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A modelling approach for the German gas grid using highly resolved spatial, temporal and sectoral data (GAMAMOD-DE)

*Philipp Hauser**

May, 2019

Abstract

Natural gas is the fossil fuel with lowest CO₂-emissions, compared to coal, lignite or oil. Regarding the ongoing energy transition in Germany, the extend usage of natural gas provide advantages that might be built a bridge to a low carbon energy system until 2050. Against this backdrop, this paper introduces a model for the German natural gas market (GAMAMOD-DE) with focus on infrastructure utilisation. Following a linear optimization approach, the model considers a highly resolved grid structure of pipelines, storages and cross-border connections to neighbouring countries. The spatial and temporal resolved gas demand is divided into three different sectors: industry, heating and electricity. An application for the year 2012 shows the performance and validation of the proposed model. Results show the utilisation of infrastructure and enable an assessment of the level of security of supply during the considered time frame. In addition, the findings suggest that although European customers suffered on cold winter days in 2012, from a system part of view, the security of supply (SoS) was always ensured. Further research should focus on analysing SoS and resilience of gas networks in the mid- and long-term, especially when sector coupling between electricity and gas is far advanced.

Keywords: Linear problem optimization; gas grid Germany, sectoral, temporal, and spatial resolved demand; energy security

JEL classification: D61 · L95 · Q32 · Q41 · Q54

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1 Introduction

Natural gas is the fossil fuel with lowest CO₂-emissions, compared to coal, lignite or oil. Regarding the ongoing energy transition in Germany, the extend usage of natural gas provide advantages that might be built a bridge to a low carbon energy system until 2050, between:

- 1) flexible¹ gas power plants can be seen as back-up capacities for fluctuating renewable energy sources (RES)²;
- 2) the German natural gas pipeline system provides a second energy transport system to connect supply and demand regions in Germany and to integrate further energy from RES, e.g. by injection of “green gas” using power-to-gas concepts;
- 3) gas pipelines and gas storages can be used for long-term storage in order to balance seasonal demand patterns.

Following the concept of using natural gas as a bridge fuel to a more sustainable energy system, the interdependence of gas and electricity grid infrastructure increase. Therefore, this paper focus on the detailed modelling of the German gas infrastructure by developing a new Gas Market Model for Germany (DE), called GAMAMOD-DE.

GAMAMOD-DE focus on a highly resolved natural gas grid representation for Germany with more than 1700 pipelines and 1400 nodes on a daily resolution for one year. Furthermore, the model considers natural gas demand regarding three energy sectors: residential heating, industrial usage and gas power plant demand. An optional interface to an electricity market model is provided and used in Hauser et al. (2019), in order to integrate individual gas power plant demands.

In academic literature, three general model based approaches can be distinguished that covers the natural gas infrastructure. The first approach comprises full equilibrium models, e.g. MAKRAL and TIMES, IKARUS or PERSUES, that represent the entire energy system including all partial energy sectors in order to investigate the impact of a fundamental change in one special commodity market, e.g. a coal phase out (Heinrichs and Markewitz, 2017) or prospects of future gas supply and its impact on the electricity sector and emission trading system (Möst and Perlwitz, 2009). Studies that are using this approach lack on a temporal resolution (mostly one point of time for each year) and spatial resolution,

¹ “flexible” means in this context that gas power plants can be ramp up and down quickly (rd. a. 15 minutes) compared to other thermal power plants

² Since 2000, significant achievements in the German electricity mix were made, as the share of renewable energy sources (RES) amounts 36% in 2017 (Umweltbundesamt, 2018), a completed nuclear phase out will be done in 2022 (cf. Article 13 (1) Atomgesetz-Änderungsgesetz) and the discussion on a phase out of lignite and hard coal is an ongoing process, most probably latest done by 2038 (Kommission-WSB, 2019). Hence, natural gas power plants and power-to-gas facilities are technologies to provide flexibility for balancing RES feed-in.

especially grid representation. Some authors use a soft link model coupling e.g. between a general equilibrium model and a partial equilibrium model to investigate price changes in gas markets on the entire energy system (Hauser et al. (2018)). Compared with these equilibrium models, GAMAMOD-DE does not consider other energy sectors endogenously, but represents grid infrastructure on a more detailed level.

A second approach proposes stylized integrated models that explicitly consider two energy sectors, e.g. electricity and gas system, in one single stylized form (e.g. Abrell & Weigt (2014), Riepin, Möbius and Müßgens (2018)). The main objective here is to study mutual effects and implications. However, the number of modelled elements is small and the opportunity to draw conclusions from model results for real world applications is limited. Hence, the importance increase of considering natural gas infrastructure and techno-economic constraints in natural gas systems that cover the system on a more detailed level. Compared to these models with less technical details, GAMAMOD-DE considers gas demand from the power sector as an exogenous parameter. However, an iterative model coupling approach with an electricity system might be an approach to cover the feedback process between the gas and electricity system.

Finally, pure natural gas market models for the European or world gas market are investigated in extensive studies (e.g. Egging, Holz and Gabriel (2010), Lochner et al. (2010) and Holz, von Hirschhausen and Kemfert (2008)). Models with focus on a subnational level with a higher level of grid representation are exceptional. Some models consider major transport pipelines, e.g. the TIGER model, in order to investigate price effects. Another application of these models is the investigation of natural gas supply interruptions, e.g. caused by geopolitical disputes (Richter and Holz (2015), Hecking John and Weiser (2014)). In contrast to these models, GAMAMOD-DE focus on the German natural gas grid infrastructure. However, geopolitical scenarios can also be investigated by using normative resp. explorative scenarios, as cross-border connections to neighbouring countries are considered in the model.

In general, gas grid models are challenging, especially when it comes to a adequately representing of technical characteristics of dynamic behaviour, pipeline pressure, and gas qualities. A state of the art approach is to simulate gas flows with a software SIMONE, e.g. used in the GASOPT model (Gillesen, Heinrichs, Hake, & Allelein, 2019). Studies that address these technical representations show two major challenges (cf. Münch et al. (2014), Grimm et al. (2018)):

- 1) detailed information about grid topology is needed and often not public available
- 2) calculation of dynamic grid state is challenging and non-linear

To sum up, gas models that considering technical characteristics and optimizing one year are hard to solve, but simulations are feasible. A common modelling approach to deal with this challenges is converting dynamic technical characteristics, like pressure and volume, into static energy units. Using this

simplification, a linear energy transport model can be established in order to investigate non-linear natural gas flows. The proposed model GAMMAOD-DE follows this simplification approach.

The outline of this paper is as follows: Section 2 introduce the optimization problem of GAMAMOD-DE, shows the system of equations, and discusses the modelling approach. Section 3 comprises an application of the proposed model for 2012 and gives an overview about used data. Finally, results were presented and discussed. Section 4 concludes the paper.

2 GAMAMOD-DE: model description

2.1 Overview

The proposed model Gas Market Model for Germany (GAMAMOD-DE) covers the German gas transport pipeline network. Figure 1 shows the topology of GAMAMOD-DE. Figure 2 describes the general structure of the model.

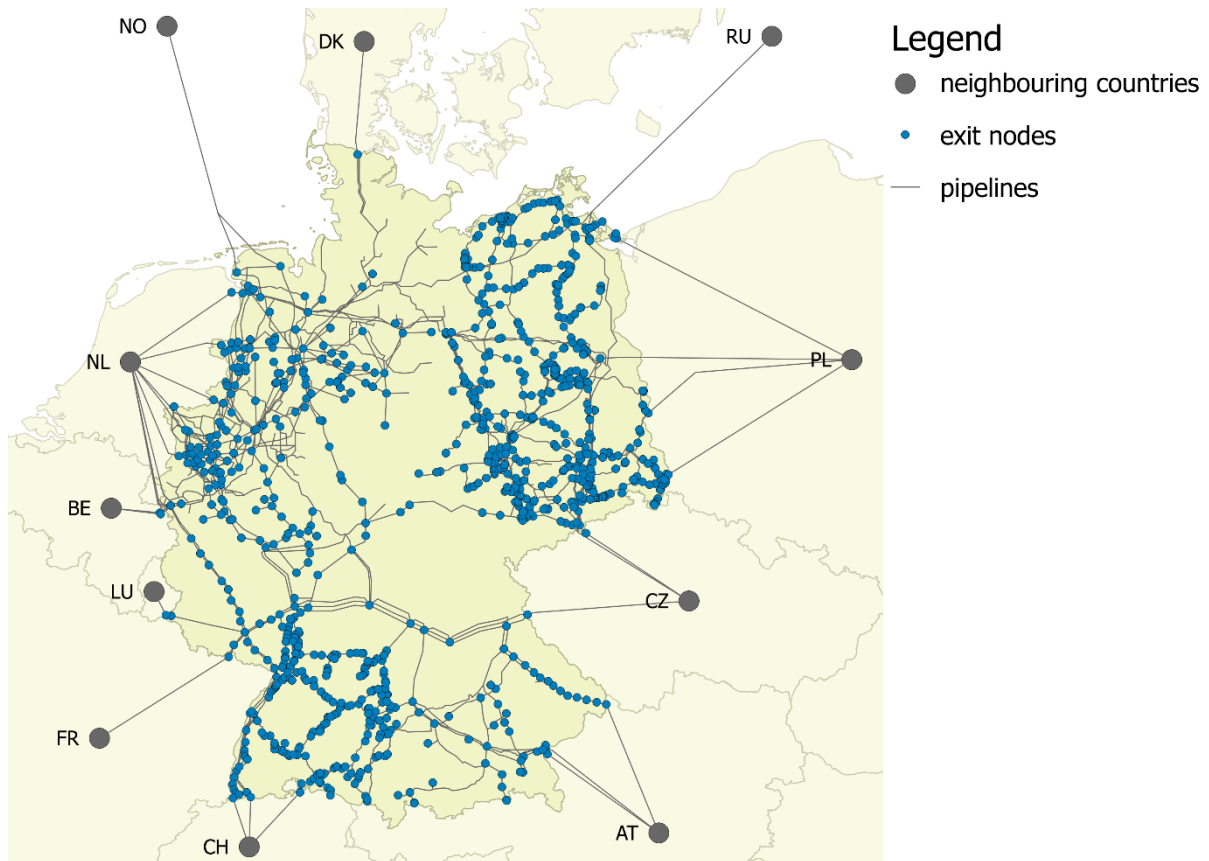


Figure 1: Topology GAMAMOD-DE

(Source: own illustration)

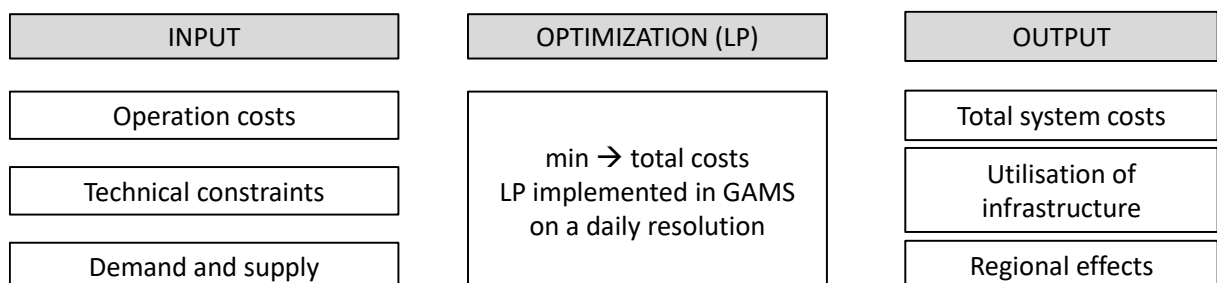


Figure 2: GAMAMOD-DE overview of input and output data

(Source: own illustration)

GAMAMOD-DE follows a linear optimization approach for one year, divided into 365 days³. It represents the natural gas transport pipeline system in Germany and connections to neighbouring countries respectively to connected countries.

2.2 Algebraic formulation

In this paragraph, the algebraic formulation of the model is introduced and all equations are described, in particular the objective function and technical and economic constraints. The sets, used in the following explanations, are described in Table 1. The used variables are described in Table 2 and the used parameters are described in Table 3.

³ For leap years, e.g. 2012, the model considers 366 days.

Table 1: Sets used throughout the model formulation

Set, Alias	Definition and number of elements	Super- set	Explanation
a	$\in A = \{a1, a2\}$ $\Rightarrow A = 2$		final energy use sector
i, j	$\in I = \{3000000, \dots, 380400031\}$ $\Rightarrow I = 1475$		nodes
$i^{exit} (i)$	$ I^{exit} = 970$	$\subset I$	nodes w/ exit flow
$j^{DemFix} (j)$	$ j^{DemFix} = 31$	$\subset I$	nodes w/ fixed demand
l	$\in L = \{11, \dots, 11751\}$ $\Rightarrow L = 1751$		pipelines
n, nn	$\in N = \{n1, \dots, n435\}$ $\Rightarrow N = 435$		NUTS3-region
pp	$\in PP = \{BNA0088a, \dots, BNA1678\}$ $\Rightarrow PP = 274$		BNetzA natural gas power plant ID
pr	$\in PR = \{pr1, \dots, pr17\}$ $\Rightarrow PR = 17$		production regions
r	$\in R = \{r1, \dots, r16\}$ $\Rightarrow R = 16$		regions (federal states in Germany)
st	$\in ST = \{st1, \dots, st37\}$ $\Rightarrow ST = 37$		storage facilities
t^d	$\in T^d = \{t0001, \dots, t0366\}$ $\Rightarrow T = 366$		time (days)
tt	$\in TT = 366$	$\subset T^d$	time horizon in model
t^h	$\in T^h = \{t0001, \dots, t8784\}$ $\Rightarrow T = 8784$		time (hours)

Table 2: Variables used throughout the model formulation

Variable		Explanation
TC		total costs
$FLOW^{pos}(l, tt)$	$FLOW^{pos}(l, tt) \geq 0$	positive flow on pipeline
$FLOW^{neg}(l, tt)$	$FLOW^{neg}(l, tt) \geq 0$	negative flow on pipeline
$LoadCut_{i,tt}$	$LoadCut_{i,tt} \geq 0$	load shedding of natural gas power plants
$PQ_{pr,t}$	$PQ_{pr,t} \geq 0$	production
$STORAGE_{st,tt}^{in}$	$STORAGE_{st,tt}^{in} \geq 0$	storage injection
$STORAGE_{st,tt}^{with}$	$STORAGE_{st,tt}^{with} \geq 0$	storage withdrawal
$STORAGE_{st,tt}^{level}$	$STORAGE_{st,tt}^{level} \geq 0$	storage level
$VOLL_{a,i,tt}$	$VOLL_{a,i,tt} \geq 0$	Volume of lost load variable

Table 3: Parameters used throughout the model formulation

Parameter	Explanation	Unit
$pC_{pr,tt}$	production costs	[EUR / GWh]
$pLimit_{pr}$	production limit	[GWh]
$pFlex_{pr}$	production flexibility	-
tC_i	transportation costs	[EUR / GWh]
$tLimit_i$	transportation limit	[GWh]
dc_a	costs for load shedding in sector a	[EUR / GWh]
dc_{pp}	costs for load shedding gas power plants	[EUR / GWh]
$mapIN_{i,n}$	mapping of nodes i to NUTS3 regions n	-
$mapNI_{n,i}$	mapping of NUTS3 regions n to nodes i	-
$mapLIJ_{l,j}$	mapping of pipelines l to nodes i, j	-
$mapPrI_{pr,i}$	mapping production pr to nodes i	-
$mapStI_{st,i}$	mapping of storages st to nodes i	-
$sPattern_{tt}$	historic storage pattern	-
$stoEff_{st}$	storage efficiency	-
$storage_{st}^{inMax}$	maximal injection	[GWh / d]
$storage_{st}^{levelMax}$	maximal level of storage	[GWh]
$storage_{st}^{withMax}$	maximal withdrawal	[GWh / d]

Objective function

The overall objective of the model GAMAMOD-DE is to minimize total system costs in order to calculate a global optimum from a system perspective. Normally, a welfare optimization approach is applied

for this purpose in economic models. Taking specific assumptions into consideration, e.g. perfect competition and a price-inelastic demand curve⁴, results of a cost minimization and welfare maximization approach are equal.

Hence, the objective of this optimization problem is to minimize total system costs TC for meeting the natural gas demand in Germany during one year. Equation (2.1) considers three main cost components: 1) costs for producing natural gas resp. importing natural gas, 2) costs for transporting natural gas through pipelines respective the direction of gas flow⁵, and finally 3) costs for reducing demand on exit nodes:

$$\begin{aligned} \min TC = & \sum_{pr,tt} PQ_{pr,tt} \times pc_{pr,tt} + \sum_{l,tt} (FLOW_{l,tt}^{pos} + FLOW_{l,tt}^{neg}) \times tc_l \\ & + \sum_{a,i,tt} VOLL_{a,i,tt} \times dc_a + \sum_{i,tt} LoadCut_{i,tt} \times dc_{pp} \end{aligned} \quad (2.1)$$

Regarding cost components a number of assumptions are made: Costs for storage operation are indirectly considered, as storage injection (resp. withdrawal) cause efficiency losses (cp. Equation XX). The production costs pc differ between German domestic production at a price level of 10 EUR/MWh and imported natural gas at a prices between 18-23 EUR/MWh in 2012. More details on the assumed data can be find in the Appendix. Costs for pipeline flow tc_l can be interpreted as effort that is needed to operate the pipeline system. These costs are mainly driven by energy consumption of combustion stations⁶.

⁴ While these assumptions are in general true for the electricity market, the gas market behaves differently in some of these aspects. First of all, only a few number of suppliers exist in the (European) gas market and it is likely that they exercise market power. Secondly, gas can be substituted more easily than electricity and, thus, the demand is not completely inelastic. However, there are some reasons why it is nevertheless appropriated to follow this approach: The results of a perfect competition market regime in gas market models can be interpreted as an ideal market outcome that EU regulators try to achieve when they introduce gas market regulation acts. Secondly, it become more difficult to substitute natural gas in future, as possible substitutes are rather significant more expensive (i.e. hydrogen or syngas) or technical processes are more sophisticate, which justifies an inelastic demand curve.

⁵ The pipeline flow relates to a directed graph with nodes and edges, while positive flows are defined as flows from start node to end node of an edge and negative flows vice versa.

⁶ From an economic point of view, the used approach for covering costs for pipeline transport does not represent the current entry-exit model that is used in the reality to distribute grid operation costs. However, the approach still reflects the fundamental costs and should be implicit considered by gas grid operators.

Energy balance

The energy balance equation ensure a stable system level in all time steps tt on all nodes i . In other words, the demand, export flows, and storage injections in one node have to be covered by produced (or imported) gas volumes, import flows, storage withdrawal, and load shedding (volume of lost load or load shedding of gas power plants), as seen in Equation (2.2).

$$\begin{aligned}
0 = & -dem_{i,tt} - \sum_{j,l, \text{mapLIJ}_{l,i,j} \times i \neq 0} (FLOW_{l,tt}^{pos} \times \text{mapLIJ}_{l,i,j}) \\
& - \sum_{j,l, \text{mapLIJ}_{l,i,j} \times i \neq 0} (FLOW_{l,tt}^{neg} \times \text{mapLIJ}_{l,j,i}) \\
& - \sum_{st \in \text{mapStI} \times i} STORAGE_{st,tt}^{IN} + \sum_{pr \in \text{mapPrI} \times i} PQ_{pr,tt} \\
& + \sum_{j,l, \text{mapLIJ}_{l,i,j} \times i \neq 0} (FLOW_{l,tt}^{neg} \times \text{mapLIJ}_{l,i,j}) \\
& + \sum_{j,l, \text{mapLIJ}_{l,i,j} \times i \neq 0} (FLOW_{l,tt}^{pos} \times \text{mapLIJ}_{l,j,i}) \\
& + \sum_{st \in \text{mapStI} \times i} STORAGE_{st,tt}^{WITH} + \sum_a VOLL_{a,i,t} \\
& + LoadCut_{i,tt}
\end{aligned} \tag{2.2}$$

$$\forall i, j \in I, tt \in T$$

Volume of Lost Load balance

In Equation (2.2), the Volume of Lost Load ($VOLL$) and the $LoadCut$ variables represent an additional solution to keep the balance between supply and demand. It can be interpreted as a reduction of demand, in particular load shedding. According to Lochner 2011, GAMAMOD-DE has the opportunity to reduce up to 50% of industry demand to lower costs (94 EUR/MWh) and all other demand up to 100% with higher compensation costs (188 EUR/MWh) through using the $VOLL$ variable (cp. Equation (2.3)). As natural gas power plants have often interruptible contracts that allow grid operators to interrupt natural gas supply by paying a compensation (here: 90 EUR/MWh), the model has the opportunity to shut down these plants demand by using the $LoadCut$ variable (cp. Equation (2.4)). In order to ensure that the model

uses load shedding as last resort, the estimated compensation costs must be on a relevant higher level than any other opportunities to balance supply and demand in the model.

$$\sum_{i, \text{map}IN_{i,n} \times n \neq 0} VOLL_{a,i,t} + \sum_{i, \text{map}NI_{n,i} \times n \neq 0} VOLL_{a,i,t} - (dem_{n,tt,a} \times lc_a) \leq 0 \quad (2.3)$$

$$\forall n \in N, a \in A, tt \in T, dem_{n,tt,a} \geq 0$$

$$LoadCut_{i,tt} - dem_{i,tt,pp} \leq 0 \quad (2.4)$$

$$dem_{i,tt,pp} \geq 0$$

In a “healthy” market where demand can always be met by supply, the *VOLL* has to be zero, and hence, no additional costs for the system should occur.

Production

Production is limited by yearly production quantities, equally distributed on a daily level. In addition, a flexibility factor is introduced, to enable higher production rates during peak demand seasons (see Equation (2.5)). Production flexibility is a country specific factor, based on Lochner (2011) and ranges from 1.12 for Germany up to 1.79 for the Netherlands. An overview about all values can be found in the Appendix (cf. Appendix A.2., Table 5). In addition, the yearly production at each production node must be equal or lower than the daily average production rate times the number of days per year $|T|$ (in 2012: 366 days). This restriction is addressed by Equation (2.6).

$$PQ_{pt,tt} \leq pLimit_{pr} \times pFlex_{pr} \quad (2.5)$$

$$\forall pr \in PR, tt \in T$$

$$\sum_{tt} PQ_{pt,tt} \leq pLimit_{pr} \times |T| \quad (2.6)$$

$$\forall pr \in PR, tt \in T$$

The variable *PQ* entails natural gas quantities of domestic produced natural gas in Germany as well as “virtual produced” natural gas in German neighboring countries. In this context, virtual production

means that neighboring countries export natural gas to Germany. This imported gas can be both, produced within the neighboring country (e.g. in the Netherlands) or transit gas, original produced in other countries (e.g. imports from Poland are mainly transit gas from Russia).

Pipeline flow

The model follows a transport model approach. Hence, technical and physical characteristics as pressure and pipeline diameter are not modeled, but they are considered indirectly⁷. The model calculates the transport of energy units. Thus, the variables $FLOW^{pos}$ and $FLOW^{neg}$ are restricted by the maximum capacity of pipelines.

$$FLOW_{l,tt}^{pos} \leq tLimit_l \quad (2.7)$$

$$FLOW_{l,tt}^{neg} \leq tLimit_l \quad (2.8)$$

$$\forall l \in L, tt \in T$$

The used transport model approach neglect influence of pressure and gas quality of the system, e.g. line packing cannot be considered in the model. Additionally, flow direction of pipelines are not fixed in GAMAMOD-DE. That means that a pipeline is allowed to have a value on FLOW_POS variable for example during the beginning of the year and also a value on the FLOW_NEG variable during a later period of the year. Hence the flow direction in a pipeline might change the direction during the year. Although reverse flows are possible in real world gas systems, the model might overestimate the flexibility of the grid infrastructure.

Storages

Storages balance demand and supply during the year in order to enable regular production and import quantities. In addition, they provide the opportunity for traders to buy natural gas in times with low gas prices, store it and sell it when gas is needed. Hence, natural gas storages play a crucial role in balancing gas prices and providing security of supply during peak demand seasons.

⁷ A detailed description of assumptions and simplifications on technical gas flows and the linearization approach is given in Appendix A.1.

$$STORAGE_{st,tt}^{level} = storage_{st}^{levelMax} \times sPattern_{tt} + (\eta_1 \times STORAGE_{st,tt}^{in}) - (\eta_2 \times STORAGE_{st,tt}^{with}) \quad (2.9)$$

$$\forall st \in ST, tt = t0001$$

$$STORAGE_{st,tt}^{level} = STORAGE_{st,t-1}^{level} + (\eta_1 \times STORAGE_{st,tt}^{in}) - (\eta_2 \times STORAGE_{st,tt}^{with}) \quad (2.10)$$

$$\text{with: } \eta_1 = \frac{1-stoEff_{st}}{100}; \eta_2 = \frac{1+stoEff_{st}}{100}$$

$$\forall st \in ST, tt \neq t0001$$

$$STORAGE_{st,tt}^{level} = storage_{st}^{levelMax} \times sPattern_{tt} \quad (2.11)$$

$$\forall st \in ST, tt = t0366$$

$$STORAGE_{st,tt}^{level} \leq storage_{st}^{levelMax} \quad (2.12)$$

$$\forall st \in ST, tt \in TT$$

The model GAMAMOD-DE covers the time period of one year. Equation (2.9) - (2.12) characterize the technical constraints of gas storage levels in the model.

In addition, the daily storage injection and storage withdrawal quantities are restricted. While some models implement a relation between storage level and maximum of storage injection resp. withdrawal capacity, this approach considers a fix rate, as shown in the following equations:

$$STORAGE_{st,tt}^{in} = storage_{st}^{inMax} \quad (2.13)$$

$$\forall st \in ST, tt \in TT$$

$$STORAGE_{st,tt}^{with} = storage_{st}^{withMax} \quad (2.14)$$

$$\forall st \in ST, tt \in TT$$

$$STORAGE_{st,tt}^{with} = storage_{st}^{withMax} \quad (2.15)$$

$$\times (intersect_{st}^{with} + slope_{st}^{with} \times STORAGE_{st,tt}^{level})$$

$$\forall st \in ST, tt \in TT$$

$$STORAGE_{st,tt}^{in} = storage_{st}^{withMax} \quad (2.16)$$

$$\times (intersect_{st}^{in} + slope_{st}^{in} \times STORAGE_{st,tt}^{level})$$

$$\forall st \in ST, tt \in TT$$

Model implementation

The model is implemented in GAMS, using the CPLEX solver. The model statistics includes 18 blocks of equations with more than 2.4 million single equations and ten blocks of variables with more than 2.4 million single variables. The model entails 12.5 million non-zero elements. The model in GAMS needs 1294 MB RAM, 471 seconds to generate the model and the CPLEX solver finds the optimal solution after 475 seconds. Data preparation is done using Microsoft EXCEL while an import of input data to GAMS and the export of results from GAMS is realized by using the gdx-interface. The visualization and spatial calculations are done using the open source software QGIS.

3 Model application for 2012

GAMAMOD-DE focus on grid infrastructure elements in the German natural gas market. The model bases on the mathematical formulation and implementation in GAMS, introduced in the previous section, and the input data collection. A first applications of a previous model version is used in Hauser, Hobbie and Möst (2017). The data handling is described in Kunz et al. (2018), a further analysis is done in Haumaier et al. (2019) and a model coupling with the Joint Market Model (JMM) is done in Hauser et al. (2019).

The objective of this sections is twofold. Firstly, a description of data base and assumptions that are used in the model is given. Secondly, a back testing for 2012 is presented in order to enable a general assessment of model results and in order to explain strengths and limitations of GAMAMOD-DE.

3.1 Data preparation

Regional disaggregation and spatial resolved natural gas demand

A special feature of GAMAMOD-DE is a highly resolved natural gas grid representation for Germany with more than 1700 pipelines and 1400 nodes. For this reason, a spatial resolution of all input data on a detailed level is needed, e.g. for allocating total German natural gas demand to local nodes. The model considers natural gas demand regarding three energy sectors. For residential heating and industrial usage the spatial resolution bases on NUTS-3 regions in Germany. The spatial resolution for gas demand in gas power plants is more detailed as the locations of gas power plants can be determined easily. Hence, the gas power plant demand is allocated to nearest exit nodes⁸. Additionally, exports are defined as additional demand on cross-border points. Finally, further natural gas demand (e.g. in transport sector), is equally distributed to all exit nodes. Further details on data preparation and sources can be find in Kunz et al. (2018, p. 74).

Production data

Production quantities in Germany (and at other production nodes) are limited according to historical production volumes. Production cost data are non-transparent and depend on local conditions. For GAMAMOD-DE, the model differs among two different cost levels: firstly, German production costs (rd. 10 EUR/MWh) that are constant during the year. Secondly, monthly cross-border prices for imported natural gas in 2012, based on historic NCG natural gas quarter futures, in a range between 22 to 26 EUR/MWh (cf. Appendix A.2.). Other non-conventional gas sources, as biogas or synthetic gases, are not considered.

⁸ The daily demand of natural gas power plants originates from the electricity dispatch model Joint Market Model (JMM), friendly provided by Sina Heidari at the Universität Duisburg Essen.

Grid infrastructure

The grid infrastructure bases on public available sources, basically graphical maps of transmission system operators. Based on these information, a representation using a geo information system (GIS) was created. Using this data, a directed graph including nodes and lines for the optimization model was created (cf. Figure 1). According to transmission capacities, technical data as diameter of pipelines and pressure were assumed to transform these values into energy related transport capacities per day (GWh per day). A detailed description to the methodology is given in Kunz et al. (2018, p. 54 f). One feature of GAMAMOD-DE is the high temporal and spatial resolution of the German gas grid. The grid topology base on maps with a low level on details and may include failures of real existing connections. In many cases, a distinction is not possible, whether pipelines cross each other or just run in parallel. Hence, the grid representation most probably overestimate connections between pipelines and flexibility in the model. However, in the current version, the model does not cover physical gas flow conditions, but energy flows.

Storages

In Germany, there exist many natural gas storages that built the highest natural gas storage capacities in the European Union. The model considers 37 storage facilities that can be distinguished in depleted gas fields, salt caverns and aquifers. All types of storages have different technical characteristics for withdrawal and injection behaviour. Especially the injection and withdrawal rate depend on the actual storage level. GAMAMOD-DE considers these characteristics. The assumptions regarding the relation between storage level and injection rate (resp. withdrawal rate) base on Lochner (2011, p. 39) and the updated data base on AGSI (2018) and GSE (2018).

Imports and exports

An analysis of the German natural gas grid without considering transit gas flows, e.g. from Russia via Ukraine and Poland through Germany to Western European countries, underestimates actual gas flows. The German gas grid system that is located in the centre between Russian gas sources and Western Europe gas demand hubs, transports natural gas volumes through the German pipeline system. Thus, exports are considered as parameters and interpreted as an additional demand that is allocated to German cross border points. On the other side, imports are modelled as variables, in order to keep sufficient dimensions of freedom for the optimization problem in the model.

The model lacks in general on available data. In particular, fundamental cost assumptions are uncertain for gas production and gas transportation as well as for storing natural gas. Cost for load shedding reflect compensation fees for industries and households and cannot be verified easily. However, they are based on a bride literature and it can be assumed that the magnitude of penalties corresponds to real costs.

3.2 Characterization of the year 2012

GAMAMOD-DE is applied for the year 2012. This year is characterized by a cold period in January and February that had led to high natural gas demand, especially to cover heating demand in households. Figure 3 shows daily average temperatures during 2012 and as a comparison the curve of the year 2015, where the winter time has not shown such deep average temperatures.

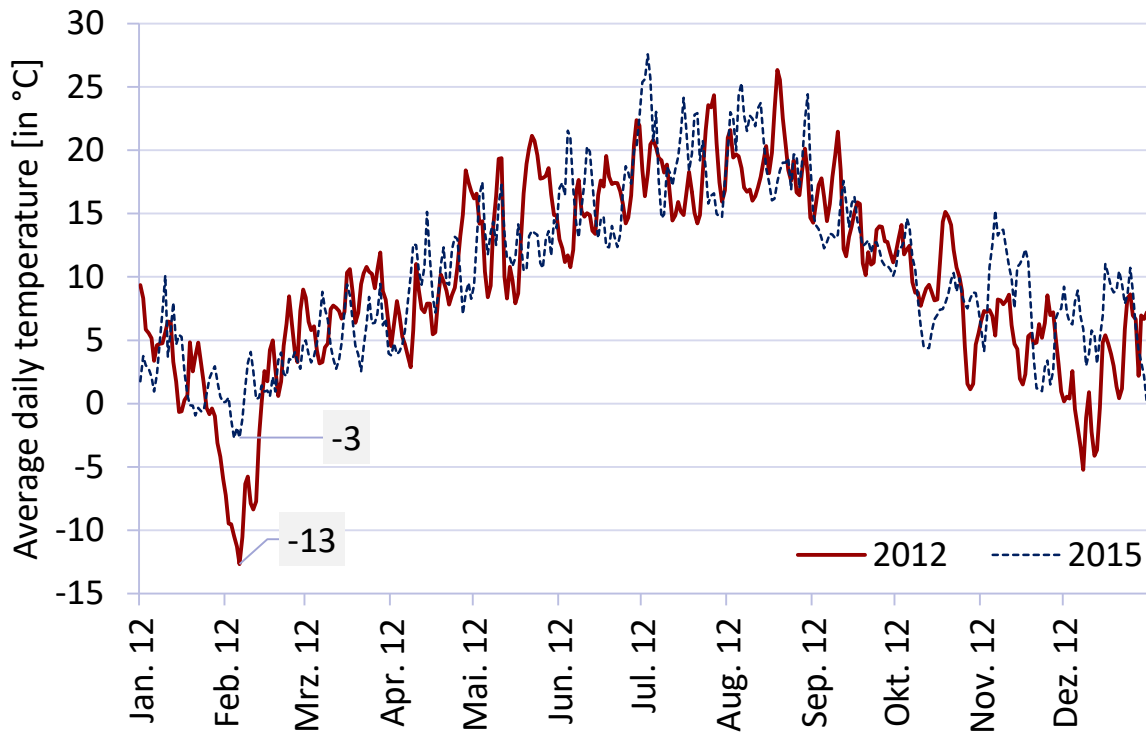


Figure 3: German daily average temperature in 2012 and 2015

(Source: own calculation, data based on Deutscher Wetterdienst (DWD, 2019))

The graph shows a negative peak from the 28th of January up to the 13th of February 2012, where daily average temperatures have been constantly below zero and partly up to minus 13 degrees, in particular on the 6th of February 2012. As a comparison, in 2015, the daily average temperature on the 6th of February has amounted only minus three degrees.

Although no physical congestion were reported, the situation in natural gas power plants in the south of Germany was tight. This cold winter period happened not only in Germany, but also all over Eastern Europe. In consequence, a high energy demand for heating occurred in parallel in Russia and Balkan States. In Germany and most Eastern European countries heat is produced by fossil fuels, i.e. coal and gas. Because of a high domestic Russian gas demand, Russian gas supplies to East European countries were reduced by 30%. In Western European countries, e.g. France, electricity based heat technologies

are predominant. Thus, these countries haven't seen a peak in natural gas, but in their domestic electricity demand. Consequently, the high gas demand in Germany was overlapped by a high electricity demand, esp. in France, Italy and Germany (Bundesregierung, 2012).

In Germany, a number of gas power plants provide heat and electricity in combined heat power plants (CHPs) for both, domestic demand and exports. To conclude, southern German gas power plants were challenged by two factors: 1) a high demand on heat energy and 2) a high demand on electricity from domestic costumers and neighbouring countries. During the mentioned time in February 2012, capacity of 3.5 GW of natural gas power plants in the grid area of Open Grid Europe, Thyssengas and Ener-gienetze Bayern were affected by these shortages (Bundesregierung, 2012).

In academic literature, the question arises whether this case could be seen as a test case for European energy dependence on Russian gas supplies. Thus, this event was also analysed by several researchers that came to varying conclusions.

Westphal (2012) point out that there was a capacity bottleneck in the south of MEGAL pipeline⁹ in Germany. Gas grid operators restricted gas supplies to customers with interruptible contracts according to the Energy Industry Act¹⁰ and in order to ensure grid stability. She concludes that a market only solution will not provide security of supply, as suppliers are interested in scarcity. Henderson and Heather (2012) argue that this event was not a crisis, caused by production constraints. However, Gazprom was not able to meet peak demand for European customers. It should be mentioned, that the second line of Nord Stream I was not yet in operation at the beginning of 2012.

In follow-up to this stressful winter 2012, Gazprom enforces its activities building Nord Stream II¹¹ (NS2) and invest in storage facilities in Europe. Currently, GAZPROM GERMNAY, a 100 % subsidiary company of GAZPROM EXPORT that is itself a 100 % subsidiary company of PAO GAZPROM, owns gas storages at four locations in Germany, i.a. the largest gas storage Rehden (4.4 bcm), and further gas storages in Austria, Czech Republic, Serbia and the United Kingdom (Gazprom Germania, 2019). Another storage is planned in Turkey. While the final decision for NS2 is still pending, almost half of the pipeline is built. However, the EU 28 member states are divided into two groups. One group that is led by Germany supports NS2 as a private investment of energy companies. A second group comprises other Eastern European countries and rejects the project in cause of the thread of increasing dependence on Russian gas.

⁹ MEGAL (Mittel-Europäische Gasleitung) transports gas starting from the Czech and Austrian Border through Germany up to France.

¹⁰ EnWG §14b, control of contractual load cutting agreements, regulation authorizations

¹¹ Nord Stream II is a pipeline project with an annual capacity of 55 bcm and a direct connection from Russia through the Baltic Sea in parallel to Nord Stream I to Germany.

3.3 Case Study: Simulating the year 2012

The initial situation of 2012 is covered by data assumptions for the parameters in the model, presented in the previous section. This section focuses on a detailed analysis on the German yearly energy balance, gas production and imports, the cut-off demand, on storage operation, and on grid situation. The latter is analysed especially in critical situation, when high demand occur. Additionally, results are discussed in relation to historic statistics.

3.3.1 German natural gas balance simulation for 2012

An overview about the results of GAMAMOD-DE simulated German natural gas market in 2012 is given in Figure 4 that depicts the gas balance twofold, in a daily resolution (left) and in an aggregated form (right). According to the energy balance, described in Equation (2.2), the sum of supply and demand components have to equal zero in each time step. While demand and export time series are exogenously given (parameters), all the components (variables) are optimized by the model.

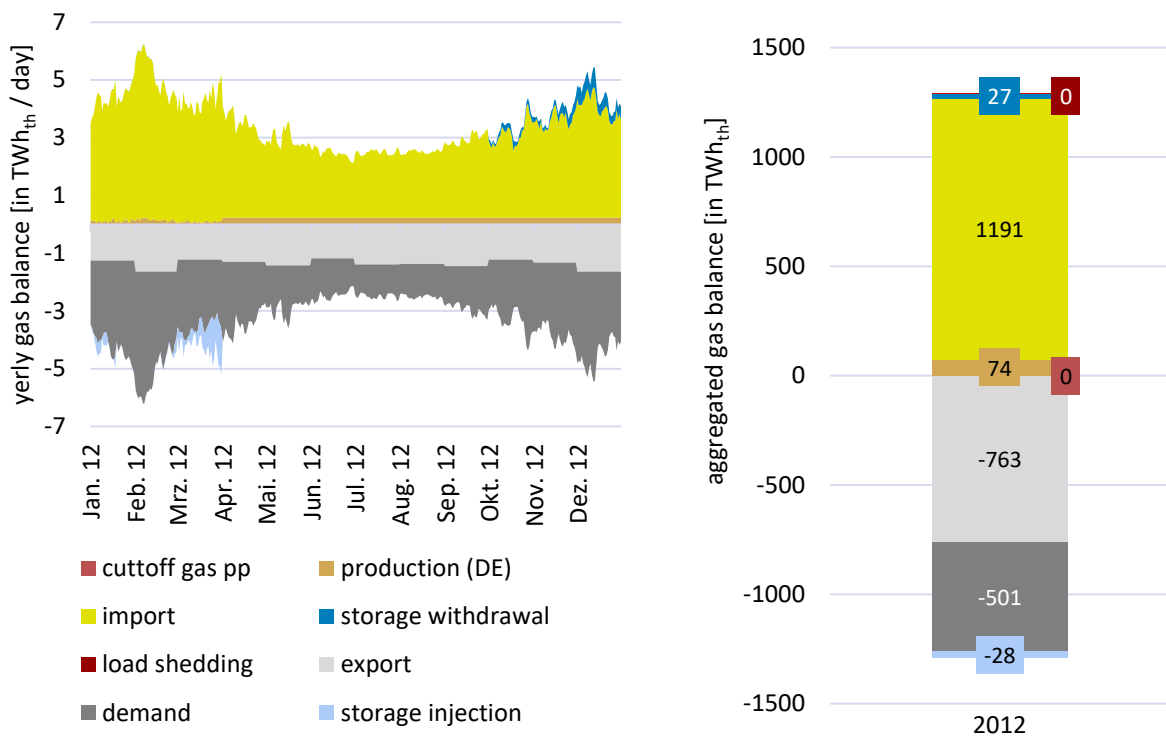


Figure 4: Simulated German natural gas balance in 2012 on a daily (left) and aggregated (right) resolution

(Source: own illustration, based on model results)

German gas imports supply the major part (92%) of the model demand¹², followed by domestic production (6%) and storage withdrawal (2%) that contributes only to a limited amount. Natural gas load shedding (<1%) is needed, when peak demand occurs, but compared to the total gas balance, it can be neglected (see also section 3.3.3 for further insights). In case of losses during storage withdrawal and injection and because of the restriction that start and end level of storages have to be equal, the energy amount of the injected gas is higher (+6%) than gas withdrawal (cf. Equations (2.9) to (2.16)).

With regard to the daily gas balance, it is shown that at the beginning of the year (January and March) the model prefers to inject natural gas into storages, and to withdraw the stored gas during November and December. The reason for that is the historic price series for natural gas imports, based on NCG quarter gas futures, where prices were lower at the beginning of 2012 (22.4 EUR/MWh) and higher at the end of 2012 (26 EUR/MWh). As the model approach includes perfect foresight, the system tries to withdraw stored gas when import prices are at the highest level and to inject gas, when import prices are at lowest level. A sensitivity analysis of different price series shows that gas storages react on the relation of gas import prices at the beginning and the end of a year (cf. Appendix A.3.).

3.3.2 Production and imports

The supply side in GAMAMOD-DE covers domestic German natural gas production and natural gas imports. In this version, “green gas”-options, e.g. biogas or hydrogen, are not considered, but this should be done in future versions.

Domestic German gas production

In the model, natural gas can be produced within Germany or imported from neighbouring countries. The model considers six domestic production nodes¹³ located in the Northwest of Germany. Figure 5 shows daily German gas production quantities.

¹² The total modelled gas demand entails gas demand by several sectors, storages and exports.

¹³ cp. production nodes pr_01 up to pr_06 described in the Appendix A.2. in Table 5

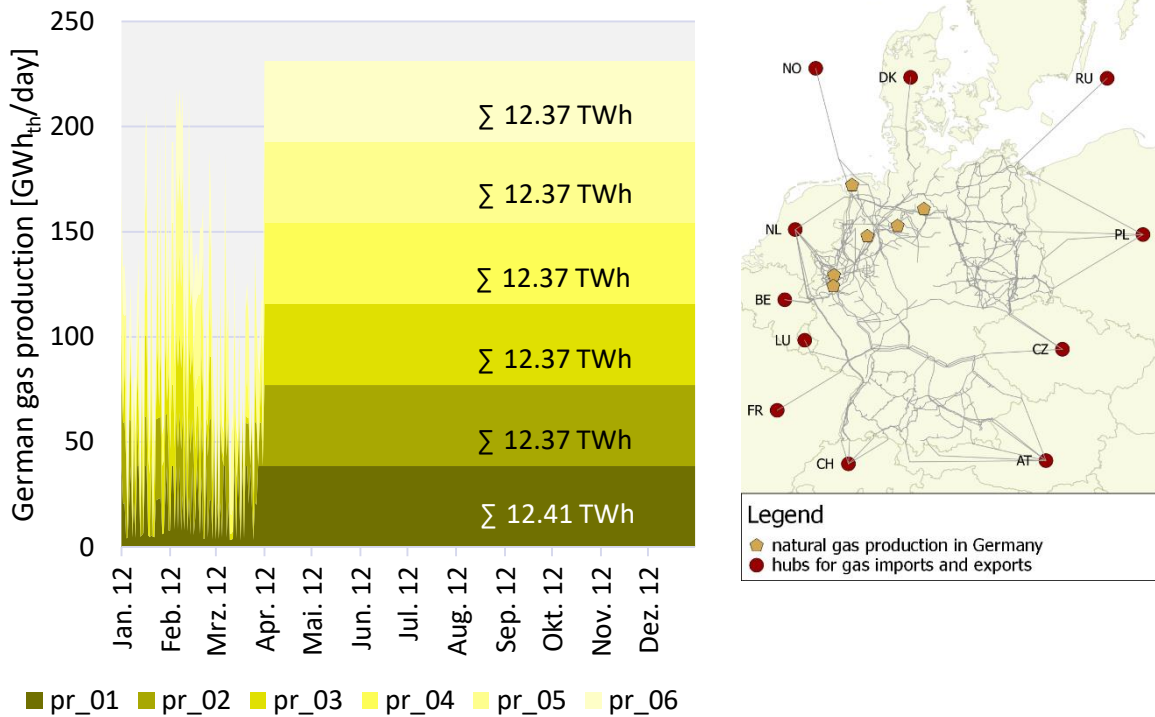


Figure 5: Daily German gas production in 2012

(Source: own illustration, based on model results)

On a local level, production during the first quarter of the year shows in each individual production node a drastic fluctuation and varies among all six production locations from no production up to maximum daily production (41 GWh_{th}/day), while for the remaining time, April to December, all German production facilities operate equally and constantly on a high level (39 GWh_{th} per day). On an aggregated level, while during the first quarter, the total German gas production fluctuates among 19 and 218 GWh_{th} per day, the constant contribution of gas production for the second, third and fourth quarter amounts 231 GWh_{th} per day.

There are several explanations for this phenomena. Firstly, the modelled approach of production flexibility allows to use temporally up to 14% higher production rates (39 GWh_{th} per day) compared to the average level (34 GWh_{th} per day). Regarding cost and price assumptions, German produced natural gas is significantly cheaper (10.2 EUR/MWh_{th}) than natural gas imports (22-26 EUR/MWh_{th}), thus, the model prefers domestic gas sources when import prices are on the highest level, or, vice versa, uses imports when the expected prices are on the lowest level. Against the background of a perfect foresight approach and with regard to the import price scheme, the model tries to use production flexibility to reduce high import costs for natural gas. In order to keep the total produced natural gas volumes per year in balance, a hesitancy in usage full flexibility is observed during the first quarter of the year, when

gas import prices are low (cf. Appendix A.2). This results are mainly driven by the model design including the perfect foresight approach and neglect of process adaptation costs. It can be expected that in reality production facilities operate more balanced during the year in order to avoid rapidly changing ups and downs in the production process.

German natural gas imports

Natural gas imports are modelled as variables and they are considered on all cross-border connections of the German gas grid. Imports in the model are assumed as natural gas volumes from neighbouring countries that can be both, actual produced natural gas (e.g. in the Netherlands or Norway) or transit gas (e.g. in Poland or Czech Republic). Figure 6 illustrates daily total natural gas imports to Germany.

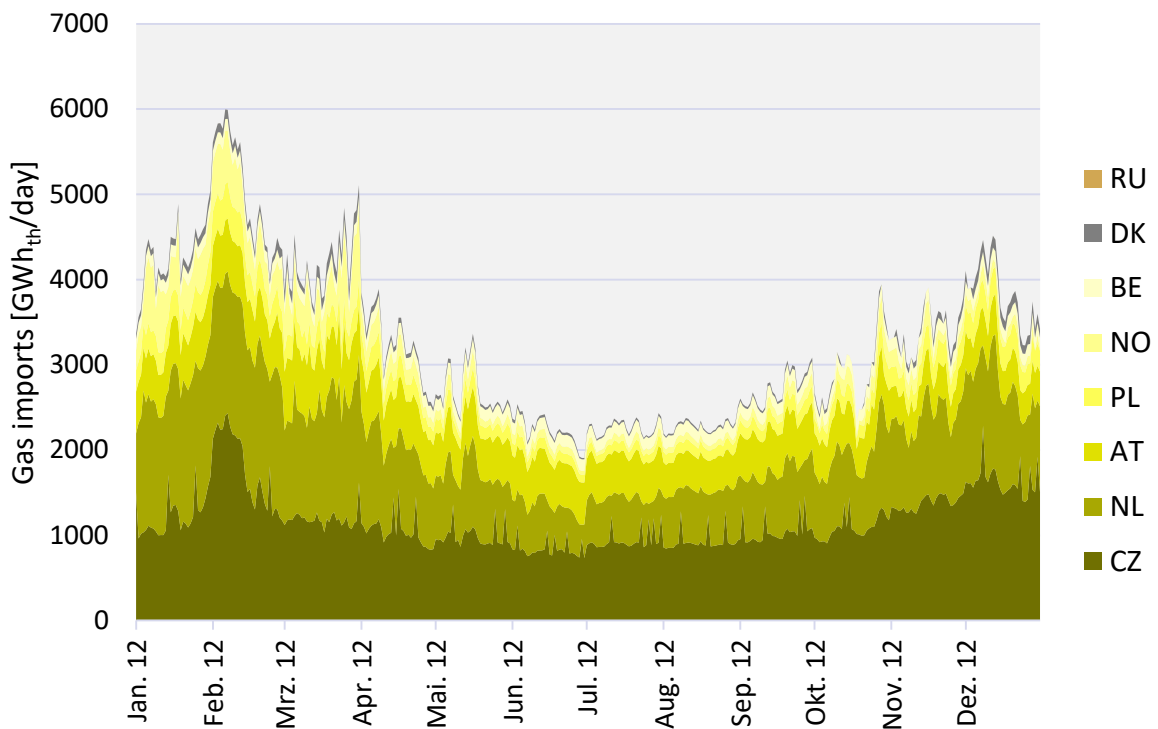


Figure 6: Daily German gas imports in 2012

(Source: own illustration, based on model results)

These imports peak in winter with daily import quantities up to 6 TWh per day and returns to a minimum import level of less than 3 TWh per day during summer months.

In general, a calibration of the model is difficult because of the absence of appropriate calibration data. Thus, a comparison on an aggregation level is pointed out in the following. The aggregated import volumes in 2012 are illustrated in Figure 7. The modelled gas imports are compared to the joined monitoring report of Bundesnetzagentur und Bundeskartellamt (BNetzA & BKartA, 2013).

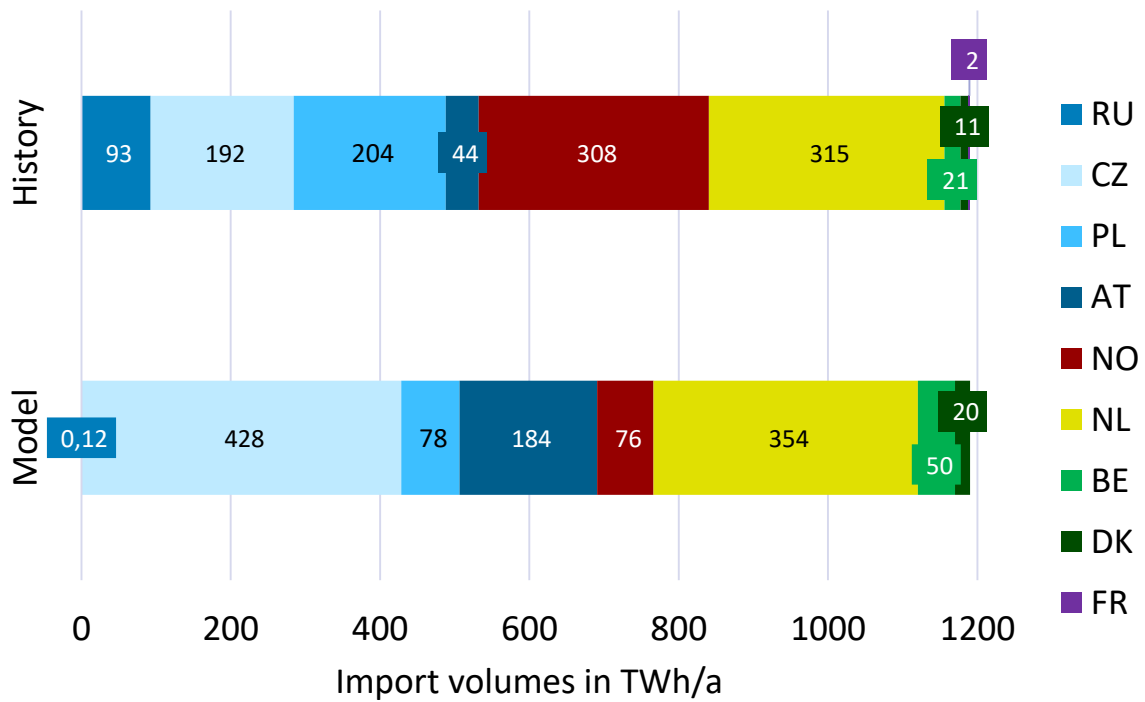


Figure 7: Model results of imported natural gas (lower bar) cp. to historical reported imports (upper bar)

(Source: own illustration, based on model results and (BNetzA & BKartA, 2013, p. 183))

Based on these assumptions, the model results reflects the general relations among all import countries. The model overestimates imports from Russian gas fields (sum of RU, CZ, PL and AT imports) that are slightly higher and underestimates imports of Norway that are considerably lower. It is noticeable that imports via Nord Stream I (direct imports from Russia) are small compared to historical total imports. Implementation of long-term contracts might improve the statistics, but represents a challenge to the lack of data.

3.3.3 Load shedding

Gas supply and demand has to be in balance, each day during the modelled period. Missing transport capacity or supply might lead to load shedding as a last and most expensive resort in order to keep the system in balance. Although in 2012 almost no interruption of demand occurred, model results show a smaller amount of load shedding of 926 GWh per year which is less than 0.2 percentage of the German gas demand in 2012. These load shedding occurs at only seven out of 970 demand nodes on 29 out of 366 days (cf. section 3.3.5 for node locations). The daily load shedding profile is shown in Figure 8.

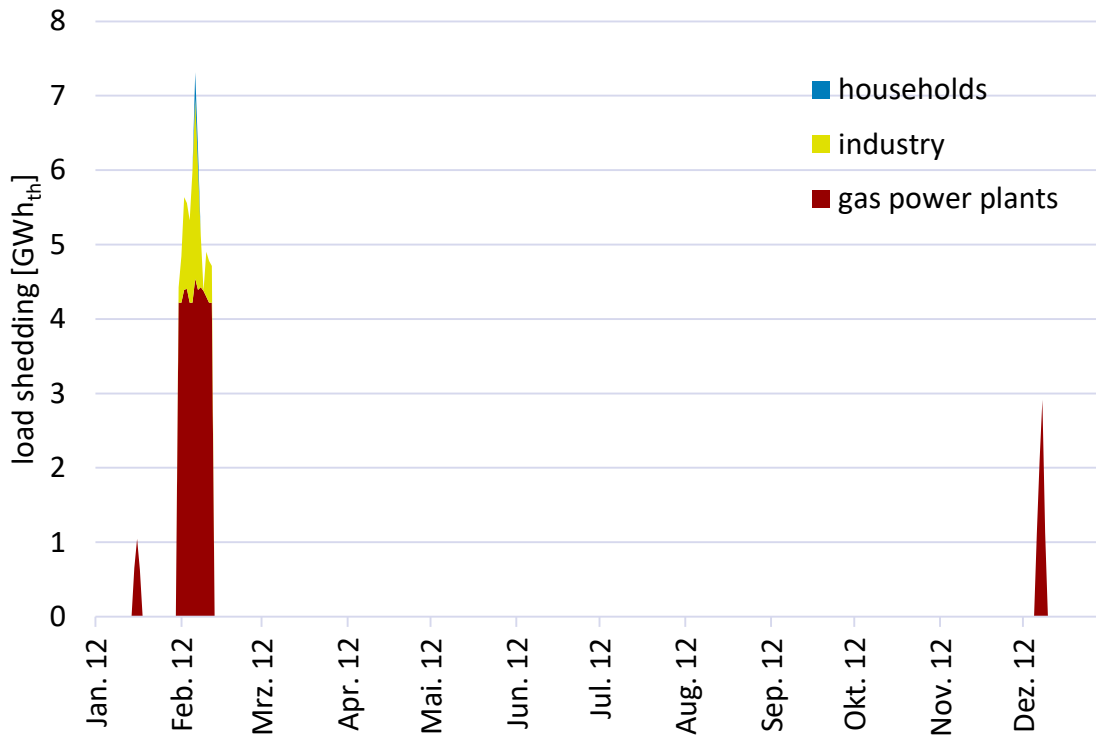


Figure 8: Daily load shedding of gas power plants, industry and households GWh per day

(Source: own illustration, based on model results)

A larger part of load shedding (90%, 838 GWh) occurs at two nodes in Thuringia in 2012. As these nodes are located on the edge of grid areas, it might be possible that a high allocation of regional demand causes to much load shedding.

3.3.4 Storage utilisation

In Germany high gas storage capacities are installed. Gas storages are needed to balance differences in gas demands (high demand during winter season and low demand during summer season) to ensure a steady gas supplies. The aggregated utilisation of all storages is shown in Figure 9 to Figure 12.

GAMAMOD-DE considers three different types of storages that differ in technical characteristics: aquifer¹⁴, salt cavern, depleted fields. Depending on the type of storage, differences in injection and withdrawal rates are implemented in the model. Figure 9 illustrates the results on daily gas withdrawal in 2012. While the maximum aggregated withdrawal rate of all storages would be more than 5.5 TWh per day, the daily maximum used withdrawal gas amounts less than 1 TWh per day and is used from October to December.

¹⁴ Only a minor part (#2 of #37) with low capacity (1 TWh of a total storage capacity of 226 TWh)

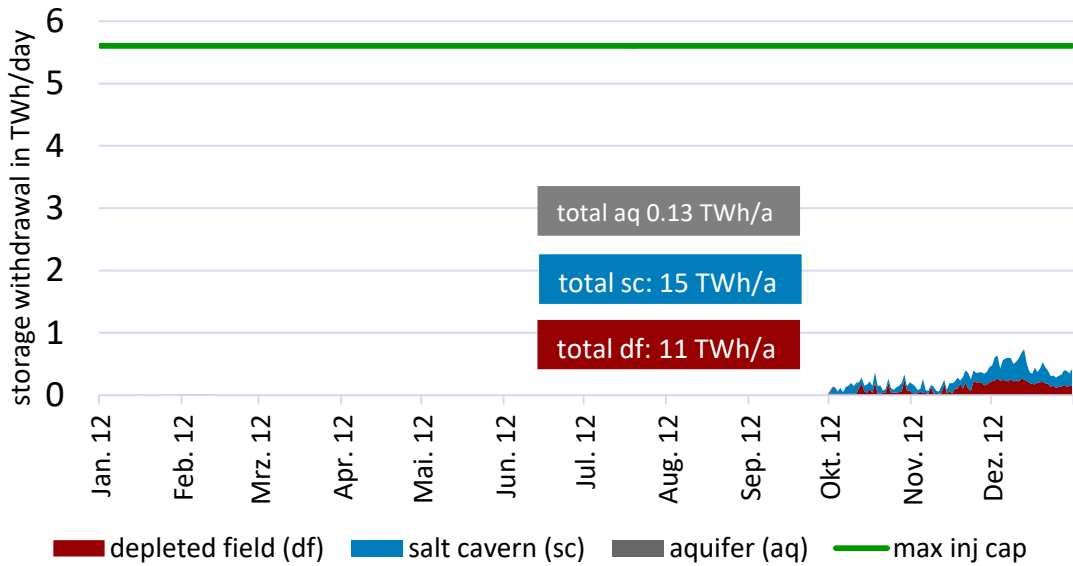


Figure 9: Total storage withdrawal

(Source: own illustration, based on model results)

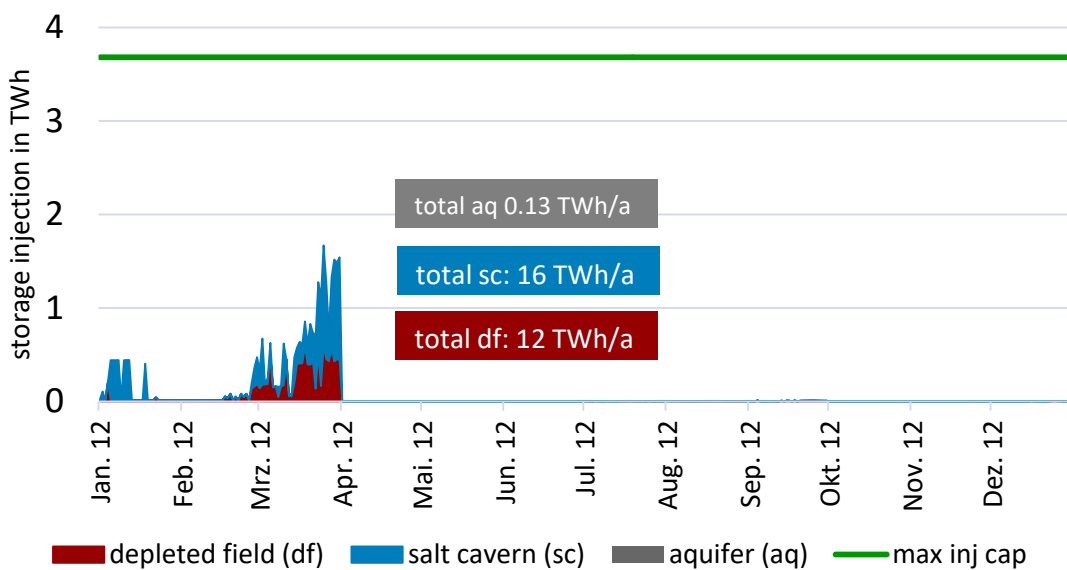


Figure 10: Total storage injection

(Source: own illustration, based on model results)

Figure 10 show the daily injected gas. The maximum injection rate is not used in the model, due to gas price structure and the assumed gas storage level. Figure 11 shows that the gas storages have already a high level at the beginning of 2012. Hence, an additional injection is limited by total storage capacities.

In accordance to the yearly storage balance, the model withdrawal natural gas by the end of 2012. Therefore, the difference between the maximum (100%) and minimum (88%) storage level amounts only 12% and a full storage cycle¹⁵ is not passed during the considered time frame.

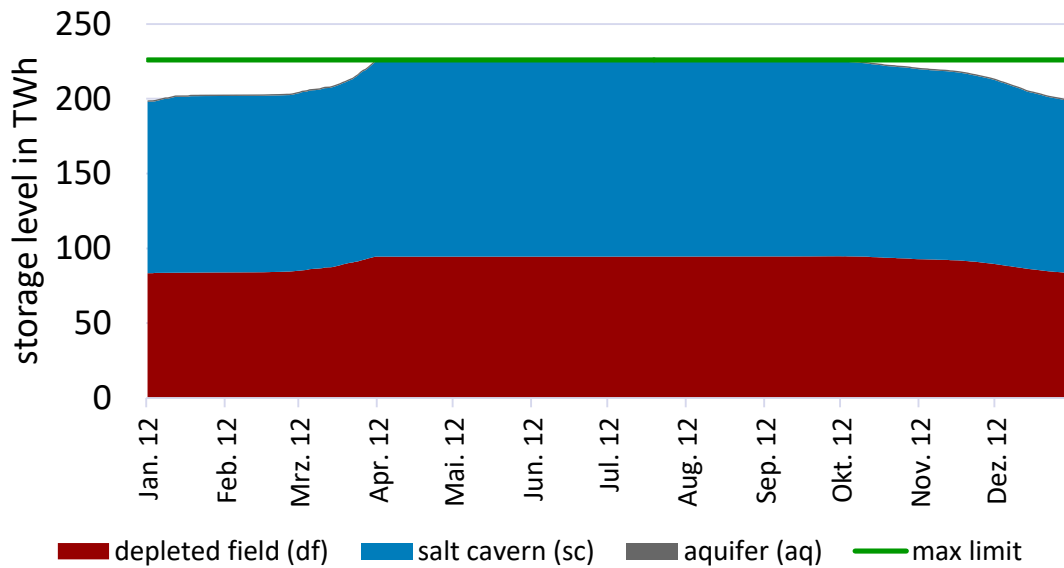


Figure 11: Total storage level

(Source: own illustration, based on model results)

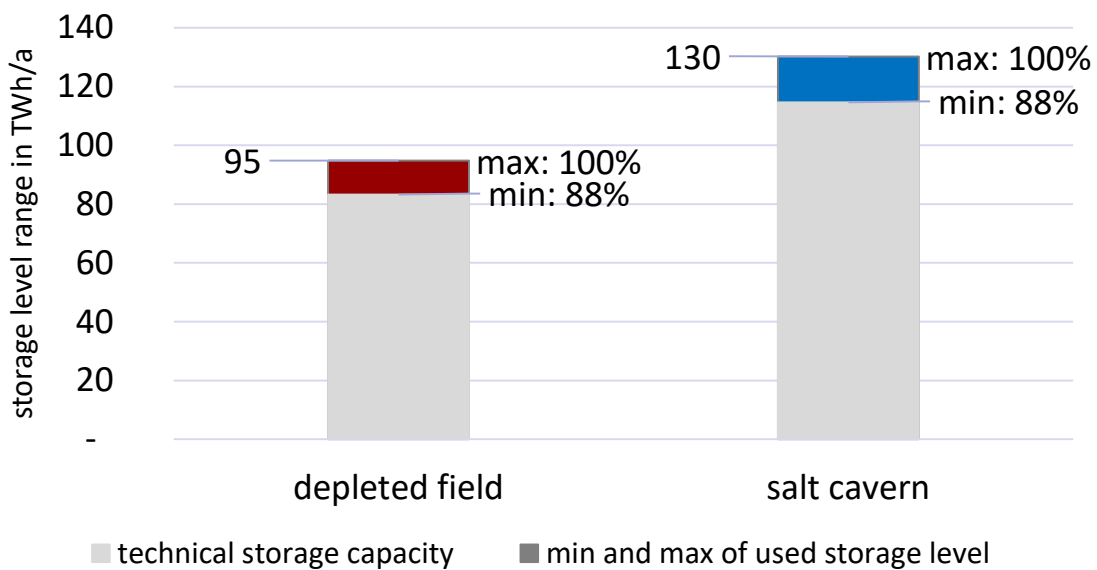


Figure 12: Used range of storage level for depleted fields and salt caverns

(Source: own illustration, based on model results)

¹⁵ In this context, a completely passed *storage cycle* would be the procedure of three phases: 1) injection of gas up to the maximum capacity, 2) storing gas over time, 3) total withdrawal of all stored gas down to a level of zero.

The analysis of gas storages has shown that gas storage facilities are not completely used in this model run. An explanation might be the assumed gas price structure that does not provide enough incentives to withdrawal gas during the beginning of 2012 and reinject gas during the end of the year. Furthermore, import capacities seem to be sufficient to meet the major gas demand. In the context of energy security, this means that gas storage capacities provide additional security of supply, as in critical situations additional gas withdrawal could supply gas demand (cf. Figure 9). In general, salt caverns are able to react a bit more flexible than depleted gas fields, due to their technical characteristic. However, a sensitivity analysis on available storage capacities has also shown, that the gas system depend on gas storages to avoid further load shedding (cf. Appendix A.4 and A.5).

3.3.5 Pipeline flows and congestion on a cold winter day

An indicator for analysing natural gas infrastructure resilience is the utilisation of pipelines. Figure 13 illustrates the pipeline utilisation (actual flow compared to pipeline capacity) on the coldest winter day in 2012, the 6th of February. In addition, locations where load shedding occurs are represented by blue circles.

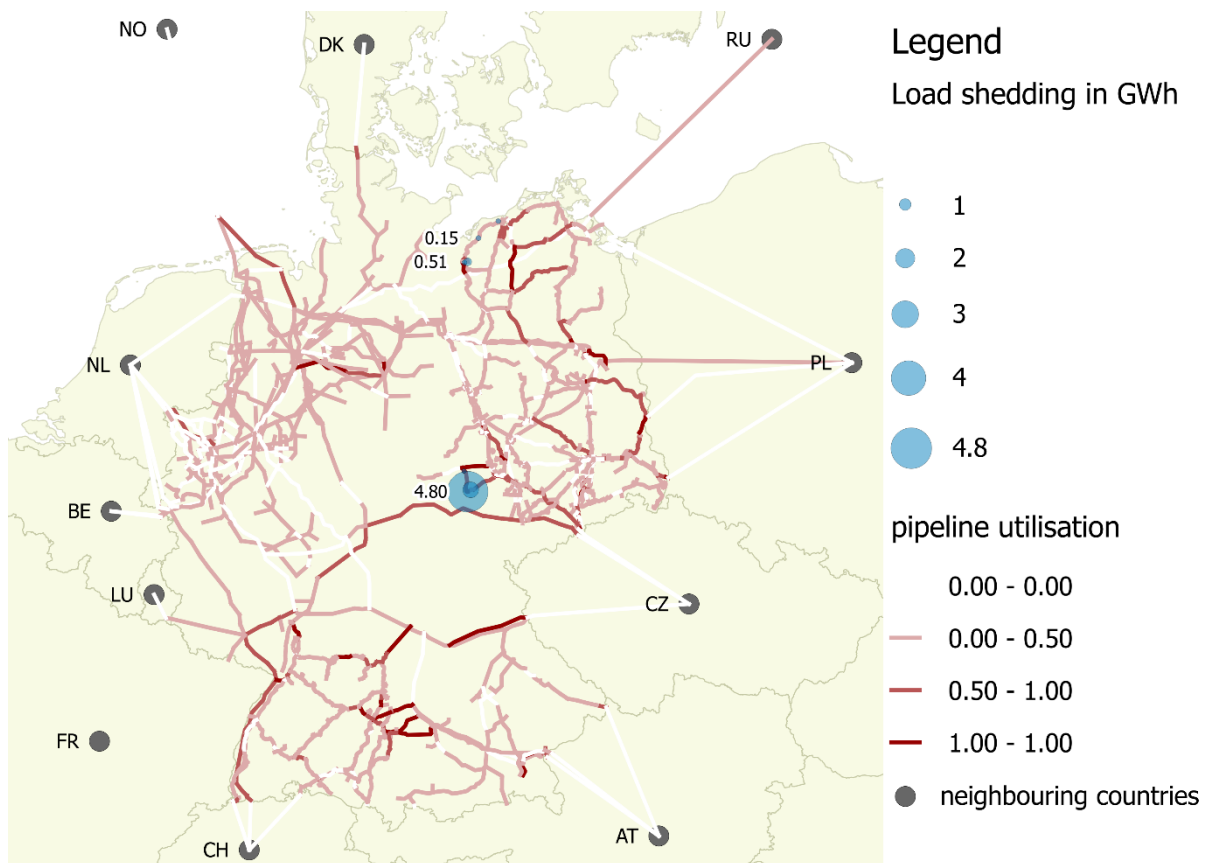


Figure 13: Average pipeline utilisation and load shedding in 2012

(Source: own illustration, based on model results)

Pipelines with highest utilisation are located in the East and in the South of the German gas grid. Load shedding occurs only in the transmission gas system of ONTRAS, while highest load shedding volumes are needed at two nodes close to Erfurt. One reason might be the low meshed gas grid and the high dependence on natural gas for heating and electricity during cold seasons.

4 Conclusion

This paper suggest a new model to investigate the German natural gas grid in the context of the ongoing energy transition in Germany and Europe, called GAMAMOD-DE. A short literature overview shows, that so far, energy system models concentrate mainly on renewable energy sources and electricity systems. Furthermore, ongoing discussion on sector coupling motivates modelling efforts to include representations of natural gas infrastructure with highly temporal and spatial resolution into energy system models.

GAMAMOD-DE provides a model approach to contribute to this research field, by focusing on a highly resolved natural gas grid representation for Germany and consideration of natural gas demand regarding three energy sectors: residential heating, industrial usage and gas power plant demand. Therefore, in the first part of this paper, the model is described in detail focusing on the algebraic formulation, assumptions and simplifications as well as used data.

The model is applied to investigate the cold winter of 2012. Hence, in the seconde part of the paper, a case study has been done to demonstrate futher model specifications. The cold winter in 2012 has shown a tight situation for the German energy system in cause of high simultaneous electric and gas demand. Authors in academic literature argue that this was not a real capacity crisis, but shows that a market only approach cannot fully provide security of supply. Nevertheless, 3.5 GW of gas power plants in Germany were not able to produce electricity. GAMAMOD-DE has been applied for re-simulating the situation of the cold winter by modelling the entire year of 2012. Results show some load shedding during the coldest winter day of the 6th of February in 2012, but also a general resilient operation of the German gas infrastructure that has provide a high level of security of supply (SoS) in 2012. For that reason, the natural gas balance, production and imports, load shedding, utilisation of storages and pipeline utilisation has been investigated in detail.

For an outlook on further research, the question of whether this level of SoS might change during the next decades should be investigated. A German phase out of nuclear power plants by the end of 2022 and a phase out of coal power plants, most probably during the 2020s and 2030s¹⁶, will might lead to spare capacities in the electricity and heating sector. Hence, a higher gas demand in cause of higher

¹⁶ Kohlekommission: 2038 or 2035

utilisation of existing gas power plants or new gas power plants would be likely. Further works should also analyse in which way proper gas supplies without geopolitical or ecological dependencies can be ensured.

Acknowledgment

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Appendix

A.1. Simplification of technical gas flow into energy flow

Including technical characteristics of gas transports in linear optimization models is challenging, as the mathematical description of the volume flow depends on non-linear variables. Detailed descriptions of modelling the technical gas flow, mathematical optimization of challenging networks and models, methods, and solutions to validate nominations in gas network optimizations can be found in (Willert et al., 2014, 2013). Following Cerbe & Lendt (2016, p. 155 ff) the basics of the technical gas flow are described. Furthermore, the simplification and assumptions are presented that were made to convert the technical gas flow into an energy flow.

In general, the volume flow \dot{V} describes the change of gas volume dV over time dt :

$$\dot{V} = \frac{dV}{dt} \quad (0.1)$$

In a simplified case, assumptions of an incompressible gas and a stationary and frictionless flow are made. Considering the continuity equation, it holds that the volume flow \dot{V} equals the pipe cross-section A times the average flow rate w :

$$\dot{V} = Aw = \text{const.} \quad (0.2)$$

Equation (0.2) can be reformulated as a mass flow, by multiplying the entire equation by density δ :

$$\dot{m} = \delta Aw = \text{const.} \quad (0.3)$$

Having the above discussed assumptions in mind, the energy content in gas pipelines can be calculated using the *Bernoulli-equation*, where total energy is equal to the sum of energy of position (mgh), pressure energy ($m \frac{p}{\delta}$) and motion energy ($m \frac{w^2}{2}$):

$$mgh + m \frac{p}{\delta} + m \frac{w^2}{2} = \text{const.} \quad (0.4)$$

The parameters mass m , gravity g , level h of a pipeline and density δ , can be considered as constant. Hence, Equation (0.4) shows that the energy flow depends only on pressure p and the square of the average flow rate w . These physical variables are determined by the operation of the gas pipeline, as lower energy flows lead to lower levels of pressure and flow rates and vice versa. Nevertheless, in order

to keep the model linear, the used approach in GAMAMOD-DE considers both parameters, pressure and average flow rate, as constant in the respective pipeline.

For each pipeline in the German pipeline system, the standard level of pressure p_N and pipeline diameter D_N are known. Additionally, the flow rate w is assumed to amount constantly 10 meter per second.

Thus, in combination with Equation (0.3), it is estimated that the energy flow \dot{E} is the product of the mass flow and the energy density ω according to Equation (0.5). Consequently, the maximum energy flow is calculated according to Equation (0.6).

Using the individual level of pressure p_N and pipeline diameter D_N^{17} , the maximum energy capacity for each pipeline can be calculated and results range among less than 4 up to 1275 GWh/day. These results are used as individual upper bounds for pipelines in the energy transport restriction that is introduced in the next section. All parameters in Equation (0.6) are known and assumed as independent of any changes in the gas system.

$$\dot{E} = \dot{m} \times \omega = \delta A w \omega \quad (0.5)$$

$$\max \dot{E} = \left(p_N \frac{M}{R \times T_N} \frac{D_N^2}{4} \pi w \right) \omega \quad (0.6)$$

with:

M	molecular weight	0.016043 kg/mol
R	gas constant	8.31448 J / (K × mol)
T _N	standard temperature	278 K
w	flow rate	10 m/s
ω	energy density	49.725 MJ/kg

¹⁷ Numerical assumptions for pipelines can be find in Kunz et al. (2018). Pressure levels are normally standardized and divided in classes from 16, 25, and 63 up to 100 bar. Pipeline diameter ranges from less than 100 up to more than 1000 mm.

A.2. Data assumptions

In this section, data assumption on cross border gas prices (cf. Table 4) and production flexibilities (cf. Table 5) are presented.

Cross-border gas prices determine costs for importing gas. Furthermore, the assumed price pattern impacts on storage operation. Therefore, the question arise what kind of gas prices should be assumed in the mode. Basically, the model covers the European spot market and neglect long-term contracts. However, in the current European gas market regime, gas prices are still influenced by long term contracts. These price components are covered by the historical price series of BAFA, as the reported monthly cross-border gas prices include both, long term contracted gas and spot market gas. The BAFA price series are calculated ex post and might be misleading for modelling storage operation in GAMAMOD-DE. For that reason, GAMAMOD-DE uses the historical NCG quarter gas price future as this series reflects also the expectation on future gas prices.

Table 4: Monthly cross border prices for natural gas imports to Germany, based on different price assumptions

Month	Cross-border price in EUR/GWh			
	BAFA 2012	BAFA 2008	BAFA 2009	NCG quarter future 2012
January	22,953.60	17,107.99	29,394.57	22,400.00
February	21,445.20	18,110.95	28,397.25	22,400.00
March	22,597.20	18,165.90	26,307.45	22,400.00
April	21,592.80	18,701.73	21,817.74	25,350.00
May	21,121.20	19,454.64	20,108.55	25,350.00
June	20,592.00	20,366.92	19,157.04	25,350.00
July	20,590.20	21,364.38	17,123.63	24,050.00
August	21,049.20	21,927.68	16,489.29	24,050.00
September	19,515.60	22,144.76	16,531.58	24,050.00
October	19,076.40	23,521.42	17,028.48	26,430.00
November	19,017.80	24,038.02	17,557.10	26,430.00
December	18,316.80	22,963.61	17,955.32	26,430.00

Source: Bundesamt für Wirtschaft und Ausfuhrkontrolle (2018), Datastream International (2019)

Production flexibility can be derivate from historical production data and provides further flexibility in the model (cf. Lochner (2011)). Indeed, the production flexibility differs among import countries. For

example, while Germany has only a low flexibility (+14%), the Netherlands can increase their production in the short-term up to 72%.

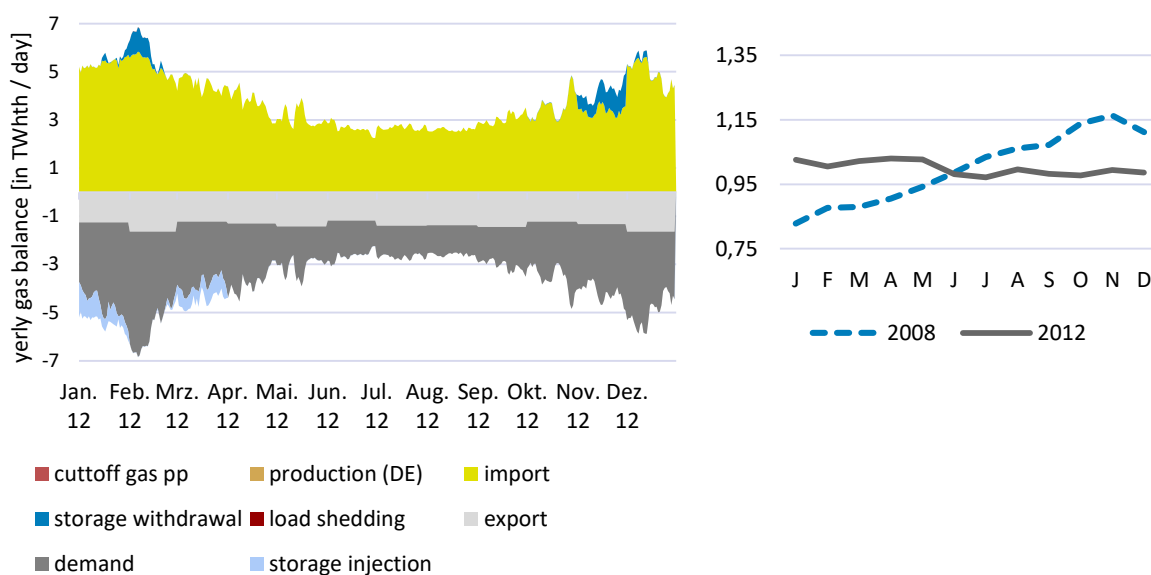
Table 5: Production flexibility factors

Production node	Country	Flexibility factor $pFlex_{pr}$
pr1 to pr6	Germany (DE)	1.14
pr7	Russia (RU)	1.12
pr8	Poland (PL)	1.14
pr9	Czech Republic (CZ)	1
pr10	Austria (AT)	1.14
pr11	Switzerland (CH)	1
pr12	France (FR)	1
pr13	Luxembourg (LU)	1
pr14	Belgium (BE)	1
pr15	the Netherland (NL)	1.72
pr16	Norway (NO)	1.19
pr17	Denmark (DK)	1.25

Source: calculations of Lochner (2011), based on IEA data

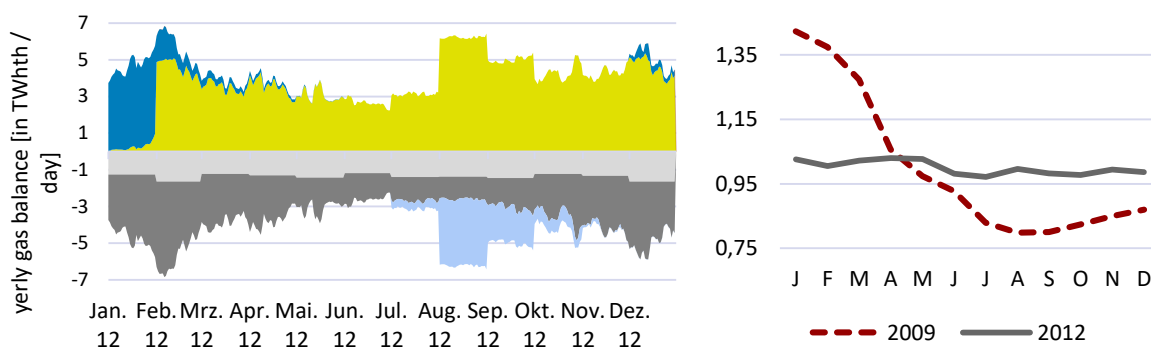
A.3. Sensitivity analysis on assumed cross-border gas prices

In this section, the impact of different assumed gas price trends is investigated.



a) Yearly gas balance w/ increasing price trend

b) increasing gas price trend



c) Yearly gas balance w/ decreasing price trend

d) decreasing price trend

Figure 14: Sensitivity on an increasing (b) and decreasing (d) cross-border gas price trend and the resulting yearly gas balances (a, c)

(Source: Own illustration)

Gas storages use price differences to inject natural gas, when gas prices are low and use the stored gas in seasons with high gas prices. The model considers perfect foresight, thus, the expected gas price in the model determines storage operations. According to the historical BAFA cross-border gas prices, two price scenarios have been analysed in this sensitivity analysis, in order to investigate the impact of rising and falling gas prices in combination with perfect foresight on model results (cf. Appendix A2, Table

4). The price trend in 2008 has shown an increasing progress (cf. Figure 14, b), while the historic price trend from 2009 has shown a decreasing price pattern (cf. Figure 14, d).

In GAMAMOD-DE, at the beginning of the year, storages are almost completely filled with gas (up to more than 90% of storage capacity). Additionally, it holds the restriction that the gas storage in the last period has to equal the initial gas storage level (cf. Equation (2.9(2.9) - (2.12))). Hence, a decreasing price trend provides incentives for the model to use more stored gas at the beginning of the year, compared to the scenario of an increasing gas price. The model strategy here is to reduce costs for importing natural gas. To sum up, the model tends to prefer storage operation, when a decreasing price trend is expected.

A.4. Sensitivity analysis on start conditions for storage levels

The initial time frame in GAMAMOD-DE considers the year 2012 starting at the 1st of January and ends at the 31st of December 2012. For the initial storage level, historical levels for the 1st of January have been assumed. Furthermore, the condition holds that storage levels at the end of the year have to equal storage levels at the beginning of the year. In January 2012, historic storage levels have been already on a high level (>90%) and the variable STORAGE_IN has a limited degree of freedom to inject further gas, due to gas storage capacities. For that reason a sensitivity analysis was done in order to simulate a synthetic time frame from May 2012 to April 2013, where lower historical storage levels have been assumed for the 1st of May 2012 (rd. 40%). Unfortunately, most data for parameters in the model have been available only for the year 2012. For that reason, the new time frame was partly synthetically prepared. Table 6 shows that the initial model run covers the period from January 2012 to December 2012 (*Original*). The new period for the sensitivity analysis is described in the next column (*Alternative*). The period May 2012 to December 2012 was modelled with original data of 2012, while the period from January 2013 to April 2013 base on the original data of January 2012 to April 2012, i.e. temperature demand (cf. last column in Table 6).

Table 6: Re-organisation of data for creating a synthetic model period

Year	Month	Original	Alternative	Synthetic
2012	January	Jan 12		
	February	Feb 12		
	March	Mar 12		
	April	Apr 12		
	May	May 12	<i>May 12</i>	May 12
	June	Jun 12	<i>Jun 12</i>	Jun 12
	July	Jul 12	<i>Jul 12</i>	Jul 12
	August	Aug 12	<i>Aug 12</i>	Aug 12
	September	Sep 12	<i>Sep 12</i>	Sep 12
	October	Oct 12	<i>Oct 12</i>	Oct 12
	November	Nov 12	<i>Nov 12</i>	Nov 12
	December	Dec 12	<i>Dec 12</i>	Dec 12
2013	January		<i>Jan 13</i>	Jan 12
	February		<i>Feb 13</i>	Feb 12
	March		<i>Mar 13</i>	Mar 12
			<i>Apr 12</i>	Apr 12

(Source: own illustration)

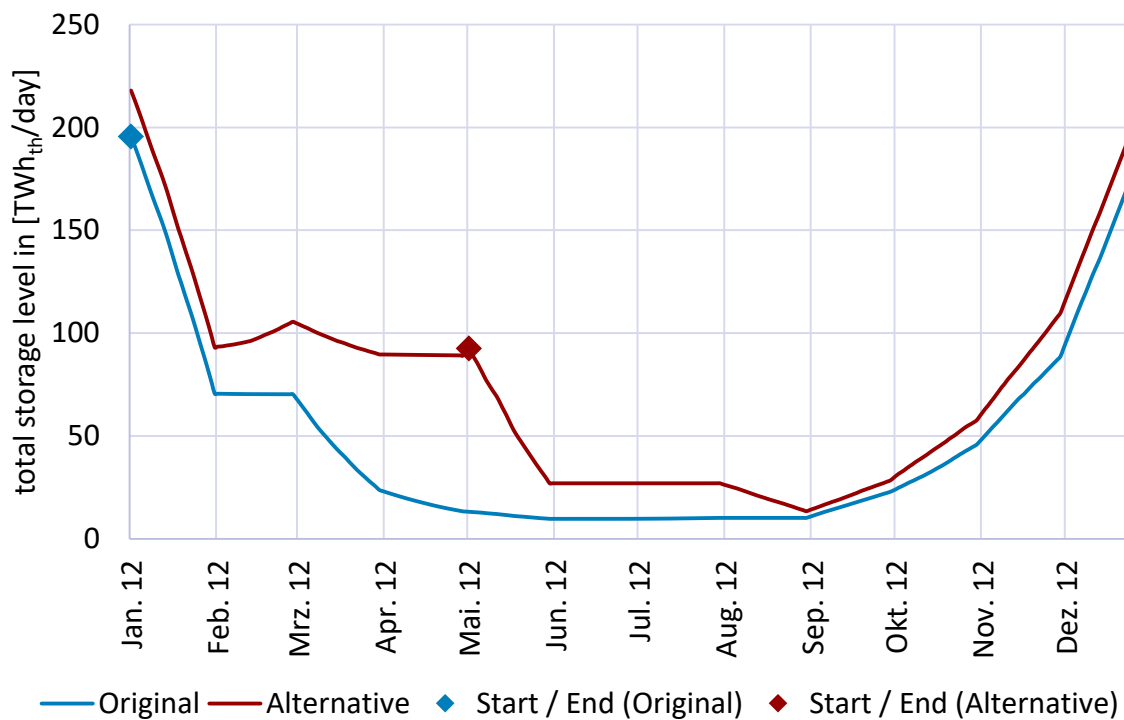


Figure 15: Comparison of total storage level in the original model with start in January (blue) and in the alternative case with start in May (red)

(Source: own illustration based on model results)

After running GAMAMOD-DE using the synthetic time period, the results were decompose, in order to compare storage levels between the initial (*Original*, blue line) and synthetic (*Alternative*, red line) scenario, as can be seen in Figure 15. Hence, the blue and red diamonds mark the respective start and end points of each model run.

The model run using the synthetic time period (*Alternative*, red line) starts in May (red diamond) with relative low storage levels (only 40% of total storage capacities). From May to June, high gas withdrawals leads to a situation where storage level reach a similar level as in the initial model run (*Original*, blue line). The injection of gas during October to December is almost the same in both cases. In order to keep the storage balance between start and end time date, the gas withdrawal during January and February in the alternative case is lower than in the original case.

This sensitivity show that the starting point of the modelled year is crucial for storage activities, mainly because of the strong constraint that start and end level of storages have to be equal. However, the sensitivity has also shown that up to the end of the year 2012 storage operations converge.

A.5. Sensitivity analysis on the impact of gas storages for security of supply

The analysis on storage utilisation (Section 3.3.4) has shown the low utilisation of storages compared to their technical available capacities. This might lead to the assumption that in 2012 gas import infrastructure has been sufficient in the German gas market and no gas storages have been needed. In order to proof this thesis, an additional model run has been done, where storage injection and storage withdrawal was fixed to zero.

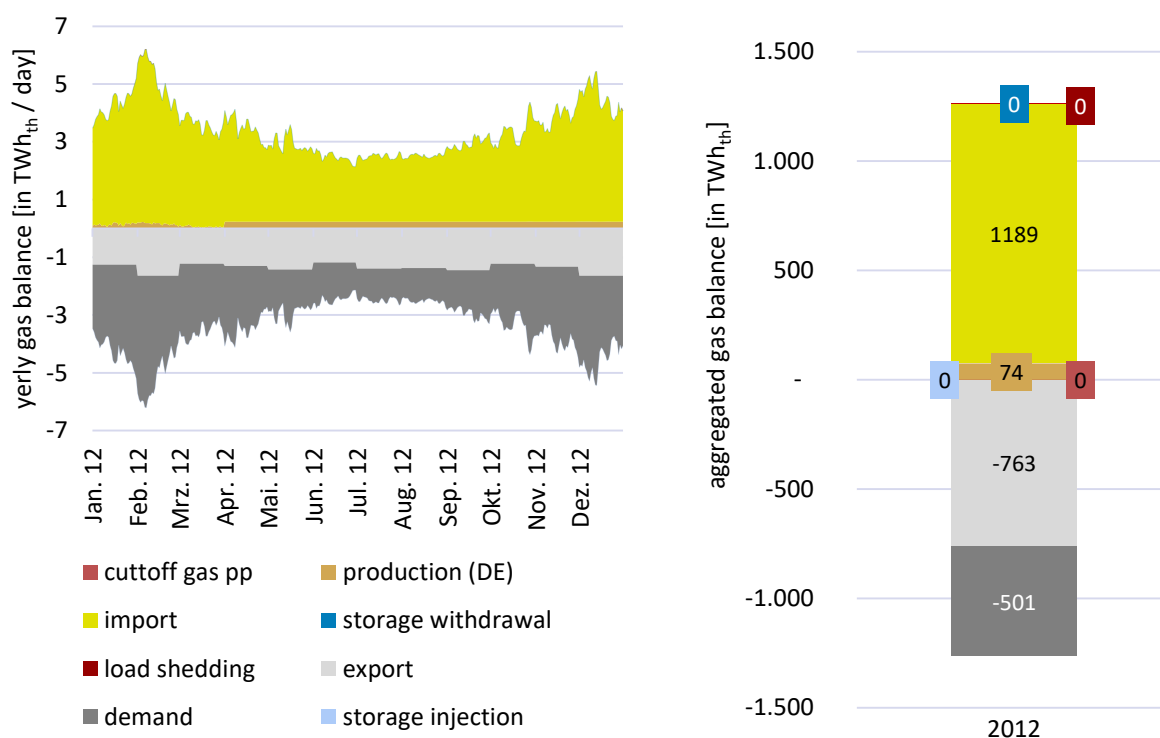


Figure 16: German natural gas balance in 2012 on a daily (left) and aggregated (right) resolution

(Source: own illustration, based on model results)

Figure 16 shows the yearly gas balance in a model run without storages. There are only slightly difference to the initial run of 2012 (cf. Figure 4). The results suggest that import capacities are sufficient to meet the gas demand in 2012. However, results show also that system costs increase in a scenario without storages by 0.33% compared to a scenario with storages. The reason for that is that the gas system has to pay the cross-border gas price at each time and cannot inject gas into storages when gas prices are low and used the stored gas when gas prices are high. Additionally, from the sensitivity in Appendix A.2 it can be expected, that gas storages are used more intensively when a decreasing gas price is expected and that the advantage of available gas storage capacities can be even larger than in this sensitivity analysis.

GAMS Code

```
*#####
```

```
*#                GENERAL SETTINGS
```

```
*#####
```

```
$set modelRun _2012
```

```
$set LoadXLS
```

```
$set LoadXLS_UDE
```

```
$set FlowModus Optimization
```

```
*#####
```

```
*#                DEFINITION
```

```
*#####
```

```
Set
```

```

i          nodes (ID numbers are equal to QGIS-IDs)
i_exit(i)  subset: nodes with exit points
i_DemFix(i) subset: fixed demand in neighbouring zones

pr         production facility
st         storage facility

l          pipelines
a          final energy use (a1=heat a2=indsutry)
           /a1*a2/
n          NUTS-Regions
r          region (national states in Germany)
t_d        time (days) /t0001*t0366/
t_h        time (hours) /t0001*t8784/
           //subset tt defined after data load
```

st_f	storage technology
p_BNetzA	NG power plants (ID numbers are equal to BNetzA list)

ALIAS

(i,j)

(n,nn)

Parameters

*setups

nodesUp(i,*)	setups nodes
nutsUp(n,*)	setups NUTS3-regions
pipelinesUp(l,*)	setup pipelines
plantsUp(p_BNetzA,*)	setup power plants
productionUp(pr, *)	setup
storagesUp(st,*)	setup storages
timesUpModel(t_d,*)	temperature per region (2012 t_h 2012 t_d)
s_patternUp(t_d,*)	storage pattern
s_charactUp(st_c,*)	storage characteristics
gaspriceUP(t_d,*)	gas price scenarios for 2012

genPowerPlants_UDE(p_BNetzA,t_d,*)	power plant generation 2012 in JMM
------------------------------------	------------------------------------

*Mappings

map_in(i,n)	maps nodes to NUTS
map_ni(n,i)	maps NUTS w/o nodes to exit-nodes

map_pi(p_BNetzA,i)	maps ng plants to NUTS
map_nr(n,r)	maps NUTS to REGIONS
map_tt(t_h,t_d)	maps time (hours) to time (days)
map_pri(pr,i)	maps production facilities to nodes
map_sti(st,i)	maps storage facilities to nodes
map_lj(l,i,j)	maps lines to node i and j
map_lfix(l,*)	maps subset for fixed flows
map_stc(st,st_c)	maps storages to storage type (aq df sc)
map_pr(p_BNetzA,r)	maps p_BnetzA federal states to regions r

*demand

dem(n,t_d,a)	demand constrained by node n time t application a
dem_i(i,t_d)	demand on node i
dem_i_sum	controll parameter for demand
numbNodes(n)	number of nodes in NUTS layer n
tempmodel_prep(t_d,r)	preperation for tempModel
tempModel(t_d,n)	Temperature in t in region r
tempRef	reference temperature
	/40/
h_Factor(n,t_d)	load profile factor for heat based gas demand
KW(n)	customers value

*for Model and t

par_A(n,t_d)	form parameter A
par_B(n,t_d)	form parameter B
par_C(n,t_d)	form parameter C
par_D(n,t_d)	form parameter D

*electricity sector

genPowerPlants_h(p_BNetzA,t_h)	NG power plants demand per [MWh_th\h]
genPowerPlants_d(p_BNetzA,t_d)	NG power plants demand per [MWh_th\d]
numbNinR(r)	number of NURS-zones in Region

*industry sector

industryDem(n)	industry NG demand [GWh_th \d]
industryRelFactor(t_d)	industry rel. Factor based on 2015 sample grid []

*Fixed Demand in neighbouring zones (Steinitz and Deutschendorf)

fixedDem(t_d,i)	fixed Demand
-----------------	--------------

*Losses

losses(t_d)	
-------------	--

*production

p_limit(pr)	production limit [GWh per day]
p_flex(pr)	flexible production
p_c (pr,t_d)	production costs
bafa(t_d)	bafa price in 2015 monnthly
p_markup(pr)	mark up on prices

*pipelines

transmission_limit(l)	transmission capacity
tr_costs(l)	transmission costs pipelines
flow_fixed_POS(t_d,l)	fixed positive flows
flow_fixed_NEG(t_d,l)	fixed negative flows

*Storages

storage_max(st)	maximum storage capacity
storage_with_max(st)	maximum withdrawn capacity GWh\ d
storage_inj_max(st)	maximum injection capacity GWh\ d
st_wIntersec(st_c)	intersection of storage characteristic (withdrawal)
st_iIntersec(st_c)	intersection of storage characteristic (injection)
st_wSlope(st_c)	slope withdrawal
st_iSlope(st_c)	slope injection
sinj_c	costs for injection
swith_c	costs for withdrawn
s_loose	efficiency losses
s_pattern(t_d)	storage pattern

*Costs of load shedding

Dummy(a)	costs in EUR\ GWh /a1 187713, a2 93856, a3 93855/
Dummy3	costs for gas power plants cur-down /93855/
LoadCutFactor(a)	maximum load shedding /a1 1, a2 0.5, a3 1/

```

#####
*
*          UPLOAD
*
#####
* Write gdxxrw option file

$onUNDF

$onecho >temp.tmp

set=i          rng=Nodes!A5          rdim=1 cdim=0
set=l          rng=Pipelines!A3       rdim=1 cdim=0
set=n          rng=NUTS!A4           rdim=1 cdim=0
set=r          rng=Region!C5         rdim=1 cdim=0
set=pr         rng=Production!B3      rdim=1 cdim=0
set=st         rng=Storage!A2        rdim=1 cdim=0
set=st_c       rng=StoragePattern!O2  rdim=1 cdim=0
set=p_BNetzA   rng=Mapping!I3        rdim=1 cdim=0

par=nodesup    rng=Nodes!A4          rdim=1 cdim=1
par=pipelinesup rng=Pipelines!A2     rdim=1 cdim=1
par=NUTSup     rng=NUTS!D3          rdim=1 cdim=1
par=productionUp rng=Production!B2   rdim=1 cdim=1
par=gasPriceUp  rng=Production!N2    rdim=1 cdim=1
par=storagesUp  rng=Storage!A1       rdim=1 cdim=1
par=s_charactUp rng=StoragePattern!O1 rdim=1 cdim=1
par=s_patternUp rng=StoragePattern!C1 rdim=1 cdim=1
par=losses     rng=Losses!A1        rdim=1 cdim=0

par=fixedDem   rng=Fixed_Dem!A2     rdim=1 cdim=1
par=flow_fixed_POS rng=FLOW_POS!A1  rdim=1 cdim=1

```

par=flow_fixed_NEG	rng=FLOW_NEG!A1	rdim=1 cdim=1
par=timesupModel	rng=Temp!A3	rdim=1 cdim=1
par=industryDem	rng=industry!A2	rdim=1 cdim=0
par=industryRelFactor	rng=industry!H2	rdim=1 cdim=0
par=map_in	rng=Mapping!A2	rdim=2 cdim=0
par=map_nr	rng=Mapping!E2	rdim=2 cdim=0
par=map_pi	rng=Mapping!I2	rdim=2 cdim=0
par=map_ni	rng=Mapping!M2	rdim=2 cdim=0
par=map_lfix	rng=Mapping!Q2	rdim=1 cdim=1
par=map_pr	rng=Mapping!X2	rdim=2 cdim=0
par=map_pri	rng=Production!B3	rdim=2 cdim=0
par=map_sti	rng=Storage!A2	rdim=2 cdim=0
par=map_lij	rng=Pipelines!A3	rdim=3 cdim=0
par=map_stc	rng=Storage!D2	rdim=2 cdim=0

\$offecho

\$onUNDF

\$if set LoadXLS \$call "gdxxrw Data_GermanyGasGrid_v18.xlsx squeeze=N cmerge=1 MaxDupeErrors=100 trace=3 @temp.tmp"

\$gdxin Data_GermanyGasGrid_v18

\$load i n r pr st p_BNetzA l st_c

\$load nodesup pipelinesup NUTSup timesupModel s_patternUp s_charactUp

\$load productionUp storagesUp

```
$load industryDem fixedDem gasPriceUp industryRelFactor losses
$OnEps
$load flow_fixed_POS flow_fixed_NEG
$OffEps
$load map_in map_ni map_nr map_pri map_sti map_lij map_stc map_lfix
$load map_pi map_pr
$gdxin
$offUNDF
;
*****
** --> Generation Power Plants, delivered by UDE
*Write gdxrw option file
$onUNDF
$onecho >temp2.tmp

par=genPowerPlants_UDE  rng=GAMS!A2          rdim=2 cdim=1

$offecho

$onUNDF
$if set LoadXLS_UDE $call "gdxrw Data_exchange%modelRun%.xlsx cmerge=1 MaxDupeEr-
rors=100 trace=3 @temp2.tmp"
$gdxin Data_exchange%modelRun%
$load genPowerPlants_UDE
$offUNDF
```

```

#####
*
*          ASSIGNMENTS
*
#####
*Generals
*Subset definition
    i_exit(i)$ (nodesup(i,'exit_point') eq 1) = yes;
    i_DemFix(i)$ (nodesup(i,'i_DemFix') eq 1) = yes;
    map_l ij(1,i,j)$ (map_l ij(1,i,j) ne 0) = 1;

*Defines the considered time scope for the optimization
Set
    tt(t_d)    subset to run model /t0001*t0366/;

*-----
*          CALCULATION OF HEAT BASED NG DEMAND   (a1)
*-----
*NUTS-3 Temperature for each day
    tempModel_prep(t_d,r) =
        timesupModel(t_d,r);
    tempModel(t_d,n) =
        sum(r,tempModel_prep(t_d,r)*map_nr(n,r));

*Parameter A-D
    par_A(n,t_d)=NUTSup(n,'A');
    par_B(n,t_d)=NUTSup(n,'B');
    par_C(n,t_d)=NUTSup(n,'C');
    par_D(n,t_d)=NUTSup(n,'D');

*h-Factor
    h_Factor(n,t_d)=

```

```

    par_A(n,t_d)/
    (1+ (par_B(n,t_d)/(tempModel(t_d,n)-tempRef))**par_C(n,t_d))
    + par_D(n,t_d)

```

```
;
```

```
*KW-Wert
```

```
KW(n) = 0;
```

```
KW(n)$ (sum(t_d,h_Factor(n,t_d)) gt 0)=
```

```
    NUTSup(n,'Ref-Dem')/sum(t_d,h_Factor(n,t_d))
```

```
;
```

```
*demand for heating per region i and time t
```

```
dem(n,t_d,'a1') = 0;
```

```
dem(n,t_d,'a1') =
```

```
    KW(n)*h_Factor(n,t_d)
```

```
;
```

```
*-----
```

```
*          CALCULATION OF INDUSTRY BASED NG DEMAND (a2)
```

```
*-----
```

```
*demand for industry generation per NUTS region n
```

```
dem(n,t_d,'a2') = 0;
```

```
dem(n,t_d,'a2') = industryDem(n)*366*industryRelFactor(t_d);
```

```
*-----
```

```
*          SUM UP AND ALLOCATION of NUTS3 DEMAND TO NODES
```

```
*-----
```

```
*counts numbers of EXIT-nodes per NUTS3 region
```

```
numbNodes(n)=NUTSup(n,'numbNodesExit');
```

```
dem_i(i,t_d) = 0;
```

```

dem_i(i_exit,t_d)=

    //allocation heat and industry (NUTS) demand to nodes
    sum((a,n)$ (numbNodes(n) gt 0),
        (dem(n,t_d,a)*map_in(i_exit,n))/
        (sum(nn,numbNodes(nn)*map_in(i_exit,nn)))
    )+
    sum((a,n)$ (numbNodes(n) eq 0),
        dem(n,t_d,a)*map_ni(n,i_exit)
    )+

    //add generation power plants
    sum(p_BNetzA,
        genPowerPlants_UDE(p_BNetzA,t_d,'Value')*map_pi(p_BNetzA,i_exit)
    )/1000 //convert from MWh_th to GWh_th by factor 1000
    +

    //fixed demand (basically for neighbouring countries)
    fixedDem(t_d,i_exit)
    + losses(t_d)/card(i_exit)
;

dem_i_sum = sum((i,t_d),dem_i(i,t_d));

*-----
*
*           PIPELINE PARAMETERS
*-----

*pipeline transmission parameter

transmission_limit(l) =
    pipelinesup(l,'limit');
```

*transmission costs: Assumption 0,17 EUR/GWh/km

tr_costs(l)\$ (transmission_limit(l) gt 0) =
 0.17 * pipelinesup(l, 'Länge')/1000;

*-----

* PRODUCTION

*-----

*production limit

p_limit(pr) = productionUp(pr,'p_limit');

*production flexibility

p_flex(pr) = productionUp(pr,'flexFactor');

*production costs

p_c(pr,t_d) = 0;

p_c(pr,t_d) = sum(i\$(map_pri(pr,i) AND nodesup(i,'foerd_c') ne 0),
 nodesup(i,'foerd_c')*map_pri(pr, i));

p_c(pr,t_d)\$ (sum(i ,nodesup(i,'cross-border')*map_pri(pr,i)) eq 1) =
 bafa(t_d);

* p_c('pr_08',t_d)=0;

*-----

* CROSS-BORDER-CAPACITIES

*-----

*corss-border-capacities are modelled through production

*-----

* STORAGE

*-----

*maximum storage volume in GW

 storage_max(st) = storagesUp(st,'storage_limit');

*storage withdrawn and injection in GWh/d

 storage_with_max(st) = storagesUp(st,'s_with_max');

 storage_inj_max (st) = storagesUp(st, 's_inj_max');

*storage loses in percentages

 s_loose(st) = storagesUp(st,'s_loose');

*storage pattern (relative $0 \leq x \leq 1$)

 s_pattern(t_d) = s_patternUp(t_d,'rel');

*execute_unload 'dataload_GasGridGermany_dynamic_v02.gdx'

*#####

* VARIABLES

*#####

Variable

 COST system costs

;

Positive Variables

 DUMMY_VALUE1(a,i,tt) Dummy-Wert (Lastabschaltung)

 FLOW_POS(l,tt) flow on lines pos

```

FLOW_NEG(l,tt)          flow on lines neg
P_Q(pr,tt)             production volume per production facility
STORAGE_IN(st,tt)     injection
STORAGE_WITH(st,tt)   withdrawal
STORAGE_LEVEL(st,tt)  level
;

#####
*
*           EQUATIONS
*
#####

```

Equations

```

OBJECTIVE                Cost minimization
ENERGY_BALANCE(i,tt)     Energy balance
DUMMY_BALANCE(n,tt,a)    DUMNMY Balance for eacht region

*Production Constraints

PRODUCTION_LIMIT_1(pr,tt)  Production limit per day
PRODUCTION_LIMIT_2(pr)     Production limit per year

*Pipeline Constraints

PIPELINE_FLOW_POS(l,tt)
PIPELINE_FLOW_NEG(l,tt)
PIPELINE_LIMIT_CONST_1(i,j,tt)  Transmission constraints
PIPELINE_LIMIT_CONST_2(i,j,tt)  Transmission constraints
FLOW_EQUATION(i,j,tt)           Equals flows

```

*Storage Constraints

STORAGE_LEVEL_CONST_START(st,tt)	storage level start first periode
STORAGE_LEVEL_CONST_1(st,tt)	storage level balance
STORAGE_LEVEL_CONST_2(st,tt)	storage level max
STORAGE_LEVEL_CONST_END(st,tt)	storage level last periode
STORAGE_WITH_CONST(st,tt)	max withdraw
STORAGE_INJ_CONST (st,tt)	max injection

;

*objective

*-----

*-----

OBJECTIVE..

COST =e=

```

sum((pr,tt),P_Q(pr,tt)*p_c(pr,tt))+
sum((l,tt),
      (FLOW_pos(l,tt)+FLOW_neg(l,tt))
      *tr_costs(l)
      )+
sum((a,i,tt),DUMMY_VALUE1(a,i,tt)*Dummy(a))

```

;

*Energybalance

*-----

*-----

ENERGY_BALANCE(i,tt)..

```
(-1)*(
dem_i(i,tt)                                //demand
+ sum((j,l)$ (map_lij(l,i,j) ne 0), FLOW_pos(l,tt)*map_lij(l,i,j)) //exports from i to j
+ sum((j,l)$ (map_lij(l,j,i) ne 0), FLOW_neg(l,tt)*map_lij(l,j,i)) //exports from i to j
+ sum(st$map_sti(st,i), STORAGE_IN(st,tt))
)+
sum(pr$map_pri(pr,i), P_Q(pr,tt))          //production
+ sum((j,l)$ (map_lij(l,i,j) ne 0), FLOW_neg(l,tt)*map_lij(l,i,j)) //imports from j to i
+ sum((j,l)$ (map_lij(l,j,i) ne 0), FLOW_pos(l,tt)*map_lij(l,j,i)) //imports from j to i
+ sum(st$map_sti(st,i), STORAGE_WITH(st,tt)) +
sum(a,DUMMY_VALUE1(a,i,tt))
=e= 0;*Dummybalance
```

*-----

DUMMY_BALANCE(n,tt,a)\$ (dem(n,tt,a) gt 0)..

```
sum(i$map_in(i,n), DUMMY_VALUE1(a,i,tt))
+ sum(i$map_ni(n,i), DUMMY_VALUE1(a,i,tt))
=l= dem(n,tt,a)*LoadCutFactor(a);
```

*Production-constraints

*-----

PRODUCTION_LIMIT_1(pr,tt)..

```
P_Q(pr,tt) =l= p_limit(pr)*p_flex(pr);
```

PRODUCTION_LIMIT_2(pr)..

```
sum(tt,P_Q(pr,tt)) =l= p_limit(pr)*card(tt);
```

*Pipeline-constraints

*-----

PIPELINE_FLOW_POS(1,tt)\$ (transmission_limit(1) ne 0)..

FLOW_pos(1,tt) =l= transmission_limit(1);

PIPELINE_FLOW_NEG(1,tt)\$ (transmission_limit(1) ne 0)..

FLOW_neg(1,tt) =l= transmission_limit(1);

*Storage-constraints

*-----

*stored volume in storage in first time step

STORAGE_LEVEL_CONST_START(st,tt)\$ (ord(tt) eq 1)..

STORAGE_LEVEL(st,tt) =e= storage_max(st)*s_pattern(tt)

;

*Storage energy balance

STORAGE_LEVEL_CONST_1(st,tt)\$ (ord(tt) ne 1)..

STORAGE_LEVEL(st,tt) =e=

STORAGE_LEVEL(st,tt-1) +

(1-s_loose(st)/100)*STORAGE_IN(st,tt) -

(1+s_loose(st)/100)*STORAGE_WITH(st,tt)

;

STORAGE_LEVEL_CONST_2(st,tt)..

STORAGE_LEVEL(st,tt) =l= storage_max(st);

STORAGE_LEVEL_CONST_END(st,tt)\$ (ord(tt) eq card(tt))..

STORAGE_LEVEL(st,tt) =e= storage_max(st)*s_pattern(tt)

;

STORAGE_WITH_CONST(st,tt)..

STORAGE_WITH(st,tt) =l= storage_with_max(st);

```
STORAGE_INJ_CONST(st,tt)..
    STORAGE_IN(st,tt) =l= storage_inj_max(st)
;
Model GERMAN_GAS_GRID /

OBJECTIVE
ENERGY_BALANCE
PRODUCTION_LIMIT_1
PRODUCTION_LIMIT_2
DUMMY_BALANCE
PIPELINE_FLOW_POS
PIPELINE_FLOW_NEG
STORAGE_LEVEL_CONST_START
STORAGE_LEVEL_CONST_1
STORAGE_LEVEL_CONST_2
STORAGE_LEVEL_CONST_END
STORAGE_WITH_CONST
STORAGE_INJ_CONST
/;
Solve GERMAN_GAS_GRID minimizing COST using lp;
```