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H2MA

# **Guidelines on the H2MA tool (Alpine Space-wide version)**

Activity 1.5

15 Apr 2024



## DOCUMENT CONTROL SHEET

### Project reference

<b>Project title</b>	Green Hydrogen Mobility for Alpine Region Transportation
<b>Acronym</b>	H2MA
<b>Programme priority</b>	Carbon neutral and resource sensitive Alpine region
<b>Specific objective</b>	SO 2.1: Promoting energy efficiency and reducing greenhouse gas emissions
<b>Duration</b>	01.11.2022 – 31.10.2025
<b>Project website</b>	<a href="https://www.alpine-space.eu/project/h2ma/">https://www.alpine-space.eu/project/h2ma/</a>
<b>Lead partner</b>	KSSENA

### Short description

H2MA brings together 11 partners from all 5 Interreg Alpine Space EU countries (SI, IT, DE, FR, AT), to coordinate and accelerate the transnational roll-out of green hydrogen (H<sub>2</sub>) infrastructure for transport and mobility in the Alpine region. Through the joint development of cooperation mechanisms, strategies, tools, and resources, H2MA will increase the capacities of territorial public authorities and stakeholders to overcome existing barriers and collaboratively plan and pilot test transalpine zero-emission H<sub>2</sub> routes.

### Document details

<b>Full document's title</b>	Guidelines on the H2MA tool (Alpine Space-wide version)
<b>Version</b>	V1
<b>Author/s</b>	Federico Parolin, Paolo Colbertaldo, Stefano Campanari, Silvia Galante, Luca Pastore, Giovanni Storto
<b>Organization/s responsible</b>	Regione Lombardia
<b>Delivery period</b>	2, 7-12

## 1. OVERVIEW

### 1.1 Scope of the tool

The H2MA tool provides a numerical tool for the visualisation and computation of data regarding the hydrogen infrastructure for mobility applications in the regions of the Alpine Space.

The H2MA tool is devised to:

- 1) Enable the visualization of available information regarding existing and planned facilities (hydrogen refuelling stations and green hydrogen production sites).
- 2) Compute cost-optimal configurations for scenarios defined by the user – the definition is performed by selecting parameters such as the share of hydrogen vehicles, techno-economic data of the technologies, constraints on distances and max capacities, etc.
- 3) Enable the visualization of the configuration obtained by the calculations.

The tool relies on a database of information, as collected by the partners of the H2MA project, regarding:

- regional geographical and statistical features;
- existing and planned hydrogen infrastructure elements (hydrogen production sites, hydrogen refuelling stations);
- renewable energy sources potential.

For the techno-economic features, default values are embedded in the tool, as extracted from recent literature and industrial data, and can be modified by the user if desired.

The tool is intended for use by the H2MA project partners, with the aim of generating (several) scenarios of the regions of interest, upon which development considerations and strategies can be derived and discussed with stakeholders. The use of the tool does not require specific engineering or information technology skills. For a proficient use, prerequisites may be a general understanding of hydrogen as an energy vector, production processes, and delivery options.

Previous versions of the H2MA tool focused on regional assessments at NUTS-2 level. This version expands the geographical span of the analysis by offering the possibility of performing assessments on the entire Alpine Space area (regions included in the H2MA projects), according to the modalities presented in the remainder of this document.

### 1.2 Features of the Alpine Space-wide version (15 Apr 2024)

This new version features the possibility to perform an analysis (including optimisation) on the entire Alpine Space area, considering all the regions involved in the H2MA project at once. To allow for a wider geographical coverage, the optimisation model features additional assumptions aimed at decreasing the computational complexity (see Section 2). In particular, the candidate HRSs are pre-selected by the algorithm and the number of typical days is smaller.

## 2. MATHEMATICAL MODEL

This section offers a brief yet complete description of the modelling approach, structure, and methods that have been used in the development of the computational model for the hydrogen mobility infrastructure optimisation, which constitutes the core element of the H2MA tool, as introduced in Section 1.1.

The objective of the model is to perform a techno-economic optimisation in order to identify cost-optimal configurations of the hydrogen production, delivery, and dispensing infrastructure in a region of the Alpine Space or in the entire Alpine Space, in scenarios selected by the user.

### 2.1 Modelling approach

The H2MA tool relies on an optimisation model that determines the cost-optimal configuration of a hydrogen infrastructure for a given spatial domain and a given hydrogen demand distribution. The model adopts a linear programming (LP) formulation to define mass and energy balances of the hydrogen infrastructure components.

The infrastructure operation is tracked over a year-long time frame with a daily resolution. To limit the computational complexity, the year is modelled through the repetition of typical days, which are obtained by applying the k-means clustering algorithm on the input RES generation profiles. By default, the H2MA tool adopts 4 typical days for the optimisation of NUTS-2 areas, and 1 typical day for the optimisation of the entire Alpine Space. However, the user can select a different number of typical days, as described in Section 5.2.4. Increasing the number of typical days increases the resolution time.

The tool includes HRS siting, considering existing conventional (diesel/gasoline) stations as candidate locations. For each NUTS-3 subarea, the adopted algorithm selects the location of HRSs in order to maximise the geographical coverage, considering the hydrogen demand in the subarea and the HRS capacity selected by the user (see Section 5.2.4).

The interested reader may also refer to the scientific literature<sup>1</sup> for further information on features and techno-economic optimisation of hydrogen supply chains.

### 2.2 Problem statement and objective function

The modelled infrastructure covers the complete hydrogen supply chain, including production, conditioning, delivery, storage, and consumption at HRSs. The H2MA tool

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<sup>1</sup> Relevant articles include:

- C. Yang, J. Ogden, “Determining the lowest-cost hydrogen delivery mode”, *Int J Hydrog Energy*, 32(2), 2007, 268-286, doi: 10.1016/j.ijhydene.2006.05.009
- M. Reuß, T. Grube, M. Robinius, D. Stolten, “A hydrogen supply chain with spatial resolution: Comparative analysis of infrastructure technologies in Germany”, *Appl Energy*, 247, 2019, 438-453, doi: 10.1016/j.apenergy.2019.04.064
- F. Parolin, P. Colbertaldo, S. Campanari, “Development of a multi-modality hydrogen delivery infrastructure: An optimization model for design and operation”, *Energy Convers Manag*, 266, 2022, 115650, doi: 10.1016/j.enconman.2022.115650

includes multiple technological alternatives for the different stages of the supply chain, as detailed in Section 2.3.

The optimisation model minimises the total annual cost of the hydrogen supply chain, which includes all capital and operational expenditures related to hydrogen production (including installation and operation of RES power generation systems in centralised H<sub>2</sub> production plants), hydrogen conditioning (compression), hydrogen delivery from production sites to HRSs, hydrogen storage, and hydrogen refuelling stations.

The optimisation problem is summarized as follows.

The required input data are:

- the set of available hydrogen production, storage, and transport technologies, with their techno-economic data;
- the topologies of the candidate transport networks for the included hydrogen transport modalities;
- the location of HRSs, as selected by the siting algorithm (see Section 2.1);
- the candidate locations of production sites;
- the upper boundaries for the installed production capacity;
- the electricity generation profiles in the case of RES-based hydrogen production.

The optimisation results yield the infrastructure configuration that minimises the total annual cost, in terms of:

- the installed hydrogen production and hydrogen storage capacities;
- the structure of the hydrogen transport networks, the exploited pathways, and the delivered hydrogen quantities;
- the hydrogen flows of each component of the infrastructure.

## **2.3 Model structure**

### **2.3.1 Hydrogen refuelling station options**

The optimisation model encompasses the installation of both conventional HRSs and HRSs with onsite hydrogen production. The former are connected to the hydrogen delivery network and are supplied from centralised production plants, while the latter include an electrolyser powered with RES electricity through a power purchase agreement (PPA) at fixed price. In terms of location, the model favours installation at sites of existing conventional refuelling stations along TEN-T road corridors, which are the most likely to host hydrogen refuelling in the development of a hydrogen mobility infrastructure.

### **2.3.2 Hydrogen production options**

The model distinguishes between centralised and onsite hydrogen production. Centralised production involves the installation of a RES power generation plant, either PV or wind-based, and electrolysis. Although the time resolution of the optimisation model is daily, intra-day fluctuations are taken into account, guaranteeing a correct match of variable

electricity generation with the electrolysis operation, under a fixed RES/electrolysis nominal capacity ration, as discussed in Section 4.

Hydrogen compression is performed at production sites, starting from 30 bar up to a pressure level suitable for the selected delivery modality (see Section 2.3.3).

Onsite hydrogen production at HRSs is based on a PPA at fixed price, assuming that the counterparty is always able to supply the required electricity.

### **2.3.3 Hydrogen delivery options**

Hydrogen delivery occurs via either hydrogen pipelines or compressed hydrogen trucks (tube trailers). Pipelines are operated between 70 and 100 bar, requiring recompression at delivery points (up to an average storage pressure of 160 bar, corresponding to Type 1 vessels). Compressed hydrogen trucks carry hydrogen at 500 bar, supplying a single HRS in each trip. Specifically, trucks release their entire payload at the destination HRS and then return to the starting point, with an exchange of trailers. In the case of trucks, a cost per km is included to account for fuel consumption.

## **2.4 Calculation procedure**

This section outlines the calculation procedure of the H2MA tool analyses, going through the main steps that lead to the hydrogen infrastructure optimisation.

### **2.4.1 Hydrogen demand**

The hydrogen demand is computed on a NUTS-2 level basis, considering the share of FCEVs by vehicle category (user input), the vehicle stocks, and the average mileages. The regional demand is then distributed on the NUTS-3 subareas based on economic and demographic data (GDP per capita, vehicle ownership, population).

### **2.4.2 Creation of candidate infrastructure**

The optimisation model implemented in the H2MA tool operates on a candidate infrastructure, which sets the available locations for the installation of hydrogen production plants and HRSs, as well as the available routes for hydrogen delivery (pipeline installations and transit of trucks).

The candidate delivery network is retrieved from the input data of the H2MA database ('Par05\_pipe\_delivery\_network.shp' and 'Par04\_road\_delivery\_network.shp' for pipeline delivery and for compressed hydrogen truck delivery, respectively). To ensure the feasibility of the optimisation problem, the largest connected<sup>2</sup> part of the network is extracted and used as candidate network for the calculation.

Two candidate centralised hydrogen production sites (one PV-based and one wind-based) are defined for each NUTS-3 subarea, possibly representing large-scale plants or an aggregate of multiple ones in the subarea. By default, the candidate location is set as the

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<sup>2</sup>A connected network is a network in which there is a path that connects every pair of points within the network. This is an essential requirement for the optimisation problem, as failure to meet it may result in HRSs being unreachable from production sites.

nearest delivery network node to the subarea centroid. The user can edit the candidate locations for PV-based and wind-based centralised production site for each NUTS-3 subarea, as described in Section 5.

The candidate locations for HRS installation correspond to existing diesel/gasoline stations ('...\input\data\Alpine Space\stations\_AS.shp'). In each subarea, the required number of stations is determined from the hydrogen demand and the HRS maximum capacity. HRSs are then sited through an algorithm that maximises the minimum distance among points. In this way, the geographical coverage is maximised.

For both hydrogen production plants and HRSs, the existing and planned sites available in the H2MA database are included in the calculation. For pipeline delivery, the model enables the creation of intermediate storage hubs, whose candidate locations are uniformly distributed in the area.

Finally, import points can be introduced with user-customised coordinates. Besides the location, each candidate import point also requires the definition of the maximum import capacity ( $t_{H_2}/d$ ) and import price ( $\text{€/kg}_{H_2}$ ), as described in Section 5.

### **3. 'INPUT DATA' DATABASE**

#### **3.1 Features**

The main pieces of information available to the tool are the input data collected in the 'input data database'. In the folders for each single region, data correspond to the values provided by the H2MA project partners, after adjustment and rearrangement for alignment to templates. In the Alpine Space folder, data are present, as retrieved from external sources or by rearranging values of the single regions from the partners.

#### **3.2 Modification or update of the input data database by user**

##### **3.2.1 Update of data of a region**

The user can add other existing/planned hydrogen refuelling stations (HRS) or hydrogen production sites (H2prd) of a region, by updating the related files (Par06 and Par07, respectively) in the database, which can be accessed in the unzipped folder on the user's computer at '...\H2MA\_v20240415\_AlpineSpaceVersion\input\data'.

At the new launch of the tool, it will be able to extract the updated information.

##### **3.2.2 Addition of a region for regional assessment**

It is also possible to add another region to be analysed as a regional assessment case. To do that, a new folder must be created in the unzipped folder on the user's computer at '...\H2MA\_v20240415\_AlpineSpaceVersion\input\data', naming the new folder with the corresponding NUTS-2 code, and pasting all the required data, according to the provided templates. For additional information regarding the proper use of templates, refer to other regions in the database present in the original .zip folder.

### 3.2.3 Addition or update for full Alpine Space assessment

The entire Alpine Space area is available for complete optimisation. To this end, the tool considers both data collected by partners, as available in the folders of NUTS-2 areas, and a new, dedicated dataset of the Alpine Space. Specifically, the latter includes:

- the candidate hydrogen delivery networks ('...\input\data\Alpine Space\Par04\_road\_delivery\_network.shp' and '...\input\data\Alpine Space\Par05\_pipe\_delivery\_network.shp');
- the TEN-T road network ('...\input\data\Alpine Space\Par03\_tent\_network.shp');
- the location of existing gasoline/diesel stations ('...\input\data\Alpine Space\stations\_AS.shp').

When the Alpine Space is selected, the optimisation is performed including the NUTS-2 regions for which sufficient data are provided. Specifically, these include (for additional details on the input data, refer to the provided templates):

- the vehicle stock by category in the NUTS-2 area (Par09\_stock.xlsx);
- the average mileage by vehicle category (Par10\_mileage.xlsx);
- the macroeconomic and demographic data by NUTS-3 subarea (Par11\_macro\_data.xlsx);
- the hourly-resolved RES generation profiles at NUTS-3 level (Par12\_res\_profiles.xlsx).

With the provided database, the Alpine Space-wide version of the H2MA tool analyses the regions included in the H2MA project at once. To include additional regions in the Alpine Space optimisation, the user needs to create a dedicated subfolder for the related NUTS-2 area (named with the official NUTS-2 code) in the 'input\data' folder, containing the data indicated above (Par09-Par12). Data regarding the presence of existing/planned HRSs (Par07) and production sites (Par06), as well as conventional stations on TEN-T network (Par08), are considered for the Alpine Space optimisation if available but are not mandatory for the analysis.

## 4. TECHNO-ECONOMIC DATA

The calculation implemented in the H2MA for the identification of cost-optimal configurations involves a large number of parameters and assumptions, in addition to the 'input data' present in the created database.

For the techno-economic features of the technologies and of the markets, default values are embedded in the tool, as extracted from recent literature and industrial data. The values can be modified by the user in the 'Data' tab, if desired. Units are also indicated.

*Table 1. Default techno-economic values.*



	CAPEX	OPEX	Lifetime	Performance and sizing parameters	
				Definition	Value
<b>Photovoltaic</b>	450 €/kW <sub>p</sub>	2%CAPEX/y	20 y	Assigned generation profile (extracted from input data)	
<b>Wind</b>	1000 €/kW <sub>nom</sub>	2%CAPEX/y	25 y	Assigned generation profile (extracted from input data)	
<b>Electrolysis</b>	600 €/kW <sub>e, nom</sub>	2%CAPEX/y	20 y	Specific electric consumption	55 kWh <sub>e</sub> /kg <sub>H2</sub>
<b>Hydrogen storage (pressurized metal tanks)</b>	400 €/kg <sub>H2</sub>	2%CAPEX/y	30 y	-	-
<b>Hydrogen compressor</b>	1500 €/kW <sub>e, nom</sub>	4%CAPEX/y	15 y	Efficiency (electricity-to-fluid)	63%
<b>Hydrogen pipelines</b>	6 M€/(km·m <sup>2</sup> )	4%CAPEX/y	40 y	Maximum section area <sup>3</sup>	1.13 m <sup>2</sup>
<b>Hydrogen delivery trucks (pressurized gaseous form)</b>	400 €/kg <sub>H2</sub>	2%CAPEX/y	20 y	Vehicle capacity	1000 kg
				Variable OPEX	1.6 €/km
<b>Hydrogen refuelling stations</b>	3 M€/(t <sub>H2</sub> /d)	2%CAPEX/y	30 y	Maximum capacity	6 t/d
<b>Hydrogen refuelling stations with onsite H<sub>2</sub> production</b>	<b>Station</b>	3.5 M€/(t <sub>H2</sub> /d)	2%CAPEX/y	30 y	-
	<b>Electrolysis</b>	720 €/kW <sub>e, nom</sub> *	2%CAPEX/y	20 y	Specific electric consumption

\* Higher CAPEX than centralised due to expected smaller capacity on average.

For electrolysis in centralised H<sub>2</sub> production sites, only combined installations of RES generation and electrolyzers are considered, with assigned nominal capacity ratios (RES/electrolysis) of 2 for PV and 1.25 for wind. Values have been estimated for cost-optimal configurations in literature<sup>4</sup>.

For electrolysis in HRSs with onsite H<sub>2</sub> production, the supply of green electricity via power purchase agreement (PPA) at fixed price is assumed, with no restrictions on time of use.

Grid electricity (for uses other than PPA-based electrolysis feeding) is set as 200 €/MWh<sub>e</sub> for purchase. This supply is used for compression units and possibly for (minor) support to centralised H<sub>2</sub> production sites. No revenue is assumed in case of surplus generation from RES plants.

## 5. USER MANUAL

### 5.1 Quick steps

- 1) Extract files from .zip folder.
- 2) Launch the tool by opening the file “H2MAapp.exe” (double click). Wait for initial window to appear. This may require some time (up to a couple of minutes, depending on hardware). The command prompt (black window) may open in background, do not close it.

<sup>3</sup>Estimated from a maximum diameter of 1.2 m.

<sup>4</sup>F. Parolin, P. Colbertaldo, S. Campanari, “Development of a multi-modality hydrogen delivery infrastructure: An optimization model for design and operation”, Energy Convers Manag, 266, 2022, 115650, doi: 10.1016/j.enconman.2022.115650

- 3) In the initial window, click on “New” button. > Select area of analysis from dropdown menu. > Click “Start”. > Wait for input data loading. This may require some time (up to a few minutes, depending on hardware); a temporary window will pop up. > Main window opens.
- 4) You are now in the main window of the H2MA tool; navigation occurs through tabs.
  - a. “Current situation” tab.
    - i. Alpine Space map. Visualise existing and planned hydrogen infrastructure on a map of the entire Alpine Space. In the map, click on points to visualise details. Zoom-in/out using the “+”/“-“ buttons on the top-left part of the map, by using the mouse wheel, or by using the touchpad. Pan the map by clicking and dragging.
    - ii. Hydrogen refuelling stations. Visualise a list of existing and planned HRSs, with their main attributes (table).
    - iii. Hydrogen production sites. Visualise a list of existing and planned hydrogen production sites, with their main attributes (table).
  - b. “Scenario definition” tab.
    - i. Enter the desired share of FCEVs by vehicle category. The tool accepts values between 0 and 1. At least one of the values must be higher than 0, otherwise there is no hydrogen demand and the tool cannot compute any cost-optimal configuration.
    - ii. Visualise/edit FCEV specific consumption values, by vehicle category. Default values are provided.
    - iii. Select hydrogen production and import features (two sub-tabs):
      - o Hydrogen production options. Select hydrogen production options to include. If ‘onsite production at HRSs’ is selected, edit the PPA electricity price according to the desired assumption.
      - o Hydrogen import points. If one or many import points want to be considered, fill in the table with latitude, longitude, max capacity, and hydrogen price.
    - iv. Select the hydrogen delivery modality from the dropdown menu. This selection is required regardless of the included hydrogen production options.
    - v. Visualise/edit tables of overall vehicles stock (all fuels). Values are provided from input data database.
    - vi. Click on “Confirm scenario” button to confirm assumptions. The map on the right side of the tab will update.
  - c. “Data” tab.
 

Visualise/edit techno-economic data and RES generation data, organised in sub-tabs. Depending on screen size and resolution, some tabs may be accessed after clicking on the left/right arrow.

Default values are provided and can be modified if desired.
  - d. “Scenario optimisation” tab.
    - i. Click on the “Initialise scenario” button to initialise the scenario for the optimisation. A progress bar will pop up. After completion, the candidate network for hydrogen delivery will be displayed.

- ii. Click on the “Start optimisation” button to start the optimisation. A message box will appear while the optimisation progresses. The optimisation may take several minutes. It is preferable to not interfere with the operation (a ‘not responding’ message may appear on the title line of the window if the user clicks elsewhere, this slows down the execution but the tool is still running).
- iii. After completion, results are visualised in figures and tables in the multiple sub-tabs located in the right part of the window. Depending on screen size and resolution, some tabs may be accessed after clicking on the left/right arrow. By clicking on a point on the maps, information appears.
- iv. In each sub-tab of results, ‘Save’ buttons are available.

Different scenarios can be run sequentially. Every time the input assumptions are varied (e.g., FCEV shares, import points, techno-economic data, ...), the scenario must be confirmed (via the “Confirm scenario” button in the “Scenario definition” tab) and initialised through the “Initialise scenario” button in the “Scenario optimisation” tab. To analyse a different region, close the “H2MA tool – Analysis” window, select the desired region in the “H2MA app” window, and click on the “New” button.

## 5.2 Extended

### 5.2.1 General features and use

The H2MA tool is distributed in a zipped folder that contains the application file (“H2MAapp.exe”) and the input information (“input” folder). Files are accessible upon extraction from the zipped folder. The “input” folder contains the H2MA database within the “data” subfolders. Users can update the database by editing the available files. New areas can be added by creating corresponding subfolders, which must be named using the official NUTS codes. Adherence with the indicated input data structure is required. The tool outputs an error message if data do not meet the requirements.

Loading and running times depend on the employed hardware. In general, data extraction is faster if the tool is operated locally (i.e., outside of any shared drives/cloud storages), while computationally-intensive operations (such as scenario initialisation and scenario optimisation) are faster if there is no other concurrent activity on the computer.

The tool works best when open as full screen window. Tables are resized in case of movement / change of window size. Figures and maps may not resize.

### 5.2.2 Opening window

The opening window (named “H2MA app”) allows the user to select the area of the analysis and start a new assessment. The areas available in the dropdown menu correspond to the subfolders present in the ‘input\data’ folder. While all folders are visualised in the menu, the analysis can only be performed for those that have a complete dataset. An error message will be displayed if a region with incomplete data is selected.

If “Alpine Space” is selected, the pop-up window reported in Figure 5.1 is displayed. The user is asked to select whether to update the Alpine Space data. This is only required after

modifications of the H2MA database (including both modifications to already available data or introduction of new areas) and needs to be performed only once after each modification.

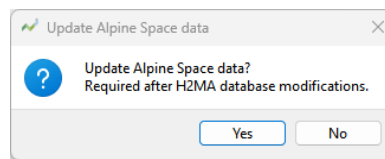




Figure 5.1. Pop-up window for Alpine Space data update.

### 5.2.3 “Current situation” tab

The “Current situation” tab allows the user to visualise information regarding the existing/planned hydrogen infrastructure within the Alpine Space area, and is organised in three subtabs:

- “Map” tab: it shows the current situation regarding existing/planned hydrogen production plants and HRSs within the Alpine Space area (Figure 5.2). A legend is available at the left bottom. The map enables:
  - zooming in/out, by using the buttons  at the top left, by scrolling the mouse wheel, or by using the touchpad gestures;
  - panning, by clicking and dragging with the mouse;
  - activate/deactivate layers, interacting with the button  at the top right;
  - visualise production site/HRS features, by clicking on points.
- “Hydrogen refuelling stations” tab: it shows a table with all the existing and planned HRSs within the Alpine Space area, as available in the H2MA database. Empty table cells correspond to missing values in the database.
- “Hydrogen production sites” tab: it shows a table with all the existing and planned hydrogen production sites within the Alpine Space area, as available in the H2MA database. Empty table cells correspond to missing values in the database.

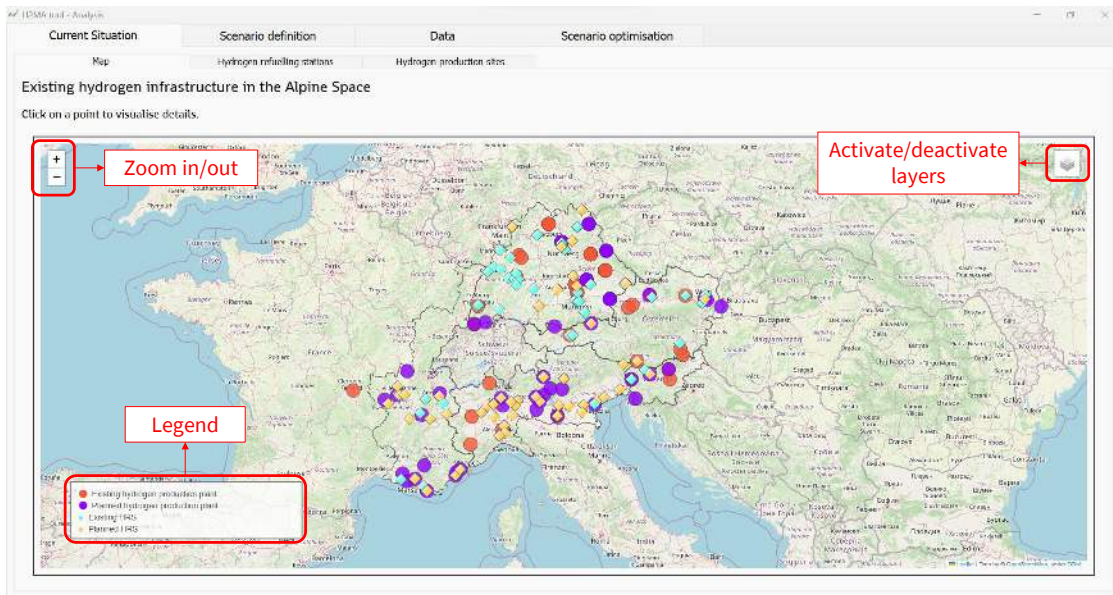


Figure 5.2. "Map" subtab within the "Current situation" tab.

### 5.2.4 "Scenario definition" tab

The "Scenario definition" tab allows the user to define the scenario assumptions that will serve as input to the hydrogen infrastructure optimisation (Figure 5.3). The left side of the tab contains the user-editable scenario assumptions, while the right side features a map of the area with the resulting hydrogen demand by subarea.

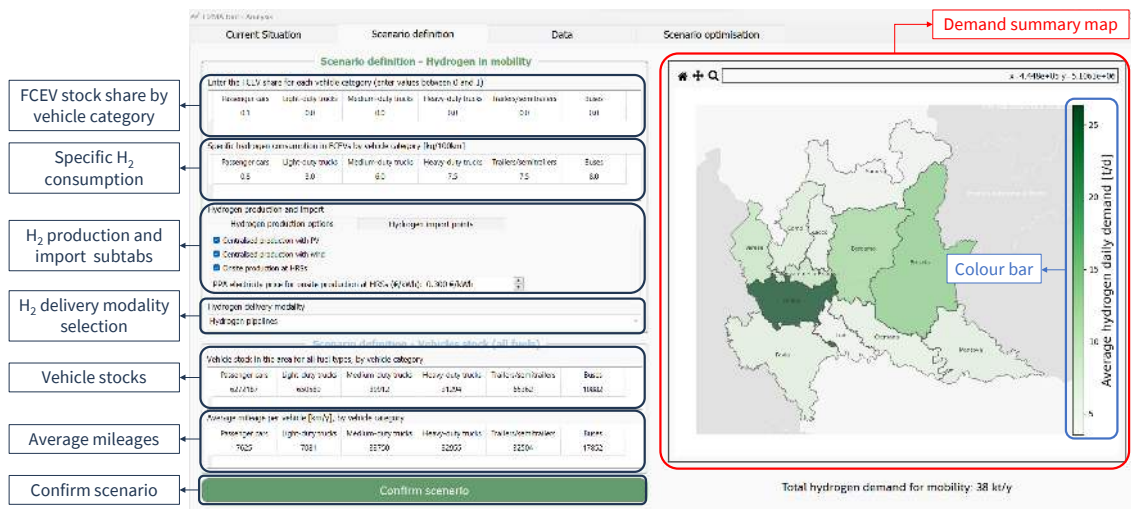


Figure 5.3. "Scenario definition" tab.

**FCEV stock share by vehicle category.** Values represent the penetration of FCEV in the stock share of the area. Only values between 0 and 1 are accepted. At the tool opening, all values are initialised to zero.

**Specific H<sub>2</sub> consumption of FCEVs by vehicle category.** Default values are provided, and can be edited by the user if desired. Only positive values are accepted.

**Hydrogen production and import.** This section is organised in two subtabs:

- *Hydrogen production options* (Figure 5.4): it allows the user to define the available production options, selecting between centralised production with PV, centralised production with wind, and onsite production at HRSs. The tool accepts any combination of the three options, but the feasibility of the problem depends on the other data and assumptions as well. If onsite production at HRSs is selected, the corresponding PPA price (in €/kWh<sub>e</sub>) must be entered in the dedicated box.

The screenshot shows a web interface titled "Hydrogen production and import". It has two tabs: "Hydrogen production options" (active) and "Hydrogen import points". Under the active tab, there are three checked checkboxes: "Centralised production with PV", "Centralised production with wind", and "Onsite production at HRSs". Below these is a text input field labeled "PPA electricity price for onsite production at HRSs (€/kWh):" with the value "0.300 €/kWh" and a small up/down arrow icon.

Figure 5.4. Selection of hydrogen production options within the "Scenario definition" tab.

- *Hydrogen import options* (Figure 5.5): it allows the user to introduce hydrogen import points, if desired. The user needs to enter the point coordinates (latitude and longitude), the import capacity (in t<sub>H2</sub>/d), and the import price (in €/kg<sub>H2</sub>). A maximum of four import points can be introduced. If the table is left to default values ("nan"), this feature is automatically deactivated.

The screenshot shows the "Hydrogen import points" tab in the "Hydrogen production and import" interface. It contains a table with the following data:

Latitude	Longitude	Capacity (t/d)	Price (€/kg)
45.2	9.2	10.0	4.0
nan	nan	nan	nan

Figure 5.5. Definition of hydrogen import points within the "Scenario definition" tab.




**Hydrogen delivery modality.** The user must select the hydrogen delivery modality (hydrogen pipelines or compressed hydrogen trucks) through the dropdown menu. A selection is required even if onsite production at HRSs is the only hydrogen production options included.

**Vehicle stock in the area by vehicle category.** Default values are retrieved from the H2MA database and correspond to the total number of vehicles in the area, considering all fuel types. The user may edit the values to analyse different scenarios. Only positive values are accepted. Stock values are used in combination with the share of FCEVs, average consumptions, and average mileages to compute the H<sub>2</sub> demand in the area.

**Average mileage by vehicle category.** Default values are retrieved from the H2MA database and correspond to the average vehicle mileage (in km travelled per year for one vehicle) by vehicle category. The user may edit the values to analyse different scenarios. Only positive values are accepted. Mileage values are used in combination with the share of FCEVs, average consumptions, and vehicles stock to compute the H<sub>2</sub> demand in the area.

**“Confirm scenario” button.** The user must click on the button to confirm the scenario assumptions. Upon clicking, the map on the right is updated, showing the H<sub>2</sub> demand distribution in the area. If any change is made on the scenario assumptions, the user must click again on the “Confirm scenario” button to save the new set of assumptions.

**Demand summary map.** It is updated anytime the “Confirm scenario” button is clicked and shows the hydrogen demand distribution by NUTS-3 subarea. A colour bar is present at the right. The map enables:

- zooming in by clicking on the button  and drawing rectangles on the map;
- zooming out by clicking on the button ;
- panning, by clicking on the button  and clicking and dragging on the map.

### 5.2.5 “Data” tab

The “Data” tab allows the user to visualise and edit (if desired) techno-economic data and RES power generation data (Figure 5.6). The tab is organised in two sections:

- i. Section ‘Techno-economic data’: it allows the user to visualise and, if desired, edit the input techno-economic parameters. For each technology, CAPEX, OPEX, and lifetime are provided. When necessary, other performance parameters are included (e.g., specific electricity consumption for electrolysis devices). See Section 4 for additional details on the available parameters. In the “Simulation settings” subtab, the user can edit the number of typical days considered in the optimisation.
- ii. Section ‘RES generation data’: it is organised in two subtabs ‘PV’ and ‘Wind’ and allows the user to edit (if desired), in each subarea, the maximum capacity and the location of centralised H<sub>2</sub> production plants powered by PV and wind, respectively. By acting on the maximum capacity, the user may favour or deactivate (by setting the value to zero) centralised production in specific subareas. The default location of centralised plants correspond to the node of the delivery network nearest to the subarea centroid. This can be modified by the user by acting on the “Latitude” and “Longitude” attributes. By clicking on the “Reset default locations” button, the default locations are restored.

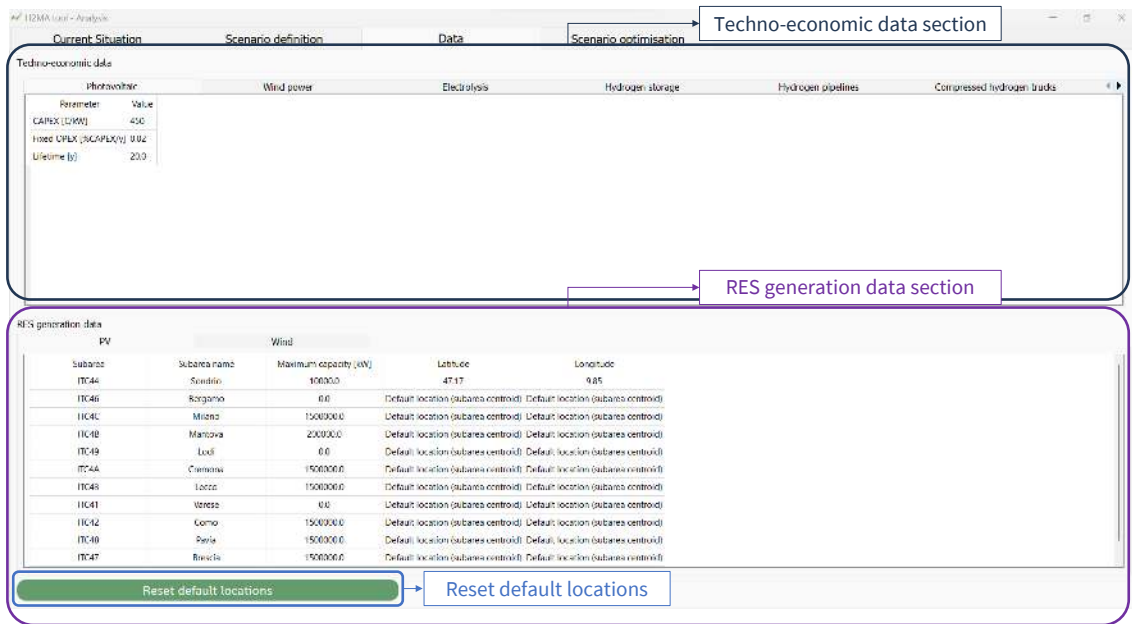


Figure 5.6. "Data" tab.

### 5.2.6 "Scenario optimisation" tab

The "Scenario optimisation" tab allows the user to run the hydrogen infrastructure optimisation (Figure 5.7), based on the input information of the H2MA database and the assumptions defined in the "Scenario definition" tab. Accordingly, this is the tab where the tool performs the main calculations (creation of the candidate infrastructure and optimisation of the defined scenario).

The left side of the tab contains buttons to initialise and run the scenario, as well as a figure where the candidate delivery network is displayed after scenario initialisation. The right side of the tab shows the optimisation results and is organised in subtabs containing various figures and tables, as described in the remainder of this section.

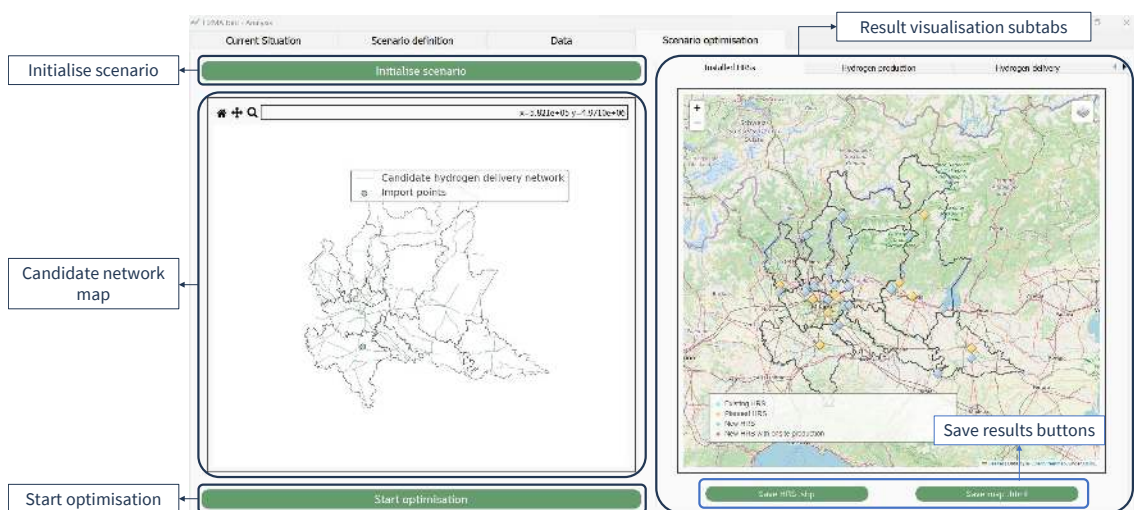


Figure 5.7. "Scenario optimisation" tab.

**"Initialise scenario" button.** The user must click on the button as first step in the "Scenario optimisation" tab. Upon clicking, a pop-up window appears, containing a progress bar



showing the level of advancement of the process. The progress window automatically closes upon process completion. Within the scenario initialisation, the tool builds the candidate hydrogen infrastructure, converting input data and assumptions into proper mathematical structures. Depending on the input data (networks of the H2MA database) and assumptions (FCEV shares, import points, ...) scenario initialisation may result in computationally-intensive operations, leading to increased computing time (some minutes may be required to complete the process).

#### **NOTES ON PROGRESS WINDOW “Scenario initialisation”**

A ‘not responding’ message may appear in the progress window. This is due to Windows behaviour, which perceives that the user is attempting to perform multiple tasks (which may correspond even to simply clicking on another window) when computationally-intensive operations are ongoing. However, its appearance does not prevent the completion of the operation in progress. Depending on the operations that the user is performing in parallel, the scenario initialisation may be slowed down.

**“Candidate delivery network” figure.** Upon completion of the scenario initialisation process, the candidate delivery network is displayed. This correspond to the available pathways that connect candidate production sites and import points to candidate HRSs. The resulting network depends on the input data of the H2MA database and on the user selection of the hydrogen delivery modality. As described in Section 2.4.2, a connected network is built in order to ensure mathematical feasibility of the problem. Accordingly, the network appearance may differ compared to the input shapefile (Par04 and Par05). In this way, the figure allows the user to evaluate the quality of the input shapefile and, if desired, modify it. In addition, the figure allows the user to verify whether import points are correctly placed.

**“Start optimisation” button.** By clicking on the button, the hydrogen infrastructure optimisation is launched. Upon clicking, a pop-up window opens, indicating that the optimisation is in progress. The window automatically closes once the optimisation is completed. Upon optimisation completion, results figure and tables in the right part of the “Scenario optimisation” tab are displayed.

The optimisation embeds the external open-source solver Cbc<sup>5</sup>, which implements state-of-the-art linear optimisation algorithms. Solution time heavily depends on scenario assumptions and on the adopted hardware. Due to the mathematical structure of the problem (which does not allow solution through simple sequential operations), it is not possible to estimate *a priori* the solution time. In general, optimisation times are higher the larger is the H<sub>2</sub> demand and are in the order of some minutes (up to a dozen).

#### **NOTES ON PROGRESS WINDOW “Optimisation in Progress”**








A ‘not responding’ message may appear in the optimisation progress window. This is due to Windows behaviour, which perceives that the user is attempting to perform multiple tasks (which may correspond even to simply clicking on another window) when computationally-

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<sup>5</sup> J. Forrest et al., coin-or/Cbc: Release releases/2.10.11, doi: [10.5281/zenodo.2720283](https://doi.org/10.5281/zenodo.2720283)

intensive operations are in progress. However, its appearance does not prevent the completion of the operation in progress. Depending on the operations that the user is performing in parallel, the scenario optimisation may be slowed down.

**Result visualisation subtabs.** Results are shown in figures and tables different subtabs, which are:

- “Installed HRSs”: it shows the map with the cost-optimal siting of the HRSs required to meet the H<sub>2</sub> demand. A legend is available at the left bottom. The map enables:
  - zooming in/out, by using the buttons  at the top left, by scrolling the mouse wheel, or by using the touchpad gestures;
  - panning, by clicking and dragging with the mouse;
  - activate/deactivate layers, interacting with the button  at the top right;
  - visualise HRS features, by clicking on points.
- “Hydrogen production”: it shows a map with the centralised H<sub>2</sub> production by subarea. A colour bar is present at the right. The map enables:
  - zooming in by clicking on the button  and drawing rectangles on the map;
  - zooming out by clicking on the button ;
  - panning, by clicking on the button  and clicking and dragging on the map.
- “Hydrogen delivery”: it shows the map of the hydrogen delivery network, together with hydrogen production sites, import points, and HRSs. A legend is available at the left bottom. The map enables:
  - zooming in/out, by using the buttons  at the top left, by scrolling the mouse wheel, or by using the touchpad gestures;
  - panning, by clicking and dragging with the mouse;
  - activate/deactivate layers, interacting with the button  at the top right;
  - visualise production sites/import points/HRS features, by clicking on points.
- “Summary table”: it shows a summary of results, providing aggregate values by subareas.

**Result saving.** Each subtab of the result visualisation section features buttons to save results. The following formats are used:

- Installed hydrogen refuelling stations: shapefile (.shp) or browser-based georeferenced map (.html).
- Hydrogen production quantity by subarea: spreadsheet (.xlsx).
- Hydrogen delivery:
  - Entire map: browser-based georeferenced map (.html).
  - Hydrogen delivery network: shapefile (.shp).
  - Installed hydrogen production sites: shapefile (.shp).
  - Hydrogen import points: shapefile (.shp).
- Summary table (aggregated values by subarea): spreadsheet (.xlsx).

## NOTES ON RESULT VISUALISATION

Existing and planned HRSs are always shown in the “Installed HRSs” map, even if the calculation discards them and prefers to install and use other HRS sites. This is due to the fact that the optimization does not differentiate between the stations, except for the fact that existing and planned are assumed at zero installation costs, as already available. The same holds for centralised H<sub>2</sub> production sites, as existing and planned plants are available at zero cost. Additional details on the interpretation of optimisation results are available in Section 6.

## 6. NOTES ON OPTIMISATION RESULTS

Data shown and made available in the ‘Scenario optimisation’ tab are the results of the optimisation process, which is executed by the tool following the approach and methods discussed in Section 2. Results must be observed critically, due to the high level of interdependency and the introduction of approximations in both data and parameters.

Results of the optimisation process strongly depend upon input data from the database and parameters from the techno-economic assumption, which are inevitably affected by uncertainty and possibly by inaccuracy. This, therefore, limits the accuracy, precision, and validity of results. Moreover, the cost-optimal configuration, shown in the ‘Scenario optimisation’ tab after each model run, is a numerical/mathematical ‘optimum’ in terms of calculation, but the model does not have access to full information regarding territorial characteristics.

For these reasons, the goal of the tool is to offer the possibility of developing multiple analysis at different conditions, in order to compare and assess effects and interactions, which will aid the definition of development goals and strategies.

An example of the impact of input data uncertainty/inaccuracy on results may be the indication of large hydrogen production in subareas that are known by the user as logistically or industrially unfavourable. This may be related to the use as input data of unnaturally favourable electricity generation profiles from PV and/or wind in those subareas, due to the random selection of one single punctual reference when extracting the information from external databases (e.g., PV-GIS or Renewables.ninja). To cope with such uncertainty, the H2MA tool offers the possibility to customise the assumptions related to centralised hydrogen production in terms of both maximum capacity and plant location, as discussed in Section 5.2.4. At any rate, tool outcome may not be treated directly as the target infrastructure configuration, but rather as support information to planning and strategy development. In this perspective, attention should be paid in interpreting and contextualising the results, given also the ample span of the area covered by the tool and its variable characteristics.