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Energy security in context of transforming energy systems: a case study for natural gas transport in Germany

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Abstract

Against the background of transforming energy systems in a sustainable manner, energy security plays a crucial role when designing energy systems in general and energy transportation systems in particular. Energy security can be understood as uninterrupted availability of energy sources at an affordable price and, thus, is influenced by technical, economic and political circumstances. Currently many national energy systems are switching from fossil and nuclear to renewable energy supply. Even though the focus often is on the electricity supply, this fuel switch effects the whole energy system including i.e. the heat and mobility sector, triggering even bigger changes. This work examines, using the example of natural gas in Germany, how the long-term transformation of energy systems influences energy security and why this should be considered in short- to mid-term transportation systems expansion planning.

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1. Introduction

In the year 2017, the German energy supply was dominated by the CO₂ emitting fossil fuels mineral oil, natural gas, hard coal and lignite, which cover 80.3% of the German primary energy consumption [1]. In order to decrease CO₂-emissions, the German government initiated a long-term transition process towards a more sustainable energy

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system with at least 80% less CO₂-emissions by 2050 in comparison to 1990, called *Energiewende*, several years ago [2]. Additionally, the government ratified the Climate Protection Agreement of Paris [3] in November 2016 [4], in which 195 countries agreed to limit the global mean temperature rise due to climate change below 2°C. Hence, there is a strong political will in Germany to expand renewable energy supply and put efforts in increasing energy efficiency. As natural gas emits less CO₂ than mineral oil, hard coal or lignite per unit energy, it may support the transition process in the short- and mid-term but on the other hand cannot play a role in a full renewable energy system. In 2017, natural gas covered 23.8% of primary energy consumption in Germany, mainly used for heating purposes.

Because German domestic natural gas resources are very limited, more than 90% of the consumed natural gas is imported from Russia, Norway and the Netherlands via pipeline [5]. Germany highly depends from a reliable natural gas supply by these countries considering technical, economic and political aspects, highlighting questions of energy security. In accordance to the International Energy Agency, energy security can be defined as uninterrupted availability of energy sources at an affordable price [6]. Due to the central position of Germany within Europe, Germany is an important transit country for gas with high long-distance transport capacities. The construction of this pipeline infrastructure is capital intensive and faces payback times of up to several decades. In order to minimize the risk of stranded investments, the expansion planning process in Germany is performed participative via biennial network development plans. These have a mid-term ten-year horizon based on trend projections and are carried out by transmission system operators for gas (TSOs). The European TSOs harmonize their individual national expansion planning processes via European wide ten-year network development plans.

This work wants to bridge the gap between the mid-term time horizon of the network developments plans and the long-term payback time of grid investments, often linked to energy security arguments. It wants to add insight of the long-term horizon given by transformation processes such as the German *Energiewende* to a mid-term grid expansion planning process with a special focus on energy security. In literature, many studies deal with policy perspectives of energy security [7,8], analyze the natural gas supply security [9], provide an index for assessing national energy security [10] or develop methods to examine how a linkage of electricity and natural gas system effects energy security [11–13]. But yet no study considered the long-term impacts of transforming energy systems on the natural gas transport grid and its influence to grid expansion planning in a comparable manner. To achieve this, the status quo of the gas transport system in Germany is analyzed in Section 2. The presented data is basis of the gas flow calculations performed for this work. The applied methods for estimating the long-term gas demand in accordance with the goals of the *Energiewende* and related gas flow calculations are given in Section 3. Section 4 shows the results with a focus on energy security and Section 5 gives a final discussion.

2. Analysis of the German Gas Transport System

The German natural gas transport system covers the chain from production to consumption via transport and storage. The gas transport in Germany is solely pipeline based, as no terminals for liquid natural gas (LNG) exist. The pipeline infrastructure can be separated into four layers: the long-distance, supra-regional, regional and local transport. The pipeline diameter reaches from up to 1,400 mm in the long-distance transport down to a few millimeters in local distribution. This work focuses on the long-distance and supra-regional layers. The considered topology model is derived from commercial [14,15] and open data sources [16,17]. Open data sources cover up-to-date routing of pipelines but no technical details like diameter or roughness. However, modelling the gas flow in the further course of this work needs these technical information. The starting year of the feed-in and feed-out data used in this work are based on the year 2015 because of data quantity and quality. The gas feed-in per grid node and hour into the gas transport grid by domestic production, storages and imports is documented in transparency portals by the TSOs (cf. [16]). Only the tiny fraction of biomethane is not documented but can be derived via [18,19], assuming a constant feed-in all-the-year. Hence, the gas feed-in data is highly reliable on a detailed level. The gas feed-out per grid node and hour is not available in a comparable extent. Annual values can be taken from the official German energy balance [20], but spatial and temporal resolved data is missing. Only data for exports and storages can (again) be found in [16]. The feed-out of the final energy sectors households and services is disaggregated spatially via the distribution of the demand drivers population and gross value added [21]. The temporal disaggregation is based on standard load profiles used by gas suppliers [22]. For estimating the spatial distribution of the gas feed-out for industry purposes data about CO₂-emissions per plant is used [23], again assuming a constant temporal profile. The gas feed-out for

electricity (and heat) generation in power or combined heat and power (CHP) plants can be derived from electricity generation data per power plant and hour from the transparency platform of the European Energy Exchange [24]. Non-energy consumption as well as “other” are also assumed constant. As non-energy use of natural gas often is production of hydrogen via steam reforming in chemical industry, the spatial disaggregation is based again on [23]. Heating plants are typically used in district heating systems and, hence, assumed to follow the household feed-out profile. Fig. 1 shows the results of the analysis.

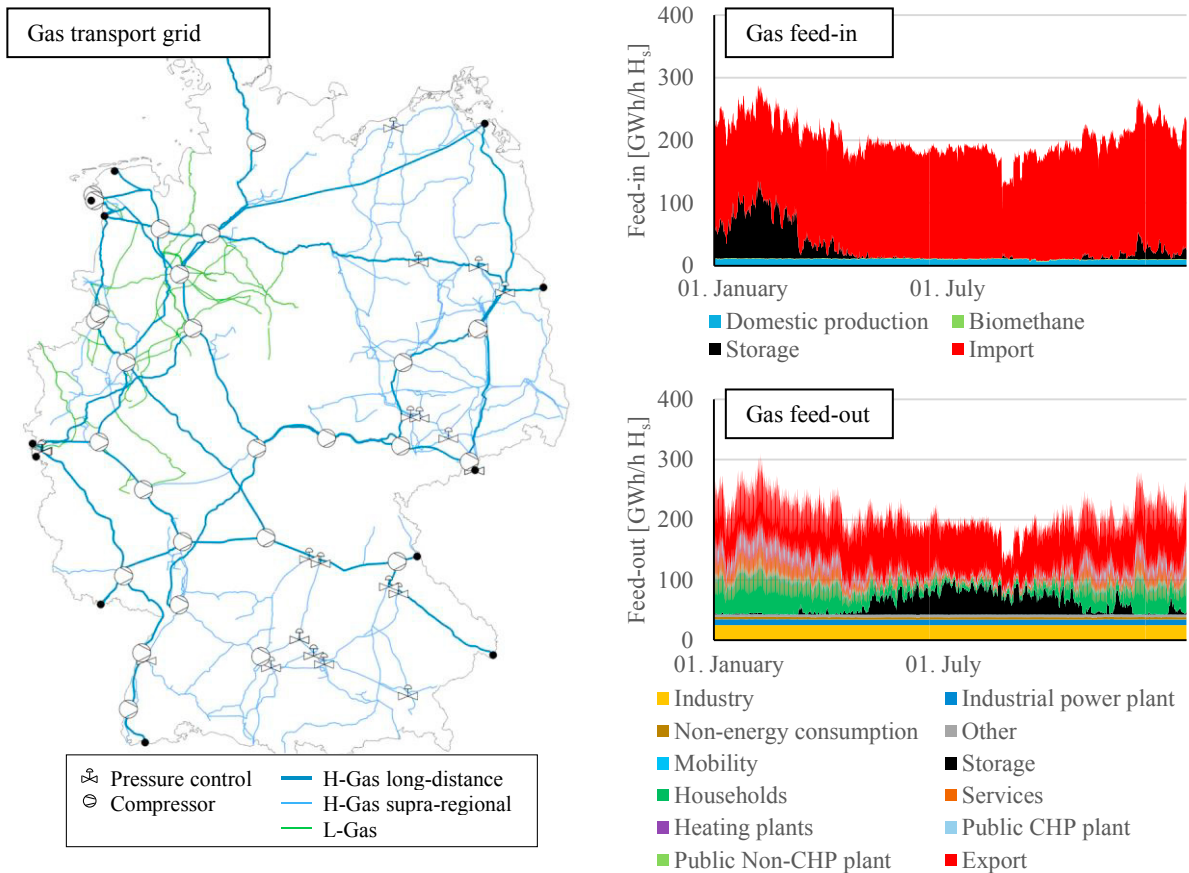


Fig. 1. German gas transport system in the year 2015, own estimation

The Gas transport grid is divided into an independent H-gas (high calorific) and L-gas (low calorific) grid with varying gas quality. The L-gas grid is fed with gas from the Netherlands and domestic production in Germany. The H-gas grid is fed with gas from Norway and Russia. As gas production in the Netherlands and Germany is decreasing due to drying resources, the L-gas grid will be converted to H-gas until 2030 [17]. As L-gas is not transported over long-distances, it is not the focus of this work. The grid contains compressor and pressure control stations, where the pressure can be increased or decreased in order to steer the gas flow actively. The further modeling covers the long-distance and supra-regional H-gas grid. The gas feed-in profile is dominated by imports throughout the year, complemented by storage feed-out in winter. The contribution of the domestic production is low and biomethane is nearly negligible. The gas feed-out can be separated in temperature independent industry feed-out including industrial power plants and non-energy consumption as well as temperature dependent feed-out in households, services, heating and public CHP power plants. The use in public non-CHP plants is as well nearly negligible as gas-fired power plants are not economic in comparison to coal-fired power plants. The higher intraday volatility on the feed-out side is balanced in the distribution grid.

3. Method

In order to derive a quantitative long-term sectoral gas demand scenario until 2050, a scenario analysis shall be examined using the energy system model IKARUS [25–28]. A detailed model description can be found in the given sources. Considering an extrapolated trend of population number, living space, gross value added or transport need, a final energy demand can be derived that has to be covered by the energy system. IKARUS is a linear programming model and, thus, covers the final energy demand in an economic manner. The goals of the *Energiewende* [29] can be modelled as restrictions of the underlying mathematical problem. The fuel and CO₂ certificate prices are taken from the 450-ppm scenario of the World Energy Outlook 2016 [30].

After deriving annual sectoral gas demand values, the resulting sectoral gas demand is spatial and temporal disaggregated according to the year 2015 (see Section 2), enabling the selection of situations worth a deeper gas flow modelling. The imports and exports of natural gas are again chosen in accordance to the 450-ppm scenario of the WEO 2016. Decided grid expansions [17] are assumed to be implemented in the year 2050. The gas flow modelling is performed using the GASOPT model considering the H-gas topology shown in Fig. 1. GASOPT models the gas flow problem as a mathematical programming problem including the pressure loss due to wall friction. As gas grids consist of active pressure increasing compressor and pressure decreasing control stations, the solution routine includes a decision about from which pipeline gas is taken and in which pipeline it is fed in order to serve the given feed-in/feed-out situation. State of the art gas flow simulation software like SIMONE [31] needs an user input of configurations containing the feed-in/feed-out information of stations. The configuration of each station is stored in a set within a list. This list contains multiple sets of combined configurations and each set is tested one-by-one in a try-and-error manner. In contrast, the chosen approach in this work ensures a holistic solution of the gas flow and configuration decision process. The approach is based on [32,33] and formulates a mixed integer linear programming problem (MIP) formulation that can be solved by state-of-the-art MIP solvers. The mathematical problem can better be understood as feasibility than optimization problem. The result quality is satisfactory for planning purposes as comparisons with SIMONE show [34].

4. Results

Fig. 2 shows the IKARUS results for the gas demand development until 2050 considering the *Energiewende* goals. Starting from the year 2015 the gas demand peaks in 2020 (+ 4.3%) and decreases until 2050 (- 55.0%). The industry consumption is more or less constant, as only limited alternatives for natural gas exist but especially the use of gas for heating purposes in households (- 59.7%) and services (- 43.5%) decreases. Additionally, the use of natural gas in public CHP power plants expires in 2025 as the model chooses a fuel switch to biomass. However, the use on public non-CHP plants only generating electricity increases as flexible gas power plants are able to complement the volatile electricity generation of wind and photovoltaic plants.

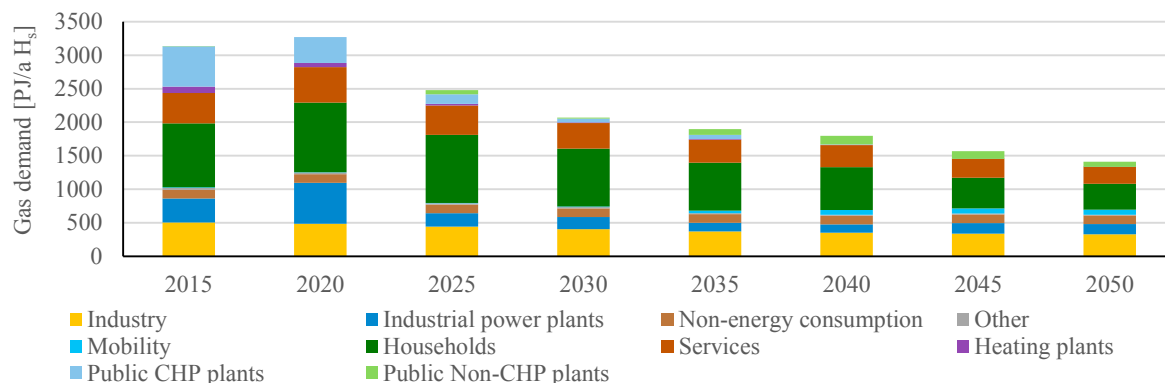


Fig. 2. Development of Gas demand in scenario *Energiewende*, own calculation

Fig. 3 shows the resulting feed-in and feed-out profile for the 8760 hours of the year 2050. The average feed-in and feed-out is with 86 GWh/h H_s only 42.4% of the year 2015 (203 GWh/h H_s). There exists no domestic production of natural gas and biomethane feed-in is still negligible. The storage operation is assumed to still balance the winter and summer feed-out as in the year 2015. The absolute seasonal and intraday volatility decreases in the feed-in and feed-out profile due to less gas demand. This questions the business model of balancing gas storages in the gas transport grid, as a technical storage need no longer exists.

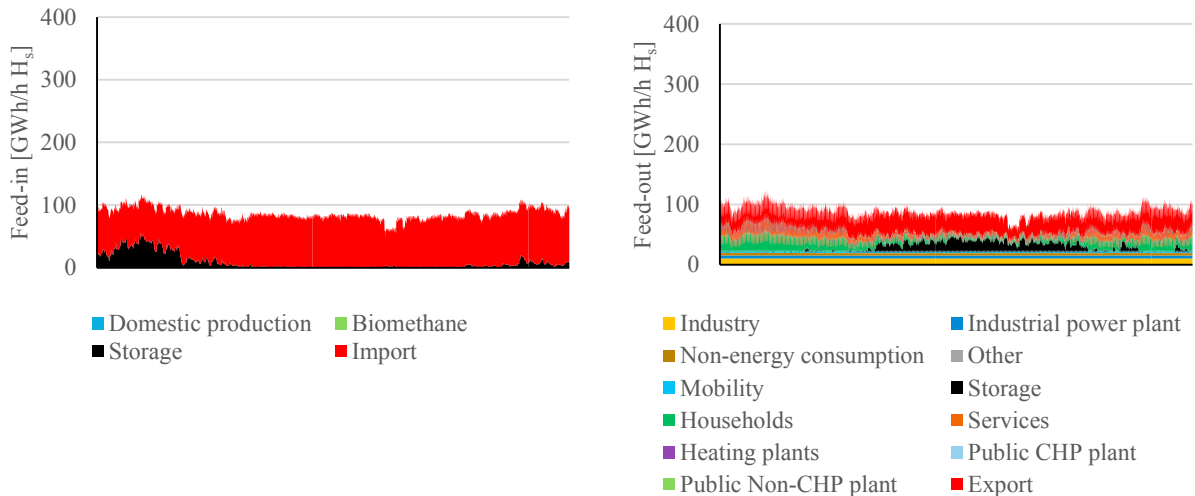


Fig. 3. Hourly feed-in and feed-out in scenario Energiewende in the year 2050, own calculation

A gas flow calculation of the hour with the highest natural gas imports (11th December, 11 am) with GASOPT shows that the feed-outs due to national gas demand and exports could easily be covered by the imports when gas from all import sources (LNG from Western Europe, Norway, Russia) is available. In contrast to the situation in the year 2015, the gas exports and national demand can also be covered when no gas from Russia or Western Europe is available as long as the other import routes can balance the missing gas quantity. For example, Fig. 4 shows the result of the gas flow calculation for the case that no Russian gas is entering the German gas system. Most important, the situation is manageable as GASOPT is able to generate a solution. The compensating high feed-ins from Norway and Belgium lead to higher flow velocities in the Western German grid, but the pipeline pressure is in allowed ranges. Further calculations show that a situation with empty storages and a simultaneous full load operation of gas-fired power plants is manageable as well. This is not the case for the year 2015.

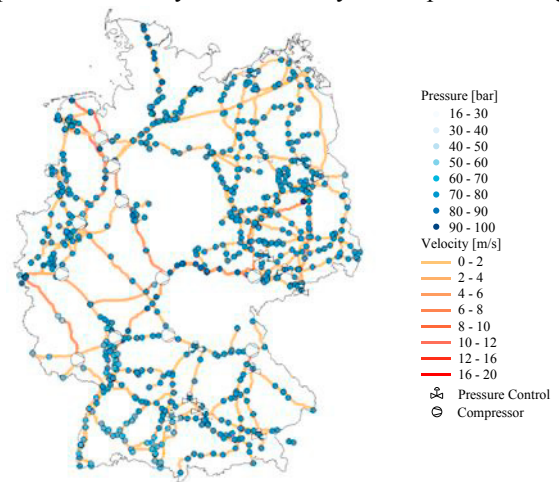


Fig. 4. Pressure and velocity during maximum import situation in 2050, no import of Russian gas, own calculation

5. Conclusion

The results of the scenario calculation show that energy security increases significantly due to reducing gas demand because of the *Energiewende*. Even situations with a complete outage of Russian gas supply or empty gas storages are manageable from a grid perspective as long as other gas suppliers compensate missing gas quantities. Hence,

further grid expansions should be carefully assessed whether they are technically necessary or not and economically feasible over a long-term horizon.

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