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SHORT DESCTIPTION

Sector-coupling is a promising approach to replace fossil fuels with renewables. However, this idea of “electrifying” the entire economy requires the rollout of new technologies and rules. The HyEfRe project helps with this by establishing green hydrogen ecosystems in eight regions. Partners will foster an investment-friendly environment for renewable energy and green hydrogen technologies. They evaluate hydrogen potentials with a new model and develop and test a new tool to calculate ideal parameters for technical plants. Their action plan for policy actors will reduce regulatory barriers impeding a timely expansion of renewables and green hydrogen.

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A. Executive Summary

The HyEfRe project tackles critical challenges in Central European energy systems, including the limited integration of variable renewable energy sources such as wind and solar, insufficient energy efficiency, and slow progress toward carbon neutrality. These structural shortcomings contribute not only to elevated energy costs but also to ongoing environmental pressures and climate change. In response, the project promotes hydrogen-based sector coupling as a key pathway to enhance system flexibility, improve overall efficiency, and accelerate the transition to clean energy systems.

A central objective of HyEfRe is to strengthen transnational cooperation, enabling regional and local stakeholders to benefit from shared knowledge, practical experiences, and coordinated approaches to green hydrogen integration. The project adopts a holistic perspective aimed at fostering an investment-friendly environment for renewable energy and hydrogen technologies. This includes advancing energy efficiency solutions, such as waste heat utilization, and improving grid balancing capabilities.

To support evidence-based planning and investment decisions, HyEfRe is developing an innovative model for assessing hydrogen potential, including storage capacity and grid-balancing opportunities. However, the true value and robustness of this model depend on its applicability across diverse real-world conditions. For this reason, particular emphasis is placed on testing the model in regions with differing economic structures, social dynamics, and legal frameworks. Such diversity is essential to ensure that the model is not only technically sound but also adaptable, scalable, and relevant in varying regulatory and societal environments. Understanding how these contextual factors influence model performance is crucial for both developers refining the system and end-users seeking to apply it effectively.

To complement the model, the project will also deliver a decision-support tool designed to identify optimal operational parameters for key infrastructure components, such as grid-balancing electrolyzers. Both tools will undergo validation through pilot actions, allowing their technical feasibility, economic viability, and practical usability to be assessed in real-life settings. These pilot activities play a pivotal role in identifying barriers, uncovering region-specific challenges, and generating actionable insights for improvement.

By analyzing renewable energy availability, grid characteristics, and energy consumption patterns, the project aims to support the development of regional hydrogen ecosystems. These ecosystems are intended to facilitate the uptake of hydrogen solutions while actively involving stakeholders from across the value chain.

The HyEfRe consortium brings together research institutions, SMEs, and development agencies with expertise spanning renewable energy systems, hydrogen integration, modelling, legal and economic analysis, and stakeholder engagement. During the initial phase, the Energy Institute Hrvoje Požar (Croatia) and Deggendorf Institute of Technology (Germany), supported by Landshut University of Applied Sciences (Germany), the University of Zagreb Faculty of Electrical

Engineering and Computing (Croatia), and HyFuture GmbH (Germany), were developing the hydrogen potential assessment model. This model is based on real-time, hourly data on renewable energy generation and electricity demand. By identifying imbalances between supply and demand, it estimates the potential for hydrogen production from surplus renewable electricity, including outputs in the form of hydrogen or hydrogen carriers, depending on the applied technology.

The model generates visual maps highlighting areas with high potential for renewable energy deployment and hydrogen production, along with associated greenhouse gas emission reduction impacts. It also simulates future scenarios of renewable energy expansion. While primarily relying on national datasets from project partners, the model also incorporates ENTSO-E data[1] where necessary. For a hydrogen potential model, ENTSO-E data is especially valuable because it provides high-resolution (often hourly) data that helps detect surplus renewable energy, enables cross-border comparisons using harmonized datasets across countries, and provides insights into grid behavior, which is essential for evaluating hydrogen's role in balancing supply and demand.

Designed with accessibility in mind, the hydrogen potential model was intended to be user-friendly, suitable for municipal planners without specialized technical expertise, and fully compatible with the decision-support tool. To ensure comprehensive validation, the model was tested in four pilot regions between 11/2025 – 05/2026, representing diverse socio-economic and regulatory environments:

- The Šaleška region (Slovenia), a former coal-based economy transitioning toward carbon neutrality;
- The Mazovia region (Poland), facing significant air pollution and smog challenges;
- The City of Pécs (Hungary), actively pursuing the development of a hydrogen-based community.

The outcomes of these pilot actions are documented in this report to provide critical insights into the model's performance under varying conditions. By systematically analyzing successes, challenges, and lessons learned, this report supports both the further refinement of the model and future users' capacity to navigate implementation barriers and adapt the solution to their specific local contexts.

[1] ENTSO-E data refers to the large set of open electricity system datasets published by this organization through its Transparency Platform, providing detailed, standardized information about how electricity systems operate across Europe. Find more information at: https://www.entsoe.eu/data/

1. Objective of pilot testing

The primary objective of the pilot testing is to assess whether the HPM tool can effectively support early-stage decision-making for siting and sizing hydrogen production infrastructure. This includes evaluating its ability to generate meaningful insights from limited, heterogeneous datasets, a common constraint at the municipal and regional levels. The pilots aim to determine whether the simplified model structure successfully lowers the barrier to entry compared to more complex energy system models, while still providing sufficiently reliable outputs for preliminary investment considerations.

Another key objective is to examine the data-related challenges associated with the model's use. The HPM relies on time-series data for renewable energy production and electricity demand, typically at an hourly resolution over a representative year. Pilot testing, therefore, investigates the availability, quality, and accessibility of such data across different regions, including the use of measured versus synthetic datasets. Particular attention is given to the effort required for data preparation, validation, and integration into the model, as these steps are often a critical bottleneck for end users.

We also have to consider that the pilot actions are structured to test the model across regions with distinct economic conditions, social dynamics, and legal frameworks. This diversity is essential for evaluating how sensitive the model is to external factors beyond purely technical inputs. Economic parameters, such as hydrogen price assumptions, investment costs, and operational expenditures, can significantly influence model outputs and their interpretation. At the same time, regulatory environments, market structures, and policy incentives may affect both the feasibility of hydrogen projects and the relevance of the model’s recommendations. Social and institutional factors, including stakeholder engagement, local expertise, and governance structures, also influence how easily the tool can be adopted and applied in practice.

The pilot testing also aims to assess the usability and user experience of the HPM tool. As a web-based application intended for non-expert users, it is essential that the interface be easy to use, the workflow be clear, and the outputs be easy to interpret. The pilots provide valuable feedback on how users interact with the tool, where difficulties arise, and how the presentation of results can be improved to better support decision-making processes.

In addition, the pilots are used to evaluate the model’s capacity to support scenario analysis and sensitivity testing. By creating and comparing multiple scenarios - such as variations in renewable energy capacity, demand profiles, or economic assumptions - users can explore different situations and better understand the key drivers influencing hydrogen potential. This capability is particularly important in uncertain and evolving energy system contexts.

Based on the testing results, we also intend to provide recommendations for further development of the HPM tool to improve both the model's technical performance and its practical usability. These findings are intended to support developers in refining the system and to help future users better understand how to overcome common barriers and effectively apply the tool in their local contexts.

2. Methodological framework

2.1. Testing approach

Pilot testing of the Hydrogen Potential Model (HPM) was conducted between late 2025 and April 2026 across three distinct regions, using a harmonized methodological framework to ensure consistent and comparable results. Partners could access the application at https://hyefre.eu/ address.

The testing workflow followed three main phases: data preparation, model execution, and results evaluation. In the first phase, each pilot region defined its geographical area (.shp files or marked it on the OpenStreetView map).

As the next step, regions collected and prepared the required input datasets, including renewable energy production and electricity demand profiles. These data needed to be provided in CSV files. Where real measured data was available, it was prioritized to ensure realism and accuracy. However, when such data was incomplete or unavailable, synthetic datasets could be generated using the tool's built-in functionality, particularly for wind and solar production. This dual approach allowed the pilots to assess not only the performance of the model under ideal data conditions but also its usability in more constrained environments.

The second phase involved creating and configuring scenarios in the HPM tool. Each region developed at least one base scenario, representing the current or most realistic configuration of the local energy system, and several alternative scenarios to explore potential future developments. These included variations in renewable energy capacity, changes in demand patterns, and adjustments to economic parameters such as hydrogen price assumptions. The use of the scenario-based approach enabled structured “what-if” analyses and provided insights into the model's sensitivity to different input conditions. Deep understanding of local stakeholders’ needs was necessary to complete this step.

Once scenarios were prepared, they were submitted online for execution using the model’s optimization engine. During this phase, users selected key economic parameters (e.g., hydrogen, oxygen, and waste heat prices) and simulation settings (e.g., time step granularity). The asynchronous nature of the computation process was also observed and evaluated, including waiting times and system responsiveness.

The final phase focused on evaluating and interpreting results. The model outputs - such as hydrogen production potential, system sizing (electrolyzer and storage), capital and operational expenditures, and payback periods - were analyzed both within individual regions and across scenarios. Particular attention was given to the clarity and usability of the results interface, as well as to users' ability to draw meaningful conclusions for decision-making.

The testing approach was not limited to technical validation. It also explicitly considered the institutional and contextual dimensions of model use. Each pilot region documented challenges related to data access, regulatory conditions, and stakeholder engagement (see current report).

This ensured that the testing process captured not only how the model performs computationally, but also how it fits into the broader decision-making environment.

Regular exchanges between pilot partners were organized at the transnational project meetings (Padua, Linz, Pécs) to share experiences, and discuss emerging challenges with the developers. This iterative and collaborative approach contributed to refining both the testing process and the understanding of the model's strengths and limitations.

2.2. Use of the Hydrogen Potential Model

During the pilot phase, the HPM was applied as a practical decision-support tool by regional stakeholders. At the core of the HPM application is the concept of a scenario, which serves as a structured container for all input data, parameters, and results associated with a specific analysis. Across all pilot regions, users relied extensively on this scenario-based approach to organize their work, enabling them to systematically compare different configurations of renewable energy production, demand patterns, and economic assumptions. The ability to duplicate and modify scenarios proved particularly valuable for conducting sensitivity analyses and exploring alternative development pathways.

The tool was used to model a typical year from an energy production and consumption perspective, with hourly resolution (8760 data points), capturing both daily and seasonal variations in renewable energy production and electricity demand. This approach was generally considered an effective compromise between model accuracy and computational efficiency. In practice, users uploaded time series data in CSV format, either as separate production and demand datasets or as pre-calculated surplus values. The ability to accept both real and synthetic data inputs was essential, as data availability varied significantly across regions.

The built-in functionality for synthetic generation of wind and solar production data was particularly useful in cases where real measurements were not accessible. By relying on meteorological reanalysis datasets, the tool enabled users to approximate renewable energy generation profiles based on location and installed capacity. While this approach does not fully replace real data, it provided a viable entry point for exploratory analyses, especially in early-stage project development contexts.

Once the input data was prepared, users configured the model by defining key economic parameters, including hydrogen price, oxygen price, and waste heat value. These parameters play a critical role in shaping the optimization results, as they influence the trade-off between capital investments and operational revenues. The pilots demonstrated that selecting appropriate values for these parameters requires not only technical understanding but also awareness of local market conditions and regulatory frameworks.

The HPM's optimization engine was used to determine the optimal sizing and configuration of hydrogen production infrastructure. The users needed to interact only with simplified inputs and received aggregated outputs. This abstraction was generally perceived as a strength, as it allows non-expert users to benefit from advanced modeling capabilities without needing to understand the underlying algorithms.

The results were accessed through the tool's visualization interface, which presents key performance indicators, including hydrogen production volumes, system utilization rates, CAPEX, OPEX, payback periods, and the levelized cost of hydrogen. Users also used the scenario comparison feature, which enabled side-by-side evaluation of different scenarios, supporting more informed decision-making.

Throughout the pilot phase, the HPM proved to be a functional and adaptable tool for preliminary analysis. At the same time, its use highlighted the importance of clear guidance, particularly in relation to data preparation, parameter selection, and interpretation of results. These aspects are further explored in the subsequent evaluation chapters.

2.3. Evaluation criteria

To ensure a consistent assessment of the HPM across all pilot regions, a common set of evaluation criteria was defined and applied throughout the testing period. These criteria were designed to capture not only the model's technical performance but also its usability, applicability, and relevance across different economic, social, and regulatory contexts.

One of the primary evaluation dimensions was data availability and quality. Given that the HPM relies on hourly time-series data for renewable energy production and electricity demand, the pilots assessed how readily such data could be obtained, processed, and integrated into the tool. This included evaluating the use of real versus synthetic data, the effort required for data formatting (e.g., CSV preparation), and the impact of data gaps or assumptions on the reliability of results. Differences across regions in data infrastructure and accessibility were carefully documented in the following chapters, as they are a key factor influencing the model's practical usability.

Another important criterion was ease of use and user experience. As the HPM is intended for non-expert users, particular attention was given to the interface's intuitiveness, the clarity of the workflow, and the tool's overall accessibility. This included assessing how easily users could create and manage scenarios, upload data, configure parameters, and interpret outputs. User feedback was collected to identify friction points, such as unclear instructions, technical limitations, and usability challenges.

The transparency and interpretability of results constituted a further evaluation dimension. While the model produces a range of quantitative outputs, it is essential that these results can be meaningfully understood and applied by decision-makers. The pilots, therefore, examined whether the key indicators provided by the tool are sufficiently clear, whether additional contextual information is needed, and how easily users can compare different scenarios. The role of visualization features and comparison tools was also evaluated in this context.

The model's sensitivity to input parameters was another critical aspect. By varying key inputs - such as hydrogen price, renewable capacity, or demand profiles - users were able to assess how changes in assumptions affect the results. This helped identify which parameters have the greatest influence on outcomes and the extent to which the model can support robust decision-making under uncertainty.

The evaluation also included a strong focus on contextual applicability, recognizing that the effectiveness of the HPM is closely linked to the environment in which it is used. This includes economic factors (e.g., cost structures, market conditions), legal and regulatory frameworks (e.g., permitting, incentives, energy policies), and social or institutional conditions (e.g., stakeholder capacity, governance structures). The pilots aimed to understand how these factors influence both the inputs to the model and the interpretation of its outputs.

Finally, the overall relevance for decision-making was assessed. This involved evaluating whether the tool provides actionable insights, whether it supports strategic planning processes, and how it complements other, more detailed modeling tools. The distinction between preliminary assessment and detailed system design was particularly important in positioning the HPM within the broader decision-support landscape.

3. Pilot region results

This chapter presents the core findings of the pilot testing activities and is structured to ensure full comparability across all participating regions. To achieve this, STRIA required each pilot region to document its experience using the HPM under an identical set of the following subchapters, which have been filled in by the responsible partners: the Šaleška region (Slovenia), the Mazovia region (Poland), and the City of Pécs (Hungary). The structure of each regional subsection follows a logical progression aligned with the HPM workflow and the overall evaluation framework:

- It begins with a regional description, outlining the local energy system, socio-economic context, and policy environment, providing essential background for interpreting the results.
- This is followed by data preparation and input assumptions, where partners describe the data sources used, challenges encountered, and any simplifications or estimations applied.
- The scenario design subsection details how base and alternative scenarios were defined, reflecting local priorities and development pathways.
- The model execution section captures the practical use of the HPM tool, including parameter selection and any technical or usability issues encountered.
- The results and key findings subsection presents the main outputs of the model and their interpretation in the local context.
- This is complemented by a sensitivity and scenario comparison analysis, highlighting how variations in inputs affect outcomes.
- Each regional chapter then identifies challenges and limitations, with particular attention to barriers related to data, regulation, and institutional capacity.
- Finally, lessons learned summarize key insights and practical recommendations derived from the pilot experience.

3.1. Šaleška region (Slovenia)

Pilot Region Description:

The Šaleška region is located in the northeastern part of Slovenia, within the broader Savinjska statistical region. It is centred around the municipalities of Šoštanj, Velenje, and Šmartno ob Paki, and is historically defined by its role as Slovenia's primary coal-based energy production hub. The Thermal Power Plant Šoštanj (Termoelektrarna Šoštanj, TEŠ) has been the dominant energy infrastructure in the region for decades, supplying a significant share of Slovenia's electricity through lignite combustion.

With the ongoing European energy transition and Slovenia's commitment to phasing out coal by 2033, the Šaleška region faces a profound socio-economic and energy transition challenge. TEŠ's planned decommissioning creates both urgency and opportunity: on one hand, thousands of direct and indirect jobs are at risk; on the other hand, the existing high-voltage grid infrastructure, industrial land, waste heat networks, and proximity to the Šoštanj district heating system (DHS) represent valuable assets for future low-carbon energy systems — including green hydrogen production.

The pilot action in the Šaleška region is led by the Energy Agency of Savinjska, Šaleška and Koroška (KSSENA), which serves as the responsible project partner for this territory within the HyEfRe project. KSSENA operates at the intersection of local governance, energy planning, and regional development, and is well-positioned to translate the outputs of the Hydrogen Potential Model (HPM) into actionable regional hydrogen strategies.

A particularly relevant local initiative is the NAHV project (Nacionalni Center za Vodik - National Hydrogen Centre), which envisions the development of a large-scale renewable energy and green hydrogen production facility on and around Družmirje Lake — a post-mining reservoir created by the subsidence of former lignite extraction areas adjacent to TEŠ. This project, led by HSE (Holding slovenskega elektrogospodarstva) and its subsidiaries, proposes the installation of up to 130 MWp of floating photovoltaic (FPV) panels on the lake surface, with the generated electricity intended to power electrolysis-based hydrogen production. The proximity of TEŠ's existing 400 kV grid connection point, the availability of process water from the lake, and the potential to use waste heat from the DHS for electrolysis optimization are cited as key site advantages.

The Šaleška pilot in HyEfRe therefore serves a dual purpose: (1) to test the HPM tool under realistic regional conditions and with real energy data, and (2) to provide a preliminary quantitative basis for assessing the hydrogen production potential of the region under different renewable energy scenarios, thereby informing the regional hydrogen roadmap developed under HyEfRe.

Data Preparation and Input Assumptions

Electricity consumption data for the Municipality of Šoštanj was provided by Elektro Celje, the regional distribution system operator (DSO). The dataset covers the full calendar year 2024 and is structured at a 15-minute temporal resolution, resulting in 35,040 data points for the annual consumption profile. The data represents aggregated metered consumption across the municipal

distribution grid and reflects actual demand patterns including seasonal variation, industrial loads, and residential consumption.

Prior to use in the HPM, the dataset was reviewed for completeness and consistency. Missing intervals, where present, were addressed through linear interpolation between adjacent valid readings. The 15-minute data was subsequently aggregated to hourly resolution to match the temporal granularity required by the HPM tool, yielding 8,760 hourly values for the reference year.

For the baseline scenario (Scenario 1), existing local renewable energy production data was sourced from available metered and estimated generation profiles for small-scale RES installations within the municipality. This reflects the current state of renewable deployment in the region, which is limited — the Šaleška region's energy system has historically been dominated by thermal generation, and distributed RES penetration remains relatively low compared to other Slovenian regions.

For the advanced scenario (Scenario 2), simulated solar photovoltaic generation profiles were prepared using PVGIS (Photovoltaic Geographical Information System), the European Commission's tool for solar radiation and PV output estimation. A 130 MWp floating PV system was modelled based on the geographic coordinates of Družmirje Lake (approximately 46.38°N, 15.05°E), using the most recent available ERA5 climate dataset within PVGIS. Key modelling assumptions included:

- **System capacity:** 130 MWp (DC peak)
- **Panel technology:** Crystalline silicon
- **System losses:** 14% (default, accounting for wiring, inverter, and soiling losses)
- **Mounting:** Fixed-tilt optimized for latitude, floating configuration (no albedo correction applied)
- **Horizon shading:** Not applied (lake surface assumed unobstructed)

The resulting hourly AC generation profile was used as the RES input for Scenario 2. It is acknowledged that floating PV systems may exhibit slightly higher performance than ground-mounted systems due to the cooling effect of the water surface, which reduces cell temperature losses; however, this effect was not explicitly quantified in the present modelling exercise.

In the absence of an established local hydrogen market in the Šaleška region, hydrogen demand data was not derived from metered consumption but was instead treated as a model parameter to be explored across scenarios. Two demand levels were considered:

- **Low demand:** Representing near-term, localized use cases such as hydrogen for municipal vehicle fleets or small industrial pilots.
- **High demand:** Representing the full offtake potential of a regional hydrogen hub, consistent with the ambitions of the NAHV project.

These demand assumptions were informed by the HyEfRe project's broader hydrogen demand analysis and available literature on hydrogen end-use sectors in Central European industrial transition regions.

Data Limitations:

It is noted that all production data for the 130 MWp FPV scenario is simulated rather than measured, as the installation does not yet exist. The consumption data, while real and high-resolution, pertains to the municipal distribution grid and does not capture industrial-scale loads that would arise if TEŠ were replaced by a hydrogen production facility of comparable scale. These limitations are reflected in the interpretation of results throughout this chapter.

Scenario Design

The Slovenian scenarios were defined for the Šaleška pilot region to systematically explore the sensitivity of hydrogen production potential to variations in RES capacity and hydrogen demand assumptions.

Scenario 1 – Baseline: Existing Local RES, Low Demand

This scenario reflects the current energy reality of the Šaleška region. Existing small-scale renewable energy installations (primarily small hydro and limited rooftop PV) are modelled as the sole source of green electricity for hydrogen production. Hydrogen demand is set at a low level, consistent with near-term pilot-scale applications. This scenario serves as the reference point against which more ambitious scenarios are evaluated and is expected to yield low hydrogen production volumes and limited economic viability due to the scarcity of surplus renewable electricity.

Scenario 2 – Floating PV: 130 MWp FPV on Družmirje Lake, Low Demand

This scenario introduces the 130 MWp floating PV system proposed under the NAHV initiative as the primary RES input. Hydrogen demand remains at the low level defined in Scenario 1. The purpose of this scenario is to isolate the supply-side effect of the large-scale FPV installation and to quantify the maximum hydrogen production achievable under low-demand constraints, which in practice would result in significant curtailment of surplus solar electricity.

Scenario 3 – Full Potential: 130 MWp FPV, High Demand

Building on Scenario 2, this scenario raises hydrogen demand to the high level, representing the full offtake potential of a regional hydrogen hub. This is the most ambitious scenario and reflects the long-term vision of the NAHV project. It is intended to assess whether the 130 MWp FPV system is sufficient to meet high hydrogen demand and to identify periods of supply-demand mismatch.

Scenario 4 – Sensitivity: Adjusted Techno-Economic Parameters

An additional sensitivity scenario was run to test the effect of varying key techno-economic assumptions, including electrolyser efficiency, electricity price, and capital cost (CAPEX). This scenario does not represent a physically distinct energy configuration but rather explores the robustness of the economic conclusions drawn from Scenarios 1–3. Notably, one parameter combination in this scenario yielded an atypically short payback period and low Levelized Cost of Hydrogen (LCOH), which is identified as a modelling outlier rather than a realistic outcome, likely resulting from an overly optimistic combination of input assumptions. This result is flagged and discussed in Section 6.

The scenario matrix is the following:

Scenario	RES Input	Hydrogen Demand	Purpose
1	Existing local RES (low)	Low	Baseline/reference
2	130 MWp FPV (NAHV)	Low	Supply-side potential
3	130 MWp FPV (NAHV)	High	Full potential assessment
4	130 MWp FPV (adjusted)	Variable	Sensitivity / techno-economic

Model Execution

The Hydrogen Potential Model (HPM) was developed within the HyEfRe project as Activity 1.2 and is described in detail in the corresponding User Manual (D.1.2.2). The model is implemented as a web-based tool and is designed to accept hourly RES generation and electricity consumption profiles as inputs, together with a set of techno-economic parameters for the electrolyser, storage, and offtake system, and to compute hydrogen production potential, capacity utilization, LCOH, and payback period on an annual basis.

Model execution for the Šaleška pilot was carried out by the KSSENA team in coordination with the HyEfRe technical partners. Each of the four scenarios defined in Section 3 was run as a separate model instance. Input files were prepared in the format specified by the HPM User Manual and uploaded via the tool's data import interface.

The following electrolyser and system parameters were applied consistently across Scenarios 1–3, with variations introduced only in Scenario 4:

- Electrolyser type: PEM (Proton Exchange Membrane)
- Electrolyser efficiency: 65 kWh/kg H_2 (specific energy consumption)
- Electrolyser capacity: Scaled to RES input (MW-scale for Scenario 2 and 3)
- Minimum load factor: 10% of rated capacity
- Storage: Compressed hydrogen storage, capacity sized to one day of peak production
- Offtake: Continuous (pipeline or truck delivery assumed)
- CAPEX (electrolyser): 900 €/kW (reflecting current market estimates for large-scale PEM)
- OPEX: 2% of CAPEX per annum
- Project lifetime: 20 years
- Discount rate: 6%
- Electricity price: Based on average wholesale price, with sensitivity tested in Scenario 4

During execution, two significant limitations of the HPM tool were encountered that are relevant for the interpretation of results and for future tool development:

a) Inability to modify inputs after scenario execution: Once a scenario has been submitted and run, the HPM tool does not allow the user to edit individual input parameters and re-run selectively. Any change to inputs requires the creation of a new scenario instance from scratch. This significantly increases the time and effort required for iterative sensitivity analysis and reduces the practical usability of the tool for planning professionals who wish to explore parameter space interactively.

b) Lack of input transparency in the results view: The HPM results interface does not display a summary of the input parameters used to generate a given set of results. This makes it difficult to verify which assumptions underpinned a particular output, especially when multiple scenario runs have been conducted over time. This limitation is particularly problematic for audit trails and for communicating results to stakeholders who were not directly involved in setting up the model runs.

Both limitations were documented and communicated to the tool development team as part of the HyEfRe feedback loop, and recommendations for addressing them are included in Section 8 (Lessons Learned).

Results and Key Findings

Baseline

Under Scenario 1, the available surplus renewable electricity for hydrogen production is minimal. Existing RES installations in the municipality generate insufficient energy beyond local demand to sustain meaningful electrolyser operation. Annual hydrogen production is estimated in the range of a few tonnes, with very low electrolyser utilization rates (below 15% of rated capacity for most of the year). The resulting LCOH is high and the payback period exceeds 25 years, confirming that hydrogen production based solely on the current RES base in Šoštanj is not economically viable without significant additional renewable capacity.

This result is consistent with expectations and validates the model's ability to correctly reflect a low-potential supply situation.

130 MWp FPV, Low Demand

The introduction of 130 MWp of floating PV significantly changes the production picture. On an annual basis, the FPV system generates approximately 140–155 GWh of electricity (depending on climate year assumptions), of which a substantial fraction is available for electrolysis after satisfying local consumption. Under low-demand constraints, much of this surplus electricity would theoretically be curtailed, as the offtake infrastructure is not sized to absorb full output.

Within the demand envelope defined for this scenario, annual hydrogen production reaches several hundred tonnes, with electrolyser utilization concentrated in the spring-to-autumn solar production season. LCOH under this scenario is estimated in the range of 4.5–6.5 €/kg H_2, depending on electricity cost assumptions — a range that approaches competitiveness with grey hydrogen in scenarios with low-cost electricity.

130 MWp FPV, High Demand

With high hydrogen demand and the full 130 MWp FPV system, the model identifies significant seasonal supply-demand mismatches. Summer months show surplus production capacity, while winter months (November–February) are characterized by insufficient solar generation to meet target hydrogen output. This finding underscores the need for either complementary RES sources (e.g., wind), large-scale hydrogen storage, or flexible demand management in any realistic implementation of the NAHV concept.

Annual hydrogen production in this scenario reaches the low thousands of tonnes, with LCOH in the range of 3.8–5.2 €/kg H_2 at assumed large-scale CAPEX. Electrolyser utilization averages approximately 35–45% annually, rising to 60–70% during peak summer months. The results suggest that the 130 MWp FPV system alone is insufficient to support a full-scale hydrogen hub operating year-round at high output, and that additional capacity or complementary flexibility mechanisms would be required.

Site-Specific Advantages Reflected in Results

The model results, when interpreted alongside qualitative site characteristics, highlight three structural advantages of the Šoštanj/Družmirje site that are not fully captured in the HPM's quantitative outputs but are essential context for decision-makers:

Grid connection: TEŠ's existing 400 kV connection to the national transmission grid eliminates one of the most significant infrastructure barriers for large-scale electrolysis, avoiding the need for costly new grid reinforcement.

Process water: Družmirje Lake provides a readily available source of water for electrolysis, reducing the logistical and cost burden of water supply.

Waste heat utilization: The proximity of the Šoštanj DHS creates an opportunity to recover and utilize waste heat from the electrolysis process, improving overall system efficiency and potentially generating additional revenue through heat sales.

Sensitivity and Scenario Comparison

A cross-scenario comparison reveals a clear progression from the baseline (Scenario 1) to the full-potential case (Scenario 3), with hydrogen production volumes, electrolyser utilization, and economic viability all improving substantially as RES capacity increases. The most significant step change occurs between Scenario 1 and Scenario 2, confirming that access to large-scale renewable generation is the binding constraint for green hydrogen viability in the Šaleška region.

Scenario 4 explored the sensitivity of LCOH and payback period to variations in the following parameters:

- Electrolyser CAPEX: Range 600–1,200 €/kW
- Electricity price: Range 40–120 €/MWh
- Electrolyser efficiency: Range 55–70 kWh/kg H_2

- Discount rate: Range 4–8%
- Project lifetime: Range 15–25 years

Key sensitivity findings are as follows:

- Electricity price is the single most influential parameter on LCOH. A reduction from 80 €/MWh to 40 €/MWh reduces LCOH by approximately 30–40%, highlighting the critical importance of securing low-cost or self-generated renewable electricity.
- Electrolyser CAPEX has a moderate effect on LCOH over the assumed project lifetime. At 600 €/kW (reflecting anticipated cost reductions by 2030), LCOH drops by approximately 15–20% compared to the 900 €/kW base case.
- Electrolyser efficiency improvements from 65 to 55 kWh/kg H_2 (representing next-generation PEM performance) reduce LCOH by approximately 10–15%.
- Discount rate has a non-linear effect, with higher rates disproportionately penalizing capital-intensive configurations such as large-scale electrolysis paired with hydrogen storage.

One parameter combination in Scenario 4 — specifically the simultaneous application of minimum CAPEX (600 €/kW), minimum electricity price (40 €/MWh), maximum efficiency (55 kWh/kg H_2), and minimum discount rate (4%) — produced an atypically low LCOH and a payback period below 8 years. This result is identified as a modelling outlier and should not be interpreted as a realistic near-term outcome. It represents a theoretical best-case boundary condition in which all favourable assumptions coincide simultaneously, which is unlikely to occur in practice. The result is retained in the analysis for completeness and to define the optimistic boundary of the feasibility space, but it is explicitly flagged as non-representative for investment planning purposes.

Scenario comparison matrix:

Indicator	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4 (base)**
Annual RES input (GWh)	<5	~140–155	~140–155	~140–155
Annual H_2 production (t)	<10	Several hundred	Low thousands	Variable
Electrolyser utilization	<15%	Moderate (seasonal)	35–45% avg.	Variable
LCOH (€/kg H_2)	>10	4.5–6.5	3.8–5.2	2.8–7.5 (range)
Payback period (years)	>25	15–20	12–17	8–22 (range)
Economic viability	Not viable	Marginal–Moderate	Moderate	Scenario-dependent

The results confirm that the Šaleška region holds genuine medium-to-long-term potential for green hydrogen production, contingent on the realisation of large-scale floating PV capacity. Under current techno-economic conditions, the project is not yet commercially viable without some form of public support or concessional financing, but the trajectory of falling electrolyser costs and rising carbon prices is expected to improve the outlook significantly by the late 2020s.

Challenges and Limitations

Data-Related Challenges

Availability of real consumption data: While high-resolution (15-minute) electricity consumption data for the Municipality of Šoštanj was successfully obtained from Elektro Celje for 2024, access to this data required formal coordination between KSSENA and the DSO and was not straightforward. Data sharing agreements and privacy considerations introduced delays. This experience reflects a broader challenge in the Central European context, where energy data access for planning purposes remains inconsistent across regions and national regulatory frameworks.

Absence of real hydrogen demand data: No metered or empirically derived hydrogen demand data exists for the Šaleška region, as there are currently no operational hydrogen end-users in the municipality. All demand inputs were therefore based on assumptions and literature values, introducing inherent uncertainty into the demand-side modelling. This limitation is common to early-stage hydrogen planning exercises but should be revisited as the regional hydrogen market develops.

Simulated RES production data: The 130 MWp floating PV scenario is based entirely on PVGIS-simulated generation profiles. While PVGIS is a well-validated and widely used tool, simulated data cannot fully capture site-specific factors such as local shading, panel soiling in a post-mining environment, floating platform movement, or the micro-climate effects of the lake surface. Measured performance data from an operational FPV system at this location would be necessary for a higher-confidence assessment.

Tool-Related Limitations

Inability to edit scenarios after execution: As noted in Section 4.2, the HPM tool does not permit modification of input parameters once a scenario has been run. This is a significant usability constraint that increases the time burden of iterative analysis and discourages exploratory use of the tool by planning practitioners who are not deeply familiar with all required parameters upfront. In the Šaleška pilot, this limitation necessitated several complete re-runs of scenarios when minor input corrections were required, consuming disproportionate time relative to the magnitude of the changes made.

Lack of input parameter visibility in results: The HPM results interface does not present a consolidated summary of the input assumptions associated with a given model run. When working across multiple scenarios over an extended period, this creates a risk of confusion between runs and makes it difficult to document or communicate the basis of results to external stakeholders

or reviewers. For a project deliverable such as this report, it was necessary to maintain a separate manual log of all input parameters used in each scenario run, which is an inefficient workaround.

Limited transparency of intermediate calculations: The HPM provides final outputs (LCOH, payback period, annual hydrogen production) but does not expose intermediate calculation steps in a user-accessible format. This limits the ability of users to verify the model's internal logic, identify calculation errors, or adapt the methodology to local conditions that may deviate from the model's built-in assumptions.

Temporal scope fixed at one year: The HPM operates on an annual basis using a single reference year of input data. This does not allow for multi-year trend analysis or the modelling of gradual capacity ramp-up scenarios, both of which are relevant for long-term hydrogen infrastructure planning.

Regional and Contextual Limitations

Theoretical nature of the pilot: It is important to emphasise that the Šaleška pilot action within HyEfRe is a theoretical piloting exercise. No physical hydrogen infrastructure has been constructed, no electrolyser has been procured, and no hydrogen has been produced as part of this pilot. The HPM was applied to real and simulated data to test the tool's functionality and to generate indicative results for regional planning purposes. The outcomes should be interpreted accordingly — as analytical outputs that inform strategic thinking, not as engineering designs or investment appraisals.

TEŠ transition uncertainty: The timeline and modalities of TEŠ's decommissioning remain subject to political and regulatory processes at the national level. The availability of grid infrastructure, industrial land, and waste heat from the DHS — all cited as site advantages — is contingent on decisions that have not yet been fully determined. This uncertainty limits the precision with which site-specific advantages can be incorporated into the current modelling framework.

Lack of wind resource integration: The Šaleška region has limited wind energy potential compared to coastal or alpine areas of Slovenia. The current scenario set does not include wind generation as a complementary RES source. In a more comprehensive assessment, the integration of even modest wind capacity could significantly improve the year-round hydrogen production profile by partially compensating for the winter deficit in solar generation identified in Scenario 3.

Lessons Learned

Looking back at the work done for the Šaleška pilot, the biggest takeaway for us was how much time and effort goes into preparing the data before you even open the model. We spent considerably more time getting the consumption data from Elektro Celje into the right format, cleaning it, and building the PV generation profiles in PVGIS than we did actually running the scenarios in the HPM. If we were to start this over, we would front-load that data audit much earlier in the process and design the scenarios around what data is actually available, rather than the other way around. It also became very clear during the work that there is a meaningful difference between using real metered data and using simulated data. The consumption figures from Elektro Celje gave me confidence in that part of the analysis. The 130 MWp FPV profile, on

the other hand, is modelled — the installation does not exist yet — and that uncertainty needs to be kept in mind when reading the results. We tried to be transparent about this throughout the report. Working with the HPM tool itself was instructive, but also occasionally frustrating. The two things we would most want to see improved are the ability to adjust inputs and re-run a scenario without starting from scratch, and a clear summary of input parameters displayed alongside the results. Without the latter, we found ourselves maintaining a separate spreadsheet just to keep track of what assumptions we had used in each run, which is not an ideal way to work.

On the bigger picture, the analysis reinforced something we already suspected going in: without the large-scale floating PV on Družmirje Lake, there is simply not enough renewable electricity in the municipality to make hydrogen production viable at any meaningful scale. The NAHV project is not just a nice-to-have — it is the prerequisite. At the same time, the site advantages that Šoštanj offers (the TEŠ grid connection, the lake water, the district heating network nearby) are genuinely significant, and I think we need to do more work to put concrete numbers on their value in future assessments.

Finally, we want to note that even though we did not build anything physical as part of this pilot, we do not think the work was any less valuable for that. Understanding the scale of what would be needed, where the seasonal gaps are, and what the realistic cost range looks like — that is exactly the kind of groundwork that needs to happen before anyone can seriously consider investing in hydrogen infrastructure.

3.2. Mazovia region (Poland)

Pilot Region Description:

Mazovian Voivodeship is the largest and economically strongest region in Poland, with a population exceeding 5.5 million inhabitants in 2024, representing approximately 14–15% of the national population. The region generates nearly one quarter of Poland's gross domestic product, making it the country's most important economic centre. In 2023, the value of GDP generated in Mazovia Region reached PLN 811.2 billion, accounting for 23.8% of national GDP. The Warsaw metropolitan region alone generated 18.3% of Poland's GDP, while GDP per capita in Warsaw reached PLN 250,357, almost 176% above the national average.

The energy system of Mazovia reflects both Poland's traditional dependence on fossil fuels and the ongoing transition towards cleaner energy sources. The region hosts several nationally significant energy assets, including the Kozienice Power Plant, one of the largest coal-fired power stations in Poland, with an installed capacity exceeding 4 GW. Kozienice remains a key element of the national electricity system and illustrates the scale of the decarbonisation challenge facing the region. At the same time, Warsaw operates one of the largest district heating systems in Europe, serving approximately 80% of the city's residents. The system is supplied mainly by large combined heat and power (CHP) plants, including Siekierki CHP and Żerań CHP. The Siekierki facility alone has a thermal capacity exceeding 2,000 MW and remains one of the largest CHP plants in Europe. These assets provide reliable heat and electricity but are also subject to increasing pressure from EU climate regulations and rising carbon costs. Consequently, they represent potential future markets for low-carbon fuels, including hydrogen and hydrogen-derived

solutions. The region continues to face significant air quality challenges, as concentrations of particulate matter (PM10 and PM2.5) and benzo(a)pyrene regularly exceed both national and EU limit and target values. In the Warsaw agglomeration, these challenges are further compounded by persistent exceedances of nitrogen dioxide (NO_2) standards, primarily associated with intensive road traffic and urban transport emissions.

Renewable energy deployment has accelerated significantly in recent years, both nationally and regionally. Poland's renewable electricity share reached approximately 25–30% of total electricity generation in 2024, depending on the methodology applied, compared to less than 15% only a decade earlier. The fastest-growing technology has been solar photovoltaics. Mazovia Region is among the leading regions in Poland in terms of distributed PV deployment due to its large population, extensive suburban development and strong municipal investment activity. Renewable generation in the region is dominated by photovoltaic systems, biomass and biogas installations, while onshore wind development remains more limited than in northern and western Poland because of land-use constraints and urban density. As a result, Mazovia functions increasingly as a major consumer and integrator of renewable electricity rather than solely as a generation region.

The growing share of renewable energy creates new challenges related to grid balancing and flexibility. Warsaw and its metropolitan area, with more than 3.2 million inhabitants, constitute one of the largest electricity demand centres in Central Europe. At the same time, distributed renewable generation introduces greater variability into the power system. The increasing electrification of transport, digital infrastructure, data centres and heating systems further intensifies pressure on electricity networks. The transmission infrastructure connecting Warsaw, Kozienice, Ostrołęka and other strategic nodes therefore plays a critical role in maintaining energy security and system stability. These conditions make the region particularly suitable for testing advanced flexibility solutions, including battery storage, demand-side response, smart grids, sector coupling and hydrogen-based energy storage. Hydrogen can provide long-duration storage capacity, support balancing services and facilitate the integration of variable renewable energy sources into both electricity and heat systems.

From an economic perspective, Mazovia Region combines a highly developed service economy with important industrial and energy-related activities. The region attracts the largest share of foreign direct investment in Poland and remains the country's leading centre for finance, information technology, telecommunications, professional services and public administration. At the same time, the wider region hosts important industrial sectors, including petrochemicals, food processing, machinery manufacturing, chemicals, logistics and energy production. The Płock industrial area, connected to ORLEN's refining and petrochemical operations, represents one of the most significant industrial clusters in Central Europe. The diversity of the regional economy increases its resilience and creates multiple potential use cases for hydrogen technologies across transport, logistics, industrial processes and energy infrastructure.

Energy costs are becoming an increasingly important factor influencing competitiveness and investment decisions. Rising electricity prices, growing costs associated with the EU Emissions Trading System (EU ETS) and the need for industrial decarbonisation have increased interest in alternative energy carriers. In Warsaw, energy expenditures are particularly relevant for public

transport operators, district heating providers, municipal services, airports, office buildings and commercial facilities. Across the wider region, logistics centres, industrial facilities and manufacturing companies are seeking low-carbon energy solutions capable of reducing emissions while ensuring energy security. Hydrogen technologies may therefore play a dual role by supporting decarbonisation objectives and enhancing resilience against future energy price volatility.

The social and institutional context of Mazovia provides an important advantage for hydrogen deployment. The region hosts a broad ecosystem of stakeholders capable of supporting innovation, demonstration and commercialisation activities. These include the Mazovian regional government, the City of Warsaw, ORLEN and ORLEN Termika, the national transmission system operator PSE, distribution system operators, Veolia Energia Warszawa, Warsaw's public transport operator Miejskie Zakłady Autobusowe (MZA), Warsaw Chopin Airport, universities, research institutes and technology providers. The presence of national ministries, regulatory agencies and major financial institutions further strengthens the region's capacity to coordinate complex transition projects.

Warsaw offers particularly favourable conditions for testing hydrogen applications because of its scale, infrastructure and institutional capacity. The city operates one of the largest public transport systems in Central Europe, serving millions of passengers annually. Warsaw Chopin Airport handles approximately 18–19 million passengers per year and represents a significant potential user of hydrogen-powered mobility and logistics solutions. The city's extensive district heating network, large municipal vehicle fleets and concentration of public institutions create multiple opportunities for testing hydrogen technologies in real operational environments. Moreover, the city's visibility and political importance increase the replication potential of successful pilot projects.

The relevance of Mazovian Voivodeship as a testing region derives from the combination of several interconnected transition challenges. The region remains linked to coal-based electricity generation through assets such as Kozienice while simultaneously experiencing rapid growth in renewable energy deployment. It must maintain security of supply for Poland's largest urban economy, modernise one of Europe's largest district heating systems, integrate increasing volumes of distributed renewable generation and reduce greenhouse gas emissions in transport and industry. Few regions in Central and Eastern Europe combine all of these characteristics within a single territory.

Data Preparation and Input Assumptions

The preparation of input data was one of the most challenging stages of the analysis due to limitations related to data access, ownership, and availability. The primary source of data was the City of Warsaw. Access to the required datasets involved administrative procedures, as energy-related information is often subject to internal data ownership policies and confidentiality requirements. As a result, obtaining complete datasets took considerably longer than initially anticipated.

To complement the information provided by the City of Warsaw, additional requests were submitted to the local Distribution System Operator (DSO) in order to obtain missing technical and

operational data. However, the availability and level of detail of the requested information varied depending on the type of data and the ownership of the assets concerned. Consequently, not all datasets could be obtained directly from external stakeholders.

The analysis was based primarily on real measured electricity consumption data collected at the pilot site. Nevertheless, several data gaps were identified during the preparation process. The most significant issue concerned the photovoltaic installation located at the hospital building. Due to restricted access to the monitoring platform and limited availability of historical generation records, actual PV production data could not be retrieved. To address this limitation, PV generation profiles were simulated using technical parameters of the installation, available meteorological data, and standard solar generation modelling approaches. Simulated profiles provide a reasonable approximation of actual production.

Another important challenge was related to data transformation and preprocessing. Electricity consumption measurements were recorded at 15-minute intervals, resulting in large datasets with a high temporal resolution. In addition, the original files were provided in formats that were not readily suitable for analysis, often containing complex spreadsheet structures, merged cells, multiple worksheets, and non-standard formatting. Considerable effort was therefore required to clean, reorganise, and standardise the datasets before they could be integrated into the modelling environment. This process included data validation, consistency checks, timestamp harmonisation, and conversion into a format compatible with subsequent analysis tools.

Overall, the quality of demand-side data was relatively high because it was based on real consumption measurements.

Scenario Design

The scenario design process was developed in close cooperation with representatives of the City of Warsaw and was based on a series of workshops, technical consultations and stakeholder meetings. The purpose of these consultations was to identify a pilot area that would be technically relevant, institutionally feasible and aligned with the strategic priorities of the city. From the beginning of the process, particular attention was paid to locations where hydrogen technologies could respond to concrete local needs rather than serve only as a theoretical demonstration. As a result, the area surrounding the Dr Rafał Masztak Grochowski Hospital, including adjacent residential buildings, was selected as the pilot area for further analysis.

The choice of this location was directly linked to the specific role of the hospital as a critical public facility. Hospitals are among the most energy-sensitive types of urban infrastructure, as the continuity and quality of electricity supply are essential for patient safety, medical procedures, diagnostics, intensive care and the operation of specialised equipment. Even short interruptions or disturbances in power supply can create significant operational risks. For this reason, hospitals are equipped with emergency power systems, traditionally based on diesel generators. However, the modernisation of such systems has become increasingly relevant in the context of energy transition, air quality improvement, climate policy and broader security concerns. During discussions with the City of Warsaw, the potential replacement or partial

substitution of conventional diesel backup generators with hydrogen-powered generators was identified as a promising direction for further exploration.

The interest in hydrogen-based backup power systems was driven by both technical and strategic considerations. From a technical point of view, hydrogen generators may provide a more stable and cleaner source of emergency electricity compared with conventional diesel units. One of the advantages discussed during the scenario development process was the possibility of reducing voltage fluctuations during generator start-up and operation. This aspect is particularly important in a hospital environment, where sensitive medical equipment can be vulnerable to sudden voltage drops, spikes or other power quality disturbances. In this context, a hydrogen-based solution could contribute not only to decarbonisation but also to improved operational reliability and protection of high-value medical infrastructure.

In addition to technical performance, hydrogen generators may offer important environmental benefits. Conventional diesel generators produce local air pollutants, including nitrogen oxides and particulate matter, and they generate noise and exhaust emissions when operating. Although backup generators are used mainly during emergency situations or testing periods, their environmental impact remains relevant, especially in dense urban areas and in the vicinity of sensitive users such as hospitals, residential buildings and public services. Hydrogen generators, depending on the technology and fuel production pathway, can significantly reduce local emissions and noise. This makes them more compatible with urban decarbonisation policies and with the need to improve air quality in Warsaw, where transport and combustion-related emissions remain important environmental challenges.

The discussions with local stakeholders also reflected broader energy security concerns. The ongoing war in Ukraine has significantly increased awareness of the vulnerability of critical infrastructure in Central and Eastern Europe. Public authorities are increasingly required to consider not only standard operational risks, such as grid failures or extreme weather events, but also more complex crisis scenarios related to military threats, cyberattacks, fuel supply disruptions and deliberate attacks on energy infrastructure. In this context, hospitals are particularly important because they must continue operating under emergency conditions. Hydrogen generators were therefore considered not only as a low-emission alternative to diesel systems, but also as a potential element of a broader resilience strategy.

Compared with conventional diesel generators, hydrogen-based systems may provide advantages in situations where lower detectability of critical infrastructure is important. They are generally quieter during operation and generate less waste heat than diesel units, which may reduce acoustic and thermal signatures. In the context of heightened security risks, including the potential threat of military aggression in the region, these characteristics were considered relevant by stakeholders. While this was not the only reason for selecting the pilot area, it strengthened the justification for analysing hydrogen as part of an emergency power supply concept for critical infrastructure.

On the basis of the identified needs, stakeholder input and available data, two main scenarios were developed. The first scenario was designed as a base scenario and represented the current

situation in the pilot area. It was constructed using actual electricity consumption data and existing energy infrastructure. This scenario reflected the present operating conditions of the hospital and neighbouring residential buildings, without assuming any additional investments in renewable energy generation, storage systems or other major energy upgrades. The purpose of the base scenario was to establish a realistic reference point and to determine whether the current energy system already creates conditions that could support local hydrogen production.

The base scenario was particularly important because it allowed the analysis to avoid unrealistic assumptions at the initial stage. Instead of immediately assuming the availability of surplus renewable energy, the existing electricity consumption patterns were first examined. This helped to assess whether any locally generated electricity could potentially be used for electrolysis and hydrogen production under current conditions. The scenario therefore served as a baseline for understanding actual demand, local energy balance and the degree to which existing infrastructure could support a hydrogen-related solution without additional investments.

The results of the base scenario showed that the potential for hydrogen production under current conditions is very limited. Nearly all locally generated electricity was consumed directly on site, leaving no meaningful surplus energy that could be redirected to electrolysis. This finding was important for the overall scenario design because it confirmed that the development of a local hydrogen ecosystem cannot be based solely on the current configuration of the pilot area. Under existing conditions, the energy balance is dominated by direct consumption, and the available renewable generation is insufficient to create regular excess electricity for hydrogen production. As a result, the base scenario demonstrated the limitations of the current system and highlighted the need for additional investments if hydrogen is to become a practical option.

In response to these findings, a second scenario was developed. This scenario can be described as an investment scenario, as it included potential future renewable energy installations on selected buildings within the pilot area. Particular attention was paid to rooftop photovoltaic systems, which were considered the most realistic and locally appropriate renewable energy technology for the analysed urban environment. The inclusion of photovoltaic installations reflected both the physical characteristics of the area and the priorities discussed with the City of Warsaw. Rooftop PV can be deployed on public buildings, hospital facilities and residential blocks without requiring large areas of additional land, which is especially important in a dense urban setting.

The investment scenario was not intended to represent an abstract or idealised future. Instead, it was designed to reflect realistic investment opportunities that could be considered by local authorities and building owners. The selection of potential PV locations took into account the presence of suitable buildings, the expected technical potential of available roof surfaces and the possibility of integrating additional generation with local electricity demand. The aim was to test whether additional renewable electricity generation could create sufficient surplus energy to support hydrogen production while maintaining a priority for local self-consumption. This approach is important because in urban energy systems, renewable electricity is often most valuable when it is consumed locally and reduces demand from the grid. Hydrogen production should therefore be considered only after the direct electricity needs of the pilot area have been taken into account.

The second scenario created a more favourable framework for analysing hydrogen applications. By increasing local renewable generation, the investment scenario allowed the assessment of whether surplus electricity could be converted into hydrogen and stored for later use, particularly in emergency power supply applications. In this configuration, hydrogen would function as a flexibility and resilience solution rather than as a stand-alone energy source. Electricity generated from rooftop PV could first cover local consumption, while any excess production could be used for electrolysis. The produced hydrogen could then be stored and used in hydrogen generators to supply critical infrastructure, such as the hospital, during outages or emergency situations. This concept links renewable energy deployment, energy storage, critical infrastructure protection and local decarbonisation in a single integrated scenario.

Following the assessment of both scenarios, the investment scenario was selected as the final scenario for further analysis. The decision was based on the results of the base scenario, which showed that the current system does not generate sufficient surplus energy to support hydrogen production. Without additional renewable generation, the potential role of hydrogen would remain highly constrained and would depend on hydrogen imported from outside the pilot area. Although external hydrogen supply could be considered in future studies, the objective of this analysis was to explore the possibility of developing a more locally integrated hydrogen solution. The investment scenario was therefore selected because it created the conditions necessary to examine hydrogen production, storage and use within the pilot area.

The final scenario also reflects local economic and policy conditions. Warsaw has strong interests in increasing the deployment of renewable energy, reducing local emissions, improving the resilience of public infrastructure and testing innovative solutions that may support the city's climate and energy objectives. The pilot area around the Grochowski Hospital is well suited to these priorities because it combines a critical public facility, nearby residential demand, potential rooftop PV resources and a clear use case for emergency power supply. This makes the scenario relevant not only from a technical perspective, but also from the point of view of public policy and municipal decision-making.

The selected investment scenario also has broader demonstration value. It addresses a challenge that is common to many cities: how to integrate renewable energy generation, emergency power systems and low-emission technologies in dense urban areas where land availability is limited and energy demand is high. Hospitals, public buildings and residential blocks are typical elements of urban infrastructure across Europe. Therefore, the lessons learned from the Grochowski Hospital pilot area may be relevant for other districts in Warsaw as well as for other cities seeking to improve the resilience and sustainability of critical infrastructure.

In summary, the scenario design process moved from an evidence-based assessment of the current situation to a more forward-looking investment scenario. The base scenario provided a realistic understanding of existing demand and infrastructure limitations, while the investment scenario introduced additional renewable generation in order to test the practical conditions required for hydrogen production and use. The final scenario was selected because it is more consistent with the project's objectives, local policy priorities and the technical requirements of a hydrogen-based solution. It demonstrates how hydrogen could support the decarbonisation and resilience of

critical urban infrastructure, particularly where conventional diesel backup systems are no longer fully aligned with environmental, operational and security expectations.

Model Execution

The main objective of the model execution was to assess whether the selected pilot area around the Dr Rafał Masztak Grochowski Hospital could generate sufficient surplus electricity to support local hydrogen production and whether such hydrogen could be relevant for backup power applications. The modelling process was therefore not limited to a purely theoretical assessment of hydrogen production. It was directly connected with the local use case identified during consultations with the City of Warsaw, namely the potential replacement or partial substitution of conventional diesel emergency generators with hydrogen-based backup power systems.

Before running the model, it was necessary to define a set of technical and economic parameters. The most important parameters included the hydrogen price, oxygen price, value of waste heat, time step, electricity demand profiles, electricity production profiles and scenario-specific assumptions concerning additional renewable generation. The hydrogen price was set at approximately 69 PLN/kg, which corresponds to around 16 EUR/kg. This value was treated as a realistic working assumption for hydrogen supplied or valued under current market conditions, while acknowledging that future hydrogen prices may decrease depending on the scale of production, electricity costs, electrolyser utilisation rates, infrastructure availability and public support mechanisms.

The oxygen price was also included as a potential by-product value from electrolysis. Based on available market information for technical oxygen, the assumed price was set at approximately 0.6 EUR/kg. This value should be interpreted as an indicative modelling assumption rather than a guaranteed revenue stream. In practice, the economic value of oxygen from electrolysis would depend on several factors, including purity requirements, compression and storage needs, certification, logistics, proximity to potential users and the ability to conclude a stable offtake contract. In the context of the hospital pilot area, oxygen may be conceptually relevant because of the presence of medical and technical infrastructure, but the analysis did not assume automatic direct use of oxygen by the hospital without additional technical and regulatory verification.

The value of waste heat was another important parameter. Electrolysis produces heat that may theoretically be recovered and used, but its practical value depends strongly on the temperature level, distance to heat consumers, required heat exchangers, integration with building systems and the presence of a stable heat demand. For this reason, a conservative waste heat value of 0,1 EUR/MWh was applied. This assumption reflects the fact that low-temperature waste heat is usually less valuable than final heat delivered through a district heating system. The value was therefore not based on the full retail or regulated heat price, but on the expected limited monetisation potential of heat recovered from an electrolyser in a local pilot setting. This approach avoided overestimating the economic benefits of heat recovery while still recognising that waste heat may contribute to the overall system value if a technically feasible use case is developed.

The model was run for both scenarios, and the results were compared in terms of the availability of surplus electricity, potential hydrogen production and the relevance of hydrogen for the identified backup power use case. The comparison confirmed that scenario selection has a decisive impact on the feasibility of hydrogen production. Under existing conditions, hydrogen production is not realistic unless electricity is imported from the grid or hydrogen is supplied externally. Under the investment scenario, however, additional renewable generation improves the potential for local hydrogen production and allows hydrogen to be considered as part of an integrated energy system.

Some technical and usability issues were encountered during model execution. One of the main challenges was related to the definition of input units in the tool interface. In the fields where electricity consumption data had to be inserted, the expected unit was not clearly indicated. A similar issue appeared in the input section for electricity production data. This created uncertainty during the first attempts to upload and run the model, as it was necessary to verify whether the tool expected values in kW, kWh, MWh.

Overall, the practical experience with the tool was positive, but it demonstrated that reliable results depend strongly on the quality of input data and the clarity of modelling assumptions. The tool enabled the comparison of the base and investment scenarios and helped identify the conditions under which hydrogen production could become relevant in the pilot area. At the same time, the process showed that model execution requires careful unit verification, data transformation and interpretation of results. The lack of clearly indicated expected units in some input fields was a minor usability issue, especially for users working with high-resolution time-series data.

Results and Key Findings

The model results indicate that the hydrogen production potential in the selected pilot area is limited but technically meaningful for a small-scale demonstration focused on resilience, emergency power supply and local energy system integration rather than large-scale commercial hydrogen production. Under the selected investment scenario, which assumes additional renewable electricity generation within the pilot area, the annual hydrogen production potential was estimated at approximately 500 kg H_2 per year. This output should be interpreted as a pilot-scale volume, suitable for testing the operation of an integrated local hydrogen system, but not sufficient to support large-scale transport, industrial hydrogen demand or continuous hospital-wide backup power supply.

The proposed system configuration is based on a small electrolyser with an indicative capacity of 15 kW. This size was selected because it corresponds to the limited renewable electricity surplus available in a dense urban environment and reflects the demonstration character of the project. Assuming an electricity requirement of approximately 50 kWh per kilogram of hydrogen produced, annual production of 500 kg H_2 would require around 25 MWh of electricity per year. With a 15 kW electrolyser, this corresponds to approximately 1,667 full-load operating hours annually. This means that the electrolyser would not operate continuously, but rather in selected periods when surplus renewable electricity is available, mainly from rooftop photovoltaic installations.

The operational logic of the system is based on local self-consumption first and hydrogen production second. During periods of high electricity demand, renewable electricity should be used directly by the hospital and surrounding buildings. Only when renewable generation exceeds local demand should the surplus be redirected to the electrolyser. This approach is particularly appropriate for an urban pilot area where renewable generation potential is limited and where the primary objective is to improve resilience and optimise local energy use, rather than maximise hydrogen output.

The selected system also includes a battery with an indicative capacity of 200 kWh. The battery plays an important balancing role in the local energy system. It can absorb short-term fluctuations in photovoltaic generation and demand, reduce the need for immediate curtailment or export of renewable electricity, and improve the operational flexibility of the electrolyser. In practice, the battery can help smooth the interaction between variable PV production, hospital demand and hydrogen production. This is important because the electrolyser should preferably operate during periods of renewable surplus, while the hospital's electricity demand remains the first priority.

Hydrogen storage was sized to accommodate the annual production volume of approximately 500 kg H_2. This is a conservative assumption, but it is justified in the context of a resilience-oriented pilot. It allows hydrogen to be accumulated gradually and used when needed, particularly in emergency situations. A storage capacity of 500 kg H_2 corresponds to approximately 16.7 MWh of chemical energy based on the lower heating value of hydrogen. If converted back into electricity through a fuel cell or hydrogen generator with an assumed electrical efficiency of around 50%, this could provide approximately 8 MWh of usable electricity for emergency purposes. This amount would not be sufficient to operate the entire hospital for an extended period under full load, but it could support selected critical loads such as priority circuits, sensitive medical equipment, communication systems, selected lighting, control systems or other essential functions.

The economic results show that the pilot system is capital-intensive, but potentially justifiable when assessed as a resilience and demonstration project. The total CAPEX was estimated at EUR 165,309.18. This includes the electrolyser, battery, hydrogen storage, grid connection, water supply requirements, control systems, safety equipment and other balance-of-plant components necessary for system integration. The main unit cost assumptions included an electrolyser price of EUR 1,860/kW, a battery price of EUR 175/kWh, hydrogen tank cost of EUR 500/kg, grid connection costs of EUR 225.63/kW, and water cost of EUR 1.9/m^3. In addition, a peak power price of EUR 3,865/kW was included in the economic assessment.

Annual operating expenditure was estimated at EUR 9,145.32. This includes fixed operation and maintenance costs, inspections, monitoring, system management, safety checks and other recurring costs required to keep the installation operational. Variable operating costs are influenced mainly by the cost or opportunity cost of electricity. If the electrolyser uses only otherwise unused renewable surplus, the electricity cost can be considered relatively low from a system perspective. However, if the same electricity could be consumed directly by local users or exported to the grid, its alternative value should be taken into account.

The levelised cost of hydrogen obtained in the model was estimated at EUR 5.28/kg H_2. This value should be interpreted carefully, as it depends strongly on the modelling assumptions, especially

the treatment of surplus renewable electricity, CAPEX allocation, equipment lifetime, operating hours and by-product valuation. It is significantly lower than the assumed hydrogen market price of EUR 16/kg, which improves the apparent economic attractiveness of the system. However, the result should not be interpreted as proof of immediate commercial competitiveness, because the project remains small-scale and site-specific. Its main value lies in demonstrating the technical and operational feasibility of hydrogen production and storage in a critical urban infrastructure context.

The model also considered potential by-product revenues from oxygen and waste heat. Electrolysis produces approximately 8 kg of oxygen for every 1 kg of hydrogen. At an annual hydrogen production level of 500 kg H_2, this would correspond to approximately 4,000 kg of oxygen per year. With an assumed oxygen price of EUR 0.6/kg, the theoretical annual value of oxygen could reach around EUR 2,400. However, this value should be treated as indicative rather than guaranteed, because monetising oxygen would require appropriate purity control, compression or storage, certification and a reliable offtake arrangement. In the context of a hospital pilot area, oxygen may be conceptually relevant, but its direct use would require additional technical and regulatory verification.

Waste heat was valued conservatively at EUR 0.1/MWh of recovered thermal energy. At this price level, the contribution of waste heat to the overall economic result is very small. This reflects the fact that the proposed electrolyser is small and that the practical value of recovered heat depends on its temperature, integration with local heat demand, connection costs and the ability to use the heat at the time it is produced. Waste heat recovery may still be technically interesting, but it is not a major economic driver in this pilot configuration.

The estimated payback period is approximately 15 years. This suggests that the project may be economically borderline if assessed only from a narrow financial perspective. However, a simple payback calculation does not fully capture the value of improved energy resilience, reduced local emissions, lower noise compared with diesel generators, operational learning, technology demonstration and alignment with Warsaw's climate and energy policy objectives. For this reason, the investment should be interpreted as a strategic pilot rather than a standard commercial hydrogen production project.

Overall, the key finding is that the selected pilot area can support a small hydrogen system if additional renewable generation and appropriate balancing infrastructure are included. The base conditions alone are not sufficient to justify local hydrogen production, but the investment scenario creates the minimum technical conditions required to test hydrogen as a flexibility and resilience solution. The optimal configuration is therefore not a large hydrogen production plant, but a compact integrated system combining rooftop PV surplus, a 15 kW electrolyser, 200 kWh battery storage and hydrogen storage sized for approximately 500 kg H_2 per year. The main operational value of the system lies in its ability to convert limited renewable surplus into a strategic energy reserve for emergency applications in critical urban infrastructure.

Sensitivity and Scenario Comparison

The comparison between the two scenarios showed that the availability of renewable electricity surplus is the key factor determining the feasibility of local hydrogen production. In the base scenario, which reflected the existing situation in the pilot area, almost all locally generated electricity was consumed directly by the hospital and neighbouring buildings. As a result, no meaningful surplus was available for electrolysis, and the hydrogen production potential remained negligible. This confirmed that, under current conditions, a local hydrogen system would not be technically justified unless hydrogen were supplied from outside the area or electricity were purchased from the grid.

The investment scenario produced significantly different results because it assumed additional rooftop photovoltaic capacity on selected buildings. Increasing local renewable generation created periods of surplus electricity that could be redirected to the electrolyser. This made it possible to estimate a pilot-scale hydrogen production potential of approximately 500 kg H_2 per year. The difference between the two scenarios therefore demonstrates that RES capacity is the most important driver of the results. Without additional renewable generation, the system cannot produce hydrogen locally; with additional PV capacity, hydrogen becomes feasible as a small-scale flexibility and resilience solution.

The analysis also showed that electricity demand strongly influences the amount of renewable surplus available. Higher local demand reduces surplus electricity and limits electrolyser operation, while lower demand or better alignment between PV generation and consumption increases the potential for hydrogen production. This means that demand-side management, load shifting and energy efficiency measures may improve the performance of the system by increasing the share of renewable electricity that can be used strategically.

Economic parameters such as hydrogen price, oxygen price and the value of waste heat affected the interpretation of economic performance, but they did not change the main technical conclusion. Even with additional revenues from oxygen or waste heat, the system remains a small demonstration project rather than a commercially optimised hydrogen production facility. The most sensitive economic drivers were CAPEX, electrolyser utilisation rate and the value assigned to surplus electricity. Low utilisation of the electrolyser increases the levelised cost of hydrogen, while higher renewable surplus and more operating hours would improve the economics.

Overall, the scenario comparison confirmed that the main drivers of the results are renewable energy capacity, local demand patterns, electrolyser utilisation and investment cost. The investment scenario was selected because it creates the minimum technical conditions required to test hydrogen production and storage. However, the results should be interpreted as an early-stage feasibility assessment focused on resilience, system integration and learning value, rather than as a mature commercial business case.

Challenges and Limitations

Several challenges and limitations were encountered during the preparation and execution of the analysis. The most important barriers were related to data availability, data ownership and the

practical process of obtaining reliable input datasets. The access to the necessary information required internal procedures and clarification of data ownership rules. As a result, the process was more time-consuming than expected. Where data gaps remained, additional information was requested from the Distribution System Operator; however, the level of detail and availability of these data were limited.

A second important limitation concerned the quality and format of the available datasets. Electricity consumption data were based on real measurements, which was a major strength of the analysis, but the files were provided in complex spreadsheet formats that required substantial cleaning and transformation. The measurements were recorded in 15-minute intervals, while the tables were difficult to edit and not immediately compatible with the modelling tool. This created additional work related to data restructuring, timestamp harmonisation, validation of units and conversion into a usable time-series format.

There were also limitations on the production side. In the case of the photovoltaic installation on the hospital building, direct access to the monitoring application was restricted, so complete measured PV generation data could not be obtained. As a result, PV production had to be simulated. This introduced uncertainty, as simulated data cannot fully reflect real operating conditions such as shading, system downtime, maintenance issues or inverter performance.

The modelling tool itself was useful for comparing scenarios, but some usability issues were identified. In particular, the expected units were not clearly indicated in the input fields for electricity consumption and electricity production data.

Lessons Learned

The modelling exercise provided several practical lessons for both future model improvement and users preparing similar analyses. The most important insight is that the quality and structure of input data have a decisive impact on the usefulness of the results. The use of real electricity consumption data was a strong advantage, as it allowed the scenarios to reflect actual operating conditions in the pilot area. However, the process also showed that measured data sets often require careful cleaning, timestamp harmonisation, validation and transformation into a standardised csv format before they could be used reliably in the modelling tool.

A second key lesson is that data access should be addressed at the very beginning of the project. Obtaining information from public institutions, asset owners and energy operators may take longer than expected due to internal procedures, data ownership rules and confidentiality constraints. Future users should define data needs early, prepare clear data templates and agree on responsibilities for providing consumption, production and technical infrastructure data. This would reduce delays and improve consistency between datasets.

The analysis also showed that scenario design should be closely linked to local conditions and stakeholder needs. The base scenario was useful because it demonstrated the limitations of the existing system and confirmed that no significant surplus electricity was available for hydrogen production. At the same time, it showed that hydrogen solutions become meaningful only when combined with additional renewable generation or other investment measures. Therefore, users

should not rely on generic assumptions, but should test whether the local energy balance actually supports hydrogen production.

Overall, the exercise confirmed that the model can support early-stage feasibility assessment and comparison of hydrogen-related scenarios. However, reliable results require well-prepared data, realistic assumptions and close cooperation with local stakeholders. Future users can overcome many challenges by starting data collection early, documenting all assumptions, testing more than one scenario, and treating model outputs as decision-support evidence rather than final investment conclusions.

3.3. City of Pécs (Hungary)

Pilot Region Description

Pécs is a medium-sized city in Southern Hungary with approximately 140,000 inhabitants and a wider urban region of around 200,000 people. The region is increasingly exploring sustainable energy solutions and low-carbon transition pathways, including renewable integration and hydrogen technologies. Pécs is particularly relevant as a pilot region because of its rapidly growing photovoltaic (PV) generation, emerging hydrogen-related initiatives, and strong academic background connected to hydrogen and fuel-cell technologies.

Energy System and Renewable Energy Context

The regional electricity system is characterized by a rapidly increasing share of solar photovoltaic generation. Solar PV is the dominant renewable electricity source in the region, while wind generation is negligible and dispatchable renewable capacity remains limited. Both residential rooftop systems and industrial-scale PV installations have expanded significantly during the last decade.

Southern Hungary has some of the country's best solar irradiation conditions, which accelerated PV deployment. As in several Hungarian regions with high solar penetration, the Pécs electricity network increasingly experiences:

- midday overgeneration,
- reverse power flows,
- local export congestion,
- and growing balancing challenges between daytime PV generation and consumption patterns.

Hourly local energy balance analyses indicate that during many daytime hours photovoltaic generation exceeds local electricity demand, creating temporary surplus electricity exported to the national grid. However, annual electricity demand still exceeds annual local PV generation,

meaning that the region is not energy self-sufficient but increasingly faces flexibility and balancing challenges.

These conditions make Pécs relevant for testing Power-to-Hydrogen (P2H) concepts, particularly flexible electrolyzer operation linked to local renewable electricity surplus. Hydrogen could contribute to:

- local grid balancing,
- renewable energy storage,
- reduction of curtailment,
- and decarbonization of municipal and industrial transport.

The electricity infrastructure is integrated into the Hungarian transmission and distribution system operated by MAVIR, MWM and E.ON. Increasing PV penetration creates growing interest in decentralized flexibility solutions and sector coupling approaches.

Economic and Industrial Context

Pécs has a diversified regional economy with strong public-sector, educational, healthcare, manufacturing, and SME components. The city has a post-industrial transition background linked to former coal and uranium mining activities, creating strong interest in new sustainable economic development pathways.

Energy costs and electricity price volatility have become increasingly important issues for industrial actors and municipalities. As a result, local interest in renewable integration, energy storage, and alternative fuels has grown significantly.

Several local companies have shown interest in hydrogen technologies and fuel-cell applications. A local SME has nearly 20 years of experience in fuel-cell-related development activities, representing an important knowledge base in the region.

Hydrogen mobility initiatives are also emerging. Two locally developed hydrogen-powered municipal waste collection vehicles are expected to enter operation in the near future, representing one of the first visible municipal hydrogen applications in Hungary.

Research, Education and Stakeholder Ecosystem

The University of Pécs (Pécsi Tudományegyetem – PTE) plays a central role in the regional knowledge ecosystem. Hydrogen-related research groups operate across multiple faculties in fields including:

- engineering and information technology,
- natural sciences,
- economic sciences.

The university also offers a dedicated two-semester postgraduate specialist engineering programme in hydrogen technologies and fuel cells. The programme focuses on hydrogen production, storage, fuel-cell technologies, and applications.

While the hydrogen ecosystem in Pécs is still at an early stage, the region already demonstrates several enabling conditions for future development. These include growing stakeholder interest, relevant university research capacities, emerging municipal pilot initiatives, and SMEs with long-term experience in fuel-cell-related technologies.

An emerging local hydrogen community has started to form around universities, SMEs, municipal actors, and sustainability-oriented stakeholders who are actively seeking pilot and cooperation opportunities.

Governance and Policy Context

Pécs participates in the European NetZero Cities programme and has demonstrated openness toward climate-neutral urban development and sustainable energy solutions. The municipality has shown increasing interest in:

- renewable integration,
- smart energy systems,
- sustainable mobility,
- and low-carbon innovation.

Hungary's national Hydrogen Strategy identifies hydrogen as a strategic technology for industrial decarbonization, transport, energy storage, and grid balancing. At the same time, significant challenges remain, including limited hydrogen infrastructure, evolving regulation, and uncertain business models.

Relevance as a Pilot Region

Pécs represents a valuable pilot region because it combines:

- rapidly growing solar PV penetration,
- increasing grid-balancing challenges,
- academic and educational capacities in hydrogen technologies,
- emerging municipal hydrogen mobility initiatives,
- industrial stakeholder interest,
- and supportive local climate ambitions.

The region offers a suitable real-world environment for testing renewable hydrogen production, flexible electrolyzer operation, sector coupling, and local hydrogen ecosystem development in a medium-sized Central European city context.

Data Preparation and Input Assumptions

The input data for the model were generated and prepared using AI-assisted methods with constrained parameters and estimated boundary conditions. The main reason for this approach was the limited availability of comprehensive, harmonized, and locally validated datasets for both electricity demand and photovoltaic (PV) production in the city of Pécs.

At the time of model execution, no complete and reliable dataset was available regarding local electricity consumption patterns or distributed solar generation. Electricity supply in Pécs is managed by multiple service providers and network actors, which made data collection and harmonization particularly difficult. Although efforts were made to obtain production and demand data from relevant stakeholders, the required datasets could not be fully collected within the project timeframe.

The production-side data presented additional challenges. PV generation was divided into two categories:

- household-sized photovoltaic systems (below 500 kW, typically HMKE systems), and
- utility-scale solar power plants.

For utility-scale installations, only partial public or regional information was accessible. For household-sized systems (HMKE), no precise and spatially resolved local production database was available. In Hungary, detailed HMKE-level generation data are generally not publicly accessible at municipal scale; therefore, estimated values and synthetic profiles had to be applied.

Synthetic solar generation data were produced with AI-supported estimation methods based on the geographical location and solar characteristics of Pécs. The spatial distribution and temporal generation profiles were therefore simulated rather than directly measured. This allowed the creation of a city-scale representation of solar generation; however, this level of territorial granularity is difficult to validate against real-world measurements due to the lack of sufficiently detailed observational datasets.

Demand-side data were also partially synthetic. Since no unified city-level electricity demand dataset was available from DSOs or TSOs, consumption profiles were generated using estimated consumption behavior and AI-assisted pattern generation. The absence of measured high-resolution local demand data introduced uncertainty into the temporal and spatial accuracy of the model.

Several data gaps had to be addressed during preprocessing:

- missing local PV generation statistics,
- incomplete household PV installation data,
- fragmented electricity consumption information,
- inconsistent spatial coverage between available datasets.

These gaps were handled through estimation techniques, interpolation, AI-generated load and generation profiles, and the application of generalized regional assumptions where local information was unavailable.

One of the main challenges during data transformation was ensuring consistency between datasets originating from different assumptions, scales, and temporal resolutions. Another significant difficulty was the lack of standardized local energy datasets suitable for urban-scale modelling. As a result, uncertainties remain regarding the exact spatial distribution of generation and consumption, especially at neighborhood and household level.

From a modelling perspective, a point-based data collection approach would likely be more practical and reliable than using territorially aggregated estimations. In such a framework, the responsibility for collecting and validating complex background data would partially shift toward the participating energy users or production units themselves, assuming access to real operational measurements can be established.

A reasonable methodological alternative could be the use of a representative set of the largest photovoltaic generation units within the selected region as reference points. For example, analysing the largest 10–20 regional PV production units could provide a more stable and verifiable dataset than attempting full territorial coverage with limited validated inputs. This would significantly reduce uncertainty while improving the transparency and reproducibility of the modelling process.

This approach could also support future energy community-based methodologies, where participating prosumers and local energy actors voluntarily provide operational production and consumption data. Such a framework could improve data transparency, reduce uncertainty in distributed generation modelling, and provide a more realistic basis for local electricity network simulations.

Overall, the project highlighted substantial differences in data availability between centralized and distributed energy systems. While some aggregated national or regional indicators exist, locally resolved and validated datasets for distributed PV generation and urban electricity demand remain limited, particularly for household-scale systems.

Scenario Design

The simulation results demonstrated that the renewable energy surplus available in the Pécs region could theoretically support significant hydrogen production potential under different economic and operational assumptions. At the same time, the comparison of the tested scenarios clearly showed that the economic viability and optimal system sizing are highly sensitive to hydrogen market price assumptions, temporal simulation resolution, and infrastructure sizing strategy.

Three primary scenarios were evaluated during the modelling process. The scenarios mainly differed in hydrogen price assumptions and temporal simulation step settings.

The first scenario applied a hydrogen price of 8 EUR/kg with a 2-hour simulation step. Under these assumptions, the system utilized approximately 70.75% of the renewable surplus energy and produced approximately 780,121 kg of hydrogen annually. However, the simulation returned unrealistic economic and technical outputs, including zero-sized electrolyzer and battery capacities, negative CAPEX values, and zero LCOH values.

From an interpretational perspective, this scenario indicates that the selected hydrogen price level was insufficient to economically justify the infrastructure investments required for large-scale hydrogen production. The model behavior suggests that under low hydrogen market prices, the optimization algorithm effectively avoided infrastructure investment because the expected revenues could not offset the investment and operational costs. Therefore, although substantial renewable surplus existed, the conversion of this surplus into economically viable hydrogen production was not feasible under these assumptions.

The second scenario used a hydrogen price of 12 EUR/kg, included a small oxygen price component (0.15 EUR/kg), and applied a coarser 4-hour simulation step. In this case, renewable surplus utilization increased to 76.33%, while annual hydrogen production increased to approximately 841,606 kg. The model proposed a significantly larger system configuration, including a 15.8 MW electrolyzer and approximately 215 MWh battery storage capacity. CAPEX increased substantially to approximately 87.3 million EUR, with yearly operational expenditure around 4.4 million EUR and an estimated payback period of 12.07 years. The resulting LCOH value was approximately 7.55 EUR/kg.

This scenario provided the most realistic and technically interpretable result among the tested cases. The model identified that higher hydrogen market prices could justify significant infrastructure investments aimed at maximizing the use of renewable surplus energy. The large battery capacity indicates that temporal balancing and intermittency management become increasingly important when attempting to stabilize electrolyzer operation using variable renewable production. The relatively long payback period also demonstrates that hydrogen infrastructure investments remain highly capital-intensive and economically sensitive even under relatively favorable hydrogen market conditions.

The third scenario used a hydrogen price of 15 EUR/kg with a 2-hour simulation step and no oxygen monetization. Under these conditions, the system achieved approximately 92.49% renewable surplus utilization and annual hydrogen production exceeding 1 million kg. The reported payback period was extremely short (0.07 years), while CAPEX remained below 1 million EUR and the calculated LCOH dropped to approximately 0.63 EUR/kg.

Although this scenario produced the highest renewable surplus utilization and hydrogen production performance, the economic indicators appear unrealistically optimistic. The results likely reflect modelling sensitivity and optimization instability under highly favorable hydrogen price assumptions. In practical terms, the scenario demonstrates the strong dependence of hydrogen system economics on future hydrogen market pricing. Once hydrogen price assumptions exceed a certain threshold, the model rapidly shifts toward highly profitable configurations. However, such outcomes should be interpreted cautiously, as real-world infrastructure, operational, financing, and regulatory costs would likely moderate these economic results considerably.

A key finding of the simulations is that renewable surplus availability alone does not guarantee economically viable hydrogen production. The interaction between surplus availability, electrolyzer utilization rate, storage sizing, hydrogen market value, and infrastructure investment costs is highly complex. The simulations showed that economically viable hydrogen production

requires not only sufficient renewable surplus, but also stable operational conditions and sufficiently high hydrogen market prices.

The results also highlighted the critical importance of temporal resolution. Different simulation steps affected both system balancing behavior and infrastructure sizing. Finer temporal resolution captures renewable intermittency more realistically but may also increase computational complexity and produce more volatile operational requirements.

Another important finding concerns the role of storage systems. As renewable surplus utilization increased, battery storage requirements increased significantly as well. This indicates that high renewable integration and high hydrogen production utilization are strongly dependent on balancing capacity. Without sufficient storage, surplus renewable production cannot be effectively converted into stable hydrogen generation.

Overall, the simulations demonstrated that the investigated system could theoretically support substantial hydrogen production potential based on renewable surplus electricity. However, the economic feasibility of such systems remains highly sensitive to uncertain future hydrogen market conditions, infrastructure investment costs, and operational assumptions. The modelling process therefore highlighted not only the technical potential of renewable-based hydrogen production, but also the importance of sensitivity analysis, scenario comparison, and cautious interpretation of optimization-driven economic outputs.

Model Execution

The practical execution of the modelling process provided valuable insight into both the strengths and the current limitations of the tool. While the platform enabled the testing of different energy system configurations and sensitivity analyses, several parameters proved difficult to define precisely due to technological, economic, and local infrastructural uncertainties.

One of the primary challenges concerned the definition of economic input parameters. Although the tool requires specific values for hydrogen price, oxygen price, waste heat value, battery cost, storage cost, and other infrastructure-related parameters, these values are highly context-dependent and cannot always be determined accurately at urban scale.

The electrolyzer investment cost, for example, was set using a reasonable average market approximation; however, in practice, this parameter strongly depends on the applied technology, system efficiency, manufacturer, and installed capacity. A further complication is that the optimal electrolyzer size only becomes visible after running the scenario itself. Therefore, it is difficult to provide a precise pre-defined investment value before the simulation results are known.

Similarly, the prices associated with water usage, waste heat utilization, hydrogen storage, and battery systems were based on estimated average values. Since the model does not represent a single industrial consumer or project-specific implementation, these parameters could only be approximated within realistic ranges. More precise costing would require site-specific technical and financial information.

The “peak power price” parameter also proved difficult to define. In real electricity procurement contracts, peak power pricing structures vary considerably depending on tariff systems, contractual agreements, and industrial consumer profiles. In some cases, peak power costs are not explicitly separated within the electricity purchasing structure at all. Consequently, only generalized or estimated values could be applied during modelling.

The oxygen price parameter was not actively considered in the simulations. In practice, oxygen utilization is only economically relevant in specific local industrial applications where a nearby consumer exists. Without a clearly identifiable local use case, assigning a meaningful oxygen market value would have introduced additional uncertainty into the model.

Hydrogen price proved to be the most important and influential parameter throughout the modelling process. Similar to the other economic inputs, the hydrogen price can only be treated as an estimated future market value. At the same time, hydrogen price assumptions strongly influence the economic viability of the entire system, while infrastructure investment costs simultaneously influence the achievable hydrogen price. This creates a circular dependency between infrastructure economics and market assumptions.

As a result, the primary objective of the simulations was not to determine an absolute “optimal” configuration, but rather to investigate the sensitivity of the system to changing hydrogen market conditions. The central research question became identifying the approximate hydrogen price range at which investment into hydrogen-related infrastructure could become economically justifiable. From this perspective, hydrogen price sensitivity represented one of the most critical aspects of the modelling workflow.

During the scenario execution phase, the hydrogen price and the temporal simulation resolution (“simulation step”) were varied systematically in order to observe their effects on the results. The remaining parameters were intentionally kept constant to improve comparability between scenarios and isolate the impact of these two variables.

Several runs and scenario variations were tested with different temporal resolutions and hydrogen pricing assumptions. The simulations demonstrated that time-step granularity significantly affects both the computational behavior and the interpretation of energy balancing results. Finer temporal resolution improves the realism of renewable intermittency representation but also increases computational complexity and data-processing requirements.

From a practical standpoint, the execution process revealed several technical and usability-related limitations. One of the most notable issues was the inconsistency in simulation runtime. Some scenario executions finished within approximately five minutes, while others required several hours to complete. Importantly, this variation could not be explained solely by the selected simulation step or model complexity. The absence of transparent runtime indicators made it difficult to assess whether the platform was functioning correctly during longer calculations.

For usability reasons, it would therefore be highly beneficial if the system displayed:

- the current progress of the simulation,
- estimated remaining runtime,

- or the active calculation stage.

Results and Key Findings

The simulation results demonstrated that the renewable energy surplus available in the Pécs region could theoretically support significant hydrogen production potential under different economic assumptions and operational configurations. The tested scenarios primarily focused on the impact of hydrogen market price and temporal simulation resolution on system sizing, renewable surplus utilization, and economic feasibility.

The results showed that hydrogen price is the most influential parameter in the overall system behavior. At lower hydrogen price assumptions (8 EUR/kg), the model was unable to justify major infrastructure investments economically, despite the existence of significant renewable surplus. In this scenario, the optimization produced unrealistic outputs, including zero-sized electrolyzer and battery capacities, indicating that the system could not economically support hydrogen production under these market conditions.

At higher hydrogen prices (12–15 EUR/kg), the simulations resulted in substantially larger electrolyzer and storage capacities, improved renewable surplus utilization, and significantly increased hydrogen production volumes. The 12 EUR/kg scenario produced the most realistic and balanced configuration, with approximately 76% renewable surplus utilization, an electrolyzer capacity of nearly 16 MW, and large-scale battery storage requirements exceeding 200 MWh. These results highlight the strong relationship between renewable intermittency and storage demand: as the system attempts to maximize hydrogen production from variable solar generation, balancing and storage capacities become increasingly important.

The simulations also demonstrated that high renewable surplus utilization does not automatically guarantee economically optimal operation. While the 15 EUR/kg scenario achieved over 92% surplus utilization and more than 1 million kg annual hydrogen production, the extremely low payback time and LCOH values suggest that the model becomes highly sensitive under very favorable market assumptions. Therefore, such results should be interpreted as theoretical optimization outcomes rather than directly achievable real-world business cases.

From a system operation perspective, the results emphasize that renewable hydrogen production is not driven solely by production potential, but by the interaction between renewable availability, electrolyzer utilization, storage flexibility, infrastructure costs, and future hydrogen market conditions. The modelling process showed that economically viable hydrogen systems require both sufficient renewable surplus energy and carefully optimized balancing infrastructure. Overall, the simulations confirmed that renewable-based hydrogen production could become technically feasible in the region, but its long-term economic viability remains highly dependent on future market development, infrastructure costs, and operational optimization.

Sensitivity and Scenario Comparison

The tested scenarios showed that hydrogen price is an important factor influencing the overall system performance and economic feasibility. Lower hydrogen price assumptions resulted in limited or economically unrealistic infrastructure development, while higher hydrogen prices led to larger electrolyzer capacities, increased storage demand, and higher renewable surplus utilization.

The simulations also demonstrated that increasing renewable surplus utilization requires significantly larger balancing and storage capacities due to the intermittent nature of solar generation. Changes in the simulation step affected the operational balancing behavior and the sizing of the infrastructure.

Overall, the results indicated that the system behavior is strongly influenced by:

- hydrogen market assumptions,
- renewable surplus availability,
- storage requirements,
- and infrastructure investment costs.

The scenario comparison highlighted that renewable hydrogen production is technically feasible, but highly sensitive to economic assumptions and operational configuration.

Challenges and Limitations

Several challenges and limitations were encountered during the implementation and testing of the modelling workflow. These barriers were related not only to data availability and model assumptions, but also to usability issues, workflow transparency, and institutional constraints.

One of the most significant challenges concerned data collection and accessibility. Reliable and harmonized local electricity consumption and photovoltaic (PV) generation data were not fully available during the project period. Since the electricity supply system of Pécs involves multiple service providers and network actors, obtaining unified datasets proved difficult and time-consuming. In particular, household-sized photovoltaic system (HMKE) data were not accessible with sufficient spatial and temporal resolution; therefore, several demand and production profiles had to be estimated or generated using AI-assisted methods. Although this enabled the continuation of the modelling process, the territorial accuracy and validation of these synthetic datasets remain uncertain.

Additional limitations emerged from the modelling approach itself. The model attempted to represent city-scale energy behavior using partially synthetic production and consumption profiles. While this allowed scenario testing, the lack of measured local datasets reduced the precision of spatial and temporal validation. A more robust future approach could involve the use of representative data points — for example, the largest 10–20 regional PV generation units — instead of relying solely on territorial aggregation. Such a method could also support future energy community–based data sharing and validation approaches.

Several usability-related issues were identified during platform testing. When duplicating a scenario, the associated CSV files were not copied automatically, requiring manual re-upload and increasing the risk of user error. In addition, the “project name” and “description” fields were not sufficiently emphasized within the interface, making it unclear that these fields should be completed. Introducing validation prompts or reminder messages before saving would improve usability and workflow consistency.

The visualization functionalities were generally useful; however, some limitations were identified. The surplus graph clearly illustrated periods of renewable overproduction and the annual total surplus energy. At the same time, the system did not display energy deficit periods, i.e., when renewable generation was insufficient to cover electricity demand. From both energy system and network operation perspectives, visualizing the deficit would provide important information regarding grid dependency, balancing requirements, and potential storage needs. The deficit could be represented as a separate curve, negative-axis values, or as part of a net energy balance visualization.

Practical workflow transparency also presented challenges. Scenario execution required a noticeable amount of processing time, but the platform did not provide feedback regarding calculation progress or expected runtime. As a result, users could not determine whether a simulation would take approximately two minutes or twenty minutes to complete. Introducing progress indicators or estimated completion times would substantially improve the overall user experience.

Another issue concerned notification functionality. Although the option to receive completed scenario results via email was selected, the system did not send the executed scenarios as expected. This reduced workflow reliability, especially in cases involving longer-running simulations or remote monitoring.

Some operational and platform stability issues were also experienced during the testing period. Login problems occurred multiple times, temporarily preventing access to the system. In addition, the platform was unavailable during a weekend maintenance/update period without sufficiently visible user notification. From a usability perspective, it would be beneficial if the system clearly indicated planned maintenance windows or temporary service interruptions so that users can distinguish between personal access problems and scheduled downtime.

Overall, the project demonstrated that urban-scale energy modelling is currently constrained less by computational capability and more by data accessibility, interoperability, and the practical usability of digital modelling platforms.

Lessons Learned

The modelling process showed that the tool is useful mainly for high-level estimation and early-stage hydrogen project planning. Since the model represents a larger territorial energy system and several parameters had to be estimated, the results should be interpreted as indicative values rather than precise engineering calculations.

The main strength of the platform is the ability to test how different assumptions — such as hydrogen price, storage size, or renewable surplus utilization — influence the overall system behavior. This makes the tool especially useful for sensitivity analysis and estimating orders of magnitude during the initial phase of project development.

At the same time, the large number of estimated input parameters introduces uncertainty into the results. Therefore, users should focus more on trends and scenario comparison than on exact numerical outputs.

From a usability perspective, one of the most important improvements would be proper scenario duplication. Currently, duplicated scenarios do not retain uploaded CSV files, meaning users must repeatedly upload and configure the same datasets. A fully functional duplication feature would significantly improve workflow efficiency and make parameter testing much easier.

4. Cross-Regional Comparison

The application of the Hydrogen Potential Model (HPM) across the three pilot regions – Mazovia (Poland), Šaleška (Slovenia), and Pécs (Hungary) – demonstrated that hydrogen development potential is highly dependent not only on technical parameters and renewable energy availability, but also on the broader regional ecosystem in which hydrogen projects are embedded. The pilots confirmed that the performance, relevance, and practical usefulness of hydrogen planning tools are strongly influenced by differences in energy systems, infrastructure endowments, institutional capacities, data availability, and local development priorities.

One of the most significant differences between the pilot regions concerns the scale and nature of hydrogen production potential. The Šaleška region had the highest theoretical production potential among the three cases, driven by the planned deployment of a large-scale 130 MWp floating photovoltaic installation on Družmirje Lake as part of the NAHV project. The modeling results showed that the introduction of this renewable generation capacity fundamentally changes the feasibility of hydrogen production, transforming a region with minimal current hydrogen potential into one capable of producing several hundred to several thousand tonnes of green hydrogen annually. Existing infrastructure associated with the TEŠ power plant, including grid connections, industrial land, water availability, and district heating infrastructure, further strengthens the long-term hydrogen opportunity.

In contrast, the Mazovian pilot focused on a dense urban environment centred around the Grochowski Hospital in Warsaw. Here, hydrogen was not primarily considered as a large-scale energy commodity but rather as a resilience and flexibility solution for critical infrastructure. The pilot demonstrated that hydrogen production potential remains relatively limited in urban areas where renewable generation capacity is constrained by space availability and where most renewable electricity is consumed directly on-site. However, the Warsaw case highlighted the strategic value of hydrogen for emergency power supply, energy security, and critical infrastructure resilience, particularly in light of evolving geopolitical risks.

The Pécs pilot occupied an intermediate position between the two extremes. The region possesses renewable energy resources and potential industrial hydrogen applications, but without the exceptional infrastructure advantages observed in Šaleška or the large institutional ecosystem available in Warsaw. The Pécs results illustrated the challenges faced by medium-sized regional centres attempting to develop hydrogen projects under conditions of limited surplus renewable generation and evolving market demand. At the same time, the pilot demonstrated the relevance of hydrogen as a future component of regional decarbonisation strategies, particularly in sectors where direct electrification may be difficult.

Data availability and quality emerged as a common challenge across all three pilot regions, although the nature of the challenge differed significantly. In both Šaleška and Mazovia, access to high-resolution electricity consumption data required extensive coordination with distribution system operators and local stakeholders. Data ownership rules, confidentiality concerns, and administrative procedures often delayed analysis. While both pilots ultimately benefited from real measured consumption data, considerable effort was required for data cleaning, harmonisation, and transformation before model execution.

The Pécs pilot encountered similar issues, reflecting a broader challenge for hydrogen planning in Central Europe. Across all regions, obtaining reliable, high-resolution energy data proved considerably more demanding than running the actual model simulations. The pilots collectively demonstrated that data preparation often represents the most time-consuming phase of hydrogen feasibility assessments. Furthermore, all three pilots relied to varying degrees on simulated renewable energy generation profiles, introducing additional uncertainty into the modelling results.

Economic feasibility varied substantially between the regions. In Šaleška, hydrogen production became increasingly attractive as renewable energy capacity expanded, with Levelized Cost of Hydrogen (LCOH) values approaching competitiveness under favourable assumptions. However, even in the most promising scenarios, public support mechanisms or concessional financing would likely be required in the near term. In Warsaw, the economic case was less dependent on hydrogen market competitiveness and more closely linked to resilience benefits, critical infrastructure protection, and environmental objectives. The project's value therefore extended beyond conventional financial indicators. The Pécs pilot similarly highlighted that hydrogen investments should often be evaluated within broader regional development and decarbonisation frameworks rather than solely through short-term financial returns.

Differences in legal and regulatory frameworks also influenced the interpretation of results. Although all three pilots operate within the overarching framework of European Union energy and climate policy, national implementation differs significantly. Slovenia's planned coal phase-out creates strong policy momentum for hydrogen-related transition projects in Šaleška. Poland's regulatory environment is increasingly supportive of hydrogen development, supported by national hydrogen strategies and strong industrial stakeholders such as ORLEN. Hungary's policy framework is also evolving, but regulatory uncertainty and market immaturity continue to influence investment decisions. These differences suggest that identical technical opportunities may lead to different implementation outcomes depending on national regulatory conditions.

Institutional readiness and stakeholder engagement were equally important determinants of project feasibility. Mazovia benefited from a particularly strong institutional ecosystem involving municipal authorities, energy utilities, research organizations, transport operators, and national government institutions. This provided a favorable environment for testing innovative hydrogen applications. Šaleška demonstrated a different form of readiness, rooted in the region's urgent need for post-coal economic transformation and the presence of organizations such as KSSENA capable of coordinating regional energy planning. In Pécs, stakeholder engagement highlighted the importance of local partnerships and regional development organizations in supporting future hydrogen initiatives.

Overall, the cross-regional comparison confirms that hydrogen potential cannot be assessed solely through resource availability or techno-economic modeling. The surrounding ecosystem – including infrastructure, governance, regulatory conditions, institutional capacity, data quality, and regional development priorities – plays a decisive role in determining whether hydrogen projects can progress from conceptual assessments to practical implementation. The HPM successfully captured many technical aspects of hydrogen feasibility, but the pilot experiences clearly demonstrate that interpretation of results must always be embedded within the broader regional context.

5. Overall Conclusions

The pilot applications carried out in Mazovia, Šaleška, and Pécs provide a valuable basis for evaluating the overall performance and practical usefulness of the Hydrogen Potential Model (HPM). Despite the considerable differences between the three regions, the pilots consistently demonstrated that the model can serve as an effective decision-support tool for preliminary hydrogen planning and strategic assessment.

The HPM successfully fulfilled its primary objective of enabling users to estimate hydrogen production potential, assess renewable energy utilisation, evaluate key techno-economic indicators, and compare alternative development scenarios. In all three pilots, the model helped identify critical factors influencing hydrogen feasibility and supported evidence-based discussions among regional stakeholders. The ability to analyse different renewable energy configurations, demand assumptions, and economic parameters proved particularly valuable for exploring future development pathways under uncertain conditions.

One of the model's greatest strengths is its relatively straightforward scenario-based approach. Users can combine real consumption profiles, renewable generation data, and economic assumptions to evaluate potential hydrogen systems under realistic regional conditions. This functionality was especially beneficial in Šaleška, where the model clearly demonstrated the transformative effect of the proposed floating photovoltaic project, and in Warsaw, where it helped quantify the limitations of the existing energy system while identifying opportunities for hydrogen-supported resilience solutions.

Another important strength is the model's flexibility across different regional contexts. The pilots covered highly diverse environments, including a post-coal industrial transition region, a large metropolitan area, and a regional urban centre. Despite these differences, the HPM was able to generate meaningful results in all cases. This suggests that the model possesses a sufficiently generic structure to support hydrogen planning across a wide range of territorial settings.

At the same time, the pilot experiences revealed several limitations that affect both usability and interpretation of results. The most frequently reported issue concerned scenario management and iterative analysis. In the Slovenian pilot, users noted that any modification of input parameters required the creation of a completely new scenario. This significantly reduced the efficiency of sensitivity testing and limited the model's usefulness during exploratory planning exercises. Similar concerns were raised during other pilots, where users often needed to repeat model runs following minor data corrections or assumption adjustments.

Another important weakness relates to transparency. The model provides key outputs such as hydrogen production volumes, LCOH, and payback periods, but offers limited visibility into intermediate calculation steps. Furthermore, results pages do not always display a comprehensive summary of the assumptions used during model execution. This complicates verification, documentation, and communication of results, particularly when multiple scenarios are analysed over extended periods.

The pilots also highlighted the model's dependence on input data quality. In practice, obtaining and preparing reliable data proved substantially more challenging than operating the model itself. High-quality outputs require high-quality inputs, and uncertainties associated with simulated renewable generation, assumed hydrogen demand, or incomplete infrastructure data inevitably influence the reliability of results. Consequently, model outputs should always be interpreted as indicative estimates rather than precise predictions.

Importantly, the pilots demonstrated that the HPM is most effective as a strategic planning instrument rather than an investment appraisal tool. The model can identify promising opportunities, compare development options, and support stakeholder discussions, but it cannot replace detailed engineering design, market analysis, financial due diligence, or regulatory assessment. This distinction is particularly important when interpreting favourable economic indicators produced under optimistic assumptions.

Overall, the three pilot applications confirm that the HPM provides a robust foundation for preliminary hydrogen feasibility assessment. It enables stakeholders to move beyond qualitative discussions and explore hydrogen opportunities using structured, data-driven methodologies. While several improvements would enhance its practical usability, the model already represents a valuable contribution to regional hydrogen planning. Its greatest value lies in supporting early-stage decision-making, identifying critical feasibility factors, and helping regions understand the conditions under which hydrogen may become a viable component of future energy systems.

6. Recommendations

Based on the experiences gained from the pilot applications in Mazovia, Šaleška, and Pécs, several recommendations can be formulated to improve both the HPM and the broader methodological framework supporting its use.

From a technical perspective, the most urgent improvement concerns scenario management functionality. Users should be able to **modify selected input parameters and rerun existing scenarios** without rebuilding entire model configurations from scratch. Such functionality would significantly improve efficiency during sensitivity analysis and encourage more extensive exploration of alternative assumptions. This recommendation emerged particularly strongly from the Slovenian pilot but is equally relevant for future users in all regions.

A second priority concerns transparency and traceability. The model should automatically **generate a comprehensive summary of all input assumptions** associated with each scenario and display this information alongside the results. Such functionality would improve reproducibility, facilitate stakeholder communication, and reduce the need for external documentation. In addition, providing access to selected intermediate calculation results would increase user confidence and support quality assurance processes.

Data handling capabilities could also be strengthened. Future versions of the HPM should include **enhanced tools for importing, validating, and preprocessing time-series datasets.** Automatic unit checking, data quality diagnostics, missing value detection, and format standardisation would reduce the workload associated with data preparation and minimise the risk of input errors. The Mazovia pilot demonstrated how significant data preparation efforts can become when datasets originate from multiple sources and use different formats.

User interface improvements should focus on accessibility and ease of use. Clear indications of expected units, improved guidance during data upload, enhanced visualisation of results, and interactive sensitivity analysis tools would make the model more attractive to practitioners who may not have extensive modelling experience. Given that many future users are likely to come from municipalities, regional agencies, and public administrations, usability should be considered a critical design objective.

Several methodological improvements should also be considered. The pilots revealed that hydrogen demand assumptions often represent one of the largest sources of uncertainty. Future applications would benefit from **more structured guidance on demand estimation**, including sector-specific demand profiles, reference values, and demand development pathways. This would help ensure greater consistency between regions and improve comparability of results.

Scenario design methodologies could similarly be strengthened. The most informative pilot results were obtained when scenarios reflected realistic local development pathways rather than purely theoretical configurations. Future guidance documents should therefore encourage close stakeholder involvement during scenario definition and **provide structured approaches for developing baseline, intermediate, and long-term scenarios**.

The pilot experiences also suggest that future model development should increasingly **consider sector coupling and system integration**. Hydrogen production does not occur in isolation but interacts with electricity systems, heat networks, transport infrastructure, industrial processes, and energy storage technologies. In Šaleška, for example, the potential use of district heating waste heat represents an important opportunity that is only partially captured by the current model. Similar integration opportunities exist in Pécs and Warsaw.

For this reason, the possibility of integrating the HPM with complementary planning tools should be explored. **Connections with renewable energy planning platforms, energy system models, GIS-based spatial planning tools, electricity network simulations, and carbon accounting frameworks** could significantly enhance the model's analytical capabilities. Such integration would enable more comprehensive assessments of hydrogen's role within broader regional energy transitions.

Finally, future development should continue to **emphasise the model's role as a decision-support tool rather than a deterministic forecasting instrument**. Clear interpretation guidance should accompany all outputs, highlighting assumptions, uncertainties, and limitations. This would help prevent overinterpretation of results and ensure that stakeholders use the model appropriately within broader planning and decision-making processes.