GIS-based analysis of hydrogen pipeline infrastructure for different supply and demand options

Sylvestre Baufumé[1], Thomas Grube[2], Fabian Grüger[3], Dennis Krieg[2], Jochen Linssen[1], Michael Weber[2], Jürgen-Friedrich Hake[1], Detlef Stolten[2]

1 Institute of Energy and Climate Research – Systems Analysis and Technology Evaluation (IEK-STE), Forschungszentrum Jülich GmbH, D-52425 Jülich, Germany, +49 2461 61-4540, s.baufume@fz-juelich.de, http://www.fz-juelich.de/iek/iek-ste

2 Institute of Energy and Climate Research – Fuel Cells (IEK-3), Forschungszentrum Jülich GmbH, D-52425 Jülich, Germany, +49 2461 61-5398, th.grube@fz-juelich.de, http://www.fz-juelich.de/iek/iek-3

3 Ingmen GmbH, Neuhöfferstr. 25, D-50679 Köln, Germany, +49 221 204-25680, grueger@ingmen.de, http://www.ingmen.de

Abstract: This study assumes a high penetration of hydrogen-fuelled vehicles (Fuel Cell Electric and Internal Combustion Engine) for Germany in 2050 and investigates how a pipeline network for hydrogen transmission and distribution could look like and what it could cost – under different scenarios for H_2 production and demand. All data are geo-referenced for their computation and displayed within a Geographical Information System (GIS) environment.

Statistical data describing the current vehicle repartition per type and district are computed to evaluate the expectable geographical distribution of hydrogen demand under several “demand scenarios” (for example big agglomerations first or equally distributed introduction). We identified most of the approximately 14,000 existing refuelling stations for conventional fuels and expect hydrogen to be delivered at some of them according to their localisation (along or near highways, within urban areas, etc…). Selected stations form the sinks of the modelled distribution network.

Then, we envisage highly differentiated hydrogen production scenarios (electrolysis using offshore wind generated electricity only or associated with onshore wind generated electricity or lignite gasification) and calculate the preliminary layouts and costs of pipeline networks able to balance the proposed demand and supply options. Finally, we compare the different options from an infrastructure planning and support perspective.

Keywords: Hydrogen transport infrastructure, Fuel stations, Geographical Information System (GIS)

1 Introduction

Following the need for significant reductions of greenhouse gas emissions, many developed countries have started extensive transformations of their energy systems – especially those who decided to abandon the nuclear energy option. Within few decades the major part of the electricity demand has to be covered by renewable energies, depending on whether CCS will contribute as intermediate solution or not. Where hydro power resources are limited and solar radiation is low as in Germany, wind power will take by far the major share of the production. One interesting option to profit from this development towards renewable energy in the transport sector is to produce hydrogen from renewable electricity and use it as a carbon free fuel in transport applications. In part this can help levelling high fluctuations of wind power and using expected excess energy in the future. For this option a transport and distribution infrastructure is indispensable. One of the obstacles to the establishment of a significant hydrogen refuelling infrastructure is the uncertainty in respect to the cost of a pipeline system for an energy efficient and economic supply of hydrogen to the stations. Our GIS-based model and the analysis presented in this paper can contribute to the reduction of this uncertainty.

2 Methodological approach

2.1 General presentation

Assuming a high penetration of hydrogen-fuelled vehicles (Fuel Cell Electric and Internal Combustion Engine) for Germany in 2050, we expect large amounts of gaseous hydrogen to be transported from the production plants to selected filling stations, where the final users would refuel, as they are used to for conventional hydrocarbon fuels. Hydrogen transport distances and quantities to be delivered advocate for the construction of a pipeline network rather than using trucks, rail or vessels (e.g. [Yang & Ogden, 2007]). Two options for the central production of hydrogen are envisaged: water electrolysis using wind generated electricity and domestic lignite gasification plants.

The model handles data characterising hydrogen demand, supply and associated transport requirements. All gathered data have been geo referenced. Although the scenarios computed in this study apply for the future, a lot of calculation assumptions are derived from current situation, as detailed in chapter 3.

2.2 Data base description

2.2.1 Statistics/ Geographical scale

This study covers the entire German territory. As the model assumes the future hydrogen demand correlates with the current structure of the motor vehicle fleet, we have been looking for national statistics describing it at the smallest administrative unit available. Vehicle fleet description was procured at the “Landkreis” level [KBA, 2009] (Status: 01/01/2009). This corresponds to the NUTS3[1] unit defined by [Eurostat, 2010] and divides the 357,120 km^2 of

[1] NUTS: Nomenclature of Territorial Units for Statistics.

Germany into 413[2] districts which surfaces range between 35 and 3,058 km^2 (Population between 34,000 and 3,440,000 inhabitants per district) according to [SÄBL, 2011a, SÄBL, 2011b].

2.2.2 Fuelling stations

The envisaged high penetration of hydrogen-fuelled vehicles requires the widespread availability of delivery points to the end-user. On the long term, we expect hydrogen to be delivered in a large network of fuelling stations. For the purpose of this study, we assume hydrogen will be proposed in a selection of service stations, based on the currently existing network. Considering the drivers, this assumption implies unchanged daily habits when switching from conventional hydrocarbon fuels to hydrogen. From the station operator perspective, this would allow a smooth entry in a new market instead of being a competitor and would mutualise the fix costs of the stations[3]. Moreover, most of the “strategic locations” (proximity to main roads and consumers) are already covered by the existing stations and it is unlikely that a large number of new locations would be available for station siting in urban area.

We collected public information to build a geo referenced data base of existing stations. This was achieved by the processing of address lists published as a service to drivers by station brands and associations of independent station operators. Approximately 12,000 fuelling stations were identified and geo-localised for the purpose of this study. This represents 81% of the 14,782 stations mentioned in [EID, 2010]. When accounting for the market shares reported in the aforementioned enquiry, it can be estimated that our data base covers almost 88% of the fuel quantities distributed in German stations.

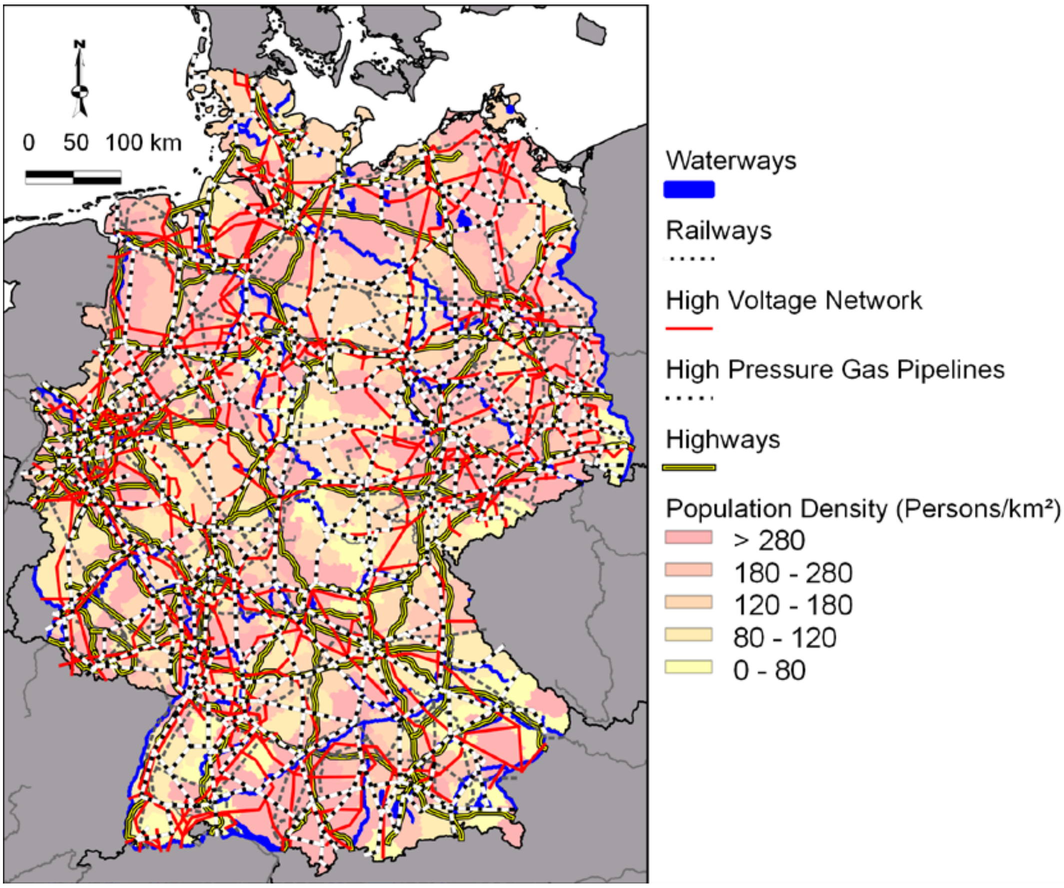
2.2.3 Pipeline routes

The construction of long distance infrastructures in Germany will need to accommodate pre-existing conditions (relief, natural obstacles, populated or protected areas…). A very few number of new corridors being available, we expect (See [Baufumé et al., 2011]) new infrastructure to follow the routes of the main existing networks (waterways, railways, highways, high pressure natural gas grid and high-voltage transmission network) – see Figure 1. The model basically allows any route for laying the new hydrogen transmission pipelines but for the purpose of this study, we shaped the algorithm to facilitate (cost advantage) the search of a path along the existing high pressure natural gas grid.

[2] Rural (“Landkreise“) and urban districts (“kreisfreien Städte“) together – Status: 01/01/2009.

[3] It also seems that the business model of the service stations significantly changed in the last years. According to the data gathered in [PSR Rating GmbH, 2009], the fuel sales accounted for 20% of their gross profit in 2008. At the same time, the shares of the station shops (Tires, batteries, car accessories, magazines, food, alcohol, tobacco etc…) rose to 85% of the fuel stations´ total turnover.

Figure 1 Current main existing transport infrastructure and population density for Germany



Source: Census Data [SÄBL, 2010], Districts [BKG, 2010], Networks: Own database

2.3 Model description

The hydrogen infrastructure can be divided into a transmission and a distribution network. Because those networks are designed in consideration of their individual tasks and therefore differ in size, capacity and density, they are considered separately in the model.

The model of the transmission network consists of point-shaped hydrogen sources and sinks as well as line-shaped connections between them. For each district, the assumed hydrogen demand is assigned to its barycentre constituting the sink of the transmission pipeline. Any point can be defined as a source with a specified hydrogen capacity. The model provides several types of connections between point-shaped elements. A main characteristic of the discussed model is the possible specification of a predefined layout for preferred pipeline routes. Wherever possible, connections between sources and sinks are favoured to run along it. As the sources and the sinks are not necessarily located exactly on this predefined route, the possibility of direct connections out of this track is also required. Therefore sinks can be connected directly to each other as well as to the specified preferred routes. Sources can be connected to the preferred routes only. As expressed in chapter 2.2.3, defining preferred pipeline routes should prevent the calculated transmission pipelines from crossing forbidden or implausible areas. During the computation, each sink is connected to a source providing enough hydrogen to fulfil its demand. The applied algorithm uses a defined cost function to select the most cost-efficient route for each sink. The sinks are taken into account consecutively while every calculated route connecting a sink and a source becomes a constraint for the following calculation. Thus, the algorithm does not result in a superposition of single connections but in a sensible overall network.

The model of the distribution network consists of point-shaped hydrogen sources and sinks with line-shaped connections as well. This network is divided into many independent sub networks, one for each administrative district. The respective barycentres of the districts form the interconnection points between the transmission network and the distribution sub-networks (i.e. the hydrogen sinks of the transmission network model are regarded as the hydrogen sources of the distribution network model). The hydrogen sinks of the distribution sub-networks are a selection of refuelling stations. It is assumed that the maximum permissible daily capacity for hydrogen delivery is the same for all selected refuelling stations. That means that the number of refuelling stations to be selected in one administrative district is defined by the district's overall demand. In contrast to the transmission network model there is no predefined network of preferred pipeline routes but only direct connections between the sources and the sinks are possible. At the small scale of the distribution network, it was considered questionable to define preferred pipeline routes in the absence of detailed information on local constraints. The applied algorithm takes all sinks of each sub network into account simultaneously while the sub-networks themselves are handled consecutively. It is assumed that the pipeline costs of the distribution network are affected significantly by the total length but not by the capacity (See chapter 3.2 – a minimal pipeline diameter is given). That is why the algorithm determines a network of minimal length (minimum spanning tree) in order to find the most cost efficient solution.

3 Main assumptions and definition of scenarios

3.1 Hydrogen demand – Tonnage and locations

3.1.1 Administrative districts to be connected

In the reference case, all districts are connected to the transmission network and therefore, there is also a distribution network in all districts.

In a second case it is proposed to connect to the transmission network only the districts where the hydrogen demand is greater than (or equal to) 8,000 t/year. This assumption should give an insight into a possible pipeline layout designed to supply significant consumption areas only, as it might be the case at the early stages of a network deployment. Moreover an additional constraint is introduced in the computation to force the "first mover" effect: in the algorithm, the sinks of the transmission network supplying the cities (area) of Berlin (Capital), Hamburg (leading German city in hydrogen and fuel cell activities), Stuttgart and Munich (automotive industry) are the first to be connected to sources such as the generation of the remaining network will necessarily increase the size of the pipelines installed for the supply of these areas.

3.1.2 Hydrogen vehicle fleet & vehicle kilometre travelled

Excluding motorcycles, heavy duty vehicles, special trucks and tractors, we assume hydrogen-fuelled vehicles belong to one of the following categories: passenger vehicles, Light Duty Vehicles[4] (LDV) and buses. According to the statistics in [KBA, 2009], they comprised on the 01/01/2009 approx. 41.3 million, 1.8 million and 75,000 units respectively. For comparison and calibration purpose, we assume in this article a very high penetration of hydrogen-fuelled vehicles as proposed in [BMVBS, 2009], leading in 2050 to approx. 38.0 million, 2.7 million and 63,000 units for hydrogen-fuelled passenger vehicles, LDV and buses respectively. We also adopt the averaged characteristics of the fleet described in the aforementioned study (See Table 1). The resulting demand of approx. 4.3 million tons H_2/year[5] has been distributed between the administrative districts proportional to the current respective repartition of passenger vehicles, LDV and buses in Germany.

Table 1 – Assumptions on hydrogen vehicle fleet and consumption

H_2 Vehicles		**H_2 Utilisation**	
Type -	Market Share [%]	Annual average mileage [km/year]	Average specific consumption [MJ/km]
Passenger Vehicles	73	11,400	0.85
Light Duty Vehicles	55	18,500	2.30
Buses	74	50,000	10.30

Source: Averaged characteristics of the fleet described in [BMVBS, 2009]

3.1.3 Fuel stations delivering hydrogen

In the model, the maximum permissible daily capacity for hydrogen delivery is set constant and identical for all stations (See chapter 2.3). For the purpose of this study, we set it to 1,700 kg/day. As a consequence, depending on the market development simulated, it might not be required to connect all the existing stations to the envisaged hydrogen distribution network and therefore a prioritisation criterion for selecting the stations is required. Inside the administrative districts, the stations were classified according to their localisation within rural, urban or dense urban area. Additionally, refuelling stations serving motorways were also identified[6]. Finally the following networking sequence[7] was chosen, until the demand is covered: first $S_{Motorway}$, then, $S_{Dense\ Urban}$, then S_{Urban}, then S_{Rural}.

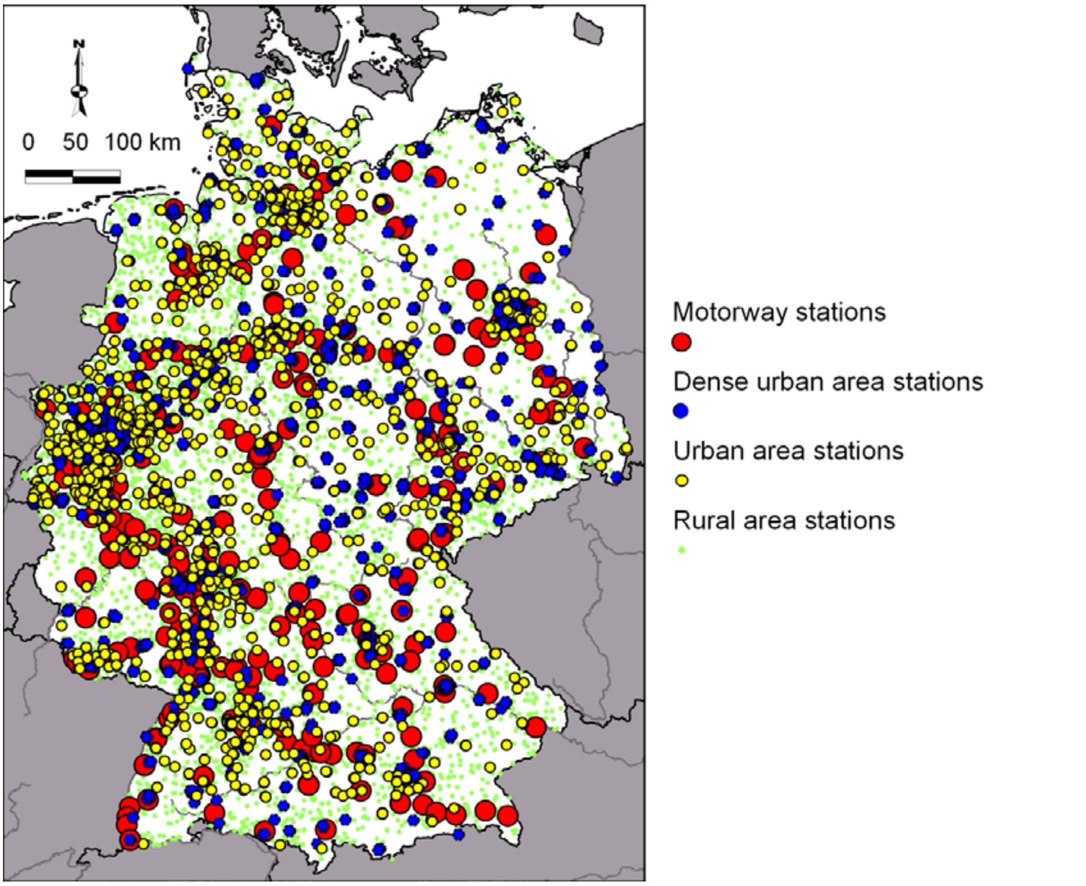
[4] We defined Duty Vehicle with a Gross Vehicle Weight Rating (GVWR) lower than 3.5 t to fall within the LDV category.

[5] Assuming LHV_{H2} = 120 MJ/kg.

[6] By combining the explicit reference to a motorway in the address and/ or a geographical position within a 25 meter band on both sides of a motorway, we identified 385 motorway stations, which is pretty in line with the 375 “Autobahntankstellen” referred to in [EID, 2010].

[7] With S_x, standing for the various categories of refueling stations.

Figure 2 Classification of refuelling stations



Source: Own database

3.2 Hydrogen pipelines – Capital costs, design and operation parameters

It is envisaged that no pipeline with a diameter lower than 100 mm will be installed. As a consequence, some sections of the distribution network will be overrated (See network characteristics in chapter 4) which will increase the specific hydrogen transport costs for these sections. The pipeline diameters are determined by a simplified flow model stating a maximum average speed of 15 m/s in the pipelines and average operating pressures of 7 and 3 MPa for the transmission and distribution pipelines respectively.

For this study, we define the exemplary capital costs $Cap\ (D)$ for pipeline installation and associated recompression stations:

Equation 1 $$Cap\ (D) = 8.33\ \times 10^{-4}\ D^2 + 0.9169\ D + 250$$

where: $Cap\ (D)$ is a capital cost in €$_{2010}$ per m of pipeline and D is the pipeline diameter in mm.

3.3 Hydrogen production – Capacity and locations

3.3.1 Water electrolysis with clustered onshore wind generated electricity

Energy production from onshore wind turbines is highly decentralized in Germany. The largest wind parks show installed capacities in the 100 MW_e range. It is assumed that large-scale electrolysers are not directly connected to single wind parks but distributed in clusters over Germany. The spatial allocation of potential wind energy capacity and production and with this latter the potential hydrogen production rely for this study on published data regarding the German wind energy potential [BWE, 2011] (See Figure 3, rows “PP” and “EP“). The above referred report is a GIS-based analysis of onshore wind potential for Germany, taking into consideration existing buildings, transport infrastructure, environmental restrictions and wind resource. Allowing a maximum surface of 1% of the territory useful for wind parks, the authors estimate a total energy production potential of approx. 200 TWh_e per year and point out that their results are likely to be underestimating the real potentials. For comparison the status of wind energy installed capacity in Germany [IWES, 2011] can be found on the same figure, row “PS“. It can be derived the wind energy utilisation – defined as the ratio of installed capacity and potential capacity – which significantly differs among German states. For example, the figure for Saxony-Anhalt (ST) is 95% whereas for Bavaria (BY) it is only 0.3%.

The respective contribution of each state to the potential onshore wind energy production is adopted for the determination of the annual hydrogen production rates, as per the Equation 2:

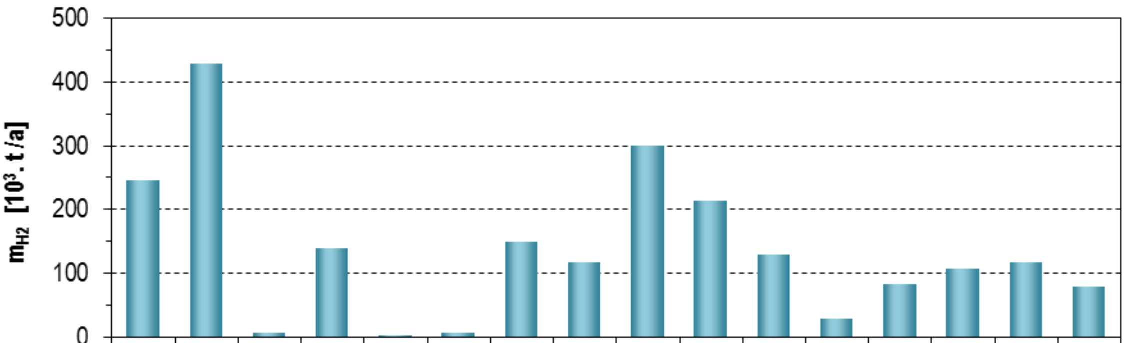
Equation 2
$$m_{H_2,\mathrm{on},i} = \frac{E_{P,i}}{E_{P,DE}} \cdot m_{H_2,\mathrm{on}}$$

where: $m_{H2,on}$ is the annual hydrogen production from water electrolysis with onshore wind generated electricity[8], E_P is the potential wind energy production. The subscripts i and DE denote the 16 German states and the total for Germany, respectively.

Feed-in sites for connection to the hydrogen transmission grid are assumed at the respective barycentres of the German states. Due to their proximity, the points representing the states “Berlin” (BE) and “Brandenburg” (BB) were merged and their hydrogen production added.

[8] Assuming an electrolyser efficiency of 70%, approx. 51% of the potential onshore wind generated electricity would be required to cover the hydrogen demand of scenario A-100% defined in chapter 3.4. It is not discussed further if this amount can be made available for hydrogen generation.

Figure 3 Assumed hydrogen production rates by German state. Installed wind power capacities (PS, status: September 2011). Energy potential (EP) and power potential (PP) from wind power in the German states



German states	BW	BY	BE	BB	HB	HH	HE	MV	NI	NW	RP	SL	ST	SN	SH	TH
m_{H2} [10^3. t/a]	247	429	6	139	3	6	150	118	300	214	129	29	83	107	118	79
PS [GW]	0,48	0,07	0,0	4,5	0,1	0,05	0,6	1,5	6,8	3,0	1,5	0,12	3,5	1,0	3,1	0,78
PP [GW]	12	21	0,30	6,7	0,20	0,30	7,1	5,7	13	10	6,1	1,4	3,7	4,9	4,3	3,7
PS/PP [-]	4%	0%	1%	67%	59%	15%	9%	27%	52%	30%	25%	8%	95%	20%	72%	21%
EP [TWh/a]	23	40	0,60	13	0,30	0,60	14	11	28	20	12	2,7	7,7	10	11	7,4

Source: [BWE, 2011, IWES, 2011], own calculations

3.3.2 Water electrolysis with clustered offshore wind generated electricity

The potential for installed offshore wind capacity is varying significantly between studies available. For example, the German Ministry of Environment (BMU) reported a potential of 35 GW in 2009 [BMU, 2009] and in 2011 already 70 GW [BMU, 2011]. The German Experts Council on Environmental Questions (SRU) estimates a its scenarios a potential around 73 GW [SRU, 2011]. The German Energy Agency (DENA) provides more detailed information [DENA, 2011]. According to the projects´ overview (status: November 2011), permits have been obtained for a total of 23 GW – taking the final construction phase numbers for each project, and including the first two wind parks in operation: Alpha Ventus with 60 MW and Bard I, which will reach 400 MW at the end of its first stage. Additional permit applications amount to another 28 GW, when assuming an average turbine power of 5.2 MW for cases where just the number of turbines is given, and counting the largest project only, where projects overlap geographically. This gives a total of 51 GW – five of them in the Baltic Sea. A large number of permits already relate to areas outside of the dedicated wind energy priority areas as defined by [BSH, 2010], and there is still additional area far from the coast that is not yet targeted by permit applications. Nevertheless, we retain here 51 GW as the potential for offshore capacity in Germany, because it indicates what project developers currently consider as potentially economically viable, i.e. enough viable to invest in the permitting process.

It is assumed that feed-in locations for the hydrogen transmission network coincide with the (onshore) connection points of the wind parks. Projects, whose grid connection locations have not been announced yet, have been assigned to the connection point of the off-shore power line nearest to the wind park. For unassigned western North Sea projects, capacities were split between Emden and Wilhelmshaven. The final distribution is obtained after assigning some small capacities to larger neighbouring ones. Assuming the wind resource and turbine nominal power identical for all offshore wind parks, the annual hydrogen production rates are given by Equation 3:

Equation 3
$$m_{H_2,\mathrm{off},i} = \frac{P_{off,i}}{P_{off,DE}} \cdot m_{H_2,\mathrm{off}}$$

where: $m_{H2,off}$ is the annual hydrogen production from water electrolysis with offshore wind generated electricity, P_{off} is the potential wind power. The subscripts i and DE denote the retained onshore connection points of the offshore wind power grids and the total for Germany, respectively.

3.3.3 Central gasification of domestic lignite

Thanks to abundant domestic reserves, Germany relies today on the combustion of lignite for electricity production in power plants (e.g. approx. 23% of the gross electrical production in 2010 according to [BMWi, 2011]). Alternatively, the gasification of lignite produces a hydrogen rich gas (syngas) which can be further converted to mainly hydrogen and carbon dioxide in a so-called shift reaction. After separation, hydrogen can be made available as a product of a gasification plant. The high moisture content of lignite and the resulting decreased mass Lower Heating Value (LHV in kJ/kg) make long-distance transport of lignite uneconomic. That is why lignite is generally used very close to mining locations. Three lignite mining regions still having significant stock can be identified (namely the “Rheinland”, “Lausitz” and “Mitteldeutschland” reserves). In this article, the respective contribution of lignite mining regions for the production of hydrogen has been determined from the reserves published in [DEBRIV, 2011]. Within a mining region, we assume identical gasification plants sited near existing lignite power plants. The contribution of each plant is expressed in Equation 4:

Equation 4
$$\forall\, i(j), \qquad m_{H_2,lign,i} = \frac{Res_{lign,j}}{N_j \cdot Res_{lign,DE}} \cdot m_{H_2,lign}$$

where: $m_{H2,lign}$ is the annual hydrogen production from lignite gasification, Nj is the existing number of lignite power plants in the region j, Res_{lign} is the lignite reserve. The subscripts i, j and DE denote the retained number of gasification plants, the three identified mining regions and the total for Germany, respectively.

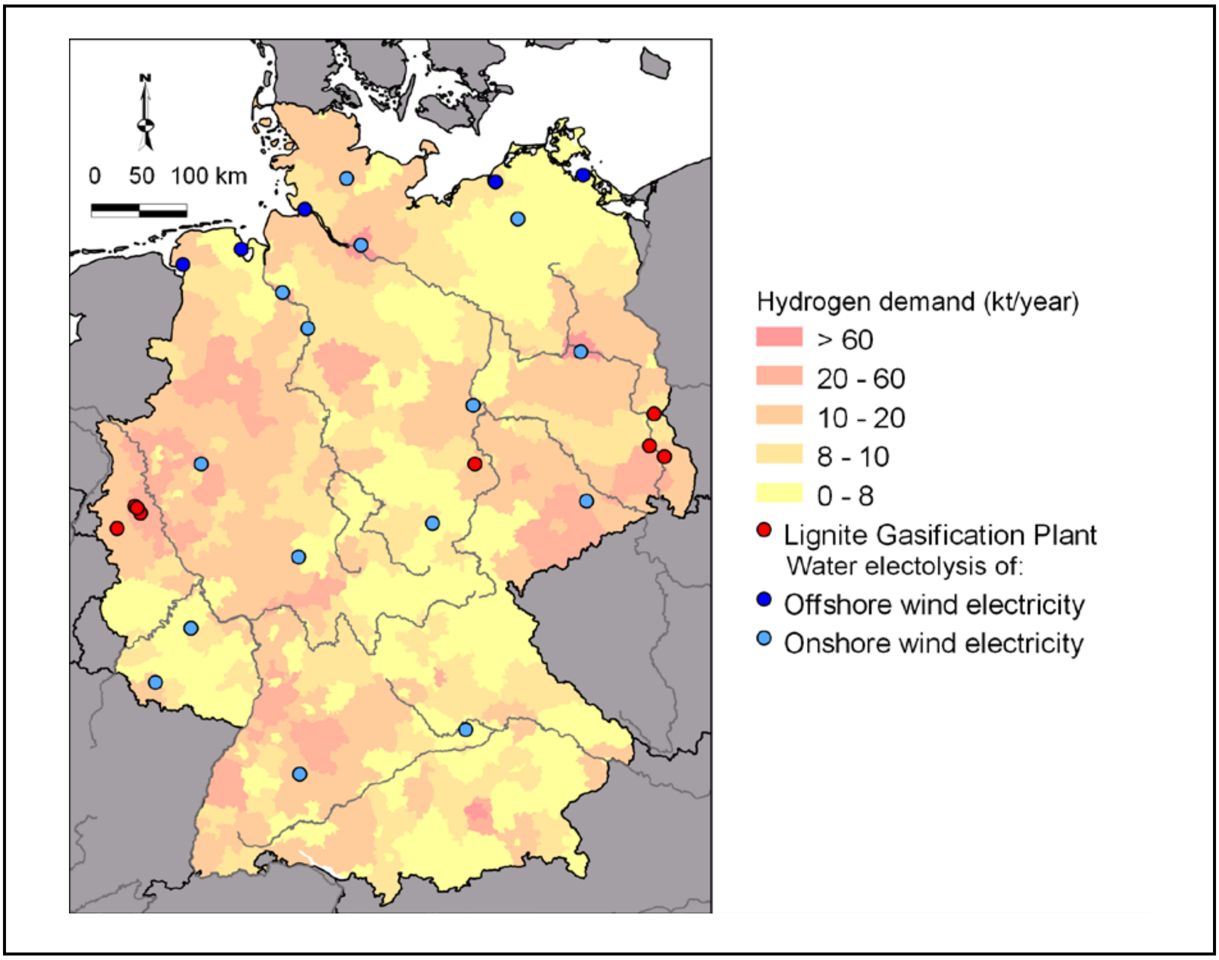
3.4 Definition of scenarios – Naming convention and main characteristics

From the proposed hydrogen demand and production options, we define in Table 2 the scenarios retained for this study. In order to facilitate the description of results a scenario naming convention is defined. The assumed repartition and quantities of the hydrogen demand are shown on Figure 4, together with the locations of the hydrogen production plants considered in the various scenarios.

Table 2 – Summary of scenarios – Naming convention and main characteristics

		H_2 Production		
		Electrolysis with **offshore** wind generated electricity: **50%** Electrolysis with **onshore** wind generated electricity: **50%**	Electrolysis with **offshore** wind generated electricity: **50%** **Gasification of domestic lignite**: **50%**	Electrolysis with **offshore** wind generated electricity: **50%** **Not transported by the pipeline network**: **50%**
H_2 Demand	**All districts**	A-100%	B-100%	C-100%
	Districts with demand: **> 8000 t/year**	A-8000	B-8000	C-8000
		Scenario names		

Figure 4 Repartition of the assumed hydrogen demand and locations of hydrogen production plants



Source: Own calculations

4 Results

4.1 Transmission network

For the proposed scenarios, the costs of the transmission networks vary between 2 and 6 Billion €, while the pipeline total lengths vary between approx. 4,700 km and 12,000 km (See Table 3). Both costs and lengths correlate with the number of districts connected to the network. The percentages of pipeline sections with low, medium and high capacity are similar in all scenarios. Depending on the considered scenario, 40 to 50% of them provide the minimum capacity with a diameter of 100 mm, while 35 to 45% have a medium capacity (diameter between 101 mm and 300 mm). Approximately 15% of pipeline elements exceed a diameter of 300 mm. Specificities of scenarios shall be discussed in the following sub-chapters.

Table 3 – Characteristics of the simulated transmission networks (exemplary cost calculation)

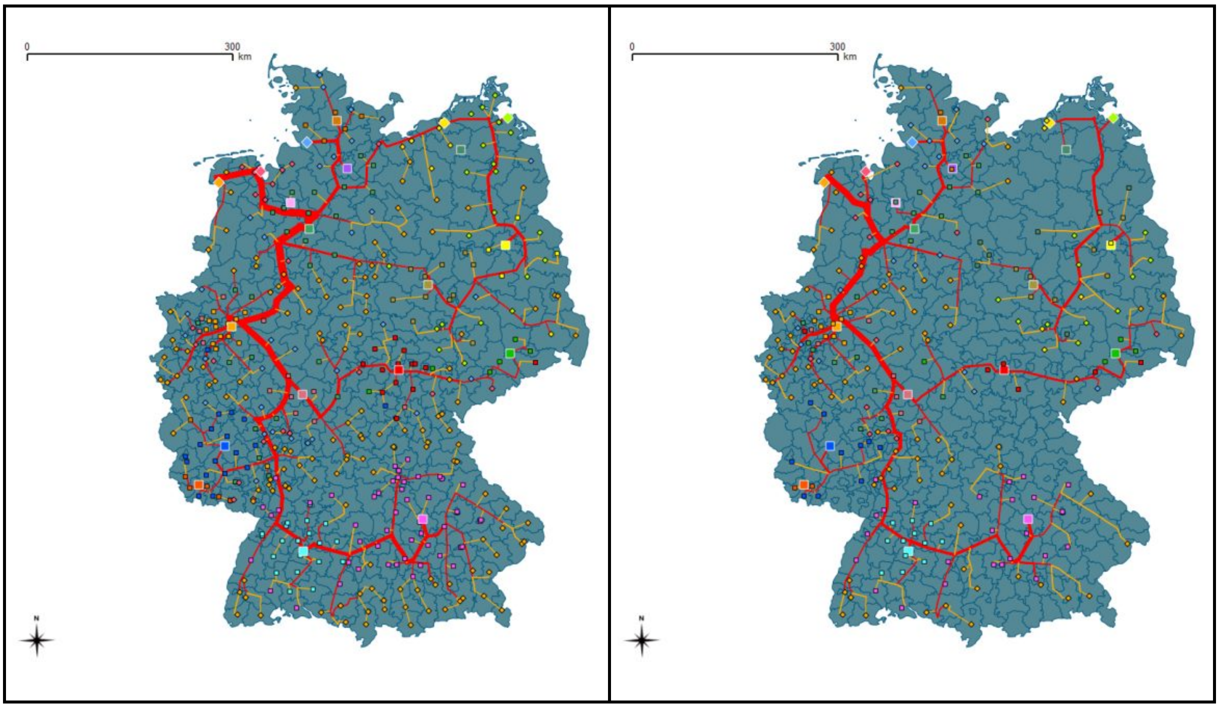
H_2 transmission network			
Scenario -	Number of districts #	Cost [Billion €]	Length [km]
A-100%	413	5.93	12,046
A-8000	242	4.40	9,246
B-100%	413	5.85	12,009
B-8000	242	4.51	9,273
C-100%	189	2.95	6,384
C-8000	119	2.18	4,682

Source: Own calculations

4.1.1 Scenarios A-100% and A-8000

The results of scenarios A-100% and A-8000 are displayed in Figure 5. Sources are represented by big squares (onshore-source) and rhombuses (offshore-source). Small symbols stand for sinks while their shape and colour indicate by which source they are supplied. Size and colour of the line-shaped pipeline branches illustrate the corresponding capacity. The scenarios differ in the number of administrative districts connected to the transmission network and in the sequence they are connected. Although the sequence of connection has a substantial impact on the result in general, the prioritisation of four districts (Berlin, Hamburg, Stuttgart, Munich, see chapter 3.1.1) has nearly no effect on the pipeline design in scenario A-8000 (See Figure 5). This is due to the proximity of hydrogen sources to those sinks. Pipelines connecting those districts are rather short and therefore marginal constraints for remaining calculations. Figure 5 also shows that the algorithm produces a sensible overall network instead of many single connections from sinks to sources.

Figure 5 Transmission networks of scenario A-100% (left) and A-8000 (right)

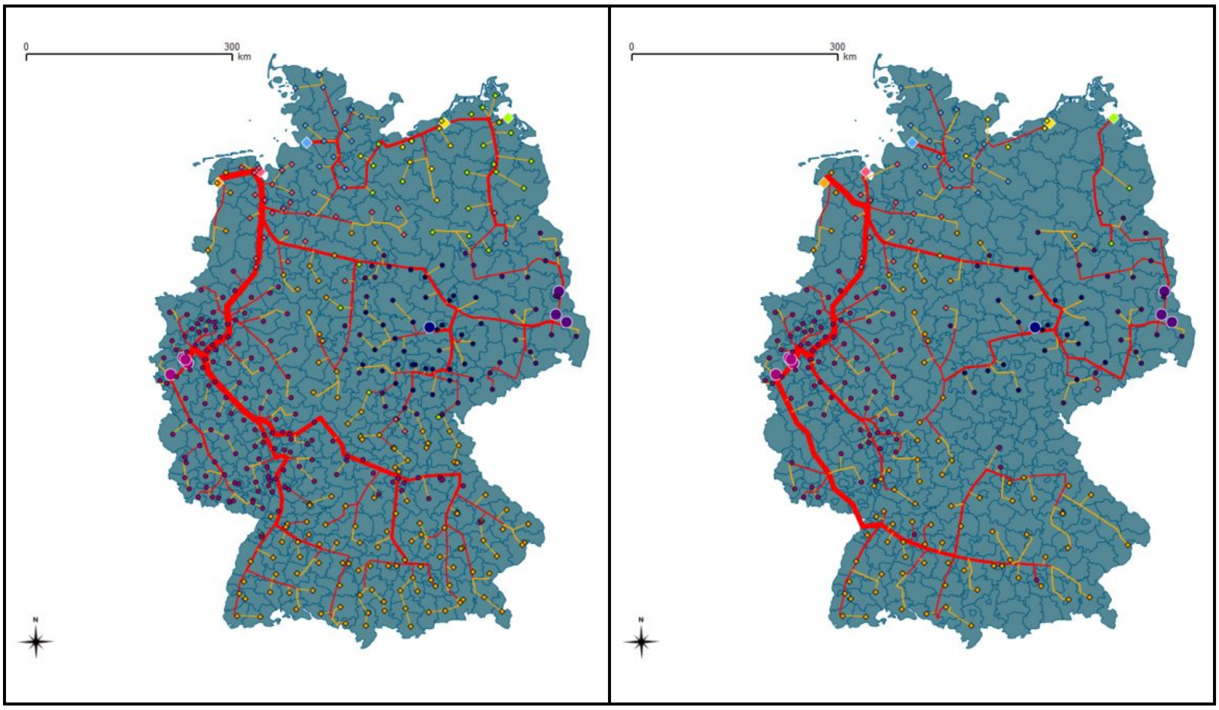


Source: Own calculations

4.1.2 Scenarios B-100% and B-8000

Figure 6 shows the resulting pipeline network of scenarios B-100% and B-8000. Sources are represented by big circles (lignite-source) and rhombuses (offshore-source). In contrast to scenarios A-100% and A-8000, the southern parts of the pipeline networks differ in shape essentially. This is caused by the prioritisation of the districts “Stuttgart” and “Munich” in scenario B-8000. Only distant sources are available for those sinks, so a long pipeline is necessary to connect them. The resulting pipeline connection is a constraint that influences further calculations. A lot of sinks in the vicinity of this pipeline are likely to use and extend this already established connection. So the long sickle-shaped pipeline of high capacity in the south-west is a consequence of the prioritisation.

Figure 6 Transmission networks of scenario B-100% (left) and B-8000 (right)

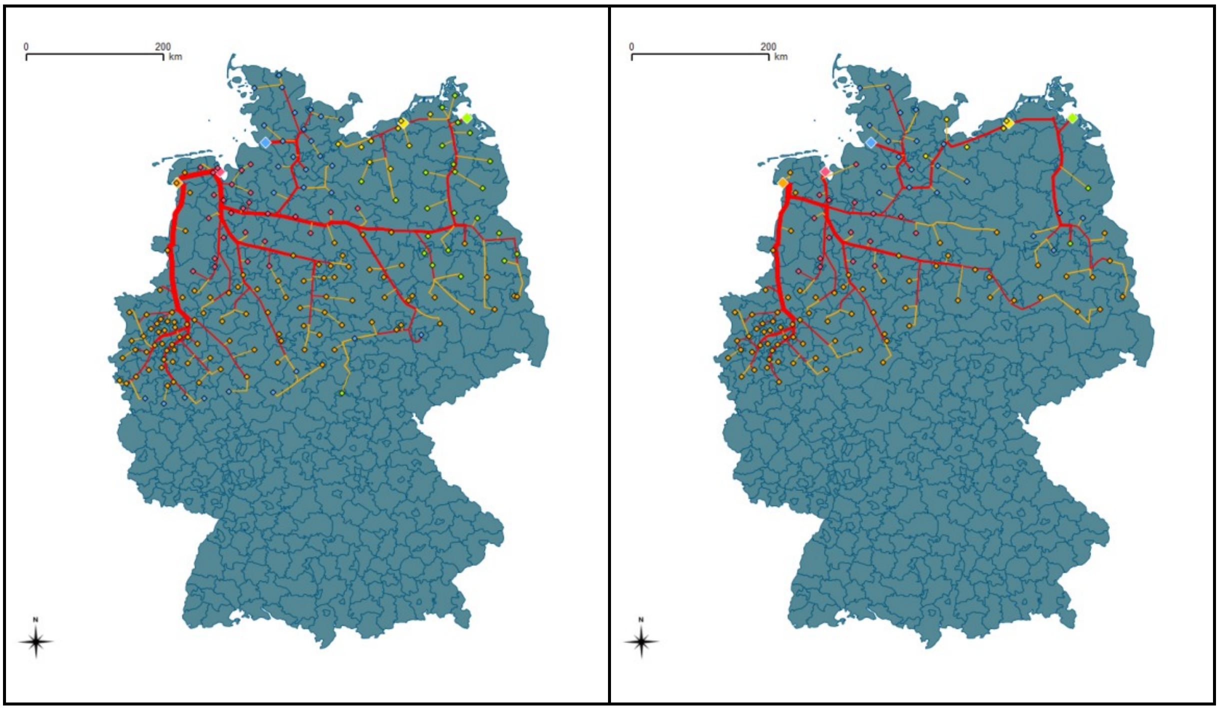


Source: Own calculations

4.1.3 Scenarios C-100% and C-8000

The results of scenarios C-100% and C-8000 are displayed in Figure 7. As before, offshore-sources are represented by big rhombuses. The results of these scenarios are influenced by the sequence of sink-connection, too. While the district “Berlin” is supplied by a western source “Emden” in scenario C-100%, it is supplied by the most eastern source “Lubmin” in scenario C-8000. This is caused by the prioritisation of “Berlin” in scenario C-8000 and the relatively low capacity of “Lubmin”. In scenario C-100% the source “Lubmin” is already exhausted when “Berlin” is to be connected to a source. So the only source providing enough hydrogen for Berlin is chosen.

Figure 7 Transmission networks of scenario C-100% (left) and C-8000 (right)



Source: Own calculations

4.2 Distribution network

The constraints concerning the distribution network are identical in all scenarios. This implicates that the sub-network of each district is identical in all scenarios too. The overall distribution network consists of the sub-networks of either all districts (scenarios A-100% and B-100%) or selected districts (scenarios A-8000, B-8000, C-100% and C-8000). The costs and lengths of the calculated distribution networks may vary significantly from scenario to scenario in general, while scenarios with the same selection of administrative districts generate identical results (See Table 4).

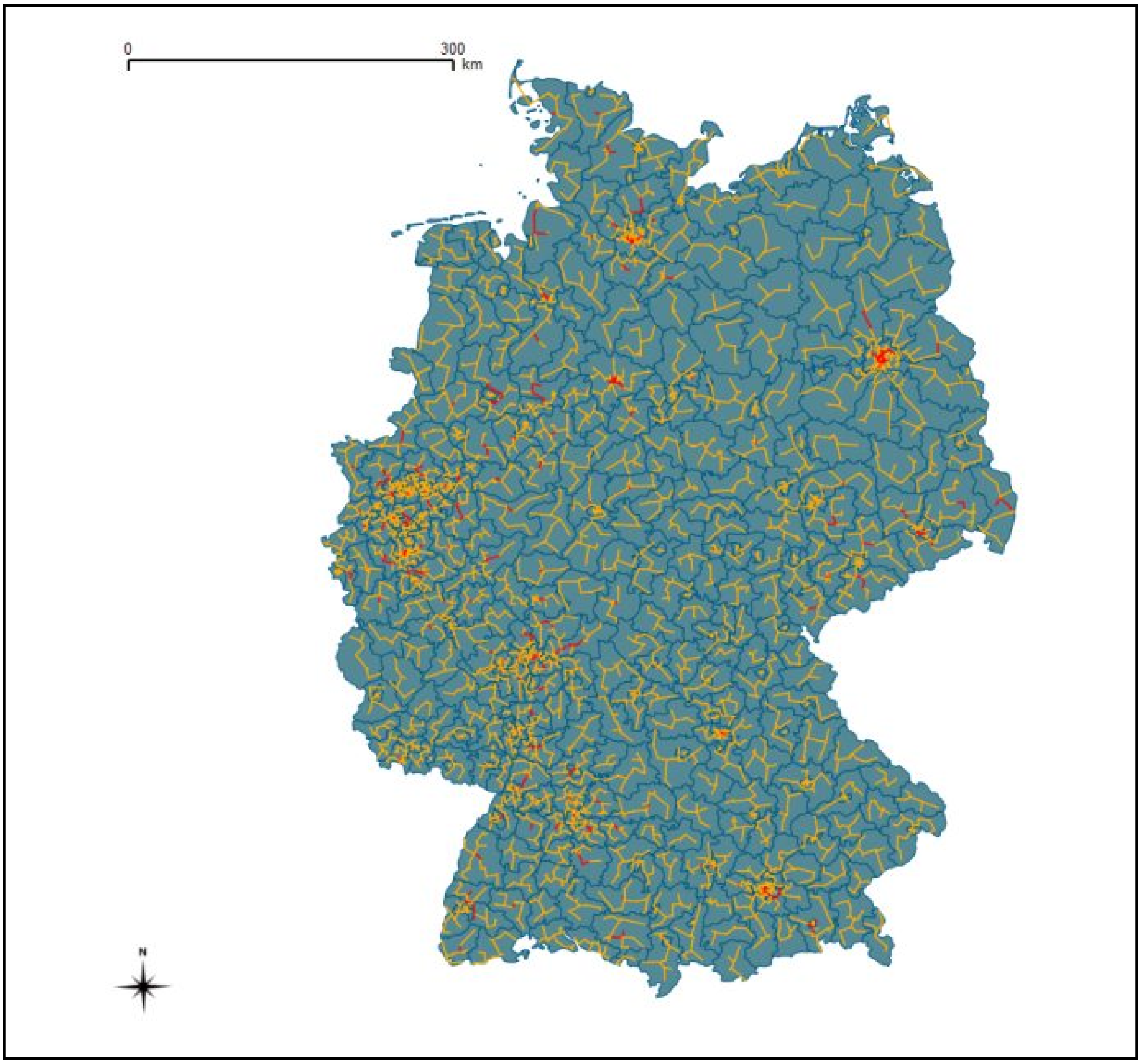
Table 4 – Characteristics of the simulated distribution networks (exemplary cost calculation)

H_2 distribution network			
Scenario -	Number of districts #	Cost [Billion €]	Length [km]
A-100% B-100%	413	10.72	26,388
A-8000% B-8000%	242	8.12	19,653
C-100%	189	5.71	13,501
C-8000	119	4.36	10,135

Source: Own calculations

As expected, the distribution network is more expensive than the transmission network and exceeds by far its length. Another notable difference is the required pipeline capacities. Compared to the transmission pipelines, most of the distribution ones are set at the minimum diameter (100 mm here), still providing a surplus-capacity (See chapter 3.2). Depending on the considered scenario, only 5% to 7% of the pipeline's branches exceed this diameter. Under our assumptions, the cost of the distribution network is significantly more affected by its total length than by its capacity. Figure 8 exemplary shows the distribution network of scenario A-100% where pipeline sections greater than 100 mm are coloured red. It is evident that most of the network provides a low capacity.

Figure 8 Distribution network of scenario A-100%



Source: Own calculations

5 Discussion

Within the course of this study, we developed a tool able to generate a sensible pipeline network between several sources and sinks. The capacities and needs of sources and sinks respectively can be defined on an individual basis (as also do their localisations) which allows computing tailored scenarios. A significant amount of technical and sociological data was also gathered and geo-referenced to refine the assumptions of future studies. The possibility to define (and weight) preferred routes for the construction of new infrastructures was also successfully implemented in this tool. For the purpose of this article, the existing gas network was proposed as the preferred route for a future hydrogen transmission network. Other routes could be envisaged. It might also be wished to restrict the allowable routes (for example, following the existing roads could be forced for the distribution network). Further works are planned to test additional scenarios, amongst others different market penetration of hydrogen-fuelled vehicles or capacities of refuelling stations.

The model simulates the final state of the network under several assumptions. Simulating the temporal network deployment would be theoretically possible. In this case, it should be strategically decided whether or not the first pipeline sections could be overrated to accommodate growing flows in the future. For long-term planning/building of new infrastructures, this would surely make more sense than allowing laying several parallel pipelines along a route and/or laying lengths of small pipelines along new routes to serve recent sinks. It however requires the model to be informed of the final supply needs.

The current model considers the time variability of neither the production nor the demand. As a consequence, buffer storages are – implicitly – required but not accounted for in the proposed calculations. As a first-level mitigation measure, we defined the production 10% in excess of the demand such as the pipelines are slightly overrated and might accommodate some demand peaks.

The cost function for pipelines is to be refined and varied to reflect the wide cost range found in the literature, as discussed in [Baufumé et al., 2011]. The recompression stations were considered in adding an averaged lump sum on top of the pipeline costs. However their position, size and number were neither precisely determined nor optimised. The model also does not consider the operating costs when defining the network.

With a view to produce more realistic results, the assumptions for the distribution network could be improved. The daily tonnage deliverable in refuelling stations could be defined for each station considering its location but also after a first feasibility check regarding the surface available. Due to the high shares of fix costs when installing small-diameter pipelines, it is also expectable that stations with low demand would not be supplied by pipelines. On site hydrogen production or trailer delivery would probably be preferred instead. Finally, the interconnection between the transmission network and the distribution sub-networks was arbitrarily defined at the barycentre of each district which do not have real meaning in the local infrastructures. Clustering demanding stations would be another option to define this point.

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