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# 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 et al. (2011).

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.



## 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) (Xu et al., 2017), 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 (Brey et al., 2012) 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 (Gim et al., 2012; Dagdougui, 2012). 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 (Sabio et al., 2012; Agnolucci and McDowall, 2013). 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 (De-León Almaraz et al., 2013; Agnolucci et al.,

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## Nomenclature

*Abbreviations*

| | |
|---|---|
| CCS | carbon capture and storage |
| EIF | environmental impact factor |
| FCV | fuel cell vehicles |
| GAMS | general algebraic modelling 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 $j$ [bar$^2$] |
| $\hat{I}_i$ | hydrogen import [m$^3$ h$^{-1}$] |
| $\lambda_{m1ij}$ | weighting factor for piecewise linearisation of pressure drop between nodes $i$ and $j$, SOS2 variable [–] |
| $\pi_i$ | squared pressure at node $i$ $\pi_i \equiv p_i^2$ [bar$^2$] |
| $\tau_{m2ij}$ | weighting factor for piecewise linearisation of pressure average between node $i$ and $j$, SOS2 variable [–] |
| CCP | pipeline investment cost [Mio Euro yr$^{-1}$] |
| FC | production facility cost [Mio Euro yr$^{-1}$] |
| $HC$ | 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$^3$ h$^{-1}$] |
| $sE_i$ | hydrogen supply at node $i$ [m$^3$ h$^{-1}$] |
| $sl1_{ij}$ | slack variable for pressure drops [bar$^2$] |
| $sl2_{ij}$ | slack variable for pressure average [bar$^2$] |
| TC | total network cost [Mio Euro yr$^{-1}$] |
| $\psi Y_{dij}$ | 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] |
| $\theta Y_{dij}$ | square root of pressure differences (linearised), $\theta Y_{dij} \equiv \sqrt{\pi_i-\pi_j}Y_{dij}$ [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 linearisation [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 linearisation [bar] |
| $\hat{\psi}_{m2}^{max}$ | maximum of $\hat{\psi}_{m2}$ [bar] |
| $\hat{\psi}_{m2}^{min}$ | minimum 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 linearisation [bar] |
| $\hat{d}_d$ | diameter of pipelines [cm] |
| $\pi^{max}$ | maximum squared pressure [bar$^2$] |
| $\pi^{min}$ | minimum squared pressure [bar$^2$] |
| $\rho_b$ | 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$^3$ h$^{-1}$] |
| $ccA_k$ | investment cost for production facilities with a capacity of $k$ [m$^3$ h$^{-1}$] |
| $cH$ | production cost of hydrogen [Euro/m$^3$ h$^{-1}$] |
| $crf$ | capital recovery factor [–] |
| $CU$ | car use per year [km/car/yr] |
| $dem_i$ | total hydrogen demand of region $i$ [m$^3$ h$^{-1}$] |
| $fc$ | fuel consumption [kg/km] |
| $ip$ | cost of imported hydrogen [Euro/m$^3$ h$^{-1}$] |
| $it$ | interest rate [%] |
| $k_{pl}$ | coefficient for pressure loss equation [bar$^2$ cm$^2$ h$^2$/km/m$^6$] |
| $kQ_d^{max}$ | maximum flow allowable in pipelines depending on diameter $d$ and pressure active in the pipeline [m$^3$ h$^{-1}$ bar$^{-1}$] |
| $L_{ij}$ | distance between regions [km] |
| $M_S$ | sum of all hydrogen demands [m$^3$ h$^{-1}$] |
| $m_f$ | production facility maintenance cost percentage [%] |
| $m_p$ | pipeline maintenance cost percentage [%] |
| $n$ | number of annuities [yr] |
| $P_i$ | population of region $i$ [person] |
| $PT$ | market penetration rate [%] |
| $Q^{max}$ | maximum flow rate allowed by general flow equation [m$^3$ h$^{-1}$] |
| $VO_i$ | 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 states/regions |
| $k \in K$ | capacities of production facilities |
| $m1 \in M1$ | base points for piecewise linearisation of pressure difference |
| $m2 \in M2$ | base points for piecewise linearisation of pressure average |

2013; Guillén-Gosálbez et al., 2010; Dayhim et al., 2014; Konda et al., 2011). Some of the earliest research has been done by Almansoori and Shah (2006), and a lot of models are based on their work or contain some components (Sabio et al., 2012; De-León Almaraz et al., 2013; Agnolucci et al., 2013; Guillén-Gosálbez et al., 2010; Dayhim et al., 2014; Konda et al., 2011; Han et al., 2012; Kamarudin et al., 2009; Almansoori and Shah, 2009; Nunes et al., 2015; Moreno-Benito et al., 2016). Apart from the technologies which are included, these works differ in their objective. Some of them evaluate the network profit (Han et al., 2012), while most concentrate on minimis-