Hydrogen refueling station cost model applied to five real case studies for fuel cell buses

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Abstract. Hydrogen Refueling Stations (HRS) are a key infrastructure to the successful deployment of hydrogen mobility. Their cost-effectiveness will represent an increasingly crucial issue considering the foreseen growth of vehicle fleets, from few captive fleets to large-scale penetration of hydrogen vehicles. In this context a detailed, component-oriented cost model is important to assess HRS costs for different design concepts, layout schemes and possible customizations, respect to aggregate tools which are mostly available in literature. In this work an improved version of a previously developed component-oriented, scale-sensitive HRS cost model is applied to 5 different European HRS developed within the 3Emotion project with different refueling capacities (kg$_{H2}$/day), hydrogen supply schemes (in-situ production or delivery), storage volumes and pressures and operational strategies. The model output allows to assess the upfront investment cost (CAPEX), the annual operational cost (OPEX) and the Levelized Cost of Hydrogen (LCOH) at the dispenser and identify the most crucial cost components. The results for the five analyzed HRS sites show an LCOH at the nozzle of around 8-9 €/kg for delivery based HRSs, which are mainly dominated by the H$_2$ retail price and transport service price and around 11-12 €/kg for on-site producing HRS, for which the electrolyzer CAPEX and electricity price plays a key role in the cost structure. The compression, storage, and dispensing sections account for between 1-3 €/kg according to the specific design & performance requirements of the HRS. The total LCOH values are comparable with literature, standard market prices for similar scale HRSs and with the 3Emotion project targets.

1 Introduction

Hydrogen fuelling stations (HRSs) are one of the most critical parts of the distribution infrastructure required to implement hydrogen-powered mobility. Without a widespread hydrogen refuelling network, hydrogen vehicles are strongly limited in terms of operation and their commercial deployment will be very limited. At the same time, without a significant fleet of operational hydrogen fuel cell vehicles, building a viable business case for setting up a network of HRSs is challenging due to the lack of consistency in hydrogen demand [1,2]. The so-called chicken-and-egg problem determines a lack of spontaneous growth in hydrogen mobility sector in European market, which is mainly driven by public or private project-

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specific funding [3]. This situation could rapidly change with the mass deployment of hydrogen mobility projects both in terms of hydrogen-powered vehicles and refuelling infrastructure, with about 3700 refuelling stations announced and planned in Europe by 2030 [4]. The deployment of HRSs throughout European cities is crucial to provide a valid commercial benchmark for the hydrogen stations in terms of used technology (production and distribution), technical specifications, layout, and economics [5].

The most mature and industrially common HRSs categories are the ones with delivered hydrogen (by compressed hydrogen via truck/pipeline or liquid hydrogen) or with production units on-site. Depending on the site specific requirements and constraints, one or the other solution is preferable. Delivery stations are simple and compact, consequently, the station investment cost (CAPEX) is moderate [6]. However, the hydrogen cost will strictly depend on the hydrogen retail price and utility costs and is not controllable by the final user (although constant with operating conditions at contract price) [7]. The fuel price must take into account also delivery and vehicle leasing fees which are usually in the same order as the retail hydrogen price [8]. An increased complexity characterizes on-site HRSs since the hydrogen production plant is integrated with the filling station and coupled with compression units. Therefore, if from an operational point of view is more versatile, directly controlling the flow rate, the CAPEX costs are generally higher and the footprint more extended [9]. On the contrary, the operational cost (OPEX) can decrease significantly in the case of low electricity price schemes or on-site electricity production from renewable energy sources [10].

According to the cost modelling approach, various levels of detail and aggregation in cost models can be achieved which can lead to substantial differences in the results. On the one hand a highly aggregated system-oriented approach estimating the HRS cost and the Levelized Cost of Hydrogen (LCOH) as a function of the HRS capacity (€/(kg/day)) can be useful for early-stage project development or quick prototyping of integrated hydrogen ecosystems [11–13]; on the other hand a more detailed component-oriented analyses which builds up the HRS cost and LCOH as an assembly of unit costs is more realistic but is usually more suitable for advanced stages of project implementation and engineering [14–17], being somewhat cumbersome to apply in early project stages due to lack of specific data. A trade-off must be found between these two approaches according to function of the objective and level of detail required by the analysis, obtaining a reliable cost output with sufficient degree of detail in the cost breakdown but at the same time maintaining a simple and versatile cost model, which can be easily applicable to different case studies.

The aim of this study was to tailor a previously developed component-oriented cost model[18] to evaluate in detail the CAPEX, the OPEX, and the LCOH for five European HRSs for fuel cell buses developed within the 3Emotion project [19] characterized by different refuelling capacities (kg_{H2}/day), hydrogen supply schemes (in-situ production or delivery), storage volumes and pressures and operational strategies. The ultimate goal of the work is to put the analysis of the sites into a clear industrial context and to be able to assess the 3Emotion sites in comparison to state-of-art references and industrial practice [14,20–22].

2 Case study: the 3Emotion project

In Table 1 the main characteristics of the five Hydrogen Refuelling Stations of the 3Emotion project are summarized. Since two different bus operators are present in the Rhoon and Versailles sites, two different business cases have been analyzed for each of the operators.

Table 1. Summary of the 3Emotion HRSs and main parameters.

Site	Hydrogen source		Nominal Capacity	Supply scheme	Compressor pressures	Compressor max. throughput	Storage capacity	Storage pressure*	Dispenser pressure
			kg/day	onsite/delivery	bar_{in}/bar_{out}	Nm^3/h	kg	kg @ bar	bar
London	Delivery trailer **	450 kg/trailer @ 350 bar	400 kg/day ≈300 km	2 del./week	350/500	Integrated in trailer	1250 kg	900 kg @350 bar trailer 350 kg @500 bar onsite	1x 350 bar
Rhoon RET	Delivery pipeline	@30 bar from SMR plant	200 kg/day ≈100 km	Upon request	2x 30/495 1x 350/900	100 Nm^3/h	250 kg	90 kg @495 bar 65 kg @877 bar	1x 350 bar
Rhoon PZH								95 kg @495 bar	1x 350 bar
Versailles SAVAC	Delivery trailer **	350 kg/trailer @ 200 bar	200 kg/day ≈200 km	3 del./week	1x 10/1080 (2-stage)	150 Nm^3/h	600 kg	350 kg @200 bar trailer 100 kg @495 bar onsite 60 kg @877 bar	350/700 bar
Versailles BE Green									1x 350/700 bar 1x 350 bar
Pau SMTU	On-site electrolysis + delivery trailer	PEMEL: 425 kW Trailer: 330 kg @200 bar	174 kg/day***	24/24h	2x 7-20/920 (5-stage)	2x 275 Nm^3/h	860 kg	230 kg @20 bar 630 kg @600 bar (330 kg @200 bar trailer optional)	8x 350 bar
Aalborg	On-site electrolysis	PEMEL: 355 kW	100 kg/day	≈80% capacity factor	1x 35/450 (3-stage)	60 Nm^3/h	242 kg	10 kg @30 bar 114 kg @300 bar 118 kg @450 bar	1x 350 bar

* Specifying different pressure levels
** Blue Hydrogen
*** Max. capacity 268 kg/day

2.1 London site

The HRS in London is located in the Temple mills depot and consists of an H_2 delivery station with a fuelling capacity of 400 kg/day against a request of 160 kg/day due to a fleet of 10 buses. Hydrogen is delivered by LH_2 trailer transporting blue hydrogen produced by SMR in the SMR plant of Rotterdam and transported for 300 km up to the HRS. The LH_2 trailer is an integrated system (not considered within the model) which includes a cryogenic tank for the LH_2, a vaporization unit to convert the LH_2 to gaseous form and an integrated compression unit for discharge of the hydrogen capacity (450 kg) up to 350 bar into the on-site storage units. The hydrogen trailer which is delivered to the HRS twice a week is later used as integrated storage, with a capacity up to 900 kg at 350 bar, in addition to the 350 kg on-ground permanent storage at 500 bar, for a total capacity of 1250 kg. Hydrogen is transferred from the trailers to the on-site storage with a hydrogen compression system directly integrated in the trailer unit, therefore no specific station equipment is needed from the HRS to discharge the supplied hydrogen. The filling system is based on a single dispenser that allows to refill the entire fleet of 10 buses in 4 hours, a procedure usually carried out during the night.

2.2 Rhoon/Rotterdam site

Rhoon is a publicly accessible HRS nearby Rotterdam supplying hydrogen to both hydrogen-powered cars and buses. Refueling occurs for buses at a pressure of 350 bar, while for cars with a dual pressure of 700 bar and 350 bar. The Rhoon HRS is supplied from the Benelux/France pipeline of 900 km overall (specifically in the section between Rotterdam and Antwerp – ≈100 km) with a pressure level of 70-100 bar which can be compressed and stored on-site at various pressures. Originally it is produced by SMR and by chloralkali process starting from LNG from a tanker in Antwerp. The hydrogen is delivered continuously at the point of connection with the Rhoon HRS at 30 bar, where it is directly fed to the first stage of compression (30/495 bar) and then to a high pressure (350/900 bar) compressor in series. The storage is composed of a medium pressure (90 kg @495 bar) and a high pressure (65 kg @877 bar) compressed gas storage unit for a total stored capacity of 155 kg. An additional medium pressure compressor (30/495 bar) has been added to upgrade the HRS with the additional buses. The station has installed 3 dispensers, one fast-filling for 700 bar with pre-cooling heat exchanger with closed-loop refrigerant circuit, one for 350 bar for cars and lastly one for 350 bar for buses (which is the one used in the 3Emotion project) without pre-cooling. In relation to the increase of the buses fleet the Rhoon HRS has been upgraded, implementing an additional medium pressure compressor (30/495 bar); an additional medium pressure buffer (95 kg @495 bar) to achieve a total storage capacity of about 250 kg of useful storage and an additional dedicated 350 bar dispenser.

2.3 Versailles site

The Versailles HRS is used to refuel a fleet of 7 buses at 350 bar with a rated capacity of around 200 kg/day operated by two transport operators (with 2 buses and 5 buses), and about 40 light vehicles using separate dual pressure dispensers (350/700 bar). Hydrogen is delivered by tube trailer with 2-3 deliveries/week from a reforming plant with carbon capture (blue hydrogen), with trailers of 350 kg of H_2 at a pressure of 200 bar which are left in the HRS as storage unit. The trailers from Versailles deliver blue hydrogen produced in the SMR plants of Frais Marais (250 km) and Port Jérôme (150 km). The compression system is divided into two stages, the first allows to reach 450 bar, while the second can reach up to 1080 bar (although it is operated at lower discharge pressures). In addition to the tube trailers

delivered 2-3 times/week that can contain 350 kg of H_2, the Versailles HRS can count on an intermediate storage of about 100 kg of H_2 at a pressure of 495 bar and a high pressure storage of 60 kg of H_2 at a pressure of around 880 bar allowing to have on the site a total availability of 510 kg of H_2 compared to a daily demand of around 200 kg. The initial dual flow dispenser (350 bar and 700 bar) with separated nozzle, has been upgraded with an additional dispenser dedicated to the fuel cell buses (350 bar).

2.4 Pau site

The HRS of Pau is a station with local hydrogen production by a PEM electrolyzer (425 kW) which can provide around 174 kg/day of hydrogen at nominal capacity to supply 8 buses; the daily production capacity is incrementable to 268 kg/day. A backup hydrogen supply via tube trailers (330 kg @200 bar) can be used for backup. Since the tube trailers in Pau are only used for backup, the production plant is not fixed. The produced hydrogen is directly stored at the electrolyzer output pressure in a low-pressure storage unit (230 kg @20 bar) which is subsequently connected to two parallel ionic compressors (20/920 bar) to compress the gas up to the high-pressure storage units (630 kg @600 bar) for a total available capacity of 860 kg, other than the possible presence of the backup trailer (330 kg @200 bar trailer - optional). The dispensing system is designed to provide one refuelling point for each bus, therefore 8 separate dispensing points are available.

2.5 Aalborg site

The HRS in Aalborg produces H_2 directly on-site with a rated capacity of about 100 kg/day. The total production capacity – 100 kg/day nominal – is obtained by a locally producing pressurized PEM electrolyzer (355 kW with an output pressure of 35 bar). The hydrogen is directly stored in a low-pressure buffer storage at 35 bar (10 kg @35 bar), then compressed by a single-piston type compressor (35/450 bar) to 300 bar and 450 bar, according to the storage unit used (114 kg @300 bar and 118 kg @450 bar). From the storages hydrogen is refuelled to the buses at 350 bar with a single dispenser

The Hydrogen Refueling Stations of the 3Emotion project are summarized in Figure 1 in terms of refueling capacity.
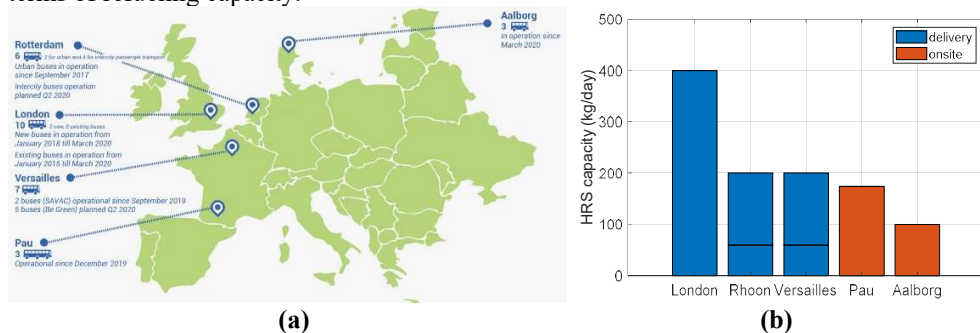

Fig. 1. (a) Summary of Hydrogen Refueling Stations in the 3Emotion project; **(b)** refueling capacity

3 Hydrogen Refuelling Station Cost Model

The implemented HRS cost model follows a component-oriented approach based on the design specification parameters. Each component is assessed in terms of CAPEX (investment cost, replacements, etc.) and yearly OPEX (energy cost, utility cost, O&M, etc.) according to the integration scheme in the overall HRS plant.

The battery limit of the cost model is limited to the local HRS boundary (hydrogen production, compression, storage and dispensing units) while grid electricity and delivered H_2 are seen as external inputs, providing material and energy inputs (kg_{H2} and kWh_e, respectively) according to the operating scheme of the HRS. In this way, the upstream electricity and H_2 production methods are not assessed in the cost model, as they are included in their retail prices ($€/kg_{H2}$ and $€/kWh_e$, respectively), as seen by the HRS operator. The cost model output is calculated at the dispenser nozzle from the HRS to the fuel cell buses at 350 bar, where the vehicle cost and consumption are not included within the scope of the HRS cost model.

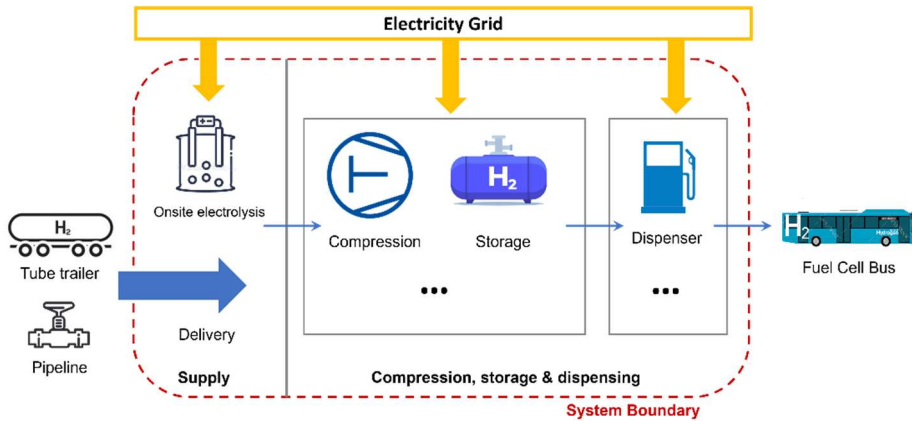A conceptual scheme of the HRS cost model is illustrated in Figure 2.

Fig. 2. Conceptual scheme of the Hydrogen Refueling Station cost model

3.1 On-site hydrogen production - electrolysis

In the on-site producing HRSs the H_2 is produced by electrolysis, which is an electrochemical conversion system which decomposes water in its constituents H_2 and O_2 via the application of a current across an electrochemical membrane electrode assembly. The electrolyzer technology determines the operating conditions at stack level (current density and required voltage levels) and system level (considering the requirements in terms of balance of plant), ultimately determining the specific energy consumption (SEC) at system level (kWh_e/kg_{H2}) and the electrical-to-hydrogen efficiency (%) [10,23].

Both on-site producing HRSs (Pau and Aalborg) implement PEM electrolysis technology therefore only this technology is analyzed in the cost model. In both the HRSs the electrolyzer is supplied from the grid (grid-connected mode).

The summary of the PEM electrolyzer technology technical parameters are reported in Table 2. Although presenting a SEC of around 6-6.5 kWh_e/Nm^3 (i.e., an electrical to hydrogen efficiency around 55-65% based on HHV) which is slightly higher compared to the competing low temperature technology which is alkaline electrolysis – 5-5.5 kWh_e/Nm^3, i.e. 70-75% efficiency based on HHV – PEM systems are more suitable for coupling with variable electrical supply profiles with high intermittency and are suitable for power modulation[24]. For this reason, PEM electrolysis is a particularly promising technology for application in HRSs, since the operating scheme is characterized by a strongly intermittent and on-off operation profile, in relation to the discrete nature of the hydrogen load (vehicle refueling). From a balance of plant point of view the PEM technology presents fairly simple operation due to the polymeric electrolyte in solid phase, which avoids any pumps or moving parts related to electrolyte management. On the other hand, higher power density values can result in higher cooling loads, although overall the additional auxiliary energy demand of

PEM electrolysis is around 5% of the SEC at stack level respect to 10% for alkaline systems[25]. The stoichiometric water consumption is around 1 lt/Nm^3 of demineralized water, where the water treatment system energy consumption is included in the additional auxiliary energy consumption (with potable water input, in case of seawater input the desalination energy consumption should be added), as well as the hydrogen purification system located downstream the electrolyzer (dryer, de-Ox, etc.) required for utilization in FCEV applications (class 5.0 purity according to SAE J2719 [26]).

Table 2. Summary of technical and economic parameters for PEM electrolysis [24].

Technical Parameters		Cost Parameters	
SEC (stack level)	6.2 kWh$_e$/Nm^3	CAPEX (system + BoP)	Eq. 1 Base-case 100 kW$_e$; 2000 €/kW$_e$; s.f. 0.45
Auxiliary energy consumption	5% SEC	Electricity cost	Country specific
Efficiency (%) based on HHV	51.7% – system	Water cost	1-2 €/m^3
	56.9% – stack	O&M	5% CAPEX/year

From a cost point of view the economic parameters are summarized in Table 2. Due to the small market reference the specific CAPEX (€/kW) of the electrolyzer system is hard to determine being extremely variable according to scale, temporal horizon, application, etc. spanning from over 3000 €/kW reported costs for small-scale, R&D oriented applications up to below 400 €/kW cost projections for large-scale applications by 2030 and onwards [10]. In order to provide a suitable cost analysis a scale-sensitive cost curve (Equation 1) has been implemented (S_{el} between 100 kW and 1000 kW) calibrated on a base-case scenario ($S_{el,base}$ 100 kW with a specific CAPEX of 2000 €/kW) scaled with a scaling factor (*s.f.*) of 0.45, based on elaborations of [27] and [28], considering reported costs for similar scales in the time-period 2015-2020 which is when the actual procurement of the electrolyzers has taken place.

$$C_{el} = C_{base} \left(\frac{S_{el,base}}{S_{el}} \right)^{s.f.} \tag{1}$$

The considered CAPEX cost is comprehensive of the whole electrolyzer system, including the balance of plant.

The production scheme is important for the OPEX determination since it is strictly linked to the operating hours and electricity and water consumptions, monetized at their respective prices (retail electricity and water prices, according to the local market conditions and classification of the network connection) [29]. Additional costs for green certificates should be considered, if applicable. A fixed yearly O&M cost of 5% of the CAPEX cost has been considered [24].
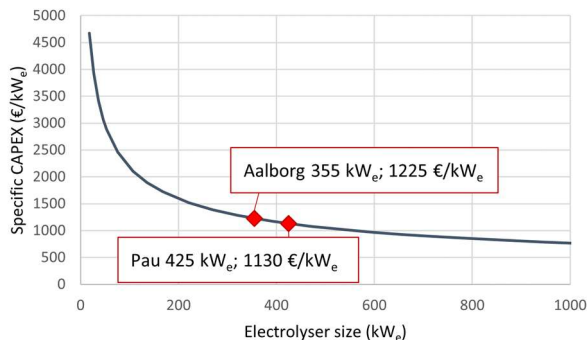

Fig. 2. PEM electrolyzer cost scaling function (€/kW$_e$ vs. kW$_e$ installed).

3.2 Hydrogen delivery

If not produced on-site, hydrogen can be delivered to the HRS externally with different transport methods and distribution schemes. Typically, hydrogen is produced in large-scale centralized plants and then distributed to different end-use consumers through a local distribution network. Since the transport & distribution cost is added to the production cost the competitiveness of on-site hydrogen production vs. hydrogen supply via delivery is not straightforward and is determined on a case-specific basis [18].

Typically, for short- to medium-range distances (local distribution within a single country or continent [20], H_2 is distributed via trucks in compressed gaseous (CGH_2) form in tube trailers (at 200/350 bar, according to the local regulation in terms of maximum pressure for transport vehicles). Liquid hydrogen trucks (LH_2) can also be used as transport vector in some specific cases, where the HRS capacity justifies the liquefaction. Thanks to the increased hydrogen mass density in its liquid form (ρ_{LH2}=71 kg/Nm^3) LH_2 trailers allow to store a much larger hydrogen mass amount in a smaller tank, with respect to gaseous hydrogen (ρ_{CGH2}=0.0898 kg/Nm^3), which much require higher pressures [30]. In very few locations in Europe a dedicated hydrogen pipeline is available which can provide a continuous supply of pressurized hydrogen at the point of connection with the final user. In these cases, delivery via pipeline is the most cost-competitive alternative due to the minimal transport & distribution cost related to the pipeline operation [31]. However, such kind of infrastructure is usually intended as a long-term strategic investment at national level due to the very high upfront CAPEX, which cannot be attributable to a single project since it serves multiple final users.

3.2.1 CGH_2 tube trailers, LH_2 trailers and CGH_2 pipeline

Industry-standard compressed gaseous hydrogen tube trailers with a capacity of 350 kg at 200 bar (around 20 m^3 geometrical volume) are used in the delivery-based HRSs (Versailles and – as a backup solution – Pau), following a discrete delivery frequency (usually expressed in deliveries/week). The tube trailer is constituted of a series of compressed vessels which can be left at the HRS, serving as an additional on-site storage volume managed according to the HRS operating scheme. Due to discharging limitations (compressor suction minimum pressure, pressure differences, etc.) not all the stored compressed hydrogen can be used from the tube trailers, a residual pressure of 10 bar (around 17 kg) is assumed to be returned to the gas supplier with the trailer.

Regarding cost, the delivered hydrogen is seen from the HRS operator as an OPEX, monetized at its retail price, which is summed to the price related to the transport & distribution services. Without entering confidential details of the supply contracts which are in place between each HRS operator and gas supplier, a generalized approach has been used in this study setting a retail price of 2.50 €/kg for grey hydrogen and 4 €/kg for blue hydrogen according to relevant cost analyses for the analyzed years [10]. Similarly, the transport & distribution service price is seen, from the HRS operator point of view, as an OPEX depending on the transport form, distribution scheme, travel distance. For the trailers, the service price is composed of a fixed price, which depends on the number of leased vehicles (as a function of the delivery frequency) multiplied by the monthly trailer lease fee, equal to 2.15 k€/month.vehicle and a variable price in function of the travel distance which includes fuel cost, tolls, special purpose vehicle taxes, etc. which is calculated for a 40-ton vehicle equal to 0.423 €/km, based on public transport cost databases [32]. With regards to the pipeline, an additional variable delivery cost related to the energy consumption of the compressors and maintenance of the pipeline is added to the retail cost, according to the transported mass and distance [33]. Furthermore, an additional fixed cost for civil works, estimated around 100,000 €, is added to the CGH_2 configuration since suitable containment structures should be put in place while operating with a large volume of pressurized hydrogen.

A summary of the technical and economic parameters of the hydrogen supply by delivery is reported in Table 3.

Table 3. Summary of technical and economic parameters for delivery hydrogen[18,32–34].

	CGH$_2$ trailers	LH$_2$ trailers	CGH$_2$ pipeline
Delivered quantity	≈350 kg @200 bar	450 kg	Upon request
H$_2$ retail cost	2.50 €/kg (grey H$_2$); 4.00 €/kg (blue H$_2$)		
Vehicle leasing cost	2,150 €/month.vehicle		-
Transport cost	0.423 €/km + 20% profit		0.2 €/(kg.1000 km)
Additional civil works	100,000 €	-	-

3.3 Hydrogen compression, storage, dispensing and balance of plant0,2*

Downstream the hydrogen supply section, the HRSs are equipped with compression, storage, and dispensing sections that follow different design concepts and contribute to the final HRS and H$_2$ cost at the dispenser nozzle.

The gas compressor unit (piston, membrane, or ionic technology) increases the pressure from the supply section (at the outlet of the electrolyzer, at the outlet of the pipeline, from a low-pressure buffer storage or directly from the trailer) to the medium- or high-pressure storage unit. The compressor throughput (Nm^3/h) is calibrated on the maximum flow rate in case of on-site H$_2$ production by electrolysis or can be reduced in case of delivery H$_2$ considering a lower flow rate throughout the day equal. According to the HRS reliability design requirements, redundancy in the compression section (f_{boost}) can be foreseen to avoid the unavailability of the HRS [35]. The compressor electrical consumption $L_{e,compr}$ (kWh$_e$/Nm^3) is calculated in Equation 2 as a function of the pressure ratio β, equal to the ratio of the nominal outlet and inlet pressures p$_{out}$/p$_{in}$, considering an isentropic multistage compression transformation[†]. The electrical consumption related to the compression is summed to the estimated cooling load. The compressor sizing is determined by multiplying the nominal[‡] electrical consumption (kWh$_e$/Nm^3) by the maximum hydrogen throughput (Nm^3/h) [31].

$$L_{e,compr} = c_p(T_2 - T_1) = \frac{c_p(T_2 - T_1)}{\eta_m \eta_e} = \frac{\sum_{i=1}^{n_{st}} c_p \left(\beta_{st}^{\frac{k-1}{k}} - 1 \right)}{\eta_m \eta_e} \approx \frac{c_p \left(\sqrt[n_{st}]{\beta}^{\frac{k-1}{k}} - 1 \right) n_{st}}{\eta_m \eta_e} \qquad (2)$$

Where c$_p$ is the isobaric specific heating value (kWh/kg.K) of the gas, T_1 is the ambient temperature (K), T_2 is the post-compression temperature (K), β is the total pressure ratio and $β_{st}$ is the single-stage pressure ratio, considering n_{st} the number of stages; k is the adiabatic coefficient; $η_m$ is the mechanical efficiency and $η_e$ is the electrical efficiency (a combined mechanical-electrical efficiency of 60% has been considered). The energy consumption is assumed to be equally spread between the compression stages as a simplifying assumption.

The storage section comprises one or more storage units, type III or type IV pressure vessels or tanks according to the nominal pressure level. The storage can be split into different pressure levels (multi-pressure HRS) or grouped at a single pressure level, according to the design of the HRS. The storage management depends on the number of controllable valves and interconnections between compression, storage, and dispensing units. The storage capacity (kg) is usually preliminarily sized according to the daily capacity of the HRS (kg/day). Typically, the storage is sized for around 1 day of nominal capacity, although such

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[†] Considering an isentropic transformation is a conservative assumption since the compressors are usually multi-stage & inter-refrigerated, therefore an isothermal transformation with T_2 equal to T_1 (ambient temperature) would be more representative of the actual compression.

[‡] In addition, the use of the nominal β is also a conservative assumption since given the dynamic charge/discharge dynamics of the storage units the compression will likely occur at a lower β respect to the nominal.

parameter can range between 0.5-5 days of nominal capacity in relation to the H_2 refuelling demand scheme and sustain possible HRS unavailability periods [36].

The dispensing unit controls the pressure-driven refueling process towards the vehicle via a pressure reduction valve with a control system that follows the refueling protocol subject to the SAE J2601 standard, which determines the Average Pressure Ramp Rate (APRR) towards the receiving vehicle tanks. Due to the characteristics of heavy-duty mobility refueling (target pressure of 350 bar, longer refueling times, higher refueled amounts, etc.) pre-cooling is usually not needed. As a generalization, dispensers can be categorized by refueling speed capacity - slow filling (>15 minutes refueling), fast filling (<15 minutes refueling) – or by pressure level - single pressure (350 bar or 700 bar) and dual pressure dispensers (both 350/700 bar refueling pressure) [15].

In addition, the HRS is equipped with general purpose plant auxiliary units (ventilation systems, safety systems, lighting, pipeline, integration, etc.), whose installed power is considered equal to 5% of the total installed power P_{inst} (sum of electrolyzer, compressors, coolers, etc.) in case of on-site producing HRSs and at least 20 kW_e for delivery HRSs. As a conservative assumption, the auxiliary systems are considered to operate 24/24h. Civil and electrical works depend on the compressed hydrogen amount and pressure levels and on the installed electrical power, respectively and are regulated by national standards.

In terms of cost, the compression, storage, dispensing and balance of plant units are all determined via cost functions for CAPEX and OPEX. The compression CAPEX is determined based on the installed electrical power (kW) and the redundancy factor f_{boost} (%) – including inter-cooling system; the OPEX depends on the electrical consumption monetized at the electricity retail price c_{el} (€/kWh), other than the O&M cost [15,31,37]. The CGH_2 storage CAPEX is calculated as a function of hydrogen capacity (kg) and pressure level (bar), taking into account the additional cost of management valves for larger quantities [15]; the OPEX is only composed of O&M since the storage unit is passive in terms of energy consumption. The dispensing unit CAPEX is determined according to the hydrogen refueling capacity (kg/day) differentiated based on the categorization of the dispensing unit (slow filling, fast filling, single/dual pressure) factor f_{disp} which varies between 1-1.5; the OPEX is only O&M since the dispensing system is passive as well (no pre-cooling considered) [15]. Finally, the balance of plant presents some additional CAPEX and OPEX costs, based on the installed power and the electricity consumption, monetized at the electricity retail price c_{el} (€/kWh) [18].

The summary of the technical and economic parameters of the compression, storage, dispensing and balance of plant sections of the HRS are reported in Table 4.

Table 3. Summary of technical and economic parameters for the compression, storage, dispensing and balance of plant sections of the HRS [31], [15,38],[14,18,36].

		Compressor	**Storage**	**Dispenser**	**Balance of Plant**
		Technical parameters			
Sizing criteria		Q_{max} production (Nm^3/h) Q_{avg} delivery (Nm^3/h)	Days of nominal capacity (kg)	Nominal capacity (kg/day)	5% P_{inst} (onsite) ≥20 kW_e (delivery)
Energy consumption		Eq. 2 + 20% cooling	-	-	24/24h; η_e=0.97%
		Economic parameters			
CAPEX		15,000 $x^{-0.4}$ f_{boost}^* €/kW_e	350-1000 €/kg_{H2}^{**}	f_{disp}^{***} 350 €/(kg/day)	200 €/kW_e
OPEX	Energy	Eq. 2 x c_{el}	-	-	P_{aux} x c_{el}
	O&M	4%$_{CAPEX}$/year	2%$_{CAPEX}$/year	2%$_{CAPEX}$/year	10%$_{CAPEX}$/year

* compressor boost coefficient; f_{boost} ≥1

[**] calibrated based on nominal pressure, stored capacity and management valves units
[***] depending on dispenser type & pressure; $1 < f_{disp} < 1.5$

4 Results and Discussion

The cost model has been run for the five HRS sites, considering a classical project finance approach with a standard time horizon of 15 years and an interest rate *i* equal to 7%. The results of the cost model in terms of HRS cost (M€ and breakdown between CAPEX and OPEX contributions) and LCOH at the nozzle (€/kg and breakdown between CAPEX and OPEX contributions) are reported in this section, together with some comparative parameters to contextualize the differences in the cost model results.

Despite the differences between each HRS, recurrent cost patterns can be identified between the delivery HRSs (London, Rhoon and Versailles) and on-site HRSs (Pau and Aalborg). In particular, the delivery-based HRSs are predominantly OPEX-driven (up to 85-90% of the annualized total cost), where the retail hydrogen price is the most significant parameter for the definition of the LCOH. In addition, the delivery configuration with on-site storage of the tube trailer helps to smoothen the compression load since the compressor is operated with lower β ratios and over longer time periods, resulting in a slight cost reduction in the compression/storage sections. On the other hand, on-site production HRSs present a higher CAPEX contribution (around 25-30% of the annualized), due to the high electrolyzer CAPEX (>1000 €/kW$_e$) cost, although the OPEX still dominates the LCOH, especially in terms of electricity price, which is an important parameter since the electrolyzer presents a very high specific electricity consumption (>50 kWh$_e$/kg$_{H2}$). For both HRSs, the compression and storage sections represent a relevant but not prevalent contribution for the LCOH (around 1-3 €/kg) according to the HRS design specifications and different design concepts in terms of required reliability, redundancy and single/multi-pressure approach (e.g. Pau presents a much more complex compression/storage section with multi-pressure storage units and parallel compressors respect to London which only presents a single on-site storage unit and the compressor is integrated within the LH$_2$ trailer). The dispensing system does not usually represent a significant portion of the total cost, although the dispensing can become more relevant in HRS with many dispensing points (e.g., Pau) or with fast fuelling or dual-pressure dispensers (e.g. Versailles) and although the dispensing system design is directly linked to the vehicle fleet refueling logistics, which can play a key role in the operation of the HRS. Figure 3 and Figure 4 illustrate an example of an HRS cost breakdown for a delivery HRS and an on-site producing HRS.
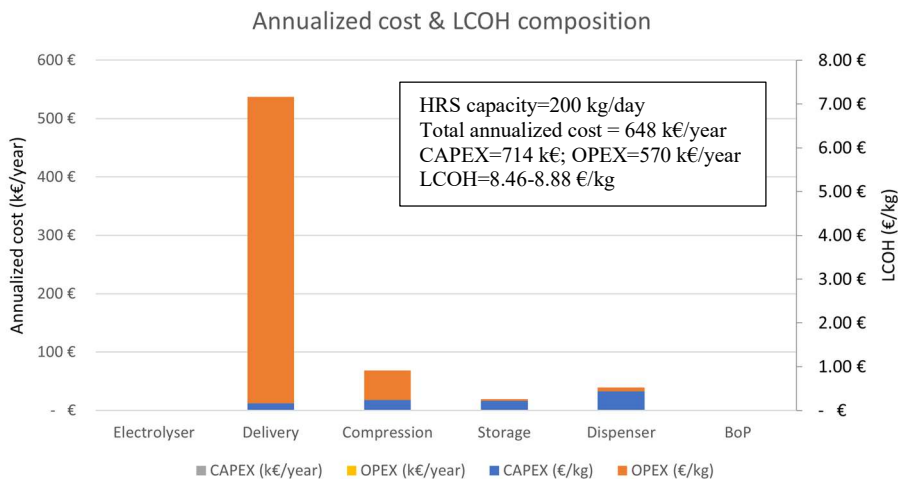

Annualized cost & LCOH composition

HRS capacity=200 kg/day
Total annualized cost = 648 k€/year
CAPEX=714 k€; OPEX=570 k€/year
LCOH=8.46-8.88 €/kg

Fig. 3. Example of delivery-based HRS (Versailles) in terms of annualized total cost (€/year) and LCOH (€/kg).

Annualized cost & LCOH composition

HRS capacity=100 kg/day
Total annualized cost = 367 k€/year
CAPEX=632 k€; OPEX=178 k€/year
LCOH=9.55-10.57 €/kg

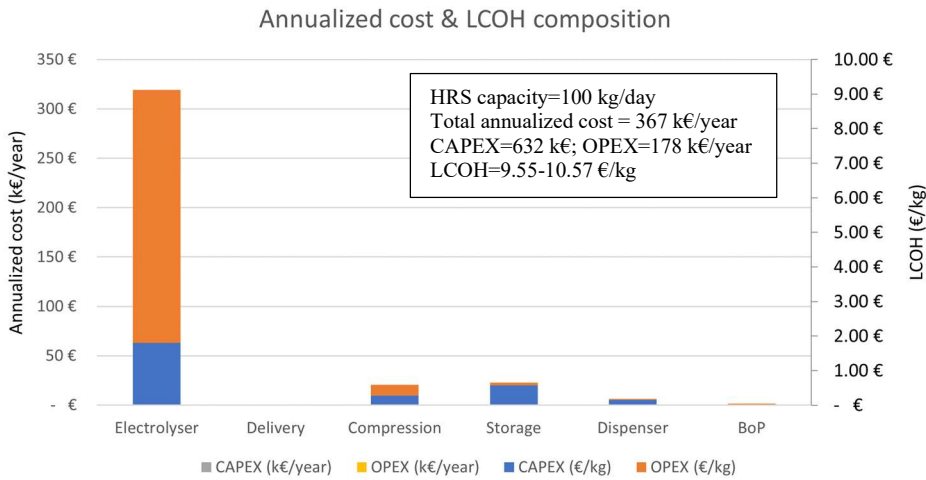CAPEX (k€/year) OPEX (k€/year) CAPEX (€/kg) OPEX (€/kg)

Fig. 4. Example of on-site production-based HRS (Aalborg) in terms of annualized total cost (€/year) and LCOH (€/kg).

Overall, similar results in terms of LCOH are be found for the different configurations (between 8-12 €/kg). For the considered HRS capacities (100 kg/day up to 400 kg/day), delivery HRS schemes (LCOH between 8-9 €/kg for London and Versailles) are still more convenient than on-site producing HRSs (LCOH around 11-12 €/kg); the Rhoon HRS presents a particularly competitive LCOH (5.75-6.15 €/kg) considering the pipeline delivery whose CAPEX is not accounted for in the HRS cost model and due to the very low service cost, even for large amounts of H_2 transported over long distances. The financial cost (considering the assumed scenario of 15 years and 7% interest rate) has an impact between 5-10% of the final cost, which is relevant especially for CAPEX-intensive HRS schemes.

The cost model results for all the HRSs are summarized in Table 4.

Table 4. Summary of cost model results for all HRSs (delivery & on-site) in terms of CAPEX/OPEX & LCOH contributions.

	CAPEX (k€)	OPEX (k€/year)	LCOH (€/kg)	$LCOH_{CAPEX}$ (€/kg)	$LCOH_{OPEX}$ (€/kg)	$C_{HRS,CAPEX}$ (k€/(kg/day))
London	414	469	8.81	0.78	8.03	4.26
Rhoon	701	375	6.19	1.05	5.14	5.77
Versailles	714	570	8.88 €	1.07	7.81	5.88
Pau	2,004	544	12.02	3.46	8.56	18.97
Aalborg	632	268	10.57	2.84	7.73	10.37

Analyzing the aggregated specific CAPEX cost based on the HRS capacity ($C_{HRS,CAPEX}$), it can be noticed that while delivery based HRSs span between 4-6 k€/(kg/day), which is quite in line with comparable literature [12], [13] instead, for the on-site producing HRS schemes, such parameter can see a two/three-fold increase due to the previously discussed higher upfront CAPEX contribution, related to the electrolyzer and the less advantageous design specifications of the rest of the systems.

5 Conclusions

A detailed component-oriented cost model has been applied to five different real HRS configurations to assess the HRS cost and the LCOH at the dispenser nozzle. The disaggregated approach to the cost model (CAPEX and OPEX for each component/subsystem) allows to correctly compose the final HRS cost and LCOH with sufficient detail, allowing to identify the most critical cost parameters for different HRS design concepts (delivery-based and on-site producing).

The results confirm that the H_2 price at the nozzle of small scale HRSs can range between 6-12 €/kg, which is in line with the literature, standard market prices for the analyzed HRS capacity range and with the 3Emotion project targets. The LCOH is mainly composed of the cost of H_2 itself (either delivered or produced on-site – which accounts for at least 5 €/kg), to which the compressor, storage and dispensing costs are added to reach the final cost at the dispenser nozzle at 350 bar. For the considered HRS capacity (100 kg/day to 400 kg/day), it is still more convenient to deliver H_2 to the HRS (LCOH 8-9 €/kg for London and Versailles) than to produce it on-site (LCOH approximately 11-12 €/kg); the Rhoon HRS has a particularly competitive LCOH (5.75-6.15 €/kg), thanks to the low cost pipeline delivery although its CAPEX is not considered within the HRS cost model, since it is a larger scale infrastructure which serves multiple users.

Delivery-based HRSs (London, Rhoon, Versailles) are typically OPEX-dominated (>85% of the annualized cost), for which the H_2 retail price represents the main cost contribution, together with the transport service price. Since the main cost contributions are externalized, it is of foremost importance to establish convenient long-term contract prices (for both gas retail and transport) with the gas supplier to ensure competitive cost reduction from the HRS operator point of view.

On-site producing HRSs (Pau, Aalborg) present a stronger contribution of the CAPEX (25-30% of the annualized cost), although the LCOH in the long term is still driven by the OPEX (in this case, especially by electricity price). Producing hydrogen on-site is still not convenient for the analyzed HRS sizes (up to 400 kg/day) since significant scale economies cannot be obtained in terms of electrolyzer cost. Also, the rest of the compressor and storage systems have to be sized according to the electrolyzer maximum production capacity (while for delivery schemes, the trailers can be discharged more gradually), and the compression ratios are generally higher with respect to delivery-based HRS schemes (starting from 30 bar respect to 200 bar in case of delivery H_2).

The cost-competitiveness of delivery-based HRS schemes with respect to on-site production HRS schemes could be inverted in the future when with larger-scale HRSs (>400 kg/day), greater economies of scale can be untapped for electrolyzer systems, and the cost of distribution & transport could surpass the cost to produce the hydrogen on-site with a decentralized approach.

Although defining an aggregate value to determine the HRS CAPEX in function of the capacity is desirable in order to assess the cost of a HRS quickly, this approach is too general. In fact, the specific HRS CAPEX cost ($C_{HRS,CAPEX}$) depends not only on the HRS capacity but also on the HRS type and design concept. Much higher values (two- to three-fold) are found for on-site producing HRSs, due to the increased CAPEX with respect to delivery HRSs. This confirms that it is not suitable to assess the cost of an HRS with respect to its nominal capacity with a one-size-fits-all aggregate cost curve and that a more detailed, component-oriented analysis is necessary.

As a future perspective of this work, the cost model should be integrated with operational aspects related to the HRS components and the vehicle fleet operation and logistics to provide a fully integrated design & operational based cost model of the HRS to assess the technical and economic implications not only at design level but also in real-life operation.

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