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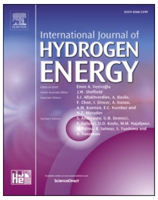

Optimal design of hydrogen delivery infrastructure for multi-sector end uses at regional scale

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ABSTRACT

Hydrogen is a promising solution for the decarbonisation of several hard-to-abate end uses, which are mainly in the industrial and transport sectors. The development of an extensive hydrogen delivery infrastructure is essential to effectively activate and deploy a hydrogen economy, connecting production, storage, and demand. This work adopts a mixed-integer linear programming model to study the cost-optimal design of a future hydrogen infrastructure in presence of cross-sectoral hydrogen uses, taking into account spatial and temporal variations, multiple production technologies, and optimised multi-mode transport and storage. The model is applied to a case study in the region of Sicily in Italy, aiming to assess the infrastructural needs to supply the regional demand from transport and industrial sectors and to transfer hydrogen imported from North Africa towards Europe, thus accounting for the region's role as transit point. The analysis integrates multiple production technologies (electrolysis supplied by wind and solar energy, steam reforming with carbon capture) and transport options (compressed hydrogen trucks, liquid hydrogen trucks, pipelines). Results show that the average cost of hydrogen delivered to demand points decreases from 3.75 €/kg$_{H2}$ to 3.49 €/kg$_{H2}$ when shifting from mobility-only to cross-sectoral end uses, indicating that the integrated supply chain exploits more efficiently the infrastructural investments. Although pipeline transport emerges as the dominant modality, delivery via compressed hydrogen trucks and liquid hydrogen trucks remains relevant even in scenarios characterised by large hydrogen flows as resulting from cross-sectoral demand, demonstrating that the system competitiveness is maximised through multi-mode integration.

1. Introduction

Numerous policies and scenarios identify hydrogen as one of the pillars of the energy transition towards carbon neutrality, providing a solution to decarbonise hard-to-abate activities and enabling sector integration [1]. In a net-zero greenhouse gas emission perspective of the energy and economic system, hydrogen has potential applications in all sectors. In transportation, hydrogen-powered fuel cell electric vehicles (FCEVs) appear promising for long-haul and heavy-duty road transport [2], while hydrogen and hydrogen-based liquid fuels are a viable option to decarbonise aviation [3] and shipping [4]. In the industrial sector, hydrogen can be exploited in boilers for high-temperature heat generation [5], or as a feedstock in the production of chemicals [6] (e.g., ammonia and methanol, or as a precursor of high-value chemicals) and in steelmaking [7]. Hydrogen injection in the gas grid also represents a viable option to decarbonise building heating when refurbishment and installation of electric heat pumps is impractical [8].

The development of an extensive delivery infrastructure is essential to unlock the hydrogen decarbonisation potential, as a distributed access to such energy vector is currently unavailable. Over recent years, governments and institutions have started to explore the development of hydrogen delivery networks, recognizing the pivotal role it holds in the energy transition. For example, the creation of a European Hydrogen Backbone is recognized central to the EU's Hydrogen Strategy [9,10], while the UK government has worked on the identification of the hydrogen transportation and storage infrastructure needs up to 2035 [11].

Within this framework, the identification of the optimal infrastructure configuration is crucial to foster hydrogen economic competitiveness. However, this task entails inherent complexity, since the various stages of the hydrogen supply chain (production, conditioning, transport, and storage) each feature multiple technological alternatives, and the cost-optimal configuration is strongly case-specific, depending on the territorial characteristics and on the type of demand points.

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As a result, the scientific community has gained increasing interest in the hydrogen supply chain (HSC) topic, developing modelling tools to design and analyse the hydrogen infrastructure. An extensive review of the existing literature can be found in Ref. [12]. So far, little attention has been given to cross-sectoral hydrogen end uses. The majority of studies considers exclusively hydrogen refuelling stations (HRSs) as demand points, focusing on the use of hydrogen in light mobility (e.g., Refs. [13–16]). However, the growing emphasis on the necessity of an economy-wide decarbonisation prompted a shift of attention towards uses in industry, heavy-duty transport, aviation, and shipping, which are deemed more promising for hydrogen deployment [17]. In the context of HSC studies, Wassermann et al. looked at the aviation sector, optimising the development of the infrastructure required to supply German airports with e-fuels, which are produced from H_2 and CO_2 [18], while Sorgolu and Dincer focused on residential heating [8]. De-Leon Almaraz et al. considered two end-use sectors, investigating liquid hydrogen truck delivery for industry and FCEVs in Hungary [19]. Vijayakumar et al. analysed the design of a hydrogen supply chain in California encompassing multiple sectors, aggregating the residential, industrial, shipping, and aviation demand in six spatial clusters [20]. Similarly, Busch et al. investigated hydrogen infrastructure development in Germany considering cross-sectoral demand aggregated at the NUTS-3 level, focusing on the role of liquid hydrogen in an integrated energy system perspective [21].

As evidenced by this overview, the existing literature on HSC lacks a detailed assessment that addresses the development of a hydrogen infrastructure with multi-sector end uses, fine spatial resolution, and optimised selection of the hydrogen transport modality. Indeed, only Refs. [8,18–21] extend the assessment beyond road mobility. However, last-mile delivery is generally excluded, as demand is aggregated in a limited number of clusters, and transport networks do not consider existing infrastructures and territorial constraints, as only Busch et al. integrate GIS data in the HSC model [21]. Multi-transport modality models with optimised selections are limited to few examples [21–25], but typically introduce simplifying assumptions in other aspects of the model (coarse spatiotemporal resolution, no last-mile delivery, schematised transport networks). Among these, only Ref. [21] considers multiple sectors.

This work aims to fill the identified research gap by expanding a multi-modality HSC optimisation model developed in previous work [12] to include cross-sectoral hydrogen demand, encompassing road transport, industrial feedstock supply and high-temperature heat generation, rail transport, aviation, and shipping. The model is applied to the Italian region of Sicily, considering 2050 as target year and building the candidate transport networks on georeferenced data. The region represents a noteworthy case study, combining a variety of potential local hydrogen end uses with a large availability of solar radiation and wind. In addition, Sicily's position as a gateway between North Africa and Europe makes its infrastructure strategically relevant, as it is expected to serve as transit point for hydrogen imports towards central and northern European countries.

The remainder of this article is structured as follows. The Materials and method section presents the adopted HSC model, and discusses the approach implemented to define the cross-sectoral hydrogen demand. The outcomes of the model application to the regional case study of Sicily are presented in the Results section and analysed in the Discussion section, while concluding remarks are presented in the Conclusions section.

2. Materials and method

This section introduces the methodological approach adopted to investigate the regional-scale development of a hydrogen supply chain with multi-sector end uses. This includes the overview of the adopted modelling framework, the model expansion to encompass cross-sectoral hydrogen demand, and the description of the analysed regional case of Sicily.

2.1. Model description

This study adopts and extends a mixed-integer linear programming (MILP) optimisation model, developed by the authors in previous works [12]. Additional details on the adopted model are available in Supplementary Material. The model objective is the minimisation of the total cost of the infrastructure, encompassing both capital and operational expenditures for hydrogen production, conditioning, transport, and storage. The technological options considered for each stage of the HSC are summarised in Fig. 1.

Hydrogen production may occur via steam methane reforming (SMR) with carbon capture and storage (CCS) or via electrolysis (EL) powered by dedicated renewable energy sources (RES), with either solar photovoltaic (PV) or wind turbines (WT). RES-EL systems are design with a fixed ratio between the EL and the RES technology capacities. Specifically, the identified optimal ratios are equal to 0.5 for PV-EL and 0.8 for WT-EL, as obtained by applying the methodology discussed in Refs. [12,26]. Additional details on the adopted methodology are available in Supplementary Material. RES-EL systems are also connected to the power grid, for a minor but not insignificant electricity exchange that mitigates intermittent operation and ensures additional revenues from the sale of electricity surplus.

The model includes delivery via pipeline (GP), compressed hydrogen truck (GT), and liquid hydrogen truck (LT). Conditioning is performed at production sites by either compressing or liquefying the produced hydrogen, depending on the selected transport technology. According to the transport modality, hydrogen can be stored in stand-alone pressurized vessels at 160 bar, in the vessels of compressed hydrogen trailers at 500 bar, or in cryogenic insulated tanks.

In this work, the model is expanded to investigate the infrastructure requirements for multi-sectoral hydrogen end uses, including land transport (passenger cars, heavy-duty trucks, buses, and trains), industry (feedstock supply and high-temperature heat generation), aviation, and shipping. Each demand site is assumed to be supplied exclusively via one of the three transport modalities, whose selection is endogenously optimised.

The model enables a time-dependent analysis, considering a year-long timeframe with a daily resolution. To reduce the computational complexity, the year is represented by a repetition of typical days. In particular, 52 typical days are identified, each repeated 7 times to constitute the 52 weeks of the year.

Two candidate networks defined the available pathways for hydrogen transport via road and pipeline, respectively. Such networks are based on Geographic Information System (GIS) spatial data, assuming that hydrogen pipelines can be installed following the paths of the existing natural gas grid and that truck routes run along the existing main roads and highways.

According to the included HSC components, the model considers six node types: transit, demand, production, intermediate storage, import, and export. Each node type is modelled according to different assumptions, as schematised in Fig. 2. Considering a generic node n, edge e, time step t, production technology p, storage option s, and transport modality m, the model formulation can be summarised with the following equations:

$$\widetilde{Y}^{m,n} q_{edg}^{e,m,t} = q_{out,s}^{n,t} - q_{in,s}^{n,t} + \widetilde{q}_{exp}^{n,m,t} \widetilde{\xi}_{exp}^{n} - \widetilde{q}_{imp}^{n,m,t} \widetilde{\xi}_{imp}^{n} \tag{1}$$

$$Q_s^{n,t+1} = Q_s^{n,t}\left(1 - \widetilde{\varepsilon}_s\right) + \left(q_{in,s}^{n,t} - q_{out,s}^{n,t}\right)\widetilde{\Delta t}\,\widetilde{N}_{td} + \left(q_{cnd}^{n,m,t}\widetilde{\xi}_{prd}^{n} - \widetilde{q}_{dem}^{n,m,t}\widetilde{\xi}_{dem}^{n}\right)\widetilde{\Delta t}\,\widetilde{N}_{td} \tag{2}$$

where: $\widetilde{Y}^{m,n}$ is the incidence matrix of the directed graph of transport modality m, $q_{edg}^{e,m,t}$ is the hydrogen transported on edge e with transport

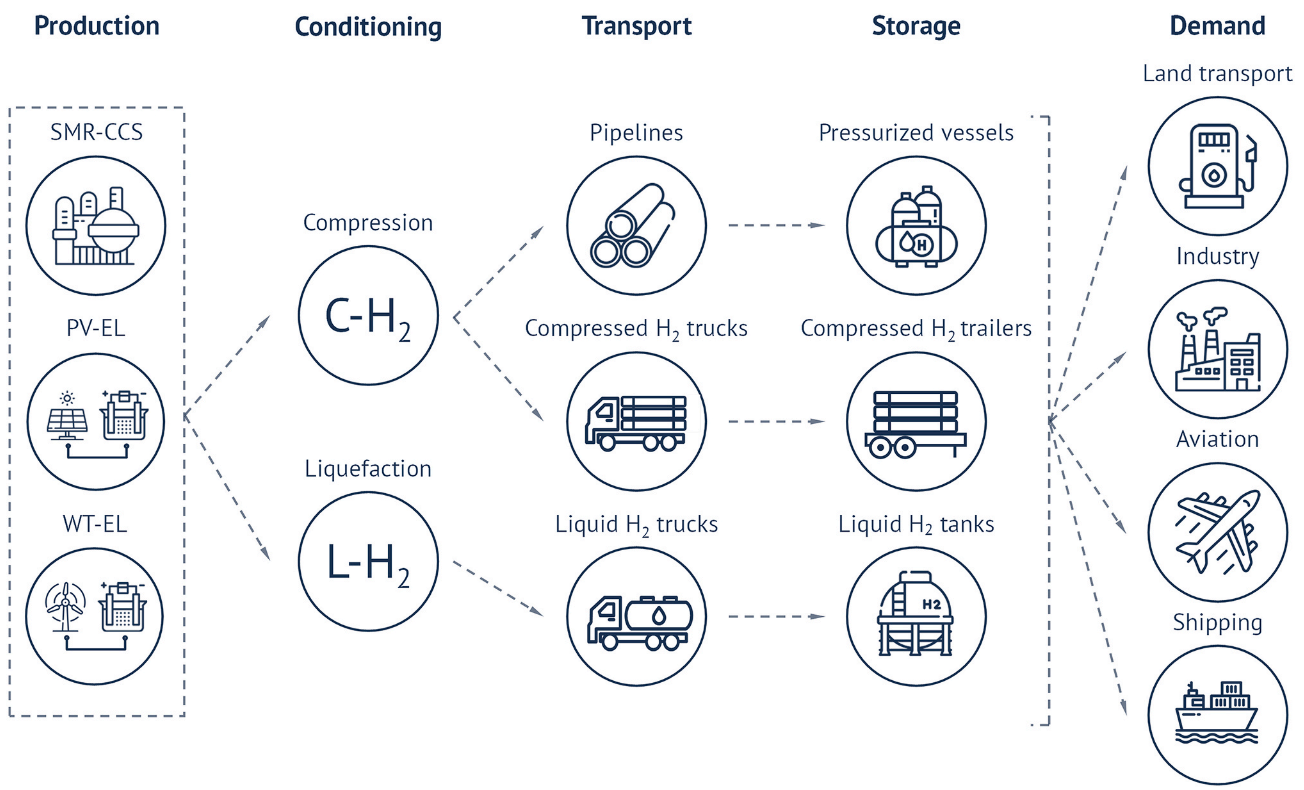

Fig. 1. Scheme of HSC technologies included in the model.

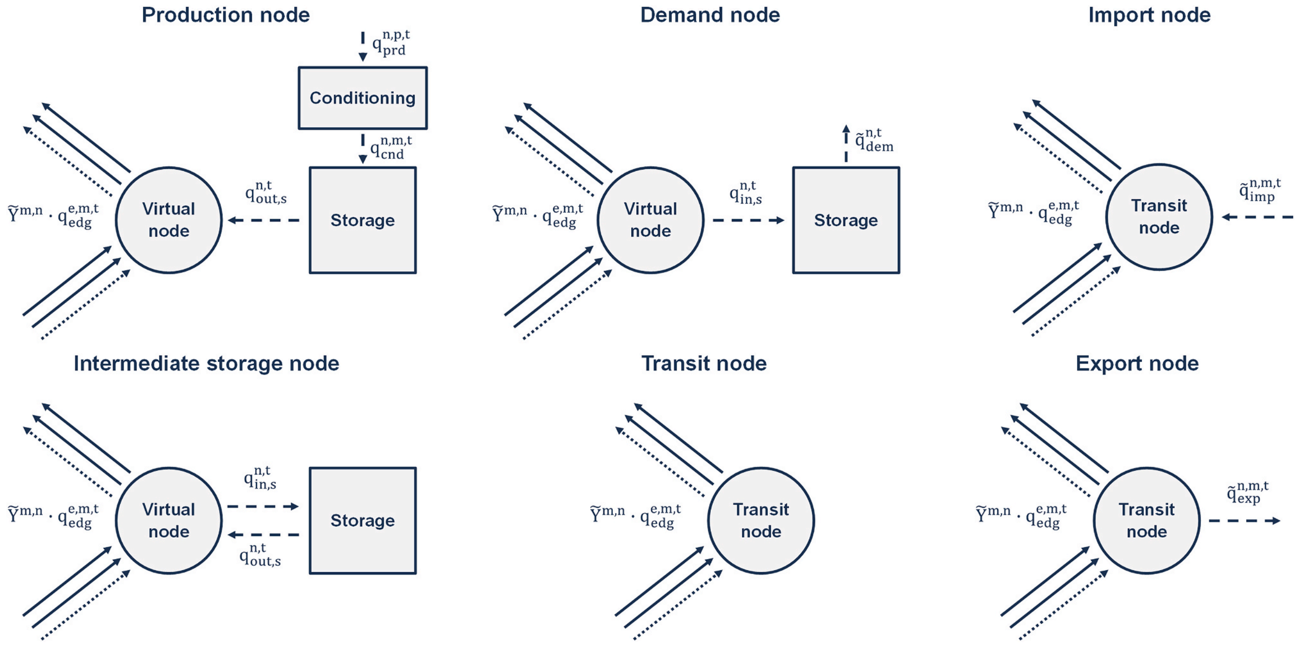

Fig. 2. Schematisation of node modelling in the HSC model.

modality m, $q_{out,s}^{n,t}$ and $q_{in,s}^{n,t}$ are the output and input storage flow for the storage option s, $\widetilde{q}_{exp}^{n,m,t}$ and $\widetilde{q}_{imp}^{n,m,t}$ are the export and import flows for transport modality m, $Q_s^{n,t}$ is the storage content at time step t, $\widetilde{\varepsilon}_s$ is the self-discharge loss coefficient for the storage option s, $q_{cnd}^{n,m,t}$ is the conditioning flow of modality m, $\widetilde{q}_{dem}^{n,m,t}$ is the demand flow of modality m, $\widetilde{\Delta t}$ is the model time resolution (one day), $\widetilde{N}_{td}$ is the number of repetitions of typical days, and $\widetilde{\xi}_{exp}^{n}$, $\widetilde{\xi}_{imp}^{n}$, $\widetilde{\xi}_{prd}^{n}$, and $\widetilde{\xi}_{dem}^{n}$ are binary parameters that indicate whether a node is of export, import, production, or demand type, respectively. For the detailed and expanded model formulation, the reader may refer to Ref. [12].

To summarise the HSC optimisation problem, 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 (road and pipeline);
- the candidate locations of production sites and intermediate storage hubs;
- the location and demand profiles of demand sites;
- the upper boundaries of the installed production and storage capacities;
- the RES electricity generation profiles for RES-based electrolysis systems.

The model output yields the cost-optimal hydrogen supply chain configuration, determining.

- the employed production, transport, and storage technologies;
- the installed production and storage capacities;
- the structure of the transport networks, the exploited pathways, and the delivered quantities;
- the operation strategy of each component of the infrastructure.

2.2. Case study

The analysis investigates the regional case of Sicily, in Italy, considering a long-term scenario (2050). To assess the impact of multi-sector hydrogen demand on the HSC design and operation, three alternative scenarios are investigated.

A single-sector scenario (labelled “1S”) featuring demand exclusively from road mobility is considered as reference, as it corresponds to the prevailing method in the existing literature. This considers a moderate penetration of FCEVs in the region, equivalent to 1.1 million FCEV equivalent passenger cars (30% stock share), without distinguishing between different vehicle categories.

The single-sector case is compared against a multi-sector scenario (labelled “MS”), which includes hydrogen demand from several industrial and mobility end uses. In particular, the study considers the applications that, according to the most recent policies, are deemed more suitable for hydrogen implementation in the short to medium term. These involve road transport, non-electrified railways, industrial high-temperature heat generation, industrial feedstocks, aviation, and shipping. Hydrogen demand for road transport is determined distinguishing the different vehicle categories, envisaging a higher penetration in heavy-duty transport and a lower penetration in light mobility.

The third analysed scenario (labelled “MS-hub”) investigates the “hydrogen hub” role that is envisioned for Italy in the Africa-Europe corridor, introducing import points that are connected to North Africa, and export points that enable hydrogen delivery towards other Italian regions and European countries. In this scenario, the infrastructure development must account for both the cross-sectoral regional hydrogen demand and the import/export northbound flows.

The characteristics of the analysed scenarios are summarised in Table 1, which highlights the end-use sectors included in each scenario. The adopted approach to evaluate the hydrogen demand in each sector, the assumptions on hydrogen production and storage, and the region’s role as hydrogen hub are detailed in the following sections.

2.3. Hydrogen end uses

This work considers cross-sectoral hydrogen uses, encompassing road mobility, rail transport, industry, aviation, and shipping. The approach used to determine the hydrogen demand in these sectors is here presented for all the three analysed scenarios.

2.3.1. Land transport

Assumptions regarding the fuel cell (FC)-vehicles stock share, mileage, and consumptions in the three scenarios are summarised in Table 2. Hydrogen demand for road transport in the single-sector scenario is determined considering a moderately high penetration of FCEV, without detailing the stock share for each vehicle category. The resulting total annual demand of the scenario is equal to 80 kt_{H2}/y and is equivalent to the consumption of 1.1 million FCEV equivalent passenger cars, which correspond to a 30% FCEV penetration in the regional stock. The hydrogen demand is computed at a NUTS-3 level based on vehicle ownership, population, and income per capita [27] and homogeneously distributed among the HRSs in each area. Hydrogen refuelling is assumed to be available in 10% of the existing gasoline/diesel station, for a total of 80 HRSs homogenously distributed in the region.

The road transport demand in the multi-sector scenarios (MS and MS-hub) is determined dividing the vehicle fleet in four categories: passenger cars, buses, trucks, and tractor-trailers. FCEV passenger cars are assumed to account for 5% of the existing stock. Again, demand is computed at the NUTS-3 level and homogeneously distributed among HRSs in each area. In this case, 2% of the existing gasoline/diesel stations are assumed to be equipped for hydrogen refuelling. The corresponding hydrogen demand is equal to 13 kt_{H2}/y and is distributed over 15 HRSs. Stock shares of FC-powered buses and trucks are defined according to Ref. [28], which provides hydrogen penetration targets for the year 2050. The bus fleet is divided into private and public buses, which feature different mileage [29] and number of vehicles [31]. Tractor-trailers are expected to feature the highest hydrogen penetration levels, as they are typically used for long-haul transport with large payloads. This analysis assumes that 48 of the existing 85 refuelling stations equipped for heavy vehicles in the region [32] will host hydrogen refuelling, ensuring a minimum distance of 10 km between each other. The resulting demand for heavy-duty transport is equal to 142 kt_{H2}/y. It is computed on a NUTS-3 level based on the vehicle stock distribution by category, and then distributed homogeneously among the refuelling stations in each area. The daily demand is assumed to be constant throughout the year. Hydrogen use in other segments of the transport sector may be of interest to extend the assessment. Among these, hydrogen deployment in off-road applications appears promising and their inclusion is therefore foreseen in future developments of this work.

Currently, Sicily features 221 km of non-electrified railway lines that are planned to be converted to hydrogen-powered trains [33]. Assuming an average consumption of 0.275 kg_{H2}/km [34] and considering that the lines are characterised by 23 rides per day on average, the hydrogen demand resulting from the conversion is 131 t_{H2}/y. Given that the impact of rail transport is marginal on the total hydrogen demand, refuelling is assumed to occur at a single filling station in Gela, common to all the hydrogen-powered lines.

2.3.2. Aviation and shipping

The future demand of clean fuels in aviation and shipping will

Table 1
Summary of the analysed scenarios in terms of included demand sectors and external connections.

Scenario	Light mobility	Heavy-duty road mobility	Rail transport	Industry	Aviation	Shipping	Import/export points
Single-sector	✓ (moderate)						
Multi-sector	✓ (low)	✓ (high)	✓	✓	✓	✓	
Multi-sector hub	✓ (low)	✓ (high)	✓	✓	✓	✓	✓

Table 2

Road transport assumptions, based on Refs. 2,28–30.

Category	FCEV stock share			Mileage [km/y]	H_2 consumption [kg_{H2}/100 km]
	Single-sector scenario (1S)	Multi-sector scenario (MS)	Multi-sector hub scenario (MS-hub)		
Passenger cars	Equivalent to 30% stock share in passenger cars	5%	5%	12,000	0.65
Buses – Public		25%	25%	36,000	8
Buses – Private		25%	25%	31,000	8
Light-duty trucks (<3.5 t)		10%	10%	30,000	3
Medium-duty trucks (3.5–12 t)		10%	10%	70,000	5
Heavy-duty trucks (>12 t)		10%	10%	120,000	7
Tractor-trailers		50%	50%	120,000	8

feature a large share of hydrogen, either pure or as hydrogen-based liquid fuels, such as e-kerosene for aviation and ammonia for shipping. The conversion of hydrogen into synthetic fuels is outside the boundaries of the adopted model, which consider the needs in terms of hydrogen energy content, since that is the main source of heating value, leaving the possible conversion steps for a separate analysis. In this work, hydrogen shares in aviation and shipping are assumed equal to 50% and 100% of today's fuel consumption, respectively. The aviation demand (51 kt_{H2}/y) is distributed on the four airports in the region according to air traffic data, considering both national and international aviation, as well as both passenger and freight transport [35]. Similarly, shipping demand (42 kt_{H2}/y) is allocated to existing commercial ports based on the current cargo and passenger transport statistics [36].

2.3.3. *Industry*

Hydrogen use in the industrial sector is estimated assuming to maintain a fraction of the current consumption as a feedstock in refineries and chemical plants and to replace part of today's natural gas consumption for energy uses. In particular, the study includes three steel plants, five refineries, one ceramics plant, two chemical plants, two cement plants, four pulp and paper plants, two glass plants, and one electronic products facility [37,38]. The food sector is separately addressed due to the high granularity of facilities. Specifically, the over 7400 enterprises are aggregated in 29 clusters based on geographical proximity, distributing the related demand homogeneously. Since industrial plants typically operate continuously, the hydrogen demand for industry applications is assumed to be constant throughout the year.

Considering the long-term reduction in oil products demand, only 50% of the current consumption of hydrogen as a feedstock in refineries is maintained in the projected demand. This share is not reduced even further since in the coming years several refineries are projected to be transformed into biorefineries, and the hydrogen demand is typically higher in these facilities [39]. Instead, the future demand for hydrogen at the two other facilities (i.e., chemical plants) is assumed to be unvaried. The hydrogen demand for industrial feedstocks results equal to 74 kt_{H2}/y.

Taking into account a strong electrification of the industrial sector, hydrogen is assumed to replace 50% of the current natural gas consumption for industrial heat generation. Such assumption is common for all the industrial subsectors, with the exception of cement production, for which a replacement rate of 20% is considered since CCS is expected to be the main decarbonisation pathway for this activity [40]. The resulting hydrogen demand for industrial heat generation results equal to 75 kt_{H2}/y.

2.3.4. *Demand summary*

Table 3 summarises the resulting hydrogen demand by sector and the corresponding number of demand points for each considered scenario. Based on the adopted assumptions, the total regional demand in the multi-sector scenarios (MS and MS-hub) results equal to 397 kt_{H2}/y, accounting for approximately 4% of the projected national hydrogen consumption in 2050, which is estimated to reach nearly 10 Mt_{H2}/y [41, 42]. In this perspective, the outcome appears consistent, given that Sicily currently features a similar impact on the national natural gas consumption.

The geographical distribution of demand points is depicted in Fig. 3 for both single-sector and multi-sector (MS and MS-hub) scenarios, excluding the import/export quantities. The bubble size of each point in the figure indicates the average daily demand the demand site. As the figure shows, road transport demand points are homogeneously distributed in the territory, and they feature a relatively low demand. On the contrary, the industrial demand is concentrated in few, large hubs, located in the proximity of the main cities (Catania in the south-eastern part of the region, Messina in the north-eastern, and Palermo in the north-western). As a result, the single-sector scenario is characterised by a homogeneous distribution of demand points characterised by a moderate demand, which is in the range 1.1–6.9 t_{H2}/d. On the other hand, hydrogen demand in multi-sector scenarios is mostly concentrated in few clusters, where the main industrial areas, ports, and airports are located. It should also be noted that, in addition to the hydrogen demand of the end-use sectors, the infrastructure development in the multi-sector hub scenario must be capable of delivering the hydrogen imported from North Africa to adjacent Italian regions and towards central or northern Europe.

2.4. *Hydrogen supply*

The employed optimisation model offers the possibility to include

Table 3

Summary of hydrogen demand assumptions.

Sector	**Annual hydrogen demand** [kt_{H2}/y]		**Number of demand points**	
	Single-sector scenario (1S)	Multi-sector scenarios (MS and MS-hub)	Single-sector scenario (1S)	Multi-sector scenarios (MS and MS-hub)
Passenger cars	80.3	12.6	80	15
Heavy-duty road transport		141.5		48
Rail transport	–	0.13	–	1
Aviation	–	50.8	–	4
Shipping	–	42.4	–	4
Industrial heat generation	–	74.3	–	47
Industrial feedstock	–	74.6	–	7

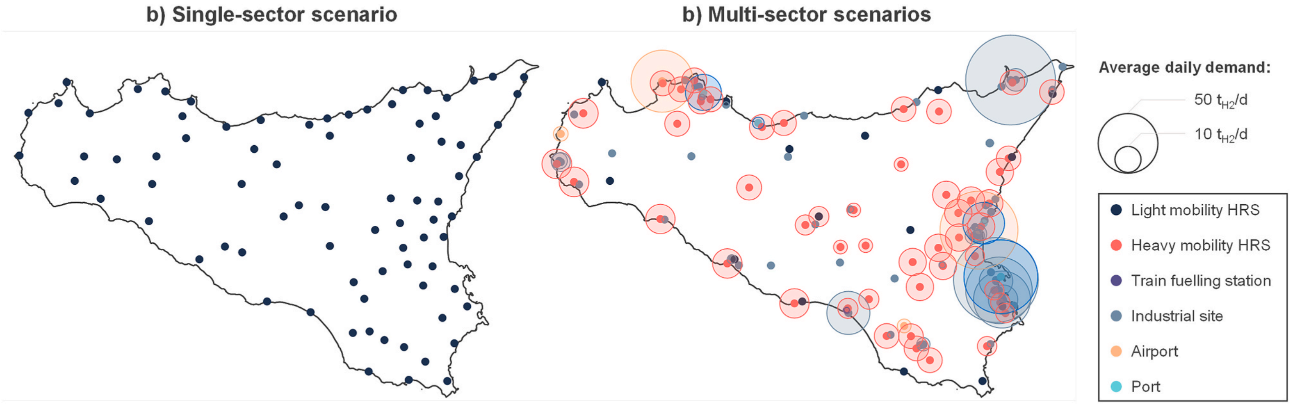

Fig. 3. Location of demand points and average daily demand (indicated by bubble size, in t_{H2}/d).

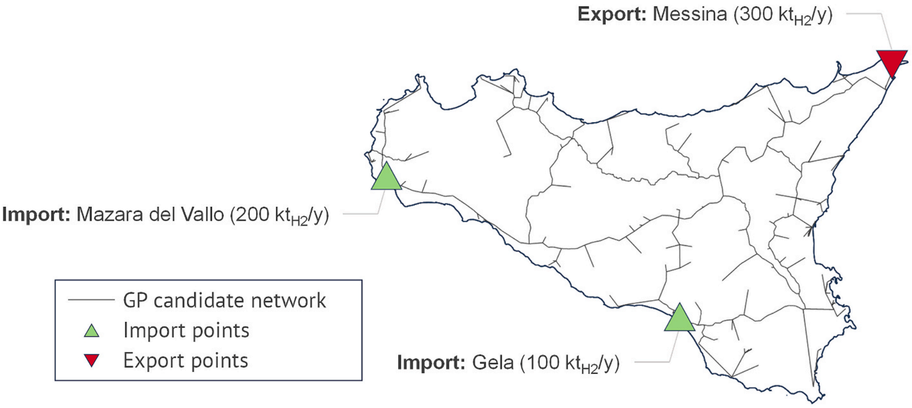

Fig. 4. Import and export points in the MS-hub scenario.

both flexible production through steam methane reforming with CCS and RES-based production through electrolysis. The existing industrial hydrogen production sites (four refineries and three chemical plants) are selected as candidate locations of SMR-CCS plants, assuming that 20% of the current hydrogen production capacity will be available for export to other uses. The centroid of each province is selected as candidate location for a centralized PV-EL system, while six WT-EL candidate sites that feature favourable wind conditions and suitable land characteristics for massive system installation are identified. The maximum PV and WT capacities per province are assumed to be five times the amount currently installed.

Intermediate storage is also included in order to compensate possible mismatches between production and demand. In particular, five candidate intermediate storage hubs are introduced, selecting their location through a random extraction among the transit nodes for both the road and pipeline networks, ensuring a minimum distance of 20 km between each other.

2.5. Italy's role as European hydrogen hub

Long-term scenarios for the European Union indicate that more than 10 Mt_{H2}/y will be imported from abroad already by 2030 [43]. In this

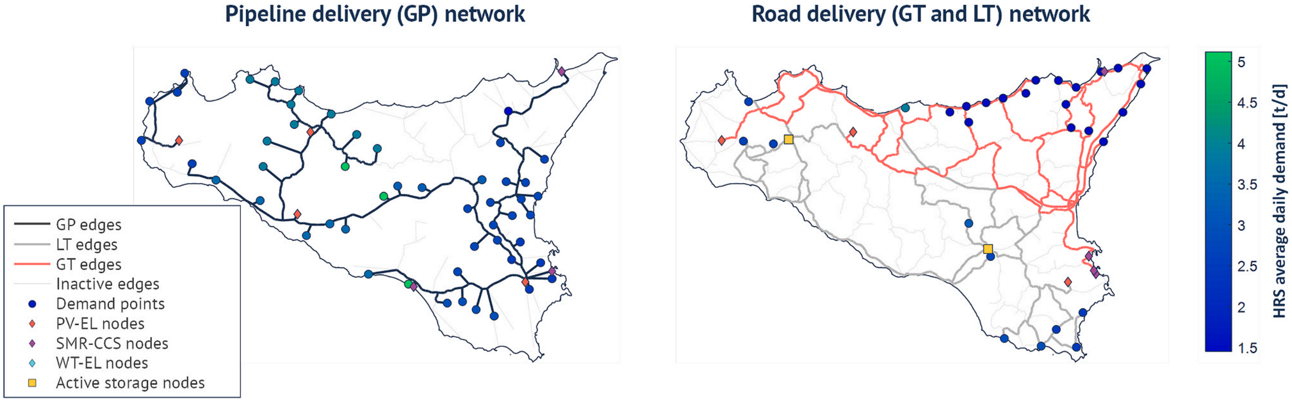

Fig. 5. Optimal transport networks in the single-sector (1S) scenario. The adjective 'active' referred to nodes or edges indicates those that are exploited in the resulting infrastructure. GP: gaseous hydrogen pipeline delivery; GT: compressed gaseous hydrogen truck delivery; LT: liquid hydrogen truck delivery.

perspective, Italy holds a strategic geographic position, acting as a gateway between North Africa and Europe. As a result, ongoing initiatives are underway to develop a "hydrogen backbone" pipeline corridor through the country, to deliver low-cost hydrogen produced in North Africa and possibly also in Southern Italy towards northern Italian regions and European countries [44].

To account for Sicily's strategic position in the hydrogen corridor, import and export points are included in the pipeline network in the MS-hub scenario. As Fig. 4 shows, these are assumed to be located in correspondence with the interconnection points of the existing gas infrastructure, which features two import points in Mazara del Vallo and Gela and an export point in Messina [9]. Based on long-term scenario for the European Union [45], the analysis assumes that 300 kt_{H2}/y are imported from North Africa (200 kt_{H2}/y in Mazara del Vallo and 100 kt_{H2}/y in Gela) and exported towards other Italian regions and northern European countries.

3. Results

Model application to the single-sector, multi-sector, and multi-sector hub scenarios enables the identification of the cost-optimal infrastructure configuration and operation in terms of the installed capacities of production and storage systems, the employed transport modalities, the exploited transport pathways (as for installed pipelines and trucks in motion per edge), and the hydrogen and electricity flows of each component.

The main indicator, used also as objective function of the model, is the average cost of delivered hydrogen, which accounts for all the capital and operational expenditures of the supply chain from the production to the delivery to the end user, excluding device installation or upgrade at the end-use facility. The list of the adopted techno-economic data is available in Supplementary Material.

3.1. *Single-sector scenario*

The resulting optimal HSC in the single-sector scenario yields an average cost of delivered hydrogen of 3.75 €/kg_{H2},. The infrastructure relies on a mix of the three included transport modalities. Out of the total 80 HRSs for, 51 are supplied via pipeline, 18 via compressed hydrogen truck, and 11 via liquid hydrogen truck.

As Fig. 5 shows, pipeline delivery supplies the HRSs with the highest average daily demand, spanning the entire region. On the other hand, compressed hydrogen trucks are used to satisfy the vast majority of demand sites in the north-eastern part of the region, where HRSs are characterized by lower hydrogen demands. Liquid hydrogen is transported via truck from a single liquefaction plant located in the south-west to almost the entire region, exploiting the larger truck capacity for long-haul delivery. Intermediate storage hubs are exploited only for liquid hydrogen delivery with an overall capacity of 0.4 kt_{H2}, since the storage needs are modest due to the comparable seasonal trends of solar-based hydrogen production and light mobility demand.

The available capacity of SMR-CCS plants is saturated, providing base-load hydrogen production throughout the whole year. PV-EL systems are installed in four of the nine candidate sites, for a total of 2 GW_e of photovoltaic and, as an effect of the fixed capacity ratio, 1 GW_e of electrolysis. The reliance on the electric grid is minimal, as grid electricity accounts for only 0.3% of the total electrolysis consumption. Instead, the electricity surplus from PV correspond to 19% of the total generated electricity. None of the WT-EL candidate sites is exploited, since the high capital cost makes this alternative not competitive in a scenario with low hydrogen demand.

3.2. *Multi-sector scenario*

With cross-sectoral end uses, the optimal HSC reaches an average cost of delivered hydrogen of 3.49 €/kg_{H2}. As in the single-sector scenario, the infrastructure relies on a combination of the three transport modalities, with 87 of the 126 demand points supplied via pipeline, 24 via compressed hydrogen truck, and 15 via liquid hydrogen truck. As Fig. 6 shows, the pipeline network crosses the entire region, supplying the large industrial hubs (see Fig. 3), whereas compressed and liquid hydrogen trucks are used for demand points with lower hydrogen requirements. Specifically, pipeline-supplied demand points feature an average consumption of 4.30 kt_{H2}/y, compared to 0.63 kt_{H2}/y and 0.47 kt_{H2}/y for compressed and liquid hydrogen trucks, respectively. In terms of demand type, pipeline delivery covers the vast majority of heavy-duty HRSs and the main industrial facilities, as well as all ports and airports. Other industrial sites are served by all transport modalities. Liquid hydrogen truck delivery transports hydrogen from a single liquefaction plant to the entire region. Again, intermediate storage is exploited only for liquid hydrogen, with an overall capacity of 1.4 kt_{H2}.

The available SMR-CCS capacity is again saturated, but it is largely insufficient to cover the demand. The higher regional hydrogen consumption calls for the installation of more and larger RES-EL plants. Overall, 8.7 GW_e of PV and 2.7 GW_e of WT are installed, so that PV-EL and WT-EL systems satisfy 59% and 35% of the regional demand, respectively. Electrolysis is mostly powered by RES, as grid electricity is only purchased during the first few weeks of the year, when both PV and WT electricity generation levels are at their lowest.

3.3. *Multi-sector hub scenario*

The cost-optimal infrastructure of the MS-hub scenario is able to both cover the regional demand and deliver hydrogen imported from North Africa to the northern regions. The resulting average cost of hydrogen delivered to demand points increases to 3.59 €/kg_{H2}, while the amount

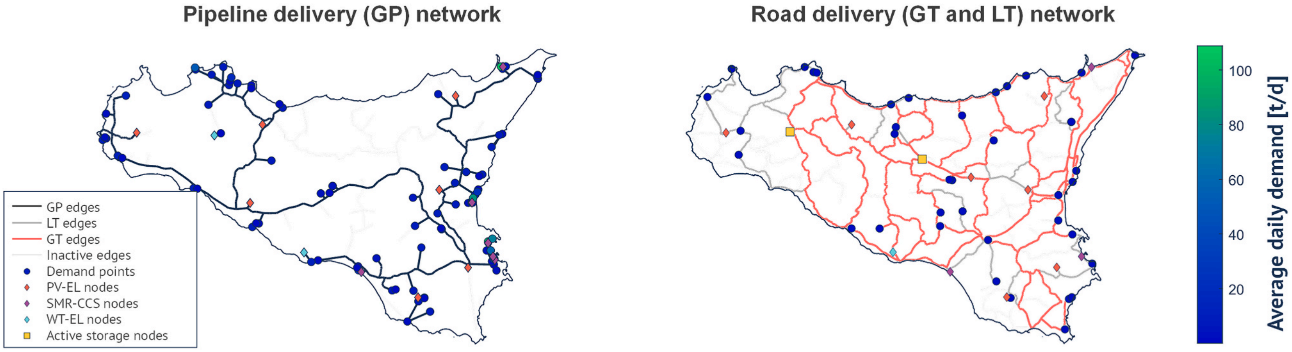

Fig. 6. Optimal transport networks in the multi-sector (MS) scenario. The adjective 'active' referred to nodes or edges is used to indicate those that are exploited in the optimal infrastructure. GP: gaseous hydrogen pipeline delivery; GT: compressed gaseous hydrogen truck delivery; LT: liquid hydrogen truck delivery.

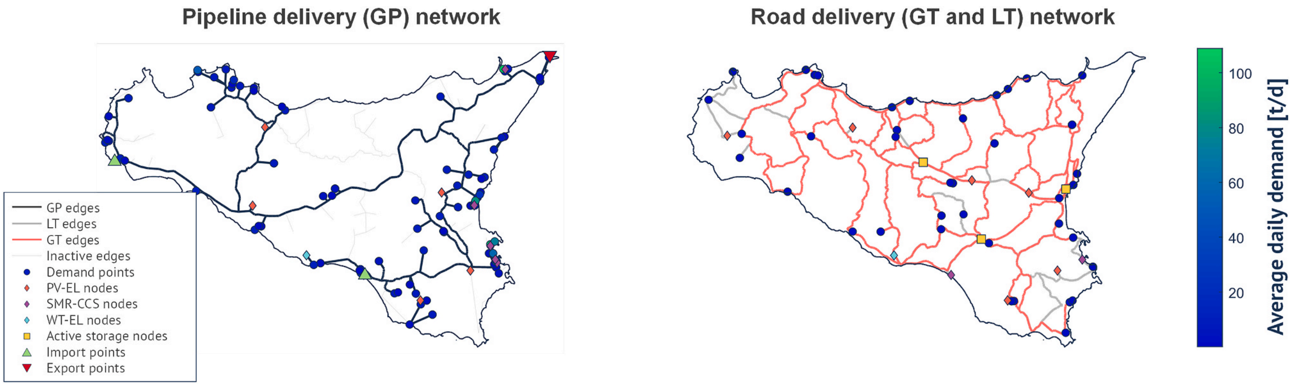

Fig. 7. Optimal transport networks in the multi-sector hub (MS-hub) scenario. The adjective 'active' referred to nodes or edges is used to indicate those that are exploited in the optimal infrastructure. GP: gaseous hydrogen pipeline delivery; GT: compressed gaseous hydrogen truck delivery; LT: liquid hydrogen truck delivery.

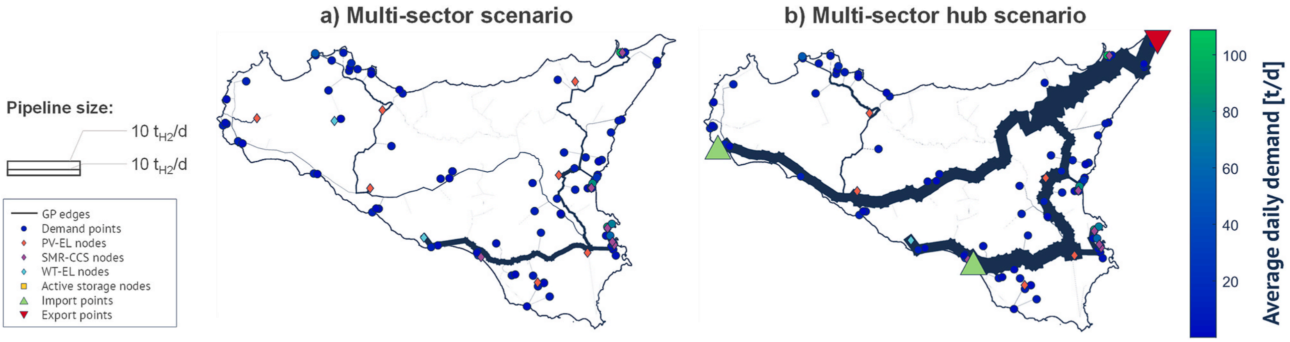

Fig. 8. Installed pipeline size in the cost-optimal pipeline networks of the multi-sector (a) and multi-sector hub (b) scenarios.

of hydrogen managed by the infrastructure almost doubles with respect to the MS scenario (697 kt$_{H2}$/y compared to 397 kt$_{H2}$/y).

Also in this scenario, the infrastructure relies on multi-mode transport. Pipeline delivery is confirmed as the most used modality, supplying 86 of the 126 demand points. The role of liquid hydrogen trucks and compressed hydrogen trucks is instead reversed, with the former supplying 26 demand points and the latter 14.

As Fig. 7 shows, the resulting cost-optimal transport networks are in line with the MS scenario, with the exceptions of the pipeline connections with import/export points and the moderate shift from compressed hydrogen truck delivery to liquid hydrogen. Pipeline-supplied demand points feature an average consumption of 4.36 kt$_{H2}$/y, compared to 0.89 kt$_{H2}$/y and 0.35 kt$_{H2}$/y for compressed and liquid hydrogen trucks, respectively. Liquefaction is concentrated in a single facility, from which liquid hydrogen is delivered to the entire region. Also in this scenario, intermediate storage is exploited only for liquid hydrogen, with an overall capacity of 1.8 kt$_{H2}$.

The available SMR-CCS capacity is saturated, while the relevance of WT-EL production slightly increases. Specifically, the system features 7.9 GW$_e$ of PV and 2.9 GW$_e$ of WT, and WT-EL and PV-EL systems satisfy 54% and 39% of the regional demand, respectively. Electrolysis is mostly powered by RES, as grid electricity only accounts for 2% of the total electrolysis consumption.

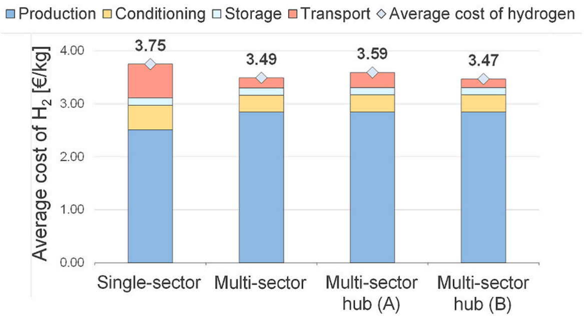

Fig. 9. Breakdown of the average cost of hydrogen for the single-sector, multi-sector, and multi-sector hub scenarios (A: transport costs allocated entirely on domestic demand, B: transport costs allocated to both domestic demand and import/export flow).

4. Discussion

The resulting cost-optimal HSC relies on a combination of the three available transport modalities in all analysed scenarios. Pipeline delivery is the dominant mode, supplying the majority of demand points, especially those with the highest hydrogen requirements. As demand increases with cross-sectoral end uses, pipeline installation becomes more cost-effective, as the significant capital cost is compensated by a higher utilisation factor. As a result, the multi-sector scenario features a more interconnected and widespread network, and pipeline delivery covers 94% of the total demand, compared to 74% for the single-sector case. On the contrary, the share of compressed hydrogen truck delivery decreases, accounting for 12% of demand in the single-sector scenario and for 2% in the multi-sector scenario, as the limited transport capacity better suits distributed HRSs. In both cases, liquid hydrogen employs a single liquefaction plant and is then distributed to several locations in the entire region, exploiting different intermediate storage hubs. The multi-sector scenario features a significantly larger hydrogen storage capacity (1.4 kt_{H2} compared to 0.4 kt_{H2}), as seasonal storage requirements are more relevant due to the flatter demand profiles.

Results of the multi-sector hub scenario are in line with those of the multi-sector scenario, with pipeline delivery covering nearly 95% of the regional demand. Fig. 8 shows how the cost-optimal pipeline network changes when accounting for the presence of hydrogen import and export in the MS-hub scenario. Specifically, the infrastructure features two main corridors that connect import and export points, from the western and southern side to the north-eastern side. As a result, hydrogen flows in the region follow north-eastbound pathways in order to exploit the corridor infrastructure. Differences in the pipeline networks are particularly pronounced in the south-western part of the region. Due to the relatively low demand, the area is characterised by the presence of small-size pipelines in the MS scenario, whereas it hosts one of the two main corridors in the MS-hub scenario, due to the presence of an import point. This indicates that regional infrastructure planning needs to consider the national and international context, as the lowest-cost configuration may significantly change accordingly.

The expansion of the HSC to cross-sectoral demand results in a reduction of the average cost of hydrogen delivered to end users, as depicted in Fig. 9. In the multi-sector scenario, the average cost of hydrogen reaches a value of 3.49 €/kg_{H2}, compared to 3.75 €/kg_{H2} in the single-sector case. The MS-hub scenario features a 3% increase of the average cost of hydrogen (Multi-sector hub (A) column in Fig. 9), resulting from the additional pipeline installations required to manage the import/export flows. This assumes that all infrastructural costs are allocated to domestic consumption. If remuneration for hydrogen transit is considered by distributing the transport contribution also on the import/export hydrogen quantity, the average cost of hydrogen delivered to regional end uses would decrease to 3.47 €/kgH2 (Multi-sector hub (B) column in Fig. 9).

As Fig. 9 shows, production has the highest impact in all scenarios, representing 67%, 81%, and 82% of the total cost in the single-sector, multi-sector, and multi-sector hub scenario, respectively. The storage contribution is the lowest, accounting for only 4% in all cases. The impact of conditioning and, especially, transport decreases significantly when shifting to cross-sectoral end uses, entailing that the multi-sector supply chain exploits more effectively the infrastructure investments. Specifically, the transport contribution decreases from 0.64 €/kg_{H2} in the single-sector scenario to 0.19 €/kg_{H2} in the multi-sector scenario. Due to the additional pipeline installations for hydrogen imports, transport accounts for 0.29 €/kg_{H2} in the multi-sector hub scenario if all costs are allocated to domestic demand (option A). Assuming perfect cost sharing on both domestic demand and import/export transit (option B), the transport contribution amounts to 0.16 €/kg_{H2}. This corresponds to 5 €/MWh and is aligned with current average entry/exit tariffs for natural gas in Europe, which are in the range 1–6 €/MWh [46]. The actual cost structure will depend on the development of hydrogen trading mechanisms.

Looking at the environmental impact, the specific GHG emissions are equal to 0.55 kg_{CO2e}/kg_{H2} in the single-sector scenario, 0.26 kg_{CO2e}/kg_{H2} in the multi-sector scenario, and 0.27 kg_{CO2e}/kg_{H2} in the multi-sector hub scenario. Emissions are due to blue H_2 production via SMR-CCS, which represents a small fraction of the total, and to the use of grid electricity. Specifically, the latter is used for H_2 conditioning and, to a limited extent, to support RES-EL H_2 production. For all scenarios, the specific emissions are well below the threshold of 3 kg_{CO2e}/kg_{H2} set by the European Commission to identify low-carbon hydrogen [47]. In addition, results represent conservative values, since an average emission factor has been assumed for grid electricity, but the transition towards a RES-dominated grid is expected to yield values close to zero.

Methods and outcomes of this work may support the development of regional and national hydrogen strategies. The Italian hydrogen strategy is currently under development, and only preliminary guidelines are publicly available at the moment [48]. Accordingly, the obtained results cannot be directly compared with national objectives. However, the assessment is in line with the approach and directions of national government bodies. Indeed, the preliminary guidelines on the national hydrogen strategy specify the need for the deployment of a network of HRSs to supply HDVs, as also highlighted in the EU's Alternative Fuels Infrastructure Directive (AFIR) [49], and estimate that FCEV penetration in long-haul HDVs may reach 80% by 2050. The guidelines also identify chemical feedstocks, refineries, high-grade industrial heat, aviation, and shipping as key sectors for H_2 adoption. Similar information is reported in the national Long-Term Strategy (LTS) [50], but specific projections are available only at the national level and aggregating all sectors. In addition, a revision of the values is expected in the coming years to align with the latest climate targets.

5. Conclusions

This work investigated the impact of cross-sectoral end uses on the development of an integrated hydrogen delivery infrastructure. The adopted optimisation model is based on a multi-modality formulation that selects the transport technology at each stage of the supply chain, considering a year-long analysis with daily resolution. Hydrogen end uses includes light and heavy road mobility, rail transport, industry, aviation, and shipping.

The analysis looked at the regional case study of Sicily in Italy. A comparison was made between a single-sector scenario with hydrogen demand from refuelling stations, a multi-sector scenario with cross-sectoral hydrogen uses (road mobility, rail transport, industry, aviation, and shipping), and a multi-sector hub scenario that includes import/export from North Africa towards central and northern European countries, in order to assess Italy's role as hydrogen hub.

Results show that the higher demand and the broader range of uses of the multi-sector scenario yield a reduction of the average cost of hydrogen delivered at demand points, which reaches 3.47–3.49 €/kg_{H2} compared to 3.75 €/kg_{H2} in the single-sector case, mostly due to a reduction in conditioning and transport contributions. This is especially relevant for pipeline delivery, whose high capital costs are offset by an increased utilisation factor. The relevance of this transport option further increases when considering import and export needs, which result in the creation of large corridors in the pipeline network. This highlights the necessity for infrastructure planning at the regional level to account for both national and international strategies, which strongly affect the cost-optimal configuration.

This work demonstrates that the optimised system performances are achieved through the integration of multiple transport modalities, even in scenarios characterised by large hydrogen flows due to multi-sector end uses. Although pipeline transport emerges as the dominant option, the use of compressed hydrogen truck and liquid hydrogen truck delivery is still relevant. These options are widely exploited for end-use points characterised by a moderate hydrogen demand, supplying more than 30% of demand nodes in all scenarios.

Given the proven response of the model to different scenarios, further development will focus on enlarging the studied spatial size, e.g., extending to the national scale and/or investigating international interactions, via high-capacity pipelines or ships.

CRediT authorship contribution statement

Federico Parolin: Data curation, Investigation, Methodology, Software, Visualization, Writing – original draft, Validation. **Paolo Colbertaldo:** Conceptualization, Formal analysis, Methodology, Writing – review & editing, Investigation. **Stefano Campanari:** Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijhydene.2024.06.049

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