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Hydrogen volumetric fraction effects on HCNG refuelling station CAPEX

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Abstract

Greening the transport sector is crucial for the achievement of the ambitious decarbonisation goals set by the Conference of the Parties (COP21) Paris agreement to keep global warming "well below 2 degrees Celsius above preindustrial levels, and to pursue efforts to limit the temperature increase even further to 1.5 degrees Celsius". Battery electric vehicles and hydrogen fuel cell electric vehicles will play a key role in the reduction of greenhouse gas emissions in the road mobility. Nonetheless, those technologies still need to face some technological challenges. Hence, hydrogen enriched natural gas (HCNG) can play an important role as bridging technology. This study envisages the upgrade of an existing compressed natural gas (CNG) refuelling station (RS) in HCNG-RS. Particularly, an analysis regarding the impact of different hydrogen volumetric fractions in the blend on the total CAPEX of the HCNG refuelling station is carried out, by evaluating the HCNG fill-up demands for a proper refuelling station sizing. The proposed HCNG refuelling station layout foresee the on-site hydrogen production by means of an electrolyser fed by PV energy. Each component of the station has been adequately sized based on the resulting peak HCNG refuelling demand. The highest CAPEX value is recorded for the 30%vol. HCNG, amounting up to 3.52 M€.

Keywords

Power to gas; HCNG; hydrogen blending; refuelling station; refuelling demand; driving range.

Highlights

- HCNG refuelling station sizing from existing CNG refuelling station.
- Hydrogen impact on HCNG fill-up demand.
- HCNG refuelling station cost breakdown.

1. Introduction

The transport sector greening is crucial for the decarbonization goals set by the Conference of the Parties (COP21) Paris agreement [1,2]. Indeed, due to the great reliance on fossil fuels, the transport segment results one of the main polluting sectors [3,4]. Battery electric vehicles (BEVs) along with hydrogen fuel cell electric vehicles (HFCEVs) are the main transport solutions to limit the temperature increase to 1.5 degrees Celsius, at least. Indeed, the growing renewable energy production, targeted for the close future, can also be exploited with different strategy, such as the mobility segment [5,6] and the power-to-Methane [7], ensuring also the system flexibility [8]. Notwithstanding, BEVs and HFCEVs still need to face some techno-economic issues mostly related to the charging/refuelling infrastructures. Furthermore, the BEVs and HFCEVs greater purchasing costs than fossil fuels cars of this phase can represent an obstacle for the light duty vehicles (LDV) fleet renewing. Also, the "chicken-and-egg" problem could delay and interfere the transport greening. Therefore, bridging technology can be crucial for overcoming some initial issues. In such regard, hydrogen compressed natural gas (HCNG) blend can play a key role towards the hydrogen employment in LDVs. The main HCNG strengths rely on the vehicles and refuelling stations (RS) compatibility with CNG internal combustion engines (ICE) and RS. In the last years, the retrofitted HCNG-ICE vehicles have been widely analysed and several improvements regarding brake thermal efficiencies and lower emissions have been proved [9,10]. Hence, the usage of HCNG fuels allow to

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exploit existing CNG fuelled vehicles, by adopting some adjustments concerning the fuel injection parameters [11,12] and the cylinder type. Those modifications guarantee the safe and reliable HCNG use. The same goes for the HCNG refuelling stations. As a matter of fact, the CNG-RS can be upgraded with additional technologies needed for the green hydrogen generation, compression and storage. In a previous publication at Ref. [13] the HCNG refuelling station layout has been described and illustrated. Lastly, a blending unit is needed for the on-time HCNG refuelling demand. Thus, HCNG can be pivotal for a partial immediate road transport decarbonization, along with a bridging technology toward hydrogen economy. Furthermore, the natural gas deployment reduction for the mobility sector is crucial in this historical phase also for the geopolitical scenarios effects [14].

2. Methodology and scope of the article

This work seeks to envisage how the hydrogen rate of the blend affects the retrofitted HCNG refuelling station costs. Currently this topic has not been disclosed yet at the best of the authors knowledge. Indeed, despite the hydrogen enriched natural gas has been widely assessed over the last decade [15], just few papers concerning the HCNG refuelling station have been assessed. Notwithstanding, the latter were neither strongly related to the HCNG-RS CAPEX. Hence, starting from an existing CNG refuelling station, the different CAPEX values derived from ranging the H_2 volumetric fraction (f) between 15%vol. and 30%vol. with steps of 5%vol. have been foreseen and compared. Therefore, the existing RS has been upgraded with a green hydrogen production system, that comprises an electrolyser fed by a PV plant. Moreover, the hydrogen compressor unit along with the low-pressure and high-pressure storage systems, respectively HPSS and LPSS, have been included in the hydrogen branch. Thus, the different impacts of hydrogen volumetric fraction on the CNG refuelling demand have been evaluated, by considering the respective hydrogen effects on the fuel lower heating values (LHVs) and on the engine efficiencies. After assessing the respective fill-ups demand, each refuelling station has been adequately sized. Thus, the total installations costs have been raised and compared. Finally, a cost breakdown between the hydrogen generation, compression and storage technologies has been showed and discussed.

3. HCNG-RS sizing

In the next subsections the refuelling processes per each H_2 volumetric range have been outlined.

3.1. The hydrogen addition effects on the HCNG fill-up demand.

Several studies have proved that retrofitted CNG fuelled internal combustion engines benefit of several improvements in brake thermal efficiencies and lower pollutants emissions, such as CO, CO_2 and NO_X [16], with no power output changing. Such benefits arise from the hydrogen addition to the CNG, by applying some modifications regarding the fuel injection parameters and the tank type. Indeed, differently from the 20 MPa CNG fuelled cylinder vehicles, the tanks filled by 20 MPa HCNG need to overcome the wall embrittlement due to the H_2[17]. Thus, similarly to the 70 MPa HFCEVs, the IV type vehicle tanks are needed for the blend usage [18].

In this subsection the effects of different f have been assessed. Starting from the CNG refuelling demand of an existing RS based in Rome, the upgraded HCNG vehicle fill-up transactions have been derived by evaluating the H_2 effect on the driving range. The HCNG sizing at each f has been carried out by evaluating the final fuelled mass and the respective driving ranges. Indeed, the lower the driving ranges, the greater the refuelling demand and the RS sizes are.

Thereby, the daily resulting HCNG mass demand has been derived for the f values ranging from the 15% to 30% with steps of 5% in volume, as follows:

$$M_{30\%HCNG} = M_{CNG} * \frac{E_{CNG}}{E_{30\%HCNG}} * \frac{BTE_{CNG}}{BTE_{30\%HCNG}} \quad (1)$$

Here:

- M_{HCNG}: daily HCNG mass to be refuelled in kg.
- M_{CNG}: starting CNG demand [kg/day].
- BTE: brake thermal efficiency [%].

Since the driving range is strongly affected by the fuels' LHVs and efficiencies, the resulting HCNG mass to provide has been outlined by comparing the CNG driving range and BTE with each blends' values

The brake thermal efficiency values have been considered as the average values of the BTE at 2000 rpm, 4000 rpm and 6000 rpm [19–21]. The fuels average BTE values at each rpm have been listed in Table 1.

Table 1. Average fuels' brake thermal efficiencies.

Fuel	BTE [%]
CNG	19.53
15%vol. HCNG	22.50
20%vol. HCNG	22.90
25%vol. HCNG	23.02
30%vol. HCNG	23.13

Moreover, the E value in Equation 1 stands for the total available energy in the pressurized tank [MJ], to be exploited by the engines. That value has been evaluated as expressed in Equation 2.

$$E = \frac{LHV}{\rho_n} * \rho * V_{tank} \quad (2)$$

In Equation 2 LHV shows the fuel lower heating value, ρ and ρ_n stands for the fuel density and the normal density, respectively in [kg/m^3] and [kg/Nm^3]. Lastly, V_{tank} is the average vehicle tank considered equal to 0.15 m^3 [22].

The retrofitted refuelling station has to ensure back-to-back fill-ups, likewise the existing CNG refuelling station does. The article in Ref. [13] investigates the thermodynamic of HCNG refuelling processes in the fastest and safest conditions. Furthermore, considering that the HCNG mass flow rate cannot exceed the 60 g/s in accordance with the safety standards of the IV type cylinder tank, envisaged in the SAE J-2601 [23,24], a total refuelling time of 6 minutes per vehicle has been conjectured. In so doing, a maximum number of 10 vehicles can be fast filled in one hour [25]. Thus, the hoses number can be easily derived. Table 2 reports the resulting LHV values, along with the peak daily and hourly vehicles refuelling per each fuel. The fuels' LHVs have been reported on volumetric basis and not in mass basis, as by definition. This is due to the changing density and mass, owed to the varying hydrogen rates. On the other hand, the tank volume is fixed per each fuel. The peak values have been engineered as a conservative approach has been followed for the RS sizing.

Table 2. Fuel fill-ups demands.

Fuel	LHV [MJ/Nm^3]	[vehicles/day]	[vehicles/hour]
CNG	35.88	178	15
15%vol. HCNG	32.11	172	14
20%vol. HCNG	30.847	176	15
25%vol. HCNG	29.59	183	15
30%vol. HCNG	28.33	190	16

Table 2 envisages that by enhancing the hydrogen volumetric fraction in the blend, the LHV shrinks due to the density lowering. Thereafter, the greater the hydrogen rate in the fuel, the lower the driving range is. Bigger tank volumes at fixed pressure or greater final pressure levels at fixed cylinder volumes are needed to match the CNG driving range. Notwithstanding, as the brake thermal efficiency increases at greater f, the minimum hourly and daily refuelling demand is recorded for the 15%vol.HCNG thanks to the more consistent LHV and density values. This strongly affects the HCNG-RS sizing.

The retrofitted HCNG refuelling stations have been dimensioned by considering 12 daily working hours, in accordance with the initial CNG refuelling station. Hence, by harnessing the hourly refuelling transactions disclosed by the Nexant et al. [26], the resulting HCNG hourly fill-ups have been obtained and depicted in Figure 1.

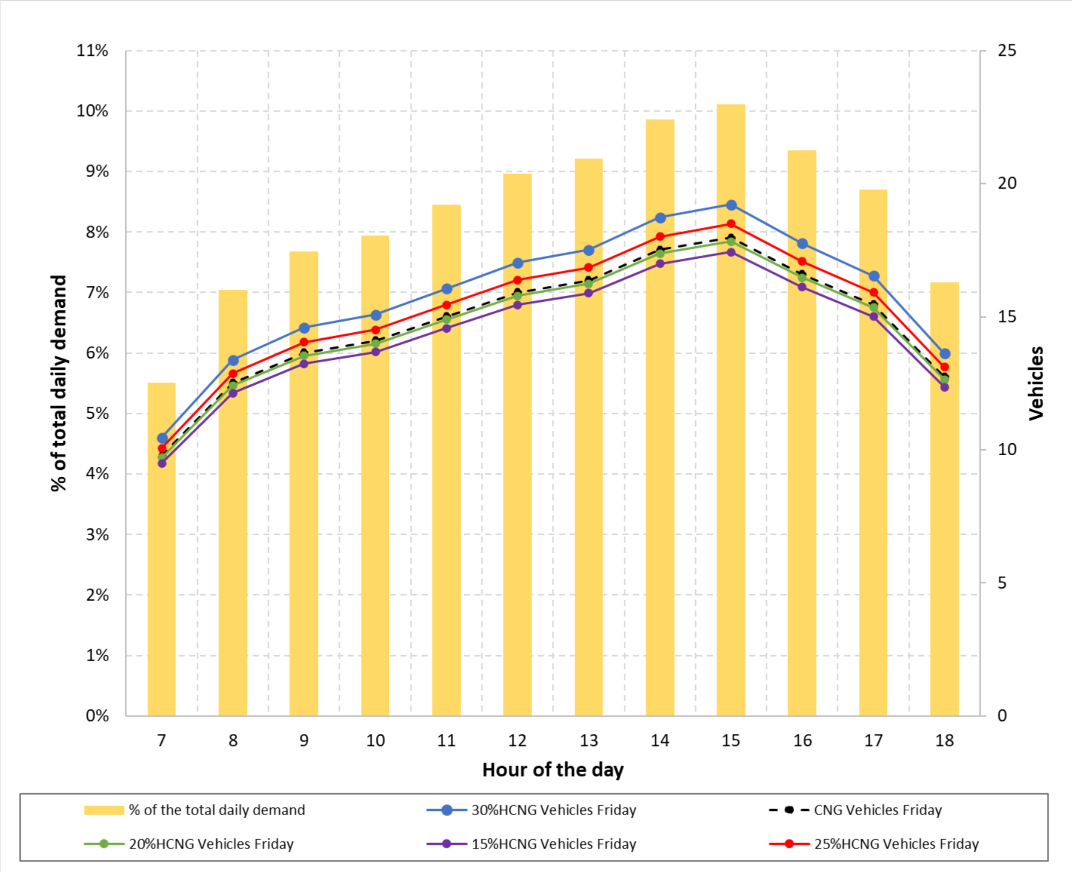

Figure 1. Daily fill-ups demand.

As foreseen in the Table 1, the 15%vol. and 20%vol. in the HCNG record a lower fast fill-ups demand than the CNG.

3.2. HCNG refuelling stations sizing

After assessing the resulting demand per each HCNG hydrogen volumetric fraction, arising from the initial CNG peak demand of 3459.28 kg/day. In the retrofitted HCNG-RS no new dispenser are foreseen, as the hydrogen molar percentage relative to the maximum 30%vol. HCNG corresponds to about the 5% of the total fuel. Hence, considering that the same tank pressure is needed, the existing CNG dispenser can fit for the assessed HCNG blends. Furthermore, as the hydrogen source is the PV energy, the solar stochasticity has been considered. Therefore, optimal oversizing is needed for the PV plants, electrolysers and storage systems, in order to optimize the green hydrogen production as much as possible. In Table 3 each HCNG refuelling station has been sized, in accordance with the peak refuelling demands, recorded on every Friday.

Table 3. HCNG refuelling stations sizes.

Fuel	Electrolyser [kW]	PV [kW]	LPSS [kg]	HPSS [kg]	Compressor [kW]	Mixer [Nm^3/h]
15%vol. HCNG	420	1200	76	91	7.5	43.3
20%vol. HCNG	550	1500	98	117	9.8	57.2
25%vol. HCNG	660	1900	119	143	12.2	70.9
30%vol. HCNG	750	2200	139	166	14.5	84.33

3.3. Economic assumptions.

After evaluating some literature surveys, the economic assumptions exploited for this analysis have been envisaged in Table 4.

Table 4. Economic assumptions.

Component	CAPEX	Source
Electrolyser	1327 €/kW	[27,28]
H_2 Storage (3MPa)	600 €/kg	[29,30]
H_2 storage (22 MPa)	773.5 €/kg	[31,32]
Compressor	7,800 €/kW	[33,34]
PV plant	1000 €/kW	[35,36]
Mixer	$13{,}302.378y^{-0.613*}$	[37]

**y* refers to the H_2 Nm^3/h flow rate.

4. HCNG-RS CAPEX

Having fixed the refuelling stations sizing and the component cost, each HCNG-RS CAPEX can be assessed, considering the hourly H_2 demand, as aforementioned. The highest CAPEX value is recorded for the 30%vol. HCNG, amounting up to 3.52 M€. This value is not due just to the highest volumetric fraction in the fuel, but it is also correlated to the lowest fuel density and LHV, as shown in Table 1. Indeed, the cost decrease at lower hydrogen volumetric fraction is not proportional to the *f* reductions. Figure 2 shows that the CAPEX decreases of the 13%, 17% and 24% for the 25%vol., 20%vol., 15%vol. HCNG.

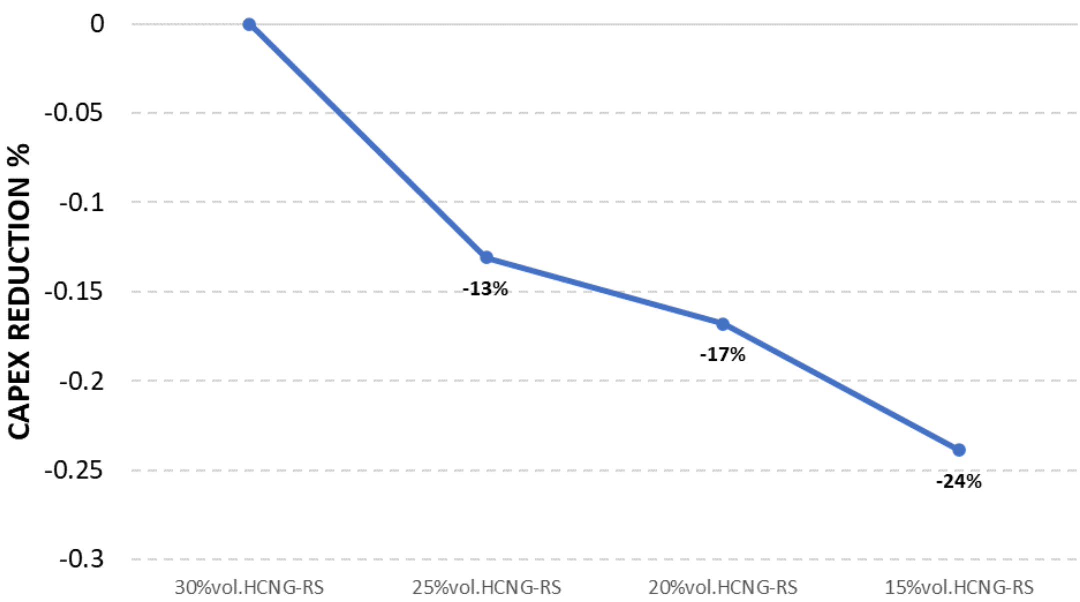

Figure 2. HCNG-RS CAPEX reduction.

Figure 3 depicts the total cost breakdown per each hydrogen fraction.

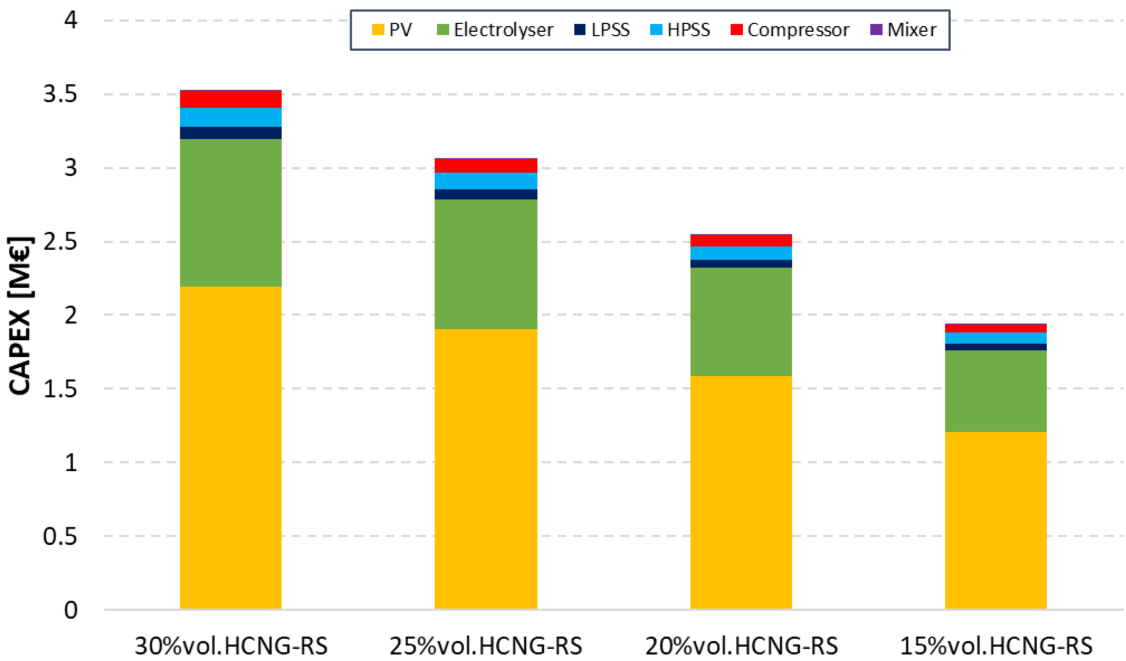

Figure 3. Total cost breakdown.

The electrolyser and the PV plant mostly impact the HCNG refuelling station cost, affecting also the levelized cost of hydrogen. The other components regarding the compression, storage and blending unit weight just the 9% on the CAPEX per each configuration. The green H_2 production affects the total expenditure at the 91%. Notably, the electrolyser weights around the 30% on the green H_2 production. On the other hand, the PV plant is around the 70% of the generation costs, see Figure 4.

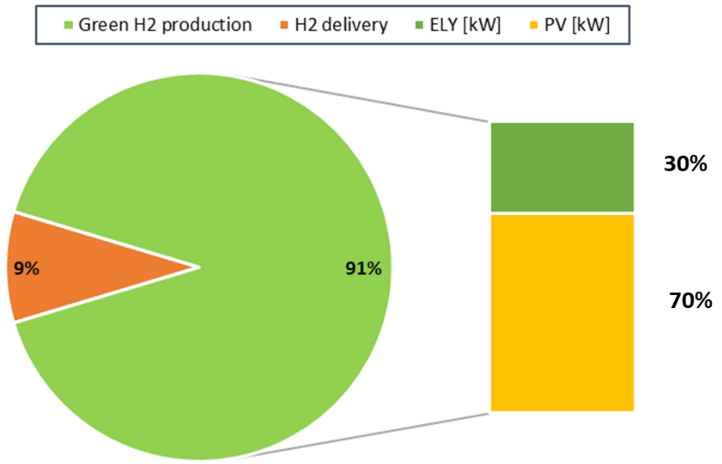

Figure 4. Green H_2 production cost vs H_2 compression, storage and blending.

Hence, different hydrogen source or decentralized hydrogen production can strongly reduce the levelized cost of hydrogen [38]. Furthermore, the economy of scale can support the hydrogen market, thanks to the reduction of the electrolysers' CAPEX.

5. Conclusion

In this work the hydrogen volumetric fractions effects have been evaluated in order to engineer an HCNG refuelling station, by upgrading an existing CNG-RS. Specifically, the hydrogen impacts on the fill-up demand has been analysed per each blend, by ranging the H_2 volumetric fraction between the 15% and 20% in step range of 5%. Hence, every HCNG refuelling station has been sized by considering the green hydrogen production via an electrolyser fed by PV energy.

The main outcomes of this assessment can be summarised as follows:

- The greater the hydrogen volumetric fraction, the lower the driving range and the refuelling demand are. Hence, the PV system, the electrolyser and the storage sizes increase, accordingly to the total HCNG-RS CAPEX,
- The blend with the hydrogen volumetric fraction up to 20% reach a greater driving range then the CNG fuelled ICE vehicles.
- The cost decrease at lower hydrogen volumetric fraction is not proportional to the *f* reductions.
- The green H_2 production affects the total refuelling station CAPEX for the 91%.
- The PV plant and the electrolyser weight around the 30% and 70% on the final green H_2 production CAPEX.
- The highest CAPEX value is recorded for the 30%vol. HCNG, amounting up to 3.52 M€.

As a side conclusion, this work aims to provide instructions and a clear approach for private companies, in order to evaluate how to properly design HCNG refuelling station, by upgrading existing CNG-RS.

Nomenclature

CAC	Carbon Avoidance Cost	HRS	Hydrogen refuelling station
CAPEX	Capital expenditure	ICE	Internal combustion engine
CNG	Compressed natural gas	LHV	Lower heating value
CNG-RS	Compressed natural gas refuelling station	LPSS	Lower pressure storage system
f	Hydrogen volumetric fraction	NG	Natural gas
FCEV	Fuel cell electric vehicles	PV	Photovoltaic
H_2	Hydrogen	RS	Refuelling station
HCNG	Hydrogen compressed natural gas		
HCNG-RS	HCNG refuelling station		
HFCEV	Hydrogen fuel cell electric vehicles		
HPSS	High pressure storage system		

Bibliography

[1] EU economy and society to meet climate ambitions. European Green Deal: Commission proposes transformation of EU economy and society to meet climate ambitions n.d. https://ec.europa.eu/commission/presscorner/detail/%5Beuropa_tokens:europa_interface_language%5D/ip_21_3541 (accessed March 23, 2023).

[2] Pastore LM, Lo Basso G, Cristiani L, de Santoli L. Rising targets to 55% GHG emissions reduction – The smart energy systems approach for improving the Italian energy strategy. Energy 2022;259. https://doi.org/10.1016/j.energy.2022.125049.

[3] European Environment Agency. Air pollution sources n.d. https://www.eea.europa.eu/themes/air/air-pollution-sources-1 (accessed March 23, 2023).

[4] European Commision. Transport and the Green Deal n.d. https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal/transport-and-green-deal_en (accessed March 23, 2023).

[5] Pastore LM, Lo Basso G, Ricciardi G, de Santoli L. Smart energy systems for renewable energy communities: A comparative analysis of power-to-X strategies for improving energy self-consumption. Energy 2023;280:128205. https://doi.org/10.1016/j.energy.2023.128205.

[6] Pastore LM. Combining Power-to-Heat and Power-to-Vehicle strategies to provide system flexibility in smart urban energy districts. Sustain Cities Soc 2023;94. https://doi.org/10.1016/j.scs.2023.104548.

[7] Lo Basso G, Pastore LM, de Santoli L. Power-to-Methane to Integrate Renewable Generation in Urban Energy Districts. Energies (Basel) 2022;15. https://doi.org/10.3390/en15239150.

[8] Ciancio A, De Santoli L. Assessing the Levelized Cost of Hydrogen Production in a Renewable Hydrogen Community in South Italy. 2023 IEEE International Conference on Environment and Electrical Engineering and 2023 IEEE Industrial and Commercial Power Systems Europe (EEEIC / I&CPS Europe), IEEE; 2023, p. 1–6. https://doi.org/10.1109/EEEIC/ICPSEurope57605.2023.10194654.

[9] Zareei J, Rohani A, Mazari F, Mikkhailova MV. Numerical investigation of the effect of two-step injection (direct and port injection) of hydrogen blending and natural gas on engine performance and exhaust gas emissions. Energy 2021;231. https://doi.org/10.1016/j.energy.2021.120957.

[10] Bauer CG, Forest TW. EEect of hydrogen addition on the performance of methane-fueled vehicles. Part II: driving cycle simulations. vol. 26. 2001.

[11] Mathai R, Malhotra RK, Subramanian KA, Das LM. Comparative evaluation of performance, emission, lubricant and deposit characteristics of spark ignition engine fueled with CNG and 18% hydrogen-CNG. Int J Hydrogen Energy 2012;37:6893–900. https://doi.org/10.1016/j.ijhydene.2012.01.083.

[12] Bysveen M. Engine characteristics of emissions and performance using mixtures of natural gas and hydrogen. Energy 2007;32:482–9. https://doi.org/10.1016/j.energy.2006.07.032.

[13] Sgaramella A, Lo Basso G, de Santoli L. How the cylinder initial conditions affect the HCNG refuelling process - A thermodynamic analysis to determine the most effective filling parameters. Int J Hydrogen Energy 2023. https://doi.org/10.1016/j.ijhydene.2023.07.323.

[14] Pastore LM, Lo Basso G, de Santoli L. Towards a dramatic reduction in the European Natural Gas consumption: Italy as a case study. J Clean Prod 2022;369. https://doi.org/10.1016/j.jclepro.2022.133377.

[15] Lo Basso G, Pastore LM, Sgaramella A, Mojtahed A, de Santoli L. Recent progresses in H2NG blends use downstream Power-to-Gas policies application: An overview over the last decade. Int J Hydrogen Energy 2023. https://doi.org/10.1016/j.ijhydene.2023.06.141.

[16] Chintala V, Subramanian KA. Hydrogen energy share improvement along with NOx (oxides of nitrogen) emission reduction in a hydrogen dual-fuel compression ignition

engine using water injection. Energy Convers Manag 2014;83:249–59. https://doi.org/10.1016/j.enconman.2014.03.075.

[17] Khab H, Chaker A, Ziani L. Effects of pressure and hydrogen addition to methane on the temperatures within a pressurized cylinder during the vehicle refueling of HCNG. Int J Hydrogen Energy 2019;44:22437–44. https://doi.org/10.1016/j.ijhydene.2019.04.209.

[18] Farzaneh-Gord M, Deymi-Dashtebayaz M, Rahbari HR, Niazmand H. Effects of storage types and conditions on compressed hydrogen fuelling stations performance. Int J Hydrogen Energy 2012;37:3500–9. https://doi.org/10.1016/j.ijhydene.2011.11.017.

[19] Zareei J, Rohani A, Wan Mahmood WMF. Simulation of a hydrogen/natural gas engine and modelling of engine operating parameters. Int J Hydrogen Energy 2018;43:11639–51. https://doi.org/10.1016/j.ijhydene.2018.02.047.

[20] Zareei J, Rohani A. Optimization and study of performance parameters in an engine fueled with hydrogen. Int J Hydrogen Energy 2020;45:322–36. https://doi.org/10.1016/j.ijhydene.2019.10.250.

[21] White CM, Steeper RR, Lutz AE. The hydrogen-fueled internal combustion engine: a technical review. Int J Hydrogen Energy 2006;31:1292–305. https://doi.org/10.1016/j.ijhydene.2005.12.001.

[22] Zheng J, Ye J, Yang J, Tang P, Zhao L, Kern M. An optimized control method for a high utilization ratio and fast filling speed in hydrogen refueling stations. Int J Hydrogen Energy 2010;35:3011–7. https://doi.org/10.1016/j.ijhydene.2009.07.001.

[23] Reddi K, Elgowainy A, Rustagi N, Gupta E. Impact of hydrogen SAE J2601 fueling methods on fueling time of light-duty fuel cell electric vehicles. n.d.

[24] Schneider J, Meadows G, Mathison SR, Veenstra MJ, Shim J, Immel R, et al. Validation and Sensitivity Studies for SAE J2601, the Light Duty Vehicle Hydrogen Fueling Standard. SAE International Journal of Alternative Powertrains 2014;3:257–309. https://doi.org/10.4271/2014-01-1990.

[25] Mayer T, Semmel M, Guerrero Morales MA, Schmidt KM, Bauer A, Wind J. Techno-economic evaluation of hydrogen refueling stations with liquid or gaseous stored hydrogen. Int J Hydrogen Energy 2019;44:25809–33. https://doi.org/10.1016/j.ijhydene.2019.08.051.

[26] H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results. 2008.

[27] Greiner CJ, KorpÅs M, Holen AT. A Norwegian case study on the production of hydrogen from wind power. Int J Hydrogen Energy 2007;32:1500–7. https://doi.org/10.1016/j.ijhydene.2006.10.030.

[28] Fan JL, Yu P, Li K, Xu M, Zhang X. A levelized cost of hydrogen (LCOH) comparison of coal-to-hydrogen with CCS and water electrolysis powered by renewable energy in China. Energy 2022;242. https://doi.org/10.1016/j.energy.2021.123003.

[29] USDrive. Hydrogen Storage Technologies Roadmap Hydrogen Delivery Technical Team Roadmap. 2013.

[30] Grüger F, Dylewski L, Robinius M, Stolten D. Carsharing with fuel cell vehicles: Sizing hydrogen refueling stations based on refueling behavior. Appl Energy 2018;228:1540–9. https://doi.org/10.1016/j.apenergy.2018.07.014.

[31] Blazquez-Diaz C. Techno-economic modelling and analysis of hydrogen fuelling stations. Int J Hydrogen Energy 2019;44:495–510. https://doi.org/10.1016/j.ijhydene.2018.11.001.

[32] Parks G, Boyd R, Cornish J, Remick R, Review Panel I. Hydrogen Station Compression, Storage, and Dispensing Technical Status and Costs: Systems Integration. 2020.

[33] Ferrero D, Gamba M, Lanzini A, Santarelli M. Power-to-Gas Hydrogen: Techno-economic Assessment of Processes towards a Multi-purpose Energy Carrier. Energy Procedia, vol. 101, Elsevier Ltd; 2016, p. 50–7. https://doi.org/10.1016/j.egypro.2016.11.007.

[34] Turton R, Bailie RC, Whiting WB, Shaeiwitz JA, Bhattacharyya D. Analysis, Synthesis, and Design of Chemical Processes Fourth Edition. n.d.

[35] Renewable Energy Agency I. Renewable power generation costs in 2019. 2020.

[36] Pierro M, Perez R, Perez M, Prina MG, Moser D, Cornaro C. Italian protocol for massive solar integration: From solar imbalance regulation to firm 24/365 solar generation. Renew Energy 2021;169:425–36. https://doi.org/10.1016/j.renene.2021.01.023.

[37] De Santoli L, Lo Basso G, Bruschi D. A small scale H2NG production plant in Italy: Techno-economic feasibility analysis and costs associated with carbon avoidance. Int J Hydrogen Energy 2014;39:6497–517. https://doi.org/10.1016/j.ijhydene.2014.02.003.

[38] Lo Basso G, Mojtahed A, Pastore LM, De Santoli L. High-temperature green hydrogen production: A innovative– application of SOEC coupled with AEC through sCO2 HP. Int J Hydrogen Energy 2023. https://doi.org/10.1016/j.ijhydene.2023.04.231.