Design of hydrogen transmission pipeline networks with hydraulics

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Abstract

In order to enable a more sustainable transport sector in the future, a mixed-integer linear programming (MILP) model is developed with the aim of designing a pipeline network for hydrogen transmission. The objective of the optimisation is the minimisation of the network cost while taking hydraulics into consideration. Relevant features, i.e. maximum flow rate and facility location problem are included. Furthermore, the objective of pipeline safety is investigated based on an index-based risk assessment by Kim and Moon [1]. To examine the capabilities of the developed model, a case study on Germany is conducted for several scenarios. The optimised networks are discussed and compared. A Pareto frontier is computed in order to study the trade-off between network cost and safety.

Keywords: hydrogen pipeline networks; hydraulics; MILP; multi-objective Optimisation

1 Introduction

As the concept of sustainability for future applications in the energy and transport sector is gaining importance, the interest in hydrogen as an alternative to fossil fuels is increasing. With its versatility concerning production, storage and transport technologies, as well as its function as a low emission energy-carrier, hydrogen offers itself to ensure energy security in a society relying on regenerative resources. Due to the continual research and improvement on fuel cell vehicles (FCV) [2], hydrogen will be especially beneficial in the transport sector.

To this end, a hydrogen supply chain (HSC) has to be put into place to secure hydrogen availability and promote popularity of FCV. The so-called 'chicken-and-egg'-dilemma [3] outlines the difficulties that are connected to the construction of an extensive HSC: companies involved in hydrogen production are reluctant to invest into the HSC without prospects of profit, while hydrogen consumers will hesitate to buy FCV as long as the infrastructure is lacking. It is, therefore, of interest to both parties, that research is conducted on the HSC and its individual components to enable a smooth transition into a hydrogen-fuelled society. The individual components of a HSC consist of hydrogen production, storage and transportation technologies. For the latter, distribution and transmission of hydrogen can be distinguished. The physical state of hydrogen is vital for the chosen transportation mode. Liquid hydrogen is, i.e. transported by cryogenic trucks, gaseous hydrogen by tube trailers or pipelines [4, 5]. Hydrogen production technologies range from highly emission-intensive, i.e., coal gasification and steam methane reforming (SMR), to carbon-neutral ones, i.e., biomass gasification and water electrolysis [6, 7]. The former technologies offer themselves to centralised hydrogen production scenarios, but should be combined with carbon capture and storage (CCS) to ensure sustainability. Water electrolysis is expected to be of interest in the future due to its modular nature and flexibility concerning the start-up process.

Mathematical models on HSC investigating a selection of hydrogen technologies have been discussed in literature many times over [8, 9, 10, 11, 12]. Some of the earliest research has been done by Almansoori and Shah [13], and a lot of models are based on their work or contain some components [6, 8, 9, 10, 11, 12, 14, 15, 16, 17, 18]. Apart from the technologies which are included, these works differ in their objective. Some of them evaluate the network profit [14], while most concentrate on minimising the investment cost [9, 12, 13, 18]. Furthermore, multi-periodity is investigated [9, 16, 18]. While most of the aforementioned works define the hydrogen demand over a grid, several studies apply geographical information systems (GIS) in order to enable a more detailed analysis of the demand distribution [19, 20].

Multi-objectivity is another much researched topic in HSC. The most favoured objective is the economic cost of the HSC. Other objectives in literature are environmental impact [6, 10, 21, 22, 23] and safety [1, 8, 24]. For the former, several approaches have been developed. Firstly, principles of Life Cycle Assessment (LCA) have been used by Guillen-Gosálbez *et al.* [10]

and Sabio *et al.* [6]. Secondly, Almansoori and Betancourt-Torcat defined the environmental impact by carbon-dioxide emission [23]. For safety considerations, a risk assessment has been developed and applied by Kim and Moon [24]. Finally, multi-objective works considering all three objectives have been conducted by Han *et al.* and Almaraz *et al.* [8, 14, 25, 26].

Little research has been conducted on hydrogen pipelines, despite them being suitable to transport large volumes of hydrogen over large distances [27]. Johnson and Ogden have developed a model that allows the optimisation of interconnected pipeline networks [28]. Baufumé *et al.* investigate scenarios for a pipeline network for Germany combined with GIS [20] and André *et al.* develop an *local search* method optimising both the network design and dimensioning [29].

In the scope of this work, a mixed-integer linear programming (MILP) model for the optimisation of a pipeline network in Germany is developed based on the non-linear programming (NLP) model by André *et al.* The detailed formulation of the MILP model is presented in Section 3. The mathematical model formulations allow the minimisation of economic cost while determining the optimal pipeline network design and diameter of the pipe segments. The implementation of the facility location problem into the model is described in three scenarios. Furthermore, the mathematical formulations are extended to a multi-objective problem. The case study on Germany is presented in Section 4. Then, in Section 5, the results for each scenario are discussed and, if relevant, compared to each other. Finally, Section 6 gives some concluding remarks and suggests future work.

2 Problem statement

The goal of this work is the design of an optimised hydrogen pipeline network. This includes the determination of the most advantageous pipeline connections, but also their dimensions. To this end, the locations of demand centres as well as their individual hydrogen demand are given. The connections between the nodes represent potential pipeline arcs; the distances that they span are defined as the delivery distance and by that as the length of a potential pipeline. The pipeline dimensions are chosen from a set of discrete diameters.

In addition to the goal of designing the optimal pipeline network and its dimensions, other factors of interest are the flow rates of hydrogen inside of the pipelines, as well as the pressure losses occurring over delivery distances. Hydraulics of the pipeline are considered to obtain this information. International import of hydrogen is enabled and the amount of hydrogen imported in a network is determined. Furthermore, the optimal location of the supply nodes is investigated.

The objective of the model is the minimisation of the total cost linked to the construction and the operation of such a hydrogen pipeline network. Total cost include the annualised investment and maintenance cost for hydrogen pipelines and hydrogen production sites. A fraction of the investment cost is allocated as annual maintenance cost. Furthermore, operational costs are considered in form of the hydrogen production cost.

3 Mathematical model

The hydrogen pipeline network problem is based on the NLP formulation by André *et al.* [29]. By approximation and addition of other features, i.e. a neighbourhood-flow approach and a restriction on the flow rate, an MILP problem formulation is developed. The model is formulated in the General Algebraic Modeling System (GAMS) and solved using CPLEX 12.7.1.0 solver on a 2.6 GHz, 128 GB RAM machine (Intel® Xeon® CPU E5-2640 v3).

Objective function The total network cost TC is composed of the pipeline investment and maintenance cost PC, the hydrogen production HC and import IC cost as well as the production site FC investment and maintenance cost.

$$TC = HC + IC + PC + FC \tag{3.1}$$

The capital recovery facor crf converts the overall investment costs to portions that are due annually.

$$crf = \frac{it(1+it)^n}{(1+it)^n - 1}$$

where it is the interest rate and n the number of annuities.

The annual maintenance cost of pipelines are estimated based on the pipeline investment cost CCP.

$$MP = m_p * CCP$$

Maintenance cost of production sites are determined in a similar manner.

Pipeline transmission A graph consisting of a set of nodes $i \in N$ is constructed. The connection between these nodes is denoted as the subset of arcs $A \in N \times N$. Hydrogen can be transported on all arcs of the subset. The subset A is adjusted with help of an adaption of the neighbourhood-flow approach that has been developed by Akgul *et al.* [30] (Section A.1.1). The approach limits the subsets of possible pipeline connections to those that connect nodes in neighbouring regions. Exceptions are made for very short arcs.

A mass balance at each node ensures that the demand dem_i is covered by either hydrogen supply directly at the node sE_i, hydrogen import $\hat{I}_i$ or flows from other nodes $\sum_{j|(j,i)\in A} Q_{ji}$:

$$sE_i + \hat{I}_i + \sum_{j|(j,i)\in A} Q_{ji} = dem_i + \sum_{j|(i,j)\in A} Q_{ij}, \forall i \in N \tag{3.2}$$

At the same time, the overall hydrogen demand of the network M_S is provided by both hydrogen supply and import. No surplus hydrogen is allowed to be produced or imported.

$$\sum_{i\in N} sE_i + \sum_{i\in N} \hat{I}_i \leq M_S \tag{3.3}$$

The hydrogen flow on the inside of the pipelines is modelled by a linearised form of the general flow equation [31]. For approximation, the square of the pressures at individual nodes is defined as a continuous variable π_i and a set of discrete diameters $d \in D$ are introduced. Piecewise approximation is applied to the bilinear pressure term $\sqrt{\pi_i - \pi_j} Y_{dij} \equiv \theta Y_{dij}$. Details on the equations for piecewise approximation can be found in the Appendix, Section A.1.2.

$$\sum_{d\in D} \hat{d}_d^{2.5} \theta Y_{dij} = k_{pl} {L_{ij}}^{0.5} Q_{ij}, \forall (i,j) \in A \tag{3.4}$$

The binary variable Y_{dij} allows the pipeline arcs of the subset A to be chosen according to the active pipeline network. Although the subset of arcs A allows for bi-directionality, the flow between two nodes is restricted to a single direction.

$$\sum_{d\in D} Y_{dij} + Y_{dji} \leq 1, \forall (i,j) \in A \tag{3.5}$$

Depending on the diameter $\hat{d}_d$ that is chosen for the active pipeline arc, the flow rate Q_{ij} is restricted by the maximum flow rate kQ_d^{max} associated with the average pressure ψY_{dij} in the pipeline.

$$Q_{ij} \leq \sum_{d \in D} kQ_d^{max} \psi Y_{dij}, \forall (i,j) \in A \tag{3.6}$$

Parameter kQ_d^{max} connects the flow rate at standard conditions Q_{ij} to the flow rate at active pipeline conditions Q_a by the equation of continuity. By this, velocities in the pipeline are restricted to $30\,\mathrm{m\,s^{-1}}$ [3]. For the determination of the average pressure in the pipeline, a simple approach is chosen:

$$\bar{\pi}_{ij} = \sqrt{0.5(\pi_i + \pi_j)}$$

This approach yields similar values as the equation commonly found in literature [31] and, at the same time, can easily be approximated by piecewise linearisation, similarly to the aforementioned pressure difference. To this end, the continuous variable $\psi Y_{dij} \equiv \sqrt{0.5(\pi_i + \pi_j)} Y_{dij}$ is introduced for the bi-linear term of the average pressure. Again, the approach is detailed in the Appendix (Section A.1.3.).

Another constraint is introduced, restricting the flow rates further. By doing so, Equation 3.4 is bound to its feasible region.

$$Q_{ij} \leq \sum_{d \in D} Q_d^{max} Y_{dij}, \forall (i,j) \in A \tag{3.7}$$

Here, Q_d^{max} is the maximum flow rate allowed by the general flow equation. Finally, the range of the squared pressures is defined by adding an upper and lower bound.

$$\pi^{min} \leq \pi_i \leq \pi^{max}, \forall i \in N \tag{3.8}$$

Both the diameter $\hat{d}_d$ and the length L_{ij} of a pipeline affect its cost. As the investment cost of pipelines is a quadratic function, the diameter has a more distinct influence. The investment cost for pipelines is based on the equations by Yang and Ogden [32] but linearised by discretisation of the diameter.

$$PC = (crf + m_p) \sum_{(i,j) \in A} L_{ij} \sum_{d \in D} (a_0 + a_{12d}) Y_{dij} \tag{3.9}$$

where a_0 and a_{12d} are the cost coefficients and m_p is the percentage of the investment cost allocated to annual maintenance.

Facility location The facility location problem is treated in three scenarios: *A)* the supply node is arbitrarily defined (base scenario), *B)* The location of a single supply node is optimised, and *C)* production sites are chosen with respect to available capacities. In the last scenario, SMR is chosen as a production technology. Each scenario brings the network model closer to reality, but at the same time, the importance of an ideal pipeline network design decreases. It has to be mentioned that all of the nodes i are considered as possible hydrogen production sites for scenario two and three. Other factors, i.e., the availability of suitable sites for the construction of production facilities, are neglected.

The maximum hydrogen supply is restricted to the overall hydrogen demand for all three scenarios.

$$sE_i \leq M_S E1_i, \forall i \in N \tag{3.10}$$

This definition prevents surplus production of hydrogen and at the same time introduces the binary variable $E1_i$, which chooses the active supply nodes from the set of available ones. For each active supply node, the pressure at which hydrogen is supplied is restricted.

$$\pi_i \geq \pi^{max} E1_i, \forall i \in N \tag{3.11}$$

It is assumed that hydrogen is supplied at maximum pressure $\pi^{max} = (p^{max})^2$. Again, the pressure bound applies only for active supply nodes, which is achieved by the use of the binary variable $E1_i$. The greater sign in Equation 3.11 has been chosen due to the necessity of enabling pressures greater than zero for those nodes that are not used for hydrogen supply. Combining this inequality equation with Equation 3.8, the pressure at node i is determined as the maximum pressure at supply nodes, while for all other cases the pressure is allowed to vary between minimum and maximum pressure as computed by the application of the pressure loss equation (see Equation 3.4).

For scenario *A)*, $E1_i$ is defined according to the desired production node. Scenario *B)* with one optimised supply node requires an additional constraint regarding the number of constructed supply nodes. This definition allows only one supply node to be activated.

$$\sum_{i \in N} E1_i \leq 1 \tag{3.12}$$

Lastly, scenario *C)* requires the extension of the binary variable $E1_i$ by the set of capacities $k \in K$. A new binary variable E_{ki} is therefore introduced and Equations (3.10) to (3.12) are adjusted accordingly:

$$sE_i \leq \sum_{k \in K} A_k E_{ki}, \forall i \in N \tag{3.13}$$

where the parameter A_k defines the capacities of each production plant size.

$$\pi_i \geq \pi^{max} \sum_{k \in K} E_{ki}, \forall i \in N \tag{3.14}$$

$$\sum_{i \in N} \sum_{k \in K} E_{ki} \leq 1 \tag{3.15}$$

Equation 3.14 is responsible for defining the pressure at which hydrogen is supplied, while Equation 3.15 is altered slightly, the adjustment permitting one production site of a certain capacity per node.

The cost coefficients for hydrogen production and import are introduced as parameters cH and ip, respectively. Accordingly, the annual cost of hydrogen production is defined as follows:

$$HC = cH \sum_{i \in N} sE_i \tag{3.16}$$

In the same manner, hydrogen import cost depends on the volume of hydrogen that is imported from other countries.

$$IC = ip \sum_{i \in N} \hat{I}_i \tag{3.17}$$

The investment and maintenance cost for the construction of hydrogen production sites is included in scenario *C)*. As before, the annual maintenance cost is assumed to be a fraction m_f of the overall investment cost.

$$FC = (crf + m_f) \sum_{i \in N} \sum_{k \in K} ccA_k E_{ki} \tag{3.18}$$

Safety objective As an additional objective, the safety of the pipeline network is of interest, especially because of the high combustibility of hydrogen as compared to conventional fuels. The index-based risk assessment developed by Kim *et al.* is, therefore, implemented for the pipeline network [1].

According to Kim *et al.*, the total relative risk of a hydrogen operation depends on the inherent risk factor (IRF) of the specific operation and the environmental impact factor (EIF) which describes the safety of its location. Since pipelines connect different regions, the total relative risk index (TRRI) depends on the safety of the starting and ending region, as well as the intermediate ones.

$$TRRI = \sum_{(i,j)\in A} IRF \; EIF_{ij} \tag{3.19}$$

The epsilon-constraint method is applied as a solution strategy for the multi-objective model version [33]. The method converts the safety objective into a constraint and minimises the annualised cost for different upper bounds on the TRRI. This way, the different Pareto-optimal solutions, each of them composing an individual hydrogen network design, are computed. The possible configurations are then visualised in the Pareto frontier, from which the most promising design can be chosen depending on preference of the developer.

Model summary Three optimisation problems can be derived from the formulations for facility location, as defined by the labels *A)* to *C)*. The model equations for each scenario are summarized in the following:

$$\text{Scenario } A) \qquad \begin{aligned} \min \quad & TC \\ \text{s.t.} \quad & \begin{cases} \text{Demand constraints (3.2)} \\ \text{Production constraints (3.10) and (3.11)} \\ \text{Import constraints (3.3)} \\ \text{Hydraulics (3.4) to (3.8) and (A.1) to (A.10)} \end{cases} \end{aligned} \tag{3.20}$$

$$\text{Scenario } B) \qquad \begin{aligned} \min \quad & TC \\ \text{s.t.} \quad & \begin{cases} \text{Demand constraints (3.2)} \\ \text{Production constraints (3.10) to (3.12)} \\ \text{Import constraints (3.3)} \\ \text{Hydraulics (3.4) to (3.8) and (A.1) to (A.10)} \end{cases} \end{aligned} \tag{3.21}$$

$$\text{Scenario } C) \qquad \begin{array}{ll} \min & TC \\ \text{s.t.} & \begin{cases} \text{Demand constraints (3.2)} \\ \text{Production constraints (3.10), (3.14) and (3.15)} \\ \text{Import constraints (3.3)} \\ \text{Hydraulics (3.4) to (3.8) and (A.1) to (A.10).} \end{cases} \end{array} \tag{3.22}$$

Each of the scenarios can be extended to a multi-objective optimisation problem by including the epsilon-constraint of the safety objective, as presented with the example of scenario *A)*.

$$\text{Multi-objective} \qquad \begin{array}{ll} \min & TC \\ \text{s.t.} & \begin{cases} TRRI \leq \epsilon \\ \text{Demand constraints (3.2)} \\ \text{Production constraints (3.10) and (3.11)} \\ \text{Import constraints (3.3)} \\ \text{Hydraulics (3.4) to (3.8) and (A.1) to (A.10)} \end{cases} \end{array} \tag{3.23}$$

4 Case study

A case study is performed on Germany to put the different model versions to test. In Germany, a great interest in alternative fuels is given in the energy and transport sector. This is closely connected to politics, but also greatly supported by the population. One of the aims pursued by politics, i.e., is to shut down all nuclear power plants until 2022 [34]. Another goal envisaged until 2050 are zero emissions [23]. The NUTS-1 resolution consisting of the 16 states of Germany is applied for each scenario the case study. For each state, the city with the largest population functions as a node.

Demand assumptions For the determination of the hydrogen demand of the individual states, a market scenario developed in the scope of Hyways project, a European consortium striving for a sustainable future with help of hydrogen [35], is chosen. With the assumption of high policy support and a modest learning curve, the market penetration rate of hydrogen is set to 40 %. Based on this penetration rate, a hydrogen demand for the transportation sector is determined

$$dem_i = \frac{1}{\rho_b} PT\ P_i\ VO_i\ CU\ fc \qquad (4.1)$$

where dem_i is the demand, PT the market penetration rate, P_i the population of each region, VO_i is the vehicle ownership in each region, CU the car use per year and fc the fuel consumption. A similar approach is frequently applied in literature [7, 8, 13, 36]. The hydrogen demand determined for each German state is presented in Table 4.1.

Nuts code	Name of state	Largest city	Population $[10^6]$	H_2 demand $[10^3\,m^3\,hr^{-1}]$
DE1	Baden-Wurttemberg	Stuttgart	10.5	376.5
DE2	Bavaria	Munich	12.4	452.5
DE3	Berlin	Berlin	3.3	69.1
DE4	Brandenburg	Potsdam	2.5	83.5
DE5	Bremen	Bremen	0.7	17.1
DE6	Hamburg	Hamburg	1.7	45.4
DE7	Hesse	Frankfurt	6.0	212.8
DE8	Mecklenburg-Western Pomerania	Rostock	1.6	51.2
DE9	Lower Saxony	Hanover	7.8	275.1
DEA	North Rhine-Westphalia	Cologne	17.5	586.6
DEB	Rhineland-Palatinate	Mainz	4.0	146.6
DEC	Saarland	Saarbrücken	1.0	37.9
DED	Saxony	Dresden	4.1	128.8
DEE	Saxony-Anhalt	Magdeburg	2.3	74.3
DEF	Schleswig-Holstein	Kiel	2.8	95.7
DEG	Thuringia	Erfurt	2.2	72.1
Total			80.4	2725.2

Table 4.1: Population and hydrogen demand of the 16 German states.

Pipeline transmission Standard conditions are defined for the consideration of hydrogen transmission. These conditions, as well as necessary physical properties of hydrogen and other parameters are presented in the Appendix (Table A.2). Other data, i.e. the defined discrete diameters of pipelines, delivery distances between nodes and bounds for pressure, is included in Tables A.2 to A.6. Tables A.7 and A.8 summarise the pipeline data for safety investigations. According to the investigations of Kim *et al.*, a risk level of IV is assigned for hydrogen transport via pipelines [24]. A risk level of IV implies several casualties in case of an accident occurring on a section of a hydrogen pipeline, as well as a negative impact on the environment of one to three years. Additionally, an interruption to the hydrogen transport occurs for several months.

Production plants As the problem formulation assumes a centralised hydrogen production scenario, SMR is chosen as a suitable technology. Three sizes of SMR plants are defined to appoint capacities, as presented in Table A.11.

5 Results and discussion

The aim of the proposed model is to design a hydrogen network with optimised diameter sizes, while satisfying the hydrogen demand in Germany. The solutions obtained by optimising the scenarios described in the model summary of Section 3 are presented. In the scope of the case study on Germany, the scenarios are defined as follows.

- Scenario *A)* (Section 5.1): Berlin (DE3) as single supply node
- Scenario *B)* (Section 5.2): Optimal location of single supply node
- Scenario *C)* (Section 5.3): Multiple production facilities

Additionally, each scenario is treated as a multi-objective optimisation problem, as described in Section 5.4.

5.1 Scenario *A*

Figure 5.1 presents the optimised network for the base scenario, which assumes Berlin (DE3), the capital of Germany, as a supply node. The data, i.e., the pipe diameters and flow rates determined by optimisation, are given in Table A.13: from Berlin, pipelines of diameters between 25 cm and 100 cm transmit hydrogen to all other parts of Germany. The largest flow of hydrogen is given in the pipeline connection between the supply node DE3 and its nearest neighbour Potsdam (DE4). With a flow rate of 2,656,217.7 $m^3\,hr^{-1}$ at standard conditions, only a pipeline of 100 cm is able to transport this large volume of hydrogen. From DE4 on, a pipeline branch stretches out in the direction of south-west. Reason for this is the large demand accumulating in that area. At Frankfurt am Main (DE7), the pipeline branch is split to provide hydrogen to the west and south of Germany. The overall annualised cost of the network system amount to 5225 Mio Euro yr^{-1}. Of this sum, 4775 Mio Euro yr^{-1} is allocated to hydrogen production. Rather high investment cost of 306 Mio Euro yr^{-1} for the pipeline system accrue due to large diameters of relevant pipeline arcs.

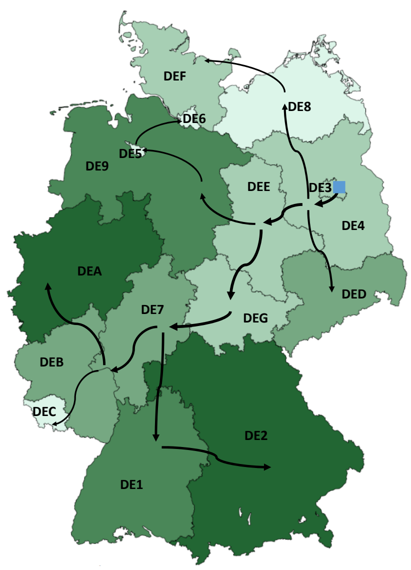

Figure 5.1: *Pipeline network design for supply node at DE3* (■).

The importance of pipeline diameter is revealed when comparing the network design of this work with the minimal spanning tree problem. In regard to delivery distance, little difference exists between both options, amounting to 1910.5 km for the base scenario and 1797.8 km for the minimal spanning tree system. This makes the gap in overall pipeline investment cost all the more surprising. While the network configuration designed by this work's model demands investments of overall 2959 Mio Euro into the pipeline system, the cost amount to 3231 Mio Euro for the shortest possible network design. The difference in overall cost can be explained by the diameters of the pipelines that are chosen for both network configurations. By minimising the objective cost, this work's model allows for an increase in delivery distance in order to decrease pipe diameters. This way, the capacity defined for the pipe diameters can be exploited for each pipeline segment of the network design.

5.2 Scenario *B*

As the distribution of demand already indicates, DE4 is not the best choice as a supply node. The eastern states of Germany have fewer inhabitants than the west and, therefore, demand of hydrogen for light-duty vehicles is lower. To locate the optimal supply node, scenario *B)* is investigated. The resulting pipeline network is presented in Figure 5.2. DE7 is identified as the optimal supply node for the given distribution of hydrogen demand. The city offers itself as a supply node due to its location in the centre of Germany,allowing for short delivery distances to cover the high demands of hydrogen in the south-west. Especially North-Rhine Westphalia (DEA) and Lower Saxony (DE9) in the north of DE7 as well as Baden-Wuerttemberg (DE1) and Bavaria (DE2) in the south stand out in terms of hydrogen demands. Those four regions are the ones with the highest hydrogen demands in overall Germany. From DE7 on, four separate pipeline branches spread out to cover the demand at all nodes. Each pipeline branch provides hydrogen for the north, east, south and west of Germany.

In comparison to base scenario, the annualised cost for the hydrogen network is reduced to 5084 Mio Euro yr^{-1} for scenario *B)*. This reduction by 140 Mio Euro yr^{-1} comes about as a result of the decreased volumes of hydrogen transported by pipelines, as presented in Table A.14. Pipeline diameters of 75 cm or less suffice for the four pipeline branches, while four pipelines of 100 cm are necessary for the base scenario (Table A.13). In contrast to the pipeline diameter, the length of the pipeline network for hydrogen delivery plays an insignificant role. Despite an additional pipeline length of about 120 km as compared to the base scenario, the overall pipeline investment cost of scenario B's network design is reduced.

5.3 Scenario *C*

With regard to capacities of SMR plants, the location of hydrogen supply nodes and the effect of their position on the network design are investigated in Scenario *C)*.

The results are presented in Figure 5.3. Six production plants of the

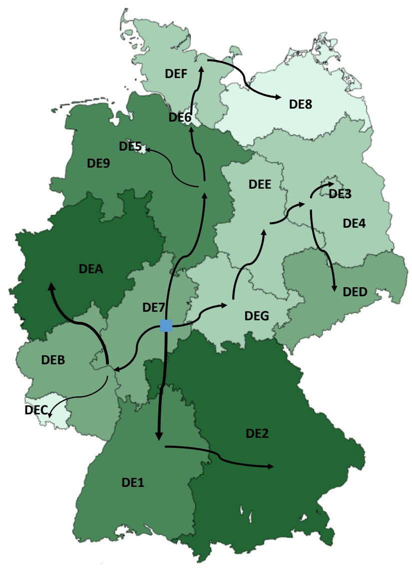

Figure 5.2: *Pipeline network design for the MILP problem with location of optimal supply node* (■).

largest possible size are built to satisfy the hydrogen demand, as presented in Tabel A.15. With hydrogen production rates between 376 to 500 $10^3\,\mathrm{m}^3\,\mathrm{hr}^{-1}$, all of the production plants utilise a large part to all of their capacity. It has to be noticed that four of the six hydrogen plants chosen during optimisation are located in the south-west, while only two plants supply the whole of the northern part of Germany. Pipelines are applied for the transmission of small volumes of hydrogen with the exception of the pipeline supplying DEA with hydrogen.

The overall annualised cost of the pipeline network amounts to 5480 Mio Euro yr^{-1}. A large part of this sum can be allotted to the investment and maintenance cost of production plants, which are determined with help of a cost analysis (Table A.12). This cost, at least in theory, would also accrue for the other scenarios, since the hydrogen which is transported has to be produced somewhere at some point. For comparison of the three scenarios, the investment cost of the pipeline network is therefore consulted. For the base sce-

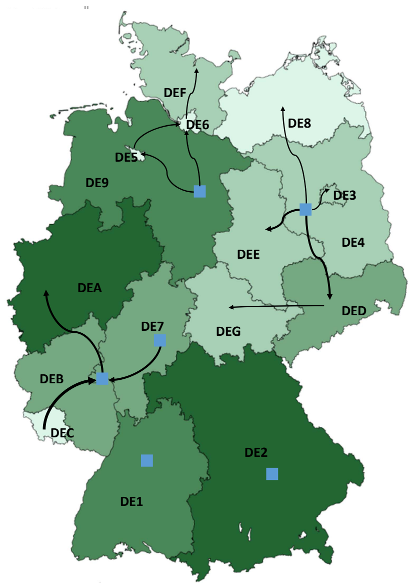

Figure 5.3: *Pipeline network design for the MILP problem with production facility location* (■).

nario, pipeline investment cost amount to 306 Mio Euro yr^{-1}. This amount is reduced to 209 Mio Euro yr^{-1} by locating the optimal supply node in scenario *B)*. Finally, by allowing several supply nodes, the number of necessary pipeline connections, and with them the cost of the pipeline system can further be reduced to 100 Mio Euro yr^{-1}.

A special feature of the pipeline network design of scenario *C)* is the import of hydrogen at DE7. A volumetric flow rate of 8034.9 $m^3\,hr^{-1}$ is imported, in addition to the 500 $10^3\,m^3\,hr^{-1}$ produced at the specific node. The import of this volume is reasonable due to the definition of the production capacities. With the capacity of the smallest available production plant being 4000 $m^3\,hr^{-1}$ and that of the medium plant being 70 $10^3\,m^3\,hr^{-1}$, only the latter would be able to produce the necessary amount of hydrogen. However, the construction of this plant would lead to a higher cost than the import of the amount of hydrogen necessary to satisfy the demand.

5.4 Multi-objective

An investigation of the trade-off between economic cost and pipeline safety is conducted for all three scenarios *A)* to *C)* The Pareto frontiers of the three scenarios *A)* to *C)* are presented in Figure 5.4. All Pareto-optimal solutions are computed by variation of the epsilon-variable in 20 equidistant steps to investigate the trade-off between economic cost and pipeline safety.

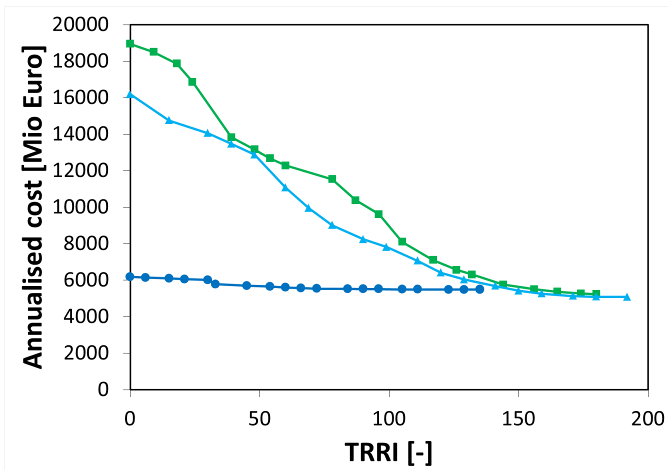

Figure 5.4: *Pareto sets of scenarios A)* [■], *B)* [▲] *and C)* [●]*) for multi-objective problem with cost and safety.*

Scenario *A)* is connected to high cost for the network design with zero TRRI. For this configuration, the whole of the hydrogen demand is covered by international import. However, with an overall cost of 18,948 Mio Euro yr^{-1}, this design is not suitable for realisation. Similarly, scenario *B)* gives a network design in which hydrogen is solely imported from other countries. Although the annualised cost of this scenario are lower than for scenario *A)*, which is triggered by the adjustment of the location of supply, the design is unsuitable due to energy security issues.

The most realistic scenario *C)* also achieves the most advantageous network designs. Such a solution is expected due to the possibility of reducing the volume of hydrogen transported by building production plants at several nodes. Furthermore, the TRRI of 147 is achieved by scenario *C)*, which is the lowest when comparing all three scenarios. The reason for this is the reduced number of pipeline connections necessary to satisfy the demand. Figure 5.5 shows the Pareto set of scenario *C)* in finer resolution. As with the Pareto frontiers of the other two scenarios, a pronounced drop at a TRRI of 30 indicates the point at which DEA is supplied by pipelines instead of import or hydrogen production at the node. From a TRRI of 72 on, the dependence of TRRI on annualised network cost decreases. This leads to networks which have similar cost but increase drastically regarding network risk. The network design should therefore be chosen from a region between a TRRI of 54 and 90.

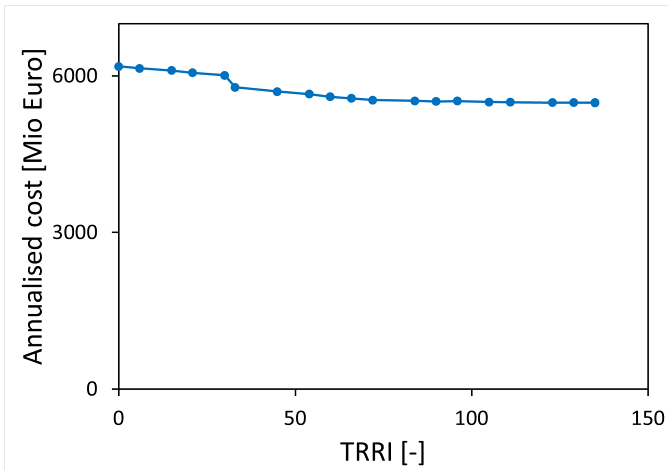

Figure 5.5: *Pareto set of scenario C)* [●]. *for multi-objective problem with cost and safety.*

6 Concluding remarks

This work has presented an MILP model for the design of a hydraulic pipeline network for hydrogen transmission. Additionally, the facility location problem has been considered in three scenarios. The first scenario has considered an arbitrarily defined node as the supply node; the second has localised the optimal node for hydrogen supply. In the last scenario, the model formulation has been extended to include capacities of hydrogen production plants. Optimisation of economic cost has been defined as the initial objective. Later on, safety of pipeline networks has been added as an objective for all three scenarios.

A case study on Germany has been conducted to investigate the capabilities of each model version. With the supply node located at DE3, large volumes of hydrogen have to be transported to the south-west of Germany. The high cost connected to this network design has been reduced by computing the optimal location of the supply node. DE7, which is located between regions with high hydrogen demand, has been found to be the best location for hydrogen production. From there, hydrogen is transported in southern, western, northern and eastern direction in pipelines with diameters smaller than 75 cm. An even lower total cost has been reached for the problem formulation that takes the capacity of production plants into consideration. By restricting the amount of hydrogen that can be produced at each production plant, hydrogen is supplied at several nodes. In turn, the pipeline network is less developed. Although the cost of the overall network design has been reduced, a higher objective than for the other two scenarios has been determined due to the consideration of investment and maintenance cost for production plants.

According to the investigations of the trade-off between network cost and safety for the scenarios *A)* to *C)*, scenario *C)* has yielded the most reasonable cost. Scenarios *A)* and *B)* rely too much on hydrogen import and, on top of that, require more pipeline connections due to the singular supply node. For scenario *C)*, which has allowed the construction of several production plants, the hydrogen transmission network has been less developed, thus reducing risk posed by the construction and operation of hydrogen pipelines.

In the future, the capabilities of the model should be checked for larger problem sizes. Furthermore, it would be of advantage to extend the facility location problem by relevant factors. Other transport technology, i.e. transport by cryogenic liquid tankers and gaseous trucks, could be included for hydrogen distribution. In addition, compressor stations should be considered to test their impact on the network design.

Acknowledgements

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A Appendix

A.1 Additional details of mathematical model

A.1.1 Neighbourhood-flow approach

The computational effort of the problem is reduced by implementing a neighbourhood-flow approach [18, 30]. It is assumes that only arcs connecting neighbouring regions are to be included into the set of feasible pipeline connections. Connections between nodes that are farther apart and separated by intermediate regions are assumed to be replaceable by a series of connected arcs.

All arcs $(i, j) \in A$ connecting neighbouring regions are included in the set A_1. The set is then extended to include very short node connections A_2, even if the regions in which the nodes are placed are not adjacent. Finally, all long-distanced connections A_3 are deleted from the set.

$$
\begin{aligned}
&\text{Let } (i, j) \in A_1 = H, \\
&\text{and } (i, j) \in A_2 | L_{ij} \leq L_{min}, \\
&\text{and } (i, j) \in A_3 | L_{ij} \geq L_{max}, \\
&\text{then } (i, j) \in NH = A_1 \cup A_2 \cap A_3.
\end{aligned}
$$

A.1.2 Piecewise linearisation for pressure difference

Piecewise approximation of the pressure losses in pipelines allows the linearisation of Equation 3.4. The term $\pi_i - \pi_j$ is replaced by introducing the SOS2-variable λ_{m1ij}.

$$\pi_i - \pi_j = \sum_{m1 \in M1} \Delta\hat{\pi}_{m1} \lambda_{m1ij} - sl1_{ij}, \forall (i, j) \in A \tag{A.1}$$

The SOS2-variable chooses the active interval in which the pressure drop is situated from the defined base points $\Delta\hat{\pi}_{m1}$. To this end, only two consecutive base points $m1 \in M1$ of λ_{m1ij} are activated on each active pipeline arc and restricted to the sum of one by he following equation:

$$\sum_{m1 \in M1} \lambda_{m1ij} = \sum_{d \in D} Y_{dij}, \forall (i, j) \in A \tag{A.2}$$

A slack variable $sl1_{ij}$ ensures that pressure losses are restricted to active pipeline arcs. An additional equation disallows the slack variables from being greater than zero for inactive arcs.

$$-M_{\pi}^{max}(1-\sum_{d\in D}Y_{dij}) \leq sl1_{ij} \leq M_{\pi}^{max}(1-\sum_{d\in D}Y_{dij}), \forall(i,j)\in A \quad \text{(A.3)}$$

Here, M_{π}^{max} defines the maximum pressure that can be lost through hydrogen transport.

The square root of the pressure loss θY_{dij} is determined by the so-called function row and with help of the SOS2-variable. Parameter $\hat{\theta}_{m1}$ quantifies the linear function at the chosen

$$\sum_{d\in D}\theta Y_{dij} = \sum_{m1\in M1}\hat{\theta}_{m1}\lambda_{m1ij}, \forall(i,j)\in A \quad \text{(A.4)}$$

Finally, values of the continuous variable θY_{dij} are restricted.

$$\theta Y_{dij} \leq \hat{\theta}^{max}Y_{dij}, \forall(i,j)\in A, d\in D \quad \text{(A.5)}$$

A.1.3 Piecewise linearization for pressure average

The average pressure inside of each pipeline arc $0.5(\pi_i + \pi_j)$ is approximated by piecewise linearisation, same as the pressure loss over the pipeline arc. The mathematical formulations are similar to those presented in Section A.1.2.

$$0.5(\pi_i+\pi_j) = \sum_{m2\in M2}\hat{\Psi}_{m2}\tau_{m2ij} - sl2_{ij}, \forall(i,j)\in A \quad \text{(A.6)}$$

The parameter $\hat{\Psi}_{m2}$ summarizes all base points used for linearisation, while the SOS2-variable τ_{m2ij} chooses the active interval. Again, only two consecutive base points are allowed to be activated by τ_{m2ij}. The SOS2-variable is further restricted:

$$\sum_{m2\in M2}\tau_{m2ij} = \sum_{d\in D}Y_{dij}, \forall(i,j)\in A \quad \text{(A.7)}$$

A continuous slack variable $sl2_{ij}$ is introduced to handle pressure differences between nodes that are not connected by a pipeline. The slack variable is restricted to inactive arcs.

$$\pi^{min}(1-\sum_{d\in D}Y_{dij}) \leq sl2_{ij} \leq \pi^{max}(1-\sum_{d\in D}Y_{dij}), \forall(i,j)\in A \quad \text{(A.8)}$$

Lastly, the average pressure on active pipeline arcs is determined by the function row and bound to the feasible region by Equation A.10.

$$\hat{\psi}^{min} Y_{dij} \leq \psi Y_{dij} \leq \hat{\psi}^{max} Y_{dij}, \forall (i,j) \in A, d \in D \tag{A.9}$$

$$\sum_{d \in D} \psi Y_{dij} = \sum_{m2 \in M2} \hat{\psi}_{m2} \tau_{m2ij}, \forall (i,j) \in A \tag{A.10}$$

A.2 Model parameters

A.2.1 Capital recovery factor and maintenance

Interest rate [%]	it	10
Number of annuities [yr]	n	30
Pipeline maintenance cost percentage [%]	m_p	5
Production facility maintenance cost percentage [%]	m_f	5

Table A.1: Cost parameters for capital recovery factor and maintenance cost.

A.2.2 Hydrogen pipeline parameters

Temperature at standard conditions [K]	273.15
Pressure at standard conditions [bar]	1
Gas mean temperature [K]	285.15
Molar mass of H_2 [$\mathrm{kg\,kmol^{-1}}$]	2.16
Ideal gas constant [$\mathrm{kJ\,kmol^{-1}\,K^{-1}}$]	8.314
Isentropic coefficient κ [−]	1.405
Hydrogen compressibility at active conditions [−]	1.322
Hydrogen density at standard conditions [$\mathrm{kg\,m^{-3}}$]	0.0899
Relative density of gas with regard to air (at standard conditions) [−]	0.0596

Table A.2: Definition of standard and active conditions and the corresponding physical properties of hydrogen.

Diameter size d	Diameter $\hat{d}_d$ [cm]	Maximum flow rate kQ_d^{max} [$10^{-3}\,\mathrm{m}^3\,\mathrm{hr}^{-1}\,\mathrm{bar}^{-1}$]
1	25	3.84
2	50	15.36
3	75	34.55
4	100	61.43

Table A.3: Discrete diameters and maximum flow rates depending on the average pressure for hydrogen transmission pipelines.

Pipeline installation cost [Mio Euro km^{-1}]	a_0	2.8×10^{-1}
Material cost and others [Mio Euro $\mathrm{km}^{-1}\,\mathrm{cm}^{-1}$]	a_1	1.29×10^{-4}
Dependence on diameter [Mio Euro $\mathrm{km}^{-1}\,\mathrm{cm}^{-2}$]	a_2	2.68×10^{-4}

Table A.4: Capital cost parameters for pipelines based on Yang and Ogden [32].

	DE1	DE2	DE3	DE4	DE5	DE6	DE7	DE8	DE9	DEA	DEB	DEC	DED	DEE	DEF	DEG
DE1		191	512	488	479	535	160	562	402	322	151	167	413	412	621	279
DE2	191		505	486	583	613	326	611	489	487	318	358	360	444	696	319
DE3	512	505		27	316	256	450	182	249	478	454	580	165	128	296	237
DE4	488	486	27		296	242	23	175	225	451	427	553	157	102	289	211
DE5	479	583	316	296		95	336	184	100	248	344	446	406	218	164	279
DE6	535	613	256	242	95		405	94	132	339	412	523	377	193	86	295
DE7	160	326	450	423	336	405		451	276	164	9	130	403	329	489	221
DE8	562	611	182	175	184	94	451		179	413	458	577	327	168	114	296
DE9	402	489	249	225	100	132	276	179		241	283	399	313	132	218	179
DEA	322	487	478	451	248	339	164	413	241		172	222	486	350	412	298
DEB	151	318	454	427	344	412	9	458	283	172		125	404	333	497	223
DEC	167	358	580	553	446	523	130	577	399	222	125		522	459	606	347
DED	413	360	165	157	406	377	403	327	313	486	404	522		188	438	190
DEE	412	444	128	102	218	193	329	168	132	350	333	459	188		264	135
DEF	621	696	296	289	164	86	489	114	218	412	497	606	438	264		377
DEG	279	319	237	211	279	295	221	296	179	298	223	347	190	135	377	

Table A.5: Distance matrix for the largest cities of the 16 German states [km].

Maximum pressure at node i [bar^2]	π^{max}	60
Minimum pressure at node i [bar^2]	π^{min}	1

Table A.6: Minimum and maximum pressures at nodes.

Level	Population
1	$< 3 \times 10^6$
2	3×10^6 - 1×10^7
3	$> 1 \times 10^7$

Table A.7: Categorisation scheme for safety levels for nodes.

Region	Size	Safety level	Region	Size	Safety level
DE1	Large	3	DE9	Medium	2
DE2	Large	3	DEA	Large	3
DE3	Medium	2	DEB	Medium	2
DE4	Small	1	DEC	Small	1
DE5	Small	1	DED	Medium	2
DE6	Small	1	DEE	Small	1
DE7	Medium	2	DEF	Small	1
DE8	Small	1	DEG	Small	1

Table A.8: Sizes and safety levels of German states for risk assessment.

$\beta = 1$	A region is crossed by a pipeline
$\beta = 0.5$	A pipeline passes near the region

Table A.9: Evaluation of the risk of a pipeline connection.

	DE1	DE2	DE3	DE4	DE5	DE6	DE7	DE8	DE9	DEA	DEB	DEC	DED	DEE	DEF	DEG
DE1	3	6	10	12	14	11	6	13.5	10	10	7	6	8	8	12	7
DE2	6	3	8	9	9	7.5	9	9	7.5	13	10	9	5	5	8.5	4
DE3	10	8	1	3	3	6	6	2	4	8	7	8	3	2 6	3.5	3
DE4	12	9	3	2	7	7.5	8	3	6	9	9	10	5	4	5	5
DE5	14	9	3	7	1	4	9	5.5	3	6	8	9	6	4	4	4
DE6	11	7.5	6	7.5	4	1	9	3	3	6	10	7	6.5	4	2	5
DE7	6	9	6	8	9	9	2	6.5	8	7	4	5	9	5	10	3
DE8	13.5	9	2	3	5.5	3	6.5	1	3	6	7	11	5	5	2	5.5
DE9	10	7.5	4	6	3	3	8	3	2	5	7	10	5	3	4	3
DEA	10	13	8	9	6	6	7	6	5	3	7	6	9	7	7	6
DEB	7	10	7	9	8	10	4	7	7	7	2	4	10	7	10.5	5
DEC	12	18	16	20	21	14	10	22	20	12	8	2	22	14	19	11
DED	16	10	6	10	15	13	18	10	10	18	20	22	2	7	12	8
DEE	16	10	4	8	11	8	10	10	6	14	14	14	7	2	10	4
DEF	24	17	7	10	11	4	20	4	8	17	21	19	12	10	2	11
DEG	14	8	6	10	11	10	6	11	6	12	10	11	8	4	11	2
Σ	184.5	154	97	133.5	138.5	117	138.5	116.5	108.5	153	151	153	124.5	91	122.5	86.5

Table A.10: External effect matrix for the 16 German states.

A.2.3 Hydrogen production parameters

Plant size d	Maximum capacity A_k $[10^{-3}\,\mathrm{m}^3\,\mathrm{hr}^{-1}]$	Capital cost ccA_k $[10^6\,\mathrm{Euro\,hr\,m}^{-3}]$
small	4	16.8
medium	70	124.8
large	500	550.8

Table A.11: Maximum capacities and capital cost of the production plants depending on plant size.

A.3 Supporting tables

A.3.1 Cost allocation

	Scenario		
Cost $[\mathrm{Mio\,Euro\,yr}^{-1}]$	A	B	C
Annualised cost	5224.5	5084.0	5480.0
Hydrogen production	4774.78	4773.8	4760.71
Hydrogen import		3.92	56.95
Pipeline investment	305.65	208.83	99.62
Pipeline maintenance	144.07	98.43	46.95
Production facility investment			350.57
Production facility maintenance			165.24

Table A.12: Cost analysis for scenarios A to C.

A.3.2 Scenario A

Inlet	Outlet	Flow rate $[\mathrm{m^3\,hr^{-1}}]$	Diameter [cm]	Velocity $[\mathrm{m\,s^{-1}}]$
DE1	DE2	452505.61	75	29.6
DE3	DE4	2656217.73	100	22.0
DE4	DE8	146906.89	50	5.2
DE4	DED	128847.35	50	4.4
DE4	DEE	2296950.59	100	20.8
DE5	DE6	45365.23	25	17.5
DE7	DE1	829010.06	75	29.3
DE7	DEB	771049.44	75	25.9
DE8	DEF	95739.26	25	18.7
DE9	DE5	62505.05	25	15.2
DEB	DEA	586554.11	75	22.5
DEB	DEC	37933.83	25	17.8
DEE	DE9	337614.90	50	14.7
DEE	DEG	1885029.87	100	19.8
DEG	DE7	1812895.55	100	23.8

Table A.13: Pipeline diameters, flow rates and velocities in pipelines for scenario A.

A.3.3 Scenario B

Inlet	Outlet	Flow rate [$m^3\,hr^{-1}$]	Diameter [cm]	Velocity [$m\,s^{-1}$]
DE1	DE2	452505.61	50	20.1
DE4	DE3	69114.69	50	10.0
DE4	DED	128847.35	50	21.1
DE6	DEF	146353.65	50	24.5
DE7	DE1	829010.06	75	12.6
DE7	DE9	483968.56	50	21.0
DE7	DEB	771049.44	50	27.0
DE7	DEG	427915.07	50	16.1
DE9	DE5	17139.82	25	9.9
DE9	DE6	191718.88	50	23.3
DEB	DEA	586554.11	75	10.2
DEB	DEC	37933.83	25	6.1
DEE	DE4	281474.93	50	22.9
DEF	DE8	51167.62	50	30.0
DEG	DEE	355780.76	50	18.9

Table A.14: Pipeline diameters, flow rates and velocities in pipelines for scenario B.

A.3.4 Scenario C

Node	Capacity [$10^3\,m^3\,hr^{-1}$]	Hydrogen production [$10^3\,m^3\,hr^{-1}$]
DE1	500	376.5
DE2	500	452.5
DE7	500	500
DE9	500	433.4
DEC	500	475.9
DED	500	479.1

Table A.15: Supply nodes with capacity of production facility for optimised network design.

Inlet	Outlet	Flow rate [cm]	Diameter [$m^3\,hr^{-1}$]	Velocity [$m\,s^{-1}$]
DE4	DE3	69114.69	25	9.3
DE4	DE8	51167.62	25	7.2
DE4	DED	200981.67	50	6.8
DE4	DEE	74305.82	25	10.6
DE5	DE6	58403.95	25	10.0
DE6	DEF	95739.26	25	24.8
DE7	DEB	295198.80	50	9.8
DE9	DE5	75543.77	25	10.8
DE9	DE6	82700.54	25	12.5
DEB	DEA	586554.11	50	24.8
DEC	DEB	437916.80	75	6.4
DED	DEG	72134.31	25	12.3

Table A.16: Pipeline diameters, flow rates and velocities in pipelines for scenario C.

Nomenclature

Abbreviations

CCS	carbon capture and storage
EIF	environmental impact factor
FCV	fuel cell vehicles
GAMS	general algebraic modeling system
GIS	geographical information system
HSC	hydrogen supply chain
IRF	inherent risk factor
LCA	life cycle assessment
MILP	mixed-integer linear programming
NLP	non-linear programming
SMR	steam methane reforming
TRRI	total relative risk index

Continuous Variables

$\bar{\pi}_{ij}$	average pressure in pipeline segment between node i and j	$\left[bar^2\right]$
$\hat{I}_i$	hydrogen import	$\left[m^3/hr\right]$
λ_{m1ij}	weighting factor for piecewise linearization of pressure drop between nodes i and j, SOS2 variable	$[-]$
π_i	squared pressure at node i $\pi_i \equiv p_i^2$	$\left[bar^2\right]$
τ_{m2ij}	weighting factor for piecewise linearisation of pressure average between node i and j, SOS2 variable	$[-]$
CCP	pipeline investment cost	$\left[Mio.Euro.yr^{-1}\right]$
FC	production facility cost	$\left[Mio.Euro.yr^{-1}\right]$

HC	hydrogen production cost	$[Mio.Euro.yr^{-1}]$
IC	hydrogen import cost	$[Mio.Euro.yr^{-1}]$
MP	pipeline maintenance cost	$[Mio.Euro.yr^{-1}]$
PC	pipeline cost	$[Mio.Euro.yr^{-1}]$
Q_{ij}	hydrogen flow rate in pipeline linking node i and j at standard conditions	$[m^3/hr]$
sE_i	hydrogen supply at node i	$[m^3/hr]$
$sl1_{ij}$	slack variable for pressure drops	$[bar^2]$
$sl2_{ij}$	slack variable for pressure average	$[bar^2]$
TC	total network cost	$[Mio.Euro.yr^{-1}]$
ψY_{dij}	average pressure in pipeline segment between node i and j with diameter d, $\psi Y_{dij} \equiv \sqrt{0.5(\pi_i + \pi_j)} Y_{dij}$	$[bar]$
θY_{dij}	square root of pressure differences (linearised), $\theta Y_{dij} \equiv \sqrt{\pi_i - \pi_j} Y_{dij}$ $[bar]$	
θY_{dij}	square root of pressure differences (linearized), $\theta Y_{dij} \equiv \sqrt{\pi_i - \pi_j} Y_{dij}$ $[bar]$	

Binary Variables

$E1_i$	establishment of a production facility at node i
E_{ki}	establishment of a production facility with capacity k at node i
Y_{dij}	establishment of a pipeline with diameter d between nodes i and j

Parameters

$\Delta\hat{\pi}_{m1}$	pressure difference used as intervals in piecewise linearization $[bar^2]$	
$\hat{\Psi}_{m2}$	pressure average used as intervals in piecewise linearisation	$[bar^2]$
$\hat{\psi}_{m2}$	square root of pressure average in piecewise linearization	$[bar]$

$\hat{\psi}_{m2}^{max}$ maximum of $\hat{\psi}_{m2}$ $[bar]$

$\hat{\psi}_{m2}^{min}$ minimum of $\hat{\psi}_{m2}$ $[bar]$

$\hat{\theta}^{max}$ maximum of $\hat{\theta}_{m1}$ $[bar]$

$\hat{\theta}_{m1}$. square root of pressure difference in piecewise linearization $[bar]$

$\hat{d}_d$ diameter of pipelines $[cm]$

π^{max} maximum squared pressure $[bar^2]$

π^{min} minimum squared pressure $[bar^2]$

ρ_b density of hydrogen at standard conditions $[kg/m^3]$

a_0 cost factor for pipelines $[Euro/km]$

a_{12d} combination of pipeline cost factors a_1 and a_2 and diameter $\hat{d}_d$ $[Euro/km]$

a_1 cost factor for pipelines $[Euro/km/cm]$

a_2 cost factor for pipelines $[Euro/km/cm^2]$

A_k capacities of production facilities of size k $[m^3/hr]$

ccA_k investment cost for production facilities with a capacity of k $[m^3/hr]$

cH production cost of hydrogen $[Euro/m^3/hr]$

crf capital recovery factor $[-]$

CU car use per year $[km/car/yr]$

dem_i total hydrogen demand of region i $[m^3/hr]$

fc fuel consumption $[kg/km]$

ip cost of imported hydrogen $[Euro/m^3/hr]$

it interest rate $[\%]$

k_{pl} coefficient for pressure loss equation $[bar^2cm^2hr^2/km/m^6]$

kQ_d^{max} maximum flow allowable in pipelines depending on diameter d and pressure active in the pipeline $[m^3/hr/bar]$

L_{ij}	distance between regions	$[km]$
M_S	sum of all hydrogen demands	$\left[m^3.hr^{-1}\right]$
m_f	production facility maintenance cost percentage	[%]
m_p	pipeline maintenance cost percentage	[%]
n	number of annuities	$[yr]$
P_i	population of region i	$[people]$
PT	market penetration rate	[%]
Q^{max}	maximum flow rate allowed by general flow equation	$\left[m^3/hr\right]$
VO_i	vehicle ownership in region i	$[cars/person]$

Sets

$(i,j) \in A$	subset of all possible pipeline connections
$d \in D$	discrete diameter sizes of pipes
$i,j \in N$	supply and demand nodes of sates/regions
$k \in K$	capacities of production facilities
$m1 \in M1$	base points for piecewise linearization of pressure difference
$m2 \in M2$	base points for piecewise linearisation of pressure average

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