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Evaluation of Hydrogen Transportation Networks  
- A Case Study on the German Energy System

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Abstract:

Not only due to the energy crisis European policymakers are exploring options to substitute natural gas with renewable hydrogen. A condition for the application of hydrogen is a functioning logistic chain. However, researchers are still discussing the most efficient way to transport large hydrogen quantities. A promising option is to convert the existing natural gas infrastructure, but technical and economical evaluation and comparison of converted transportation networks are missing. This study presents a novel approach to develop hydrogen networks by applying the Steiner tree algorithm to derive candidates and evaluate their costs. This method uses the existing grid (brownfield) and is compared to a newly built grid (greenfield).

The methodology is applied to the German gas grid and demand and supply scenarios covering the industry, heavy-duty transport, power, and heating sector, imports, and domestic production. Five brownfield candidates are compared to a greenfield candidate. The candidates differ by network length and pipeline diameters to consider the transported volume of hydrogen. The economic evaluation concludes that most brownfield candidates’ cost is significantly lower than of the greenfield candidate. The candidates can serve as starting points for flow simulations and policymakers can estimate the cost based on the results.

Keywords: Hydrogen Transportation Network, Steiner Tree Algorithm, Minimal Spanning Tree, Infrastructure Conversion, Conversion Cost Evaluation
1 Introduction

The Paris Agreement, signed by 192 countries, commits the countries to keep global warming well below 2.0 °C, preferable at 1.5°C [1]. The key to achieve this objective is to cut human-caused greenhouse gas emissions. A highly potent greenhouse gas used across all sectors is natural gas. A widely discussed substitute is green hydrogen [2,3]. Studies of greenhouse gas neutrality often see areas of application for hydrogen, regardless of the specific political policies [4–7]. Green hydrogen supports the implementation of sustainable and renewable energy systems [8–10]. Especially after 2030, the demand for green hydrogen will increase and become a relevant factor for energy supply and storage [10,11].

Sector coupling technologies, including the production of green hydrogen through electrolysis, are key to reduce emissions [12]. This requires, on the one hand, large-scale implementation of renewable energy sources and on the other a fundamental transition of current energy transportation infrastructure [14]. Studies have so far investigated various transport options for hydrogen i.e., by road, rail, ship, and pipeline [15–17]. The optimal transport option depends among others on the existing transportation conditions. Whenever a larger demand is assumed, transport via a pipeline system is considered the most economic option [14,18,19]. Cerniauskas et al. (2020) [20] investigated the possibility to re-utilize the existing natural gas pipeline infrastructure. They show, based on a spatial model for the hydrogen supply chain, that up to 80% of the existing gas grid can be technically reassigned. storages as part of a hydrogen transportation system are investigated by Zivar et al. (2021) [21]. They show that large energy storage in gas grids will be an important part of the system. Several studies show that salt caverns are advantageous to store large amounts of hydrogen [21–23].

Most studies so far concentrate on the hydrogen system without detailed transportation routes or grid design and hydrogen transportation infrastructure development is mentioned as a gap in the literature [24]. Existing analyses of transportation grids focused on single aspects of potential hydrogen grids only: Either analysis for single sectoral investigations or indications for the hydrogen grid topology.

A major part of the single sector studies sees the mobility sector as the key element for hydrogen demand. An example is Reuß et al. (2019) [25] with their analysis of various hydrogen transport options to supply the German mobility sector [18]. The transport sector is also a central element for the hydrogen grid in older studies by Baufumé et al. (2013) [25] or Krieg (2012) [26]. Based on GIS-data of fuelling stations the authors derived transmission network options for Germany. Krieg (2012) [26] also considers the existing natural gas network as an orientation for the topology of the hydrogen network. For short distance transport, these studies also consider trailers to supply the customers. A further study by Weber and Papageorgiu (2018) [27] focuses on a transmission grid to supply the mobility sector by using cost-based minimisation problem to derive the network. Tili et al. (2019) [28] focus on the mobility sector in France deriving a transportation grid based on the demand, different electrolysis locations, and usable hydrogen distribution grids.

Studies with a focus on several sectors often only indicate a possible hydrogen network. Husarek et al. (2021) consider different possible supply chains and import routes for the German hydrogen market and assume a supply via pipelines as the most reasonable option [29]. However, the grid is rather an abstract
net transfer capacity representation between regions within Germany than a detailed representation of a gas network [29]. The study only indicates where a hydrogen grid could be necessary. Welder et al. (2018) [30] derive a hydrogen grid for Germany by using a multi-nodal energy system optimization approach for a power-to-gas scenario. However, they only consider the mobility and industry sectors for hydrogen demand [30]. An analysis on a European level is provided by Caglayan et al (2021) [31]. The authors model the European energy system and consider a dedicated infrastructure for hydrogen. However, the results are more suitable for identifying an abstract network than for providing information about the concrete topology [31]. The European gas transmission operators provide an idea of a complete European hydrogen transportation grid [32]. They focus on the reassignment of major parts of the existing natural gas network. However, the concrete approach to derive the proposed so called “European Hydrogen Backbone” remains unclear.

Since the future demand for hydrogen depends on various parameters and sectors, the status quo of research does not provide a comprehensive picture. The single sector studies neglect demand by additional sectors and studies with a focus on several sectors lack of concrete hydrogen networks. Thus, there is a lack of a comprehensive, up-to-date approach to derive possible topologies for a hydrogen grid depending on scenarios for all supply and demand sectors and locations under a climate-neutral energy supply. The central question of this paper is which candidates exist for a hydrogen network considering several sectors, demand locations, and hydrogen volumes in the example of Germany.

This issue is addressed by proposing a novel procedure for the development of hydrogen grid infrastructure candidates and applying this approach to Germany as a case study. Therefore, the paper is structured as follows: In Section 2 possible scenarios for German hydrogen demand and supply per sector and implied locations are presented. This is followed by an overview of the applied method in Section 3 and the implementation, creating candidate topologies for a German energy system in Section 4.1 as well as their evaluation in Section 4.2. The paper finishes with a discussion of the results in Section 0 and the conclusion in Section 6.

2 Scenario Development for the German Energy System

In the last years, several studies have been published on how hydrogen is supplied and consumed in Germany [10,33–35]. Since the German government published the National Hydrogen Strategy in 2020, these interests are backed by a policy perspective [36]. Based on this information, a scenario for the future supply and demand of hydrogen can be developed to derive hydrogen network candidates. By assuming the use of hydrogen specific sectors, locations for supply and demand can be identified. These locations are then to be connected via the hydrogen grid and build the foundation for developing hydrogen grid candidates.

2.1 Hydrogen supply

Regarding the hydrogen supply, two options are distinguished: import or domestic production [10]. For Germany, the majority of hydrogen will be imported, potentially from the Netherlands, the UK, Norway and Iceland [10] but also national electrolysis is expected. In Prognos et al. (2021) [33], it is assumed that Germany produces 31 % of the hydrogen required domestically and imports 69 %. The location of
electrolyzers is still a matter of debate and therefore assumptions need to be made. This paper assumes that domestic production will take place at locations where a large surplus flow of renewable energy in the power grid (residual load) is expected or where cavern storage facilities exist. Import is assumed at the current interconnector locations of the natural gas grid. The exact locations of renewable related are provided by Weyhing (2021) [37]. In this work, it is assumed to be worthwhile to operate an electrolyzer if the annual surplus electricity per grid node from renewable power production is greater than one TWh by the year 2030. Cavern storage and interconnector locations are taken from GIE [38] and ENTSO-G [39,40].

2.2 Demand by the industrial sector
Wietschel et al (2021), assume demand in steel production, ammonia synthesis, and ethylene production[10]. Prognos et al (2021) also anticipate high demand in industry, specifically in the production of paper, chemicals, pig iron and steel, other metals as well as petroleum processing [33]. Therefore, these sectors and locations are classified as future hydrogen demand. Locations of basic chemicals, petroleum refining, steel and raw metal manufacturing and synthetic fuel and ammonia production are derived from the DemandRegio project [41].

2.3 Demand by the power sector
It can be expected that hydrogen will be used as a long-term storage medium for electricity. Therefore, in Prognos et al (2021) electricity production demands the majority of hydrogen [33]. Furthermore, combined heat and power production might represent a consumer in the future, to ensure district heating. Thus, it is likely that the electricity sector demands hydrogen in the future. Demand locations of the electricity sector are assumed to be located wherever an electrolyzer or storage is located. This data is derived from Weyhing (2021) [37] and ENTSO-G [39,40].

2.4 Demand by the transport sector
In the transport sector, there is great uncertainty in the application of hydrogen. As shown by Wietschel et al. (2021) [10], various studies analyze a potential role of hydrogen, but not in the same range. However, the use of hydrogen or hydrogen derivatives in the aviation and shipping sector can be considered certain. Further, the application of hydrogen in heavy duty transport is likely. Conclusively, Wietschel et al. (2021) and Prognos et al. (2021) [10,33] expect the demand for hydrogen to increase here. Regarding passenger cars, hydrogen application is unlikely as the positive aspects of direct electrification outweigh the disadvantages [33]. Thus, for the simulation, fuel stations for heavy duty transport are considered as modelled by Rose et al (2020) [42]. Due to a lack of information on locations for aviation and shipping, it is considered that these production facilities will correlate with the expected locations of electrolyzers as discussed above.

2.5 Demand by the heating sector
There are several options for decarbonizing the residential and commercial heating sector, such as the use of heat pumps. Gerhardt et al (2020) [35] conclude that it is cheaper and more efficient to use heat pumps for residential heating than hydrogen, which is backed by Prognos et al. (2021) [33]. Therefore, no hydrogen demand from the heating sector (decentral heating by households) is considered.
2.6 Summary

All in all, four types of locations are considered. First, supply locations via import or from local production. Second, demand locations from the industry sector as stated above. Third, demand locations from the electricity sector as they are associated with locations, where hydrogen will be also produced locally and finally locations for hydrogen demand from the transport sector, hence for shipping, aviation and heavy-duty trucks.

3 Approach

The approach to derive and evaluate hydrogen network candidates is divided into four steps (Figure 1). The first step is to identify a scenario and thus locations for a specific region. The locations (and a given grid for the brownfield approach) are used to derive terminal nodes and, in the third step, identify possible network candidates by applying the Steiner tree algorithm [42] using different weights. In the fourth step, the candidates are evaluated based on economic parameters.

The Steiner tree algorithm is a specification of the minimum spanning tree using the shortest path. The used graph $G(V,E,w)$ with his vertices ($V$), edges ($E$), and weights ($w$) needs to be undirected, loop free, without parallel edges and with no negative weights. Furthermore, terminals ($t$, vertices that must be included in the network) are a subset of all vertices. A Steiner tree is a subgraph $T_G(t)$ where all terminals are connected. In Steiner trees, the vertices that are not terminals are called Steiner points. The Steiner tree algorithm finds a minimal Steiner tree by minimizing the sum of the weights, which can be understood as the objective of a minimization problem [43–45].

Thus, the Steiner tree algorithm requires a given set of terminals from a given graph (network) and a predefined objective function. The underlying graph in this case is the current natural gas transport infrastructure in Germany and the terminal vertices are relevant production and demand locations derived from the scenario development. Figure 1 gives an overview of the process.

![Figure 1: Four-step-approach to derive and evaluate hydrogen network candidates](image)
3.1 Development of Terminals

In the first step, a set of terminals is derived and mapped to the corresponding locations of the associated gas network nodes. For all datasets, the location needs to be defined in the form of coordinates. For the locations of heavy-duty transport, coordinates are not given [42]. Here, the original data contains the names of the highway intersections of the locations and these need to be assigned manually. In the case of the other sectors, the input data provides the coordinates.

3.2 Development of Candidates

In general, two methods for developing network candidates can be distinguished: a brownfield and a greenfield approach. The first refers to a development based on an existing system, in this case, based on the existing natural gas transport pipeline system. The latter creates a completely new system, in this case designing a completely new hydrogen pipeline transport system.

3.2.1 The Brownfield Approach

The brownfield approach assumes that the natural gas transport network can be repurposed for hydrogen transport. The overall cheapest option is to reuse the pipelines without modification, which, however, results in higher maintenance and repair costs than with adaptations [20]. Other alternatives as described by Cerniauskas et al. (2020) are not considered, since the costs of excavating the pipeline cannot be estimated nor can a risk assessment of the admixture of inhibitors be done [20]. In addition, the costs for inhibition admixture estimated by Cerniauskas et al. (2020) are higher than those using pipelines without modification [20].

Figure 2: The used gas transportation network and terminal nodes derived from the scenario

With the assumption of conversion, the existing network can be used as the basis for the Steiner tree algorithm. For the correct use of the algorithm, an undirected graph without parallel edges and negative
weights must be given. For this purpose, the transport network for Germany is taken from KonStGas [46] and further improvements are provided by the MathEnergy project [47], (see Figure 2). More details on the topology data in the form of point data are available in the supplementary material. As a further prerequisite of the Steiner tree algorithm, there must be a set of terminals that is a subset of the nodes contained in the network. This is given by the terminals derived in Section 3.1 and illustrated in Figure 2.

Since the algorithm minimizes the weights of the edges, there is the possibility of determining different resulting networks (referred to as candidates) through different objectives. The objective can be divided into two characteristics that are required of a hydrogen infrastructure. On the one hand, the conversion should be as cost-efficient as possible. On the other, the needed volume of hydrogen should be considered. The volume is considered in the objectives by using volumetric parameters.

Two cost-related objectives are derived. Since costs are directly related to the length of the network, the shortest possible network could be advantageous. Therefore, the first objective is described simply by the length of the corresponding pipeline. Secondly, an investment objective is derived by considering the length and diameter of each edge by investment costs. Due to the assumption of converting the transport network without modification, the capital expenditures (CapEx) calculation of Cerniauskas et al. (2020) for conversion without modifications is used [20].

Two objectives consider the volume of hydrogen. The hydrogen network should be able to transport large quantities of hydrogen. First, the reciprocal value of the volume of the corresponding pipeline is used, as this favours a larger volume. Second, a penalty function for small diameters is applied. The length of a pipeline is the initial value of the objective function. If the diameter is smaller than 600 mm (the median and the average diameter of the pipelines in the existing transport network), it is penalised with an additional length of 5 km. The penalty function is based on an expert assessment.

Additionally, a fifth objective combines both requirements: the CapEx calculation of Cerniauskas et al. (2020) [20] divided by the volume of the pipeline. All five candidates and their corresponding objectives are listed in Table 1. The variable l refers to the length, whereas the variable d refers to the diameter.

3.2.2 The Greenfield Approach

The greenfield approach considers the construction of a dedicated hydrogen grid infrastructure. In contrast to the brownfield approach, the locations of the terminals as found in Figure 3 are not mapped to the gas network nodes. For the comparison to a new pipeline scenario (worst-case), the cheapest possible greenfield grid is considered. Thus, the straight-line distance between nodes is calculated to compute the length of edges. This assumes that new hydrogen pipelines can be laid everywhere without any complications. The complete graph with the straight-line distances as weights serves as the basis for the Kruskal algorithm to compute a minimum spanning tree, implemented using the networkx algorithm [48]. The result represents the last candidate to be evaluated. The diameter of the pipelines is approximated to be about 600 mm, as this is both the median and the average diameter of the pipelines in the existing gas network.
Figure 3: Exact locations of terminals derived from the scenario

Table 1: Overview of network candidates and objectives

<table>
<thead>
<tr>
<th>Type</th>
<th>Candidate</th>
<th>Objective</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brownfield</td>
<td>Length</td>
<td>$l$</td>
<td>E.1</td>
</tr>
<tr>
<td>Brownfield</td>
<td>Invest</td>
<td>$l \times (1.67 \times 10^{-4} \times d^2 - 2 \times 10^{-13} \times d - 7.8 \times 10^{-10})$</td>
<td>E.2</td>
</tr>
<tr>
<td>Brownfield</td>
<td>Reciprocal value of volume</td>
<td>$\frac{1}{\pi \times \left(\frac{d}{2}\right)^2 \times l}$</td>
<td>E.3</td>
</tr>
<tr>
<td>Brownfield</td>
<td>Penalty for small diameters</td>
<td>$l \forall \text{Diameter} &gt; 600 \text{ mm}$</td>
<td>E.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$l + 5 \text{ km} \forall \text{Diameter} \leq 600 \text{ mm}$</td>
<td></td>
</tr>
<tr>
<td>Brownfield</td>
<td>Invest / Volume</td>
<td>$\frac{1.67 \times 10^{-3} \times d^2 - 2 \times 10^{-13} \times d - 7.8 \times 10^{-10}}{\pi \times \left(\frac{d}{2}\right)^2 \times l}$</td>
<td>E.5</td>
</tr>
<tr>
<td>Greenfield</td>
<td>Greenfield</td>
<td>Straight line distance</td>
<td>E.6</td>
</tr>
</tbody>
</table>

3.3 Evaluation of Candidates

The evaluation of the candidates is primarily based on their cost. To assess these, cost information for new hydrogen pipelines (greenfield approach), for the conversion of existing natural gas pipelines (brownfield approach), as well as the costs for decommissioning of pipelines are needed (green and brownfield approach). Furthermore, next to the investment perspective, the operation costs need to be considered, as the cheapest grid from an investment perspective has not to be the cheapest overall. Therefore, operation and maintenance over the period of one year are also evaluated (green and
brownfield approach). Finally, the cost-based evaluation allows a selection of suitable networks for further analyses, which can determine the performance of the network under different hydrogen flow situations. The following Table 2 gives an overview of the used cost formulations.

Table 2: Cost formulas for evaluation

<table>
<thead>
<tr>
<th>Specific cost type</th>
<th>Formular</th>
<th>Equation</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>New pipeline:</td>
<td>( c_{\text{new}} = \frac{2,340,000 , \text{€}}{\text{km}} )</td>
<td>E.7</td>
<td>[49]</td>
</tr>
<tr>
<td>Pipeline conversion</td>
<td>( c_{\text{conversion}} = \frac{270,000 , \text{€}}{\text{km}} )</td>
<td>E.8</td>
<td>[49]</td>
</tr>
<tr>
<td>Decommissioning of pipelines</td>
<td>( c_{\text{decommissioning}} = \frac{113,000 , \text{€}}{\text{km}} )</td>
<td>E.9</td>
<td>[50]</td>
</tr>
<tr>
<td>Operation and Maintenance</td>
<td>( c_{\text{operation/a}} = \text{OPEX}<em>{\text{fixed}} + \text{OPEX}</em>{\text{variable}} )</td>
<td>E.10</td>
<td>[20]</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>= 1000 \cdot \left( [1.1 \cdot 10^{-4} \cdot d^2 - 1.6 \cdot 10^{-2} \cdot d + 2] \right.</td>
<td>E.10</td>
<td>[20]</td>
</tr>
<tr>
<td></td>
<td>+ \left. [1 \cdot 10^{-4} \cdot d^2 - 1.5 \cdot 10^{-12} \cdot d - 2.9 \cdot 10^{-10}] \right) \frac{\text{€}}{\text{km}}</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

For the final evaluation, the costs are multiplied by the corresponding lengths of newly constructed, decommissioned, or converted pipelines of the candidates and summed up. Table 3 gives an overview of the resulting parameters. Costs for new pipelines are only considered for the greenfield approach, conversion costs respectively only for the brownfield. Decommissioning is considered in both cases, with greenfield leading to a full decommissioning of the existing grid, as well as operation and maintenance costs. For the operation and maintenance costs, a residual life of 20 years is assumed, and the greenfield approach considers an average diameter of 600 mm and the maximal mode of the diameter classes of the brownfield candidates.
Table 3: Evaluation formulas for absolute cost

<table>
<thead>
<tr>
<th>Absolute cost type (for candidate n)</th>
<th>Formular</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absolute new pipeline costs</td>
<td>$C_{new,n} = c_{new} \cdot l_n$</td>
<td>E.11</td>
</tr>
<tr>
<td>Absolute pipeline conversion costs</td>
<td>$C_{conversion,n} = c_{conversion} \cdot l_n$</td>
<td>E.12</td>
</tr>
<tr>
<td>Absolute decommissioning costs</td>
<td>$C_{decommissioning,n} = c_{decommissioning} \cdot (l_{existing network} - l_n)$</td>
<td>E.13</td>
</tr>
<tr>
<td>Absolute operation costs</td>
<td>$C_{operation,n} = c_{operation} \cdot l_n$</td>
<td>E.14</td>
</tr>
<tr>
<td>Absolute overall costs</td>
<td>$C_n = C_{new,n} + C_{conversion,n} + C_{decommissioning,n} + C_{operation,n}$</td>
<td>E.15</td>
</tr>
</tbody>
</table>

4 Results

In the following, the results are presented. First, the candidates are presented. Second, they are compared to each other, and an evaluation is given. More details on the topology data of the different network candidates in the form of point data are available in the supplementary material.

4.1 Candidates

The six candidates are visualised in Figure 4. The thickness of the pipelines represents the underlying diameters of the grid. Visualisations of subgraphs A and B, where the cost-based candidates are presented, show a tendency towards smaller diameters. On the contrary, subfigures C and D show a tendency towards bigger diameters, which correlates with their objectives giving more importance to the security of supply. The candidate Investment/Volume (subfigure E) represents a mixture of the candidates. Lastly, the Greenfield candidate in subfigure F stands out of the norm because of its uniform diameter, which was manually set to 600 mm, and a single connection from east to west in the North of Germany.

Generally, one must consider, that if mainly small diameters are chosen in a network, this could be an indicator that the feasibility of flow simulations is not guaranteed. This applies particularly, if one assumes that, in the case of Germany, the infrastructure not only fulfils the task of domestic supply, but also transit requirements. However, this should be analysed in further studies.
To make a preliminary assessment of the feasibility of a possible flow of a network, the distribution of the diameters of the brownfield candidates is shown in Figure 5 (greenfield all 600mm). The cost-based candidates Length and Invest are, as expected, comparatively short with 10,437 km respectively 11,268 km. Thus, around one-third of the existing grid is converted leaving two-thirds to be decommissioned. Overall, the cost-based candidates tend to select smaller diameters which might limit the usability of these candidates in real flow situations. The longest network has the candidate Reciprocal Value of Volume with an overall length of 14,619 km, which means that half of the existing network is converted. The candidate Penalty for Small Diameters is shorter than the candidate Invest with a length of 10,810 km. Most of the diameters are between 400 to 1000 mm, which makes this a promising, potentially cost-efficient candidate considering possible hydrogen volumes. To some extent, the objectives consider the volume of hydrogen show successful results, as larger diameters increase the likelihood that the supply can be secured, and Germany could also function as a transit country for Europe. This is especially the case for the last brownfield candidate Investment/Volume, where both elements, cost, and volume of

**Figure 4: Derived Candidates of possible hydrogen transportation grids**
hydrogen, are included in the objective. This leads to a relatively long network of 12,241 km including large diameters, such as the transit pipelines.

![Figure 5: Length of the different derived brownfield candidates by diameter](image)

The Greenfield candidate stands out mainly because of its short length of only 6,678 km. As described in Section 3.2.2 no geographic condition was considered in the creation of this candidate making it a relatively conservative benchmark. Therefore, this approach also allows pipelines through neighbouring countries if this is considered the shortest path. With only two east-west connections in the north of Germany, the transportation of hydrogen from southeast to southwest may not be ensured. In addition, in the area where the important transit pipelines are located, there are no continuous connections, e.g., in the northeast and the south. In the case of Germany being a transit country, this could lead to a situation in which no hydrogen could be transported in these areas.

**4.2 Candidate Evaluation**

The cost-based evaluation for each candidate is done based on their length and diameter distribution. The result of the methodology described in Section 3.3 is listed in Table 4 where the four cost components are listed for each candidate.

The biggest cost components for the brownfield candidates are the conversion cost and for the Greenfield candidate the new construction cost. The costs of new pipeline construction are greater by a factor of 8.6, which results in significantly greater costs for the Greenfield candidate despite a 36 % shorter network than the shortest brownfield candidate. Moreover, one can see a negative correlation between the conversion and decommissioning costs since they depend on the length of the candidate. The Greenfield candidate stands out, where the entire network must be decommissioned. At a cost of over three billion Euros, this cost is significant accounting for 18.62 % of the total cost associated with the candidate.
The last cost component, costs of operations and maintenance, depends on both the length of the pipeline and the diameter of the pipelines included in the candidate. Therefore, it is not surprising that candidate Invest is the most favourable of the brownfield candidates since the objective takes both factors into account. The high cost of the two candidates Reciprocal value of volume and Investment/Volume correlate with the selection of pipelines with large diameters. The low cost of the Greenfield candidate can be explained by the assumption of a uniform diameter of 600 mm. In the case of a higher mean diameter of 900 mm, the costs of operation and maintenance are doubled.

The following rating in Table 5 results from the sum of the cost components. In general, the two cost-based candidates are the least costly, while candidate Length is the cheapest. The total cost of candidates Length (10,436 km) Penalty for small diameters and Invest (11,238 km) are within the same range. The costs of the candidate Reciprocal Value of Volume are above Length and Invest. The candidate Greenfield shows total cost within the range of Invest / Volume but if the higher diameter is considered to cost increase and is within the range of the candidate Penalty for small diameters. The diameter and consequently the volume of hydrogen is a central factor concerning the total cost and even though the candidate Greenfield is the shortest it can be one of the most expensive ones.
### Table 5: Rating of the different derived network candidates

<table>
<thead>
<tr>
<th>Rating</th>
<th>Candidate</th>
<th>Type</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Length</td>
<td>Brownfield</td>
<td>21,529 M€</td>
</tr>
<tr>
<td>2</td>
<td>Invest</td>
<td>Brownfield</td>
<td>24,219 M€</td>
</tr>
<tr>
<td>3</td>
<td>Invest / Volume</td>
<td>Brownfield</td>
<td>28,018 M€</td>
</tr>
<tr>
<td>4</td>
<td>Greenfield (600 mm)</td>
<td>Greenfield</td>
<td>28,386 M€</td>
</tr>
<tr>
<td>5</td>
<td>Reciprocal Value of Volume</td>
<td>Brownfield</td>
<td>33,502 M€</td>
</tr>
<tr>
<td>6</td>
<td>Greenfield (900 mm)</td>
<td>Greenfield</td>
<td>40,366 M€</td>
</tr>
<tr>
<td>7</td>
<td>Penalty for Small Diameters</td>
<td>Brownfield</td>
<td>41,315 M€</td>
</tr>
</tbody>
</table>

### 5 Discussion & Conclusion

As shown in Section 4, the presented method can successfully be applied to create potential hydrogen network candidates based on forecasts of demand and supply as well as an existing natural gas grid. Furthermore, it is obvious from the results, that the usage of the existing grid is beneficial in the case study of Germany, as the differences in cost are overwhelming. However, some limits need to be discussed concerning the analysis and results.

The presented method allows for the creation of brownfield and greenfield candidates for a specific region. The advantage of this approach is the possibility to compare both results, as all candidates are created based on the same input parameters but using different objectives for the Steiner tree algorithm. A limitation of the approach is, that it does not guarantee that the presented candidates can fully fulfil the supply task. The volume of hydrogen is considered in some of the objectives but does not allow a conclusion on whether the supply can be guaranteed at all times. This aspect can be addressed by further flow calculations using the candidates. However, the method fulfils its goals of presenting different candidates, which can be discussed by decision makers and further analysed in detail.

Furthermore, the method allows for using different objectives including the volume of hydrogen for the Steiner tree algorithm increases the likelihood to derive candidates that fulfil the demand at all times and support the security of supply. The results show, that applying these objectives leads to grids with on average higher diameters, while cost based weights lead to candidates with smaller diameters.

Regarding the results for the Greenfield candidate, the assumption is made, that all pipelines have a diameter of 600 mm or 900 mm, and costs are corresponding. Although this seems to be a useful approximation as of today, if more information on possible diameters is accessible, the cost calculation of the Greenfield candidate can be made more specific. However, from the analysis, it becomes clear, that using the existing infrastructure will be more cost effective in most cases than creating a whole new network. Nevertheless, the method as presented here does not allow for a mixture of green and brownfield approaches. The results indicate that the Greenfield candidate is not always the most
expensive and that a mixture of approaches may offer a better solution. As most hydrogen demand will be linked to the grid at existing natural gas grid connection points (due to the substitution of existing demand of natural gas by hydrogen), this seems not to be a major weakness of the method and the Greenfield candidate can be understood more likely as a benchmark candidate for a worst case (no existing grid to be used at a region).

Lastly, it must be stated that the method aims for a minimum spanning tree, not considering a redundant structure of the new hydrogen grid. This can be problematic regarding the security of supply. However, this can be overcome in practice by using two parallel pipelines instead of one where it is useful.

Thus, the key findings concerning the procedure applied in this work can be summarised as follows. By employing brownfield approaches, networks can be tailored to particular needs by choosing specific objectives. Moreover, green and brownfield approaches and their associated candidates can be compared successfully within the framework of this method, showing in the case study a dominance of brownfield approaches regarding cost effectiveness.

6 Outlook

From the discussion, further research questions can be derived. First, a more detailed procedure could be taken for the greenfield approach. For example, the Euclidean Steiner tree algorithm proposed by GeoSteiner [51] could be applied to develop a greenfield candidate, that might be even shorter. However, this is likely to require considerably more computational effort. In addition to that, taking into account interactions with geological constraints, as done by Krieg (2012) [26] could give a better approximation of the cost for the greenfield approach. Considering the brownfield approach, it would be interesting to compare different conversion options, e.g. coating of surfaces or the admixture of inhibitors, and get an approximation of their costs for conversion [20]. Besides that, a candidate that combines new construction of pipelines and conversion of the existing grid is not yet implemented in the methodology but would be an interesting topic for further research. The most relevant research question following the development of candidates is to evaluate their feasibility through flow calculations.

Lastly, the procedure developed in this paper is not only applicable to Germany but can be extended to other regions through customization. This requires a region-specific scenario development, in which the site selection for production and demand, as well as an estimate for the cost variables, is done. With the results, it is possible to develop network candidates and estimate the magnitude of the cost through the methodology. To complete the analysis, the candidates can serve as a basis for further flow calculations to assess their feasibility.

7 Author Contributions

This paper is based on the results of analysis from FvMR, supported by findings from JG and BG. The methodological approach was developed by FvMR with the support of SS, BG, and JG. The data to derive and evaluate the network candidates were gathered by FvMR together with JG and BG. The code base was developed and improved by FvMR with the support of SS and DR. The writing process was coordinated by FvMR and the paper was written by FvMR, JG and, BG with the contributions of DR.
The visualizations were created by FvMR and JG. The writing and editing process was further supported by ME. The research process was initiated by BG, JG, SS, and JMK. All authors have read and agreed to the version of the manuscript.

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10 Literature


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