D5.5. A preliminary report on the methodology for replication

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Acronyms and abbreviations

IPCEIs	Important Projects of Common European Interest
H2Vs	Hydrogen Valleys
FT	Follower Territory
FCell	Hydrogen Fuel Cell
UX	User Experience
ECSIM	ElectroChemistry SIMulation Tools
FCEV	Fuel Cell Electric Vehicles
LCOH	Levelized Cost of Hydrogen
HRS	Hydrogen Refuelling Station
CAPEX	Capital Expenditures
OPEX	Operational Expenditures
PEM	Proton Exchange Membrane

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1 Executive Summary

This document, "D5.5. A Preliminary Report on the Methodology for Replication," is a comprehensive exploration of the strategies and methodologies pivotal for the successful replication of Hydrogen Valleys (H2Vs) in Europe. Hydrogen Valleys are integral to the EU's broader objectives of transitioning to a sustainable, low-carbon economy, enhancing industrial competitiveness, driving job creation and economic development, and bolstering energy independence and security.

The report delves into various aspects essential for the replication of H2Vs, including assessing the region's energy consumption, potential hydrogen demand, existing energy infrastructure, and the availability of renewable energy sources. It also scrutinizes the legal and regulatory framework and conducts a thorough financial analysis, including cost, revenue streams, and risk assessment. A key focus is on stakeholder engagement, recognizing its importance in ensuring the smooth implementation and operation of Hydrogen Valleys.

A significant contribution of this report is the introduction of an innovative software tool designed to assist in replicating H2Vs. This tool facilitates technical solutions, advanced techno-economic analysis, and provides vital data for stakeholder decision-making. It's an instrumental component in demonstrating the interoperability between different components of the hydrogen value chain.

The methodology outlined in the report is comprehensive, considering various elements like energy consumption patterns, renewable energy source potential, existing infrastructure, and future hydrogen demand trends. The financial and legal aspects are thoroughly analysed to ensure the viability and compliance of Hydrogen Valleys with EU standards.

2 Introduction

The development and replication of Hydrogen Valleys are gaining significant momentum in Europe and are poised to play a pivotal role in addressing several critical challenges facing the continent. These challenges include:

- **Climate Change Mitigation:**

  Hydrogen Valleys are integral to Europe's strategy for transitioning to a sustainable, low-carbon economy. As comprehensive ecosystems connecting hydrogen production, transportation, and use in various sectors, they represent a shift towards energy systems that can significantly reduce greenhouse gas emissions. Hydrogen's versatility in decarbonizing sectors that are hard to electrify, such as heavy industry and transport, positions it as a key enabler in curbing global warming.

- **Enhancing Industrial Competitiveness:**

  The push for Hydrogen Valleys is a strategic move to boost the competitiveness of the EU's renewable hydrogen industry. Large investments across the hydrogen value chain, facilitated by initiatives like Horizon Europe, are propelling technological advancements and industrial growth. These investments not only foster innovation but also create new market opportunities, placing Europe at the forefront of the emerging global hydrogen economy.

- **Job Creation and Economic Development:**

  Hydrogen Valleys are catalysts for job creation and opportunities in various sectors. By integrating research, innovation, and skill development, these projects offer new career paths and training opportunities, especially in the hydrogen industry. The European Commission’s commitment to doubling the number of operational Hydrogen Valleys by 2025 is a testament to their potential in driving economic development and job creation [1]. The investment in education and skills training, as highlighted by the allocation of funds under the Erasmus+ program for the hydrogen economy, further underscores this commitment [1] .

- **Energy Independence and Security:**

  In light of geopolitical challenges, such as the situation with Ukraine, the development of Hydrogen Valleys is also seen as a strategic asset in enhancing Europe's energy security. By reducing reliance on external fossil fuel supplies and moving towards self-sustaining energy ecosystems powered by renewable hydrogen, Hydrogen Valleys contribute to Europe’s broader energy independence and resilience goals. This is further supported by various EU programs offering investment opportunities in Hydrogen Valleys, such as the Recovery and Resilience Facility and the Cohesion policy funds [1] .

In summary, the replication of Hydrogen Valleys in the upcoming years is a multifaceted strategy addressing several urgent issues facing Europe. It represents a significant step towards a sustainable energy future, enhancing industrial competitiveness, creating jobs, and fortifying Europe's energy independence and security. The comprehensive approach, involving sustained investments and collaboration across sectors, underlines the EU's commitment to leveraging hydrogen technology for a more resilient and prosperous future.

Having established the pivotal role of Hydrogen Valleys in tackling Europe’s foremost challenges, it becomes essential to delve into the specific mechanisms and strategies that underpin this ambitious endeavour. The subsequent subsections will explore current European key initiatives in detail, illuminating how each contributes to the realization of robust and sustainable Hydrogen Valleys across Europe.

2.1 Renewable Energy Directive (RED III):

RED III's ambitious goal of 42.5% renewable energy consumption by 2030 directly supports the expansion of Hydrogen Valleys. These valleys, as hubs for renewable hydrogen production and use, are integral to achieving the industry, transport, and building sector targets set by RED III [2]. By fostering renewable energy, particularly hydrogen, RED III provides a regulatory backbone that encourages the development and scalability of Hydrogen Valleys across Europe.

2.2 EU's Geopolitical Response and Energy Security:

The urgency to enhance energy security following the Ukraine conflict propels the significance of Hydrogen Valleys. These valleys serve as strategic assets in diversifying Europe's energy sources, reducing reliance on external fossil fuel supplies. They represent a shift towards self-sustaining energy ecosystems, powered by renewable hydrogen, thereby contributing to the EU’s broader energy independence and resilience goals.

2.3 Investment Initiatives and Strategic Projects:

The IPCEIs on hydrogen play a crucial role in driving technological and infrastructural advancements within Hydrogen Valleys [3] . By facilitating the development of cutting-edge technologies and establishing robust hydrogen infrastructure, these initiatives lay the groundwork for the efficient operation and expansion of Hydrogen Valleys. They ensure these valleys are equipped with the necessary tools and systems to thrive as innovative energy hubs.

2.4 The REPowerEU Plan and Hydrogen Acceleration:

REPowerEU's [4] focus on scaling up renewable hydrogen production aligns with the core objectives of Hydrogen Valleys. The plan's ambition to produce and import significant amounts of renewable hydrogen by 2030 underpins the growth of Hydrogen Valleys, ensuring a steady supply of clean energy. This also accelerates the integration of hydrogen in hard-to-decarbonize sectors, showcasing the versatility and potential of Hydrogen Valleys in the broader energy landscape.

2.5 The European Hydrogen Bank Initiative:

The establishment of the European Hydrogen Bank is pivotal for the financial viability of Hydrogen Valleys [5] . By providing investment security and funding opportunities, this initiative enables the practical realization of Hydrogen Valleys. It supports the development of hydrogen projects across the value chain, from production to end-use, ensuring that Hydrogen Valleys have the financial backing to develop, expand, and connect across regions, thus fostering a robust and interconnected hydrogen economy in Europe:

- **Investment Security**: The European Hydrogen Bank (EHB) is designed to stimulate and support investment in sustainable hydrogen production. This initiative is integral to the EU's strategy to achieve climate-neutrality by 2050 and aims to accelerate investment to meet ambitious targets, such as producing 10 million tonnes of renewable hydrogen domestically by 2030.
- **Addressing Initial Financial Challenges**: The EHB addresses initial financial challenges to create a burgeoning renewable hydrogen market. It offers support during the early stages of hydrogen projects, many of which are still in the planning phase, ensuring that these initiatives can progress from concept to reality.
- **Reducing Cost Gaps**: The EHB aims to cover and lower the cost gap between renewable hydrogen and fossil fuels. An auction system for renewable hydrogen production is planned, offering fixed price payment per kg of hydrogen produced, thereby supporting producers for up to 10 years of operation. This financial mechanism is crucial for early projects to be viable and competitive.
- **Leveraging Private Investment**: To meet the REPowerEU plan's goals, substantial investment is needed, estimated at €335-471 billion. While the majority of funding is expected from private sources, public funding through EU financial instruments plays a

significant role in attracting and leveraging these private investments. The EHB streamlines access to these instruments for member states and project developers, making it easier to secure necessary funding across the hydrogen supply chain.

- **International Collaboration and Market Development**: The EHB also has an international dimension, supporting EU partner countries in their green transition efforts and renewable energy investments. It aids in developing reliable supply chains and rules-based international hydrogen markets, essential for the global advancement of hydrogen technologies.

2.6 Hydrogen Europe Research Association's Strategic Roadmaps:

The Clean Hydrogen Partnership, a continuation of the successful FCH JU and FCH 2 JU, aims to support research and innovation in clean hydrogen solutions. This aligns with the strategic goal of Hydrogen Valleys [6] , which is to demonstrate the interoperability and synergy between all aspects of the hydrogen value chain. By advancing hydrogen technologies and applications, the Clean Hydrogen Partnership contributes significantly to the development and scaling up of Hydrogen Valleys, ensuring they meet the EU's 2030 energy and climate targets and ultimately the goal of climate neutrality by 2050.

Each of these elements contributes to a conducive environment for the development and replication of Hydrogen Valleys, ensuring that these regional ecosystems can effectively drive Europe's transition to a sustainable and secure energy future.

2.7 A software tool to help with the H2Vs Replication

Therefore, the introduction of software tools for replicating and understanding Hydrogen Valleys is a crucial aspect in the strategic development of these comprehensive hydrogen ecosystems across Europe. The Replicability tool, that will result from this project, offers significant benefits:

2.7.1 Technical Solutions and Techno-economic Analysis:

Software tools like the Replicability Tool presented by the Aragon Hydrogen Foundation provide technical solutions and enable advanced techno-economic analysis for Hydrogen Valleys. It will allow for detailed simulations of hydrogen ecosystems, facilitating a deeper understanding of their operational dynamics and economic viability. This capability is essential for ensuring that the replication of Hydrogen Valleys is both feasible and profitable.

2.7.2 Facilitation of Replication:

That tool is an innovative instrument that ease the replication of Hydrogen Valleys in various territories. It will provide essential data and insights that can guarantee the investment required for establishing a Hydrogen Valley. This is particularly important in assessing and mitigating risks associated with such significant investments, ensuring that new Hydrogen Valleys are set up efficiently and effectively.

2.7.3 Case Study Applications and Demonstrations:

The application of that tool in case studies demonstrates their practical utility. It will be able to quantify potential hydrogen production from various renewable sources, like offshore wind energy, providing tangible evidence of the productivity and sustainability of Hydrogen Valleys.

The development of such software tool aligns with the broader objectives of the Clean Hydrogen Joint Undertaking and the strategic roadmaps set by the Hydrogen Europe Research Association. That tool is instrumental in demonstrating the interoperability and synergy between different components of the hydrogen value chain and other energy systems, thus playing a key role in advancing the European Hydrogen Economy.

3 Methodology for Replication

To replicate Hydrogen Valleys in mainland regions, a detailed feasibility study is crucial, entailing:

1. Energy Consumption and Renewable Resource Assessment: Evaluate the region's energy usage and the availability of renewable energy sources.
2. Existing Energy Infrastructure Evaluation: Analyse the current energy infrastructure for potential integration with hydrogen technologies.
3. Hydrogen Demand Analysis: Determine the potential demand for hydrogen within the region.

The study should then delve too into:

4. Legal and Regulatory Framework Review: Assess the legal and regulatory environment influencing the project.
5. Financial Analysis: Conduct a financial assessment covering costs and potential revenue streams.
6. Risk Assessment: Identify and evaluate risks, including environmental, legal, and regulatory factors.
7. Stakeholders' engagement.

The study aims to provide:

- Insights into the project's financial and technical feasibility.
- An overview of the benefits, including employment generation, CO2 emission reduction, and broader socio-economic impacts.
- A comprehensive understanding of potential risks for informed decision-making.

3.1 Energy consumption and availability of renewable energy sources in the region

Embarking on the journey of replicating Hydrogen Valleys, it is necessary to delve into a meticulous examination of the region's energy dynamics:

3.1.1 Analysing the energy mix

This section will include an assessment of the current energy mix of the region, including the proportion of energy that is generated from renewable sources. This will help to understand the current state of the region's energy system and identify areas where improvements can be made by means of green H2 technologies.

Guideline:

- The first step is **to identify the sources of energy** that are currently being used in the region. This may include conventional sources such as fossil fuels (e.g. oil, coal, and natural gas), as well as renewable sources such as wind, solar, hydropower, geothermal, others, etc.
- Once it has been identified the sources of energy, it will be **determined the share of each energy source in the overall energy mix** of the region. This can be done by calculating the percentage of energy that is generated from each source, based on data from energy production and consumption.
- **Analysing trends in the energy mix over time**. This can be done by comparing data from different years or time periods to identify changes in the share of each energy source.

  This should include:
  - projections for both the short-term and long-term future, and
  - take into account factors such as population growth,
  - economic development, and
  - technological advancements.

  This will help to understand how the energy mix has evolved over time and identify potential drivers of change.
- **Assess the sustainability of the current energy mix** by evaluating the environmental and economic impacts of each energy source.

  This may include factors such as:
  - greenhouse gas emissions,
  - air and water pollution, and
  - the cost of production and distribution.

  Identify any sources of energy that may pose a risk to the environment or be economically unsustainable in the long term.
- **Identify opportunities for improvement:**

  This may include:
  - increasing the share of renewable energy sources,
  - improving energy efficiency, or
  - transitioning to alternative fuels such as hydrogen.

Overall, analysing the energy mix in the region is an important step in determining the feasibility of a Hydrogen Valley project. It will help to understand the current state of the energy system and identify areas where improvements can be made. By considering the sustainability of the energy mix and identifying opportunities for improvement, it can be developed a more informed strategy for transitioning to a more sustainable and renewable energy system.

3.1.2 Identify and gather other relevant data

Information collection on the current and future energy consumption patterns of the region. This may include data on:

- the region's electricity demand,
- seasonal variations in energy demand,
- and energy consumption trends.

3.1.3 Research availability of renewable energy sources and determine their potential

This section will include the identification and research of the renewable energy sources available in the region. This may include:

- wind,
- solar,
- hydropower,
- geothermal energy,
- etc,

The potential capacity of each renewable energy source and its suitability for meeting the energy demand of the region should be assessed. Also, it should be done research of the existing renewable energy infrastructure in the region, such as wind turbines and solar panels.

3.1.4 Identification of any gaps and challenges

Gaps or challenges that may impact the feasibility of using renewable energy sources to meet the energy demand of the region. This may include:

- technical limitations,
- environmental concerns, or
- regulatory barriers,
- assessment of the potential costs and benefits of transitioning to a renewable energy system.

This information will help to understand the energy landscape of the region and determine the potential for using hydrogen as a renewable energy carrier.

3.2 Existing energy infrastructure

Data should also be collected on the existing energy infrastructure on the region, including:

- the electricity grid,
- gas network, and
- any other relevant infrastructure.

The data on the existing energy infrastructure will provide insights into how the hydrogen valley project can be integrated with the existing infrastructure. This will help identify opportunities to use existing infrastructure, such as pipelines and storage facilities, to minimize the capital costs associated with building new infrastructure.

This information will be crucial in determining the feasibility of building and operating a hydrogen valley in the region.

3.3 The potential hydrogen demand and future trends

Research the potential demand for hydrogen in the region, including potential customers such as:

- transport companies,
- industrial users (feedstock, thermal loads, etc), and
- public authorities.
- residential.

This will help to estimate the size of the market and determine the required capacity of the hydrogen valley.

Nonetheless, market and industry trends will help to identify potential opportunities and challenges associated with the project, this will include research on:

- Government policies and incentives,
- technological advancements, and
- market forecasts.

3.4 Legal and regulatory framework

As we embark on the ambitious journey of replicating a Hydrogen Valley, it is critical to recognize that the legal and regulatory framework forms the backbone of our project's feasibility and success. This landscape is not just a checklist of compliance requirements; it is a dynamic ecosystem that shapes how we approach hydrogen production, storage, distribution, and integration into the energy market. Understanding and navigating this framework is not only about adhering to the rules—it's about aligning our project with the broader objectives and values of the European Union, particularly in terms of environmental sustainability, energy security, and market innovation.

The Importance of a Comprehensive Legal and Regulatory Assessment

The legal and regulatory environment in which a Hydrogen Valley operates is intricate and multi-faceted. It encompasses everything from environmental protection standards and safety regulations to market access rules and cross-border trade considerations. A thorough assessment of this framework is crucial for several reasons:

- **Risk Mitigation**: Identifying potential legal and regulatory barriers early in the project can prevent costly delays and redesigns. It ensures that the project progresses smoothly, without encountering unforeseen compliance issues.

- **Strategic Planning**: Understanding the regulatory landscape helps in strategic decision-making. It allows us to choose locations, technologies, and business models that are not only compliant but also advantageous within the given legal context.

- **Stakeholder Confidence**: Demonstrating a deep understanding of and compliance with legal and regulatory requirements builds trust among stakeholders, including investors, partners, and regulatory bodies. It shows that the project is credible, reliable, and aligned with EU standards.

Conducting the Assessment

To conduct a successful legal and regulatory assessment for replicating a Hydrogen Valley, the following steps are recommended:

- **In-depth Research**: Start with a comprehensive analysis of all relevant EU directives, such as the Industrial Emissions Directive, Renewable Energy Directive, Seveso Directive, and others that impact hydrogen production and distribution. This research should be extended to national and local regulations of the region where the Hydrogen Valley is planned.

- **Engagement with Regulatory Bodies**: Active engagement with EU and national regulatory bodies is essential. This not only helps in obtaining accurate and up-to-date information but also in advocating for regulatory changes that can support innovative hydrogen technologies.
- **Legal Expertise**: Collaborate with legal experts specializing in energy law to interpret complex regulations and assess their implications for the project. This expertise is invaluable in navigating the legal nuances and ensuring full compliance.
- **Monitoring and Adaptation**: The regulatory landscape is not static. Continuous monitoring of legislative developments is necessary to adapt the project strategy as needed. This proactive approach can identify opportunities presented by new regulations or subsidies.
- **Cross-Border Coordination**: For Hydrogen Valleys spanning multiple jurisdictions, coordinate closely to understand and harmonize different legal requirements. This is crucial for ensuring seamless operation across borders.

3.5 Financial Analysis: cost and revenue streams

This analysis will consist in an assessment of the costs associated with building and operating a hydrogen valley in the region, including the costs of hydrogen production, storage, and distribution.

Additionally, research on the potential revenue streams should be done, such as sales:

- to industrial customers,
- public authorities, and
- transport companies, as well as
- the potential for exporting hydrogen to other regions.

The financial landscape of replicating a Hydrogen Valley encompasses a spectrum of costs associated with its establishment and operation, including hydrogen production, storage, and distribution, as well as diverse revenue streams as mentioned above.

To rigorously assess these financial dimensions, our methodology delves into a comprehensive Cost Analysis, evaluating Capital and Operational Expenditures, and Decommissioning Costs. Equally critical is the Revenue Stream Analysis, which involves estimating direct and indirect revenues and conducting a thorough Market Analysis. This is complemented by Financial Modelling and Projections to evaluate economic viability, alongside strategies for Funding and Financing, and an Economic Impact Analysis to gauge the broader regional effects. Each of these components is crucial for constructing a detailed financial picture that supports the strategic decision-making necessary for the successful replication of Hydrogen Valleys.

Cost Analysis:

- Capital Expenditure Assessment: Compile a detailed inventory of initial investment costs, including infrastructure, technology procurement, and land acquisition.
- Operational Expenditure Analysis: Conduct ongoing reviews of operational costs encompassing maintenance, labour, utilities, and administrative expenses.
- Decommissioning Cost Projection: Forecast future costs related to the dismantling and recycling of Hydrogen Valley infrastructure upon project conclusion.

Revenue Stream Analysis:

- Direct Revenue Estimation: Analyse potential income from hydrogen sales to diverse sectors, including industrial, public, and transport sectors.
- Indirect Revenue Exploration: Investigate potential revenue from carbon credits, government incentives, and strategic partnerships.
- Market **Analysis**: Perform a thorough market analysis to understand demand trends.

Financial Modelling and Projections:

- Develop and refine financial models to project cash flows, assess profitability, and identify break-even points. Incorporate sensitivity analysis to evaluate the impact of variable market and operational conditions.

Funding and Financing Strategies:

- Identify and evaluate potential funding sources, including grants, loans, equity investments, and public-private partnerships. Formulate strategies to effectively secure these financial resources.

Economic Impact Analysis:

- Assess the broader economic impact of the Hydrogen Valley on local and regional economies, focusing on job creation, industrial growth, and economic development.

3.6 Risk assessment

This section aims to identify and evaluate a range of risks, encompassing environmental, legal, and regulatory challenges, as well as potential technical and financial risks, including the aspect of social acceptance.

This represents an ambitious goal, yet it aligns perfectly with the European endeavour concerning Hydrogen Valleys. There's a need for innovative and ambitious methods to secure investments and, consequently, to foster the advent of the Hydrogen Economy.

It has to be said that the quality of the results of this section will depend to a large extent on the information that can be collected through the Follower Territories. Mainly on what has been demonstrated so far in HEAVENN, but also in other H2Vs, which is the financial risk and the administrative and regulatory risk.

3.7 Stakeholder engagement

Engaging with stakeholders, including local authorities, businesses, and communities, is crucial for gaining support and understanding their needs and concerns. Stakeholder engagement in Hydrogen Valley projects is not just a procedural step; it's a strategic approach that enriches the project with diverse insights and fosters a cooperative environment. By systematically engaging with stakeholders, the project not only enhances its viability but also contributes to building a more inclusive and sustainable energy future.

3.7.1 Importance of Stakeholder Engagement

Stakeholder engagement is pivotal for multiple reasons:

- Building Support and Trust: Engagement with stakeholders fosters trust and support, crucial for the smooth implementation and operation of Hydrogen Valleys.
- Informed Decision-Making: Understanding the perspectives and concerns of various stakeholders’ aids in making informed decisions that are more likely to be accepted and supported.
- Risk Mitigation: Early identification of potential issues through stakeholder feedback can help mitigate risks before they escalate. Additionally, it is essential to implement an iterative process of risk review throughout the entire project. This ongoing evaluation ensures that emerging risks are promptly addressed and that the project adapts to evolving circumstances, thereby safeguarding its successful execution and alignment with objectives.
- Community Integration and Social License: Gaining the social license to operate by ensuring the project aligns with community values and expectations is key to long-term success.

3.7.2 Engagement Methodology

Identification of Stakeholders:

- Mapping: Create a comprehensive map of all potential stakeholders, categorizing them based on their influence, interest, and potential impact on the project.

Engagement Planning:

- Strategy Development: Develop a tailored engagement strategy for each stakeholder group. This includes setting clear objectives, choosing appropriate communication channels, and determining the frequency of engagement activities.

  By prioritizing stakeholder engagement in the pre-deployment phase, Hydrogen Valley projects can ensure that they are aligned with the needs and expectations of all involved parties, paving the way for a smoother deployment phase and ultimately contributing to the project's success.

  This process involves setting clear objectives, selecting suitable communication channels, and determining the frequency of engagement activities:

Execution of Engagement Activities:

- Local Authorities: Collaborate through formal meetings and workshops to align the project with regulatory requirements and local development plans.
- Businesses: Engage with local and industry businesses through networking events, industry forums, and direct consultations to explore collaboration opportunities and address industry-specific concerns.
- Communities: Conduct public forums, town hall meetings, and social media engagements to gather community input, disseminate project information, and address public concerns.

Feedback Integration and Adaptation:

- Feedback Mechanism: Establish a feedback mechanism to collect and analyse stakeholder input.
- Adaptation: Use the gathered insights to adapt project strategies and operations, ensuring they align with stakeholder expectations and needs.

Continuous Monitoring and Reporting:

- Ongoing Interaction: Maintain regular communication with stakeholders to keep them informed about project progress and developments.
- Reporting: Provide transparent reports on how stakeholder feedback has been integrated into the project.

4 Conclusions

The findings of this report underscore the potential of Hydrogen Valleys as a critical component in Europe's transition to a sustainable energy future. The detailed methodologies and analysis presented provide a clear roadmap for replicating H2Vs effectively across different regions. The innovative software tool developed plays a crucial role in this process, offering the necessary technical and economic insights for successful implementation.

The report highlights the need for continuous stakeholder engagement and the importance of a comprehensive legal and regulatory assessment to navigate the complex landscape successfully. The financial analysis elucidates the economic feasibility and the potential for sustainable growth in the hydrogen sector.

In conclusion, the successful replication of Hydrogen Valleys, as detailed in this report, represents a significant stride towards achieving Europe's goals of a resilient, sustainable, and competitive energy future. The methodologies and tools presented herein are not only instrumental in realizing these ambitions but also set a precedent for global initiatives in sustainable energy development.

5 Appendix I: the upgraded "Replicability Tool"

As the HEAVENN hub transitions towards a more intricate Hydrogen Valley framework, the enhanced tool must adapt to encapsulate this evolving complexity, yet retain its user-friendliness. In light of this, FHa initiated a "Follower Territory Survey" aimed at gaining deeper insights into the energy landscape of Follower Territories (FTs) and the awareness level of end-users regarding hydrogen technologies and simulation tools.

The finalized survey, detailed in Appendix II and conducted by Northwest Germany (EWE), Denmark (HVDK), and Ireland (HyE), has enabled FHa to pinpoint specific areas needing enhancement. Figure 1 provides a concise overview of these improvement domains, particularly highlighting the need for simplified regional data collection, increased customization options for users, and the integration of additional models.

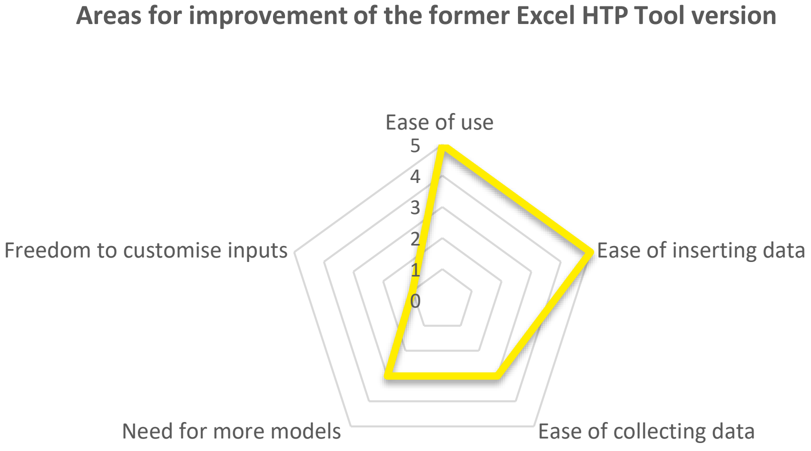


Figure 1. Diagram illustrating potential enhancement areas for the original Excel HTP Tool, as identified from the Survey results.

Key findings from the Follower Territory Survey are summarized as follows:

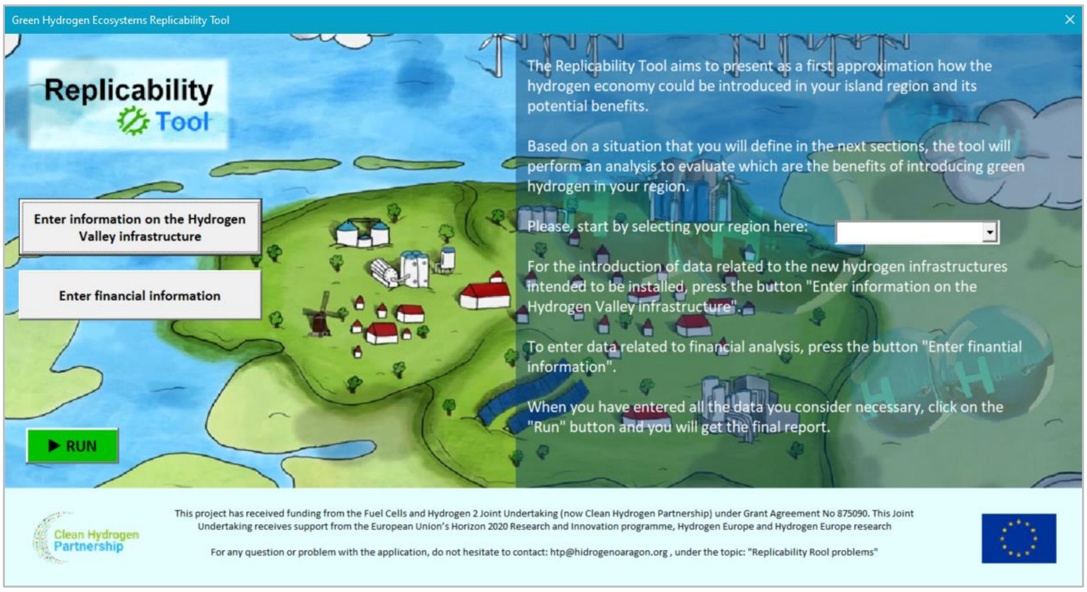
- The case studies display a high degree of heterogeneity, with common characteristics including significant renewable energy curtailments.
- Concerns are prevalent regarding safety issues.

- A diverse spectrum of skills and varying levels of experience with hydrogen exist among FTs users.

Additionally, several enhancements were proposed to improve the tool:

- Facilitate ease of use for individuals with limited IT or hydrogen technology expertise, and those unfamiliar with the energy sector.
- Allow users to develop distinct scenarios tailored to their specific island contexts.
- Provide capabilities for inputting regional data and sizing infrastructure requirements.
- Incorporate options for entering financial aids such as co-funding, subsidies, and loans.
- Offer more comprehensive results interpretation, including job creation statistics, flow charts, etc.

In response to this valuable input, FHa will utilize the feedback to refine and develop a more accessible and user-friendly tool for a broader user base.



The Replicability Tool aims to present as a first approximation how the hydrogen economy could be introduced in your island region and its potential benefits.

Based on a situation that you will define in the next sections, the tool will perform an analysis to evaluate which are the benefits of introducing green hydrogen in your region.

Please, start by selecting your region here:

For the introduction of data related to the new hydrogen infrastructures intended to be installed, press the button "Enter information on the Hydrogen Valley infrastructure".

To enter data related to financial analysis, press the button "Enter finantial information".

When you have entered all the data you consider necessary, click on the "Run" button and you will get the final report.

This project has received funding from the Fuel Cells and Hydrogen 2 Joint Undertaking (now Clean Hydrogen Partnership) under Grant Agreement No 875090. This Joint Undertaking receives support from the European Union's Horizon 2020 Research and Innovation programme, Hydrogen Europe and Hydrogen Europe research

For any question or problem with the application, do not hesitate to contact: htp@hidrogenoaragon.org , under the topic: "Replicability Rool problems"

Figure 2. Screenshot of the initial window with the design of the new development being done on the Replicability Tool.

Before proceeding with the development of the tool, it is important to note that the upcoming models presented in the following sections will fall into two distinct categories:

a. Those cases of models imported from proven reputation public repositories on the Internet. That is, **open-source models**, based on Python, from websites like NREL Github chanel, or related with papers presented in recognised journals like IEEE (with MIT license [7]). An example of this is "*SoDa: An Irradiance-Based Synthetic Solar Data Generation Tool*" [8], which exemplifies the calibre of resources utilized.

b. In scenarios where open-source models are unavailable, the approach will shift to utilizing a **simplified model** derived from the corresponding Sankey diagram.

Building upon the foundation laid out at the start of this document, addressing the tangible need for software tools that instil confidence in both hydrogen project developers and their investors became imperative. This necessity called for a significant enhancement in the precision and rigor of the new tool. Substantial efforts have been invested in integrating more advanced models, developed by renowned international organizations, with the existing Excel-based tool (VBA). Consequently, this evolution marks a transition from a solitary application framework to a contemporary, dual-component system: a Frontend (Excel) coupled with a Backend (Python).

5.1.1 Techno-economic modelling of a Hydrogen Valley

To achieve successful replication, the model's programming will adhere to the subsequent logic:

- Initially, it will quantify the hydrogen needs within the Hydrogen Valley.
- The algorithm's primary goal will be to fulfil these hydrogen requirements through production via electrolysers situated within the Hydrogen Valley.
- A critical aspect will be the integration of logistics in the programming, bridging the gap between demand and production.

Figure 3 illustrates this logic in the form of a Sankey diagram, visually representing the diverse energy flows from production to end-use applications. As previously noted, the enhanced tool is designed to improve user experience and clarify the underlying computations. Therefore, diagrams like these will be incorporated into the tool's reports, enabling users to pinpoint potential system inefficiencies and comprehend the energy management processes.

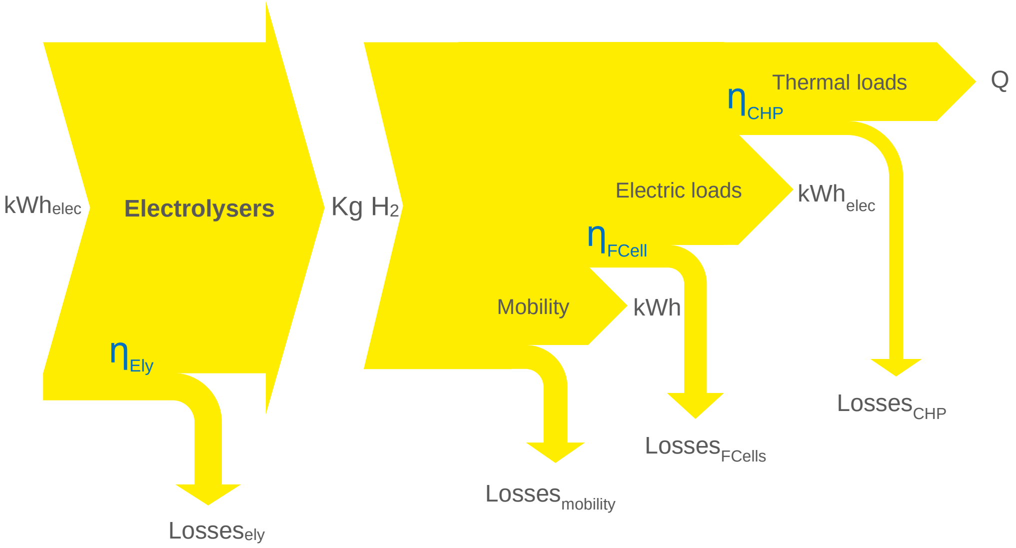


Figure 3. Energy flow Sankey diagram depicting a typical Hydrogen Valley setup.

$$\boxed{H_2\ Demand\ \left(\frac{kg\ H_2}{year}\right) = D_{Mobility} + D_{Elec} + D_{Therm} + D_{Blending} + \cdots} \quad (1)$$

Where:

$D_{Mobility}$ = hydrogen demand from fuel cell mobility applications (heavy transport, vans, buses, vehicle fleets, etc.)

D_{Elec} = hydrogen demand from fuel cells that will power electrical loads.

D_{Therm} = hydrogen demand corresponding to that part of hydrogen consumed by a CHP fuel cell to meet heat demands.

$D_{Blending}$ = hydrogen demand corresponding to green hydrogen kilograms injected into the natural gas network.

η_{Ely} = electrolyser performance.

η_{FCell} = performance of fuel cells providing only electrical energy.

η_{CHP} = thermal performance of fuel cells providing CHP.

Losses = energy lost in any energy transformation that takes place along the hydrogen value chain.

kWh_{elec} = electrical energy input (to the electrolyser(s) plant) from renewable energies (directly or indirectly through PPAs).

Q = thermal energy load (kWh).

Note:

Prior to delving into the various elements of the HEAVENN hydrogen valley, **it is essential to revisit the evolution that the valley has undergone from its initial concept as outlined in the Grant Agreement**. Presently, the production side of the valley includes components that diverge from the initial focus on promoting electrolysis technologies. An example of this is the generation of hydrogen as a byproduct from a chlor-alkali facility at the Delfzijl chemical park. Consequently, the development of this tool, aimed at fostering new Hydrogen Valleys and catalysing the growth of the electrolyser and fuel cell industry, will **primarily concentrate on modelling the systems originally envisioned in the Grant Agreement**. It is important to note that **the validation of these models will predominantly rely on literature sources, given that the HEAVENN project will not have access to the necessary operational data for their empirical verification**.

ELEMENTS OF THE YEARLY HYDROGEN CONSUMPTION

Electric loads (Fuel Cells):

Hydrogen fuel cells represent a technology that generates electrical power by merging hydrogen with oxygen, producing electricity through a chemical reaction, where water vapor is the sole byproduct. These fuel cells are emerging as a clean, efficient substitute for traditional generators powered by fossil fuels, owing to their zero emissions of greenhouse gases and pollutants. In the realm of electric power, hydrogen fuel cells find diverse applications, including providing electricity for buildings (i.e. a Data Centre in HEAVENN), vehicles, and remote areas without grid access. The Sankey diagram depicted in Figure 4 provides a visual representation of energy flows within fuel cells, specifically those used for meeting electrical load demands.

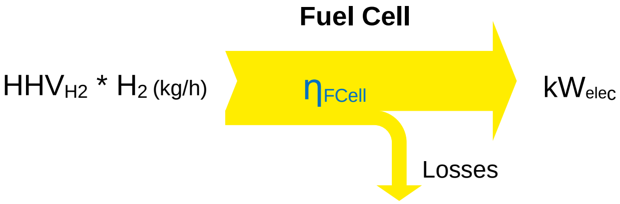


Figure 4. Sankey diagram of a generic fuel cell application.

The diagram leads to the formulation of an equation that can be employed to calculate the hydrogen demand required by these fuel cells.

$$Power\ (kW_{elec}) = \eta_{FCell}\left(\dot{m}_{H2}\left(\frac{kg}{h}\right) * HHV_{H2}\left(\frac{kWh}{kg}\right)\right) \tag{2}$$

Where:

kW$_{elec}$ = electric power demand.

η$_{FCell}$ = performance of the fuel cell (providing only electrical power).

$\dot{m}_{H2}$ = hydrogen mass flow consumed by the fuel cell.

HHV$_{H2}$ = High Heating Value of the hydrogen molecule.

Then, the annual electric energy demand corresponds:

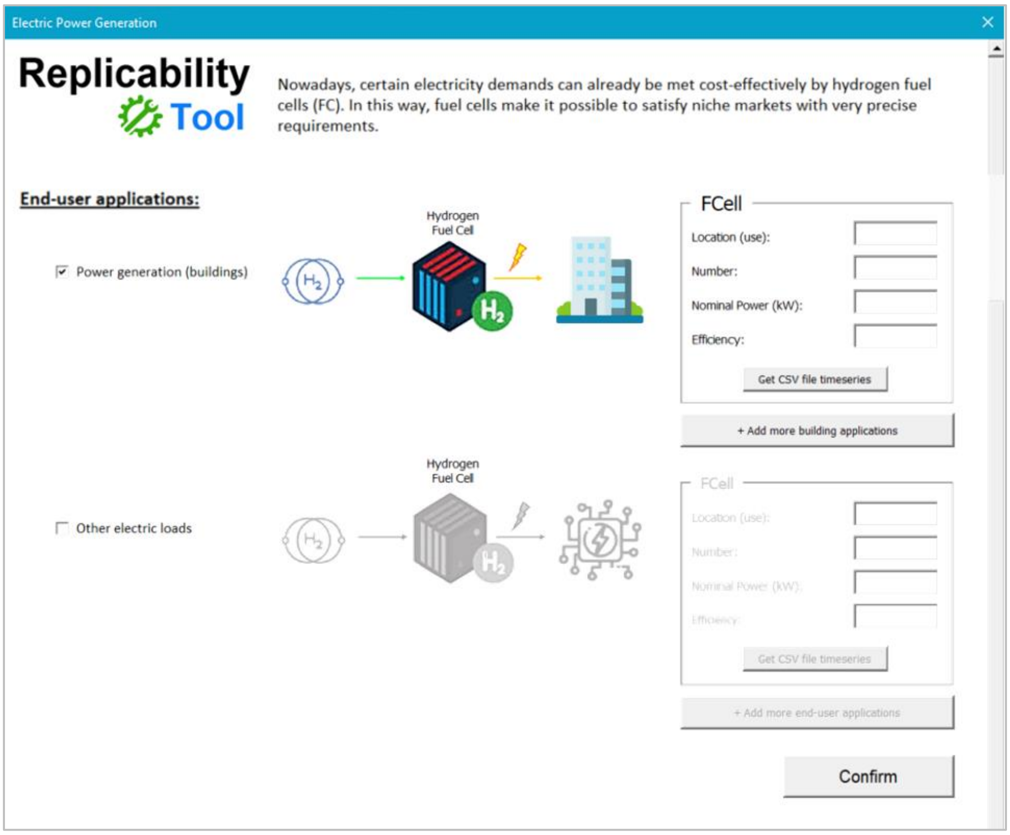
$$\sum_{i=1}^{hours\ per\ year}\left(Power_i\ (kW_{elec})\right) = \eta_{FCell} * \sum_{i=1}^{hours\ per\ year}\left(\dot{m}_{H2}\left(\frac{kg}{h}\right) * HHV_{H2}\left(\frac{kWh}{kg}\right)\right) \tag{3}$$

Therefore, the hydrogen demand can now be cleared from (3):

$$\boxed{\dot{m}_{H2}\left(\frac{kg}{h}\right) = \frac{\sum_{i=1}^{8760 hours}\left(Power_i\ (kW_{elec})\right)}{HHV_{H2}\ (kWh/kg) * \eta_{FCell}}} \tag{4}$$

Here below, Figure 5 shows an example of the Replicability Tool interface where the user could enter the hourly time series of the annual electric power demand for the desired application.

$$\sum_{i=1}^{8760}\left(Power_i\ (kW_{elec})\right) \tag{5}$$


Electric Power Generation

Replicability Tool

Nowadays, certain electricity demands can already be met cost-effectively by hydrogen fuel cells (FC). In this way, fuel cells make it possible to satisfy niche markets with very precise requirements.

End-user applications:

☑ Power generation (buildings)

FCell
Location (use):
Number:
Nominal Power (kW):
Efficiency:

☐ Other electric loads

FCell
Location (use):
Number:
Nominal Power (kW):
Efficiency:

Figure 5. Interface of the tab for entering the data relating to the electrical loads to be supported by the fuel cells.

This new addition, designed to meet the Follower Territories' requirements for user-friendliness and enhanced user experience (UX), allows users to input real-time electric demand series or more refined data (refer to Figure 6). This feature facilitates more accurate simulations of the respective Hydrogen Valley.

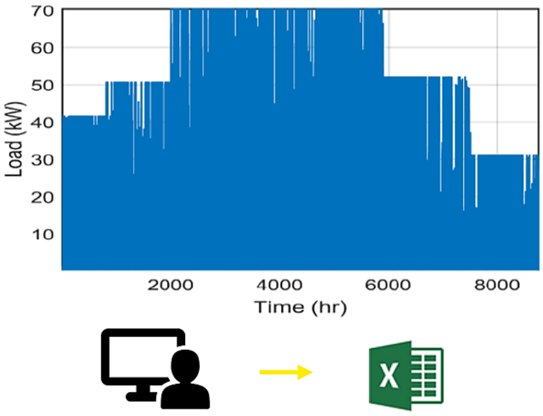


Figure 6. Illustration of an annual seasonal load curve measured hourly with a peak demand of 70 kW. This load curve can be seamlessly incorporated through the interface of the updated Replicability Tool.

As highlighted in the aforementioned “Note”, the final model for Fuel Cells (FCells) is subject to potential modifications upon discovery of reliable open-source models. Indeed, various candidate codes have been identified and are currently under evaluation for their potential integration into the tool:

- ECSIM [9] / OPEM: “The Open-Source PEMFC Simulation Tool (OPEM) is a modelling tool for evaluating the performance of proton exchange membrane fuel cells. This package is a combination of models (static/dynamic) that predict the optimum operating parameters of PEMFC” [10], [11].
- NREL / SAM (System Advisory Model) / SAM_Fuelcell [12].

Table 1 displays the technical and economic parameters that users can input to characterize fuel cells. It should be noted that this list of parameters may undergo revisions in line with the ongoing enhancements of the tool, reflecting the iterative process inherent in this type of modelling work.

Table 1. Technical and economic parameters of a fuel cell.

Fuel cell	
CAPEX (€/kW)	
Nominal power (kW)	
OPEX (€/kW)	
Expected useful life (years)	
Efficiency (%)	

Heat demand (i.e.: domestic hydrogen boilers - Hoogeveen (Nijstad-East))

Domestic hydrogen boilers represent a cutting-edge advancement in residential heating technology, offering a sustainable and efficient alternative to traditional fossil fuel-based systems. These boilers utilize hydrogen, a clean-burning fuel, to generate heat for home heating and hot water, thereby significantly reducing carbon emissions. As the world shifts towards greener energy solutions, hydrogen boilers are gaining attention for their potential to leverage existing gas network infrastructure while contributing to the decarbonization of domestic heating. Their integration into homes not only aligns with global environmental goals but also paves the way for a future where renewable energy sources play a central role in everyday energy consumption.

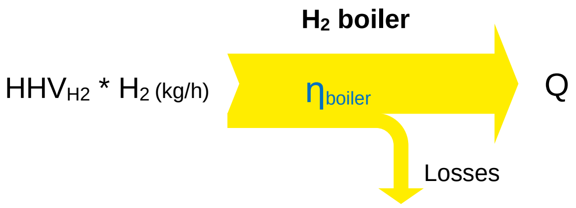


Figure 7. Sankey diagram of a generic hydrogen boiler.

Table 2 displays the technical and economic parameters that users can input to characterize fuel cells.

Table 2. Technical and economic parameters of a domestic hydrogen boiler.

Hydrogen boiler	
CAPEX (€/kW)	
Nominal power (kW)	
OPEX (€/kW)	
Expected useful life (years)	
Efficiency (%)	

Combined Heat & Power (CHP) fuel cell systems

Hydrogen fuel cells have a significant role in combined heat and power (CHP) systems, where they simultaneously produce electricity and heat. The design of CHP systems is such that they efficiently capture and utilize the heat produced during the fuel cell reaction. This efficiency minimizes energy wastage typically seen as excess heat. These systems are versatile, suitable for residential, commercial, and industrial uses. They not only contribute to a reduction in greenhouse gas emissions but also offer a dependable electricity supply, even in the event of power grid failures. This reliability makes them an essential component for communities and enterprises seeking sustainable energy alternatives. As the push for clean and effective energy solutions grows, hydrogen fuel cell-based CHP systems are emerging as a compelling choice for various applications.

Figure 8 features a Sankey diagram that visually depicts the energy flows in fuel cells utilized for CHP purposes.

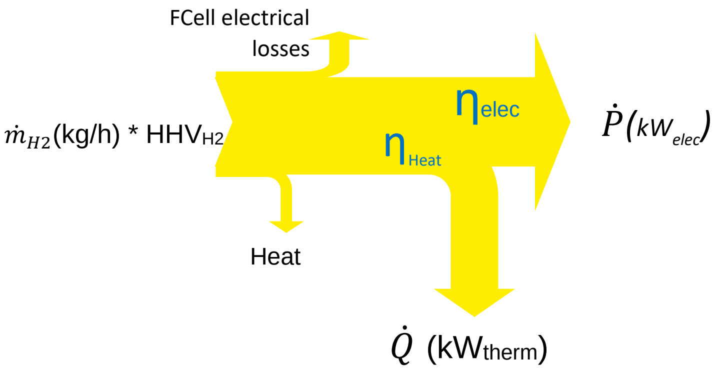


Figure 8. Sankey diagram of a generic fuel cell for CHP applications.

The Sankey diagram enables the formulation of the following equation to determine the hydrogen requirement for these fuel cells.

$$\dot{Q}_{demand}(kW)_i = \eta_{Heat} * \left(\dot{m}_{H2}\left(\frac{\text{kg}}{\text{h}}\right)\right)_i * HHV_{H2}(kWh/kg) \qquad (6)$$

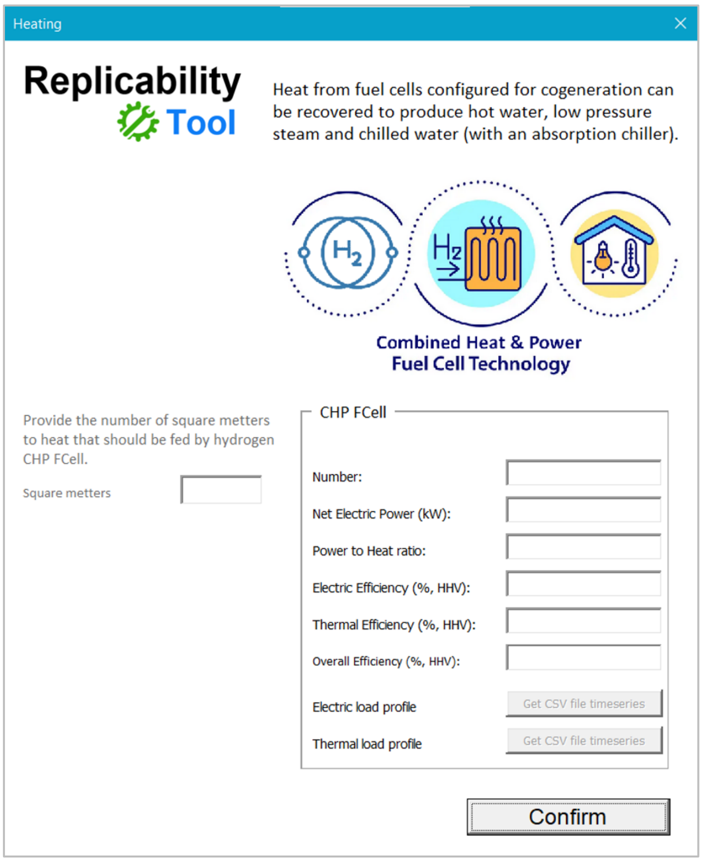
Where:

$\dot{Q}_{demand}(kW)_i$ = thermal power demanded during hour i.
η_{Heat} = thermal performance of the CHP fuel cell.

Then, the component of hydrogen demand corresponding to the heat loads supported by the CHP appliances will be [13]:

$$\boxed{\dot{m}_{H2}\left(\frac{kg\ H_2}{\text{h}}\right)_i = \frac{\dot{Q}_i(kW_{therm})}{HHV_{H2}\,(kWh/kg) * \eta_{Heat}}} \qquad (7)$$

Where $\dot{Q}_i$ is the hourly heat demand, which can be entered by the user as in the previous case:



Heat from fuel cells configured for cogeneration can be recovered to produce hot water, low pressure steam and chilled water (with an absorption chiller).

Provide the number of square metters to heat that should be fed by hydrogen CHP FCell.

Square metters

CHP FCell

Number:
Net Electric Power (kW):
Power to Heat ratio:
Electric Efficiency (%, HHV):
Thermal Efficiency (%, HHV):
Overall Efficiency (%, HHV):
Electric load profile
Thermal load profile

Figure 9. Interface of the tab for entering the data relating to the thermo-electric loads to be supported by the CHP fuel cells.

$$\dot{P}_{demand}(kW_{elec})_i = \eta_{Elec} * \left(\dot{m}_{H2}\left(\frac{\mathrm{kg}}{\mathrm{h}}\right)\right)_i * HHV_{H2}(kWh/kg) \qquad (8)$$

Where:

$\dot{P}_{demand}(kW_{elec})_i$ = electric power demanded during hour “i”.
η_{Elec} = electrical performance of the CHP fuel cell.

Table 2 presents the range of technical and economic parameters that users can input to define the characteristics of these fuel cells. It's important to note that this list of parameters is subject to potential updates as the tool undergoes further enhancement.

Table 3. CHP fuel cell parameters.

CHP fuel cell	
CAPEX (€/kW)	
OPEX (€/kW)	
Expected useful life (years)	
Net Electric Power (kW)	
Power to Heat Ratio	
Electrical Efficiency (%, HHV)	
Thermal Efficiency (%, HHV)	
Overall Efficiency (%, HHV)	

Mobility demand

The methodology for estimating hydrogen demand for mobility is outlined in the forthcoming Equation (9).

$$\boxed{\dot{m}_{H2}\left(\frac{kg\ H_2}{year}\right) = \text{Nº buses} * \left(\frac{Distance}{year} * \frac{kg_{H2}}{100km}\right)} \qquad (9)$$

Furthermore, Table 4 details the technical and economic parameters available for user input to effectively characterize these fuel cell electric vehicles (FCEV).

Table 4. Fuel cell electric vehicles parameters

Fuel cell electric vehicles	
CAPEX (€/bus)	
OPEX (€/year)	
Expected useful life (years)	
H_2 fuel consumption per 100 km (kg/100km)	
Equivalent litres of diesel	
Average distance covered (km/year)	

Blending station (x - 20% vol H_2 injected):

Hydrogen blending is the practice of integrating hydrogen gas with natural gas within pipelines, aiming to lower carbon emissions and advance towards more sustainable energy solutions. The proportion of hydrogen in the mix can vary, starting from minimal percentages and nowadays potentially reaching up to 20% hydrogen (only in UK [14]).

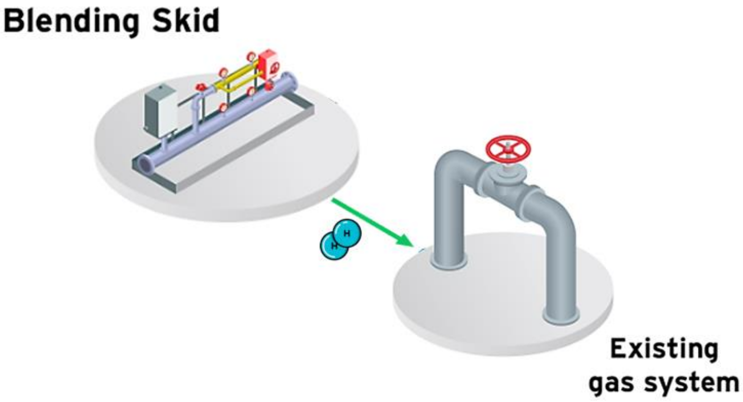


Figure 10. Diagram illustrating a parallel blending station (or skid) adjacent to the natural gas network, injecting green hydrogen.

The integration of hydrogen into existing natural gas networks serves as a transitional strategy towards a broader hydrogen-based economy. A critical aspect of hydrogen blending lies in maintaining the safety and integrity of the pipeline system and ensuring that existing equipment and appliances are not adversely affected. Additionally, hydrogen blending opens avenues for improved energy storage and more efficient distribution methods.

For the successful implementation of hydrogen blending, a hydrogen blending station plays a pivotal role. To establish a blending station that is economically viable, several key parameters must be carefully evaluated and integrated into the planning process.

Table 5. Blending station (X-20% vol. H2 injected) parameters.

Blending station (x-20% H_2)	
CAPEX (€)	
OPEX (€/hr)	
Expected useful life (years)	
Energy consumption (kWh/Nm^3) or (kWh/kg)	
Max volume injected of H_2 (Nm^3/hr) or (kg/h)	

ELEMENTS OF YEARLY HYDROGEN PRODUCTION

The initial segment of this section highlighted the need to meet hydrogen demand through hydrogen production facilities, specifically electrolysers.

Central to the thriving functionality of a Hydrogen Valley is the attainment of cost-effective green hydrogen. To realize this goal, it is crucial for stakeholders to assess their profitability accurately.

In the subsequent sections, we will explore two key aspects:

- firstly, the tool's ability to comprehensively **simulate the dynamic behaviour** of a Proton Exchange Membrane (PEM) electrolyser plant, and
- secondly, the various **business models** that emerge based on the plant's connection modes. These include operating in isolation with a Renewable Energy Source (REE) installation, functioning in self-consumption while connected to the grid (including Power Purchase Agreements or PPAs), being solely grid-connected (also with PPAs), or exclusively utilizing the curtailment opportunities of a REE plant.

Full simulation of the electrolysis plant

In line with the dual-component system approach, the following code packages have been integrated to achieve the most accurate simulation of the electrolysis plant(s) possible. According to Figure 11 below, it can be seen that the following packages have been included:

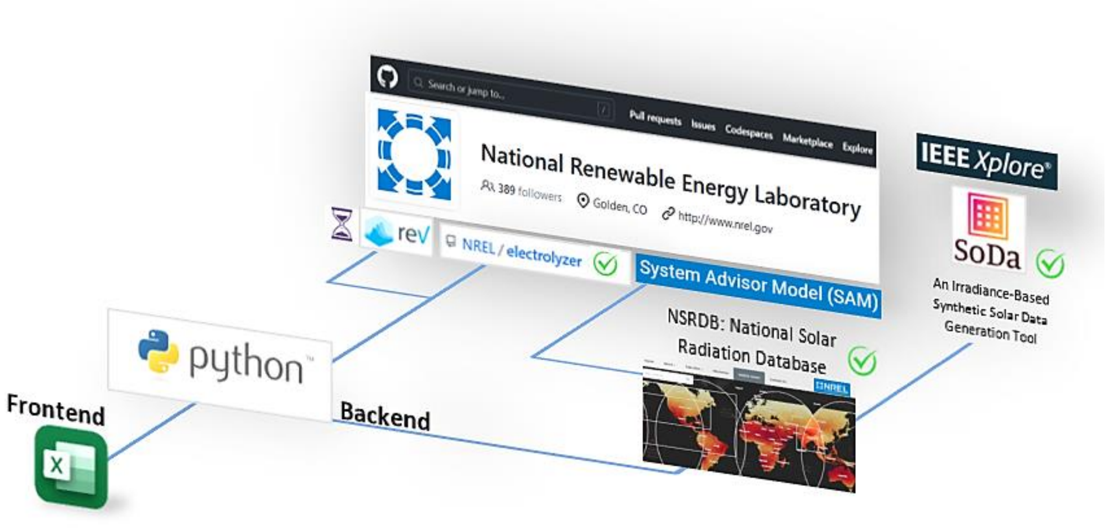


Figure 11. Conceptual scheme of the frontend & backend development applied to the simulation module of the hydrogen production plant.

- **SoDa (PySoDa)**: “An Irradiance-Based Synthetic Solar Data Generation Tool” [8]

  PySoda is an irradiance-based synthetic Solar Data generation tool to generate realistic sub-minute solar photovoltaic (PV) power time series. Soda emulates the weather pattern for a certain geographical location using 15, 30, 60-min averaged irradiance and cloud type information from the National Solar Radiation Database (NSRDB) [15].

  This code is the basement that allows to simulate the dynamics of the electrolysis plant as it can downscale the granularity of the meteorological time series to the second.

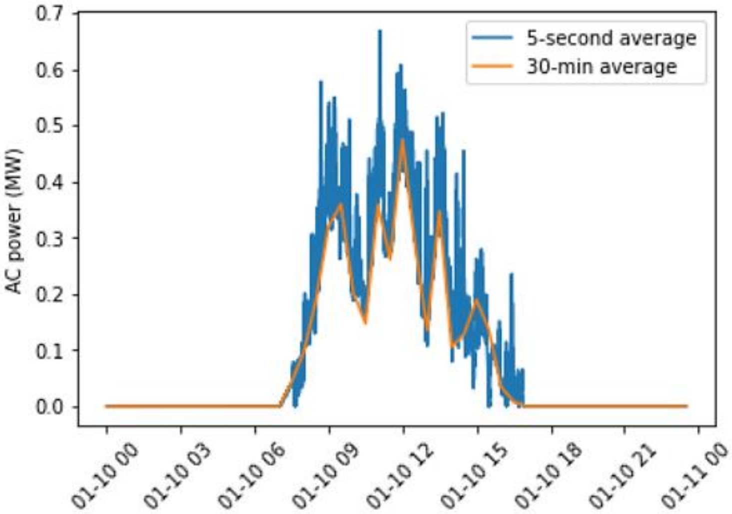


Figure 12. Example graph of the synthetic calculation (5 sec timestep) of the AC power output of a PV plant versus the data calculated from the 30-minute time series.

- **SAM – PySAM (NREL):** The System Advisor Model (SAM) [16] is a free techno-economic software model that facilitates decision-making for people in the renewable energy industry:
  - Project managers and engineers,
  - Policy analysts,
  - Technology developers,
  - Researchers.

  SAM can model many types of renewable energy systems.

  PySAM [17] is a Python package that you can use in a Python script to make calls to the SAM Simulation Core (SSC) compute modules. It provides access for tools for accessing SAM default values and input variables.

Consequently, this repository is utilized for the computation of energy output from various Renewable Energy Source-Electricity (RES-E) plants. The energy thus generated serves as the main input for the operation of the electrolysis plant.

- **Electrolyser (NREL):** This code [18] delivers an exhaustive simulation of the dynamic behaviour of a Proton Exchange Membrane (PEM) electrolyser plant, traversing multiple levels of simulation. It begins with the electrochemical phenomena within the cell, extends through stack-level behaviour, and culminates with Balance of Plant (BOP) calculations. Given the relative simplicity of this final step, integration with the H2A - Hydrogen Analysis Production Models (NREL) [19] is under consideration for enhancement.

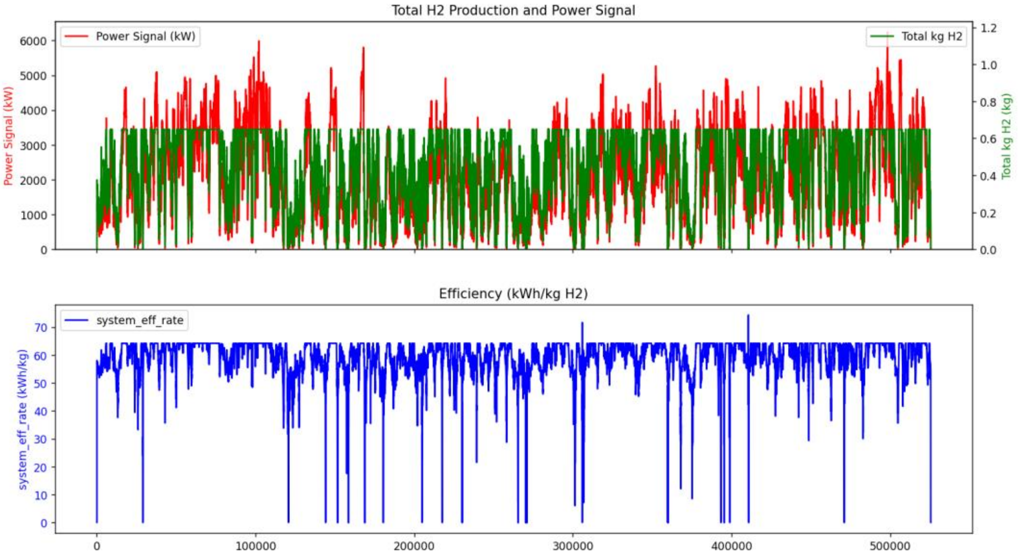
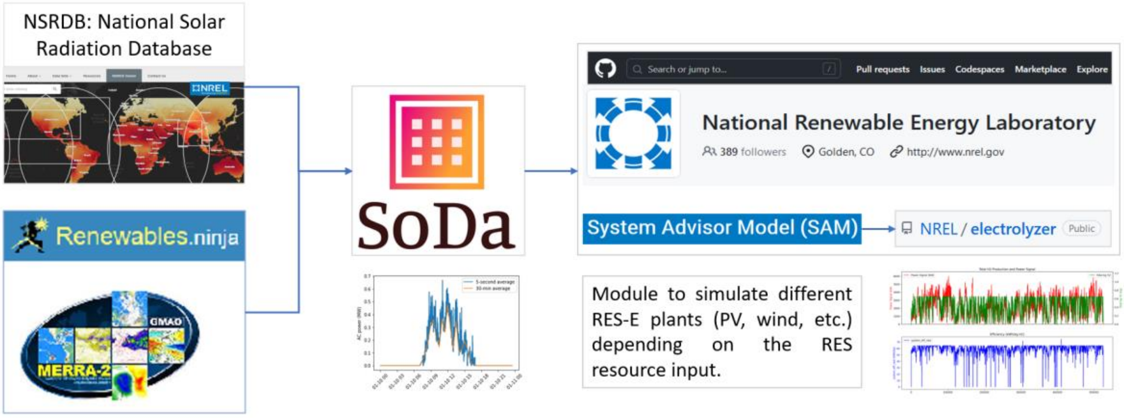


Figure 13. Chart depicting a case study (1-year) for an electrolysis facility equipped with two 1.25MW Proton Exchange Membrane (PEM) stacks, amounting to a total capacity of 2.5MW. The graph features the power output from a 5 MW offshore wind turbine shown in red, and the hydrogen production rate represented in green. Additionally, displayed at the bottom in blue, is the minute-by-minute operational efficiency of the plant.

This comprehensive simulation framework enables the calculation of a wide array of operational variables for a PEM electrolyser, such as current intensity, cell overpotentials, steady-state degradation, and degradation due to start/stop cycles. The latter is particularly pivotal for ascertaining stack replacement schedules, a fundamental aspect in Operational Expenditure (OPEX) calculations, which also includes factors like capacity factor.

Moreover, the code encompasses a module dedicated to calculating the Levelized Cost of Hydrogen (LCOH). This component considers a spectrum of Capital Expenditure (CAPEX) and OPEX elements, notably the costs of electricity, water, and stack replacement. Stack replacement costs are determined based on the stack's annual degradation rate. Additionally, the code's capability to account for degradation enables the projection of annual hydrogen production across the stack’s lifecycle, gradually decreasing as the stack approaches its operational lifespan's conclusion.

Consequently, revisiting the operations of these three modules, the sequence of information processing can be outlined as follows (see Figure 13): initially, data on Renewable Energy Source (EERR) resources are collected. These data are then processed to enhance granularity, aiding in simulating the dynamics of an electrolyser. Subsequently, the System Advisor Model (SAM) module is engaged to compute the renewable energy production, tailored to the specific plant type (wind, solar PV, etc.). The next step involves simulating the time series for the power output of the EERR plant, which is instrumental in estimating the production capacity of the electrolyser plant. This comprehensive process culminates in the time series reflecting the output power of the EERR plant, effectively simulating the operational output of the electrolyser plant.



Module to simulate different RES-E plants (PV, wind, etc.) depending on the RES resource input.

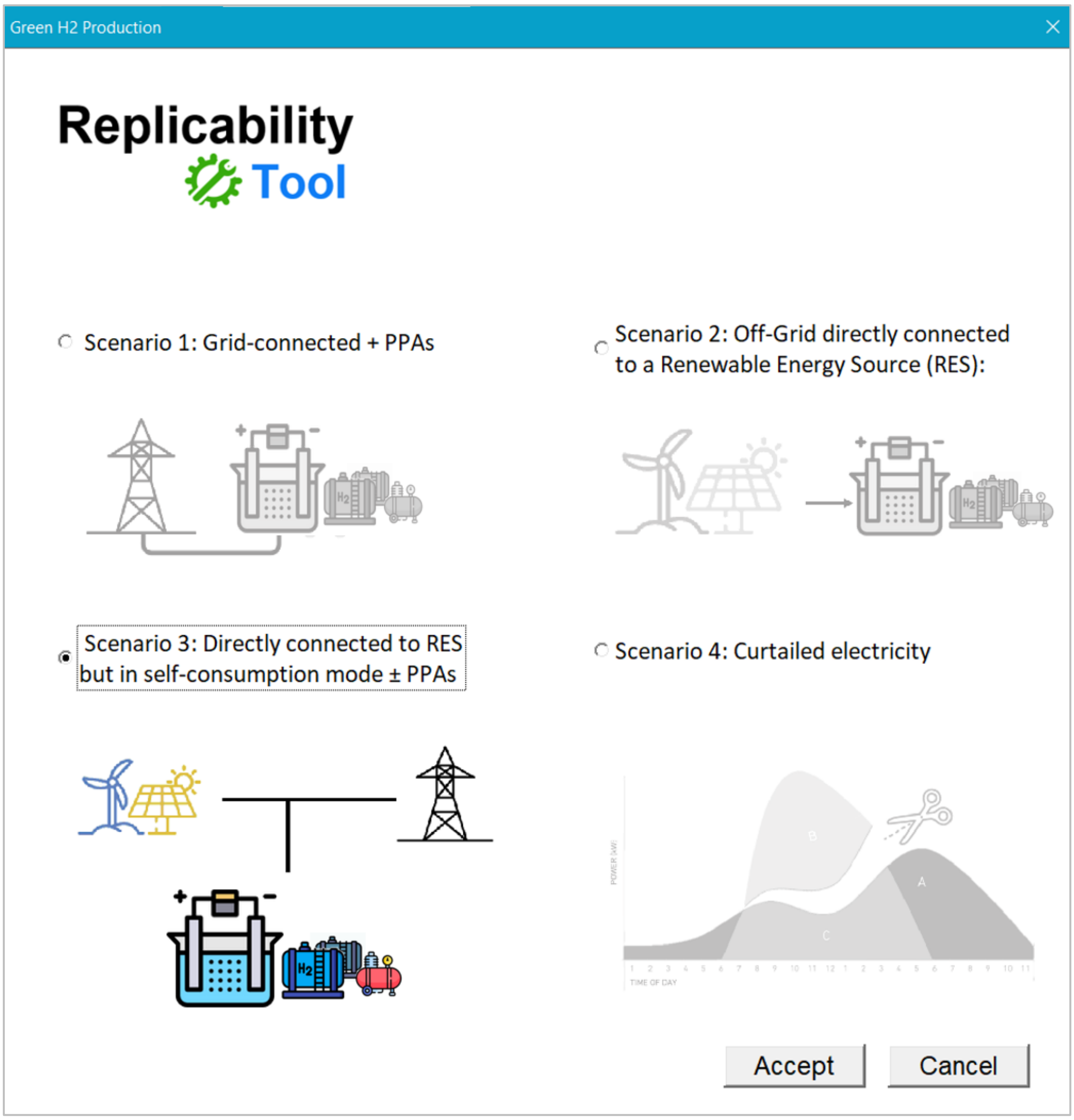
Figure 14. Schematic diagram of the information processing flow inside the Replicability Tool.

Methods of Supplying Energy to the Electrolysis Plant

As highlighted in the second bullet point, there are various methods for powering the electrolysis plant, each impacting the final financial assessment differently.

This segment illustrates how the tool aims to capture the primary methods currently available for connecting an electrolysis plant for green hydrogen production.

The subsequent Figure 15 displays the four aforementioned connection options.



Green H2 Production

Replicability Tool

○ Scenario 1: Grid-connected + PPAs

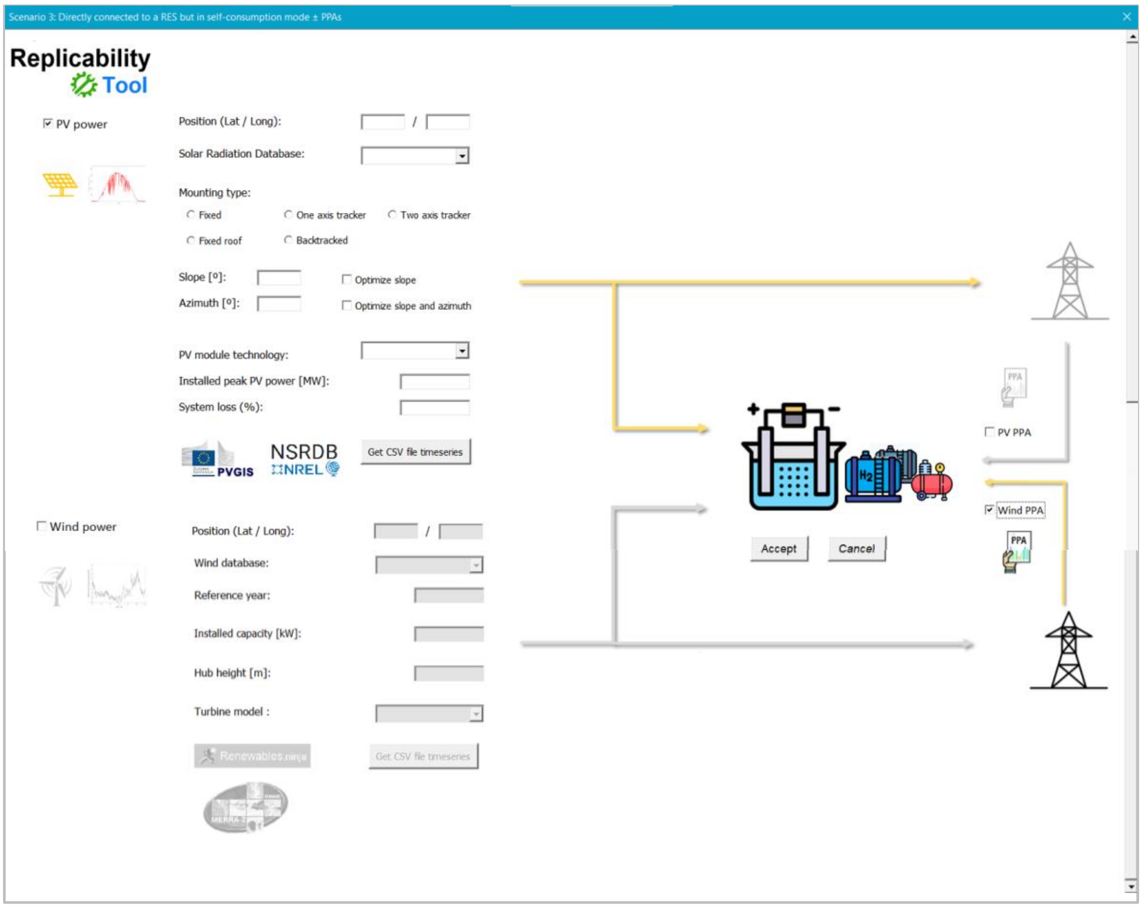
○ Scenario 2: Off-Grid directly connected to a Renewable Energy Source (RES):

● Scenario 3: Directly connected to RES but in self-consumption mode ± PPAs

○ Scenario 4: Curtailed electricity

Figure 15. Screen for selecting the connection mode of the electrolysis plant.

Upon selecting the connection mode for the electrolysis plant, the tool progresses to the next interface (Figure 16). Here, users will have the opportunity to select and specify the type of Renewable Energy Source (RES) plant, while concurrently choosing the origin of the renewable Power Purchase Agreement (PPA).



Scenario 3: Directly connected to a RES but in self-consumption mode ± PPAs

Replicability Tool

☑ PV power

Position (Lat / Long): /

Solar Radiation Database:

Mounting type:

○ Fixed ○ One axis tracker ○ Two axis tracker

○ Fixed roof ○ Backtracked

Slope [º]: ☐ Optimize slope

Azimuth [º]: ☐ Optimize slope and azimuth

PV module technology:

Installed peak PV power [MW]:

System loss (%):

☐ Wind power

Position (Lat / Long): /

Wind database:

Reference year:

Installed capacity [kW]:

Hub height [m]:

Turbine model :

☐ PV PPA

☑ Wind PPA

Figure 16. Screen for "Self-Consumption + Grid Connection (PPAs)" mode, enabling selection of the type of RES-E source and the origin of the PPA.

ELEMENTS OF THE SUPPLY CHAIN NETWORK

100% H2 pipeline

Hydrogen pipelines represent a specialized form of infrastructure designed for the transportation of hydrogen gas across different locations. Distinct from conventional natural gas pipelines, which typically consist of steel and primarily carry methane, hydrogen pipelines are constructed using materials specifically chosen for their resistance to hydrogen's corrosive properties. These pipelines are increasingly recognized as a viable means for the efficient transport and distribution of hydrogen. This is particularly relevant for the large-scale utilization of hydrogen in industrial processes or as a storage medium for surplus renewable energy.

At this initial stage, energy balances are not factored in. The collected data will primarily serve to assess the cost implications of this phase and evaluate the overall profitability of the business model. Nonetheless, there is a need for further research in literature to incorporate an energy balance model that accounts for variations based on pipeline distance.

Table 6. 100% H2 pipeline parameters.

100% H2 pipeline	
CAPEX (€/km)	
OPEX (€/year)	
Expected useful life (years)	
Energy consumption (kWh/Nm^3 per km) or (kWh/kg per km)	
Max volume (Nm3/hr) or (kg/h)	
P_{min} & $P_{máx}$ (bar)	

Tube trailers

The transportation of hydrogen via tube trailers involves the conveyance of the gas in cylindrical containers, termed tube trailers, mounted on trucks. This method is typically employed for delivering hydrogen to sites not served by pipeline networks, including various industrial facilities and remote areas.

In the initial phase of this process, energy balances are not considered. The essential data gathered at this stage will be instrumental in determining the costs associated with this transport method and in evaluating the economic viability of the business model.

Table 7. Tube trailer parameters.

Tube-trailers	
Storage capacity (kg/ trailer)	
Trailer cost (€/trailer)	
Distance (km) /day	
Diesel price (€/l)	
Average fuel consumption (l/km)	
Nº of trailers	
Expected useful life (years)	

HRS (Hydrogen refuelling station)

Hydrogen refuelling stations are specialized facilities engineered for storing and dispensing hydrogen fuel to power hydrogen-fuelled vehicles. While conceptually akin to traditional gasoline stations, these facilities are equipped to dispense hydrogen gas instead of petrol.

Key to the operation of these stations are multiple processes designed to ensure the safe and efficient refuelling of vehicles. A crucial aspect of this operation is the cooling phase, primarily facilitated by a device known as a chiller. The need for this phase is driven by hydrogen's intrinsic properties and the requirements of hydrogen-powered vehicles. Typically, hydrogen is stored at high pressures, potentially reaching up to 700 bar in vehicle fuel tanks. Compressing hydrogen to these levels naturally induces heat, as per gas laws. However, to ensure safe and efficient tank filling, the hydrogen must be at a lower temperature when dispensed into the vehicle. This temperature reduction is achieved during the cooling phase.

The chiller's role involves extracting heat from the hydrogen gas and transferring it to another medium, like water or air. This effectively cools the hydrogen, making it suitable for vehicle tank dispensation.

This cooling phase is critical for several reasons:

- Safety: High-temperature hydrogen gas can elevate pressure, posing potential safety hazards.
- Efficiency: Cooling increases hydrogen density, allowing for more fuel to be stored in the tank.
- Vehicle Protection: High-temperature hydrogen can potentially harm the fuel tank or shorten its lifespan.

The necessity of a chiller extends beyond merely the storage pressure of hydrogen. Factors like ambient temperature, refuelling speed, and specific vehicle tank requirements also influence this need. For example, in high ambient temperature regions, hydrogen can significantly heat up during compression, leading to higher temperatures upon dispensation into the vehicle's tank. This can result in issues like overpressure, reduced fuel capacity, and potential tank damage. Thus, in such climates, even at lower pressures like 350 bar, pre-cooling may be necessary, particularly for rapid refuelling scenarios. While the SAE J2601[1] standards underscore the importance of temperature compensation in refuelling protocols, they do not explicitly detail the exact scenarios necessitating pre-cooling for 350 bar systems. However, given the emphasis on safety and performance, it is inferred that pre-cooling is advantageous in situations prone to elevated hydrogen temperatures during fuelling.

Now, to examine the comprehensive layout of a hydrogen refuelling station, we present a diagram that delineates its various components:

---

[1] SAE J2601_201407 is the standard for light vehicles.
SAE J2601/2_202307 is the standard for heavy-duty vehicles.
SAE J2601 is also being referenced in ISO 19880-1.

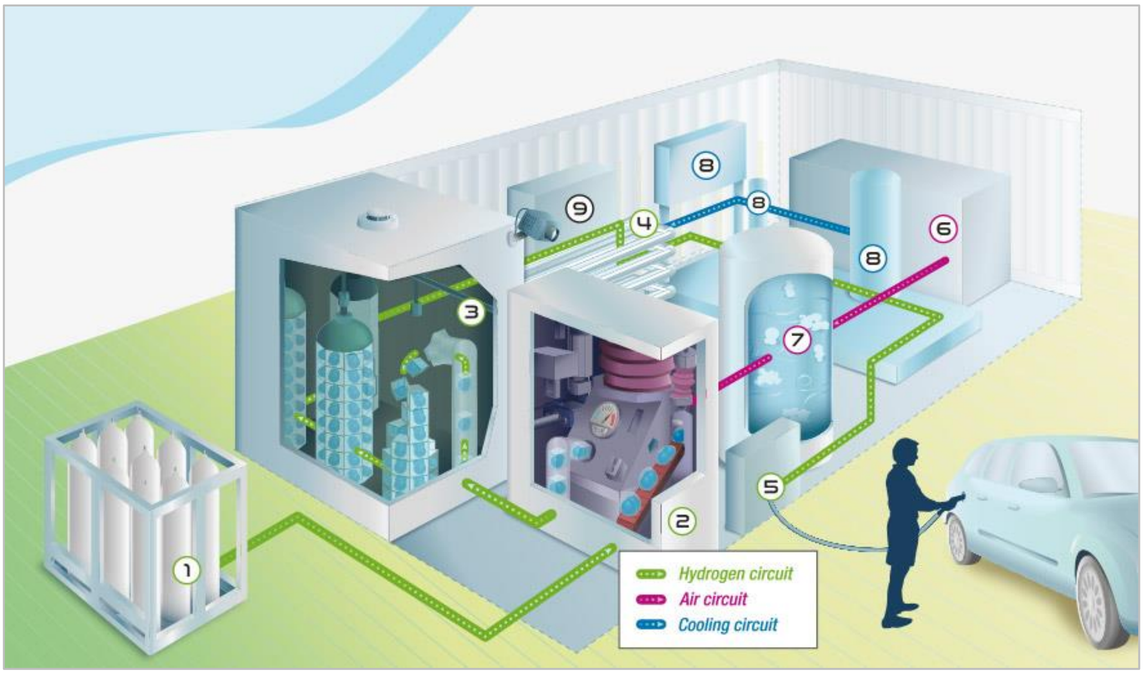


Figure 17. A Hydrogen Refuelling Station Diagram
(https://h2me.eu/about/how-an-hrs-works/)

The following details outline the key components of a hydrogen refuelling station:

- Hydrogen Source: Hydrogen at low pressure is stored in various forms, such as cylinder racks, tanks, or tube trailers.
- Booster: Hydrogen is compressed using boosters. In stations serving hydrogen at dual pressures,700 bar for light vehicles and 350 bar for heavier transport like buses or trucks, the boosting occurs in two stages:
  - Initially, the pressure is increased to 500 bar.
  - Subsequently, it's further elevated from 500 bar to 1000 bar[2].
- Buffers: After undergoing this two-stage pressure increase, hydrogen is then stored in two distinct types of vessels:
  - High-pressure vessels (up to 1000 bar) for refuelling vehicles requiring 700bar.
  - Low-pressure vessels (500 bar) for those needing 350 bars.
- Exchanger: Prior to distribution, hydrogen is cooled using an exchanger in conjunction with a refrigeration unit.

---

[2] The maximum storage pressure will depend on the capacity of the rack and the number of vehicles to be dispensed per day.

- Dispenser: This facilitates the distribution of hydrogen into the vehicle's tank, enabling rapid filling within a few minutes.
- Air Compressor for ATEX Classified Control Elements: Pneumatic systems, driven by compressed air, are predominantly used for control elements as they are intrinsically safe. Their non-sparking nature makes them ideal for environments with explosive or flammable atmospheres, where electrical systems could be hazardous.
- Buffer Tank: This component regulates and provides the necessary air for the control functions to operate effectively.
- Refrigeration Unit: This unit is responsible for supplying the cooling fluid to the exchanger. It consists of a buffer tank to store and regulate the liquid flow, the pumps, and an electrical control cabinet.
- General Control Cabinet: This is the primary electrical control centre of the station.

The accompanying illustration, courtesy of the Hydrogen Mobility Europe website, showcases these elements, including the hydrogen source, compressor, chiller (for the cooling phase), and dispenser. Typically, the chiller is positioned post-compression and pre-dispensation in the processing flow. It is important to note that the specific configuration and components may vary based on the individual design of the hydrogen refuelling station.

In summary, the cooling phase, facilitated by a chiller, is integral to the safe and efficient functioning of a hydrogen refuelling station and the refuelling process of hydrogen-powered vehicles, especially under conditions of high ambient temperature and when rapid refuelling is required.

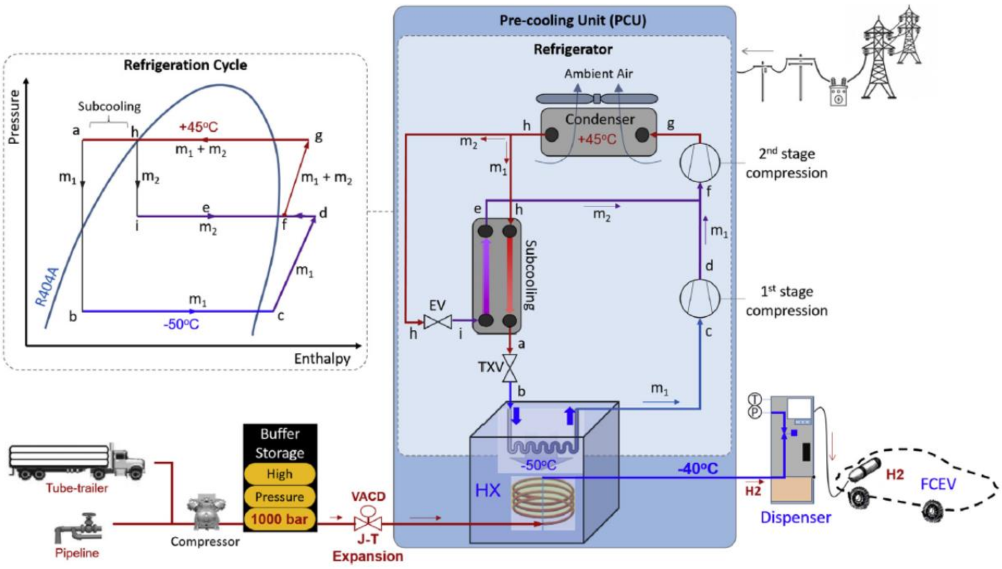


Figure 18. Diagrammatic representation illustrating the functionality of the Precooling Unit (PCU) within a Gaseous Hydrogen Refueling System (HRS), encompassing a compressor, high-pressure buffer storage, the PCU itself, and a dispenser [20].

The necessary data will be employed to determine the expenses associated with this phase and to evaluate the financial viability of the business model.

The Hydrogen Refuelling Station (HRS) model incorporates components such as:

- Stationary hydrogen storage facilities designed for refuelling both light vehicles and heavy-duty transport, including buses:

Table 8. Stationary hydrogen storage parameters (HRS)

Stationary hydrogen storage vessels	**1000 bar**	**500 bar**
Number of tanks		
CAPEX (€)		
OPEX (€/year)		
Expected useful life (years)		
Volume (kg)		

- Compressor (or booster):

Table 9. HRS compressors parameters.

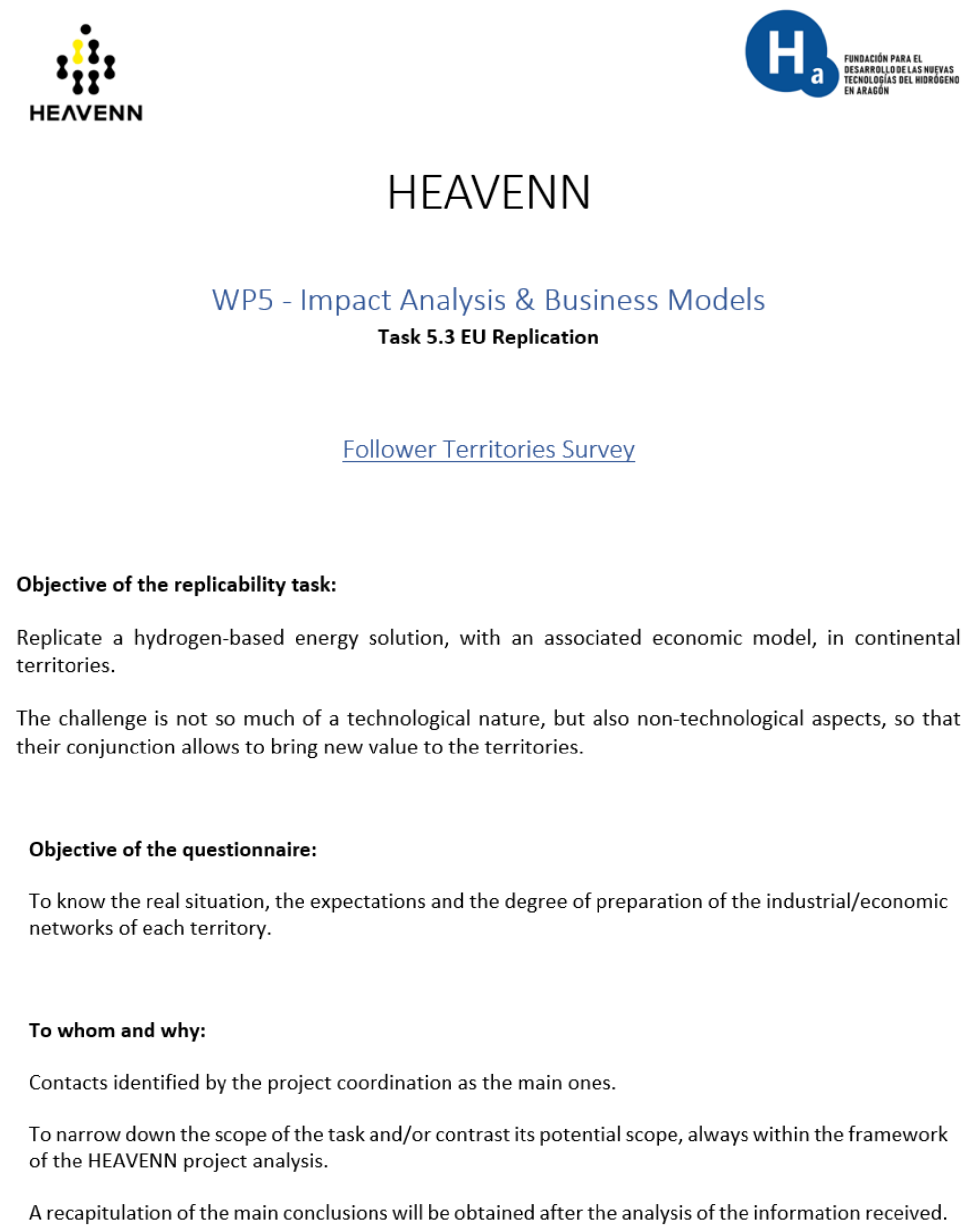
HRS hydrogen compressor (booster)	
CAPEX (€)	
OPEX (€/year)	
Expected useful life (years)	
Energy consumption (kWh/Nm^3)	
Max compression hourly (Nm^3/hr) or (kg/h)	

- The hydrogen dispensers for light vehicles and heavy-duty vehicles refilling:

Table 10. HRS hydrogen dispenser parameters

HRS hydrogen dispenser	**700 bar**	**350 bar**
CAPEX (€)		
OPEX (€/year)		
Expected useful life (years)		
Electricity demand (kWh/Nm^3)		
Max dispensed volume (Nm^3/hr) or (kg/h)		

6 Appendix II: Follower Territories Survey



HEAVENN

WP5 - Impact Analysis & Business Models

Task 5.3 EU Replication

Follower Territories Survey

Objective of the replicability task:

Replicate a hydrogen-based energy solution, with an associated economic model, in continental territories.

The challenge is not so much of a technological nature, but also non-technological aspects, so that their conjunction allows to bring new value to the territories.

Objective of the questionnaire:

To know the real situation, the expectations and the degree of preparation of the industrial/economic networks of each territory.

To whom and why:

Contacts identified by the project coordination as the main ones.

To narrow down the scope of the task and/or contrast its potential scope, always within the framework of the HEAVENN project analysis.

A recapitulation of the main conclusions will be obtained after the analysis of the information received.

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Therefore, we need to start working on two main aspects:

- Who are you?
- What do you need?

1. Who are you?

1.1. Who is the person in charge of the replication study in your territory?

Please define:

- Your entity:
- The context of your entity in the region:
- Your position, responsibility: i.e Regional Sustainability Officer.
- Your level of technical knowledge (your studies could be useful)
- Your knowledge about hydrogen technologies

1.2. What does your territory/entity expect from the HEAVENN project?

Please describe:

- Do you already have a hydrogen deployment project ongoing/planned in your region? (if YES, please describe it in 10 lines maximum). Please note that we are referring to projects beyond HEAVENN.
- What are your expectations from the HEAVENN project?
- What do you consider replication to be?
- What do you expect from a replication tool*?

*A **replication tool** is a software intended to help follower territories to translate the HEAVENN project to their own islands. To get an idea of what it looks like, please visit http://h2territory.eu/replicability-tool/ , you will find the first version developed during the BIG HIT project (hydrogen valley in Orkney islands). This tool will be used during this survey. It is a multi-parameter Excel-based tool that incorporates energy (heat, power, mobility), infrastructure, and financial parameters, and provides a techno-economic assessment relating to the deployment of a H2-based ecosystem in the specified island or territory.

1.3. What is your project?

Please, provide more information:

- The case/s study/ies you may already have planned / in mind. The more detailed, the better.

  Here below, some items you could think about:

  - Infrastructure (which one and where, could you provide some map?)
  - Your potential/considered territories for replication analysis
  - Business Models
  - Social impact
  - Environmental impact
  - Scenarios
  - Time horizons
  - ... feel free to add more details.

1.4. Other aspects we should be aware of?

- Energy territory context?
  Please, provide a brief introduction of the energy system for the potential replication territory?
  Here below, some items you could think about:
  - Wind and solar resources?
  - Other renewable energy infrastructure (i.e. tidal)?
  - Seasonal demand?
  - Infrastructure related to H2:
    - Existence of gas grid
    - RES curtailment
    - Need for heating / cooling
    - Ferry routes
- Economic territory context?

  For instance, "our territory's main income is tourism, and due to that we want to focus on PV farms, as onshore windmills would be counterproductive"
- Policy context (environmental, social, energy market)?
- Social territory context?
  - Social acceptance of RES projects.
  - Do they have taken place any participatory activities during a project at this territory?
- Other social agents: local communities, regions/counties?
- Other complementary techno-economic resources of the territory (present and potential)
- Others?

2. What do you need?

To be efficient in the goal of replicating the hydrogen valleys in your territories, a software tool is being improved. This tool is based on the HTP Tool developed for the BIG HIT project.

The aim of this item is to have, not only feedback from your experience with this tool, but to think with you further, even “out of the box”.

Therefore, once you have responded to the previous questions, you will be better prepared to use the tool with your needs in mind.

Please, download the HTP tool here. Now it’s time to play. Try to use the current HTP Tool for your purposes within your case study. In order to avoid biasing your user experience, only instructions uploaded on the HTP site will be available.

2.1. What do you expect from a replication tool?

Please, describe:

- Is it user-friendly for you? (i.e.: What about units, vocabulary?)
  Could you evaluate next points (1-very bad, 6-very good)?

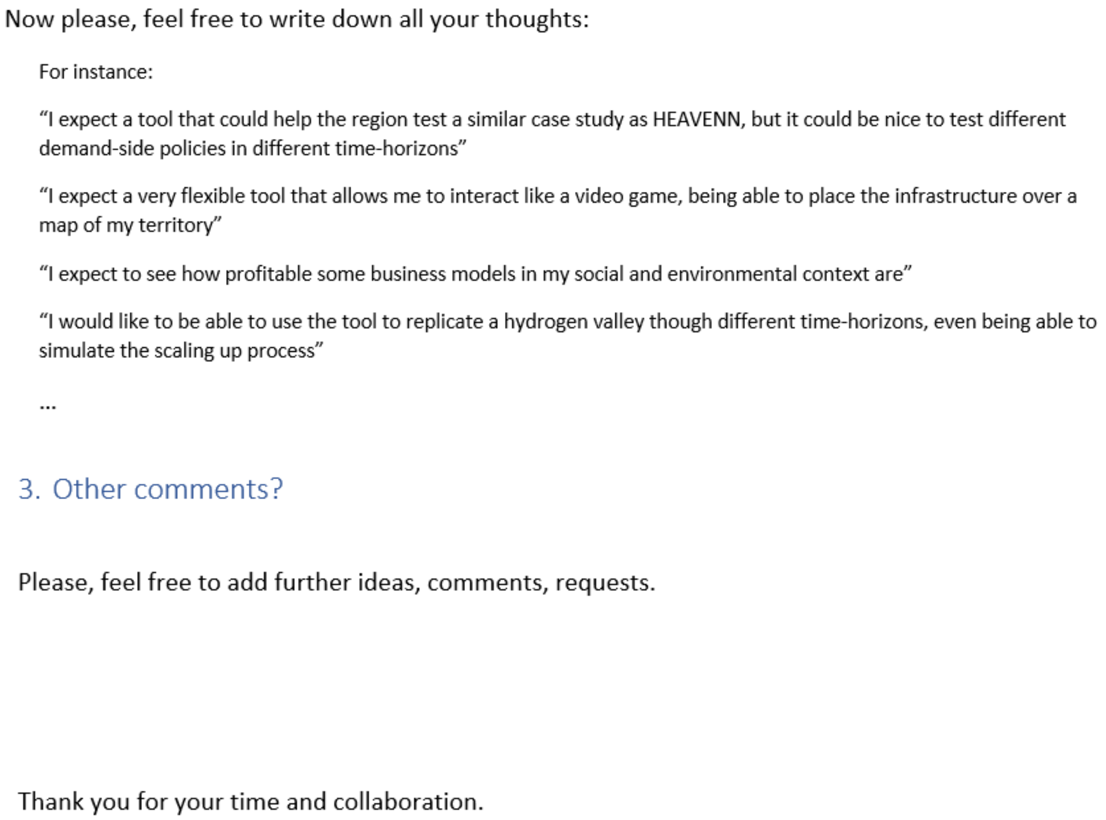
○ Ease of use	1	2	3	4	5	6
○ Ease of inserting data	1	2	3	4	5	6
○ Ease of collecting data	1	2	3	4	5	6
○ Need for more models	1	2	3	4	5	6
○ Freedom to customise inputs	1	2	3	4	5	6

- Is it useful for your case study?

- What would you add/delete?

    - Interpretation/analysis of results needed?

    - Subsidies/grants/loans into the calculations to make it more useful for decisionmakers and policy makers.



Now please, feel free to write down all your thoughts:

For instance:

“I expect a tool that could help the region test a similar case study as HEAVENN, but it could be nice to test different demand-side policies in different time-horizons”

“I expect a very flexible tool that allows me to interact like a video game, being able to place the infrastructure over a map of my territory”

“I expect to see how profitable some business models in my social and environmental context are”

“I would like to be able to use the tool to replicate a hydrogen valley though different time-horizons, even being able to simulate the scaling up process”

…

3. Other comments?

Please, feel free to add further ideas, comments, requests.

Thank you for your time and collaboration.

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