Green Hydrogen Supply Chain Network Design for Aviation: Model Development and Case Study for German Airports in 2050.

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Abstract. Hydrogen-based propulsion concepts for aircraft are considered a promising technology towards the decarbonization of aviation. While the development of respective aircraft models is in progress, questions regarding the supply network of green hydrogen are arising. We present a formulation of the hydrogen supply chain network (HSCN) design problem that focuses on the aviation sector. The mixed-integer linear programming model minimizes the total cost of hydrogen supply by deciding on locations, capacities, transportation modes and flows. The respective supply chain starts with the generation of renewable electricity used in the electrolysis of water. The gas hydrogen obtained from this process is liquefied before being used to refuel the aircraft. Moreover, various transportation and storage processes for gas and liquid hydrogen are involved between the electrolyzers and the airports. Our model formulation considers the spatially dispersed availability of renewable electricity, the techno-economic characteristics of hydrogen storage, liquefaction and transportation (e.g., economies of scale), as well as the specific requirements of hydrogen handling (e.g., losses). The application is illustrated for Germany in 2050, considering the hydrogen pipeline backbone projection. Optimal network design and results are presented.

Keywords: HSCN Design · MILP · Hydrogen · Aviation

1 Introduction

The aviation sector was responsible for about 0.9 Gt (3%) of total global carbon dioxide (CO_2) emissions in 2019 and it is expected to rise to 1.5-2 Gt in 2050 [**?**]. However, the aviation industry targets to achieve net zero CO_2 emission of flight operations [**?**]. The use of hydrogen as fuel in aircraft can reduce CO_2 emissions of flight operations by 100% and overall climate impact (including

CO_2 and non-CO_2 emissions) by 90% [?]. Therefore, it is considered by academia and civil aviation organizations to be one of the most important energy carriers for aviation's future, as a direct fuel (the concern of this study) or feedstock for the synfuels [?,?,?]. Companies and research institutions are working towards the future widespread use of hydrogen-fueled aircraft. First demonstrations of short-range small-sized hydrogen-fueled aircraft have been completed [?]. Furthermore, Airbus aims to introduce the first commercial hydrogen-fueled airplane in 2035 and targets widespread use by 2050 [?]. With measures being taken to achieve aviation's net zero target (in flight operations) and the spread of hydrogen-fueled aircraft, aviation's need for hydrogen will increase to significant levels. In 2021, global green hydrogen production was 1.2 Mt for all sectors, whereas the green hydrogen demand of the aviation sector alone is projected to range between 20 Mt and 42 Mt in 2050 according to [?] and [?]. This drastic projected increase in green hydrogen demand requires the development of effective supply chain structures. Therefore, green hydrogen supply infrastructure and distribution networks have become a key research focus for green aviation. Although it is a sustainable fuel, green hydrogen is more costly to produce and distribute than conventional fuels. For the net zero carbon emissions strategy in aviation to be viable, hydrogen must also be cost-competitive. Hence, a cost-effective end-to-end HSCN needs to be designed. To this end, this study attempts to design an HSCN to minimize cost over a given geography and time.

2 Problem Description

The hydrogen supply chain for aviation contains production, liquefaction, storage and transportation stages. Production is the process of electrolyzing water using green electricity to produce gas hydrogen. Unlike many other sectors, the hydrogen demand for aviation is in the liquid form due to the low energy density of gas hydrogen. Therefore, the gas hydrogen produced must be liquified to avoid supersized aircraft fuel tanks. Gas storage tanks are used for the gas form and cryogenic tanks are used for the liquid form to keep it below -253 °C. While transporting liquid hydrogen in pipelines is not feasible over long distances, transporting gas hydrogen in trucks is economically disadvantageous. Our problem can be generically modeled as a network as in Figure 1. The hydrogen flow passes through hydrogen production, gas storage, liquefaction, liquid storage and reaches the airports. Storage and liquefaction facilities can locate at the suppliers and/or airports. Apart from the suppliers and airports, the facilities do not operate elsewhere. Throughout the network, hydrogen exists in the gas form up to the liquefaction stage and in the liquid form thereafter. Truck and pipeline modes are used for transportation. Pipeline utilization is differentiated as the use of existing or newly installed pipelines. If the existing hydrogen pipelines are used, the transportation cost is the service fee for using it determined by the network operator. If aviation-specific pipelines are installed and used, the transportation cost is calculated considering all capital expenditures (CapEx) and operational expenditures (OpEx). New pipelines can be installed

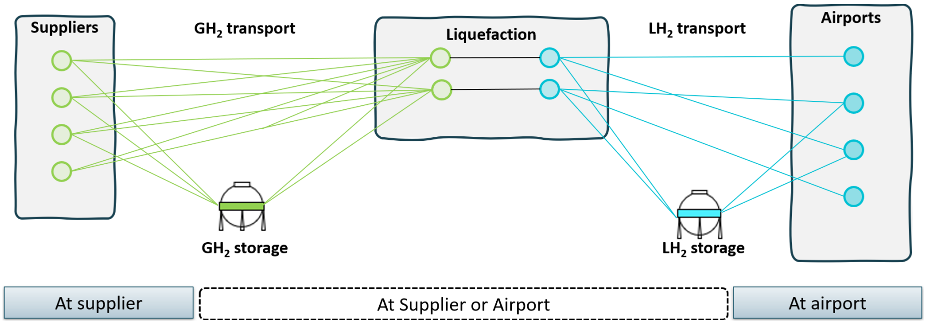

Fig. 1. Generic network model

on 3 routes: supplier-to-supplier junction (closest point to the supply node on the existing infrastructure), airport-to-airport junction (closest point to the airport on the existing infrastructure) and supplier-to-airport. Namely, if existing pipelines do not pass directly through the suppliers/airports, they can still be utilized by installing new pipelines between junctions and suppliers/airports. Junctions add no cost but rather help to design a cost-effective network.

The problem is an HSCN design problem involving hydrogen and aviation specifications. We aim to decide on facility locations and capacities, transportation modes and hydrogen flows while minimizing the network cost. The problem is approached from a system perspective, which means the cost minimization of the entire network, not just of one player (airport, transporter, etc.). Literature includes numerous related supply chain network design research for hydrogen and other applications. Almansoori et al. [**?**] designed cost-minimized hydrogen networks for road transportation in Germany considering various carbon emission and tax scenarios. Lahnaoui et al. [**?**] attempted to design a network consisting of wind farms, hydrogen production plants and distribution hubs to serve road transportation in France and Germany considering various demand scenarios. Üster et al. [**?**] designed an optimal natural gas pipeline network by extending existing infrastructure for Turkey's case. Our study differs from others in the literature in that it includes aviation industry requirements (liquid demand), takes into account losses on the road and in the processes, and includes different transportation methods (truck, existing and new pipelines) in a single study.

3 Mathematical Model

In this section, we present our mathematical model which combines network design, and the distribution of hydrogen. The underlying graph $G = (V, A)$ consists of nodes $V = D \cup S \cup N$ for airports D, suppliers S, and set N containing liquefaction plants, storage tanks, and junction points, as well as directed edges A for pipelines and truck services. A node $(v, i) \in V$ is a facility v with a specific configuration $i \in \varGamma_v$ which has a capacity $w\colon (V, \varGamma) \to \mathbb{R}_{\geq 0}$, CapEx, and OpEx.

Decision variables $x_{v,i} \in \{0,1\}$ indicate that a node is opened. For a facility v, only one configuration $i \in \mathit{\Gamma}_v$ can be used, i.e., $\sum_{i \in \mathit{\Gamma}_v} x_{v,i} \leq 1$. Further, $\mathit{\Delta}$ contains a set $\mathit{\Delta}_a$ defining all transport services with different configurations for any connection $a \in A$. Each such edge configuration $(a,j) \in (A, \mathit{\Delta})$ provides a maximum capacity $u \colon (A, \mathit{\Delta}) \to \mathbb{R}_{\geq 0}$, CapEx, and OpEx.

A pipeline connection $a \in A$, $j \in \mathit{\Delta}_a^p$ has a binary decision option, whereas a truck connection $a \in A$, $j \in \mathit{\Delta}_a^t$ offers a scalable service,

$$y_{a,j} \in \begin{cases} \{0,1\} & j \in \mathit{\Delta}_a^p \\ \mathbb{Z}_{\geq 0} & j \in \mathit{\Delta}_a^t \end{cases}$$

for every connection $a \in A$.

The demand at nodes is given by $d \colon V \to \mathbb{R}$ with $d(v) > 0$ for sinks (airports), $d(v) < 0$ for sources (suppliers), and $d(v) = 0$ otherwise. We assume oversupply, i.e., $\sum_{v \in V} d(v) \leq 0$, such that any demand of the airports can be satisfied.

The clear separation of gas and liquid network components allows the use of a single-commodity flow $h_{a,j} \in \mathbb{R}_{\geq 0}$ which represents the amount of either gas or liquid hydrogen initially entering an edge.

As hydrogen is a volatile substance, the flow in our model is subject to loss during its transportation, reloading, and even storage which is covered by $\lambda^1 \colon (A, \mathit{\Delta}) \to [0,1]$ and $\lambda^2 \colon V \to [0,1]$. We obtain a general flow conservation within our network with excess

$$\mathrm{ex}_h(v) := \lambda^2(v) \sum_{(a,j) \in \delta^+(v)} \lambda^1(a,j) \cdot h_{a,j} - \sum_{(a,j) \in \delta^-(v)} h_{a,j} \begin{cases} = & d(v) & v \in D \\ \geq & d(v) & v \in S \\ = & 0 & \text{else} \end{cases}$$

which is weak at sources (due to oversupply) and strict otherwise for ingoing edges $\delta^+(v)$ and outgoing edges $\delta^-(v)$ at node $v \in V$.

The linear function $C(h,x,y)$ includes all costs which accrue for designing and operating the hydrogen supply network,

$$\begin{aligned} C(h,x,y) = & \sum_{a \in A, j \in \mathit{\Delta}_a^p} c_h^1(a,j) \cdot h_{a,j} + \sum_{a \in A, j \in \mathit{\Delta}_a^t} c_h^1(a,j) \cdot y_{a,j} \\ & + \sum_{v \in V, i \in \mathit{\Gamma}_v} c_h^2(v,i) \left(\sum_{a \in \delta^+(v), j \in \mathit{\Delta}_a} \lambda^1(a,j) \cdot h_{a,j} \right) \\ & + \sum_{v \in V, i \in \mathit{\Gamma}_v} c_x(v,i) \cdot x_{v,i} + \sum_{a \in A, j \in \mathit{\Delta}_a} c_y(a,j) \cdot y_{a,j} \end{aligned}$$

with four types of cost parameters. The parameters c_h^1 and c_h^2 include all costs for edges and nodes, respectively, which depend on the amount of hydrogen processed. The parameters c_x and c_y cover all costs for nodes and edges, respectively, which are independent of the hydrogen flow.

Our problem can be modeled as a mixed integer linear program as follows

$$
\begin{aligned}
\min_{h,x,y}\; & C(h,x,y) \\
\text{s.t.}\quad & \mathrm{ex}_h(v) = d(v) && v \in D \\
& \mathrm{ex}_h(v) \geq d(v) && v \in S \\
& \mathrm{ex}_h(v) = 0 && v \in N \\
& \sum_{(a,j)\in\delta^+(v)} \lambda^1(a,j)\cdot h_{a,j} \leq \sum_{i\in\mathit{\Gamma}_v} w(v,i)\cdot x_{v,i} && v \in V \\
& \sum_{i\in\mathit{\Gamma}_v} x_{v,i} \leq 1 && v \in V \\
& h_{a,j} \leq u(a,j)\cdot y_{a,j} && a \in A,\ j \in \mathit{\Delta}_a \\
& x_{v,i} \in \{0,1\} && v \in V,\ i \in \mathit{\Gamma}_v \\
& y_{a,j} \in \{0,1\} && a \in A,\ j \in \mathit{\Delta}_a^p \\
& y_{a,j} \in \mathbb{Z}_{\geq 0} && a \in A,\ j \in \mathit{\Delta}_a^t \\
& h_{a,j} \geq 0 && a \in A,\ j \in \mathit{\Delta}_a
\end{aligned}
$$

4 Case Study and Results

In the case study, we design a hydrogen network for Germany and the year 2050. We consider 16 German states as hydrogen suppliers and for simplicity, the geographical center of them are accepted as exact locations. Taking into account the changing climatic conditions for renewable energy sources in the states and the power grid infrastructure across Germany, the cost of supplying green electricity is calculated in each state. The cost of producing gas hydrogen from this electricity is then calculated for each state. In this phase of the research, it is assumed that aviation's green hydrogen demand can be met without any production capacity constraints. Production cost and techno-economic data are provided by researchers from the HyNEAT project [**?**], of which this study is a part. The 23 largest German airports, which account for 99.7% of air traffic in terms of passenger numbers [**?**], are taken as demand nodes.

The strategic hydrogen pipeline projection from [**?**] that is available to all sectors is used as the existing backbone. Aviation-specific new pipeline extensions can be decided by the mathematical model. This backbone has been mapped on QGIS along with airports and suppliers, and then coordinates of supplier and airport junctions have been determined. The distances between all nodes are calculated and then used to calculate the transportation cost. Since economically more efficient, gas hydrogen can only be transported in pipelines and liquid hydrogen in trucks. We implemented and solved our model with Python 3.11, SCIP 8.0.3, and Gurobi 10.0.2. Figure 2 presents a high-level network design and shows supplier selection and employed transportation modes. The results show that only 6 suppliers supply all airports. This results in each airport not being able to source from the nearest and cheapest supplier even though it is inclined to do so, but the economies of scale effect of consolidating the demand of multiple airports into a single supplier minimizes the total cost of the network. We observe that the supply to the airport is mostly done by installing new pipelines

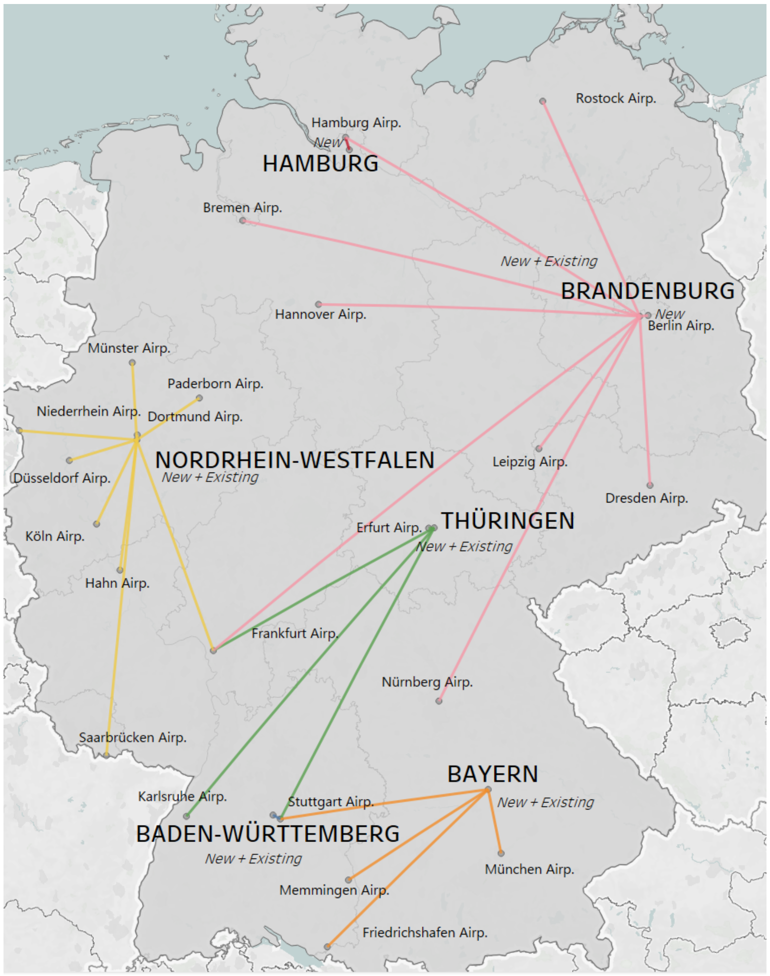

Fig. 2. H_2 Network illustration for Germany

to junctions and using the existing pipeline, only between Hamburg-Hamburg Airport and Brandenburg-Berlin Airport new pipelines are installed directly. No truck mode is used in the network, which we can attribute to the advanced infrastructure of the projected pipeline, high truck fuel cost and driver salary. We also found that the two cheapest suppliers are not included in the network, but suppliers in airport-dense areas are included, despite producing more costly hydrogen. To conclude, the case study indicates that cost-efficient networks are characterized by using suppliers in airport-dense areas, piping hydrogen to airports in gas form and liquefying it there. For future work, we examine how green electricity/hydrogen supply capacity constraints, import options and use of hydrogen in synfuel production affect the network. Besides, we formulate a multi-period model with a multi-objective function including environmental factors such as life cycle emissions in addition to the current cost minimization.

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