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Methodology for Individual Port Hydrogen Production, Storage and Infrastructure Plans including Modelling Approach

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Contents

1. Introduction

NS H2V ports project aims to facilitate and develop green hydrogen production, storage, delivery, and use in the North Sea ports.

Ports have a key role in coastal tourism and maritime shipping logistics operations. Nevertheless, they are also higher energy users. Consequently, in accordance with energy transition scenarios, developing alternative maritime power solutions became the real challenge. So, global governance dealing with local market and trade development aims to drive actors to progress in local production and enhance import / export strategies. Concerning the NS H2VPorts' project, the main challenge is the creation of a local (North-Sea area) collaboration for hydrogen production and use integration in coastal and ports' activities. Port's ecosystem is then analysed to evaluate potential in local production, distribution and use, while import and export strategies are introduced to study possible exchanges between actors. Finally, the global trade balance for ports' sustainability is evaluated via the hub structure creation. If a generic approach is structured (and presented) in the following, the methodology should be applied individually, depending on the real case-study scenarios. In the framework of the NS H2VPorts project, four different case-studies are considered; one per each-port member: the port of Bremen, the port of Brest, the port of Den Helder and the port of Esbjerg.

In line with this framework, the Activity 1.3 of WP1 provides a generic approach to support green-ports' hydrogen production and infrastructure planning phase. In this phase, plans are developed for hydrogen production, storage, and distribution. Various technologies (electrolysis, storage in pressurized tanks or underground storage facilities, pipelines, etc.) are considered, taking logistical and economic factors into account. Because of local policy, specific plans will differ depending on ports' ecosystems and authorities' strategies. As part of the master plan (refer to Activity 2.3), this document establishes generic guidelines and tools to be proposed to support port decisions in planning activities in green hydrogen value chain.

2. Methodology description

This document is a structured approach in a step-by-step process to implement strategies and support making decisions on tasks definition and resources allocations; the resulting template of which will be adapted/implemented to each port.

➢ ***General Methodology to develop planning phase***

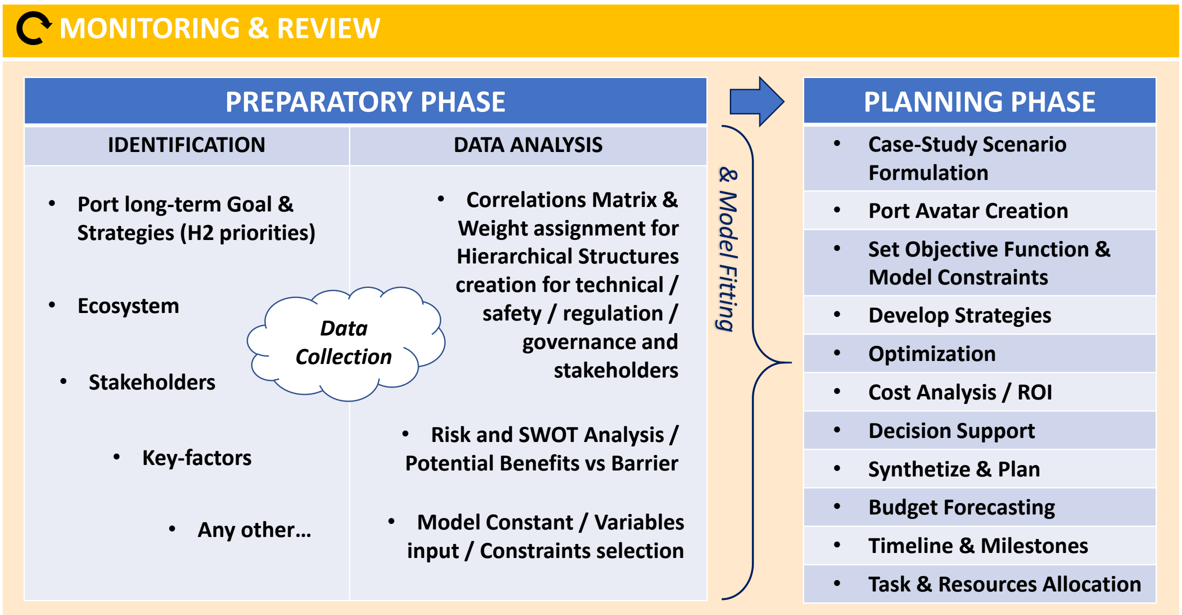

Figure. 1. Methodology to implement strategies for project planning.

The principles of the structured approach are illustrated in Figure 1. The first step of the proposed methodology is data collection to define the port ecosystem, its needs, and its limits [1]. This is referred to as the preparatory phase. Based on each port's long-term strategies, priorities, and governance structures, data are collected on both key actors (such as energy suppliers, investors, and port authorities) and key factors (such as regulations, incentives, and funding schemes).

Once collected, data is processed and classified to create a structured database. This database supports a data-learning approach and enables the first level of analysis. Two main uses of data are distinguished:

- The first set of data is used for model fitting [2].
- The second set of data is used to generate tables and matrices, and to create hierarchical structures that can be exploited in decision-support systems [3,4].

In addition, the preparatory phase includes an assessment of both potential benefits and still-pending barriers. In short, this phase produces a detailed *state of the art* of the port: its scope, long-term objectives, technologies and infrastructures (equipment), and relevant actors. It establishes the basis for identifying opportunities, risks, and barriers to hydrogen market ramp-up in port ecosystems.

Once topics and key factors are defined, the planning phase begins. This involves defining case-study scenarios, setting constraints, and outlining strategies for model fitting and optimisation. An economic analysis is carried out to estimate the cost of hydrogen-related infrastructure, covering both capital expenditure (CAPEX) and operational expenditure (OPEX), including maintenance.

The approach combines model application with optimisation methods to determine the optimal sizing and configuration of hydrogen and renewable energy infrastructures. The outcome of this step is the creation of a port avatar (a digital model of the port), which enables testing and selection of optimal strategies for enhancing the hydrogen value chain while minimising overall system costs.

To strengthen the robustness of the methodology, a decision-support tool is developed. This tool integrates modelling results, scenario analyses, and optimisation outputs to support governance and investment decisions.

Finally, results are consolidated into a project plan, which includes detailed budget forecasting, activity planning, and resource allocation. At this stage, timelines and milestones are established, and tasks are assigned to specific stakeholders. This ensures that technical, economic, and governance dimensions are linked together in a coherent roadmap for project implementation.

3. Port's Planning: The Template

According to the proposed methodology, this section deals with the template presentation. The main objective is to clarify the procedure for a better understanding of approach implementation. Figure. 2 represents the step-by-step structured process, with the different phases and the expected results (or annexes studies and documents); described as follows.

3.1. Preparatory Phase

The first step of the methodology is the preparatory phase. As its name suggests, this phase represents the preliminary study aimed at gathering data on port terminals, including their equipment, activities, and energy needs, as well as the policies and administrative frameworks of local authorities. This operation allows for the identification of port infrastructure, import/export strategies, and overall energy consumption patterns.

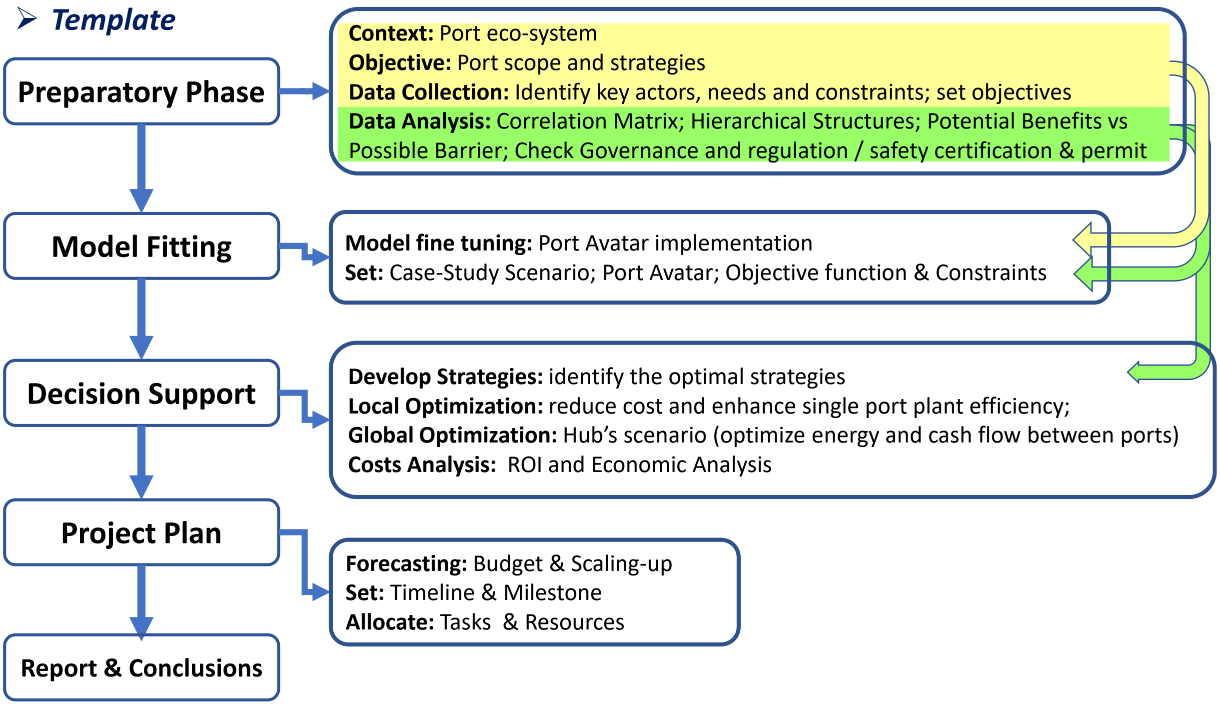

Figure 2: Template for port hydrogen production, storage, and infrastructure planning.

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To achieve this, it is essential to define the port environment, which includes the port ecosystem and its strategic priorities (Figure 3). Within this scope, hydrogen facilities—whether existing or potential—are mapped as strategic assets for enhancing the port's green hydrogen value chain (Figure 4). The port's energy resources and hydrogen priorities are then organised in line with local authority strategies, listing milestones, required actions, equipment, and services [1]. This stage therefore involves an evaluation of opportunities, with the aim of identifying priorities, targets, and resources.

It is important to note that multiple development scenarios can be considered. For example, some ports may prioritise local hydrogen production based on onshore or offshore renewable energy plants, thereby developing the entire value chain. Others may focus primarily on hydrogen import strategies, limiting their activities to end-use applications. Similar considerations apply to hydrogen storage and bunkering technologies (e.g. liquid versus gaseous hydrogen), as well as transportation methods (pipelines, vessels, containers, etc.).

In parallel with this analysis, an equally important task of the preparatory phase is data collection. This activity is dedicated to systematic information sharing in order to define the guidelines for each case study. Data collection for each port is carried out through contributions from project partners, as part of Activity 1.2 of WP1.

Once collected, data are classified into two separate databases:

- The first dataset is used for model fitting, allowing calibration of technical and economic models.
- The second dataset is used to generate hierarchical structures, which can later be exploited in the decision-support phase.

Finally, a risk analysis is performed, comparing potential benefits with outstanding barriers. Once topics and key factors are identified, the process advances to the planning phase, where case-study scenarios, constraints, and strategies for model fitting and optimisation are defined.

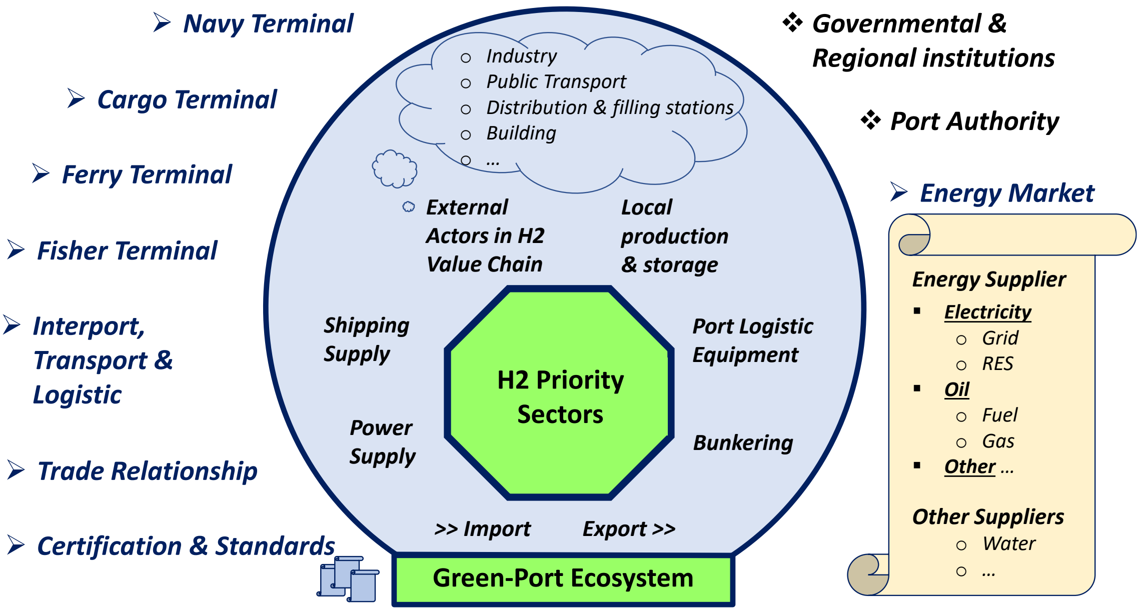

Figure 3: Green ports ecosystem and Priority Sectors in H2 deployment.

Figure. 4: Green Hydrogen facilities.

3.2. Model fitting

Port modelling consists of creating a mathematical model that simulates the energy behavior of power installations within the port ecosystem [2]. The objective is to develop a simple yet accurate model that reflects the port's behavior while avoiding high complexity and long computation times. Each power system of the port (Renewable energy sources, electrolysers, batteries, etc.) is presented by mathematical equations that link the inputs and the outputs and the internal state of the system such as state of charge for batteries and pressure for Hydrogen tank; as shown in figure 5. Information related to port's ecosystem and strategies are also accounted to be exploited during the optimization process (refer to the decision support phase).

Model fitting consists of updating the model's parameters based on the previous information and data collected in the previous steps, in order to create the port avatar. This virtual model aims to simulate the behavior and the interactions between the different renewable energy sources and storage systems in the ports and the energy flow between port equipment. The port avatar considers also the port energy activities and the meteorological data.

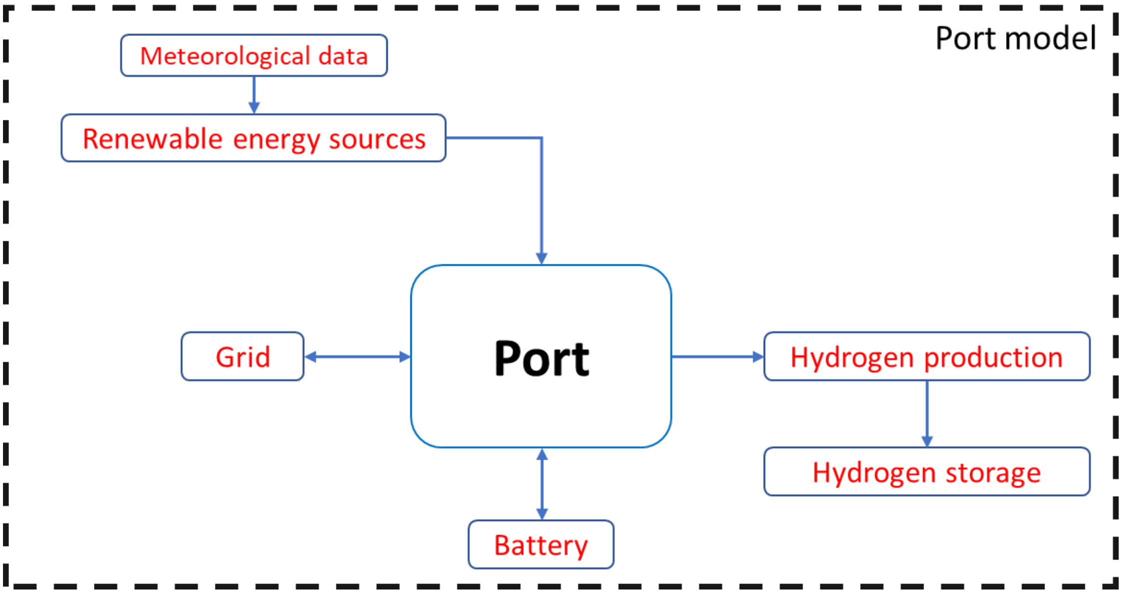

Figure 5: Green Port modelling for Avatar creation.

3.3. Decision Support

Once port's strategies and Avatar are defined, the decision support phase is introduced. Particularly, this step is composed of several processes: the extrapolation of the data analysis started in the preparatory phase, the model optimization (local and global) and the economic analysis.

3.3.1. Data analysis extrapolation

The data analysis and extrapolation phase is the direct continuation of the data treatment initiated during the preparatory phase (Figure 6). In this step, the collected information is processed and classified, with each item assigned a specific weight or priority to create hierarchical structures [3].

Part of this dataset is applied to model optimisation, while the remaining information supports comparative studies, risk analysis, and decision-making processes. Hierarchical or weighted structures are particularly important, as they guide the prioritisation of decisions based on port strategies and goals defined earlier. Figure 7 illustrates an example of case-study strategy selection: depending on the priorities identified in the planning document, the information is ordered accordingly. As a result, potential solutions must align with the established hierarchy.

This approach is especially useful for qualitative data, which are classified to support comparative analyses [3,4]. Meanwhile, quantitative data are primarily treated through modelling and optimisation techniques. Ultimately, the outputs from both the decision-support process and the modelling activities are integrated within the economic analysis, ensuring that technical, strategic, and financial considerations are assessed together.

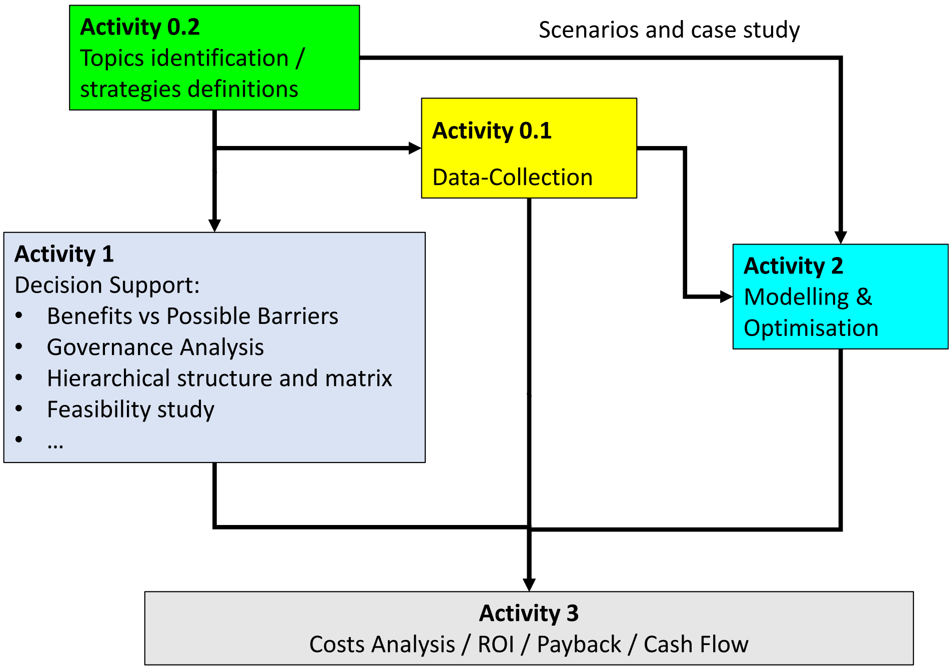

Figure. 6: Data treatment for decision making support.

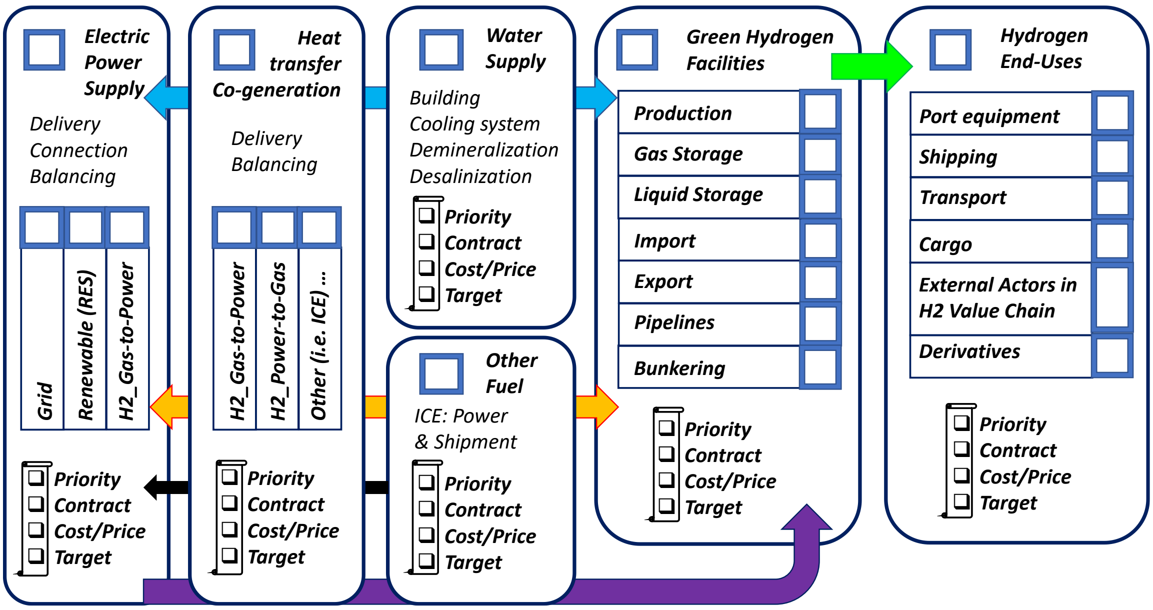

Figure 7: Case-study proposal for objectives definition and activities plan.

3.3.2. Local optimization

Given the persistently high costs of hydrogen technologies, effective energy management and optimal system sizing are essential to reduce investment expenditures and improve operational efficiency. The main objective of the local optimisation algorithm is therefore to determine the optimal configuration and sizing of the different power devices—such as renewable energy sources, hydrogen storage, electrolyzers, and batteries [2].

This optimisation is carried out on the single port avatar, taking into account the specific ecosystem characteristics, operational requirements, and local constraints. Where available from the data collection phase, additional parameters such as system ageing and maintenance costs can also be integrated into the optimisation process to improve accuracy and ensure long-term sustainability of the proposed solutions.

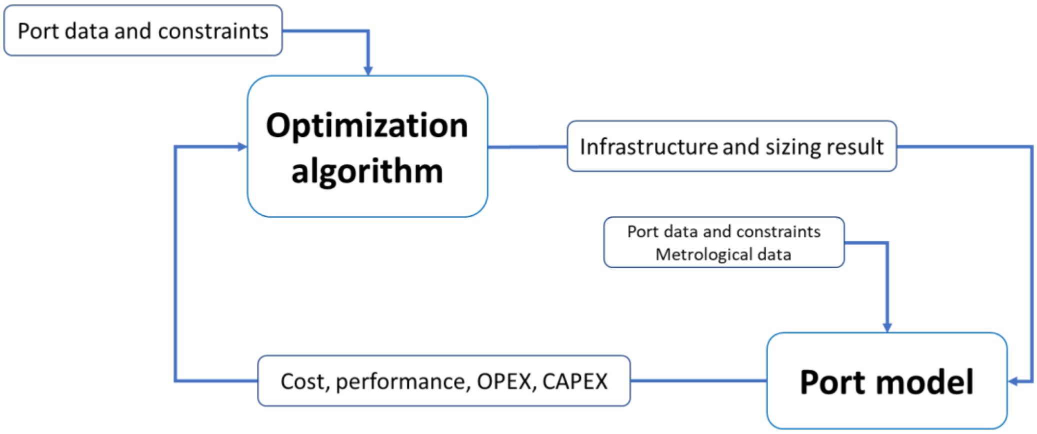

Figure 8. The architecture of optimization algorithm.

The local optimization algorithm behavior is represented in figure 8. It will provide the optimal sizing of the different energy systems of the port with respect to the defined constraints and limitations. Moreover, it provides information on plant performance and costs. It is possible to state the produced / imported and/or the consumed / exported hydrogen (depending on port applications and strategies), and evaluate benefits, by analyzing cash flows, return of investment, and payback indicators.

The local optimization is performed based on linear programming or an equivalent method, which is a mathematical approach to minimize an objective function, with the respect to constraints and limitations that are expressed as in the form of inequalities or linear equations. In this case, the objective function will be expressed based on cost and plant efficiency, while port constraints and limitations, such as power limitations, budget limitations, and power balance will be reformulated as inequalities or linear equations. The adopted optimization algorithm is simple, efficient, and flexible method. By reducing its computational efforts, the model is simulated for several years to enable in-depth analysis over the long-term periods.

3.3.3. Global optimization

Ports may have different ecosystems, activities, administrative constraints, and barriers. Therefore, the results of this local optimization will vary from one port to another. For example, some ports may need hydrogen for their activities but may not be able to produce it, or produce insufficient quantities. Others, however, may have the potential to produce large quantities of hydrogen without a significant internal need. In this context, the scenario of a hydrogen hub, based on an exchange between the four ports, would allow for greater infrastructure sharing and profitability [4]. The global optimization aims to maximize the hydrogen exchanges between the North Sea ports. To maximize the profits and optimize the hydrogen traffic, the global optimization takes into consideration the needs in terms of hydrogen import export of each port, the hydrogen transportation methods (pipelines, vessels...), the distance, and the time.

3.3.4. Economic Analysis

Economic analysis builds on the outcomes of both local and global optimization. While decision-support tools will guide qualitative choices, the optimization results will provide a quantitative assessment of costs and benefits.

Local optimization focuses on determining the total cost of hydrogen production and storage at each port, alongside local benefits and efficiency levels. Global optimization, in turn, assesses hydrogen imports and exports across ports, capturing the associated costs and benefits of these exchanges.

Key economic indicators—such as return on investment, payback period, and cash flow—will then be calculated to evaluate overall project performance. These results will feed directly into the business plan, supporting financial consolidation and budget forecasting.

3.4. Planning Phase

This phase forms the core of the document. It is here that all elements come together to develop the business plan and budget forecast, define the roadmap with clear timelines and milestones, and allocate tasks and resources. It is important to note that while the applied methodology provides inputs for comparative and descriptive analysis, and the model optimization supports the evaluation of energy balance, hydrogen facility sizing, and cost analysis, each port remains responsible for preparing and validating its own roadmap and business plan. This includes developing budget forecasts and setting timelines and targets, as illustrated in Figure 9.

Figure 9: Timeline proposal.

Additional documents may be included depending on each port's internal procedures and standards. A simple proposal for task allocation among stakeholders is presented in Table 1. The purpose is to clarify the role of each actor, indicating whether they are responsible for decision-making, providing expertise or consultation, carrying out specific actions, or serving as end users [1].

Table. 1: Stakeholder tasks and responsibilities matrix proposal.

Stakeholders List: [1) Port Authority; 2) Government institution; 3) Municipality; 4) Private company part of port ecosystem; 5) Green energy supplier; 6) H2 end-user; 7) logistics; 8) port equipment; 9) ship; N) ...]

Tasks	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**...**
Develop H2 strategies									
Monitor H2 market									
Enhance renewables Ecosystem									
Define R&D areas for H2									
Investigate H2 requirement and needs									
Upscale electrical distribution infrastr.									
Port equipment electrical/H2 powered									
Port ship electrical/H2 powered									
H2 system facilities									
H2 system maintenance									
H2 production									
H2 gas storage									
H2 liquid storage									
Pipelines									
Filling station for port vehicles									
Filling station for public transport									

Bunkering									
Ship equipment									
Port terminal equipment									
Ship permitting contact & certification									
Port permitting contact & certification									
H2 import									
H2 export									
Develop logistic and support structures									
Business case H2 vs maritime fuels									
Secure public/private funding									
Port management									
Ship management									
Asses scaling-up									
Set-up partnership for H2 sharing									
Enhance end-use H2 value chain									
Build coalitions/create hub ecosystem									
...									

3.5. Reports and Conclusions

The last phase is characterized by procedure sum-up, with the creation of a suited portfolio structure, as represented in figure. 10. Portfolio must be synthetic, ordered and it must contain all the performed analysis. The case-study number, scenario and targets have to be accessible in the document head, followed by comparative and descriptive analysis, such as comparison between the potential benefits and possible barriers. Subsequently, quantitative results and economic analysis are presented before the real work plan documents' presentation. A final report summing monitoring activities and recommendations can be also attached.

Case-Study N° # **NS H2VPorts**

Geographical Area	Port	Long-Term Objectives	Relevant actors
NS Area	#####	Green H2 production, storage, distribution & use @ one port size to be extended to hub's scenarios	Private authority, Public authority, Institutions in general, Infrastructures and Service Providers, General Public

Case-Study Context	Scope
Ecosystem: Stakeholders / Governance / Targets / Strategies	Production / import / consumption for port equipment / consumption for transport / end-uses' value chain / infrastructure creation / Bunkering / create partnership

Potential Benefits vs.	Possible Barriers and Risk Analysis
New Economy & Job positions / Local energy autonomy / CO2 reduction (environment + incentives' possibility)	Safety / Regulation / Certification & Permits / investment cost / Storage & vessel pending questions (Liquid? Gas? Containers?)

Economic Analysis
Costs analysis / ROI / Feasibility study / Business plan / Budget forecasting for Funding

Work Plan
Road Map / Timeline & Milestones / Tasks and Resources

Figure 10: Example of Portfolio including all the documents to finalize in the planning phase.

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