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Optimized size and schedule of the power-to-hydrogen system connected to a hydrogen refuelling station for waste transportation vehicles in Valle Camonica

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Optimized size and schedule of the power-to-hydrogen system connected to a hydrogen refuelling station for waste transportation vehicles in Valle Camonica

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Abstract. The aim of this work is the implementation of an optimization model for a hydrogen production facility connected to a refuelling station for heavy-duty vehicles, operating in the field of waste management and transportation. The model is composed by two subsequent mixed integer linear programming problems. The first problem addresses the problem of vehicle refuelling schedule and the second deals with the plant design and operation. The outputs of the model are the design and operation parameters of the plant and the vehicle refuelling schedule, allowing for the minimum levelized cost of hydrogen. Different possibilities for the electricity supply are investigated: grid electricity, solar photovoltaic and hydroelectric. The most profitable option is the installation of a 10 MW solar photovoltaic field, with a connected 3.3 MW Electrolyzer and 3700 kg storage. The resulting levelized cost of hydrogen is 10.24 €/kg. If no revenues from the sold electricity are considered, buying electricity from the grid becomes the most cost-effective option. The electrolyzer and storage size for this case are 760 kW and 405 kg, with a levelized cost of hydrogen of 13.75 €/kg. A sensitivity analysis, performed on the latter case, shows that the most sensible input parameters are the electrolyzer specific consumption and the cost of the electricity. A statistical analysis is also performed, considering a randomized failure distribution, obtaining the optimal values for the electrolyzer capacity of 700-800 kW and a hydrogen storage size of 1300-1400 kg. The costs, considering current electricity prices and no subsidies, are still high for hydrogen penetration in the energy market.

1. Introduction

The European commission "Green deal" stated that the primary sustainability objective for 2050 is to reach net 0 emissions of greenhouse gasses [1]. To reach this challenging objective it is necessary to increase the production of green electricity and promote carbon free energy carriers. Hydrogen produced by electrolysis is one of the most attractive carbon free energy carriers and it can be pivotal for transitioning from fossil fuels to green energy sources. Hydrogen is an excellent substitute to fossil fuels for high temperature applications, it can be used to store electricity over long periods of time with small losses and it can be used as a fuel in the mobility sector. Hydrogen is promising in the sector of heavy-duty road transport, including waste management vehicles. Fuel cell electric vehicles offer a way to have zero tailpipe emissions without the problems concerning range and payload that battery electric vehicles have. The penetration of hydrogen, in particular green hydrogen, in the mobility sector is yet minimal, mostly due to costs and availability on the market.

According to "Our World in Data Emission report" Road Transport caused almost 12% of greenhouse gas emission in 2016 and heavy-duty vehicles account for a great part of it [2]. Companies working with heavy-duty vehicles are considering switching to fuel cell electric vehicles to reach environmental sustainability and decrease emissions of local and global pollutants. In the Italian scenario hydrogen is not available as a fuel, hence it is necessary to design a dedicated hydrogen production facility, connected to a hydrogen refuelling station. The excessive costs and unavailability of hydrogen in nowadays infrastructure are holding decarbonization and penetration of hydrogen in the mobility sector back. One of the solutions to this is provided by modelling, which will allows considering all the viable solutions for keeping costs of hydrogen down.

The aim of this work is the implementation of an optimization model for a hydrogen production facility connected to a refuelling station, specifically for heavy-duty vehicles operating in the field of waste management and transportation. The model supplies information on the optimal sizes and operation of the hydrogen production plant as well as an optimal refuelling schedule for the vehicles. The model takes in account the peculiar characteristics of heavy-duty vehicles in the field of waste management and transportation. The model can support the decision-making process in the design phase of hydrogen production facilities and hydrogen refuelling stations.

The work starts with a literature review on the topic that is presented in the next sections. Following the literature analysis, the theoretical model is created. The theoretical model takes in account all the characteristic equations of the components. The inputs for the model are all gathered from literature sources, datasheets of products or directly from companies. The remaining non available data are inferred. The theoretical model is implemented as a mixed-integer linear programming (MILP) optimization problem. A cost optimization algorithm is implemented in MATLAB®, with the YALMIP toolbox, and the optimization is performed through the Gurobi™ solver. The last part of the work is the post-optimality analysis, performed on several parameters of interest, to check the response of the model to changes in input parameters.

The problem of producing hydrogen in the most cost-effective way possible is recent and is drawing attention from companies and governments. In the Italian scenario 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 [3]. Perna *et al.* continued the work considering more hydrogen sources and plant configurations [4]. 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 [5]. The problem of refuelling optimization was analysed by Golla *et al.* that incorporated the optimization model of the refuelling schedule in a vehicle routing problem model [6]. Golla *et al.* noticed that with an optimized refuelling schedule, with respect to a "naive" one, the size of the electrolyzer could be reduced by 40% with related savings on the capital expenditures.

Hydrogen production through electrolysis is a well-known process in chemical engineering, however the coupling of hydrogen production with renewable energy sources in real world scenarios, such as the refuelling of a fleet of heavy-duty vehicles, is a very recent problem. The possibility to apply refined optimization methods to integrated scenarios is fundamental to develop best practices and to speed-up the penetration of hydrogen in the European energy scenario.

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 hydrogen production facility is described in Figure 1. The plant is composed by a Polymer Electrolyte Membrane (PEM) electrolyzer fed by renewable energy coming from either the grid, a solar plant, or a hydroelectric plant. The hydrogen produced at low pressure is processed by a three-stage reciprocating compressor.

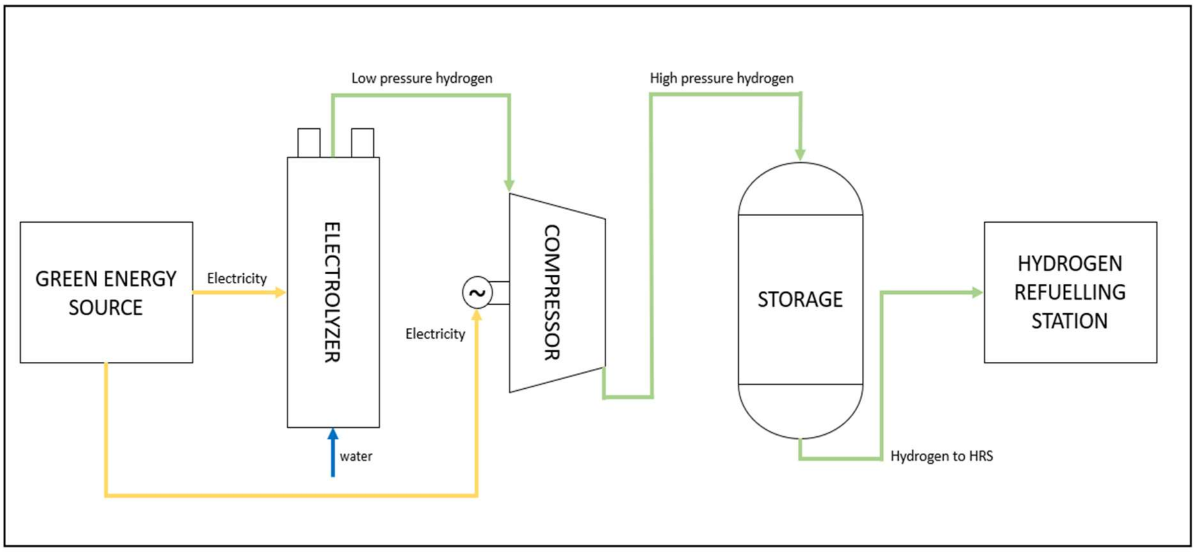

Figure 1: Block diagram of the plant comprising the power-to-hydrogen system and refuelling station considered in this work.

The hydrogen compressed goes from the compressor to a tube trailer storage. The tube trailer storage was selected by the company involved in the waste management sector to ease the process of moving hydrogen between different depots. The last piece of equipment is the hydrogen refuelling station.

2.2 Tecno-economic optimization model, Refuelling

The model solves two mixed integers linear programming problems, The first MILP deals with the refuelling of the vehicles. To reduce the size of the electrolyzer the hydrogen demand must be as distributed as possible. This can be achieved optimizing the schedule of the refuelling events. The secondo MILP problem takes as an input the hour demand of hydrogen and optimizes the levelized cost of hydrogen, varying design, and operation parameters of the plant, presented in the subsection "Plant layout and components". Both problems are solved in hour resolution over a one-year period. The refuelling optimization is connected to the usage of the vehicles. For this study, the fleet of heavy-duty vehicles of Valle Camonica Servizi, utility operating in the field of waste management and transportation in the north of Italy, is considered. The fleet is composed by eighteen vehicles with distinctive characteristics. The vehicles are divided in three groups as presented in Table 1.

Table 1: Waste management vehicles characteristics.

Series	Type	Total vehicle weight (Full load) [tons]
200	Road truck	28
400	Demountable truck	22
700	Auxiliary truck	20

The data on the vehicles consumptions, daily schedule and working shifts are provided by the company Valle Camonica Servizi and are based on the year 2021. The vehicles hydrogen consumption, including auxiliaries use, is not available in literature. The consumptions are computed starting from a Joint European Center report on heavy-duty vehicles [7]. 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:

$$\Delta TTW_{\%} = \frac{TTW_{vcs,diesel} - TTW_{JEC,diesel}}{TTW_{JEC,diesel}} \tag{1}$$

$\Delta TTW_{\%}$ is then used to compute the tank-to-wheel hydrogen consumption of the waste transport vehicles in Valle Camonica, $TTW_{VCS,H2}$ (kWh/km), by correcting the literature hydrogen consumption, $TTW_{JEC,H2}$ (kWh/km), as:

$$TTW_{VCS,H2} = TTW_{JEC,H2} + TTW_{JEC,H2} \times \Delta TTW_{\%} \tag{2}$$

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. More accurate results could be achieved with real hydrogen consumption data. The daily schedule of the vehicles is used to compute the hydrogen consumption for each vehicle. The optimization problem described in equations 3-12 is solved considering the inputs described in detail in the subsection “model inputs”. The symbols related to the inputs in the equation are specified in the nomenclature and in Table 8, Table 9 and Table 10. The objective function of the first mixed integer programming problem aims to minimize the peak hydrogen demand m_d (kg). Mathematically:

$$\min f(i) = max_{1\le i\le N}\left(\sum_{j=1}^{18} m_{r,ij}\right) = \max_{1\le i\le N}(\mathrm{m}_d) \tag{3}$$

where i represent the time unit and goes from 1 to 8760, while j is the number of vehicles and goes from 1 to 18. Equation 3 is subject to a series of constraints summarized in table 2. The hydrogen demand profile is converted to energy demand and then used as input to the second MILP problem.

Table 2: Constraints for the refuelling optimization problem.

Description	**Equation**		
Truck storage starting point mass	$m_S(i=1)$	$= T_{h2}$	(4)
Truck storage equation	$m_s(i+1)$	$= m_r(i) - m_c(i) + m_s(i)$	(5)
Refuelling event equation	$\xi_{r1} T_{h2} \times \alpha_r$	$\le m_r$	(6)
Refuelling event equation	$T_{h2} \times \alpha_r$	$\ge m_r$	(7)
Maximum number of refuelling per hour	$\sum_{j=i}^{18} \alpha_{r,j}$	$\le R_{max}$	(8)
Refuelling only if vehicle j at time i is at depot	$\alpha_{r,ij}$	$\le idx_{ref,ij}$	(9)
Variables upper bound	m_s, m_r	$\le T_{h2}$	(10)
Hydrogen in tank lower bound	m_s	$\ge \xi_{r2} T_{h2}$	(11)
Hydrogen refuelled non negativity	m_r	≥ 0	(12)

2.3 Tecno-economic optimization model, Hydrogen production

The aim of the second problem is to compute design and operation parameters of the plant to obtain the minimum levelized cost of hydrogen, from now on, LCOH (€/kg). To reach this objective the cost analysis is performed to be specific to the component capacity:

$$LCOH = \frac{Total\ expenses\ (€) - Revenues(€)}{Hydrogen\ produced\ (kg)} = \frac{\sum_{k=1}^{n} C_{k,a} \times P_k +\ C_{fix,y} + C_{el,y} - R_y}{m_{y,H_2}} \quad (13)$$

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:

$$C_{k,a} = C_{k,inv,a} + C_{k,rep,a} + C_{k,O\&M} \quad (14)$$

$C_{inv,a}$ 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:

$$C_{inv,a} = C_{inv} \times \frac{r(r+1)^{LT_p}}{(1+r)^{LT_p} - 1} \quad (15)$$

$$C_{rep,a} = \frac{C_{rep}}{(1+r)^{LT_c}} \times \frac{r(r+1)^{LT_p}}{(1+r)^{LT_p} - 1} \quad (16)$$

$C_{fix,y}$ is related to the hydrogen refuelling station. 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 second problem objective function is based on the minimization of the LCOH, as:

$$min\ \ f(i) = \frac{\sum_{k=1}^{n} C_{k,a} \times P_k +\ C_{fix,y} + C_{el,y} - R_y + C_{su} \times N_{su}}{m_{y,H_2}} \quad (17)$$

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. The second MILP problem variables are presented in table 3. The constraints equations are presented in Tables 4 to 7, The storage equations are modelled as the truck storage, with a difference in the starting point. In equation 4 the tank of the trucks is full at the start of the problem, which is common for mobility application. The starting quantity of hydrogen in the plant storage is imposed to be higher or equal to the ending quantity. This modelling technique allows for repeatable yearly cycles.

Table 3: Hydrogen production tecno-economic optimization variables.

Variables	Type	Dimension
E_{str}	Continuous	i+1
$_{el}$	Continuous	i
E_p	Continuous	i
β	Binary	i+1
γ	Binary	i
δ	Binary	i
P_{el}	Continuous	1
P_{str}	Continuous	1
P_{res}	Continuous	1

Table 4: Constraints related to the storage operation.

Description	Equation	
Storage starting point	$E_{Str}(i=1) \geq E_{str}(i=end)$	(18)
Storage equation	$E_{str}(i+1) =\ \ E_p(i) - E_d(i) + E_{str}(i)$	(19)

Table 5: Constraints related to the variable capacity of components.

Description	Equation	
Electrolyzer variable capacity	$E_p \leq P_{el}$	(20)
Storage variable capacity	$E_{str} \leq P_{str}$	(21)
Renewable energy source capacity	$E_p \leq P_{res} \times P_{G,res}$	(22)

Table 6: Constraints related to the electrolyzer hydrogen production.

Description	Equation	
Hydrogen produced at high load	$E_p \geq E_{el} \times \eta_{el,1} - M(1-\delta)$	(23)
Hydrogen produced at high load	$E_p \leq E_{el} \times \eta_{el,1} + M\delta$	(24)
Hydrogen produced at low load	$E_p \geq E_{el} \times \eta_{el,2} - M(1-\delta)$	(25)
Hydrogen produced at low load	$E_p \leq E_{el} \times \eta_{el,2} + M\delta$	(26)
Electrolyzer energy demand a high load	$E_{el} \geq \xi_{load} \times P_{el} - M(1-\delta)$	(27)
Electrolyzer energy demand at low load	$E_{el} \leq \xi_{load} \times P_{el} + M\delta$	(28)

Table 7: Constraints related to the electrolyzer operation.

Description	Equation	
Start-up definition	$\gamma \geq 1 - \beta(i) + \beta(i+1) - 1$	(29)
Start-up in respect to electrolyzer turn on	$\gamma \leq \beta(i+1)$	(30)
Start up in respect to electrolyzer turn off	$\gamma \leq 1 - \beta(i)$	(31)

The variable size is modelled with equations 20 to 22, summarized in Table 5. The instantaneous variables must be lower than the capacity of the component for all the hours of operation of the plant. This modelling technique is common to avoid second order problems.

The hydrogen quantity at the electrolyzer output is dependent on the electrolyzer load. The deterioration of the efficiency of the electrolyzer, for loads lower than 40%, is modelled with a step function. The binary variable δ is used to switch between the specific consumptions. The equations 23 to 28, describing this behaviour of the model, are summarized in table 6.

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. The Start-up variable is defined with equations 29-31, as in table 7.
In the last part of the second MILP problem the lower and upper bounds are implemented. All the variables are subject to non-negativity constraints and have upper bounds.

2.4 Model features

The model has several calculation possibilities and features making it a versatile tool to support the design phase of power-to-hydrogen plants.

- Switching between energy supplies is possible. The direct purchase of green electricity from the grid is the base case, but it is possible to add the installation of new renewable energy sources such as solar photovoltaic or hydroelectric, by providing the costs and energy generation of the chosen energy source.
- Two ordinary maintenance events are implemented in the model. This events last for 48 hours and in those hours the plant is shut down. The first event is scheduled in the first half of the year and the second in the second half, considering the days of lowest hydrogen demand.
- It is possible to perform the optimization with a randomized failure distribution. An arbitrary number of failures can be decided prior the simulation. The failures cause the shutdown of the plant for 72 hours after the hour the failure happens.

These simulation type that is possible to achieve is defined at the start of the simulation. With the use of several decisional flags the model allows to switch between different layouts or simulation possibilities.

2.5 Model input data

The input data are taken from literature references, technical documentation, or direct company data. The unavailable inputs are inferred. Table 8, 9, and 10 contain the inputs with references and symbols to match the symbols used in the equations in the previous section.

Table 8: Economic input.

Name	Value	U.O.M.	reference	Symbol
Interest rate	0.03	[-]	[3]	r
Electrolyzer start-up cost	0.001	€/start-up	Own assumption	C_{su}
Plant lifetime	20	y	Own assumption	LT_p
Electrolyzer capex	1500	€/kW	Company data	$C_{inv,el}$
Electrolyzer opex	2	Capex %	[8]	$C_{O\&M,el}$
Electrolyzer lifetime	10	years	Company data	LT_{el}
Electrolyzer subst. capex	40	Capex %	[9]	$C_{rep,el}$
Compressor capex	$36079.54 * Pc^{(0.6038)}$	€/kW	[4]	$C_{inv,cmp}$
Compressor opex	8	Capex %	[4]	$C_{O\&M,cmp}$
Storage capex	600	€/kg	[10]	$C_{inv,str}$
Storage opex	2	Capex %	Own assumption	$C_{O\&M,str}$
HRS capex	500000	€	Company data	$C_{inv,hrs1}$
HRS construction capex	1000000	€	Company data	$C_{inv,hrs2}$
HRS opex	5	Capex %	Company data	$C_{O\&M,hrs}$
Solar photovoltaic capex	750	€/kW	[11]	$C_{inv,sol}$
Sollar photovoltaic opex	16.9	€/kW	[11]	$C_{O\&M,sol}$
Hydro capex	3309	€/kW	[12]	$C_{inv,hyd}$
Hydro opex	5	Capex %	[12]	$C_{O\&M,hyd}$
Value of selling electricity	70	€/MWh	Average market value	C_{sell}
Cost of Buying electricity	200	€/MWh	Average market value	C_{buy}

Table 9: Technical input data.

Name	Value	U.O.M.	reference	Symbol
El. specific consumption	55	kWh/kg	[13]	$\eta_{el,1}$
El. specific consumption at low load	70	kWh/kg	Own assumption	$\eta_{el,2}$
Electrolyzer operative pressure	30	bar	[13]	P_{el}
Electrolyzer operative temperature	70	°C	[13]	T_{el}
Electrolyzer min load	10%	[-]	Company data	ξ_{load}
Electrolyzer outlet temperature	30	°C	Company data	T_{out}
Compressor isentropic efficiency	0.8	[-]	[3]	$\eta_{is,c}$
Compressor electric efficiency	0.96	[-]	[3]	$\eta_{el,c}$
Compressor mechanical efficiency	0.98	[-]	[3]	$\eta_{m,c}$
Compressor outlet pressure	400	bar	[12]	P_{out}
Number of compression stages	3	[-]	Own assumption	-
Cooling temperature	30	°C	Own assumption	T_{cool}
Solar photovoltaic efficiency	20%	[-]	[14]	η_{sol}
Solar photovoltaic generation profile	Hour profile	kWh/kW	[15]	-
Hydroelectric generation profile	Hour profile	kWh/kW	[16]	-

Table 10: Refuelling Input data.

Name	Value	U.O.M.	Reference	Symbol
Daily distances "series 200"	350	km	Company data	-
Daily distances "series 400"	210	km	Company data	-
Daily distances "series 700"	60	km	Company data	-
Work shift "series 200"	6:00 AM to 1:00 PM	[-]	Company data	-
Work shift "series 400"	6:00 AM to 1:00 PM; 3 PM to 7 PM	[-]	Company data	-
Work shift "series 700"	6:00 AM to 1:00 PM	[-]	Company data	-
Depot time "series 200"	2 PM to 8 PM	[-]	Company data	-
Depot time "series 400"	2PM, 3PM, 7PM, 8PM	[-]	Company data	-
Depot time "series 700"	2 PM to 8 PM	[-]	Company data	-
Vehicles tank size	60	kg	[17]	T_{h2}
Min. hydrogen refuelled	20% tank dimension	kg	Own assumption	ξ_{r1}
Min. hydrogen in tank	20% tank dimension	kg	Own assumption	ξ_{r2}
Max. refuelling per hour	8	[-]	[17],[18]	R_{max}
Starting hydrogen in tank	60	kg	Own assumption	T_{h2}
Hydrogen mass per year	104.5	ton	Company data	-

2.6 Model output data

The model outputs are all the information for the design and operation of the plant. In particular:

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

3. Results and discussion

3.1 Case studies and calculation mode selection

The case studies selected are related to the green energy provisioning. All the available possibilities are considered:

- purchase of the electricity from a renewable energy plant already existing,
- installation of a solar photovoltaic field connected to the electrolyzer,
- installation of a hydroelectric power plant.

Another common renewable energy source in literature is wind power. The installation of a wind farm is not considered in this work due to the lack of a sufficient wind power generation in Valle Camonica, the considered location for the present work. Both solar and hydroelectric power are abundant in the Valle Camonica, thus the purchase of the green electricity from the grid is tied to the already exiting renewable plants in the area, in particular the hydrogen production facility is connected directly to a renewable power plant, ensuring a green hydrogen production.

These cases are analysed with a single point simulation to find the minimum LCOH and their results are compared. The second case, solar photovoltaic installation, is analysed with two approaches: The first considering the solar photovoltaic field of fixed capacity and the second considering no revenues from the electricity. The first case is considered the reference case. The analysis will be deepened for the reference case with a sensitivity analysis on the most meaningful parameters and a statistical analysis with failures.

3.2 Single point calculation results

The results for the single point simulation are presented in Table 11. The first case has the minimum values of electrolyzer capacity and storage dimension between all the case studies. This is normal considering that is the only case with continuous energy supply through the year. However, the cost of electricity, considering the average market value, has a significant impact on the final LCOH.

Table 11: Results for the single point simulation case.

Variable	UDM	BUY	SOLAR 1	SOLAR 2	HYDRO
Renewable energy rated power	kW	0	10000	9815.50	3817.67
Electrolyzer capacity	kW	764.52	3302.75	3300	859.40
Storage size	kg	405.85	3728.39	3787.75	2544.04
Compressor rated power	kW	18.99	82.05	81.98	21.35
Electrolyzer equivalent hours	h/year	7540	1754	1808	6714
RES equivalent hours	h/year	[-]	1282	1282	2040
Hours of operation	h/year	8712	2108	3116	8676
Number of sturt-ups	Start-up/year	3	282	459	26
LCOH electrolyzer	€/kg	1.18	5.08	5.07	1.32
LCOH storage	€/kg	0.20	1.86	1.89	1.27
LCOH compressor	€/kg	0.15	0.36	0.36	0.16
LCOH HRS	€/kg	1.20	1.20	1.20	1.20
LCOH RES / Electricity	€/kg	11.02	6.43	6.32	14.16
LCOH Revenues	€/kg	0	-4.70	0	-1.35
LCOH plant	€/kg	13.75	10.24	14.84	16.76

The second and third case are related to the solar photovoltaic installation. The solar power generation profile is taken considering solar radiation of Milan. These cases have the highest sizes of electrolyzer and storage. This is necessary since in the case of solar power generation the energy production is very intermittent and is not evenly distributed through the year. The low cost of solar plant installation, both in terms of capital expenditure and operational expenditure, makes the investment in solar power profitable even without the connected hydrogen production facility. The model, during the simulation, always maximized the value of the solar photovoltaic field. To produce comparable results the photovoltaic field capacity is fixed at 10 MW for the case “SOLAR 1”. The LCOH of the plant is 10.24 €/kg, the lowest among all the cases, mostly because of the high revenues from the electricity. The solar photovoltaic field became less profitable if no revenues coming for electricity are considered, as depicted in the case “SOLAR 2”. This result is interesting in the prospective of a future scenario where the abundance of renewable energy sources will lead to energy curtailment events.

The last case is the installation of a new hydroelectric power plant. The hydroelectric generation profile is obtained as an average value of Italian hydroelectric power generation. Hydroelectric power is a less intermittent source compared to solar power and in fact the use of both the renewable energy source and the electrolyzer rise consistently if compared to the solar power case. However, the high capital cost, connected to the construction of the hydroelectric power plant, make it the less profitable alternative among all the case studies.

3.3 Sensitivity analysis

The sensitivity analysis is a powerful tool to address model reaction to variation in input parameters. This type of analysis is also useful to understand which input values have significant impact on the results. The chosen parameters for this analysis are the following:

- electrolyzer capex,
- storage capex,
- cost of electricity,
- electrolyzer specific consumption.

These values are considered because they are most likely to vary depending on the market and on the development of the hydrogen technology. For the analysis, a variation of $\pm 50\%$ is considered for the first three variables. The variation on the electrolyzer specific consumption has a $-35\%; +50\%$ range. This range is considered since lowering the specific consumption under 35% would have led to efficiencies higher than one. The results of the sensitivity analysis are summarized In Figure 2,3 and 4.

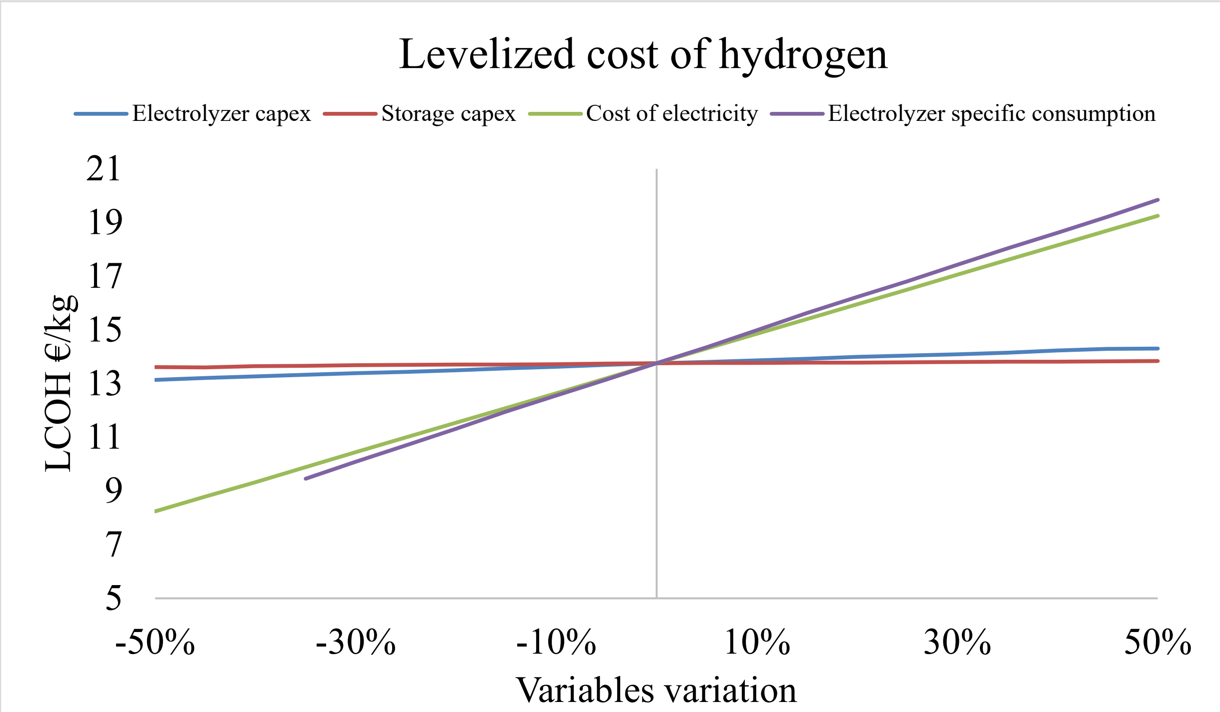

Figure 2: Levelized cost of hydrogen trend with respect to 50% variation in electrolyzer and storage capex, cost of electricity and electrolyzer specific consumption.

The variation of electrolyzer and storage capital expenditure has a minor effect on the LCOH with variations in the order of 5%. The variation of the electricity cost has a major impact on the LCOH that goes from 8 €/kg to 19 €/kg with respect to a $\pm 50\%$ variation. The electrolyzer consumption is the value that most affected the optimization result among the chosen one. A 35% reduction in the specific consumption cause the LCOH to decrease by 30%.

The variation of electrolyzer capital expenditure and cost of electricity gives a small contribution on the size of the components. The variation of the storage capital expenditure, on the other hand, has a considerable effect on the size of the electrolyzer and storage.

In both these cases can be noted how if the size of the electrolyzer rise the size of the storage reduce and vice-versa. The size of the electrolyzer and the size of the storage are two major components of the final LCOH, which is the target value to minimize. The model balances the size of the storage and electrolyzer to reduce the increase of the LCOH.

The variation on the electrolyzer specific consumption has a minor impact on the size of the storage but a great effect on the electrolyzer size. To produce the required amount of hydrogen, which is fixed by the vehicles hour demand, with a lower or higher specific consumption the electrolyzer size must scale accordingly.

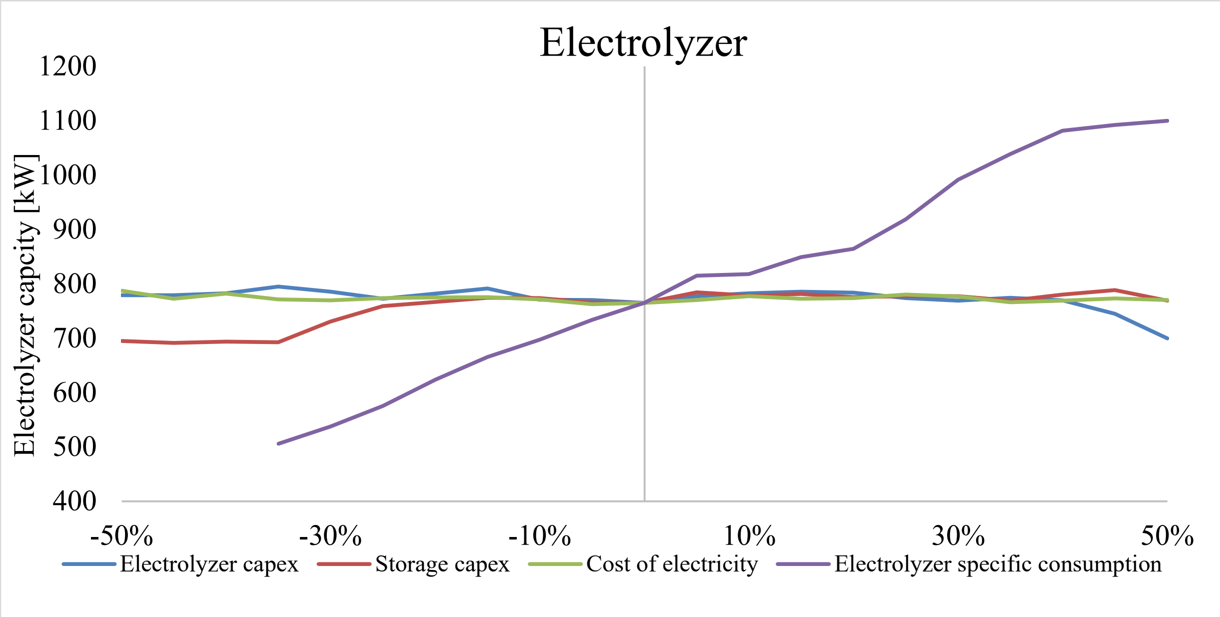

Figure 3: Electrolyzer size trend with respect to a 50% variation in the electrolyzer and storage capex, cost of electricity and electrolyzer specific consumption.

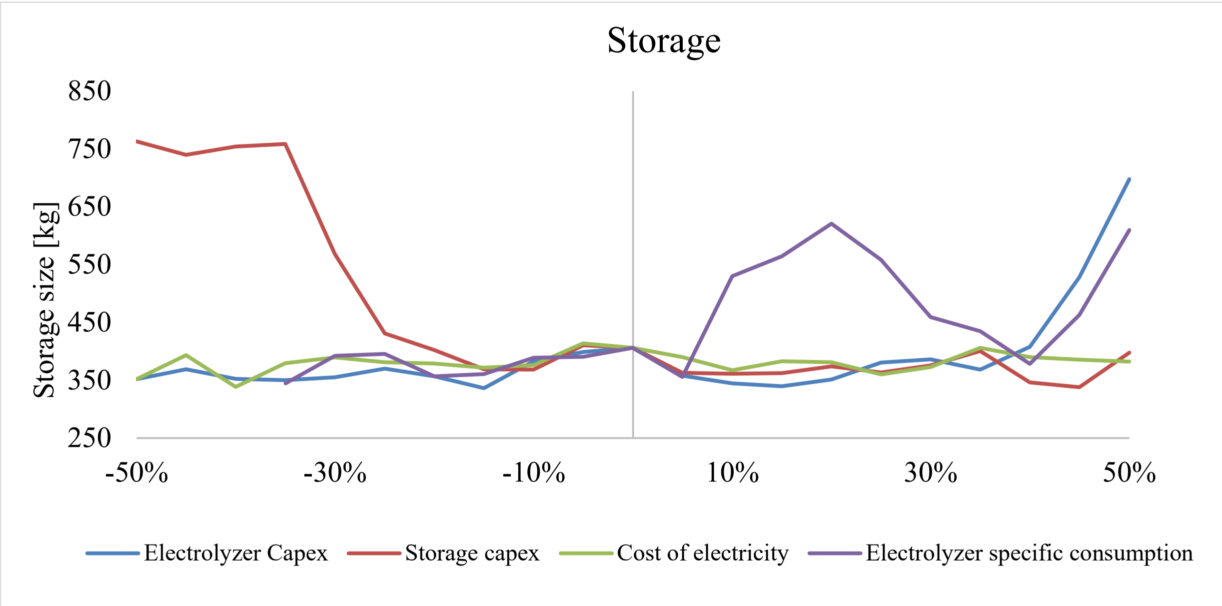

Figure 4: Storage size trend with respect to a 50% variation in the electrolyzer and storage capex, cost of electricity and electrolyzer specific consumption.

3.4 Statistical Analysis results

The statistical analysis is based on 500 simulations considering 4 failures appearing randomly during the year and causing the shut-down of the plant for 72 hours. In the Figure 5-6 are shown the results for the storage size and electrolyzer capacity. The electrolyzer capacity is minorly affected by the random failure distribution. The optimal size is between 700 kW and 800 kW, close to 764 kW, value obtained without considering the failures. This behaviour is tied to the hydrogen quantities, that do not vary during the year if failures appear.

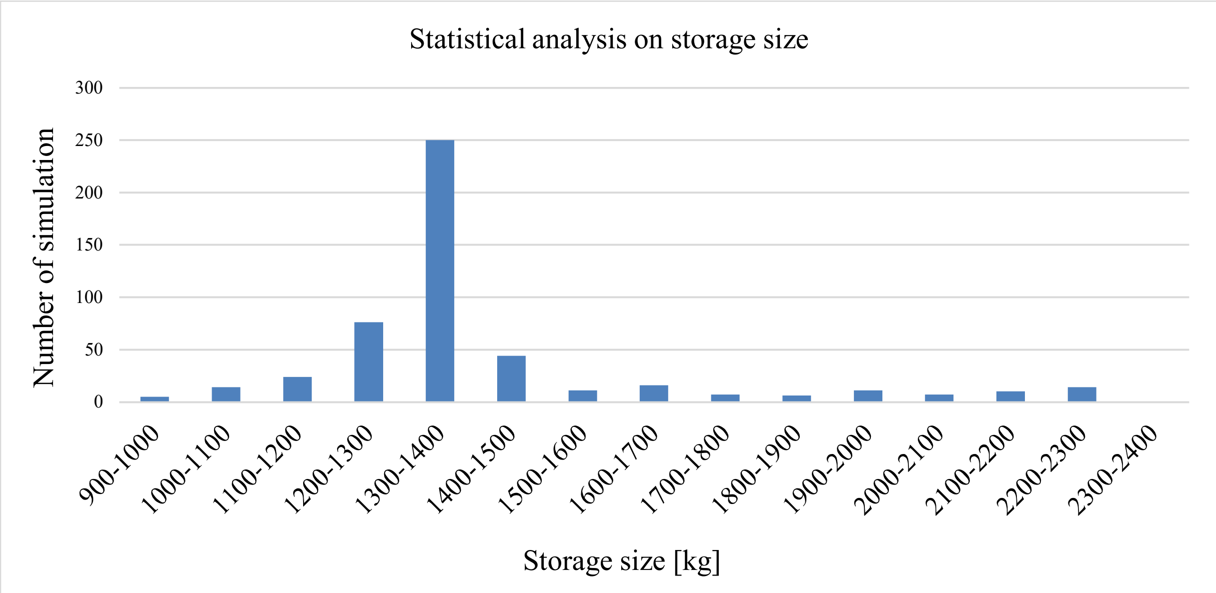

Figure 5: Statistical analysis on storage size considering four random failures, causing the shutdown of the plant for 72 hours.

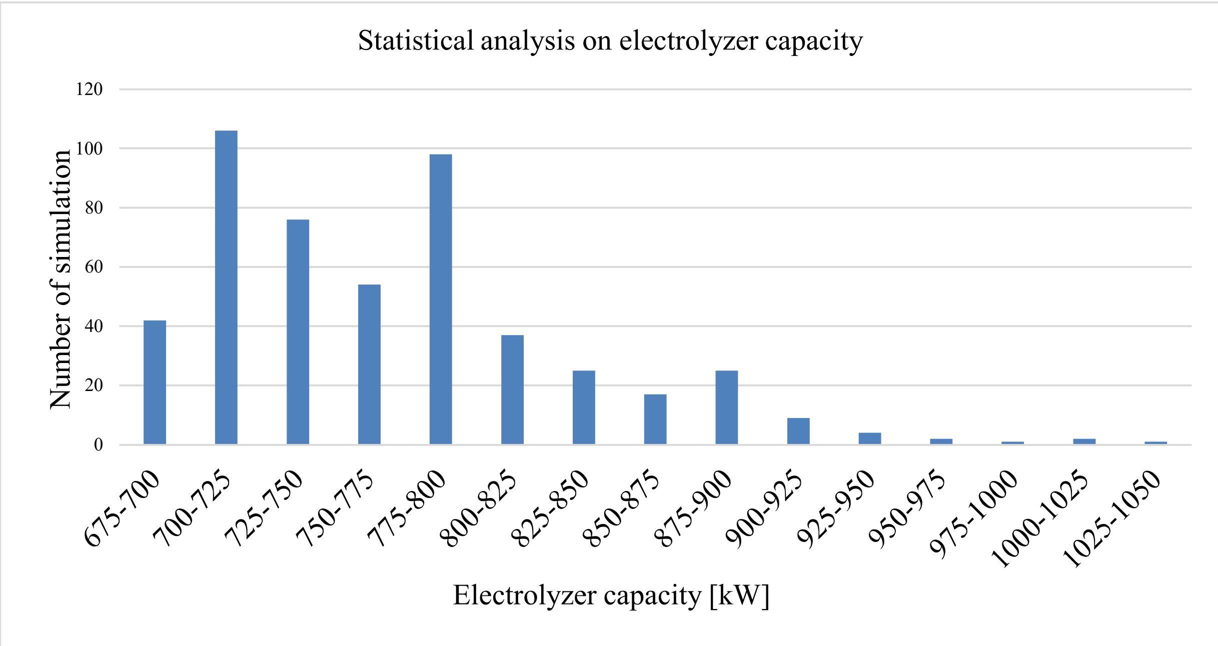

Figure 6: Statistical analysis on electrolyzer size considering four random failures, causing the shutdown of the plant for 72 hours.

On the other hand, the storage optimal value rises from 405 kg to 1300-1400 kg. The increase is proportional to the three days of storage needed to sustain the hydrogen refuelling station with no hydrogen production from the electrolyzer. The fact that more than 200 of the simulation ended up between 1300 kg and 1400 kg is related to the refuelling distribution. With a uniform refuelling schedule there is low variation between simulations.

4. Conclusion

The current work aims to implement an optimization model to define the design and operation parameters of a hydrogen production facility connected to a hydrogen refuelling station. The refuelling station is dedicated to heavy duty vehicles operating in the field of waste management and transportation. The conclusion and remarks on the work presented in this article are the following.

- The most convenient electricity supply method for hydrogen production is the connection of a 10 MW solar photovoltaic field to a 3.3 MW Electrolyzer and 3700 kg storage, with a Levelized Cost of Hydrogen (LCOH) of 10.24 €/kg.
- In case the electricity cannot be sold to the market value, the most cost-effective option is to buy the energy directly from the grid. The Electrolyzer size for this case is 760 kW and the storage size is 405 kg, with a resulting LCOH of 13.75 €/kg; however, this value is influenced by the fluctuation of the energy market prices.
- The electrolyzer specific consumption is the parameter that mostly influence the profitability of the plant. A 35% variation in electrolyzer specific consumption dimmish the LCOH by 30%. The result is interesting in the prospective of breakthrough technology that can rise the electrolyzer efficiency.
- The optimal sizes for electrolyzer and storage are between 700 kW and 800 kW for the electrolyzer and between 1300 kg and 1400 kg for the storage considering four failures randomly distributed during the year.
- Given the current costs of the equipment and electricity, the levelized cost of hydrogen in the presented cases is still high to allow penetration of hydrogen in the mobility sector without subsidies, not considered in the present work.

4.1 Future works

The model is implemented with two different MILP problems and considering a fixed schedule and routing of the vehicles. Future works following this analysis may consider the vehicles routing problem associated with the waste management to produce a unique MILP problem. Another interesting possibility would be considering innovative solutions for energy supply, such as floating solar panels. In Valle Camonica there are several hydroelectric power plants with water basin. As analysed by Cazzaniga et al. the hybridization of hydroelectric plant has several advantages [19].

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	-
$m_{y,h2}$	Quantity of hydrogen per yar	kg/y
$C_{inv,a}$	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
m_r	Refuelled hydrogen mass in truck tanks	kg
m_s	Stored hydrogen mass in truck tanks	kg
m_d	Hydrogen mass demand	kg
α_r	Refuelling event binary variable	-

Symbol	Definition	Unit of measurement
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
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	Efficiency variation binary variable	-
P_{el}	Electrolyzer capacity	kW
P_{str}	Storage capacity	kg
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	-
ξ_{load}	Electrolyzer load factor coefficient	-

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