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Optimizing hydrogen transportation system for mobility by minimizing the cost of transportation via compressed gas truck in North Rhine-Westphalia

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HIGHLIGHTS

- The cost of transporting hydrogen is minimized using four different compressed gas trucks.
- Hydrogen production and demand are projected for 2030 and 2050 in North Rhine-Westphalia, Germany.
- The main hydrogen is transported and stored at high pressure level in 2050.
- Compressed hydrogen at 250 and 350 bar are mainly used for transportation in 2030.
- The demand is met without regional export in 2030 and with export in 2050.

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ABSTRACT

This study develops a method to identify the minimum cost of establishing hydrogen infrastructure using a mono-objective linear optimization. It focuses on minimizing both the capital and operation costs of hydrogen transportation. This includes costs associated with the establishment of storage and compression facilities as well as transportation links.

The overarching goal of the study is therefore to build a cost-efficient transportation network using compressed gas trucks for mobility and to apply it to the federal state of North Rhine-Westphalia by 2050. It is assumed that hydrogen production will be established by 2050 and, based on excess electricity from wind energy in North Rhine-Westphalia and the surrounding areas, limited by the projected installed wind installed capacity by 2050. Hydrogen is then distributed as a compressed gas, depending on the hydrogen demand of a given year, for each NUTS 3 district of North Rhine-Westphalia in 2030 and 2050.

The results show that the hydrogen demand on the region, which increases from 2030 to 2050, has an impact on how and at which flow hydrogen demand is transported from the production nodes to the different distribution hubs. In 2050, hydrogen is predominantly transported and stored between the storage nodes and the distribution hubs at a high-pressure level of 500 and 540 bar, whilst it is mainly transported at 250 and 350 bar in 2030. Production is predominantly found to be transported at high pressure for both years and located in the region in 2030, whereas imports from the south and north are required in 2050.

1. Introduction

Among the energy sectors, the transportation sector still faces challenges restricting its development to a more sustainable and environmentally friendly sector.

On the one hand, the transportation sector is faced with an increase in energy requirements, for example in Germany, the transportation sector's share of energy demand has increased over the last 25 years – unlike the final energy consumption. In fact, the transportation sector's share of final energy requirements in Germany increased from 26.1% in 1990 to 29.8% in 2015 [1].

On the other hand, the transportation sector, and especially road transportation, is still highly oil-dependent. In Germany, the share of alternative fuel vehicles among newly registered passenger cars was still below 2% in 2015, while the share of petrol and diesel cars accounted for 66% and 32%, respectively [1].

This dependency on oil, in addition to the consequences of carbon emissions, impacts and restrains the efforts of the European Union to decarbonize the transportation sector by fixing the threshold of oil dependency in 2050 to 70% less than in 2008 [2].

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Nomenclature

Subscripts

st, st'	operated by a CGT where the hydrogen is at pressure level of P^{st}
y	year
C	related to compression cost
S	related to storage cost
T	related to transportation cost
Tra	related to trailer cost
Cab	related to cab cost
$\sim$	linear approximation

Network parameters

$G(N,V)$	network of nodes N and vectors V
$P \subset N$	production nodes
$S \subset N$	storage nodes
$D \subset N$	distribution nodes
i,j,k,f	nodes or locations
d_{ij}, d_{ik}	distance between the locations i and j, and i and k
S_i^{st}	stored flow at node i and hydrogen condition st
Q_{ij}^{st}	transported flow between the two nodes i and j at hydrogen condition st
$d_i(y)$	hydrogen demand for the year y and the location i
d_{min}, d_{max}	minimum and maximum hydrogen demand
$E_i(y)$	annual electricity generation at the location i and for the year y
$I_i(y)$	total installed capacity at location i and for the year y
p_i	production at the location i
p_{max}	maximum hydrogen production

Technical parameters

st_0, st_f	initial and final hydrogen conditions
$P^{st}, P^{st'}$	operating pressure
D_{travel}	annual average distance in km travelled by a person
$Pop_i(y)$	population at location i and for the year y
$p_{FCEV}(y)$	share of FCEV among total passenger cars for the year y
E_{H2}	proton exchange membrane (PEM) electrolyzer production rate
η	electrolyzer operation efficiency and total losses
HV_{H2}	heating value of hydrogen
$\dot{W}_{\Delta S \to 0}$	adiabatic work
η_C	compressor efficiency
$tt_{l/u}^{t}$	total loading (l) and unloading (u) time
$n_{r.t}^{t}$	maximum number of round trips
n_T^{t}	number of CGT
n_{driver}	number of drivers
S_a	average truck speed

Cost parameters

$\times$ C	total annual cost related to $\times$
$LCOH_\times$	levelized cost of hydrogen related to $\times$
CC $\times$	capital cost related to $\times$
$CRF_\times$	capital recovery factor related to $\times$
$CF_\times$	capacity factor related to $\times$
$O\,\&\,M_\times$	operations and maintenance related to $\times$
$OM_\times$	$O\,\&\,M_\times$ as a percentage of $CC_\times$
$n\times$	economical lifetime related to $\times$
i_{dr}	discount rate
TC	transportation cost
TCC	transportation capital cost
TOC	transportation operation cost
FC	fuel cost
LC	logistics cost
F_p	unit fuel cost
TC_{driver}	driver wage
CC	compression cost
CCC	compression capital cost
COC	compression operation cost
$c_T(st,st')$	cost of compressing hydrogen from P^{st} to $P^{st'}$
EC^{st}	annual energy cost to operate a compressor
SC	storage cost
SCC	storage capital cost
SOC	storage operation cost

Among the promising alternatives for conventional fuel is the use of low-carbon hydrogen in fuel cell electric vehicles (FCEVs). Unlike electric cars, FCEVs can have a long range and a shorter charging time. Furthermore, hydrogen can also be a storage solution for excess electricity from renewable energy (RE) sources particularly onshore and offshore wind. In fact, the wind (on-shore and off-shore) installed capacity has grown by 40 GW in 2014 [3], increasing the electricity generation form renewable resources that accounted for more than 22% of the global generation [4].

However, the definition and installation of an adequate, cost-effective infrastructure is still one of the problems restricting its deployment as a feasible solution. Many solutions for the hydrogen supply chain are therefore likely to emerge, depending on hydrogen demand, regional resources, and the evolution of technologies – related to hydrogen production and consumption. Currently, the main objective is to improve economic feasibility by reducing the total cost of the total supply chain or by acting on different steps including production, storage, transportation, and distribution.

The optimization of a possible future hydrogen infrastructure has been the subject of research in different studies. The literature review shows examples of optimizing the total hydrogen infrastructure by (a) limiting the analysis to one method of hydrogen transportation and (b) investigating the different parts of hydrogen delivery pathways, including the stages of hydrogen production, storage, transmission, and distribution in separate studies.

Type (a) analyses focus on one method of hydrogen transportation, either via trucks or via a pipeline system [5,6]. In cases in which all transportation modes were taken into account, the geographical representation was omitted by restricting the study to a grid decomposition [7], or the geographical visualization was limited to either one region [8,9] or one country [10,11].

The cost effectiveness of the whole supply chain was often improved by analyzing only one part of the pathway (b) [12–15].

For instance, at the delivery mode, [13] developed models to identify the lowest-cost delivery mode and the results show that for road transportation, the compressed gas truck is used for small stations and very low demand, while liquid hydrogen is used for long distances and moderate demand. The optimum pressure at which hydrogen has to be delivered was analyzed as well, investigating mainly pressure at 350, 500 and 700 bar [16]. The results showed that for FCEVs operating at 700 bar nominal working pressure, lowering the delivered hydrogen pressure (DHP reduces the cost associated to the delivery infrastructure but impacts on the FCEV driving range and the refuelling frequency).

The production pathway was analysed as welly by investigating the reduction of energy needs in industrial electrolyzers [12]. A dynamic model was developed in another study to determine the performance and the cost of an electrolyzer plant purchasing electricity and selling hydrogen in the wholesale market under the Swiss regulatory context