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Comparison between optimal refueling infrastructures for zero emission waste transportation vehicles in Valle Camonica

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Abstract. The aim of this work is to conduct a comprehensive and fair comparison between fleets of vehicles powered by different technologies, namely electricity, compressed hydrogen, and liquid hydrogen. The study followed a well-defined methodology, starting with the development of a mixed-integer linear programming (MILP) model using MATLAB and the YALMIP toolbox. The primary objective of the model is to minimize the total annual cost associated with the infrastructure required for refuelling the fleet of zero-emission vehicles. The battery electric vehicle refuelling infrastructure is used as a benchmark, with a total annual cost of around 200000 €/y. The compressed hydrogen and liquid hydrogen infrastructure are comprehensive of a solar photovoltaic field. The hydrogen refuelling facility are analysed varying the price of the electricity. In the most profitable configuration, the compressed hydrogen refuelling facility cost around 320000 €/y and for the liquid hydrogen 480000 €/y. The sensitivity analysis, performed varying the cost of electricity, shows that it is never convenient to use hydrogen vehicles even in condition of high electricity prices. When it is possible to use electric vehicles and there are no constraints related to payload, range or refueling logistics they must be employed, as they are the most cost-effective solution to cancel the vehicles emissions.

1. Introduction

The urgency to decarbonize our world has been widely recognized, as highlighted by global initiatives such as the European Union (EU) Green Deal [1]. The transportation sector, which heavily relies on fossil fuels, is a major contributor to greenhouse gas emissions. Heavy-duty road transport is a significant source of carbon dioxide (CO2) emissions and requires targeted decarbonization strategies. Recent studies indicate that heavy-duty vehicles contribute significantly to the CO2 emissions produced by the transportation sector, making up approximately 20% of the global CO2 emissions [2].

The transition to zero tailpipe emission vehicles is a crucial objective to mitigate the environmental impact of road transport and strive towards sustainable mobility. Hydrogen vehicles and electric vehicles are two leading technologies for achieving zero tailpipe emissions in heavy-duty road transport. Hydrogen vehicles offer a promising solution for decarbonizing the sector, with two primary alternatives for the storage of hydrogen: compressed hydrogen and liquid hydrogen. Although liquid hydrogen is not yet commercial, it is a promising alternative for the future. Electric vehicles, on the other hand, are powered by advanced batteries and have gained significant momentum in recent years.

The aim of this work is to conduct a comprehensive and fair comparison between fleet of vehicles powered by different technologies, namely electricity, compressed hydrogen, and liquid hydrogen. The study is conducted in collaboration with Valle Camonica Servizi, a company operating in the field of waste management and transportation. The collaboration with Valle Camonica Servizi ensures that the research aligns with real-world practicality and addresses the specific needs and challenges faced by the waste management and transportation sector.

The study followed a well-defined methodology, starting with the development of a robust mixed-integer linear programming (MILP) model using MATLAB and the YALMIP toolbox. The foundation of the model is established based on a previous work [3]. The primary objective of the model is to minimize the annual cost associated with the infrastructure required for refuelling the fleet of zero-emission vehicles. Specifically, the focus is on optimizing the infrastructure costs while not considering the individual vehicle costs. The model incorporated different types of refuelling infrastructure options available for the vehicles. By considering the various infrastructure configurations, the model aimed to identify the optimal combination of components, plant size, and operational strategies to support the zero-emission fleet effectively. Input data for the model were derived from multiple sources, including collaboration with Valle Camonica Servizi, as well as relevant literature. This approach ensured that the model is based on accurate and up-to-date data, reflecting real-world conditions and industry best practices. The results obtained from the model were subjected to rigorous analysis, enabling valuable insights and recommendations to be derived. Moreover, a sensitivity analysis is performed to assess the robustness of the model's outputs and examine the influence of various input parameters and assumptions. This comprehensive analysis provided a deeper understanding of the model reliability and consistency in generating optimal results.

In the field of modelling energy refuelling or production infrastructure, various studies have focused on achieving economic efficiency. Among them, Minutillo et al analysed the levelized cost of hydrogen for hydrogen refuelling stations with on-site hydrogen production via a solar photovoltaic field, obtaining values ranging from 9.29 €/kg to 12.48 €/kg [4]. Perna et al. continued the work considering more hydrogen sources and plant configurations [5]. On the other hand, numerous studies are being performed to apply optimization methods to the field of hydrogen production and management. On this topic Crespi et al. produced an optimization model to compute the cost optimization of a photovoltaic field connected to a hybrid energy storage system [6]. In the context of vehicle refuelling, Gruger et al. (2018) conducted a study exploring the sizing of refuelling infrastructure. They examined the cost-effectiveness of various scenarios and strategies for zero-emission vehicles [7]. Furthermore, Mehrez (1985) and Yuan (1995) investigated optimization models for vehicle refuelling, each proposing approaches to optimize the refuelling process [8] [9]. The problem of refueling optimization is analyzed by Golla et al. that incorporated the optimization model of the refueling schedule in a vehicle routing problem model [10]. Golla et al. noticed that with an optimized refueling schedule, with respect to a “naive” one, the size of the electrolyzer could be reduced by 40% with related savings on the capital expenditures, even if in the presented work hydrogen storage is not considered. It is worth noting that while these studies have contributed valuable insights on specific aspects of economic optimization in the field of energy refuelling or production infrastructure, there appears to be a gap in the literature when it comes to a comprehensive study considering all aspects from the economic evaluation of the plant to the optimization of refuelling strategies.

The following article sections describe in detail the implemented model and its results. Section “Plant configuration and Modelling” deals with the equipment present in the hydrogen production facility and with the theoretical model explanation. Section “Results and discussion” deals with the results of the analysis. Finally, section “Conclusions” discusses the results obtained and draws the final conclusions with some remarks on possible future works.

2. Plant configuration and Modelling

2.1 Plant layout and components

The different needs of the different fleets of vehicles require a different kind of infrastructure. The plant layouts of the three solutions are presented in figure 1 to 3. The electric vehicles infrastructure comprises a battery electric vehicle refuelling station that is directly connected to the grid. It is designed to provide charging facilities for electric vehicles, utilizing the power supply from the grid. This infrastructure is kept simple per the company's requirement, being the electric vehicle infrastructure the benchmark for the study.

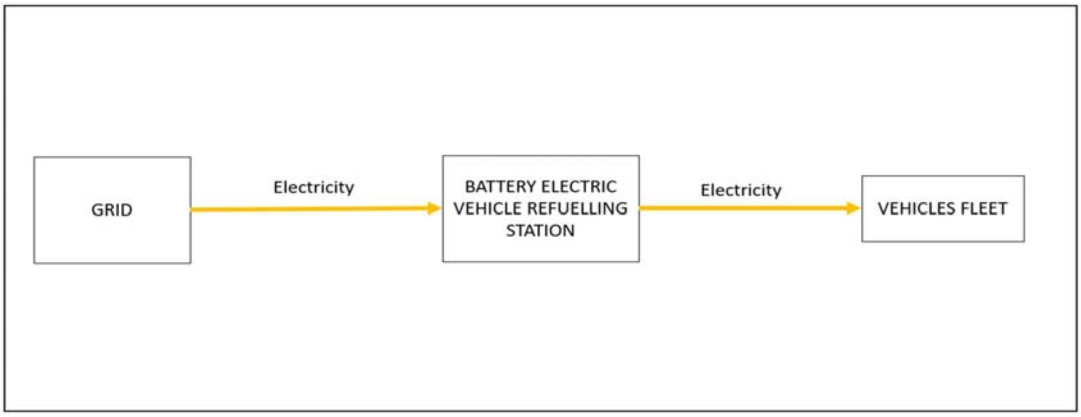

Figure 1: Battery electric vehicle refuelling infrastructure layout.

The compressed hydrogen plant consists of multiple components, including a solar photovoltaic field that harnesses solar energy, the grid for supplementary power supply, an electrolyzer for hydrogen production through water electrolysis, a compressor to pressurize the produced hydrogen, and a compressed hydrogen storage system. Additionally, a hydrogen refuelling station is incorporated within this infrastructure to enable the refuelling process for vehicles powered by compressed hydrogen.

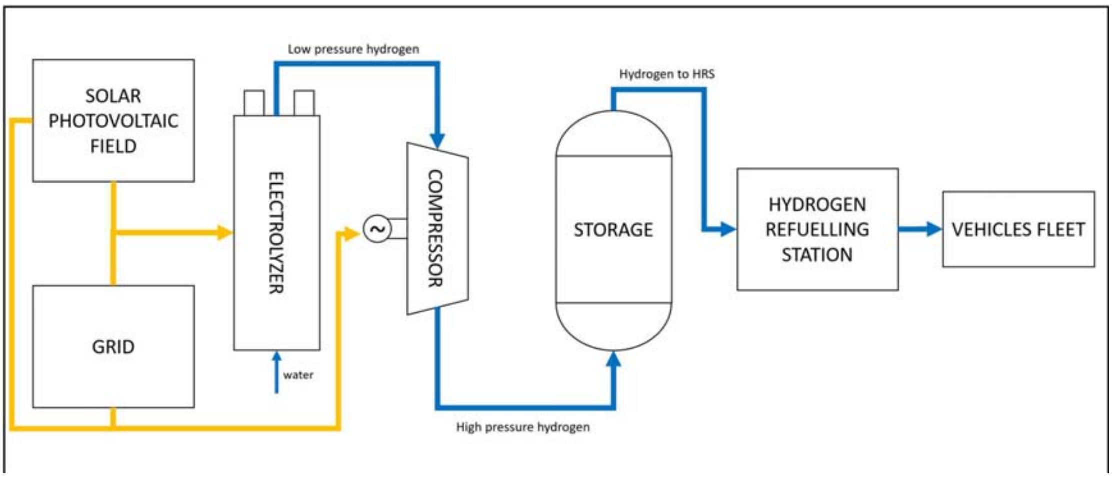

Figure 2: Compressed hydrogen vehicles refuelling infrastructure layout.

The liquid hydrogen plant also utilizes a solar photovoltaic field to capture solar energy and the grid for additional power needs. Like the compressed hydrogen plant, it incorporates an electrolyzer for hydrogen production, but in this case, it includes a liquefaction unit to convert the hydrogen gas into liquid hydrogen. The plant also features a storage system for liquid hydrogen and a dedicated liquid hydrogen refuelling station to cater to vehicles requiring this type of fuel.

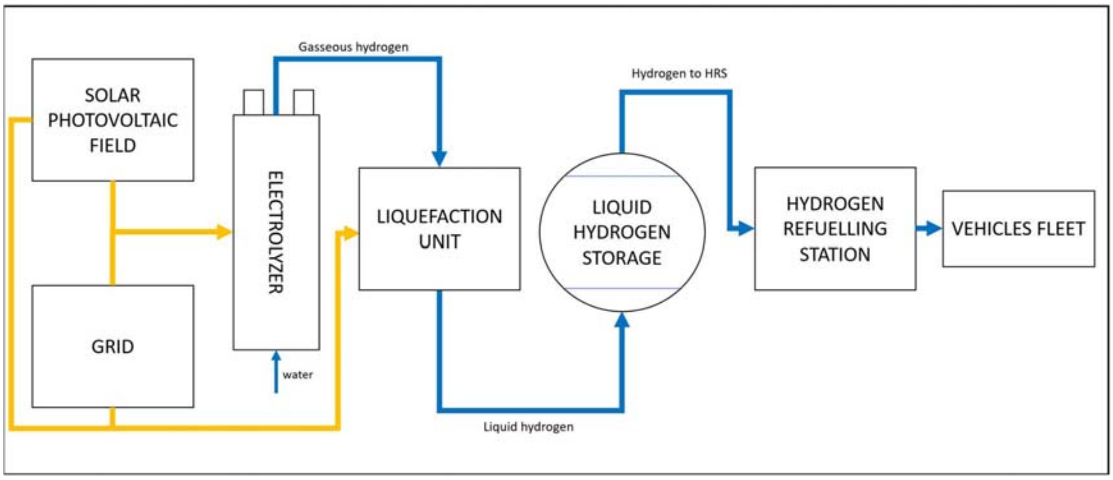

Figure 3: Liquid hydrogen vehicles refuelling infrastructure layout.

2.2 Tecno-economic optimization mode

2.2.1 Economic model

For each configuration presented above the aim is to provide the optimal size of the components, operation of the plant and operation of the vehicles refuelling to obtain the minimum total annual cost. To reach this objective the cost analysis is performed to be specific to the component capacity:

$$Year_{cost} = Expenses\left(\frac{€}{y}\right) - Revenues\left(\frac{€}{y}\right) = \sum_{k=1}^{n} C_{k,a} \times P_k + C_{fix,y} + C_{el,y} - R_y \tag{1}$$

Being k the number of components to design in the plant and P their dimension. For each component k the specific costs are computed as:

$$C_{k,a} = C_{k,inv,a} + C_{k,rep,a} + C_{k,O\&M} \tag{2}$$

$C_{inv,a}$ is related to all the components of the plant, while the $C_{rep,a}$ is related to components with a life span inferior to the plant life span. The actualization of this costs is performed as:

$$C_{inv,a} = C_{inv} \times \frac{r(r+1)^{LT_p}}{(1+r)^{LT_p} - 1} \tag{3}$$

$$C_{rep,a} = \frac{C_{rep}}{(1+r)^{LT_c}} \times \frac{r(r+1)^{LT_p}}{(1+r)^{LT_p} - 1} \tag{4}$$

$C_{fix,y}$ is related to the components with a fixed capacity such as the refuelling stations. The installation cost of one station is not depending on any component size in the plant and do not scale with size. Moreover, $C_{el,y}$ and $R_{el,y}$ are related to the yearly costs and revenues coming from the electricity bought or sold.

The objective function is based on the minimization of the total annual cost, as:

$$min\ f(i) = Year_{cost} = \sum_{k=1}^{n} C_{k,a} \times P_k + C_{fix,y} + C_{el,y} - R_y + C_{su} \times N_{su} \tag{5}$$

The last term, C_{su} is the cost of the electrolyzer start-up. It is a fictional cost, implemented to avoid unnecessary start-up of the electrolyzer, and it is multiplied by the number of start-ups per year.

2.2.2 Technical model description

The function to minimize is subject to a series of constrains, as it is typical of this kind of study. The constraints are expressed thought a series of variables, which are presented in table 1. The model is the same for each kind of infrastructure. This is fundamental to ensure fair comparison. In the following section for simplicity all the variables are presented to be generic to the type of infrastructure. At the beginning of the simulation, it is possible to select the kind of vehicles in the fleet. The constrains not related to a specific infrastructure, for example the liquefaction unit operation with electric vehicles, will not be considered. The variables present in the model can be continuous or binary. The model solves a problem defined over a year of utilization of the plant in hour resolution.

Table 1: Model optimization variables.

Variables	Type	Dimension
$E_{Res\rightarrow El}$	Continuous	(1,8760)
$E_{Res\rightarrow Cmp}$	Continuous	(1,8760)
$E_{Res\rightarrow Lu}$	Continuous	(1,8760)
$E_{Grid\rightarrow El}$	Continuous	(1,8760)
$E_{Grid\rightarrow Cmp}$	Continuous	(1,8760)
$E_{Grid\rightarrow Lu}$	Continuous	(1,8760)
$E_{Grid\rightarrow Brs}$	Continuous	(1,8760)
$E_{El\rightarrow Lu}$	Continuous	(1,8760)
$E_{El\rightarrow Cmp}$	Continuous	(1,8760)
$E_{Res\rightarrow Grid}$	Continuous	(1,8760)
$E_{CH_2str\rightarrow CH_2HRS}$	Continuous	(1,8760)
E_{CH_2-V}	Continuous	$(N_v, 8761)$
α_{CH_2}	Binary	$(N_v, 8761)$
$E_{CH_2-HRS_{in}}$	Continuous	(1,8760)
R_{CH_2}	Continuous	$(N_v, 8761)$
$E_{LH_2str\rightarrow LH_2HRS}$	Continuous	(1,8760)
E_{LH_2-V}	Continuous	$(N_v, 8761)$
α_{LH_2}	Binary	$(N_v, 8761)$
$E_{LH_2-HRS_{in}}$	Continuous	(1,8760)
$E_{LH_2str\rightarrow LH_2HRS}$	Continuous	$(N_v, 8761)$
R_{LH_2}	Continuous	$(N_v, 8761)$
E_{BEV-V}	Continuous	$(N_v, 8761)$
α_{BEV}	Binary	$(N_v, 8761)$
R_{BEV}	Continuous	$(N_v, 8761)$
E_{CH_2str}	Continuous	(1,8761)
E_{LH_2str}	Continuous	(1,8761)
E_{CH_2HRS}	Continuous	(1,8761)
E_{LH_2HRS}	Continuous	(1,8761)
P_{res}	Continuous	(1,1)
P_{el}	Continuous	(1,1)
P_{CH_2str}	Continuous	(1,1)
P_{LH_2str}	Continuous	(1,1)
β	Binary	(1,8761)
γ	Binary	(1,8761)

The number of hours in a year is set to 8760, thus the size of the variables is either 8760 for flows, 8761 for storages and 1 for capacity. The variables related to the vehicles have a dimension equal to 8760, 8761 or 1 and the other dimension that is equal to the number of vehicles considered in the analysis, in Table 1 namely N_v.
Some of the variables have a dimension of 8761. This modelling choice is considered to define the state of the storages and vehicles tank at a time before the beginning of the simulation.

The variables presented in the table above are re-arranged in a series of equations representing the constraints of the optimization problem. The constraints are useful not only to provide the necessary information to the objective function but also to accurately describe the behaviour of the system. In the next tables the equations of the model are presented. The dependency of the variables regarding time is expressed using the letter “i”.

Table 2: Constraints related to the flows of energy inside the plant.

Description	Equation	
Hydrogen produced by electrolyzer	$\sum E_{X\to EL} \times \eta_{el} \leq E_{El\to Cmp} + E_{El\to Lu}$	(6)
Energy consumption of compressor	$E_{Res\to Cmp} + E_{Grid\to Cmp} \geq C_{s,cmp} \times E_{El\to Cmp}$	(7)
Energy consumption of liquefaction unit	$E_{Res\to lu} + E_{Grid\to lu} \geq C_{s,lu} \times E_{El\to Lu}$	(8)

In table 2 the equation related to the energy consumption of the components are presented. To simplify the writing of the equations instead of writing each contribution for each component to a specific flows the notation "$X \to$ " is used. It stands for all the flows contribution to a certain component.

Table 3: Constraints related to storage and refuelling stations operation.

Description	Equation	
Storage starting point	$E_{Str}(i = 1) \geq E_{str}(i = end)$	(9)
Storage equation	$E_{str}(i + 1) = E_{in,str}(i) - E_{out,str}(i) + E_{str}(i)$	(10)
Refuelling station starting point	$E_{HRS}(i = 1) = 0$	(11)
Refuelling station equation	$E_{hrs}(i + 1) = E_{in,hrs}(i) - E_{out,hrs}(i) + E_{hrs}(i)$	(12)
Hydrogen processing delay	$E_{hrs,in}(1 \div \delta_{hrs}) = 0$	(13)
Hydrogen processing delay	$E_{hrs,in}(\delta_{hrs} \div end) = E_{str\to HRS}(1 \div 8760 - \delta_{hrs})$	(14)
BEV station equation	$E_{BEV-HRS,out} = E_{BEV-HRS,in} \times \eta_{bev-hrs}$	(15)

To avoid repetition the constraints related to the storage and refueling stations are written in general form and they are valid for compressed hydrogen and liquid hydrogen. These equations are presented in table 3. Equation 9 shows the relation between the starting and ending point of the storage. The amount of energy at the beginning of the year must be the same at the end of the year, in this way it ensure the possibility of cyclic operation over years. Equation 13 and 14 model the logistic need of the refueling station. In real application after the hydrogen is compressed or liquefied and sent to the refueling station it needs some time before it is available for vehicles refueling. This time cannot be neglected to provide an accurate vehicle refueling strategy.

Table *4*: Constraints related to the variable capacity of components.

Description	Equation	
Electrolyzer variable capacity	$\sum E_{X\to EL} \leq P_{el}$	(16)
Compressed storage variable capacity	$E_{CH_2str} \leq P_{CH_2str}$	(17)
Liquid storage variable capacity	$E_{LH_2str} \leq P_{LH_2str}$	(18)
Renewable energy source capacity	$\sum E_{Res\to X} \leq P_{res} \times P_{G,res}$	(19)

In table 4 are presented the equations that consider the size of the components. All the energy at the inlet or outlet of the components must be lower than their size. For equation 19 it is used a similar notation to equation 6, with the difference that in this case it is a short notation to express all the fluxes that are generated from the renewable energy source.

Table 5: Constraints related to the electrolyzer operation.

Description	**Equation**	
Start-up definition	$\gamma \geq 1-\beta(i)\ +\beta(i+1)-1$	(20)
Start-up in respect to electrolyzer turn on	$\gamma \leq \beta(i+1)$	(21)
Start up in respect to electrolyzer turn off	$\gamma \leq 1-\beta(i)$	(22)

The Start-up variable is defined with equations 20-22, presented in table 5. The electrolyzer start up is modelled with the two binary variables β, γ. This kind of formulation allows the binary variable γ to be 1 only when the variable related to the electrolyzer start-up changes from the value 0 to the value 1.

Table 6: Constraints related to vehicles refuelling.

Description	**Equation**	
Energy inside the vehicles at starting point	$E_V(i=1)=T_s$	(23)
Storage equation for each vehicles	$E_v(i+1)\ =\ E_{in,v}(i)-E_{out,v}(i)+E_v(i)$	(24)
Amount of energy refuelled at starting point	$R_V(1) \qquad =0$	(25)
Energy refuelled in the vehicles	$R_V(2 \div end) \geq \alpha_v \times (\xi_{v,min} \times T_s)$	(26)
Energy refuelled in the vehicles	$R_V(2 \div end) \leq \alpha_v \times (\xi_{v,max}\ \times T_s)$	(27)
Maximum number of vehicles refuelled per hour	$sum(\alpha_v) \qquad \leq R_{max}$	(28)

In Table 6 from equation 23 to 28 the generic model for vehicles refuelling is presented. This formulation applies to all kinds of vehicle and is based on the concept of generating the amount of energy required, in the form of hydrogen or electricity, starting from the vehicles missions and consumptions. In this way it is possible to adjust the refuelling of the vehicles to obtain the minimum total annual cost. Vehicles are considered to start with a full tank or battery. The refuelling of the vehicles can take place only if it is possible to refuel a minimum amount. This methodology is applied to avoid unnecessary refuelling events. The variable α is related to the refuelling events and is 1 if in a certain hour a vehicle is refuelling while it is 0 if a certain vehicle is not refuelling.

2.3 Model input data

The input to the model are all the technical data for the vehicles and all the tecno-economic data for the plant analysis. Before diving into the detailed values used it is fundamental to specify what kind of vehicles are considered for this analysis and which assumptions are made.

2.4 Vehicles analysis and vehicles input description.

The vehicles and their mission are fundamental to define the plant design and operation hence the annual cost for the refuelling infrastructure. The fleet considered for this study is composed by 63 vehicles with different characteristics. The vehicles characteristics are briefly described in table 7.

Table 7: Waste management vehicles characteristics.

Series	Type	Daily Distances	Work Shift
0-100	Passenger car	GPS Data	6 AM-12 PM Mon. to Fry.
200	Road truck	GPS Data or 350 km/day	6AM-12 PM Mon. to Sat.
400	Demountable truck	GPS data or 210 km/day	6AM-12 AM; 13 PM-19 PM Mon to Fry
600	Commercial vehicles	GPS Data	6 AM-12 PM Mon. to Fry.
700	Auxiliary truck	GPS Data or 60 km/day	6 AM-12 PM Mon. to Fry.
800	Commercial vehicle	GPS Data	6 AM-12 PM Mon. to Fry.
900	Auxiliary truck	GPS Data	6 AM-12 PM Mon. to Fry.

To perform the analysis each vehicle of the Valle Camonica Servizi fleet is considered to have an electric, compressed hydrogen or liquid hydrogen equivalent. The vehicles input necessary to start the model, for each kind of vehicles, are the following:

- vehicles hour distances, i.e., the mission of the vehicles,
- time in the year that vehicles spend at the depot, i.e., when it is possible to refuel the vehicles,
- vehicles consumption,
- vehicles tank size or battery pack size.

The company Valle Camonica Servizi provided the consumption data for their fleet for the year 2022, nowadays operating with diesel and gasoline. Consumptions are provided in two different ways. For 43 out of 63 vehicles GPS data are available. GPS data provide the distance covered and the time a certain vehicle is outside of the depot, daily. The GPS data were used to derive the daily missions of the vehicles and thus distances covered hourly. For the remaining vehicles the hourly distance covered is inferred from the average year consumption and distance, both provided by the company. The equivalent electric or hydrogen vehicles are considered to have the same missions thus starting from the company data it is possible to derive the vehicles distances and the depot time. A different discussion must be made for vehicles consumption and tank size. It is possible to search for these values in the literature, but a couple of problems arise. Availability of data in literature may be lacking information on specific vehicles with alternative powertrain, moreover, plugging literature data inside the model can be not representative of the specific use of the vehicles. The approach is to tailor the literature data considering the real use of the vehicles in Valle Camonica and assume to reasonable values the unavailable data. The consumptions are computed starting from a Joint European Center report on heavy-duty vehicles [11]. In this report different type of engines are evaluated on the same trucks, with same routes and payloads. The diesel consumption data of the vehicles on duty in Valle Camonica, expressed as tank-to-wheel consumption in kWh/km, are compared with consumption data of the diesel trucks in the report. The relative difference between the literature diesel consumption and the effective diesel consumption in Valle Camonica, $\Delta TTW_{\%}$ (-), is computed as:

$$\Delta TTW_{\%} = \frac{TTW_{vcs,diesel} - TTW_{JEC,diesel}}{TTW_{JEC,diesel}} \tag{29}$$

$\Delta TTW_{\%}$ is then used to compute the tank-to-wheel hydrogen consumption of the waste transport vehicles in Valle Camonica, $TTW_{VCS,NEW}$ (kWh/km), by correcting the literature consumption, TTW_{JEC} (kWh/km), as:

$$TTW_{VCS,NEW} = TTW_{JEC} + TTW_{JEC} \times \Delta TTW_{\%} \tag{30}$$

The scope of this approach is to take in account the real operation of the vehicles, even if the tank-to-wheel efficiency computed in the presented way is an overestimation. The real consumption data do not only account for the specific usage of the vehicles, but also for age related inefficiencies. The approach to consider a literature reference and apply an increment on consumption due to real operation works best when there is abundance of literature data. This is the case of the electric vehicles, for which all the vehicles in the fleet of Valle Camonica Servizi have an electric equivalent on which is applied the consumption increment. On the other hand the data for some of the compressed hydrogen vehicles are not available in literature. The literature equivalent of some of the vehicles in the compressed hydrogen fleet, such as the small commercial vehicles of the 800 series, are assumed starting from data of vehicles of similar weight class. The extreme case is the liquid hydrogen one. Liquid hydrogen vehicles are not commercially available thus no real driving data on consumption can be used. For the liquid hydrogen fleet the consumptions are derived from the compressed hydrogen vehicles. A slight increase in the consumption of the liquid hydrogen vehicles in respect to the compressed hydrogen is considered to take in account the weight of the liquid hydrogen storage on board. The last piece of information to model the vehicles is the tank size. Following the same reasoning, the value for the tank size is taken by literature, data-sheet of vehicles manufacturer or assumed to a reasonable value considering similar vehicles. The input data for vehicles consumptions and tank sizes are presented in the Table 8 and Table 9. In Table 10 other input related to the refuelling operation are presented.

Table 8: Vehicles average consumption input data.

Series	CH2 consumption [kWh/km]	LH2 consumption [kWh/km]	BEV consumption [kWh/km]
0-100	0.38	0.40	0.23
200	3.35	3.52	2
400	3.57	3.75	2.14
600	1.4	1.47	0.66
700	3.89	4.09	2.33
800	0.87	0.93	0.15
900	3.98	4.17	2.4

Table 9: Vehicles tank size input data.

Series	Tank size CH2 [kg]	Tank Size LH2 [kg]	Tank size BEV [kWh]
0-100	8.3	11.7	74
200	32.9	44.9	540
400	32.9	44.9	540
600	30.8	43.12	138
700	32.9	44.9	540
800	19.6	27.44	17
900	32.9	44.9	540

Table 10: Other vehicles input data.

Name	Value	U.O.M.	Reference	Symbol
Min. refuelling quantity	20% tank dimension	kg	Own assumption	ξ_{r1}
Min. energy in tank	20% tank dimension	kg	Own assumption	ξ_{r2}
Max. refuelling per hour CH2	8	[-]	Own assumption	R_{max}
Max. refuelling per hour LH2	8	[-]	Own assumption	R_{max}
Max. refuelling per hour BEV	10	[-]	Own assumption	R_{max}

It is important to notice that, even considering the conservative approach on the consumption of the new vehicles, there are no payload, range or refuelling problems for the vehicles. Electric, compressed hydrogen and liquid hydrogen vehicles are equivalent to complete the daily missions.

2.5 Plant input description

The plant data are taken from literature references, technical documentation, or direct company data. The unavailable inputs are inferred. Table 11 and Table 12 contain the inputs with references and symbols to match the symbols used in the equations in the previous section.

Table 11: Economic input.

Name	Value	U.O.M.	Reference	Symbol
Interest rate	0.03	[-]	[4]	r
Electrolyzer start-up cost	0.001	€/start-up	Own assumption	C_{su}
Plant lifetime	20	y	Own assumption	LT_p
Electrolyzer capex	1200	€/kW	[12]	$C_{inv,el}$
Electrolyzer opex	2	Capex %	[13]	$C_{O\&M,el}$
Electrolyzer lifetime	10	years	Company data	LT_{el}
Electrolyzer subst. capex	40	Capex %	[14]	$C_{rep,el}$
Compressor capex	$36079.54 * Pc^{(0.6038)}$	€/kW	[5]	$C_{inv,cmp}$

Name	Value	U.O.M.	Reference	Symbol
Compressor opex	8	Capex %	[5]	$C_{O\&M,cmp}$
Liquefaction unit fix capex	1000000	€	[15]	$C_{inv,lu}$
Liquefaction unit var capex	2393300	€/(tons/day)	[15]	$C_{inv,lu}$
Liquefaction unit opex	4	Capex %	[15]	$C_{O\&M,lu}$
CH2 Storage capex	405	€/kg	[16]	$C_{inv,ch2str}$
CH2 Storage opex	2	Capex %	[17]	$C_{O\&M,ch2str}$
LH2 Storage capex	50	€/kg	[18]	$C_{inv,lh2str}$
LH2 Storage opex	2	Capex %	[18]	$C_{O\&M,lh2str}$
CH2 HRS capex	500000	€	Company data	$C_{inv,chrs1}$
CH2 HRS constr. capex	1000000	€	Company data	$C_{inv,chrs2}$
CH2 HRS opex	5	Capex %	Company data	$C_{O\&M,chrs}$
LH2 HRS capex	1500000	€	Company data	$C_{inv,lhrs}$
LH2 HRS opex	5	Capex %	Company data	$C_{O\&M,lhrs}$
BEV HRS capex	200000	€	Company data	$C_{inv,bevrs}$
BEV HRS opex	5	Capex %	Company data	$C_{O\&M,vebrs}$
Solar photovoltaic capex	750	€/kW	[19]	$C_{inv,sol}$
Solar photovoltaic opex	2.3	Capex %	[19]	$C_{O\&M,sol}$
Value of selling electricity	0; 20; 115	€/MWh	[20]	C_{sell}
Cost of Buying electricity	150	€/MWh	[20]	C_{buy}

Table 12: Technical input data.

Name	Value	U.O.M.	Reference	Symbol
El. specific consumption	55	kWh/kg	[21]	η_{el}
Electrolyzer operative pressure	30	bar	[21]	P_{el}
Electrolyzer operative temperature	70	°C	[21]	T_{el}
Electrolyzer min load	10%	[-]	Company data	ξ_{load}
Electrolyzer outlet temperature	30	°C	Company data	T_{out}
Compressor isentropic efficiency	0.8	[-]	[22]	$\eta_{is,c}$
Compressor electric efficiency	0.96	[-]	[22]	$\eta_{el,c}$
Compressor mechanical efficiency	0.98	[-]	[22]	$\eta_{m,c}$
Compressor outlet pressure	400	bar	Own assumption	P_{out}
Number of compression stages	2	[-]	Own assumption	-
Cooling temperature	30	°C	Own assumption	T_{cool}
Liquefaction unit specific consumption	10	kWh/kg	[23]	$C_{s,lu}$
CH2 refuelling station delay	24	h	Own assumption	δ_{chrs}
LH2 refuelling station delay	6	h	Own assumption	δ_{lhrs}
Solar photovoltaic efficiency	20%	[-]	[24]	η_{sol}
Solar photovoltaic generation profile	Hour profile	kWh/kW	[24]	-
BEV refuelling station efficiency	0.955	[-]	[25]	$\eta_{bev-hrs}$

2.6 Model output data

The model outputs are all the information that the model gives after a simulation. The model output are defined for the refuelling infrastructure as well as for the vehicles fleet. Information on optimal operation of design of the refuelling infrastructure and vehicles logistic is provided. In particular:

- information on plant components capacity,

- information on the operation of the plant such as renewable energy source and electrolyser equivalent hours,
- complete definition of the refuelling events, thus schedule and amount of hydrogen or electricity to refuel in each vehicle at each refuelling event,
- information on fixed and variable costs.

3. Results

3.1 Case study

The selection of case studies is driven by the objective of comparing the performance and economic viability of three different vehicle fleets: electric, compressed hydrogen, and liquid hydrogen. The electric fleet served as a benchmark for comparison, representing the available technology in the field.

For the compressed hydrogen and liquid hydrogen fleets, three distinct cases are considered with respect to market considerations. The Italian national price for electricity in recent years is experiencing huge fluctuations. The price considered in this study is 115€/MWh, which is in the middle between the 2019 and 2022 price. The In the first case, no excess electricity generated by the hydrogen production infrastructure can be sold back to the grid, so with a price of sold electricity of 0. The second case assume the ability to sell excess electricity to the grid at a reduced price, reflecting a potential but limited revenue stream. It is considered a price of around 20% of the original PUN. Lastly, the third case considered the scenario where excess electricity can be sold to the grid at market price, thus maximizing potential revenue selling electricity at 115€/MWh. This distinction is necessary to have a correct understanding of the renewable energy plant operation.

To conduct a comprehensive analysis, the key variables of interest are the size of the renewable energy plant and the size of the electrolyzer, in the compressed hydrogen and liquid hydrogen fleets. These parameters are crucial for evaluating the production capacity and determining the optimal scale of the hydrogen production infrastructure. Additionally, the size of the hydrogen refuelling station is predetermined, as it represented an existing facility with specific constraints. As for the storage, a constant size is assumed, as it primarily serves as a medium for processing hydrogen at the hydrogen refuelling station inlet, resulting in minimal impact on the overall annual cost.

By considering these factors and scenarios a comprehensive analysis could be conducted to assess the economic feasibility and optimal design of the refuelling infrastructure facility for each fleet.

3.2 Single point calculation results

Table 13: Compressed hydrogen fleet results

Variable	BEV	C = 0 €/MWh	C = 20 €/MWh	C = 115 €/MWh
RES size [kW]	0	2739.86	2966.94	5000
El size [kW]	0	1337.81	1257.39	560.13
Compressed Storage size [kg]	0	200	200	200
Compressed H2 HRS [kg]	0	1500	1500	1500
Compressor size [kW]	0	95.52	89.78	39.99
El Utilization factor [-]	0	0.28	0.296	0.66
El Utilization [h]	0	5868	5730	8712
Electrolyzer start up	0	228	237	1
Peak H2 demand	0	146.11	156.52	173.46
Mean H2 Demand	0	6.76	6.77	6.76
Energy from grid [kWh]	1176000	452253.21	440265.08	1565365.85
Energy from res [kWh]	0	3039073.24	3632405.97	6121477
Energy to grid [kWh]	0	0	580030.98	4195260.46
Year cost RES [€/y]	0	185383.78	200748.17	338308.90

Year cost electrolyzer [€/y]	0	172130.31	161782.86	72069.50
Year cost compressor [€/y]	0	41090.65	39580.92	24290.85
Year cost CH2 storage [€/y]	0	7064.47	7064.47	7064.47
Year cost CH2 HRS [€/y]	0	125823.56	125823.56	125823.56
Year cost BVRS	23918.86	0	0	0
Year cost from GRID [€/y]	176400	67837.98	66039.76	234804.88
Revenues [€/y]	0	0	-11600.62	-482454.95
Total year cost [€/y]	200318.86	599330.76	589439.12	319907.21

The results of the analysis mentioned in the above section are presented in table 13 and 14. The electric fleet is named in the tables as the "BEV" case, and it is compared against the compressed hydrogen and liquid hydrogen fleet. For the compressed and liquid hydrogen fleet three different scenarios on the possibility to sell the energy produced are considered. The price at which it is possible to sell the electricity is considered 0, 20 or 115 €/MWh. In case is impossible to sell energy to the grid there is the minimum size of the renewable plant, that is coupled with the maximum size of the electrolyzer. With the price of electricity rising the model considers the solar fields with higher capacity. In case of selling electricity at 115 €/MWh the model installs the biggest possible solar photovoltaic plant, which for sake of comparison in this case is set to 5 MW. It is also interesting to notice that if the size of the plant goes to those values also the energy from the grid rises. This happens because in this condition it is more convenient to produce the maximum amount of energy from the solar field, sell it to the grid at high price and use the grid to power the electrolyzer. In this situation we can also notice that the size of the electrolyzer is the smallest. This case is not considered of much interest because it defeats the purpose of the refueling infrastructure. In general, for all the considered cases the year cost is higher compared to the electric vehicles refueling infrastructure.

Table 14: Liquid hydrogen refuelling results.

Variable	BEV	C = 0 €/MWh	C = 20 €/MWh	C = 115 €/MWh
RES size [kW]	0	2796.91	3367.64	5000
El size [kW]	0	1257.67	1343.22	512.45
Liquid Storage size [kg]	0	200	200	200
Liquid H2 HRS [kg]	0	1500	1500	1500
Liquefaction unit size [kW]	0	228.67	244.22	93.17
El Utilization factor [-]	0	0.31	0.29	0.76
El Utilization [h]	0	8036	5615	8712
Electrolyzer start up	0	57	251	1
Peak H2 demand	0	6316.18	5227.75	5516.57
Mean H2 Demand	0	234.82	234.81	234.83
Energy from grid [kWh]	1176000	874365.05	471859.30	2071966.55
Energy from res [kWh]	0	3138426.09	4122990.82	6121477
Energy to grid [kWh]	0	0	582122.22	4180716.65
Year cost RES [€/y]	0	189243.68	227860.78	338308.90
Year cost electrolyzer [€/y]	0	161818.74	172826.48	65935.31
Year cost L.U. [€/y]	0	69904.34	69904.34	69904.34
Year cost LH2 storage [€/y]	0	872.16	872.16	872.16
Year cost LH2 HRS [€/y]	0	175823.56	175823.56	175823.56
Year cost BVRS	23918.86	0	0	0
Year cost from GRID [€/y]	176400	131154.76	70778.90	310794.98
Revenues [€/y]	0	0	-11600.62	-482454.95
Total year cost [€/y]	200318.86	728817.24	706423.76	480856.83

Liquid hydrogen powered vehicles results show a similar trend compared to the compressed hydrogen vehicles. Most of the discussion made for the compressed hydrogen fleet can be applied also to these case studies. The component that has the major impact on the results, if compared to the compressed hydrogen result, is the liquefaction unit. The liquefaction unit consume more energy compared to the compressor and has a higher cost. This year cost of the plant is also influenced by the higher hydrogen consumption of the liquid hydrogen fleet that requires slightly bigger components. The lower cost of the hydrogen storage and the bigger vehicles tank are not sufficient to make liquid hydrogen a suitable solution.

3.3 Sensitivity analysis

The sensitivity analysis is computed varying the cost of electricity, which is the main driver for the analysis for each kind of infrastructure. In figure 4 there are the results of this analysis summarized. For this analysis is considered the case for which it is not possible to sell the electricity produced by the renewable power plant to the grid, to make a comparison with the battery electric vehicles infrastructure.

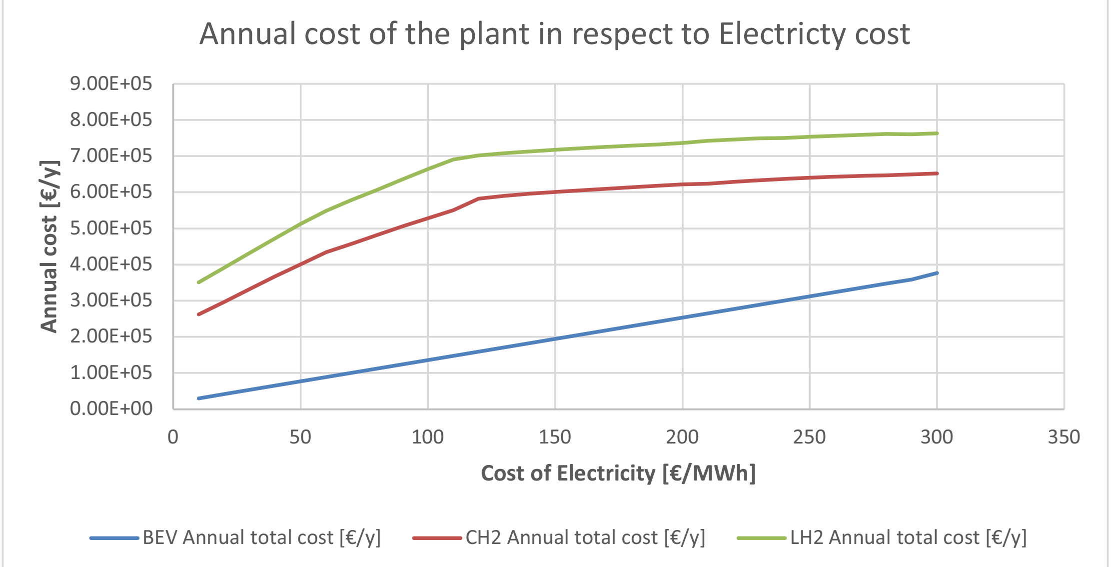

Figure 4: Annual cost of the refuelling infrastructure for different kind of vehicles varying the cost of electricity.

The annual cost of the BEV vehicles is always lower compared to compressed hydrogen vehicles and liquid hydrogen vehicles. The latter are never competitive and show the higher annual cost. The curve of the annual cost the battery electric vehicle infrastructure is linear. The compressed hydrogen and liquid hydrogen annual cost are linear but with a change in steepness between 100 and 120 €/MWh. This happens because around that price the model chose to install the maximum size of the photovoltaic field to support the hydrogen production. After that threshold is surpassed the annual cost increase with a lower steepness. In the proposed analysis the most convenient option is to use battery electric vehicles in respect to the hydrogen vehicles. However, it is important to point out that in this analysis takes in account fleet of vehicles that can be renewed with all the types of fleets without any range, payload, or refuelling constraints.

4. Conclusion

The current work aim to implement an optimization model to make a comparison between different kind of refuelling infrastructure for a fleet of vehicles operating in the field waste management and transportation. The main findings are the following:

- To renew the fleet of vehicles to a battery electric vehicle fleet it will be necessary to use 1176 MWh of energy coming from the grid with a total annual cost of 200318 €/y.
- The analysis of the compressed and liquid hydrogen can vary considerably if it is possible to sell or not sell the produced electricity to the grid. In the case of no possibility to sell electricity to the grid the compressed hydrogen infrastructure requires the installation of a 1267 kW electrolyzer and a 2739 kW photovoltaic field, with a total annual cost of 599330.76 €/y.
- The liquid hydrogen infrastructure fleet is never competitive compared to the compressed hydrogen and battery electric vehicles fleet. In the case of no possibility of selling electricity to the grid the size of the photovoltaic plant is 2796 kW and an electrolyzer of 1257 kW. The annual cost is 728817 €/y.
- The sensitivity analysis shows that, even varying the cost of electricity, it is never convenient to use compressed hydrogen vehicles and liquid hydrogen vehicles if compared to the battery electric vehicles.
- The analysis shows that, if it is possible to use battery electric vehicles, they must be employed. The only situation for which hydrogen must be considered is when it is impossible to use battery electric vehicles due to logistic needs.

4.1 Future works

The model aims to compare different possibility to renew a fleet of vehicles with different characteristics considering for all the vehicles the same powertrain technology. It can be beneficial to consider a hybrid fleet of vehicles that comprise different technologies. Another interesting possibility is to implement a new feature of the model not only for the vehicle consumption but also to consider an electric or thermal load in addition to the vehicle refuelling. This could open the possibility to simulate the future vehicles fleet refuelling infrastructure as energy hubs.

Nomenclature

Symbol	Definition	Unit of measurement
C_{fix}	Fixed costs	€
Cel,y	Cost of electricity per year	€/y
R_y	Revenues per year	€/y
P_k	Generic component capacity	-
$C_{inv,a}$	Actualized investment cost	€
$C_{rep,a}$	Actualized replacement cost	€
$C_{O\&M}$	Operation and maintenance cost	€
LT_p	Plant lifetime	y
LT_c	Component lifetime	y
r	Interest rate	-
TTW	Thank-to-wheel efficiency	kWh/km
E_r	Refuelled energy in truck tanks	kWh
E_s	Stored energy in truck tanks	kWh
E_d	Energy demand	kWh
α_r	Refuelling event binary variable	-
idx_{ref}	Refuelling index	-
C_{su}	Start-up cost	€/su
i	Hours per year	-
j	Number of vehicles	-
n	Total number of components to optimize in the plant	-
E_{str}	Energy stored in hydrogen tank	kWh

Symbol	Definition	Unit of measurement
E_{el}	Energy supplied to the electrolyzer	kWh
E_p	Energy content at the electrolyzer output	kWh
β	On/off binary variable	-
γ	Start-up binary variable	-
δ	Delay due to refuelling station operation	-
P_{el}	Electrolyzer capacity	kW
P_{str}	Storage capacity	kWh
P_{res}	Renewable energy source rated power	kW
VCS	Valle Camonica Servizi	-
JEC	Joint European Center	-
R_{max}	Maximum number or refuelling per our	-
ξ_{r1}	Minimum refuelled quantity coefficient	-
ξ_{r2}	Minimum fuel in vehicles tank coefficient	-
LU	Liquefaction unit	-
CMP	Compressor	-
HRS	Hydrogen refuelling station	-
BEV	Battery Electric vehicle	-
CH2	Compressed hydrogen	-
LH2	Liquid hydrogen	-
RES	Renewable energy source	-

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