Evaluation of Hydrogen Transportation Networks

A Case Study on the German Energy System

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Evaluation of hydrogen transportation networks - A case study on the German energy system

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A B S T R A C T

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 transportation infrastructure. However, the most efficient transport of large hydrogen quantities is still unclear, and deeper analyses are missing. A promising option is converting the existing gas infrastructure. 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 goal is the technical and economic evaluation and comparison of hydrogen network candidates.

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 those of the greenfield candidate. The candidates can serve as starting points for flow simulations, and policymakers can estimate the cost based on the results.

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 implementing sustainable and renewable energy systems [8–10]. Especially after 2030, the demand for green hydrogen will increase and become relevant for energy supply and storage [12, 11].

Sector coupling technologies, including the production of green hydrogen through electrolysis, are key to reduce emissions [13]. Green hydrogen requires, on the one hand, the large-scale implementation of renewable energy sources and, on the other hand, a fundamental transition of the 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 greater demand is assumed, transport via a pipeline system is considered the most economical option [14,18,19]. Cerniauskas et al. (2020) [20] investigated the possibility of re-utilise the existing natural gas pipeline infrastructure. Based on a spatial model for the hydrogen supply chain, they show that converting up to 80% of the existing gas grid is technically possible. Further, Zivar et al. (2021) investigate storage as part of a hydrogen transportation system [21]. They show that large energy storage in gas grids will be an important system element. Several studies show that salt caverns are advantageous for storing large amounts of hydrogen [21–23].

Most studies 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].

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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 Reuβ et al. (2019) analysing 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]. The authors derive transmission network options for Germany based on the GIS data of fuelling stations. 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 using a cost-based minimisation problem to derive the network. Tlili et al. (2019) [28] focus on the mobility sector in France, deriving a transportation grid based on the demand, different electrolysis locations, and useable hydrogen distribution grids.

Studies focusing 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 optimisation approach for a power-to-gas scenario. However, they only consider the mobility and industry sectors for hydrogen demand [30]. Caglayan et al. provide an analysis on a European level (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 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 conversion of major parts of the existing natural gas network. However, the concrete approach to derive the proposed so-called “European Hydrogen Backbone” remains unclear.

The current literature shows a research gap concerning the development of hydrogen transportation networks. 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 focusing on several sectors lack concrete hydrogen networks. Additionally, topologies provided by the European gas transmission operators lack a transparent methodology and data to replicate the derivation of the network. 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. Thus, with this paper we present a methodology to derive hydrogen transportation networks for a climate-neutral energy supply. The approach includes a technical and economic evaluation and comparison of network candidates considering a grid that must cover supply and demand nodes at the end of the energy transition.

We address this issue by proposing a novel procedure for the development of hydrogen grid infrastructure candidates, considering the possible conversion of an existing gas transmission grid, and applying this approach to Germany, based on the goal of climate neutrality in 2045, as a case study. Therefore, the paper is structured as follows: In Section 2 we present possible scenarios for German hydrogen demand and supply per sector and implied locations. This is followed by an overview of the applied method in Section 3 and the implementation, creating candidate topologies for a German hydrogen network in Section 4.1 and their evaluation in Section 4.2. We finish with a discussion of the results in Section 5 and the conclusion in Section 6.

2. Scenario development for the German energy system

In recent years, several studies have shown possible supply and demand scenarios of hydrogen for Germany [10,33–35]. Since the German government published the National Hydrogen Strategy in 2020, a policy perspective backs up these interests [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 will then be connected via the hydrogen grid, building the foundation for developing hydrogen grid candidates.

2.1. Hydrogen supply

Two options exist regarding the hydrogen supply: import or domestic production [10]. For Germany, most hydrogen will be imported, potentially from the Netherlands, the UK, Norway, and Iceland [10], but also national electrolysis is expected. Prognos et al. (2021) [33] assume that Germany produces 31% of the hydrogen required domestically and imports 69%. The location of electrolysers is still a matter of debate, and therefore assumptions need to be made. We assume that domestic production will occur where a large surplus flow of renewable energy in the power grid (residual load) is expected or where cavern storage facilities exist. Further, we expect import at the current interconnector locations of the natural gas grid. Weyhing (2021) [37] provides the exact locations of the renewables. Therefore, the author assumes a worthwhile operation of an electrolyser 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 producing paper, chemicals, pig iron and steel, other metals, and petroleum processing [33]. Therefore, we classify these sectors and locations as future hydrogen demand. The locations of basic chemicals, petroleum refining, steel and raw metal manufacturing, synthetic fuel and ammonia production are derived from the DemandRegio project [41].

2.3. Demand by the power sector

Studies show that the use of hydrogen as long-term storage for electricity is a relevant option. 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 will demand hydrogen in the future. Hence, we assume the electricity sector's demand locations wherever an electrolyser 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 significant uncertainty in the application of hydrogen. As shown by Wietschel et al. (2021) [10], various studies analyse the 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, we assume that these production facilities will correlate with the expected locations of electrolysers, as discussed above.

2.5. Demand by the heating sector

There are several options for decarbonising the residential and commercial heating sector, such as using heat pumps. Gerhardt et al. (2020) [35] and Prognos et al. (2021) [33] conclude that it is cheaper and more efficient to use heat pumps for residential heating than hydrogen. Therefore, we do not consider hydrogen demand from the heating sector (decentral heating by households).

2.6. Summary

All in all, the paper considers four types of locations. 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 of local hydrogen production, 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 consists of four steps (Fig. 1). The first step is to identify a scenario and locations for a specific region. The locations (and a given grid for the brownfield approach) are used to derive terminal nodes and identify possible network candidates in the third step by applying the Steiner tree algorithm [43] 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 (blue nodes in Fig. 2). 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 minimising the sum of the weights, which can be understood as the objective of a minimisation problem [44–46].

The first step of the Steiner tree algorithm is the calculation of the metric closure of G. The calculation of the shortest path between all vertices uses the Dijkstra algorithm. The result is a graph G_c that connects every vertex and provides the information of the shortest path as the weight of the direct connection. In the second step, a subgraph T of G_c connects all terminals giving information on the weight of every direct connection. The third step computes the minimal spanning tree with the objective to approximatively minimise the overall weight of the edges of subgraph T ($\min Z = \sum E, s.t. E \in T$). The fourth and last step converts the minimal spanning tree of T into the original path from G, considering that the shortest may connections include nodes that are no terminals but elements of the initial network [43].

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. Thus, the terminals are the four types of locations provided in Section 2. Fig. 1 gives an overview of the paper's approach, and Fig. 2 shows the procedure of the Steiner tree algorithm.

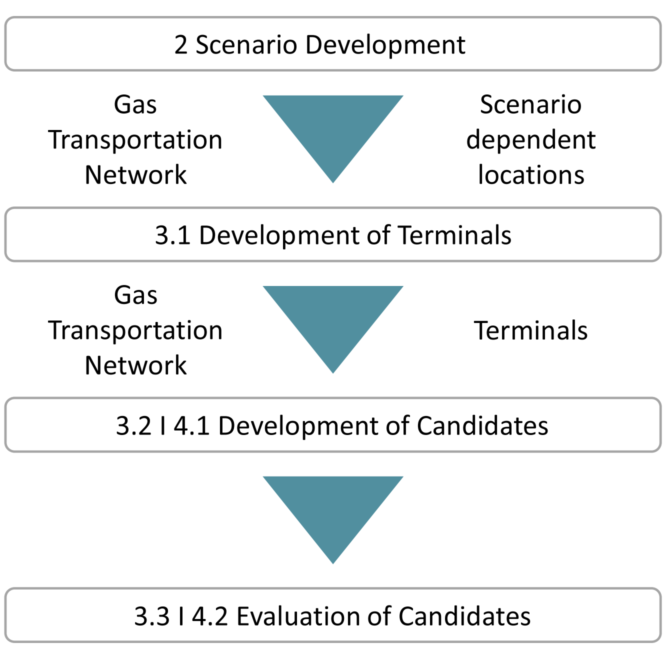

Fig. 1. Four-step approach to derive and evaluate hydrogen network candidates.

3.1. Development of terminals

The terminals to create the brownfield networks are current gas transmission grid nodes. The mapping of the supply and demand nodes to the nearest gas transmission grid node provides the terminals of the brownfield networks. Thus, a set of terminals is derived and mapped to the corresponding locations of the associated gas network nodes. All data sets of the terminals need the location in the form of coordinates. Weyhing (2021) [37], ENTSO-G [39,40], and GIE [38] provide specific locations for supply (electrolysers and interconnectors), storage and demand by the electricity sector. The DemandRegio project [41] offers coordinates for terminals of the industrial demand. No specific demand coordinates exist for the locations of heavy-duty transport [42]. However, the original data contains the names of the highway intersections of the locations. Based on this information, the coordinates are assigned manually.

3.2. Development of candidates

Generally, 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 an entirely new system, in this case, designing a completely new hydrogen pipeline transport system.

3.2.1. The brownfield approach

The brownfield approach assumes that converting the natural gas transport network for hydrogen transport is possible. The overall cheapest option is to reuse the pipelines without modification, which results in higher maintenance and repair costs than with adaptations [20]. Other alternatives 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

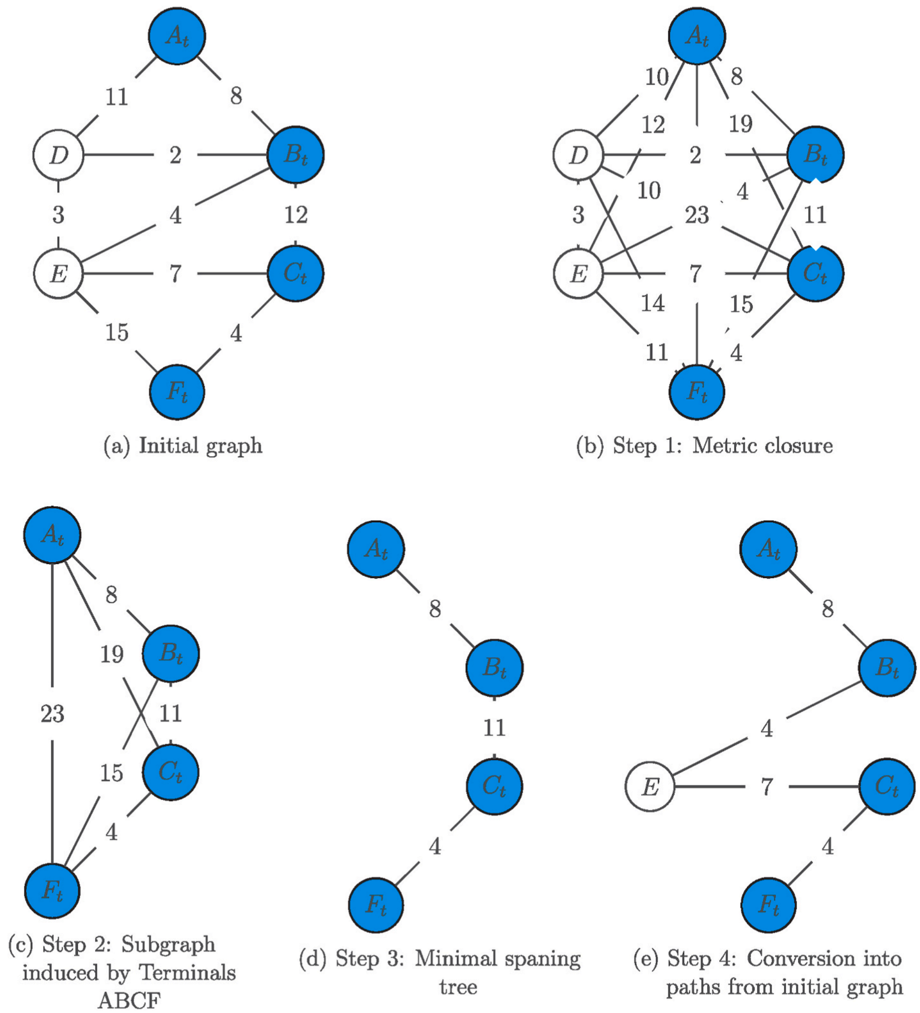

Fig. 2. The Steiner tree algorithm according to Hagberg, Schult, and Swart (2008) [43].

Cerniauskas et al. (2020) are higher than those using pipelines without modification [20].

With the assumption of conversion, the existing network is the basis for the Steiner tree algorithm. The correct use of the algorithm requires an undirected graph without parallel edges and negative weights. For this purpose, the transmission network for Germany from KonStGas [47] builds the basis, and further improvements from the MathEnergy project [48] are included (see Fig. 3). 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. The locations derived in Section 3.1 and illustrated in Fig. 3 represent these terminals.

Since the algorithm minimises the weights of the edges, there is the possibility of determining different resulting networks (referred to as candidates) through different objectives (see E.1-E.5). The objective consists of two characteristics that require 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. Using volumetric parameters within the objectives realises the consideration of the volume.

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 (E.1). Secondly, an investment objective is derived by considering the length and diameter of each edge by investment costs to consider the cost that depends on the diameter (E.2). 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].

The hydrogen network should be able to transport large quantities of hydrogen. Two objectives consider the volume of hydrogen. First, the reciprocal value of the volume of the corresponding pipeline is used, as this favours a larger volume (E.3). Second, a penalty function for small diameters is applied to avoid the use of small diameters (E.4). The penalty function is based on an expert assessment. 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.

Additionally, a fifth objective considers both requirements: the CapEx calculation of Cerniauskas et al. (2020) [20] divided by the pipeline volume to integrate aspects of cost and volume into one objective (E.5). 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 exact locations of the supply and demand sectors represent the nodes to

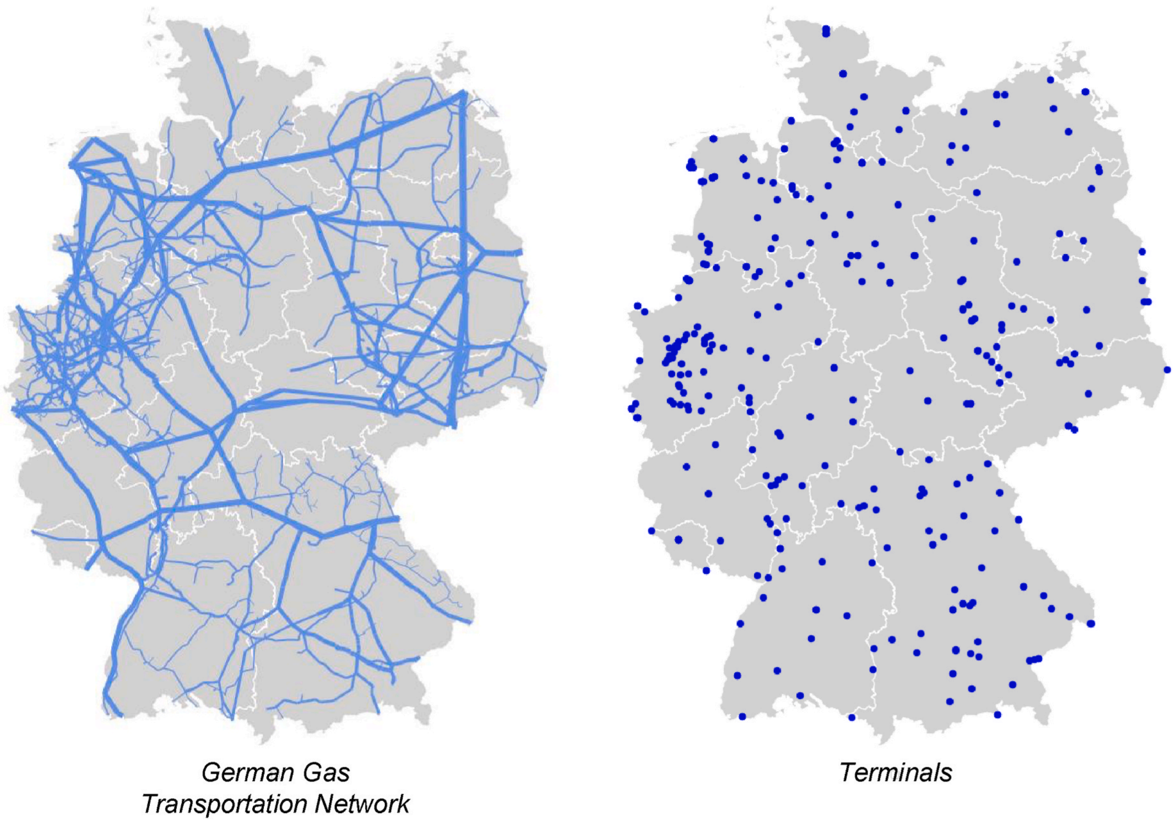

Fig. 3. The used gas transportation network and terminal nodes derived from the scenario.

Table 1
Overview of network candidates and objectives.

Type	Candidate	Objective	Equation
Brownfield	*Length*	l	E.1
Brownfield	*Invest*	$l*(1.67*10^{-4}*d^2-2*10^{-13}*d-7.8*10^{-10})$	E.2
Brownfield	*Reciprocal value of volume*	$\frac{1}{\pi*\left(\frac{d}{2}\right)^2*l}$	E.3
Brownfield	*Penalty for small diameters*	$l\forall Diameter > 600\ mm$ $l+5\ km\forall Diameter \leq 600\ mm$	E.4
Brownfield	*Invest/Volume*	$\frac{l*(1.67*10^{-4}*d^2-2*10^{-13}*d-7.8*10^{-10})}{\pi*\left(\frac{d}{2}\right)^2*l}$	E.5
Greenfield	*Greenfield*	$\sqrt{(x_i-x_j)^2+(y_i-y_j)^2}\triangleq$Straight line distance	E.6

be connected by the network. Thus, the locations in Fig. 4 are not mapped to the gas network nodes like the creation of terminals of the brownfield approach. For the comparison to a new pipeline scenario (worst-case), the cheapest possible greenfield grid is considered. Thus, calculating the straight-line distance between nodes ensures the shortest length of edges (E.6). This approach assumes the building of new hydrogen pipelines everywhere without any complications. The complete graph with the straight-line distances as weights is the basis for the Kruskal algorithm to compute a minimum spanning tree, implemented using the networkx algorithm [43]. The result represents the last candidate for the evaluation. The diameter of the greenfield pipelines is approximated to be about 600 mm. This diameter represents the median and the average diameter of the pipelines in the existing gas network. As a second element, the paper assumes the maximal mode of the diameter classes of the brownfield candidates (which is 900 mm) to consider two variations of the greenfield approach.

3.3. Evaluation of candidates

The evaluation of the candidates is primarily based on their cost (E.11-E.15). The assessment of the cost requires information for new hydrogen pipelines (greenfield approach (E.7)), for the conversion of existing natural gas pipelines (brownfield approach (E.8)), as well as the costs for decommissioning of pipelines are needed (green and brownfield approach (E.9)). Furthermore, the operation costs need to be considered next to the investment perspective, 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 computed (green and brownfield approach (E.10)). In a further step, the paper assumes the total operation and maintenance costs as an annuity over the remaining residual life of 20 years.

Finally, the cost-based evaluation allows a selection of suitable networks for further analyses, which can determine the network's performance under different hydrogen flow situations. The following Table 2 gives an overview of the used cost formulations.

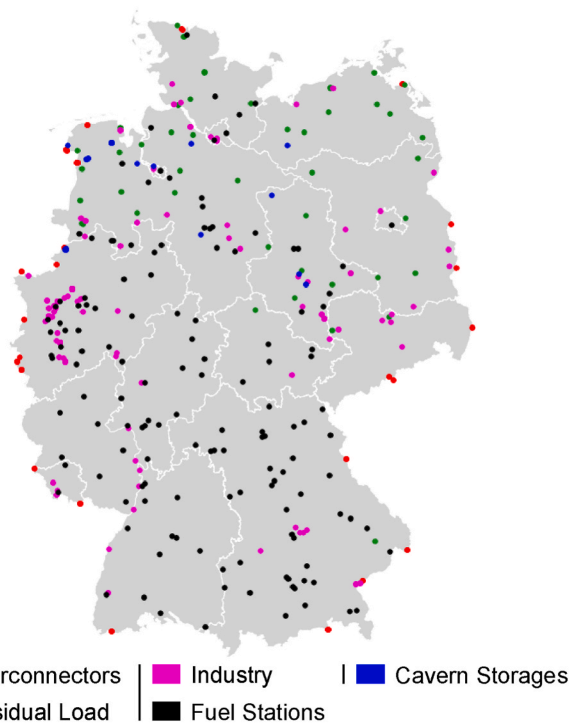

Fig. 4. Exact locations of the supply and demand nodes derived from the scenario.

Table 2
Cost formulas for evaluation.

Specific cost type	Formula	Equation	Source
New pipeline: c_{new}	$c_{new} = 2,340,000 \frac{€}{km}$	E.7	[49]
Pipeline conversion $c_{conversion}$	$c_{conversion} = 270,000 \frac{€}{km}$	E.8	[49]
Decommissioning of pipelines $c_{decommissioning}$	$c_{decommissioning} = 113,000 \frac{€}{km}$	E.9	[50]
Operation and Maintenance $c_{operation}/a$	$c_{operation} = OPEX_{fixed} + OPEX_{variable} = 1000 \cdot ([1.1 \cdot 10^{-4} \cdot d^2 - 1.6 \cdot 10^{-2} \cdot d + 2] + [1 \cdot 10^{-4} \cdot d^2 - 1.5 \cdot 10^{-12} \cdot d - 2.9 \cdot 10^{-10}]) \frac{€}{km}$	E.10	[20]

For the final evaluation, the costs are multiplied by the corresponding lengths of the candidates' newly constructed, decommissioned, or converted pipelines and summed up. Table 3 gives an overview of the resulting parameters. Costs for new pipelines appear only in the greenfield approach, and conversion costs respectively in the brownfield approach. Decommissioning appears in both cases. The greenfield approach leads to a complete decommissioning of the existing grid. In the case of the brownfield approach, the decommissioning results form the difference between converted pipelines and the current gas transmission grid.

Table 3
Evaluation formulas for absolute cost.

Absolute cost type (for candidate n)	Formula	Equation
Absolute new pipeline costs C_{new_n}	$C_{new_n} = c_{new} \cdot l_n$	E.11
Absolute pipeline conversion costs $C_{conversion_n}$	$C_{conversion_n} = c_{conversion} \cdot l_n$	E.12
Absolute decommissioning costs $C_{decommissioning_n}$	$C_{decommissioning_n} = c_{decommissioning} \cdot (l_{existing_{network}} - l_n)$	E.13
Absolute operation costs $C_{operation_n}$	$C_{operation_n} = c_{operation} \cdot l_n$	E.14
Absolut overall costs C_n	$C_n = C_{new_n} + C_{conversion_n} + C_{decommissioning_n} + C_{operation_n}$	E.15

4. Results

In the following, the results are presented. First, the section presents the candidates. Second, the section compares them to each other, and finally, provides the evaluation. 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

Fig. 5 visualises the six candidates. 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 (representing the 600 mm case) and a single connection from east to west in the North of Germany.

Generally, one must consider that if mainly small diameters are part of the network, this could indicate that the feasibility of flow simulations is not guaranteed. This aspect applies particularly, if one assumes that, in the case of Germany, the infrastructure fulfils not only the domestic supply task but also transit requirements. However, this should be analysed in further studies.

Fig. 6 shows the distribution of the diameters of the brownfield candidates (Greenfield all constant). The information on the diameters enables a preliminary indication of the feasibility of a possible flow of a network. As expected, the cost-based candidates' Length and Invest are 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 most extended network has the candidate *Reciprocal Value of Volume* with an overall length of 14,619 km, meaning a conversion of half of the existing network. 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 and 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 of securing the supply, and Germany could also function as a transit country for Europe. This aspect is especially the case for the last brownfield candidate *Investment/Volume*, where both elements, cost and volume of hydrogen, are included in the objective. Considering both aspects lead to a relatively long network of 12,241 km, including large diameters, such as the transit pipelines.

The *Greenfield* candidate stands out mainly because of its short length of only 6678 km. As described in Section 3.2.2, no geographic condition was considered in creating this candidate, making it a relatively conservative benchmark. Therefore, the straight-line approach allows pipelines through neighbouring countries if this is the shortest path. Only two east-west connections in the north of Germany may not be sufficient to ensure hydrogen transportation from southeast to southwest. In addition, there are no continuous connections in the area where the important transit pipelines are located, e.g., in the northeast and the

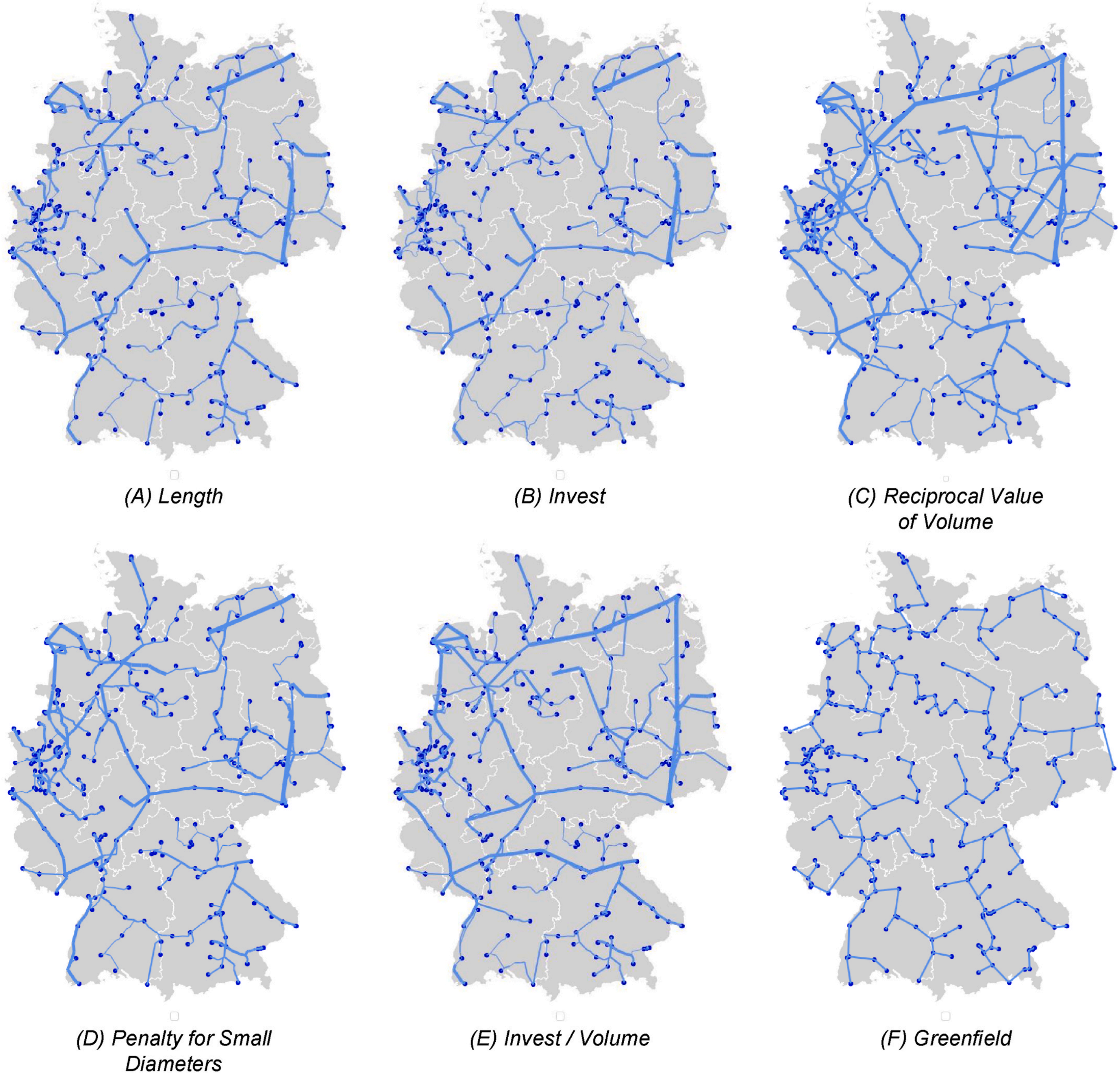

Fig. 5. Derived Candidates of possible hydrogen transportation grids.

south. In the case of Germany being a transit country, this could lead to a situation where 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. Table 4 lists the result of the four cost components of the methodology described in Section 3.3 for each candidate.

The biggest cost components for the brownfield candidates are the conversion cost and the new construction cost for the Greenfield candidate. 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 candidate's length. The *Greenfield* candidate with the entirely decommissioned gas transmission network stands out. At the cost of over three billion Euros, this cost accounts for 18.62% of the total cost associated with the candidate.

The last cost component, costs of operations and maintenance, depends on the pipeline's length and the pipeline's diameter of the candidate's pipelines. Therefore, it is not surprising that candidate *Invest* is the most favourable of the brownfield candidates since the objective considers both factors. 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 depends significantly on the diameter. In the case of a higher mean diameter of 900 mm, the costs of operation and maintenance are twice the cost of 600 mm.

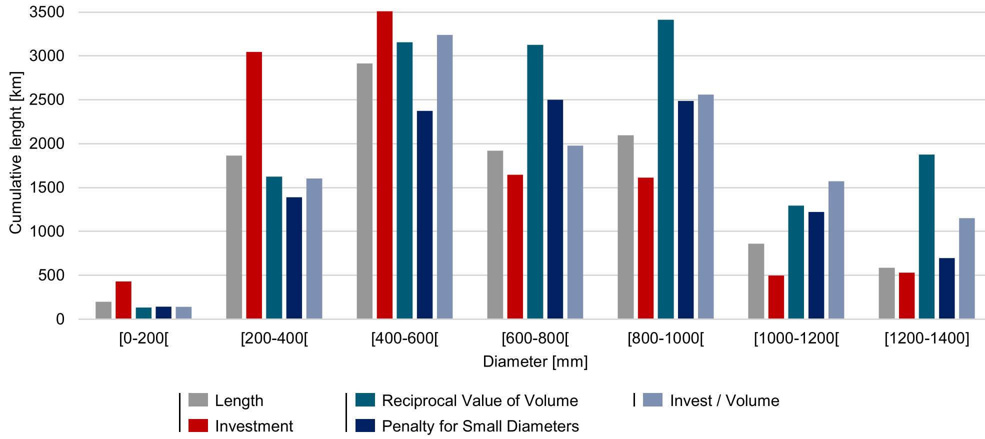

Fig. 6. Length of the different derived brownfield candidates by diameter. As stated above, the total length of the Greenfield variations is 600 or 900 mm for the whole network.

Table 4
Cost components of the different network candidates.

Candidate	$costs_{new}$	$costs_{conversion}$	$costs_{decommissioning}$	$costs_{operation}$/a
Length	0 M€	2,818 M€	2,501 M€	945 M€
Invest	0 M€	3,042 M€	2,407 M€	804 M€
Reciprocal Value of Volume	0 M€	3,947 M€	2,028 M€	1,767 M€
Penalty for Small Diameters	0 M€	2,919 M€	2,459 M€	1,132 M€
Invest/Volume	0 M€	3,305 M€	2,297 M€	1,395 M€
Greenfield (600 mm*)*	15,626 M€	0 M€	3,680 M€	454 M€
Greenfield (900 mm*)*	15,626 M€	0 M€	3,680 M€	1,053 M€

The rating in Table 5 results from the sum of the cost components shown in Table 4. Generally, 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 candidate Reciprocal Value of Volume cost is above *Length* and *Invest*. The candidate Greenfield shows total cost within the range of *Invest/Volume,* but if the higher diameter is considered, the 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.

5. Discussion & conclusion

As shown in Section 4, the presented method can successfully be applied to create potential hydrogen network candidates based on demand and supply forecasts and an existing natural gas grid.

Table 5
Rating of the different derived network candidates.

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

Furthermore, it is evident from the results that using the existing grid is beneficial in the case study of Germany, as the differences in cost are overwhelming. The advantageous conversion of existing gas transmission infrastructure is in line with investigations of Cerniauskas et al. (2020) [20] or the assumption of the European gas transmission operators [32]. However, this section discusses some limits 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. With these findings, we provide data and form concrete networks. Other approaches like Weber and Papageorgiu (2018) [27], Welder et al. (2018) [30], or Caglayan et al. (2021) [31] give only a rough structure and do not enable further analysis of transportability. The result of the European gas transmission operators [32] uses a large part of the existing transmission grid but lacks detailed data for further analysis.

A limitation of the approach is that it does not guarantee that the presented candidates can fully fulfil the supply task. Some objectives consider the volume of hydrogen but do not fully 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. Starting point would be analyses based on existing software for gas transmission networks like SIMONE or MYTNS [51–54]. However, current studies only include injection scenarios into the existing gas grid and do not cover simulations with pure hydrogen [55].

However, all candidates contain and connect all demand and supply nodes of the scenario provided in Section 2. Thus, all candidates can basically transport hydrogen from all sources and to all demands. However, the realisation depends on the specific transport quantities. The most promising candidate seems to be *Invest/Volume,* as it integrates the volume and considers the cost. Thus, the candidate provides significant transport capacity while keeping costs as low as possible. Nevertheless, our approach fulfils its goals of presenting different candidates, which decision-makers can discuss and further analyse in detail.

Furthermore, the method allows for using different objectives, including the volume of hydrogen for the Steiner tree algorithm increases the likelihood of deriving 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, we assume that all pipelines have a diameter of 600 mm or 900 mm, and costs are corresponding. Although this seems to be a useful approximation, if more information on possible diameters is accessible, the Greenfield candidate's cost calculation can be 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 for 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, methods that aim for a minimum spanning tree do not consider a redundant structure of the new hydrogen grid. Studies like Husarek et al. (2021) [29] or Caglayan et al. (2021) also do not cover this aspect as they indicate rather net transfer capacities and do not provide a concrete pipeline structure. The aspect of neglecting redundancies can be problematic regarding the security of supply. However, using two parallel pipelines instead of one can contribute to overcome this issue. Analyses by German gas transmission operators for individual pipeline sections show that parallel pipelines are suitable in the conversion phase [49]. This result is in line with the assumptions of the European gas transmission operators [32]. In the later stages of hydrogen network development, parallel pipelines open up the possibility of creating redundancy in the hydrogen network.

Thus, the key findings concerning the procedure applied in this work can be summarised as follows. By employing brownfield approaches, the choice of specific objectives enables the customisation of networks according to the particular needs of the underlying scenario. 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

Further research needs and questions result from the discussion. First, the greenfield approach requires a more detailed procedure. For example, the Euclidean Steiner tree algorithm proposed by GeoSteiner [56] could help to develop a greenfield candidate that might be even shorter. However, this is likely to require considerably more computational effort. In addition, considering interactions with geological constraints, as done by Krieg (2012) [26], could better approximate the cost of 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 customisation. The application for other regions requires a region-specific scenario development, including selecting sectors and locations of production and demand and estimating the cost variables. 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.

Author contributions

This paper is based on the results of analysis from Flora von Miculicz-Radecki, supported by findings from Johannes Giehl and Benjamin Grosse. The methodological approach was developed by Flora von Miculicz-Radecki with the support of Sarah Schöngart, Benjamin Grosse, and Johannes Giehl. The data to derive and evaluate the network candidates were gathered by Flora von Miculicz-Radecki together with Johannes Giehl and Benjamin Grosse. The code base was developed and improved by Flora von Miculicz-Radecki with the support of Sarah Schöngart and Daniel Rüdt. The writing process was coordinated by Flora von Miculicz-Radecki, and the paper was written by Flora von Miculicz-Radecki, Johannes Giehl, and Benjamin Grosse with the contributions of Daniel Rüdt. The visualisations were created by Flora von Miculicz-Radecki and Johannes Giehl. The writing and editing process was further supported by Maximilian Evers. The research process was initiated by Benjamin Grosse, Johannes Giehl, Sarah Schöngart, and Joachim Müller-Kirchenbauer. All authors have read and agreed to the version of the manuscript.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The final candidate data and topology data in the form of point data is available in the supplementary material. Further data will be made available on request.

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Appendix A. Supplementary data

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