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Load Flow Calculations of Large Transmission Gas Networks based on Public Data

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ABSTRACT

The coupling of natural gas networks and other energy sectors like the power grid is becoming increasingly essential for a low-carbon, environmental-friendly integrated energy system. The existing natural gas transmission network can work as a backbone in the whole energy system. Efficient and effective network data processing, network flow calculations, and powerful results visualization are all required when analyzing a large gas network on a high-resolution regional level. This paper will demonstrate and discuss a gas network simulation framework along with a complete toolchain to fulfill the task using the German gas transmission network.

INTRODUCTION AND BACKGROUND

Against the global background of long-term decreasing CO_2 emissions and decarbonization, many countries initiate the energy system transition towards renewable energy participation. In 2011, the German government proposed *Energiewende* which aims at reducing 80-95% use of fossil fuels by 2050 compared to 1990 [1]. To achieve the goal, a growing share of renewable energy is encouraged in supplying, meanwhile, the consolidation of new infrastructures with existing energy systems should be considered for economic benefits. As natural gas still plays a crucial role in the German energy system [2] and foreseen provides essential support to other renewable energy systems like power grids and green gas transmission [3], the natural gas network is going to be the backbone for the future energy systems.

The natural gas network will not only provide existing transmission tunnels for hydrogen and biomethane but contribute to increasing the share of renewable electricity supply like wind and solar using Power-to-Gas (PtG) technologies [4]. In addition to studies at detailed energy transition techniques, researches regarding the short- and mid-term planning on the energy transition process based on the existing gas network are required. This requires efficient and effective flow calculations and analyzing on a high-resolution regional level.

To simulate a specific gas-network based energy transmission scenario, supply and demand profiles, corresponding reinforcement and development of the gas transmission grid should be closely included in the gas infrastructure modeling and analysis. The supply is decided by natural gas and other planned renewable energy source, while the demand can be predicted following energy consumption tendency. The German official energy balance data are open to the public [5] and thus can be used in the gas network flow calculation.

This paper presents a gas network simulation framework along with a complete toolchain to provide the gas network simulation and analysis results in designed energy supply scenarios. The work includes the construction of network topology based on the German existing natural gas grid, the supplies and demands collection and allocation using specific demand modeling based on public statistic data, and steady-state network simulations and validation of the calculation results. A large natural gas network like the German transmission network can assist in distinct integrated energy supplying scenarios only based on public data using the toolchain. For scenarios in cooperation with other energy systems, the toolchain can provide technical validation in the perspective of the gas network with flow parameters change (e.g. increase and decrease at supply and demand nodes, pipe flow parameters including gas characteristics, etc) in specific energy supply and demand situation.

APPROACH

Network Topology

The German natural gas network is a significant part of the European gas transportation system. With 11,000 km pipelines, the German gas network not only feeds Eourpean secondly-largest consumption market but also works as a pivot to transit gas to other EU countries (e.g. gas from Switzerland to Italy and gas from Belgium to the UK). Meanwhile, the most complicated market structure compared to other EU countries makes the German grid a symbol of the European gas network. An overview of German natural gas volume is shown in Figure 1. In Germany, natural gas is traditionally delivered through a three-tier gas value chain of a few importing companies, about 15 regional transmission system operators, and more than 700 local distributors [6]. While significant amounts of gas are transported to other EU countries via the German transmission system, a closely meshed distribution network delivers gas to domestic end consumers.

The network topology of the German gas transmission system can be retrieved utilizing freely achievable geographic data from transparency public platforms such as the European Network of Transmission System Operators for Gas (ENTSOG) [7] and Platte [8]. Public data is trustful for up-to-date pipeline routings but non-georeferenced and lack of technical details like pipeline diameters, roughness, and maximum operating pressure. These technical details are required for flow calculation and can be provided by commercial georeferenced datasets like VGE network map [9], and also from other literature, conferences and workshops. The German transmission network is divided into two systems: H-gas (high calorific) and L-gas (low calorific) since 2015, which is long-distance and supra-regional. In this paper, we select a partial German L-gas network and the whole German network containing both L-gas and H-gas for testing. In the long term, the L-gas grid in Germany will be converted to H-gas due to production decline. [10].

The considered topology model for further simulation is an undirected topological graph consisting of nodes and edges. The nodes represent import, export, underground gas storage, industrial consumptions, regional households, services, heating, power plants, and connections. All nodes are divided into three types: supplies, demands, and interconnections. The interconnection node is generated with inter-connection pipes. Note that storage nodes may switch between supply and demand node in a distinguished time period. The edges are represented for pipelines, controlling units fo pressure and flow (i.e. compressor stations, valves, and control valves). Despite all transmission pipelines and active elements collected from databases, a list of connected new pipes (inter-connection pipes) is created to ensure the network full-connected before simulation.

Finally, the German natural gas transmission network (both L-gas and H-gas) is built and applied in load-flow calculations. The topology profile of the network is shown in Figure 2, while some of the topology details are listed below:

- Nodes:
    - (L-gas) 2747 nodes: 2709 demands, 38 supplys
    - (L-gas and H-gas) 7456 nodes: 7280 demands, 176 supplys
- Edges:
    - (L-gas) 3068 edges: 2713 pipes, 355 active elements (compressor stations, valves and control valves)
    - (L-gas and H-gas) 8603 edges: 7064 pipes, 1539 active elements
    - DN: 50~1400 mm
    - Maximum pipe pressure: 16~100 bar

Supplies and Demands based on Public Data

Since 2013, the European gas flow data can be downloaded from the ENTSO-G transparency platform. For the supplies, a mapping table is created to allot ENTSO-G import data to supply nodes in the German gas network. The demands are categorized into two groups: public gas demand data (e.g. exports data from ENTSO-G) and demands which have to be modeled utilizing additional public statistic data (e.g. private house gas demand is modeled using data of population, number of households, etc). As the public data sets are distinct in different temporal resolution and regional granularity in gas demand sectors, a demand model is therefore required to allocate the demands to nodes. A grouping by socio-economic indicators according to Arbeitsgemeinschaft Energiebilanzen (AGEB) is defined in the demand model for calibration. Figure 3 shows the AGEB demand for the year 2016 and our grouping of demand sectors. Note that the “Sonstige(others)” in AGEB refers to the overall value and thus difficult for allocation. With a limited 2.6% contribution to all demands (24.3/940 TWh Hs), it is neglected in our demand modeling and our modeled demand data for the German gas network.

The Official Eurostat data and contained socio-economic indicators are provided across administrative borders in the Nomenclature des Unités Territoriales Statistiques (NUTS) classification [11]. On the first two levels of resolution (NUTS0 and NUTS1), national information about states and major regions are made available. The second level of resolution (NUTS2) gives input data for regional gas demand modeling and the third level (NUTS3) enables detailed modeling in specific small regions. This kind of data allows us to include socio-economic parameters into the regional demand model dependent on the spatial granularity of the parameters – per country, per region or per municipality.

To assign demand at all demand nodes, the demand model needs to firstly get regional gas demand (model data at NUTS3 level) for all sectors and then do the node-level allocation. The Regional gas demand may be modeled in two conceptual ways: Bottom-Up (BU) and Top-Down (TD). BU collects highly detailed spatial data sets and sums them up at higher levels, while TD proceeds a regionalization of statistical data and allocates it into lower-levels. Both methodologies are used in our demand modeling for distinct demand sectors in the light of data overall perspective and available granularity. A combination of both methodologies requires calibration that can be complex due to imbalance between inflow and outflow. In this paper, we modeled the gas demand at node-level for the year 2016 and calibrated the results with data from Net Connect Germany (NCG, https://www.net-connect-germany.de/) and Gaspool (https://www.gaspool.de). Results showed a 4% deviation (excluding 2% "Sonstige") in Figure 4.

In private housing demand modeling, the very detailed data on population, number of households and the Germany residential building structure from the Census 2011, are collected and modeled applying BU to cluster in NUTS3 level. With the available statistical data on heating per unit for distinct building stocks (based on structure, type, and age), population, heating technology, and climate factors, gas consumption in heating can be estimated from each building to NUTS3 level. Industrial gas demand uses a TD model and determined by specific energy demand in economic sectors. For industries in the same field, employment statistics are used to estimate energy demand on the municipality level in the scenario design. With modeled demand data in NUTS3 level for all sectors, temporal resolution of gas demand is modeled by an allocation of hourly load profiles with a typical sigmoidal relation, and demand calibration is made after a weighting according to sectoral distribution parameters and calculation of regional consumptions.

The conversion or transformation of energy in large scale industrial applications, Combined Heat and Power (CHP) generation, as well as gas-based electricity production and power plants, is modeled individually for each location adopting a conservative valuation (peak load) which may lead to an overestimation of locations and facilities with limited utilization (full load hours). A comparison with electrical transmission network models provides additional power plant data.

Simulation and Evaluation

Quantitative and detailed analysis through case studies about supply and demand in existing and future gas transmission infrastructures requires an abstract representation of the underlying investigation object – a model. Input data for a model consists of demand and supply scenarios and topology for the transport infrastructure. Output data depend on the approach and objective of the respective study. Preparing gas network models is a data-driven process and in accordance, with the spatial extent of the underlying topology, the database is set up in a geographic information system (GIS). A database and standardized data management are used for the processing of scenarios about gas demand and supply.

Elements organized as entities in the database are points and pipe segments. Gas transmission pipelines are treated as linear constructions for transferring gas between points which are classified into different types as entry and exit points. Gas demand and supply are assigned to points, as a basic principle, namely power plants for electricity generation and district heating grids, storages, import terminals, and distribution networks. Regional aspects of energy demand and their spatial reference are included during the scenario design in GIS.

To fulfill the network scenarios simulation and evaluation, a comprehensive toolchain is designed in this paper for flow calculation and scenario analyzing tasks. The toolchain including above network topology generation, supplies and demands allocation with calibration, and the API-link to commercial simulation software with results visualization for validation is programmed as a Python toolkit and easy to expand and transplant. As the complete network model contains large quantities of data, a flexible and stable database MongoDB is used as the basis of data delivery and operating. The load-flow calculation is implemented by commercial network simulation software Simone using API to communicate with the toolchain. Simulation parameters and results are all stored in MongoDB, while the evaluation of the scenarios is made based on the visualization and analyzing module of the toolchain. The working procedure and data flow of the toolchain is illustrated in Figure 5.

CASE STUDY

To validate our integrated gas network analyzing tools, demands and supplies data of Germany in the year 2016 is fed within the German natural gas transmission network describe above in Network Topology. Supplies extracted from public gas import data and demands allocated to each node are obtained using relevant methods in Supplies and Demands based on Public Data. The first hour of 2016 is selected for load-flow calculation which is implemented with setting pressures of supply nodes in Simone. The visualization of simulation results including nodes pressure, pipes flow, and velocity are shown in Figure 6.

As the main sources for gas are from the North Sea and Russia in the simulated scenarios, the results of nodes pressure and pipes flow demonstrate a suitably general gas flow direction from northwest to southeast. In comparison to larger L-gas and H-gas network, the L-gas network shows a more stable flow due to relevant richer data and fewer pipelines. Meanwhile, with unchanged active elements settings in the same L-gas grid, the larger network presents a very low pipes flow velocity in the whole network, which indicates an improvement in more proper active-elements settings and in feed-in data quality to get better calculation results.

To illustrate the potential application of the toolchain to assist in integrating with other energy systems, this paper constructed a virtual situation in which the Gas to Power share in Germany natural gas and power system are increased by 20%. Based on the first-hour scenario in the German network with demands for the year 2016, an increasing gas demand of 4026 MW is added in 83 TPP nodes (20% increase at each TPP node). With no change in configurations of compressor stations, the new scenario provides a possible supplies-change solution.

Supply will change at network supply nodes in order to meet the increasing demands at TPP nodes distributed in the German gas transmission network. Figure 7 shows all supplies with a flow change in the network. Gas supplies from import nodes at Dornum (northwest Germany) and Waidhaus (southeast Germany) increased most and served the majority contribution to newly added TPP demands. With the same compressor configurations, the newly demand increasing scenario will lead to supply decreasing at some supply nodes to ensure the gas flow stability in the whole network. Significant supply change always occurs at import nodes and underground gas storages (UGS). Figure 8 gives a more detailed supply change at supply nodes with a change larger than 5%. Note that supplies change in UGS may have a sign change (e.g. negative to positive: GS-0689, GS-0101; positive to negative: GS-0677). This case proves that the current German natural gas transmission network can meet the designed scenario with 20% increase in the TPP demand and provides a transmission scheme with the smallest change in operating parameters based on the toolchain.

CONCLUSIONS

The results of gas flow scenarios show that the integrated toolchain in this paper is available to provide technical assessment for large transmission gas network only using public data. The load-flow calculation can only be implemented with the allocated flow at every supply and demand node after properly pre-processing of the raw data obtained from public platforms. The top-down approach used in this paper is validated as a trustful solution (4% deviation excluding 2% demands) for making scenarios in hourly-resolution supplies and demands. To fulfill a timely simulation of different gas flow scenarios, the huge amount of data used from network topology generation to load flow calculation can be processed using a NoSql database, and easy to achieve results visualization and analysis.

Using the toolchain, a variety of gas flow scenarios (e.g. different import plans, reduced/increased regional gas demands, changed network topology, etc.) are available to be further analyzed and discussed. The toolchain is also easy for extending as a Python package and be used for other large gas networks with required data.

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AUTHOR BIOGRAPHY

Dongrui Jiang s a research fellow at the Energy and Resource Management Department of the Technische Universität Berlin; there she is currently doing her PhD research in the field of European future integrated energy systems. Her main subjects of interest in this field are natural gas network flow simulations and optimization. She studied in the major of oil and gas storage and transportation for both Bachelor and Master in Southwest Petroleum University, China.

Steven Hotopp holds a Dipl.-Ing. degree in industrial engineering, main subject "energy and resource engineering" from Clausthal University of Technology. He is currently working at the Department of Energy and Resource Management, TU Berlin. His main research field is gas infrastructure modeling and simulation on European level. Apart from that, he has successfully led several gas research and industry projects on topics as scenario-based planning of gas network development, integrated co-simulation of electricity and gas networks, cost efficiency benchmarking and regulatory data monitoring.

Matthis Wacker is a research assistant at the Department of Energy and Resource Management in Technische Universität; there he studied applied Geophysics for bachelor's degree and then the master's degree with a focus on energy and resource management. He successfully completed this course in 2018. He currently focuses on gas transport simulations and gas demand modelling in high regional and temporal resolution.

Univ.-Prof. Dr.-Ing. Joachim Müller-Kirchenbauer leads the Department Energy & Resource Management at Technische Universität Berlin and held the chair Gas Supply Systems at TU Clausthal University from 2010 to 2015. Before he worked for almost 20 years as consultant, headed several units at the federal network agency and was lecturer at RWTH Aachen University.

FIGURES

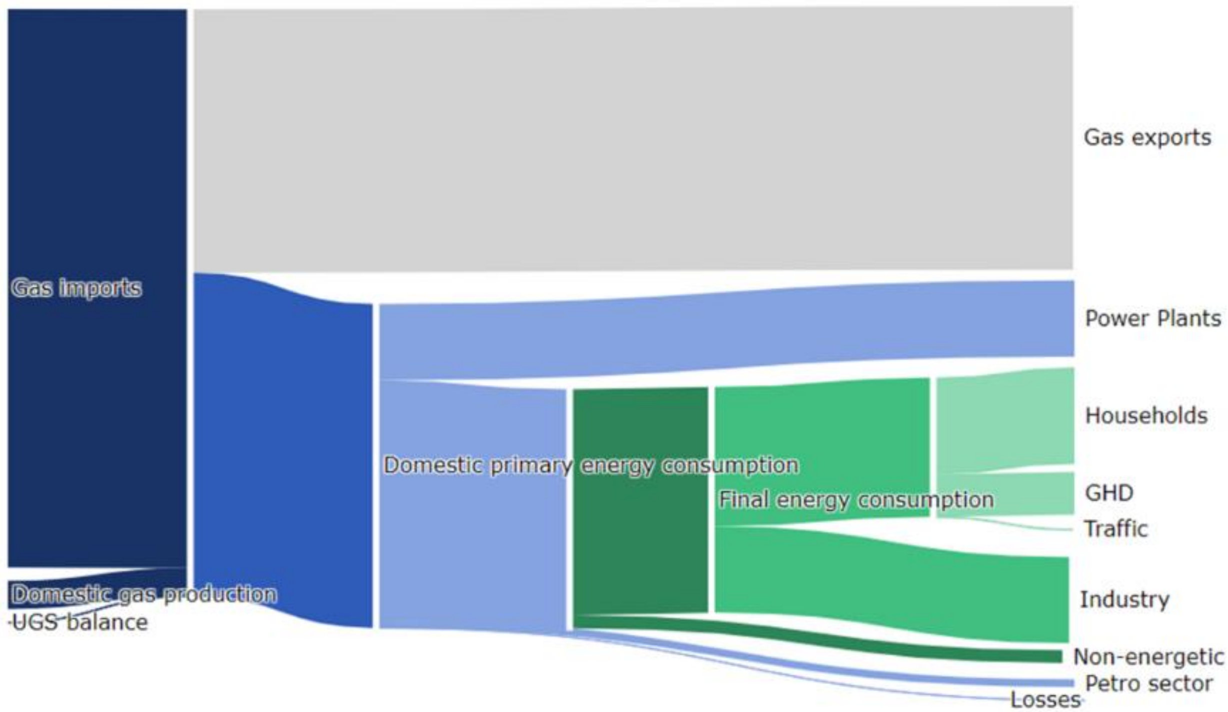


Figure 1 – Overvie of German natural gas volumn

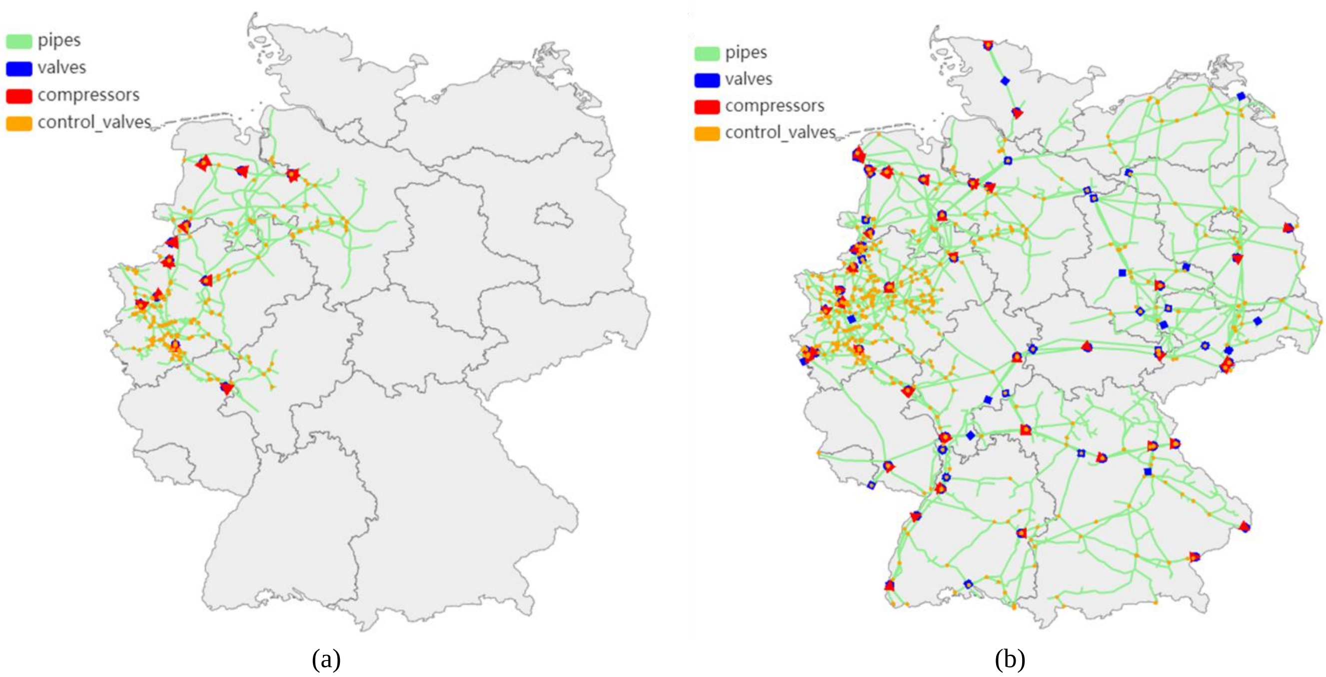


Figure 2 – German gas transmission network: (a) L-gas, (b) L-gas and H-gas

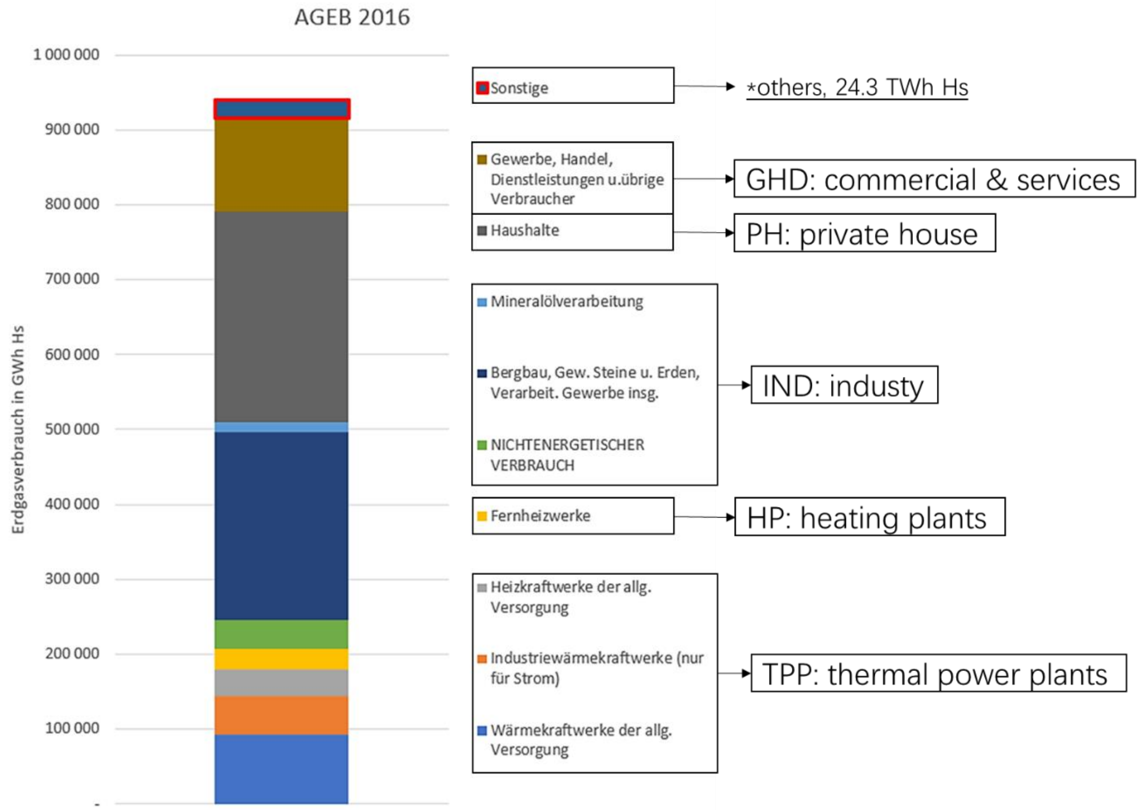


Figure 3 – AGEB 2016 gas demand sectors and the regrouping in our demand model

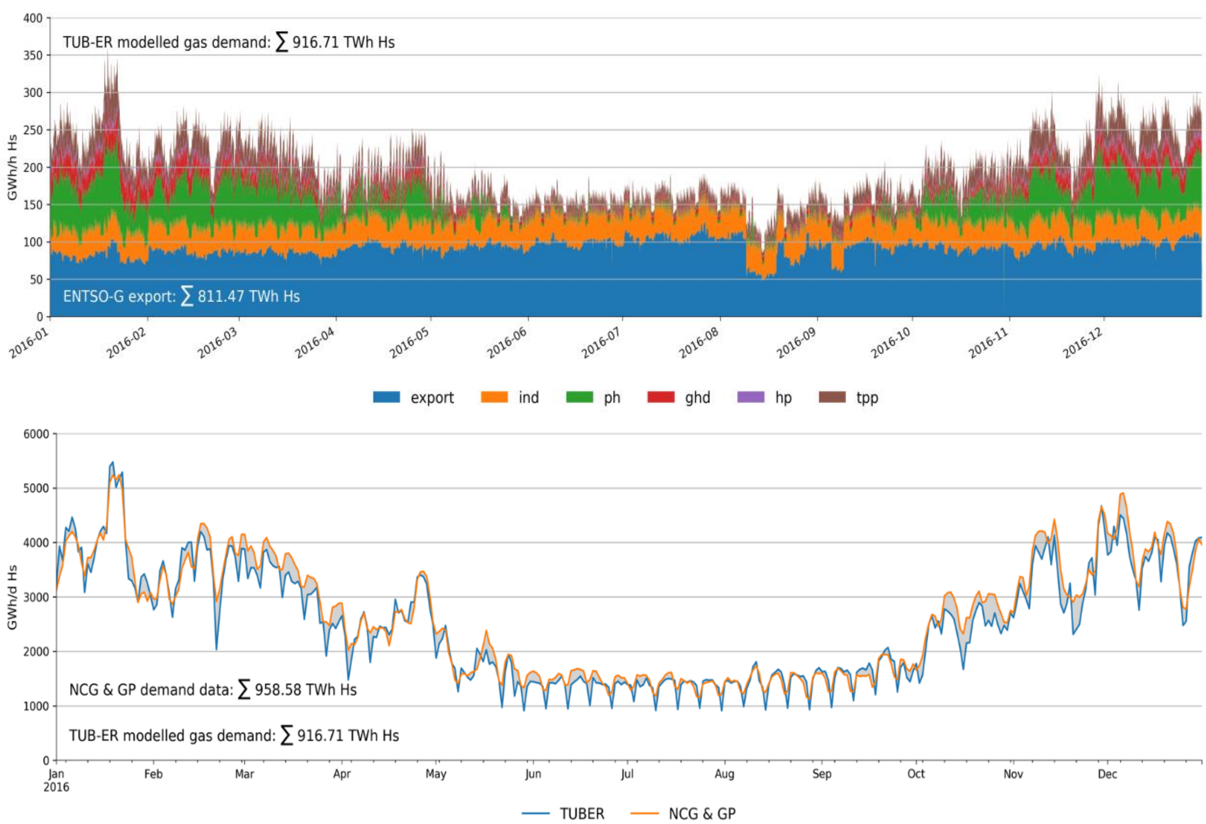


Figure 4 – Calibration of the modelled gas demand data for the year 2016 (above: modelled gas demand in differect

sectors; below: comparison with NCG&Gaspool demand data)

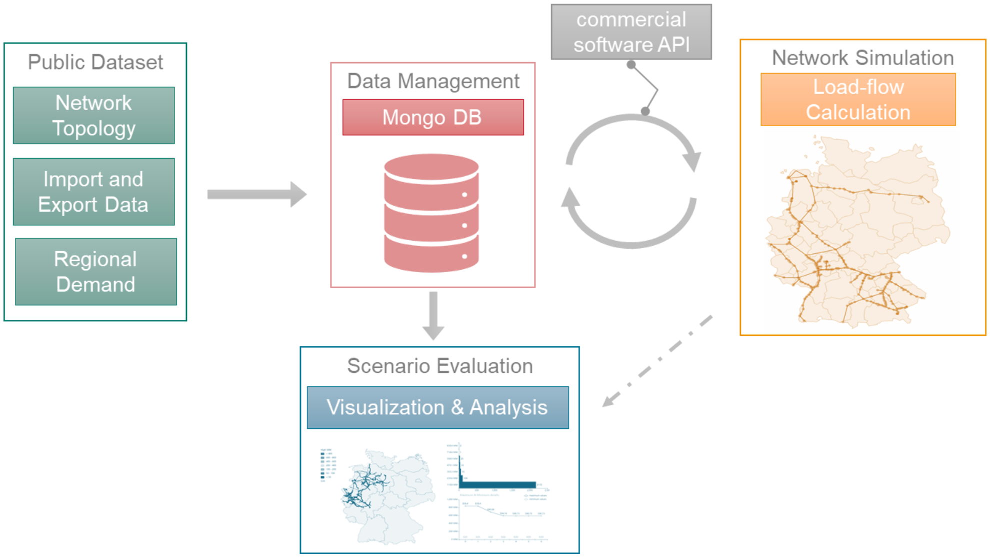
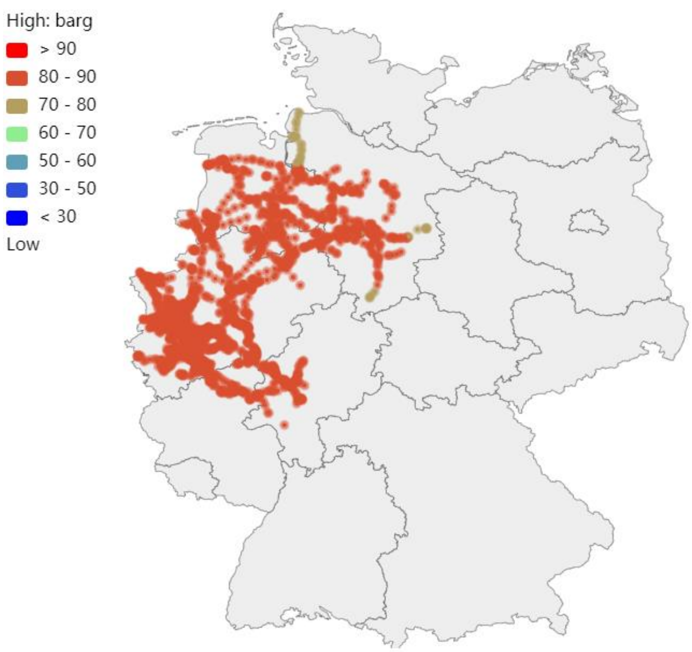
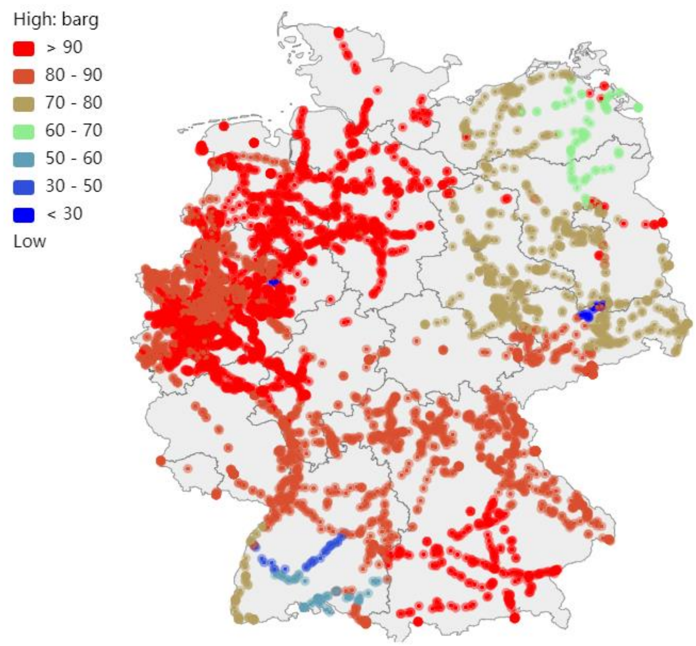


Figure 5 – Working procedure and data flow of the toolchain



(a1)



(a2)

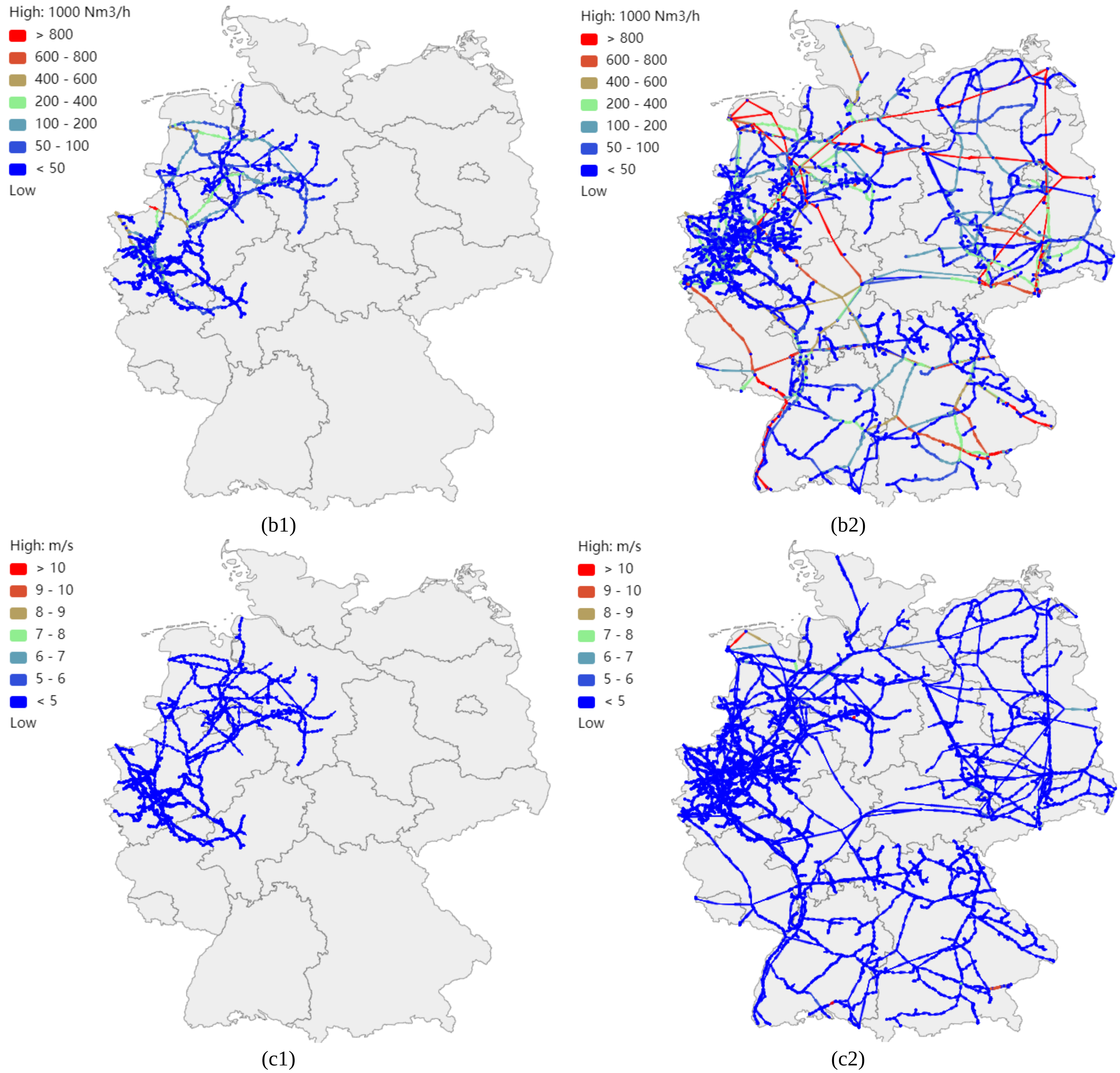


Figure 6 – Flow calculation result of Germany Transmission Network in 2016: (a) pressure of nodes, (b) flow of pipes, (c) velocity of pipes; 1: L-gas network, 2:H-gas and L-gas network

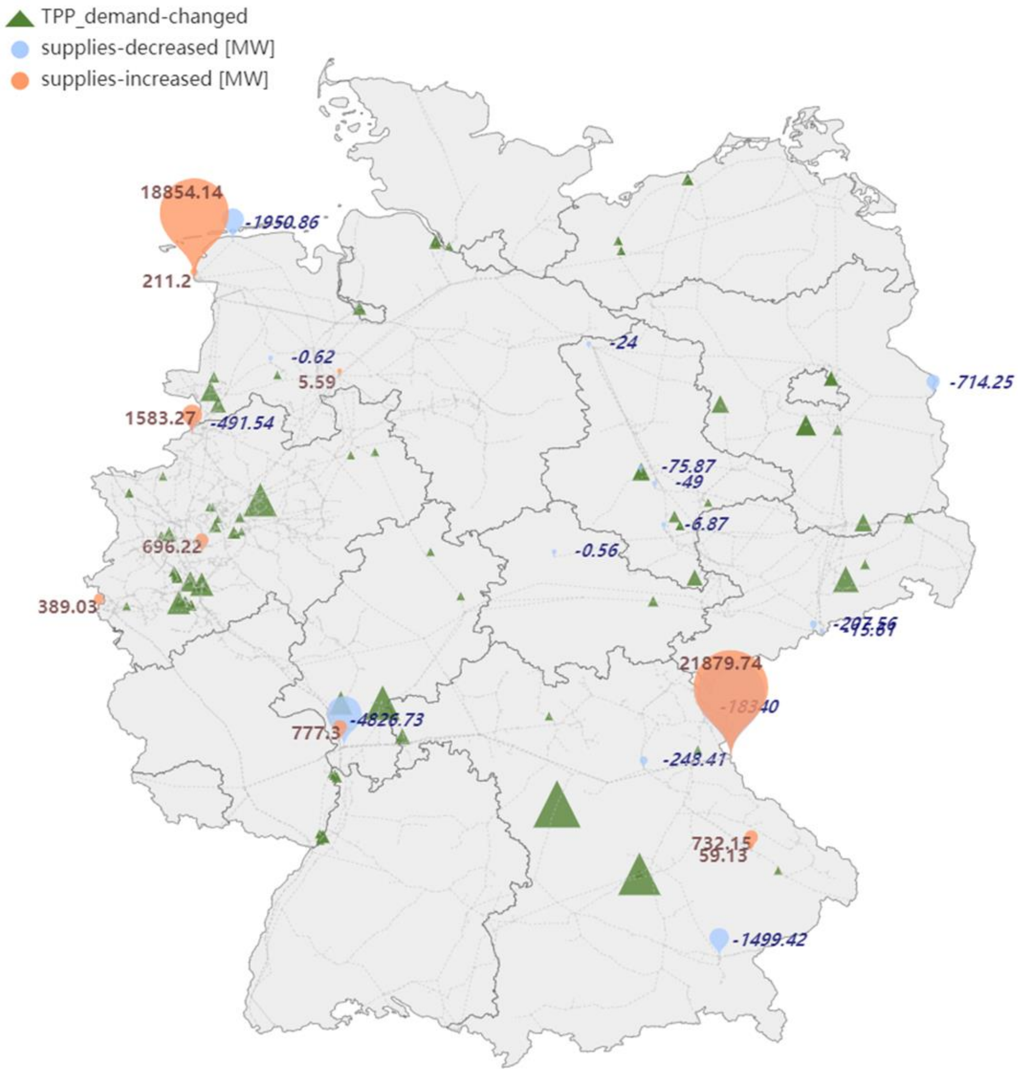


Figure 7 – TPP with increased demand by 20% and changed supplies in the TPP demand increasing scenario

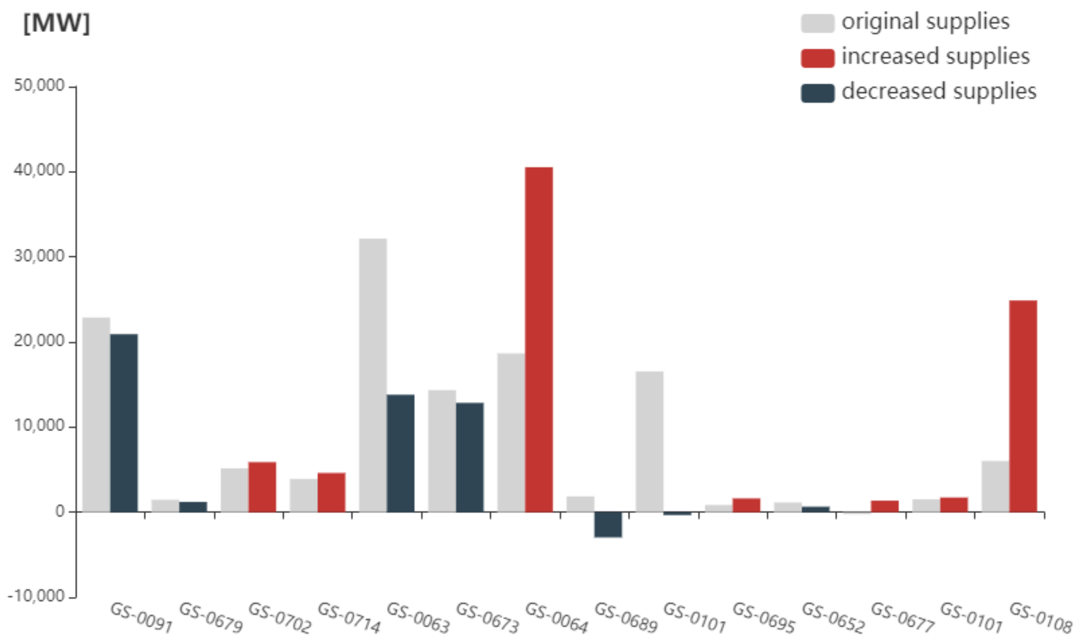


Figure 8 – Supplies change at supply nodes in TPP demand increasing scenario (supply nodes with a change greater than 5% are selected)