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IMPACT OF THE OPTIMIZATION METHOD ON REDUCING THE INFRUSTRUCTURE COST OF HYDROGEN TRANSPORTED AT DIFFERENT STATES OF AGGREGATION

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ABSTRACT

The analysis developed investigates the minimum cost of transporting hydrogen for various delivery distances and demands. The calculations are model-based and estimate the minimum transport cost via road infrastructure using three different methods, i.e. a comparative analysis, and two optimization models. For that, different states of aggregation are chosen for transformation processes, transport and storage options ranging from compressed hydrogen at different pressure levels to liquid hydrogen and liquid organic hydrogen carrier. Key findings from the modelling results reveal that low and medium compressed gas are used at low hydrogen demand and transport distance, while the share of liquid based options increases with the transport distance. The results show as well the importance of the modeling method to reduce the cost, and its impact on the choice of the state of aggregation for hydrogen transport. Thus, a more elaborate optimization model estimated daily reduces the cost by privileging flexible storage option as liquid and increases the share of liquid organic hydrogen carrier at low demand.

Keywords: Hydrogen transport, cost optimization, liquid organic hydrogen carrier (LOHC), compressed hydrogen, liquid hydrogen.

NONMENCLATURE

Abbreviations

TPD	Tons per day
RTT	Road truck
CGH	Compressed gas hydrogen
LH	Liquid hydrogen
LOHC	Liquid organic hydrogen carriers
SoT	State of transport

Symbols

s, t	Different states of transport
T_s	Groupe of states of transport
Pt	Operating pressure
$m[\mathrm{t}]$	Tube/ Tank trailer capacity
$tt_{l/u}[\mathrm{t}]$	Total loading and unloading time
C_T	Transformation cost
C_S	Storage cost
C_S	Road transport cost
$LCOTH$	Levelized cost of transporting hydrogen
$LCOH_T$	Transformation levelized cost
$LCOH_S$	Storage levelized cost
$LCOH_S$	Road transport levelized cost
D_y	Annual demand flow
Z_{min}	Minimization cost
Z_{op}	Optimization cost
Z_{dy}	Dynamic optimization cost
$\dot{w}_s[s,t]$	System transformation work
pd	Time period
$Nrt_{pd,m}[\mathrm{t}]$	Maximum number of roundtrips
α_s	Sizing factor
C_b	Base case cost
S_b	Base case size
P_c	Compressor power
$Pr_{h,net}$	Net production rate
Pr_h	Production rate
$C_t[t]$	Tube/ tank cost
$lc[s,t]$	Linear levelized total cost
$sc[t]$	Linear levelized storage cost
$tc[s,t]$	Linear levelized transport and transformation costs
Tr_d	Daily transported capacity
St_d	Daily stored capacity

1. INTRODUCTION

The current energy system is dealing with the limited resources of fossil fuels, the geopolitical problems linked to their exploitation, and the increase of carbon emissions and other greenhouse gases with their impact on climate change. One alternative for improving the current situation is the adoption of renewable energy sources, which apply the transformation of the entire energy system because of the potential of coupling between the different sectors. Thus, hydrogen can play a major role to lower carbon emissions in the transportation sector by the use of fuel cell technology [1, 2]. In the meantime, hydrogen can be used as a short- and long-term energy storage option, and as a direct chemical raw material for ammonia and methanol production for instance. In addition, also sector coupling with different industry sectors is possible, e.g. in refining, treating metals, and food processing.

Sector coupling and the potential for fuel cell vehicles in road transportation makes hydrogen a good candidate as a future energy vector. However, the design and the installation of an adequate, cost-effective infrastructure is still one of the main challenges to overcome. Against this background, this paper aims to investigate the influence of different hydrogen states on the transport cost using three different models including a comparative and a cost optimization analysis.

Many studies for instance, assesse and compare different transport and storage pathways [1, 3, 4] to identify the profitable alternative. Yang and Ogden [3] investigate the cost-effective configuration to transport and distribute hydrogen from centralized production plant to local distribution network of refueling station using compressed gas trucks, liquid trailers and pipeline system. In contrast, other studies in literature used linear programming to investigate the optimum infrastructure solution and apply it in regional and national cases. The studies, however, differ concerning the scope of application and the functions optimized. For instance, in some analyses the whole infrastructure is optimized [5-8], while other work focuses on special aspects of the supply chain, e.g. production, storage or distribution.

2. METHODOLOGY

The study aims to investigate the impact of hydrogen operated at different states of transport SoT on reducing the cost of an input hydrogen flow along a given transport distance. For that, the road system is chosen as infrastructure using road trucks RTT at three different states of aggregation, as compressed gas hydrogen CGH, as liquid hydrogen LH or bound in liquid organic hydrogen carrier LOHC. For CGH, five operation pressure level ranging from 180 to 540 bar corresponding to the current CGH market and future projections are investigated [9]. Table 1 summarizes the different tubes and tank trailers, which are used to store and transport hydrogen depending on SoT t as well as the operating pressure Pt, along with the corresponding capacity m[t] and the total loading and unloading time $tt_{l/u}$[t].

Table 1 Transport parameters for different SoT t

	CGH					LOHC	LH
Pt in bar	180	250	350	500	540	1.013	
SoT t	2	3	4	5	6	7	8
$m[t]$ in kg	350	668	885	1100	1230	1500	3600
$tt_{l/u}$[t] in h	2.5	2	1.5	1	1	1.5	3

To allow the comparison between different SoT, the same transport step are used for the different states t. First, hydrogen is initially a gas at ambient pressure (s $=$ 0) or pre-compressed to 20 bar (s $=$ 1). The hydrogen is then transformed to a new SoT t using a corresponding system delivering a total specific wok for transformation $\dot{w}_s$. The resulted hydrogen at the new state t is stored in different tube trailers or tanks of total net capacity m[t] (Table 1), and then loaded to be transported by a RTT to the refueling stations where the hydrogen is delivered at its final state as compressed gas at 700 bar. For all processes, the RTT is supposed to wait until it is unloaded adding a total loading and unloading time $tt_{l/u}$[t] (Table 1). In case of LOHC, a dehydrogenation process is added at the destination to separate the hydrogen from the carrier.

The total cost is estimated for the whole process by assuming the production and consumption costs fixed independently of the operating SoT. Thus, only the total cost associated to hydrogen transport is optimized and defined by the sum of the cost of transformation C_T, storage C_S and road transport C_R. These three costs can be linearized as a product of the annual demand flow D_y and the respective levelized cost of hydrogen calculated annually $LCOH_T$, $LCOH_S$ and $LCOH_R$.

Three models are then used: a minimum cost comparison Z_{min}, a cost optimization model Z_{op}, and a dynamic cost optimization Z_{dy}. The first one compares different pathways of transforming and storing hydrogen and provide the minimum option [3]. The second one, uses linear programming to identify the optimum combination of trucks at different SoT t, which deliver the minimum cost. Finally, the third one uses the same optimization problem but decouples the transported capacity from the stored one by calculating daily the hydrogen transported and the capacity available for storage to meet the daily demand.

3. INPUT PARAMETRS

The model input parameters include the different technical and economical parameters used to define the different levelized costs associated to transformation, storage and transport. Thus, a technical assessment investigate the energy needs associated to each transformation, while an economic one define the different cost parameters.

3.1 Technical assessment

For the three ways of storing hydrogen, as CGH, LH and LOHC, the according transformation work is estimated. First, the work of compression is calculated based on the work of a multistage compressors [9]. The liquefaction work is calculated by the ideal work associated to a literature review of different liquefaction processes [10-16]. Finally, hydrogenation and dehydrogenation work is simulated using ASPEN as the process is still in its early research stage [17]. Table 2 shows the results of the system work $\dot{w}_s[s,t]$ for the initial conditions $s = \{0,1\}$.

Table 2 Matrix of transformation work $\dot{w}_s[s,t]$ in kWh/ kg

s \ t	2	3	4	5	6	7	8
0	2.75	2.97	3.19	3.42	3.47	6.02	12
1	1.07	1.24	1.42	1.62	1.66	4.31	10.53

The tube trailers with the capacity $m[t]$ used to store hydrogen at the SoT t (Table 1) are the same as for transport. This maximum tube trailer capacity limits the transported capacity. Hence, each single RTT of capacity $m[t]$ can perform only a maximum number of roundtrips $Nrt_{pd,m}$[t] over a period of operating time *pd*. Therefore, to meet the hydrogen demand additional trucks are needed increasing the total trucks operating in the same time during *pd*. In the meantime, each truck performing one trip is operated by a number of drivers limited by the driver working hours. The different parameters are defined daily and annually by adapting the definition introduced in Lahnaoui et al. [9] to different period times pd when the RTT is operating.

3.2 Economical assessment

The cost parameters chosen for investment and operating the different plants include the investment cost related to the different transformation processes and storage technologies. For that, a sizing factor α_s is used to scale the cost form a base known case C_b per system size S_b [18] as shown in the equation below.

$$\frac{C}{C_b * S_b} = \left(\frac{S}{S_b}\right)^{\alpha_s}$$

Depending on the respective technology, S is described by different parameters described in Table 3 together with the economic assumptions for the cost parameters C_b, S_b and α_s.

	Compression		Liquefaction		Hydrogenation	
	Value	Unit	Value	Unit	Value	Unit
C_b	1164	*€/kW*	47895	*€/(kg/h)*	31881	*€/(kg/h)*
S_b	4000	*kW*	1167	*kg/h*	11574	*kg/h*
α_s	0.8	-	0.65	-	0.7	-
S	compressor power size P_c in kW		net production rate $Pr_{h,net}$ in *kg/h*		production rate Pr_h in *kg/h*	
	[18], [19]		[18], [19]		[20], [21], [22]	

Table 3 Assumption for transformation capital cost

For compression, as the pressure level has an impact on the investment cost, the capital cost uses an additional sizing factor corresponding to the operating pressure Pt [23]. For capital cost of liquefaction, losses due to boil of have to be taken into account using the net production rate $Pr_{h,net}$ is expressed by the production rate Pr_h, taking into account a boil-off rate BoR of 1 % and the total storage time Th_{St} in hours as expressed by the equation below.

$$Pr_{h,net} = Pr_h * \left(1 + \left(1 - e^{-BoR*Th_{St})}\right)\right)$$

The same methodology is used for capital cost of storage [18] by replacing the product $C_b * S_b$ with a base case cost $C_t[t]$ of a system that has a capacity $m[t]$ using a sizing factor $\alpha_s[t]$. The tube cost range from 385.0 *k€ at 180 bar to* 1197.5 *k*€ at 540 bar [9], while the tank cost lie between 57.1 k€ and 1732.5 k€ for LOHC and LH, respectively [22, 24].

Operations and maintenance cost can be generalized into fixed and variable ones. For the fixed one it includes the operations and maintenance associated to the storage and transformation it is fixed as a percentage of the total corresponding capital cost [9, 23]. Concerning the variable operations and maintenance cost, it includes the cooling water requirements and the work needed to transform hydrogen. The second parameter depends on the electricity cost, which are variable depending on the annual consumption band [25].

Concerning the cost related to the use of the truck, the same parameters defined for the compressed gas truck [9] are adapted to the other state of aggregation and different operating periods pd, and defined as a sum of capital investment, fuel cost and labour cost.

4. MODEL

The minimization model uses the levelized cost function $lc[s,t]$ defined from the linearized levelized cost [23, 26] associated to transformation, storage and road transport as defined in the equation below.

$$lc[s,t] = LCOH_R[t] + LCOH_T[s,t] + LCOH_S[t]$$

Thus, the minimization cost Z_{min} is defined by comparing the different states t as shown below.

$$Z_{min} = \min_{t\in \boldsymbol{T_s}} \left(lc[s,t] * D_y\right) \quad \text{with } T_s = \{2,3,4,5,6,7,8\}$$

The two costs Z_{op} and Z_{dy} can be described using the same methodology [9, 23] as a *LP*. The first method uses a yearly techno-economic analysis and the same cost function $lc[s,t]$ as shown below.

$$Z_{op} = \min \sum_{t\in \boldsymbol{T_s}} lc[s,t] * D_y[t]$$
$$D_y = \sum_{t\in \boldsymbol{T_s}} D_y[t]$$
$$D_y[t] \geq 0$$

For the dynamic formulation, the yearly demand is replaced by the daily demand in the cost functions, and the daily stored capacity St_d is decoupled from the transported one Tr_d. Thus, two levelized cost function are defined $sc[t]$ and $tc[s,t]$ associated to the linearized cost of storing hydrogen as well as transporting and transforming it, as defined below.

$$\begin{cases} sc[t] = LCOH_S[t] \\ tc[s,t] = LCOH_R[t] + LCOH_T[s,t] \end{cases}$$

This allows to formulate the *LP* associated to Z_{dy} as expressed below.

$$Z_{dy} = \min \sum_{t\in \boldsymbol{T_s}} \left(tc[s,t] \sum_{d,year} Tr_d[t] + sc[t] \sum_{d,year} St_d[t] \right)$$
$$D_y = \sum_{t\in \boldsymbol{T_s}} \sum_{d,year} Tr_d[t] + St_d[t]$$
$$St_d[t] \geq 0$$
$$Tr_d[t] \geq 0$$

5. RESULTS AND DISCUTION

First, the general results of the minimum cost Z_{min} are shown. Then, the optimum cost results Z_{op} and Z_{dy} are presented and compared to each other.

5.1 General cost results

The results corresponding to the minimum cost Z_{min} are shown in Fig 1 for the electricity prices corresponding to the case of France [25]. The compressed gas trucks CGT with a low-pressure level have 180 and 250 bar, while a high-pressure CGT has 500 and 540 bar.

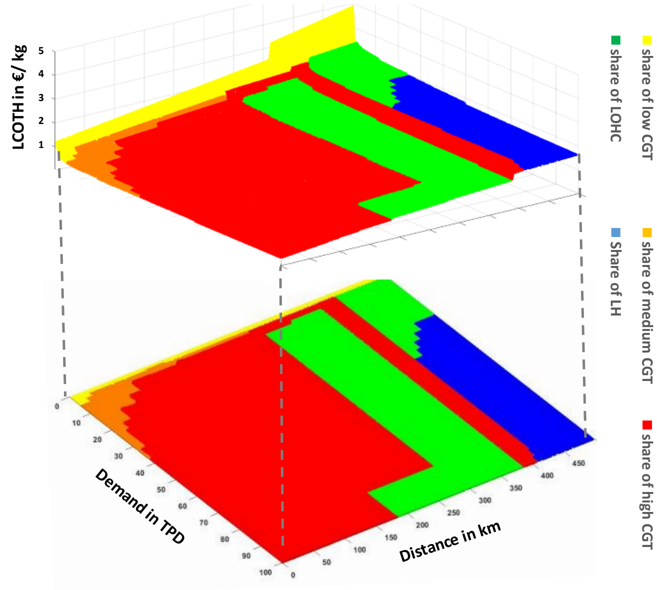

Fig 1 Levelized cost of transporting hydrogen $LCOTH$

The results show that $LCOTH$ is below 4 €/ kg for the demand range chosen between 0.5 and 100 TPD, and the distance range between 1 and 500 km D. Higher cost occur for a low daily demand D_d below 2 TPD and a high transport distance exceeding 400 km. At low daily demand, the cost increases for more than 1 €/ kg.

At high transport distance, LOHC is first used to transport a daily demand below 30 TPD. Exceeding this value, LOHC is gradually replaced by LH until 48 TPD. From this point on all hydrogen is transported as a liquid.

Medium-pressure CGH is used as a transition state transport between low and high CGH for a distance transport reaching 75 km, and hydrogen demand ranging between 2 and 30 TPD. High CGH are used for the main transport below 180 km. An exception around 400 km is noticed, when normally LOHC should be used, and was replaced by high CGH due to logistic cost [9].

5.2 Optimum cost results

Fig 2 shows the average share of CGH, LOHC and LH for Z_{op} at five different daily demand profiles. The average share was calculated for two ranges of distance of 1 until 250 km, and 250 until 500 km.

At low range distance below 250 km, the use of transport state with higher transported capacity increases with the hydrogen demand. At low flow below 25 TPD, only CGH is used with a gradual switch from low and medium CGH at 5 TPD to high CGH at 25 TPD. Thus, low and medium are mainly used at 5 TPD at a share of 56.0%, while high

CGH is used at a share of 74.8% and 91.5% at 10 and 25 TPD respectively. At a medium demand of 50 TPD, high CGH is widely used, but LOHC start as well to be used as transport state. Finally, with the increase of the demand, the use of LOHC increases as well to reach 10% at 100 TPD transported flow.

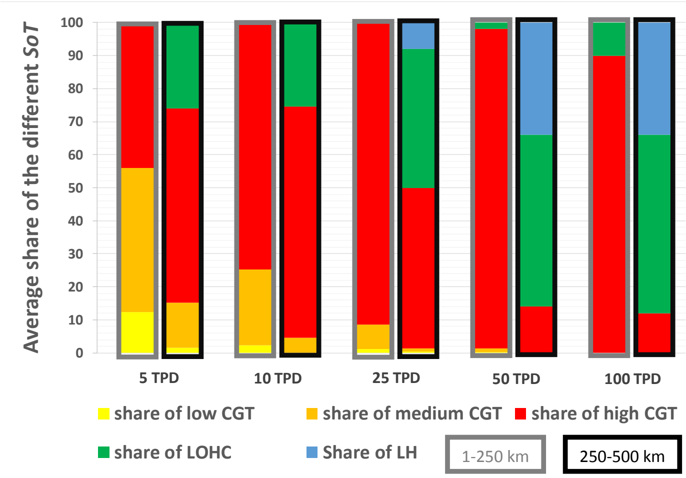

Fig 2 Average share of *SoT* for Z_{op}

Concerning the distance range above 250 km, mainly high CGH is used for low demand, while liquid transport is adopted at high transported flows. Thus, high CGT is mainly used at 5 and 10 TPD along a low share of medium CGT. At transported flow of 25 TPD, the hydrogen is equally transported using liquid states and compressed hydrogen. Finally, at high demand above 50 TPD the LOHC share increases to 52% and 54% at transported flows of 50 and 100 TPD respectively, along with LH share that reaches 34% and 34.2% respectively.

5.3 Results comparison

Decoupling storage and transport capacities benefits for low hydrogen demand because of the higher cost related to the use of low to medium CGT. Thus, the share of LOHC below 25 TPD for different cost methods is investigated as shown in Table 4.

Table 4 Share of LOHC use for different methods

		Z_{min}	Z_{op}	Z_{dy}
1 – 250 km	**5 TPD**	0%	0%	3 %
	10 TPD			5 %
	25 TPD			2.6%
250 – 500 km	**5 TPD**	23.40%	22.2%	56.7%
	10 TPD	27.50%	26.0%	66.0%
	25 TPD	30.20%	46.9%	62.0%

Table 4 shows that, for low range distance below 250 km, LOHC is used as a transport state only for the dynamic optimization. Between 250 and 500 km, Z_{dy} uses the highest share of LOHC for transporting 5, 10 and 25 TPD, respectively. In fact, in the dynamic optimum method, the assessment is performed daily, which allows to store the surplus of hydrogen transported at the end of the day and not consumed and made it available for local consumption for future use. By allowing this, storage is privileged over transport, and liquid storage benefits from that as it allows more flexibility because of the pumped LOHC stored in tanks, while compressed hydrogen is still restrained by its tube capacity.
In the one hand, the use of LP reduces the cost in all distance and flow ranges studied because it allows the use of different states simultaneously. In the other hand, the difference between Z_{op} and Z_{dy} is apparent at low demand because of low and medium CGT replacement by LOHC. Thus, Table 5 shows the impact of the calculation methods on the cost reduction below 25 TPD.

Table 5 Cost reduction of the optimum cost methods compared to the minimization

	1 – 100 km			100 – 200 km		
	5 TPD	10 TPD	25 TPD	5 TPD	10 TPD	25 TPD
(1)	7.38%	6.02%	1.79%	8.49%	2.57%	1.12%
(2)	11.12%	10.24%	7.19%	12.58%	5.90%	3.98%
	200 – 300 km			**300 – 400 km**		
	5 TPD	10 TPD	25 TPD	5 TPD	10 TPD	25 TPD
(1)	3.45%	1.47%	1.56%	3.37%	1.69%	0.97%
(2)	6.73%	5.71%	3.51%	6.06%	0.79%	0.96%
				400 – 500 km		
				5 TPD	10 TPD	25 TPD
(1)				2.25%	2.10%	1.00%
(2)				9.95%	8.64%	3.96%

(1) Z_{op} reduction to Z_{min}

(2) Z_{dy} reduction to Z_{min}

Table 5 shows that both optimization methods allow to reduce the transport cost. Mainly, a high cost reduction is achieved below 10 TPD and 100 km, as the optimization method allows the simultaneous use of CGT below 350 bar in addition to LOHC. The impact of using a dynamic approach on reducing the cost increases with the increase of the flow because of the increase of LOHC share (Table 4). The same behavior could be noticed as well with the increase of transport distance, except in the range of 300 to 400 km where high CGH are used due to logistic cost [9]. Thus, the restrained use of LOHC at this range distance doesn't allow to perform a major cost reduction, and impact manly on Z_{dy}.

6. CONCLUSION

The analysis investigates the impact of the minimization method on the cost and the use of liquid and gaseous states to transport hydrogen. Thus, linear programming allows to reduce the cost in contrast to minimum comparative analysis because of the simultaneous use of seven different states of transport. This is mainly the case at low demand where the levelized cost of hydrogen is higher. Moreover, a share of compressed gas below 350 bar is replaced by LOHC in case of daily analysis because of the increase of LOHC stored in tanks at the end of the day. This dynamic optimization allows to further reduce the cost at low demand, because of lower storage cost compared to road transport cost.

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