DRAFT

SHIELD

Modelling Framework and Interlinkages

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EXECUTIVE SUMMARY

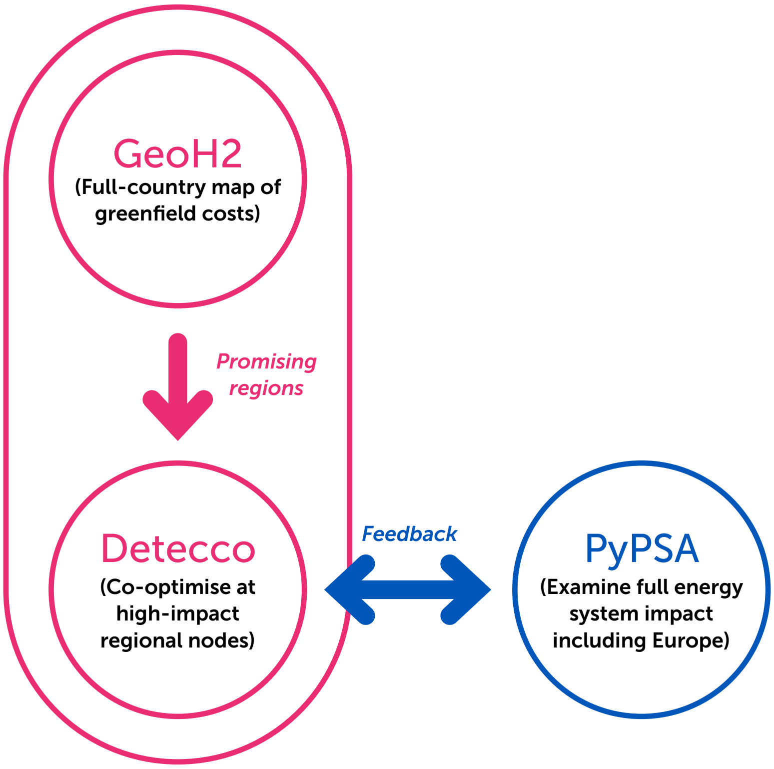
This report details the modelling framework used in the Strategic Hydrogen Integration for Effective Low-Carbon Development (SHIELD) project to assess the cost-efficient integration of hydrogen and ammonia in Ukraine. It presents the utilised models, their interlinkage, the scope of expected results, and the development timeline. We envision that these models will provide a decision-making toolkit regarding the potential roles of hydrogen and ammonia in Ukraine's energy future. They will be made publicly available in open-source repositories for future application.

The key objectives of the SHIELD modelling effort are to evaluate the least cost of green hydrogen/ammonia production in Ukraine considering uncertainties, and to provide decision support tools and evidence to facilitate policy formulation which accounts for both opportunities and risks. We aim to do this by integrating different techno-economic models and exploiting their synergies. To this end, the modelling framework incorporates three tools:

- **GeoH2:** A model that calculates the locational cost of hydrogen or ammonia production, storage, transport, and conversion to meet demand in a specified location.
- **Detecco:** A model that optimizes the production and use of different energy carriers in parallel to satisfying a general energy demand.
- **PyPSA:** A model that integrates the energy system through different carriers across Europe and Ukraine and incorporates risks.

To account for the strengths and weaknesses of each tool and leverage their synergies, we envision combining them as shown in Figure A. The modelling process begins by applying GeoH2 to conduct an explorative spatial analysis of the Levelized Cost of Hydrogen (LCOH) and Levelized Cost of Ammonia (LCOA). This initial assessment identifies promising areas for further exploration with Detecco, which is used to co-optimise the energy supply across different vectors accounting for transmission alternatives such as lines, pipelines or trucks. Meanwhile, PyPSA models the entire energy system to determine whether hydrogen and ammonia are part of the cost-optimal system configuration. The results from Detecco can be compared with PyPSA's allocation of hydrogen and ammonia production within the grid. Additionally, any curtailed energy identified in PyPSA can be fed back into Detecco, further refining cost optimization and improving the overall efficiency of the system.

FIGURE A:
Interrelation among tools.



Through the proposed modelling framework, we anticipate generating three research outputs:

1. **Exploring the impact of the cost of capital:** We will investigate how the cost of capital across Ukraine will impact the feasibility/location of green hydrogen and ammonia investments, while considering that infrastructure investments near the front line are riskier. This study will be performed through the integration of GeoH2 and Detecco.
2. **Whole energy system modelling in Ukraine:** We will generate a comprehensive view of the value of hydrogen and ammonia in the Ukrainian power system using PyPSA, as well as the value of the integration of the Ukrainian energy system into the European market.
3. **Risk-averse planning and distribution of costs:** We will consider the uncertainties that the Ukrainian system faces going forward. It will take a risk-averse approach, to system planning for resilience, to limit its exposure to negative scenarios. It aims to identify additional investments which can build resilience and explore how these costs can be distributed across different energy consumers. Preliminarily, this task will be performed with GeoH2 and Detecco exploiting the modelling versatility to include some stochastic methods.

1. Introduction

This report details the modelling framework used in the Strategic Hydrogen Integration for Effective Low-Carbon Development (SHIELD) project to assess the cost-efficient integration of hydrogen and ammonia in Ukraine.

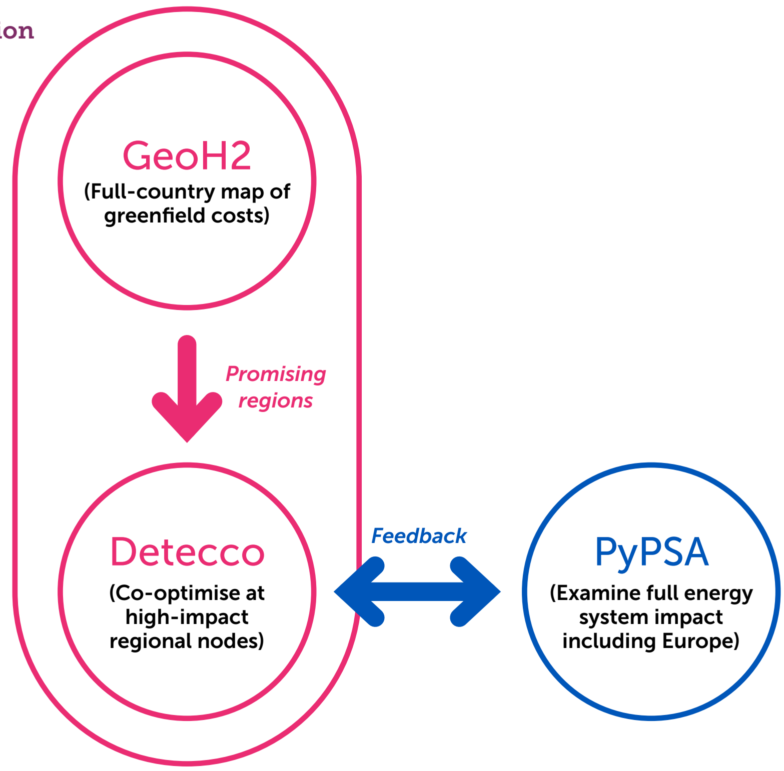
The SHIELD project analyses the potential role of green hydrogen and ammonia in Ukraine's energy system as part of its broader energy security and decarbonisation goals. To do this, it employs several modelling approaches. This report serves as an overview for different stakeholders to understand the scope of the modelling.

The models developed in this project are designed to provide decision-making tools to facilitate a comprehensive understanding of the roles of hydrogen and ammonia in Ukraine's energy future. Once the models are fully developed and tested, they will be publicly available in an open-source repository.

The SHIELD modelling framework includes three main tools. The first is **GeoH2**, a model that calculates the locational cost of hydrogen or ammonia production, storage, transport, and conversion to meet demand in a specified location. Next, we use **Detecco**, a model that optimizes the production and use of different energy carriers in parallel to satisfying a general energy demand. Finally, we use **PyPSA**, a model that integrates the energy system through different carriers across Europe and Ukraine and incorporates risks.

Considering the strengths and weaknesses of these three tools, we have established how they can be used in an interrelated workflow. **Figure 1** illustrates how the GeoH2 and Detecco tools can be integrated into effectively a single soft-linked entity while the PyPSA implementation for Europe and Ukraine is used as a separate model.

FIGURE 1: Modelling framework: Interrelation among tools.



The role of the first entity (i.e., the combination of GeoH2 and Detecco) is: (i) to establish the regional potential for green hydrogen and ammonia production based on the availability of geographical renewable resources;
(ii) to optimise the cost of the technological mix, considering different options for energy transport; and (iii) to determine the cost of supplying demand at key locations (for instance, interconnection points with the rest of Europe). The role of the second entity (i.e., PyPSA) is to provide a comprehensive analysis of the value of hydrogen or ammonia in the Ukrainian and European energy systems and associated risks.

These models share information to enhance their assessments and validate results. In this regard, for instance, the PyPSA model can determine the value of hydrogen or ammonia in reducing the need for transmission reinforcements, which cannot be estimated in GeoH2 and Detecco due to their reduced number of nodes in transmission level.
Under certain assumptions, this value can be incorporated into the objective function of Detecco as an investment cost saving, thereby yielding more accurate results.

To present the details of the SHIELD modelling approach, the remaining chapters of this report are structured as follows. Section 2 outlines the objectives and research questions of the project as they relate to the modelling effort. Section 3 presents the modelling methodology, providing further details on each tool (i.e., GeoH2, Detecco, and PyPSA). Section 4 explains the rationale behind the interrelation of the models, highlighting the strengths of each and the opportunities for synergy. Section 5 provides an overview of the expected outcomes during the model development. Finally, Section 6 concludes the report with a timetable for model development.


Photo byActiv Solar / flickr

2. Objectives & research questions

The objectives of the SHIELD modelling are the following:

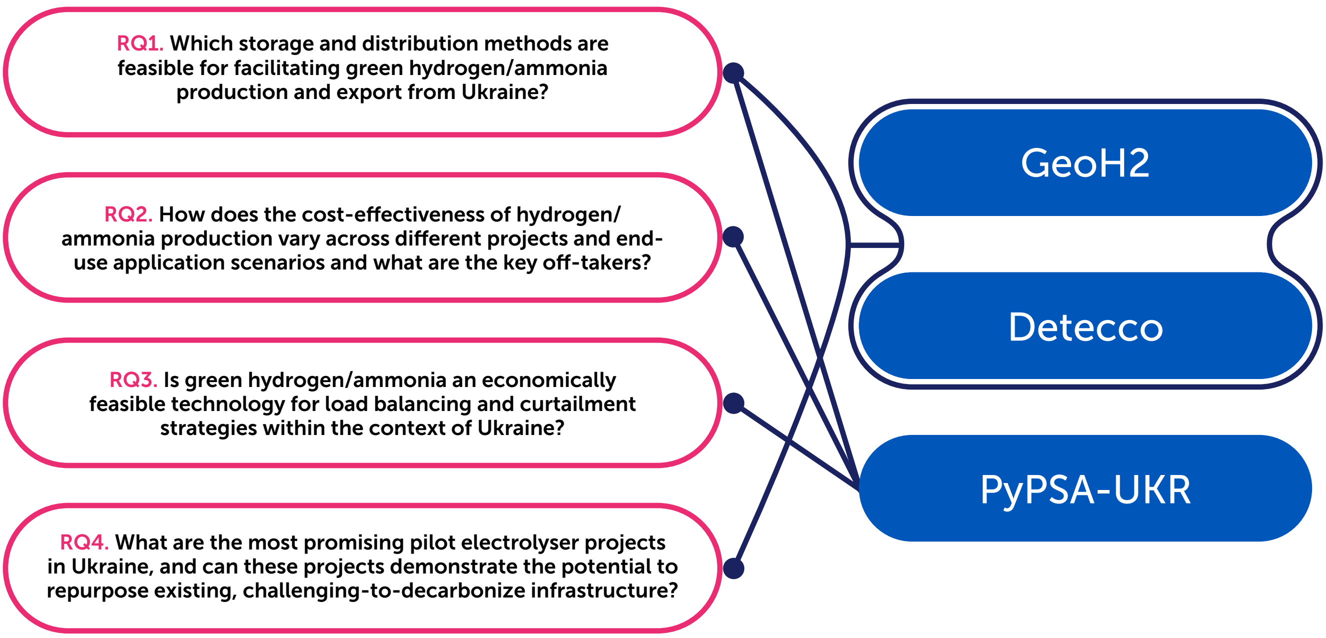
- **O1.** Evaluate the least cost of green hydrogen/ammonia production in Ukraine considering different uncertainties such as those associated with the cost of capital, and the broader geopolitics context.
- **O2.** Provide decision support tools and evidence to enable the Ukrainian government to understand the impact of hydrogen development on the energy system and to facilitate policy formulation which accounts for both opportunities and risks.
- **O3.** Integrate different techno-economic tools (i.e., GeoH2, Detecco and PyPSA) to exploit synergies of the combination of them.

The research questions associated with those objectives are:

- **RQ1.** Which storage and distribution methods are feasible for facilitating green hydrogen/ammonia production and export from Ukraine?
- **RQ2.** How does the cost-effectiveness of hydrogen/ammonia production vary across different projects and end-use application scenarios and what are the key off-takers?
- **RQ3.** Is green hydrogen/ammonia an economically feasible technology for load balancing and curtailment strategies within the context of Ukraine?
- **RQ4.** What are the most promising pilot electrolyser projects in Ukraine, and can these projects demonstrate the potential to repurpose existing, challenging-to-decarbonize infrastructure?

These questions are mapped to the SHIELD modelling tools as shown in Figure 2.

FIGURE 2: **Mapping of research questions to SHIELD tools.**



Although **RQ1** can be evaluated using each model independently, the strengths and weaknesses of each model allows each to emphasise distinct elements during the investigation. GeoH2 provides a greenfield assessment that Detecco will elaborate upon, while PyPSA investigates integration with the European electricity network and related congestion challenges. By using them together, we can answer RQ1 in greater detail.

RQ2 and **RQ3** will primarily be addressed through the PyPSA model, involving a comparison of various end-use sectors and the economic viability of hydrogen or ammonia, alongside presenting a curtailment profile for different regions in Ukraine. For specific projects and end-use sectors with a well-defined quantity of either ammonia or hydrogen required, GeoH2 may also be used to provide detailed insights.

RQ4 is answerable via GeoH2 in conjunction with an in-depth analysis from Detecco. Pilot project costs can be evaluated based on location-specific renewable potential with GeoH2. In the same vein, Detecco can consider the use of reconditioning old infrastructure for hydrogen or ammonia usage.

Photo by Andreas M on Unsplash

3. Methodology

In this section, GeoH2, Detecco, and PyPSA are presented. We show their general structure and how they can be applied for the Ukrainian context.

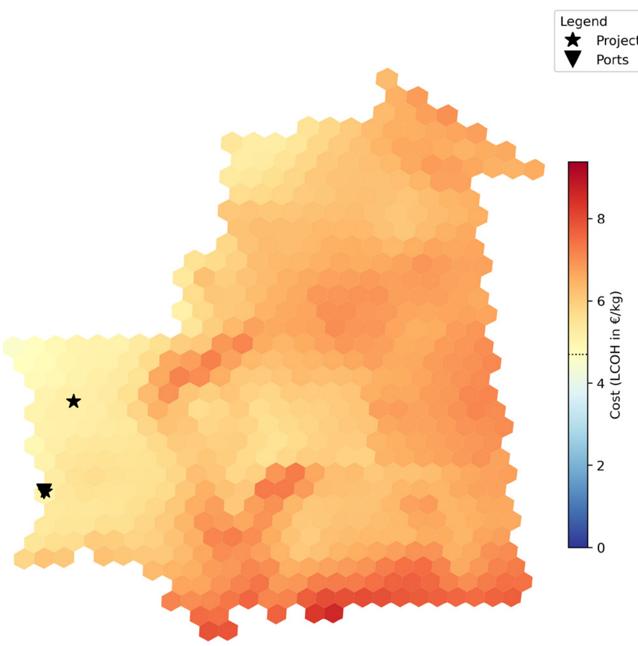
3.1 GEOH2

GeoH2 is a geospatial model that optimises the cost of green hydrogen or ammonia production, storage, transport, and conversion. The model and data input are open-source, making it a first-of-kind model for such analysis. It calculates the optimal cost of producing green hydrogen or ammonia in H3 hexagons[1] throughout an area of interest. This is done using site-specific renewable energy potential and assumes greenfield off-grid design. This means each hexagon is optimised as an isolated unit. It also calculates the cost of transporting it via truck or pipeline and converting it to a user-defined end state (i.e., pressurized hydrogen, ammonia, or liquefied hydrogen) in a specified location.

The output of GeoH2 is a spatial mapping of the levelized cost of hydrogen (LCOH) or ammonia (LCOA) at the demand location specified. These modelled costs can be compared to current or projected prices for energy and chemical feedstock in the region to assess the cost-competitiveness of green hydrogen. An illustrative example output from GeoH2 is shown in **Figure 3** below.

GeoH2 uses both open-source spatial and techno-economic input data. On the spatial side, it uses ERA5 wind and solar[2] data for generation sizing. It also uses OpenStreetMap[3], Corine Land Cover[4], and Global Oceans and

FIGURE 3: Illustrative GeoH2 results for an ammonia demand placed at a port in Mauritania under an example set of techno-economic input data. This illustrates the type of map output which GeoH2 creates.



1 https://h3geo.org/

2 ERA5 https://www.ecmwf.int/en/forecasts/dataset/ecmwf-reanalysis-v5

3 Geofabrik GmbH and OpenStreetMap Contributors, Openstreetmap data excerpts, 2018. https://download.geofabrik.de/

4 Marcel Buchhorn, Bruno Smets, Luc Bertels, Bert De Roo, Myroslava Lesiv, Nandin-Erdene Tsendbazar, Martin Herold, & Steffen Fritz. (2020). Copernicus Global Land Service: Land Cover 100m: collection 3: epoch 2018: Globe (V3.0.1) [Data set]. Zenodo. https://doi.org/10.5281/zenodo.3518038

Seas[5] data to constrain land availability to suitable areas for plant construction. Techno-economic parameters include the costs for plant and transport infrastructure (including CAPEX, OPEX, and interest rates); infrastructure lifetimes and capacities; process-related efficiencies and constraints for electrolysis and Haber-Bosch; and other country-specific economic parameters. For full details, please refer to the model GitHub[6] or MethodsX[7].

The role of GeoH2 in the analysis of the Ukraine case is two-fold. First, GeoH2 is used to produce an overview map of promising hydrogen or ammonia production locations in the country. This is used to identify regions of interest, which can be studied with Detecco. This "filtering" step is done using GeoH2 as it would be computationally challenging to run in Detecco; GeoH2 can produce a potential map for Ukraine on the timescale of hours, while Detecco would take far longer. Second, for end-uses of hydrogen and ammonia with defined demand quantities and locations, GeoH2 can quickly and simply identify the cost of hydrogen or ammonia achievable throughout all of Ukraine. Where projects are more complex (i.e., the demand of energy is multi-vector or the location of delivery is dispersed), GeoH2 again hands off to Detecco for detailed analysis.

This provides a detailed spatial analysis of the potential hydrogen and ammonia production sites, which can also be made available with an online dashboard.

3.2 DETECCO

Detecco (Deterministic energy carrier co-optimisation) is a model developed under the Calliope[8] framework, which optimises the energy supply, storage and transportation through different energy carriers (i.e., ammonia, hydrogen and electricity).

Similar to GeoH2, the input data consider geospatial and techno-economic factors. Firstly, regarding geo-spatial data, Detecco takes as inputs ERA5 wind and solar[9] data on a 0.25 degrees grid (in terms of latitude and longitude). The Moderate-resolution Imaging Spectroradiometer[10] (MODIS) database is utilised to determine land availability, the United Nations Environment Programme (UNEP)[11] dataset used to account for protected areas, and the Shuttle Radar Topography Mission (SRTM)[12] dataset is employed to consider the elevation and the slope across the territory. Secondly, in terms of techno-economic data, the model requires key techno-economic parameters, such as CAPEX, OPEX, efficiencies and other relevant features.

5 MarineRegions.org, Global oceans and seas. https://www.marineregions.org/downloads.php

6 GeoH2 repository https://github.com/ClimateCompatibleGrowth/GeoH2

7 Halloran, C., Leonard, A., Salmon, N., Müller, L., & Hirmer, S. (2024). GeoH2 model: Geospatial cost optimization of green hydrogen production including storage and transportation. MethodsX, 12, 102660. https://doi.org/10.1016/j.mex.2024.102660

8 Calliope documentation https://calliope.readthedocs.io/en/stable/

9 ERA5 https://www.ecmwf.int/en/forecasts/dataset/ecmwf-reanalysis-v5

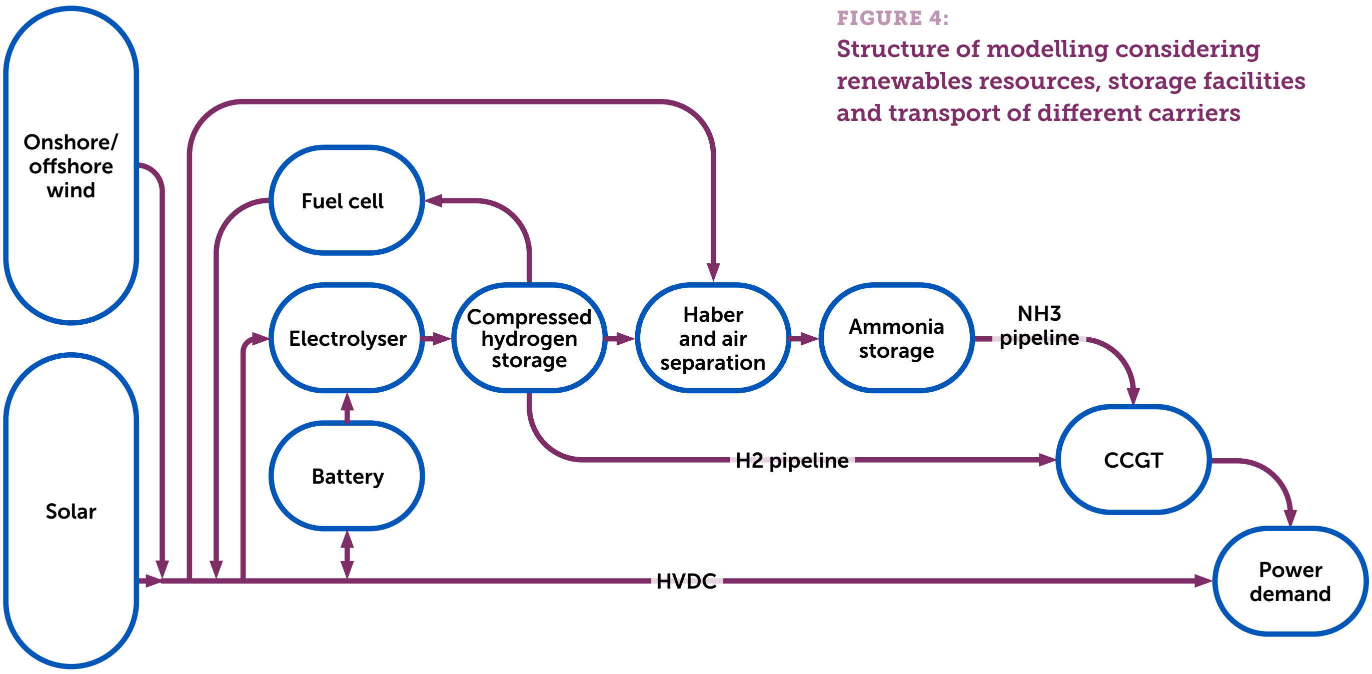
10 MODIS colections in earth engine https://developers.google.com/earth-engine/datasets/catalog/modis

11 World data base on protected areas https://resources.unep-wcmc.org/products/1919c32890074ce5a589a1a99b48994b

12 NASA digital elevation https://developers.google.com/earth-engine/datasets/catalog/USGS_SRTMGL1_003

The structure in **Figure 4** shows an example of how Detecco can model how different facilities interact to supply a specified demand. In the example, the main energy source is from renewables (i.e., solar and wind). Then, the produced electric energy can either go directly to supply the demand through high-voltage DC (HVDC) transmission lines, be stored in electric storage, go to electrolysers to produce hydrogen, or go to the Haber-Bosch to produce ammonia and store it. The energy can be transported to the supply location either by HVDC power lines, hydrogen pipelines, and ammonia pipelines. In the case of Figure 4, the demand is in the form of electrical demand, so a combined-cycle gas turbine (CCGT) transforms the energy in the hydrogen or ammonia carrier to an electrical carrier. Nevertheless, in a general case, demand can be in any of the modelled carriers.

FIGURE 4:
Structure of modelling considering renewables resources, storage facilities and transport of different carriers



In the context of Ukraine, Detecco will provide an in-depth analysis of the potential of hydrogen and ammonia as energy carriers within the energy system. It helps determine the optimal energy mix to meet a given demand and identifies the least-cost solution under greenfield assumptions. The model can estimate both the cost of satisfying domestic demand and the cost of exporting energy in any of the available carriers. Thus, the competitiveness of Ukraine's energy system could be assessed by comparing the supply cost and export price.

3.3 PYPSA

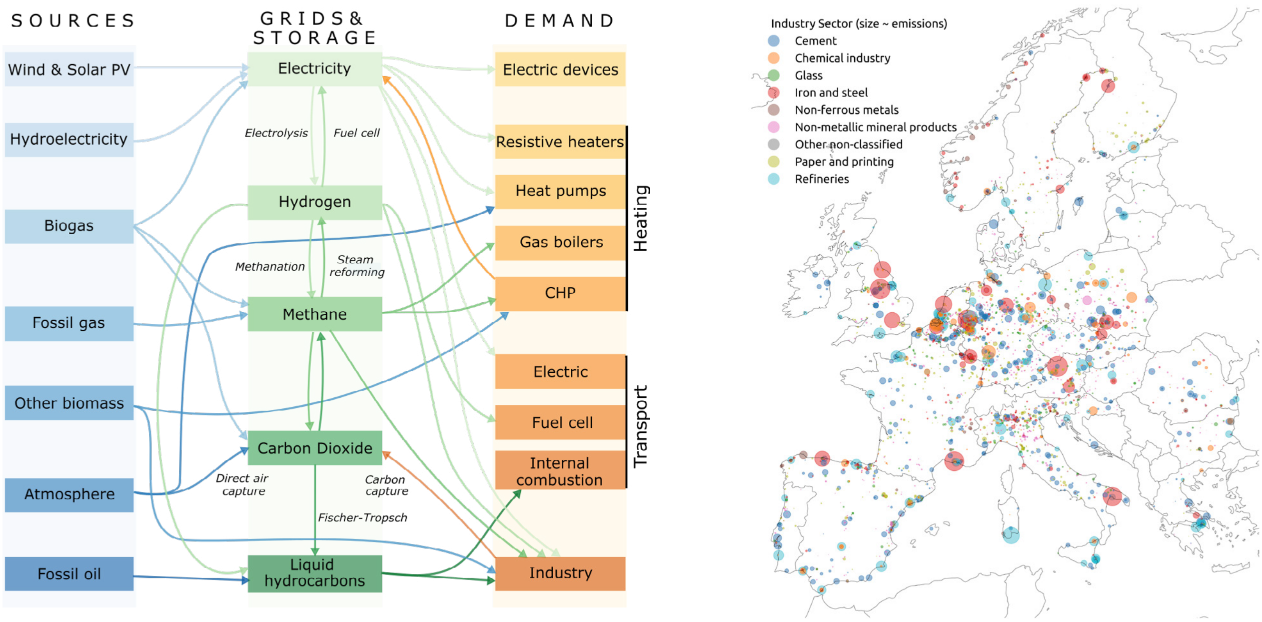
PyPSA is an open-source model of the European energy system at the transmission network level, encompassing the entire European Network of Transmission System Operators for Electricity (ENTSO-E)[13]. It incorporates the electricity, heating, transportation and industry sectors for cost-effective planning and decarbonisation

[13] J. Hörsch et al., PyPSA-Eur: An open optimisation model of the European transmission system, Energy Strategy Reviews, Volume 22, 2018, https://doi.org/10.1016/j.esr.2018.08.012.

assessments (see **Figure 5** at the left hand). The model can distinctly include hydrogen and ammonia production, storage, and distribution, connecting them to their respective end-use[14]. Through sector coupling, PyPSA offers insight into the significance of hydrogen steel manufacturing and ammonia fertilisers in a decarbonised energy network (in Figure 5 at the right hand, there is a map with different industries modelled). Its open-source modular framework ensures transparent and reproducible energy system modelling. It has a spatial component that can give insights into the installed capacity at distinct locations.

Finally, PyPSA features a preconstructed European Electricity Network that provides a topologically connected model of the European high-voltage grid (220 kV to 750 kV) based on OpenStreetMap data[15].

FIGURE 5: At the left hand is shown a flowchart of PyPSA modelling capabilities, at the right hand is observed the off-takers modelling.



The role of the PyPSA model in Ukraine's analysis is focused on its link with the European Union (EU). At present, the EU serves as emergency support for Ukraine's grid, but this is likely to evolve. Ukraine is expected to fully integrate with the EU grid, affecting its electricity market. Organisations like Instrat and Green Deal Ukraina have used PyPSA to study Ukraine. However, there is a lack of research specifically on hydrogen in Ukraine.

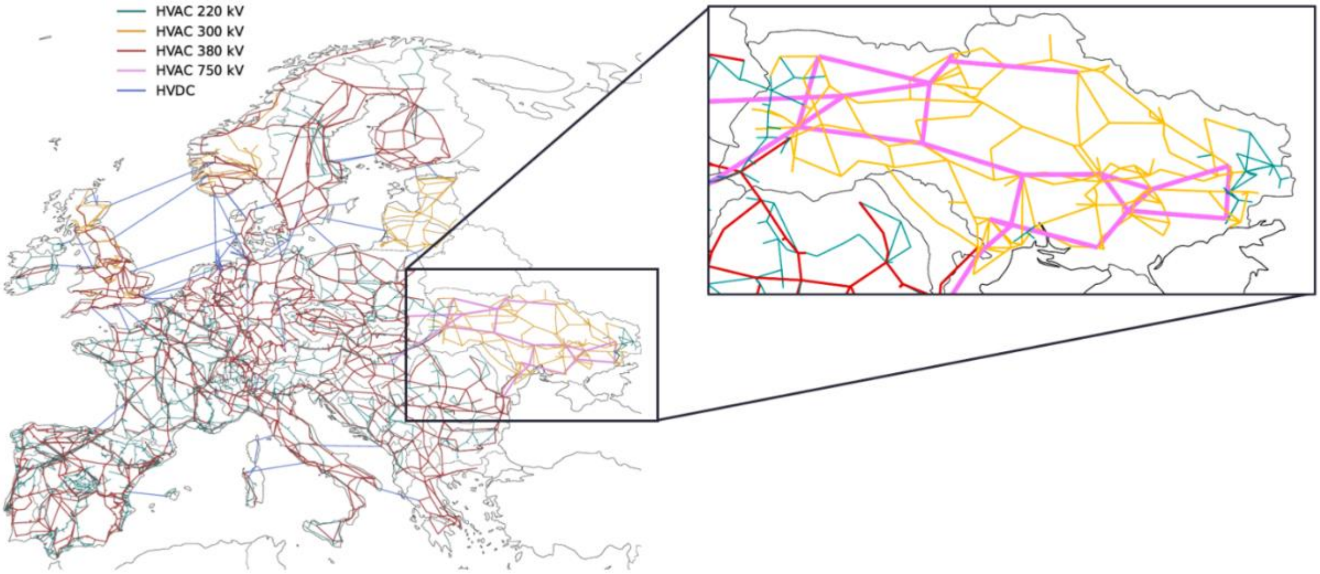
This analysis will assess the competitiveness of various sectors to identify the most promising ones, crucial given Ukraine's limited capital.

[14] F. Neumann et al., The potential role of a hydrogen network in Europe, Joule, Volume 7, Issue 8, 2023, https://doi.org/10.1016/j.joule.2023.06.016.

[15] Xiong, B., Fioriti, D., Neumann, F. *et al*. Modelling the high-voltage grid using open data for Europe and beyond. *Sci Data* **12**, 277 (2025). https://doi.org/10.1038/s41597-025-04550-

With sufficient time, additional features for an evaluation of risk associated with the war in Ukraine will be developed. An scheme of the Ukraine representation into the model is shown in **Figure 6**.

FIGURE 6: Network modelled in PyPSA for the case of Ukraine and the rest of Europe



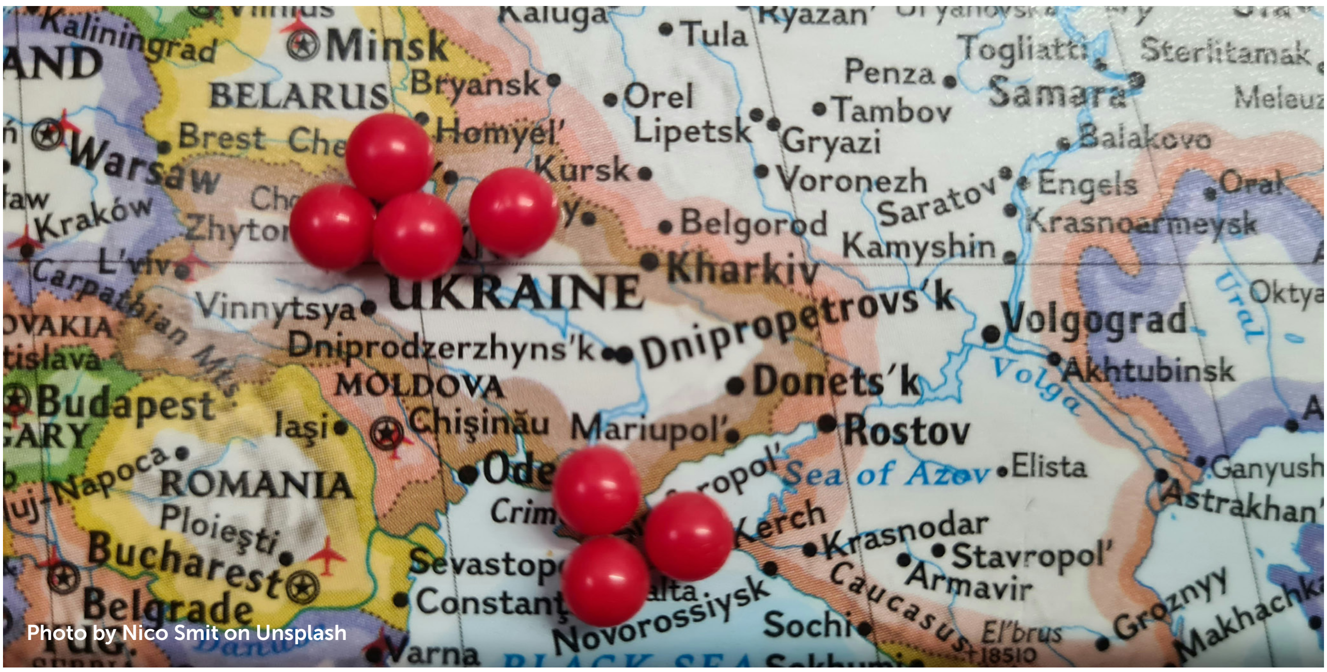


Photo by Nico Smit on Unsplash

4. Interlinkage between models

This section compares the three models, highlights their strengths and synergies, and provides an overview of the interlinkage structure among them. The interlinkage will and their expected contributions to the analysis of Ukraine.

Table 1 provides a high-level comparison between GeoH2, Detecco, and PyPSA based on several criteria. These criteria, and a justification for why they are important to consider within the SHIELD product, are provided below.

- **Geographical resolution:** The level of spatial granularity considered in the models. The geographical distribution of renewable resources is a critical factor in SHIELD modelling, considering the natural variability of these resources across Ukraine. Additionally, our modelling should account for the geographical variability in the cost of capital.
- **Transmission representation:** The ability of the models to represent various modalities of transmitting energy. Transmission representation is key as an optimal trade-off between different energy vectors can lead to significant cost savings.
- **Demand modelling:** How demand is modelled, including demand response. Based on use cases, certain demands can integrate a level of demand response. Over time, demand response may compete with other storage technologies, such as ammonia and hydrogen storage. A robust quantification of the value of green hydrogen and ammonia should consider the integration of these technologies.
- **Storage technology:** The types of storage modelled. Various sources of flexibility should need to be modelled in SHIELD to assess the value of hydrogen and ammonia in the Ukrainian energy system for this purpose.
- **Distributed generation:** Whether distributed generation in modelled. In contrast to large-scale conventional technologies (e.g., nuclear or thermal generators), distributed generation can enhance the reliability and resilience of the Ukrainian energy system. It can also serve as a potential substitute for hydrogen and ammonia in providing resilience to the power grid.
- **Emission accountability:** How and whether emissions are modelled. Modelling strategies or policies for achieving net-zero emissions (such as carbon taxes) is essential to support informed decision-making.

Given the features of each tool highlighted in **Table 1**, we can summarise their strengths and weaknesses as shown in **Table 2**.

TABLE 1: General comparison among GeoH2, Detecco and PyPSA-UKR.

Model	GeoH2	Detecco	PyPSA-UKR
General description	A model that determines LCOH or LCOA for green H2/NH3 within a determined area. This is done at a specified level of spatial granularity based on renewable energy resources and techno-economic parameters.	A model that co-optimises the supply of energy harnessing multiple carriers: electricity, hydrogen, and ammonia. This model features high-dimensional resource availability. Transmission can be represented either in terms of power or pipelines, built in a greenfield manner for a limited number of nodes.	A model that optimises the supply of electricity and sector-coupled ammonia or hydrogen, including investment in generation and transmission. It features high-resolution modelling of the European power system. Ukraine can be represented with several nodes.
Geographical resolution	High-resolution (can be selected from H3 hexagon standard)	High resolution (potentially the same as GeoH2). Computation speed is low.	Has 180 nodes for Ukraine.
Transmission modelling	Transmission is allowed via road (trucking) or pipeline. Costs are calculated based on the distance to the nearest road (allowing for road construction if needed) or greenfield pipeline construction. The cheapest option is used in LCOH/LCOA calculations. However, there is no formal optimisation done.	In principle, the model considers different trade-offs between carriers for the optimisation. Power systems do not follow Kirchhoff's laws.	The model can optimize the trade-off between power systems and pipelines for hydrogen. Pipelines for ammonia and truck transportation are not included. However, they can be included as it was done in PyPSA-EUR-SEC.
Demand modelling	Annual demand is an input to the model. This is distributed temporally based on the mechanics of the transport type (trucking or pipeline).	Can incorporate a percentage of demand response	Can incorporate a percentage of demand response.
Storage technologies	Storage of H2 or NH3, as well as battery storage, are allowed in plant optimisation.	Enables the integration of energy storage technologies that could potentially compete with hydrogen and ammonia.	Enables the integration of a pool of energy storage technologies that could potentially compete with hydrogen and ammonia.
Distributed generation	Incorporates wind and solar generation which are more distributed than central thermal alternatives.	Distributed generation based on variable renewable energy can be incorporated.	Can be incorporated
Emission accountability	May be incorporated	Considered.	Considered

TABLE 2: Strengths and weaknesses among GeoH2, Detecco and PyPSA-UKR.

	GeoH2	Detecco	PyPSA-UKR
Strengths	Determines the geo-localised potential of hydrogen or ammonia production, serving as an ideal tool to identify zones according to their potential.	Integration of different energy systems (i.e., power, hydrogen and ammonia), though representative zones (currently limited to ~5 per run). Optimises the energy mix through different carriers considering the transmission balance.	Considers a detailed version of energy systems. The value of Ukrainian integration into the EU energy system can be analysed in a deeper way compared GeoH2 or Detecco.
Weaknesses	Minimal consideration of system coupling (e.g., power system with ammonia or hydrogen network). The resulting cost therefore serves as an upper bound.	Interconnection with EU modelling is limited (e.g., it could report the cost of production in different borders, but other consequences in the EU are not considered by Detecco).	Given the complexity, this model requires longer developing and validation times. The geo-localisation of devices depends on a predetermined set of locations.

Based on this comparison, we identify synergies between GeoH2 and Detecco. Both models consider a high resolution in terms of geospatial localisation, which facilitates interlinkage between them. The weaknesses of GeoH2 are in many ways covered by Detecco's strengths. For instance, energy systems coupling among different carriers, which is minimally considered in GeoH2, is covered in detail by Detecco. Therefore, the cost of production can be refined by interlinkage between GeoH2 and Detecco to consider different trade-offs in transport of energy carriers. This versatile modelling interlinkage allowing the assessment of different locations and assumptions.

Meanwhile, the comparison illuminates the importance of PyPSA-UKR as a stand-alone tool. Its comprehensive view on the energy system enables the possibility to make a complete assessment of the value of the hydrogen and ammonia production deployment in Ukraine, and their integration in the EU market. Likewise, the role of hydrogen/ammonia technologies to provide flexibility in the integration of variable energy resources into the power systems may be modelled considering the integration with the bulk power system of the rest of EU.

This leads to the treatment of the three models two entities: (1) the integration between GeoH2 and Detecco, leveraging synergies; and (2) PyPSA-UKR. These two entities can however interact in the following ways:

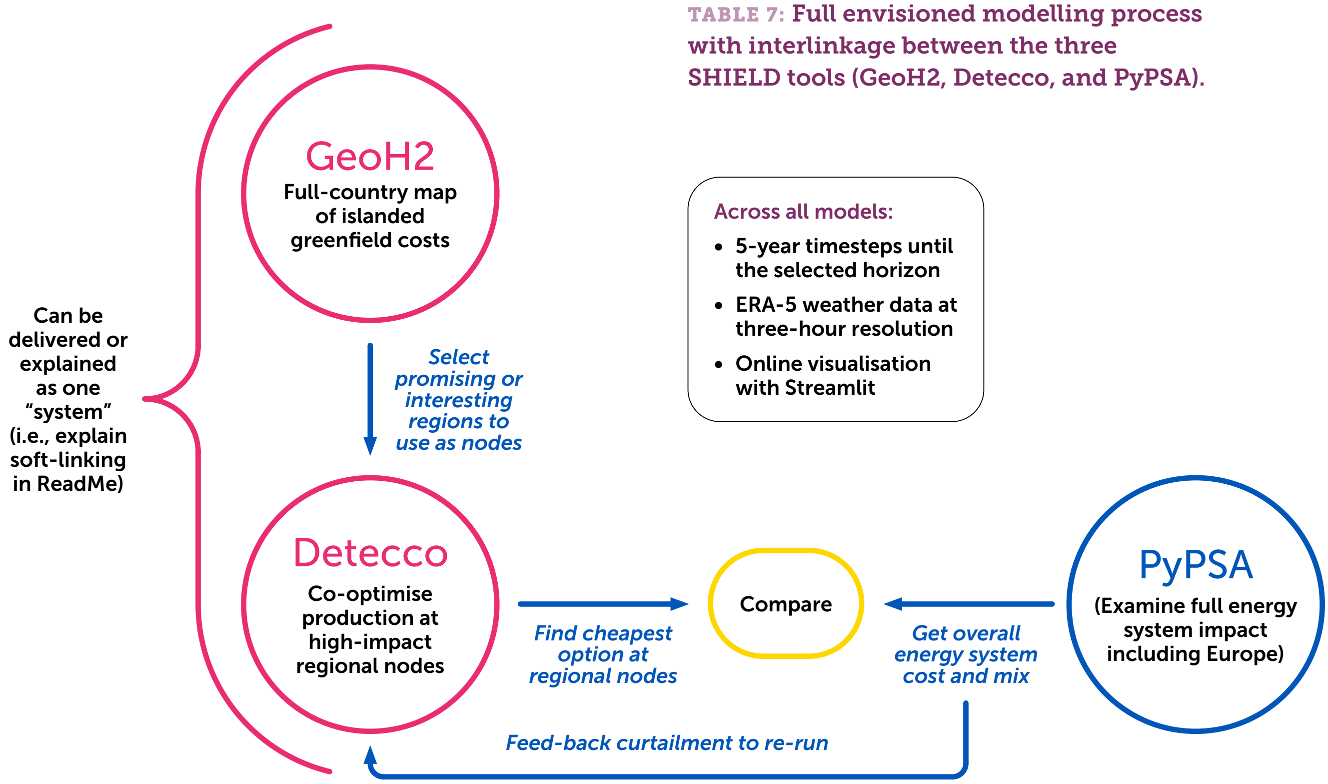
- **Benchmarking:** Even when both models have different emphasis and respond to different questions, the outputs should be coherent.
- **Feedback:** Considering that Detecco currently has a limited number of nodes, the estimated value of hydrogen and ammonia may be less accurate than the results of PyPSA, which has more nodes and could potentially

provide a better representation of certain values (e.g., transmission deferral within a zone). In such situations, refining these values and incorporating them into Detecco could improve the accuracy of its estimations.

Accounting for this full set of synergies and interactions, the full modelling process is illustrated in detail in **Figure 7**. The envisioned modelling process for each scenario begins with GeoH2 conducting a first-pass, conservative calculation of LCOH and LOCA. This initial assessment helps identify promising areas for further exploration. Detecco then performs an analysis co-optimising the energy supply from a set of areas identified by GeoH2 to the demand locations through different transport alternatives such as transmission lines, pipelines or trucks. Meanwhile, PyPSA models the entire energy system to determine whether hydrogen and ammonia are part of the cost-optimal system configuration. The results from Detecco, identifying the cheapest options for hydrogen or ammonia production, can then be compared with PyPSA's allocation of hydrogen and ammonia production within the grid. Additionally, any curtailed energy identified in PyPSA can be fed back into Detecco, further refining cost optimization and improving the overall efficiency of the system.

The feedback loop between Detecco and PyPSA is crucial for comparing the calculated LCOH of the two models, enhancing trust in the results and revealing any uncertainty. GeoH2 identifies the cheapest hydrogen production sites initially, while Detecco advances this, and PyPSA includes grid considerations, leading to lower LCOH. This comparison aligns results and explains discrepancies.

TABLE 7: Full envisioned modelling process with interlinkage between the three SHIELD tools (GeoH2, Detecco, and PyPSA).



5. Intended research outcomes using these models

This section outlines three core research outputs, and how we expect to produce them using the interlinked SHIELD modelling framework.

5.1 EXPLORING THE IMPACT OF COST OF CAPITAL

The goal of this part of the research will be to explore the impact of varying costs of capital on the feasibility of hydrogen and ammonia production in Ukraine. This is based on the notion that any development geographically closer to front-lines or under greater perceived risk may be likely to receive worse financial terms to implement infrastructure to account for such risk. This would increase the cost of capital, which is a key driver of whether green hydrogen or ammonia are feasible, as these are capital-intensive projects.

To explore this question, we will use the GeoH2 and Detecco model pipeline. First, we will source information about how costs of capital vary throughout Ukraine's territory. These will be investigated by project partners at the Kyiv School of Economics and TU Munich. Using this information, we will sub-divide GeoH2 into cost of capital "zones". It will be evaluated whether this varying cost of capital changes the most feasible regions in the country for development as compared to a uniform cost of capital across the country. Detecco will then be applied, considering the promising regions identified by GeoH2, and will integrate different transport options as well as coupling between different energy carriers. Consequently, the output of this phase will be the comprehensive cost assessment of power, hydrogen or ammonia across different locations, considering local demand, potential export demand, and the transportation of energy carriers alongside cost of capital.

The results of this work are intended to feed into the decision support tools envisioned in this project. For instance, feasibility maps and quantitative results will ideally be visualised on a web interface (e.g., a dashboard showing several predefined sensitivity analyses on cost of capital, or possibly in a user-friendly framework which enables stakeholders to input their own assumptions).

5.2 WHOLE ENERGY SYSTEM MODEL IN UKRAINE

The goal of this part of the research is to analyse and quantify the potential benefits of incorporating hydrogen into Ukraine's energy system, including storage, distribution, and sector coupling strategies. This is under a whole energy system view including transmission capacity and constraints and the integration with the European electricity grid.

To explore this question, we will use PyPSA. The comprehensive energy system model is planned to be open source, allowing for adaptability and use in future simulations. As the conflict in Ukraine persists, this model can only represent a specific scenario, typically an optimised version of the current conditions. However, certain essential insights will remain relevant in subsequent analyses.

We expect that key assessments to be completed in this modelling research will include the following:

- **Cost-Benefit Analysis of Grid Integration with EU:** Evaluating the economic and technical impact of incorporating Ukraine into the European electricity network and green hydrogen and ammonia production, with an emphasis on potential transmission line enhancements.
- **Locational Levelized Cost of Hydrogen:** Determining the most economical locations for hydrogen production and evaluating the regional competitiveness in sectors that utilise hydrogen and ammonia. This includes access to the grid and transmission limitations.
- **Curtailment Patterns and Spatial Distribution:** Assessing the scope and spatial distribution of renewable energy curtailment, with potential for hydrogen production.

5.3. RISK-AVERSE PLANNING AND DISTRIBUTION OF COSTS.

This part of the research addresses the uncertainty surrounding investment in hydrogen and ammonia infrastructure within Ukraine's evolving geopolitical landscape. Such uncertainty is influenced by the shifting control of occupied territories, the frequency of attacks on infrastructure, and the unpredictable timeline of the war's conclusion. Given these factors, ensuring a resilient energy system—one with the ability to survive and quickly recover from extreme and unexpected disruptions[16]—is essential for Ukraine's future energy security.

A resilient system would help mitigate the consequences of adverse events and reduce reliance on a limited number of critical assets.

Consequently, resilient energy system planning must assess how the system can function under high-risk scenarios while optimising key performance metrics, such as loss of load or overall cost. This research will explore the extent to which investment in hydrogen and ammonia infrastructure can enhance the resilience of Ukraine's energy system by reducing dependency on large, centralised assets and enabling greater adaptability in adverse conditions.

However, resilience comes at a cost. Under normal conditions, the system is expected to incur higher capital and operational expenses due to additional investments required to safeguard against risks. These costs may disproportionately affect specific economic sectors, raising concerns about equity and fairness in cost distribution. Therefore, the proposed model must incorporate mechanisms to evaluate how costs are allocated among different energy consumers (off-takers), ensuring that resilience planning aligns with broader socio-economic considerations.

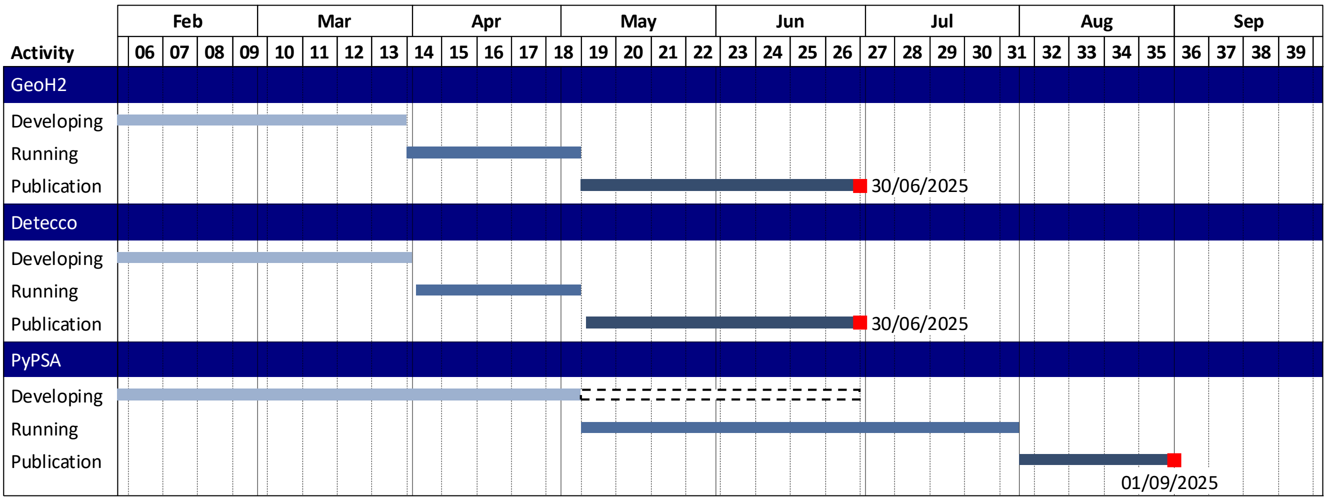
We anticipate conducting this research using GeoH2 and Detecco, leveraging the models' versatility. The optimization phase may need to account for stochasticity through different scenarios and modify the objective function to consider the possibility of hedging the system against unfavourable scenarios.

[16] Jasiūnas, J., Lund, P. D., & Mikkola, J. (2021). Energy system resilience–A review. *Renewable and Sustainable Energy Reviews*, 150, 111476. https://doi.org/10.1016/j.rser.2021.111476

6. Timeline

In this section, we detail the timeline for the development and application of the tools in the SHIELD modelling framework. The GeoH2 model is well-established but requires minor modifications to be suitable for Ukraine. Likewise, the Detecco model requires small adjustments for scenario execution. The aim is to complete the GeoH2 and Detecco model development by the end of March 2025 and initiate scenario runs leading up to a start in April 2025. The first publication from this work is expected to be finished by the end of June, as shown in **Figure 8**.

TABLE 8: Gantt chart of the modelling developments



The PyPSA model requires development from the ground up, resulting in a longer timeframe before initial results can be produced. The preliminary scenarios are expected to be executable in early May, with the complete version projected to be completed by the end of June. A publication presenting the results is expected to be finalised in late August.

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