy realities
- Open-source modelling improves long-term usability, fostering transparency, knowledge sharing, and capacity building for national stakeholders
- Engagement with power system planners and operators enhances model credibility, ensuring real-world alignment and effective knowledge transfer
- An integrated, sector-coupled approach is essential, ensuring the model captures PtX deployment across power, heating, transport, and industry over time

To achieve the desired outcomes, a comprehensive and **high-resolution energy system model** for the country must be developed. This model should feature both spatial and temporal granularity, ensuring an accurate representation of the energy landscape. The modelling should be developed by a **consortium which includes a national partner,** in close exchange with a group of national experts and potentially other actors, working on energy systems in the country.

A key aspect of the model is the ability to provide an **integrated and sector coupled approach**, which would consider the interdependencies between the power, heating, transport, and industrial sectors. It should also model flexibility provisions (and requirements) in the power sector in the context of renewables integration with the aforementioned sectors.

A model focused only on the power sector overlooks sectoral PtX deployment, requiring external assumptions and failing to show how PtX products contribute to decarbonisation over time. The model should clearly define which PtX products are used in which end-use sectors (industry, transport, heat) over time, ensuring a sector-specific, time-based decarbonisation roadmap.

To ensure long-term usability and capacity building within the country, the **model should preferably be open-source**, enabling future users to adapt and refine the tool for national planning needs. An open-source approach fosters transparency, knowledge sharing, and skill development, supporting robust energy system planning.

Even if national authorities do not use the open-source model as their primary model, ideally, some national energy planners can be trained on applying the open-source model. As a second-best approach, other institutions like universities can complement the standard process of national energy planning and contribute insights to enable a broader societal discussion on PtX.

Examples of well-established open-source modelling energy system model initiatives :

- OSeMOSYS: **http://www.osemosys.org/**
- PyPSA: **https://pypsa-meets-earth.github.io/index.html**

4.2 Stakeholder Engagement

Lessons learned :

- Early stakeholder mapping ensures effective engagement, using an Influence vs. Interest matrix to identify key actors and prioritise involvement
- Partnerships with national organisations improve stakeholder access and credibility, ensuring better data validation, participation, and alignment with national policies
- Regular engagement sessions strengthen model adoption, allowing stakeholders to provide feedback and refine recommendations for greater impact

A **robust stakeholder engagement strategy** is essential for the successful setup, validation, and adoption of the project's results. A **national partner who can facilitate access to key stakeholders** is a crucial enabler, ensuring meaningful participation and knowledge exchange.

At project initiation, a **stakeholder mapping** process should be conducted, categorising actors using a typical Influence vs. Interest matrix. This should include representatives from the private sector, government institutions, research organisations, and civil society. Stakeholders with high influence and high interest should be prioritised, with **regular feedback sessions** integrated throughout the process to maintain engagement and alignment.

At a minimum, **two stakeholder engagement sessions** should be held:

1. **Project initiation phase** – To discuss and refine proposed scenarios before model implementation.
2. **Results validation phase** – To present draft findings and gather feedback before finalising policy recommendations.

This structured engagement approach enhances stakeholder buy-in, result credibility, and policy impact, ensuring that the final outputs are both technically sound and practically implementable. It should also create a sense of national ownership of the project among the participating stakeholders. Ideally, national energy planners should be involved from the beginning to the end, with the aim of enabling them to run the model independently later on.

4.3 Model Set-Up

Lessons learned:

- PtX production routes must be country-specific, reflecting national resources, infrastructure, and policies for accurate energy planning
- PtX export potential should be analysed, considering global market demand, trade opportunities, and price forecasts for a long-term strategy
- Industry sector modelling must include temperature-specific processes, ensuring appropriate technology selection for decarbonisation
- Energy uses in industry and PtX alternatives need precise modelling, integrating them accurately into the optimisation framework
- A 5-year time resolution is ideal, balancing computational efficiency and decision-making accuracy for transition planning
- Fugitive emissions and fossil fuel infrastructure must be considered, capturing leakages and phase-out impacts for full decarbonisation

The consultant should employ a **comprehensive techno-economic energy system model** covering power, heat, transport, and industrial feedstock to analyse the country's transition until 2050. This should be accomplished at **5- or 10-year timesteps**. The model must feature **high geo-spatial and temporal resolution** to ensure detailed and accurate scenario assessments. The consultant's ability to develop and refine the model using existing national energy data, both publicly available and proprietary, is essential for producing reliable and actionable insights.

The model should incorporate an **optimisation framework** that minimises both investment and operational costs, while adhering to predefined constraints for each scenario pathway. Key to these pathways is the analysis of the role which PtX molecules play in both the sectoral decarbonisation pathway and the export potential, including the possibility of no PtX exports. Similarly, the infrastructure built out needed to enable this and the associated costs are critical. Given the uncertainties in energy forecasting, exploring alternative pathways is critical for expansion planning.

Key parameters to consider include:

- Technology costs and advancements
- Sectoral demand trends
- Renewable energy deployment limits
- Grid constraints and expansion needs
- Fossil power plant performance and phase-out implications
- Fuel price volatility, PtX price forecasts and trade opportunities
- Future climate policies, including carbon taxation

A core focus of the analysis should be on **deep decarbonisation strategies** across all sectors, assessing their impact on the power system's scale and operational characteristics at an hourly time step. The model must capture the **interactions between power, heat, and transport** (sector coupling), ensuring granular technical detail and system flexibility. All flexibility potentials and constraints for modelled technologies should be explicitly integrated to reflect real-world operational limitations.

For the **industry sector**, the model **should differentiate decarbonisation technologies based on temperature requirements**, accounting for solutions such as heat pumps, hydrogen boilers, and biomass boilers. This differentiation is crucial for identifying sector-specific transition pathways and ensuring technological feasibility across industrial applications

4.4 Data Preparation and Collection

Lessons learned:

- Prioritise public data, however ensure that the most current information is utilised
- A wide range of data will be required that should ideally be validated via key stakeholder engagement

The consultant's initial offer should give an indication how the necessary (but often rather limited) data could be approximated, in case neither the consultant nor any national partner project can provide country-specific data. **Public data sources are preferred** for the modelling exercise, especially for the provision of an open-source model. Indeed, public data allows for more open discussions with stakeholders during the development of the project.

A **consultation process regarding the assumptions and data sources** is key, to align the results of the study to the national context, obtaining results that are relevant for the national discussions in the country of analysis.

4.5 Scenario Definition

Lessons learned:

- Scenarios must be country-specific, reflecting national energy systems, policies, and socio-economic conditions
- At least one scenario should model high climate ambition, preferably net-zero emissions, to assess deep decarbonisation feasibility
- Stakeholder involvement in scenario development is crucial, ensuring assumptions align with national priorities and policy realities

Defining scenarios effectively is critical to ensuring relevant, realistic, and actionable energy transition pathways. **At least three scenarios should be developed**, covering different energy-related CO2eq emission budgets through 2050, with a minimum of a 5-year resolution. Aligning scenarios with national conditions, energy priorities, and policy commitments is essential to generating accurate and applicable insights.

National partners play a key role in scenario development, ensuring that assumptions and constraints reflect national realities. **This process should be validated** through comprehensive stakeholder engagement (see the Stakeholder Engagement section above). Scenarios should also align with short-, mid-, and long-term climate goals, ensuring coherence with national and global decarbonisation commitments. Depending on a country's energy planning and long-term strategies, a fourth scenario may be introduced to capture additional uncertainties or alternative transition pathways.

4.6 Sensitivity Analysis

The sensitivity analysis aims **to evaluate the impact of key uncertainties on the energy system's development under different scenarios**. By systematically testing variations in critical parameters, the analysis helps identify risk factors, tipping points, and policy implications, ensuring more robust and adaptable energy planning.

The **sensitivities** required to be tested **will vary depending on the specific circumstances within a given country.** Certain key variables affecting the economics and constraints of the optimisation modelling need to be identified in the definition of scenarios to be included as part of the sensitivity analysis. While potential sensitivities should already be outlined in the bid received, it is more **important to have a defined maximum number of sensitivities which can be tested and are included within the financial offer provided**. The final selection of sensitivities will likely be refined through stakeholder engagement to ensure relevance and alignment with national priorities.

To reflect potential uncertainties, critical variables for sensitivity testing may include:

- Sectoral applications of green hydrogen (e.g. for high-temperature industrial process heat)
- Economic competitiveness of renewables versus fossil fuels
- Sustainability criteria for green hydrogen production
- Technical constraints in achieving high electrification levels
- Infrastructure limitations and expansion needs
- Fluctuations in the cost of capital
- CO_2 reduction targets and climate policies

The sensitivity analysis should provide an overview of the way certain variables can influence the development of the energy sector in the country under the defined scenarios.

4.7 Energy Transition Pathways Analysis

- The analysis of the initial results will require critical scrutiny to assess their applicability to the real world
- A national team of energy experts will be crucial to ensure that the results are adapted to the national context, taking into account real world constraints and opportunities
- To create more applicability and ownership of the results, they should be evaluated in the context of energy system planning documents

It is essential to recognise that a model's outputs are inherently constrained by its inputs, assumptions, and predefined boundaries. Therefore, **initial results must be critically analysed through the lens of real-world applicability** to ensure their relevance and feasibility. This scrutiny is particularly crucial when the consultant conducting the modelling exercise is either not based in the country under assessment or has limited firsthand experience of its energy landscape.

For instance, a model might identify an optimal location for green hydrogen production based on high full load hours from overlapping solar and wind resources. However, it may fail to account for practical constraints, such as remoteness, lack of infrastructure, and logistical feasibility. Similarly, a model might suggest an inland site for green hydrogen production in a water-scarce region, overlooking the potential water supply challenges. This occurred in the South African energy study, where additional analysis was required to assess whether water freed up from coal phase-out could meet the demands of green hydrogen production. To mitigate such risks, it is strongly recommended that:

- **A team of national energy experts is involved in validating model outputs** and assessing their feasibility
- **Additional constraints are introduced where necessary to enhance model realism**
- **Final results are evaluated against existing energy system planning documents,** identifying any discrepancies and suggesting potential improvements

By integrating national expertise and conducting real-world validation, the model's insights can be refined to support effective and implementable energy planning strategies. Ideally, national energy planners can be trained on the model to enable continued use in energy planning.

4.8 Policy Recommendations

- Policy recommendations must be actionable, politically relevant, and comprehensive and, if possible, include implementation timelines to ensure alignment with national energy planning
- Stakeholder engagement is crucial to validate recommendations, address barriers, and improve feasibility, ensuring stronger policy adoption
- Recognising study limitations and identifying areas for further research strengthens credibility and provides a foundation for future energy planning refinements

Building on the modelling results and the current national energy landscape, it is advisable **to request the consultant to provide preliminary recommendations for amending long-term energy plans**. A key focus should be on aligning short-term (2030) actions with deep decarbonisation targets for 2050, ensuring a coherent and actionable transition pathway.

To enhance political relevance, **policy recommendations must be tailored to ongoing national discussions and priorities**. They should be specific, actionable, and comprehensive, covering all key dimensions of the study, including:

- Infrastructure requirements (grid expansion, renewable energy siting, green hydrogen hubs, etc.)
- Financing mechanisms (investment incentives, risk mitigation, and market development)
- Regulatory adaptations (permitting processes, market structures, and carbon pricing)
- Geographical implementation (regional prioritisation based on resource availability and demand)
- Temporal implementation (phased approach aligned with policy milestones and industrial readiness)

To ensure feasibility, **policy proposals should be tested with stakeholders before publicatio**n. Their input can refine recommendations, address potential political or economic barriers, and improve adoption prospects. Additionally, **the final recommendations should acknowledge knowledge gaps identified during the study and outline priority areas for further research**. Explicitly stating study limitations enhances transparency and credibility, guiding future refinements in energy system planning.

By integrating stakeholder insights, real-world constraints, and forward-looking research on PtX allocation, these policy recommendations can drive effective and sustainable energy transitions while remaining practical and politically viable.

5 Conclusion

The methodology presented emphasises key considerations for effectively modelling the allocation of hydrogen and PtX products to competing uses within a specific national context by applying total energy system cost optimisation. The different aspects described here are based on the experience of implementing such modelling exercises in Argentina and South Africa, which had a positive influence on policies on the development of hydrogen in both countries.

From a modelling perspective, it is important to capture the country‘s different sectors, including power, industry, buildings and transport, and to understand their potential defossilisation pathways. The results of the cost optimisation then show in which sectors PtX products should and should not be used from an economic perspective. Using an open-source model is the most appropriate way to guarantee transparency in the results, and ensure potential for replication and further use of the analysis by relevant stakeholders, including the government, energy institutions, industry and academia.

The modelling process for hydrogen and PtX products should be transparent from the outset and have clear rules, providing involved stakeholders with transparency and coherence. The sample Terms of Reference in Annex I reflect this idea and serve as the basis for the contract with potential consultants and as a guideline for governments to better understand the different components of the modelling exercise. The implementation process also highlights the importance of a strong focus on stakeholder engagement and participation. This should target not only the national governmental institutions, including energy planners, to guarantee the adoption of the modelling and its results in local energy planning processes, but also other relevant stakeholders in the energy and industry sectors, who can provide important contextualisation of the country‘s economy and energy system. This is essential for defining scenarios and defossilisation pathways and for the potential development and application of hydrogen across different sectors.

The results of the modelling exercise should include feedback and reviews as part of the stakeholder engagement and consultation process. Transforming the model‘s quantitative results into actionable policy recommendations enables the modelling exercise to have a greater impact and reach a wider audience. Both policymakers and energy modellers can benefit from this exercise, so their involvement in the entire modelling process is ideal. All the steps presented in this guideline aim to ensure that the modelling exercise can be adopted and implemented as part of national energy planning processes, thereby enhancing its impact and outreach.

Literature

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Annex:
Sample Terms of Reference (ToR) for allocation scenario modelling

Note: These sample ToRs contain country placeholders that need to be specified.

Content

List of abbreviations

PtX	Power-to-X
RES	Renewable Energy Sources
ToRs	Terms of Reference

1. Context

Electricity-based sustainable molecules and fuels will be crucial to reach climate neutrality in the industry sector, but will also play an important role as a back-up in power systems with increasing penetration of variable RE, and in applications like long-haul aviation and shipping. Currently, green synthetic fuels and feedstocks are more expensive than their fossil competitors. Moreover, due to limited renewable energy sources (RES) that can be deployed in Europe, future demand markets outside of Europe are required in adequate quantities in the short- and medium-term. The import of PtX products from countries with high and cheap RES potential is a promising approach to both contribute to the expected vast amount of synthetic fuels needed and support sustainable investments in RES and PtX value chains in the Global South. However, those potential export countries need to carefully weigh the pros and cons of using PtX products domestically for their own defossilisation versus exporting them to the Global North.

Objective

This project aims to

1. Explore the country's potential for the development of PtX applications based on renewable energy sources,
2. identify and evaluate the most promising PtX pathways for [Country placeholder],
3. leverage independent technical expertise on short-term, mid-term and long-term energy and decarbonisation strategies for [Country placeholder],
4. identify and fill relevant knowledge gaps with a focus on PtX, and
5. develop consistent scenario designs around which to base a sustainable dialogue with a group of key [Country placeholder] stakeholders.

This study aims at developing a range of detailed energy transition pathways/scenarios for [Country placeholder] to achieve, at lowest cost, ambitious decarbonisation targets up to 2050, in order to better inform ongoing and upcoming policy and expert discussions on this topic. The pathways to be developed should demonstrate how and which PtX products can contribute to the decarbonisation of power, transport and industrial sectors as well as considering the export potential of PtX products.

The project should also consider solutions that are off the electrical grid as well as assess the required renewable energy sources that can be integrated into the power system to allow the implementation of PtX applications in the country. The total system costs of the pathways must be analysed in detail, based on an in-depth economic and technical assessment.

Particular attention should be given to the short-term 2030 horizon, so as to understand how long-term decarbonisation commitments (2050) translate into short and mid-term priorities (2040), including its strong link to climate action. A focus should be to understand which mid-term priorities are 'no regrets' for all PtX technology options, and which technologies are essential to demonstrate feasibility in the 2020s. This approach aims to provide guidelines for investors and developers on the time frames available for the development of supply chains and future demand loads – especially for green hydrogen production and use – that will need to be ready to scale up after 2030.

These results will require detailed modelling of the [Country placeholder] energy system with high spatial and temporal resolution. The modelling should be developed by the consultant (or consortium) in exchange with a group of [Country placeholder] experts and with the client. The modelling of the energy system and its interaction with both electricity and molecule demand (transport systems, industrial feedstock demand and mining) will be crucial. The study should also model flexibility/storage provision (and requirements) in the power sector in light of the expected increasing penetration of variable RE between the evaluated sectors, with a focus on the system needs to successfully implement PtX applications. Additionally, the consultant should consider existing relevant work developed in [Country placeholder] related to energy scenarios, hydrogen roadmaps, flexibility studies as well as mid- and long-term energy and climate targets.

This comprehensive assessment of the contribution and effect of production, use and export of electricity-based molecules shall support the work of the public authorities in their mid-to-long term planning for a resilient transformation of the [Country placeholder] energy system in order to achieve their climate ambitions.

It is expected that the consultant has experience in modelling PtX pathways as well as analysing its potential service offering to the energy sector.

2. Tasks to be performed by the contractor

The contractor is responsible for providing the following services:

Scope

Three main scenarios should be analysed by means of energy system cost minimisation:

- a 'current policy scenario',
- an 'optimised scenario' and
- a 'best case scenario'.

TThis should include several sensitivity analyses on key parameters including the role of other power generation sources e.g., hydropower, biomass, nuclear energy, etc., the impact of an electric grid interconnection between [Country placeholder] and neighbouring countries, and the export of synthetic fuels (e-fuels and biofuels) or green products (such as green direct reduced iron (DRI)).

The following questions are at the core of the required analysis. The consultant is responsible for providing the required services to answer, at least, these questions:

1. (How much renewable electricity should be integrated into the [Country placeholder] power system by 2050 in order to achieve decarbonisation targets of each scenario modelled
    a. What are the implications of the required transformation with respect to renewables deployment for the 2030 and 2040-time horizon?
    b. What is the impact of those high shares of renewable electricity on
        i. Total system costs and investment needs (generation, transmission and distribution infrastructure) and
        ii. Balancing of supply and demand at hourly time steps? What would be the role, if any, of fossil-fuel based generation in the [Country placeholder] power supply and other energy carriers e.g., blue hydrogen?
2. What is the role of renewable-based electrification in supplying power demand for household, tertiary, industry and transport? In particular:
    a. Which end-use subsectors should rather be supplied by direct electrification rather than by synthetic gas/liquid or bioenergy and to which corresponding level?
    b. What are the implications of the results regarding renewables-based electrification for long-term power demand growth?
3. What is a) the forecasted national PtX demand (industrial, transportation and feedstocks) in [Country placeholder] and b) the forecasted PtX export volumes over the 2030-, 2040- and 2050-time horizons?
    a. To what extent would green hydrogen and PtX be a suitable option in applications that cannot be directly electrified, including e.g., chemical feedstock shipping or aviation?

    b. What are the implications of this demand side modelling on RES deployment to produce the forecasted PtX demand?

4. What are the infrastructure implications of these results for projections on the size and operation of the [Country placeholder] energy system for the 2030-, 2040- and 2050-time horizon?:
    a. What would infrastructure requirements be for:
        i. Electron transfer i.e. transmission and distribution networks?
        ii. Molecule transport i.e. pipelines?
    b. How does each scenario impact requirements for RES generation capacity?
    c. For the provision of additional flexibility to the power system using demand-side management, e.g., smart charging of electric vehicles, storage, PtX, among others?
5. What is the socio-economic impact of the development of PtX applications and renewable-based energy systems of the three scenarios (see WP 2 below), with particular emphasis on job creation?

Proposed work packages:

WP 1: Model set-up and data collection

WP 1.1. Model set-up

The consultant should use an adequate techno-economic energy model for [Country placeholder] (including power, industrial heat, industrial feedstock, and transport) for the transition period from today until 2050, including high geo-spatial and temporal resolution. An important criterion for the selection of the consultant will be their ability to develop such a model, by accessing and working with existing data on the [Country placeholder] energy system, both in the public domain and potentially beyond it. The client will – to the limit of its ability - support the consultant in this task, in dialogue with a consulting committee of key stakeholders. We expect that this consulting committee can help to facilitate data access and validation.

The model should be able to integrate the different energy sectors (power, heat and transport) and end-use demands (domestic, services, industry – including feedstocks). This should be accomplished as comprehensively as possible and will require capability for sector coupling, if in a simplified yet meaningful manner. The analysis must focus on the impact of deep decarbonisation strategies for [Country placeholder] on the implications regarding the size and operational characteristics (at hourly time step) of the [Country placeholder] power system. As such, the power system (and its interaction with demand) should be modelled with a higher level of granularity and technical details for all scenarios being modelled. The model should be able to choose between different technologies (e.g. heat pumps, hydrogen boilers, biomass boilers) to decarbonise the industrial sectors represented. It should in particular integrate flexibility potential and constraints for all modelled technologies.

It is however not required to model power grid infrastructure in detail (no load-flow modelling). A simplified multi-region approach with Net Transfer Capacities between the regions would be a sufficient first approximation. This multi-region description of the power system should ideally also be reflected (to some extent) in the modelling of the heat and transport systems. In addition, the model should integrate a simplified description of the balancing reserve requirement to ensure system stability. Given the limited connections of the [Country placeholder] grid in certain renewable rich regions, the model should include capabilities for inclusion of non-connected or off-grid renewable generation. This will be particularly important in the context of molecule generation for export purposes.

The level of granularity of the model (higher geo-spatial and temporal resolution) as well as the level of integration between the different energy sectors (power, heat and transport) will be a key parameter in evaluating consultant's proposals. Given the relevance of the model set-up and data access for this project, the consultant must address the following points in their proposal (see also below the section on data preparation):

- Describe in detail which modelling platform they intend to use and why such a platform is appropriate for performing the required analysis,
- Provide an overview description of the technical and economic input and output parameters of the model,
- Outline which data are needed to perform the analysis, including
  - › A description of the data that will be sourced by the consultant to set-up the model,
  - › A description of the additional data (details will be helpful) that are needed to perform a satisfying analysis but cannot be provided by the consultant.
- Explain the methodology applied for defining renewable energy technology potentials and time series,
- Describe the approach taken to modelling sectoral demand for each of the scenarios listed
- Describe the technologies represented in the model in all sectors.
- Describe the methodology for the assessment of PtX potential in the country, including meeting the national demand versus export potential of the molecules. Other parameters should be considered such as the potential of CO2eq abatement by satisfying national demand versus exporting molecules to potential global markets.

The consultant is expected to make a balanced and well-justified proposal, which will be discussed in an initial workshop with the consulting committee and then refined with the client, considering stakeholder feedback from the workshop. The proposal must also explain which input and output data will be delivered following completion of the project and to what extent the model can be transferred to national institutions, including training on its use and maintenance.

WP 1.2. Data collection and preparation

The client will support the collection and validation of the required input data. The consultant should specify as precisely as possible for all the most relevant input parameters of the model if:

a) [Country placeholder]-specific data can be provided by the consultant from their own database (data validation for key parameters (such as technology costs) should ultimately be performed through consultation with the client's partners, or via sector-specific stakeholder consultation) or if those data should be provided by the client
b) The consultant should also describe briefly how those data could be approximated, in the event that neither the consultant nor the client can provide [Country placeholder]-specific data

In order to best document this point, the consultant must develop and populate a table similar to that given in the Annex (indicative). Offers that provide significant [Country placeholder]-specific data (or makes propositions/assumptions in case the consultant does not hold such data) will have an advantage.

The client, to the best of their ability, will assist arranging stakeholder meetings for the collection of input data or data validation of key dimensioning parameters (such as sectoral demand side projections or technology costs). It will however be advantageous for the consultant to be able to lead these activities independently.

The first stakeholder workshop should be performed during this WP. This initial workshop is anticipated to be online.

WP 2: Scenario Definition

Three main scenarios should be defined up to 2050, preferably in 5-year intervals. The scenarios definition and underlying energy related CO2eq trajectories will be based on discussions with the client.

Important exogenous assumptions include those related to the development of global markets for PtX products, for which the consultant should present a reasonable proposal based on existing analyses. This proposal will be discussed with the client and its partners.

The energy-related CO2eq trajectories (policy targets) will be defined from a top-down analysis of the overall greenhouse gas emissions trajectories for [Country placeholder] and allocated to the different sectors. These target trajectories will operate as the main constraint for the energy system optimisation. The following energy transition pathways present an example of how this investigation could be accomplished :

1. A current policy scenario, based on [Country placeholder]'s current long-term climate commitment (max [xx] Mt CO2eq in 2030; current NDC and interpolation until 2050)
2. Optimised Scenario, with targeted approach in line with climate ambitions and reasonable achievability
3. Best case scenario, with most ambitious and accelerated decarbonisation targets / net zero until 2050

In addition, the consultant must include a sensitivity analysis on key exogenous dimensioning parameters, including but not limited to:

1. Variations in technology cost assumptions
2. Stricter constraints posed on the technical potential of renewable deployment
3. The role of coal and natural gas in the [Country placeholder]n energy sector development
4. The level of nuclear power maintained in the electricity mix
5. An electric interconnection between [Country placeholder] and neighbouring countries
6. A ratio of PtX product export to domestic use
7. Import of PtX molecules from neighbouring countries
8. Level of national demand for PtX products
9. Level of global demand for PtX products
10. Global PtX cost levels

The consultant should provide a cost for each potential sensitivity analysis.

WP 3: Analysis of energy transition pathways

The model results should evaluate the cost-optimal evolution of the [Country placeholder]n power system up to 2050 that is required to meet, at the lowest possible cost, the current and higher ambition decarbonisation targets set for power, heat and transport, highlight the potential of integrating PtX application in the decarbonisation process as well as green hydrogen feedstock for non-electrifiable sectors. It is expected that the model provides various outputs (GW, number of appliances, costs) and information on the short-term operation of the system (hourly intervals) in order to inform an assessment of system dynamics and flexibility requirements.

The hourly model run should cover entire years for the different proposed scenarios up to 2050. The following output should be provided for every modelled year:

- Energy system costs and CO2eq emissions, in line with climate action targets.
- Primary energy demand (by sector) based on assumptions on the economic growth rate and efficiency gains.
- Power generation (TWh) and capacity (GW) by technology, including the new installed capacities required to fossilise heat and transport, as well as curtailment levels of renewables.
- Electric transmission between the nodes of the model (allowing for a first-order quantification of grid reinforcement needs – and costs – through a simplified approach based on geographic distance between the nodes).

- Storage: Short-term electricity storage (e.g. batteries and pumped-hydro,) and heat storage; long-term energy storage, including Power-to-Gas, which allows the production of green hydrogen and/or synthetic methane to be utilised by the system (in both the heat and transport sectors).
- Industrial heating: demand and supply of the different technologies (in case the model provides a full representation of the industrial heating requirements). This includes the competition of direct electrification versus the use of molecules to supply industrial heating.
- Transport: demand (road, rail, shipping and aviation) and shares of the demand supplied by different fuel types (including green hydrogen, synthetic hydrocarbons, direct electrification, biofuels), or at a minimum result on electric vehicle deployment and EV power system integration (at least in a simplified fashion).
- Industry/ feedstock: demand for different industry processes and end-products (including green hydrogen, synthetic hydrocarbons, biofuels).
- Installed PtX capacities.

The analysis should be complemented by an estimation of the balancing reserve requirement with increasing shares of variable renewables as well as a qualitative description of the impact of those high shares of renewables on system stability.

Interim results should be presented to stakeholders in a workshop. It is anticipated that this will be in person in [Country placeholder]. It will be advantageous for the consultant to be able to lead this activity independently.

WP 4: Policy recommendations for incentivising efficient decarbonisation, system integration and system flexibility

Based on the analyses of WP 3 and considering the current situation in [Country placeholder], the consultant will be asked to report their preliminary key recommendations for amending current long-term energy plans for [Country placeholder]. A particular focus should be on the implications that the 2050 deep decarbonisation objective imply for the 2030 horizon. However, the clientreserves the right to publish the final report with their own conclusions and recommendations.

Final results must be presented in a public event in [Country placeholder].

Project Timeline

The indicative timeline of the project is as follows.

Certain milestones, as laid out in the table below, are to be achieved by certain dates during the contract term, and at particular locations:

Milestone	Indicative Deadline/place
Project kick-off and start of WP 1.1 and WP 2	First week after initiation of contract / virtual
First expert and stakeholder consultation	6 weeks after initiation of contract / virtual
Short interim report on WP 1.1, WP 1.2 and WP2.	10 weeks after contract initiation
Presentation of first interim results on WP 3	16 weeks after contract initiation

Expert and stakeholder group workshop / discussion (online) of interim results (WP 3 and WP 4)	20 weeks after contract initiation
Submission of draft report and presentation to client and implementing partners	28 weeks after contract initiation
Presentation of final report in public event in [Country placeholder] and, to the extent applicable, together with training for national stakeholders on the model	tbd
Submission of final report	tbd
Training for national stakeholders in [Country placeholder] (alternative if not in combined with public event, see above)	tbd

The project proposal should discuss the proposed time frame and identify potential risks for not meeting it.

Period of assignment: From [start date] until [end date].

3. Annexes

Indicative approach for data collection and preparation (Chapter 2, WP 1.2)

Table 1. Input parameter and data availability (example – the number of entries (lines) must be provided by the consultant depending on its modelling approach)

Input parameter	**Does the consultant provide [Country placeholder]-specific data for that parameter?**	**In case, neither the consultant, nor the [Country placeholder] partner has access to the relevant data, how does the consultant propose to approximate that data**
Resource potential for RES at high geographic resolution	Yes	No
Hourly heat/cooling demand curves for industry, tertiary sector, households	Partially (for household and tertiary sector). No data for industrial heat.	In order to approximate the heat demand curves in the industry sector, the consultant proposes to…
Power plant database in [Country placeholder] (status quo)	Yes	Yes, …

Time-series for RES	Partially (for wind and solar), not for hydro	For approximating the hydro time series, the consultant proposes…
Financial and technical assumptions for relevant technologies	Yes	No
Other relevant parameters		