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Deutsches Institut für Wirtschaftsforschung 2019

Global Gas Model

Model and Data Documentation v3.0 (2019)

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April 2019

https://www.ntnu.edu/web/iot/ggm

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Notation

Table 1 Units of measurement

Unit	Description	kWh	cm (m^3)	Used in GGM
cm	Cubic meter	9.8-11.9	1	11.4
kWh	kilo Watt hour	1	0.083 - 0.10	1/11.4 = 0.0877
mbtu	1000 British thermal units	0.293	0.0257 (=1/38.9)	1/38
mcf	1000 cubic feet	0.276-0.335	1/35.31	1/35.31
mtpa	million tonnes (of LNG) per annum	Never used	1.15-1.39 x 10^9	1.3 x 10^9

- Model units are kcm (1000 m^3), mcm (million m^3), costs and prices are in € / kcm; flows and capacities in mcm/d
- Input units for volumes and capacities are bcm or bcma (billion cubic meter/year); storage working gas is measured in mcm and extraction in mcm/d
- We use HHV – Higher Heating Values. See table below for a range of actual values.
- Volumetric units have precise conversions – for the same temperature and pressure.
- Energy units have precise conversions
- Because natural gas composition varies between regions and production wells, conversion between volumetric and energy units vary.
- mtpa is generally used to measure LNG (liquefied natural gas). BP: 1.36 bcm/ton; Calculations based on GIIGNL min, avg, max 1.15-1.27-1.39. We process LNG data that uses mtpa. However, we convert to volumetric units.

Table 2 Range of energy content of natural gas

Gas type	MJ/m3	kWh/cm	cm/kWh	Source
Groningen (20% N_2!)	35.17	9.77	0.1024	Taqa eConverter
Natural gas (USA) LHV/NCV	36.60	10.17	0.0984	Engineering Toolbox
General – Global	37.68	10.47	0.0955	BP
General – USA	38.26	10.63	0.0941	EIA
National Grid UK		11.00	0.0909	Taqa eConverter
LNG – lower end of range	39.9	11.08	0.0902	GIIGNL
Bayernets		11.19	0.0894	Taqa eConverter
Natural gas (USA)* HHV/GCV	40.6	11.28	0.0887	Engineering Toolbox
Fluxys		11.63	0.0860	Taqa eConverter
LNG - higher end of range	46.2	12.83	0.0779	GIIGNL

Sources:

Taqa eConverter https://www.gasstoragebergermeer.com/econverter

Engineering Toolbox https://www.engineeringtoolbox.com/fuels-higher-calorific-values-d_169.html

Introduction

This report is part of the data documentation for the Global Gas Model (GGM) as prepared for analyses in the H2020 SET-Nav project[1] and subsequent studies. Since some data are proprietary we cannot make available all input data we have used. By describing input data, the processing steps, and the resulting input files we aim for maximum transparency and to allow anyone to reproduce the data sets from scratch if desired.

GGM was developed by Egging (2010, 2013), also based on expertise gained in the development and application of the European Gas Model (Egging et al., 2008) and the World Gas Model (Egging et al., 2010, 2009). GGM was applied with various data sets and versions in studies of the future global (Holz et al., 2015) and European gas markets (Holz et al., 2016, 2017). In addition to the impact of climate policy, supply security has been a recurring concern (e.g. Richter and Holz, 2015). Moreover, a stochastic version that used a scenario tree was applied in Egging and Holz (2016). In the SET-Nav project, GGM contributed to the analyses of projects of common interest (PCI), their profitability and public support requirements (Kotek et al., 2018). This is a deterministic model version (i.e. no probabilistic scenario tree).

If you find significant omissions or errors in this document, the GAMS code or the MS Excel files I would be grateful if you can send me an email at ruud.egging@ntnu.no.

Model structure

GGM is implemented in GAMS[2]. The deterministic GGM reads input from three MS Excel workbooks[3], which is processed further in the model. The structure and contents of the MS Excel workbooks are described in this document, as are the relevant assignments in GAMS processing these data. A brief description of the underlying data sources and processing steps is also given.

Figure 1 gives a schematic overview of the types of actors along the natural gas value chain that are represented in the Global Gas Model. For each actor, we use specific input data that is documented in the following.

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[1] SET-Nav www.set-nav.eu (H2020 grant agreement no. 691843)

[2] GAMS www.gams.com

[3] The stochastic version reads scenario tree definitions from an extra workbook.

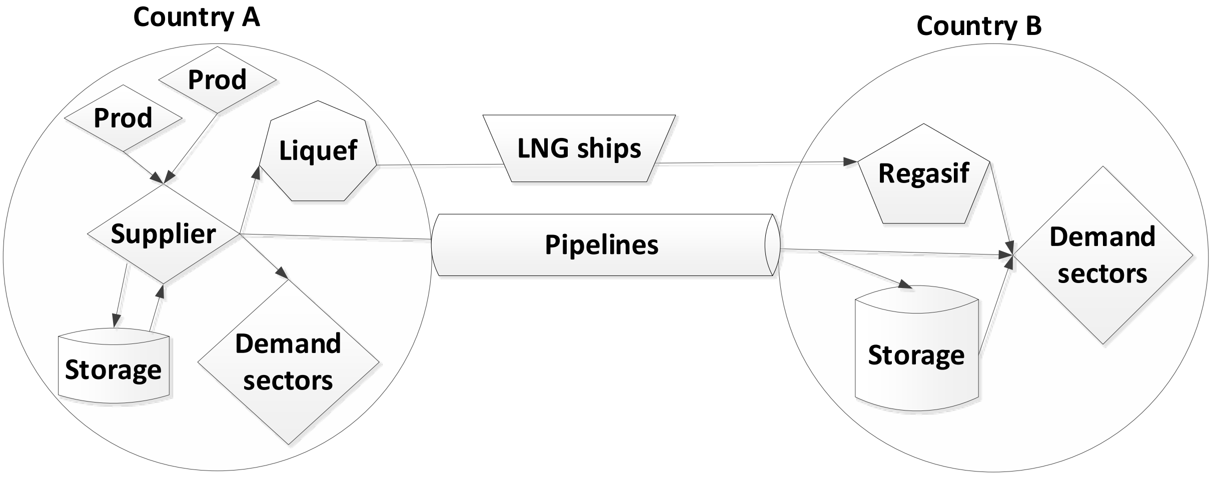

Figure 1: Actors and value chain represented in the Global Gas Model

Table 3 presents the main data categories relevant for natural gas market models. The actual input data are collected and formatted in three MS Excel workbooks (Table 4).

Table 3 Gas market data categories

Data category	Abbrev	Model parameters	Input parameters
Production	P	Yearly capacities Yearly costs	Reference production values, cost and other calibration parameters
Consumption	C	Seasonal intercept and slope of demand curves	Reference consumption values and prices, sector shares, seasonal loads, seasonal price adjustments
Pipelines	Arcs: A – P	Capacities, investment costs, operational costs, loss rates	Length, offshore part, initial capacities, investment costs, operational costs, loss rates, maximum allowed expansions
Liquefaction terminals	Arcs: A – L		Initial capacities, investment costs, operational costs, loss rates, maximum allowed expansions
Regasification terminals	Arcs: A – R		
LNG ships	Arcs: A – V	Costs, losses	Length of shipping routes, costs and losses per distance unit
Storages	W	Working and extraction capacities, investment and operational costs, loss rates	Initial capacities, investment costs, operational costs, loss rates, maximum allowed expansions

Note: We use *W* for storages to clearly distinguish from *S* which is used for suppliers in other model versions.

This documentation provides the background information for data collected in the three Excel files indicated in Table 4 below. For each workbook, the documentation starts with an overview on the structure of the file and subsequently explains each sheet of the file. When deemed relevant, we give actual data values and offer a brief explanation. Each workbook contains more information in the

Readme-sheets. Additionally, in Section 0 we describe how the model parameters are calculated based on the input values read from the MS Excel workbooks. For internal process documentation purposes, we also describe workflow and processing steps for files that are not available to people outside the GGM research group.

Table 4 MS Excel workbooks with input data

File name	Location	Type of data	Comment
data.xlsx	data\set-nav	Scenario independent data	
data_proj.xlsx	data\set-nav	Future projections consumption and production for scenarios + EU sector shares and seasonality	Seasons and sectors non-EU in data.xlsx
data_calib.xlsx	data\set-nav\<scenario>, e.g., data\set-nav\NPS-Ref data\set-nav\SDS-Vision	Calibration data for production and consumption	

File data.xlsx

This section describes the first part dataset of the Global Gas Model, which is consolidated in the MS Excel file data.xlsx. The second part of the data is in sheet data_proj.xlsx and is presented in Chapter File data_proj.xlsx.

The following sections discuss structure, data sources and processing steps for each sheet of data.xlsx. They also include some advice on how and where to modify the data, if necessary. More detail on the sources and the reasons for our specific data choices can be found in the Appendix (Sections 10-12). The file data.xlsx contains the following work sheets.

Table 5 sheets in data.xlsx

Sheet	Information on	Comment
Readme	This workbook	Self explanatory
Other	Parameters values	Section 3.1
N	Geographical nodes; consumption seasonality and sector shares for non-EU	Section 3.2, seasons & sectors for EU not here but in data_proj.xlsx
A	pipelines, liquefaction and regasification terminals	Section 3.3
V	distance matrix for shipping of LNG	Section 3.4
W	gas storages	Section 3.5
M	market power	Section 3.6

Note that in MS Excel, the name manager shows definitions that are used by GAMS when reading the Workbook:

Name	Value
Arcs	{"GALB_ITA";"GAUT_CZE";"GAUT_DEU";"GAUT_HUN";"GAUT_ITA";"GAUT_SVK";"GAUT_SVN";"
ArcsData	{"Arc","Start","End","P","L","R","V","len","off","2015","2020","2025","2030","2035","2040","204
Countries	{"CAN";"CAN";"MEX";"USA";"USA";"USA";"USA";"USA";"USA";"USA";"USA";"USA";"USA";"ARG";
DistCutOff	15
LNGDistances	{"","RMEX_A","RMEX_P","RUSA_1","RARG","RBRA","RCHL","RCOL","RESP_M","RBEL","RDEU","
MarketPower	{"","domestic","export","CHN","BLR","UKR","TUR","factor","ratio";"NOR","EPS","0.25","","","","","
Nodes	{"CAN_E";"CAN_W";"MEX";"USA_1";"USA_2";"USA_3";"USA_4";"USA_5";"USA_6";"USA_7";"USA
NodesData	{"Node","Node","Node","Node","Node","Node","Node","Node","Node","Node","Cons","Cons","
Other	{"BFLiq","20";"BFPipe","7";"BFReg","10";"BFShip","8";"BICLiq","365000";"BICReg","182500";"BI
Regions	{"NAM";"NAM";"NAM";"NAM";"NAM";"NAM";"NAM";"NAM";"NAM";"NAM";"NAM";"NAM";"NA
Resources	{"R1";"R2";"R3"}
Seasons	{"L";"H";"P"}
Sectors	{"RES";"IND";"POW";"TRA"}
StorageData	{"","","","inj","extr","WG","extr","WG","WG","WG","WG","WG","WG","WG","WG","WG","WG","W
Storages	{"Seas";"LNGS";"Peak"}
Years	{"2015";"2020";"2025";"2030";"2035";"2040";"2045";"2050";"2055";"2060"}

Data.xlsx - Sheet O – Other data

The sheet O (which stands for "Other data") contains some set definitions and parameter values.

- Production resources. $R = \{R_1, R_2, R_3\}$
- Storage types seasonal, LNG terminal, Peak. $W = \{Seas, LNGS, Peak\}$
- Years used in the data sets $Y = \{2015, 2020, 2025, \ldots, 2060\}$
- Seasons low, high and peak demand (EU perspective) $D = \{L, H, P\}$
- Sectors residential and commercial sector (building heating), industry, electric power generation, transport $K = \{RES, IND, POW, TRA\}$

Here we present the entire table. Next, we indicate where values originate from.

Table 6 Data table in worksheet O

Parameter	Value	Unit	Description
BFPipe	7	€/kcm/1000 km	Operational tariff for using pipeline capacity
BICPipe	109500	€/kcm/1000 km/ y	Unit investment cost for onshore pipe capacity
BLPipe	0.020	[]/1000 km	Pipeline loss fraction
BIPipeOffshMult	2	[]	Multiplication factor offshore pipe investment cost
BFLiq	20	€/kcm	Operational tariff for using liquefaction capacity
BFReg	10	€/kcm	Operational tariff for using regasification capacity
BFShip	8	€/kcm/1000 sea miles	Operational tariff for using shipping capacity
BICLiq	365000	€/kcm/y	Unit investment cost for liquefaction capacity
BICReg	182500	€/kcm/y	Unit investment cost for regasification capacity
BLLiq	0.100	[]	Liquefaction loss fraction
BLReg	0.015	[]	Regasification loss fraction
BLShip	0.003	[]/1000 sea miles	Shipping loss fraction
DistCutOff	15	1000 sea miles	Cut off distance for allowing LNG shipping
YearStep	5	Years	Number of years between two stages
RES	-0.25	[]	Price elasticity for residential sector
IND	-0.40	[]	Price elasticity for industry sector
POW	-0.75	[]	Price elasticity for electric power
TRA	-0.25	[]	Price elasticity for transport sector
L	183	Days	Number of days in low demand period
H	120	Days	Number of days in high demand period
P	62	Days	Number of days in peak demand period
BIStorX	5000	€/kcm/y	Unit investment cost for storage extraction
BIStorW	150	€/kcm	Unit investment cost for storage working
CostInfl	0.02750	[]	Yearly cost inflator
PriceInfl	0.02750	[]	Yearly price inflator
Real	0.05000	[]	Real discount rate for NPV calculations

DiscRate	0.07888	[]	Nominal discount rate used in the model

In this model version, investment cost data used in the model was not scaled up (i.e. multiplied by the number of years in each period). The values presented above are five times as large the values otherwise used (i.e. with upward scaling), and are now scaled down in the model by a factor five.

1.1.1 Operational and investment costs and losses

Details for data ranges for costs and losses are presented in the Appendix in Table 41, for pipelines in Section 10, Table 45 for LNG data in Section 11 and Table 59 for storages in Section 12.

Usually, using a shipping distance cutoff in the model makes the model size smaller and the solution time shorter. Currently the value for DistCutOff = 15 (i.e. 15000 sea miles), which is large enough to not exclude any shipping routes.

1.1.2 Price-demand elasticities

The values for residential, industry and power generation originate from IEA estimates used in the ENGAGED project (FP5, ECN, DIW and others. Van Oostvoorn et al. (2003)). We have set transportation equal to residential, as it is also expect to be not very price sensitive.

1.1.3 Discounting and inflators

We assume a cost inflation rate of 2.75% per year roughly in line with prevailing values in developed countries over the past few decades, and a real discount rate of 5% per year. PriceInfl is used to increase the willingness to pay in the model, and DiscRate is used as the discount rate in the objective function.

Data.xlsx – Sheet N – Nodes data

The Nodes sheet comprises several types of information. On the one hand, it provides the set of model nodes and their types, countries, and regions. On the other hand, it comprises some data on consumption. There are three main types of nodes:

1. Geographical node: production and/or consumption and/or transit
2. Liquefaction
3. Regasification

Data sheet N is structured as listed in Table 7. Data sources are listed in column "Source". Note that the table continues at the next page.

Table 7: Summary of sources for model nodes, consumption and production data

Column	Description	Source
Country	Name of Country – Auxiliary column	Own
Region	Region – Auxiliary column	Own
N	Model node for geographical region (part of) a country, or representative liquefaction or regasification node	Own
CN	Country code	Own
Rgn	Region code	Own

Column	Description	Source
C	Marked for consumption	Own
P	Marked for production	Own
W	Marked for storage	Based on sheet W
L	Marked for liquefier	Based on sheet A
R	Marked for gasifier	Based on sheet A
Transit	Marked if no production and no consumption	Own
Split	Number of production nodes in the same country	Formula based
POW	Demand share of sector – power production	Van Oostvoorn (2003)
IND	Demand share of sector – industry	Van Oostvoorn (2003)
RES	Demand share of sector – residential	Van Oostvoorn (2003)
TRA	Demand share of sector – transport	Own
L	Relative seasonal load share – low demand period	Various
H	Relative seasonal load share – high demand period	Various
P	Relative seasonal load share – peak demand period	Various

Auxiliary columns are included in this and other worksheets for convenience, but not read by GAMS as part of the data set.

The sector and seasonal data in the last seven rows are only for non-EU countries. For EU countries, these data are provided in the file data_proj.xlsx

Table 8: Global regions represented in GGM

Abbreviation	Region
NAM	North America
SAM	South America
EU	EU28
ROE	Other European countries
AFR	Africa
RUS	Russia
CAS	Caspian region (Caucasus)
MEA	Middle East
ASP	Asia Pacific

Data.xlsx – Sheet A - Arcs

Arcs represent connections between nodes as well as ways of how traded gas can be transported. Gas can be transported in two states: liquid and gaseous. The different states are processed and transported differently, which is reflected in distinct costs and loss rates in the model. Transport in gaseous state requires pipelines between (production, consumption, and transit) nodes, as illustrated in Figure 2.

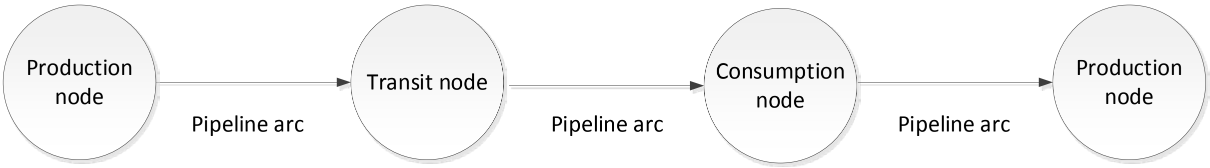

Figure 2. Example of a pipeline path

Transport in liquid state needs three steps: liquefaction, shipping and regasification, see Figure 3.

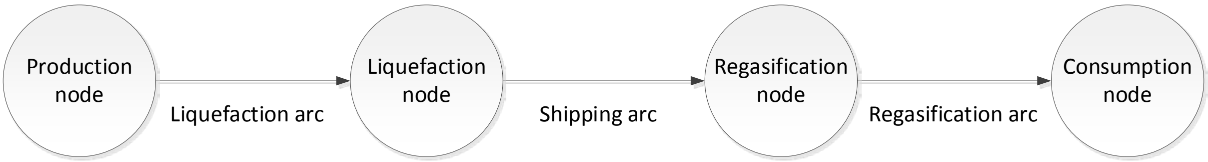

Figure 3. Example of a path in the LNG value chain

Therewith, there are four different types of arcs: pipelines, liquefaction arcs, shipping arcs as well as regasification arcs.

The sheet is structured as depicted in Table 9. In addition to the structural explanation, the source for each column is specified. As data sources differ for capacities of pipelines, liquefiers and gasifiers, each following section contains a detailed description of how data has been obtained and provides a summary of the sources.

Table 9 Summary of sources by scenario and data type

Column	Description	Source
Arc	Unique identifier	Own
Start	Outward node	Own
End	Inward node	Own
P	Marked for pipelines	Own
L	Marked for liquefiers	Own
R	Marked for gasifiers	Own
V	Not used	Own
len	Length in 1000 km	Some specific sources, many own estimates
off	Length offshore part 1000 km	Some specific sources, many own estimates
2015	Capacity in 2015, in bcm	Depending on category; differs for P, L, R
2020	Capacity in 2018, in bcm[4]	Depending on category; differs for P, L, R
2025	Capacity in 2025, incl. FID projects with anticipated commissioning before 2026	Depending on category; differs for P, L, R
2030-2060	same value as previous	
c_cal	Calibration factor operational cost	Value determined by researcher
i_cal	Calibration factor investment cost	Value determined by researcher

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[4] From selected arcs we allow endogenous arc expansions in 2015 that would come online in 2020.

Column	Description	Source
d_max1	Maximum allowed expansion in 2015[5]	Value determined by researcher
d_max2	Maximum allowed expansion in 2020	Value determined by researcher
d_max3	Maximum allowed expansion rest of horizon	Value determined by researcher

1.1.4 Documentation for pipelines

Pipeline capacities between countries have been collected from various sources. Large countries such as the US, Russia, China, and India are split into several nodes. For these countries, we also include domestic pipelines, i.e. pipeline capacities between the country's model nodes. See the later section on production and consumption for details about how these countries have been split in their representation in the GGM.

For Europe, ENTSO-G offers a large database with information on European cross-border infrastructure, including pipelines.[6] For the United States, data on pipelines can be found on the website of the U.S. Energy Information Administration (EIA).[7] For countries and regions other than the US and Europe, an existing data sheet (from Holz et al., 2015) was used as well as various web sources such as pipeline operators' websites. In addition, some Projects of Common Interest (PCI) in Europe were added to the data set based on European Commission information. The relevant information for model purposes includes start and end point (country or region), capacity and approximate length (i.e., total length and offshore length as part of the total).

Europe: The data by ENTSO-G lists all cross-border pipelines in Europe. This information was collected for the years 2015 and 2020 based on the report and data sets from 2016 and 2018. The data source provides, among others, information on start and end point of the pipeline and its capacity. Additional information on development plans for the gas pipeline network can be found on the system development maps that are available on the ENTSO-G website. Information on pipelines under construction and the opportunity for endogenous expansion has been added accordingly to the model's input data set.

USA/North America: The U.S. Department of Energy's Energy Information Administration (EIA) offers a large online database on their gas network. The table on state-to-state capacity has been used and aggregated according to the model nodes in the GGM. The data set comprises information on start and end of a pipeline as well as its capacity for the United States and their connection to neighboring countries (Canada and Mexico). Investment plans for new infrastructure are available on the same website.

Other: For other regions, data was available from earlier versions of the Global Gas Model. Additional web-based research gave a few insights, specifically for Russia, China, Central Asia, and

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[5] Note that there is a one period gap between investment decision and availability of new capacity.

[6] https://www.entsog.eu/maps#

[7] https://www.eia.gov/naturalgas/data.php

South America. For China, Russia, India and Canada, domestic pipeline data are based on web searches and professional journals of the oil and gas industry.

Due to different units used by the individual sources, some data needed to be converted, using the conversion rates in Table 1 Units of measurement. The model input capacity has a unit of billion cubic metres per year. For US data, a conversion from million cubic feet per year to bcma became necessary with the following conversion: $1ft^3 = (12*0.0254)^3\ m^3$: 1000 mmcf = 1000/35.31 bcm.

Generally, the raw data from the different sources and databases has been collected and transformed to a set consisting of start node, end node, length and capacity in bcm. In case there are several connections between nodes (e.g. several pipelines between the same two countries in the same direction), these capacities have been aggregated.

Table 10: Data sources for pipelines

	EU	USA	Other
2015	ENTSOG Transmission Capacity Map 2016	EIA state-to-state capacity	Various
2020	ENTSOG Transmission Capacity Map 2018	EIA state-to-state capacity	Various
2025	ENTSO – G System Development Map 2017 -2018	EIA Pipeline projects	Various
2030		EIA Pipeline projects	Various

1.1.5 Documentation for liquefaction and regasification data

For most countries with liquefaction (regasification) there is one representative liquefier (regasifier). For countries that are split in multiple geographical nodes, this applies for each geographical node. For some countries, where East coast and West coast (e.g, Mexico, France, Spain) imply significantly different shipping distances we have two or three representative regasifiers. Capacity data is aggregated to the representation level in the model.

A large and detailed database on liquefaction and regasification capacities is provided in the yearly report published by the International Group of Liquefied Natural Gas Importers (GIIGNL). This report gives a summary of operational terminals for liquefaction and regasification around the world. Furthermore, it comprises a summary of planned projects and projects under construction with an information about start-up date and capacity. The reports from 2016 (ENTSOG 2016) (p. 22-24 (li), 29-31) and 2018 (ENTSOG 2018) (p. 24-26 (li), p. 36-39) have been used for input data in 2015 and 2020. Additional information on planned projects and projects under construction has been collected from the reports GIIGNL (2016-2018)ʹ (2016: p.20/21, p. 26-28; 2017: p. 19-23; 2018: p. 22/23 p. 32-35).

For Projects of Common Interest (PCI) and planned projects in Europe, the Gas Infrastructure Europe (GIE) database gives an overview with a map (GIE n.d. (a)) and provides an investment database (GIE n.d. (b)). These projections were used to cross check and complete information from GIIGNL.

All data from GIIGNL on liquefaction is given in mtpa (million tonnes per annum); regasification in bcma (billion cubic metres per annum). The GIE database uses mtpa for planned projects and bcm for existing capacities. The GGM uses bcma as the input data unit. This is where unit conversion becomes crucial. Due to different gas characteristics, the conversion factor differs among the countries. A table on gas characteristics from different gas fields as well as a conversion factor to bcm is given in GIIGNL (2011, p. 12).

Table 11: Data sources for liquefaction and regasification

	EU	Other
2015	GIIGNL 2016	GIIGNL 2016
2020	GIIGNL 2018	GIIGNL 2018
2025	GIE LNG map 2017, GIE LNG Investment, Database 2005- 2016, GIIGNL 2016 – 2018	GIIGNL 2016 – 2018
2030-2060	With one or two exceptions equal to previous	

Data.xlsx – Sheet V – LNG shipping distances

The sheet V contains a distance matrix for shipping distances between representative liquefaction and regasification nodes in the model. All liquefaction terminals are listed vertically to the left, all regasification terminals horizontally on top. The matrix contains values in thousands of sea miles and is structures as shown in Table 12. Ports and distances have been obtained as explained in the following paragraph.

Table 12: Structure of the distance matrix for ports

	Regasification node 1	Regasification node 2	…
Liquefaction node 1	Distance between liquef node 1 and regas node 1 in 1000 sea miles	…	…
Liquefaction node 2	Distance between liquef node 2 and regas node 1 in 1000 sea miles	…	
Liquefaction node 3			
….	….	….	

Each model node that has a capacity for liquefaction or regasification needs a port for shipping. Therefore, each of these nodes has one representative port in its area assigned in order to estimate shipping distances. The ports are selected based on the largest capacity of liquefiers and regasifiers in the area comprised in the node. Once all nodes are matched with a port, a distance matrix is being set up mapping the shipping distances between liquefaction and regasification terminals filled with values in thousand sea miles. An existing matrix from DIW provided the input for many distances. Missing distances were obtained in two ways. Either by using existing nodes as reference values or by calculating the distance between the reference node and the new port. As shipping costs are about € 8 / kcm / 1000 sea miles, deviations of a few hundred sea miles have minor impact on model results.

The deviation in shipping cost is in the order of about 1% of end-user prices only. In addition, if reference nodes were not applicable, distances have been calculated using a web service[8].

Data.xlsx – Sheet W - Storage

The global gas model takes natural gas storage into account. The data needed for calculations comprises details on location, type, working gas capacity and withdrawal rate (injection rate). The storage types have been grouped in either peak shaving unit or seasonal storage. The sheet is structured as shown in Table 13. A summary of the sources is listed and described in detailed in the following paragraphs.

Note that the table continues at the next page.

Table 13: Data structure and sources for gas storage data

	Column	Description	Source
	Node	Node with storage	Own
	Type	Type of storage	IEA Natural Storage Information and own categorization
	loss	Injection loss in fraction	
	oper	Operational extraction costs in $/kcm	
	Calib (inj)	Injection calibration	
	Calib (WG)	Working gas calibration	
	Calib (extr)	Extraction calibration	
Working Gas (WG), injection (inj), Extraction (extr)	2015	WG/inj/extr capacity in 2015, in mcm/ mcm/d /mcm/d	OECD: IEA Natural Gas information 2016 USA: EIA, 2016 Non-OECD in EU: GIE storage database 2016 Non-OECD: Cedigaz 2017
	2020	WG/inj/extr capacity in 2020, in mcm/ mcm/d /mcm/d	OECD: IEA Natural Gas information 2018 USA: EIA, 2018 Non-OECD in EU: GIE storage database 2018 Non-OECD: Cedigaz 2017
	2025	WG/inj/extr capacity in 2025, in mcm/ mcm/d /mcm/d; Including FID projects with start before 2026	Non-OECD in EU: GIE storage database 2018
	2030	WG/inj/extr capacity in 2030, in mcm/ mcm/d /mcm/d; Including FID projects with start before 2031	Non-OECD in EU: GIE storage database 2018
	2035-2060	Same value as previous	
	d_max	In mcm	

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[8] https://sea-distances.org/

File data.xlsx

The data input for the GGM-data document originates from three main data sources: IEA Natural Gas Information, GIE storage database and EIA Natural Gas section. The following paragraphs give a brief overview on the databases and the data they include.

IEA Natural gas information: The largest database can be found in the *IEA Natural Gas Information* that it published every year. It contains data for all OECD countries on underground storage and LNG storage and provides details on storage location, name, type, working gas capacity, withdrawal rate and number of sites. The reports from 2016[9] and 2018 [10]serve as input for years 2015 and 2020 in the model.

GIE storage database: The Gas Infrastructure Europe (GIE) provides a database[11] with information on underground storages for all European countries including the non-EU and non-OECD countries Belarus, Russia and Ukraine. Details about amongst others location, name, type, operator, start year, working gas capacity, withdrawal rate and injection rate are listed. Reports from 2016 and 2018 serve as input for the years 2015 and 2020 in the model.

EIA: The US Energy Information Administration (EIA) provides a large database with information on all US natural gas underground storages – this includes location, name, state, number, type, working gas capacity, operator and withdrawal rate. The database on Natural Gas Annual Field Level Storage (Survey form EIA-191) was used for the years 2015[12] and 2018[13] as model input for 2015 and 2020.

In addition, information on the Caspian region for the year 2016 can be found in a Cedigaz report. This was added to the data input for 2015 and 2020.

Data/Unit conversion was necessary for US data and non-OECD countries in Europe. Conversion factors originate from BP and GIE 2016. The following values have been used:

1 m^3 of LNG = 615 m^3 of NG, 1ft^3 = $(12*0.0254)^3$ m^3 and 11.4 TWh = 1 bcm of NG

Merging data from different data sources comes along with mismatching units and lack of detail. The final data is in mcm for working gas capacity and mcm/d for withdrawal capacity. All information from the different databases has undergone some processing in order to have the same format for all information. This included unit conversion in the first place. After, storages were assigned a category according to their type (see Table 14 for assignments, where PEAK stands for peak shaving unit, SEAS for seasonal storage and LNGS for LNG storage) and a model node according to their location. All data was then aggregated by model node and type such that each node has a maximum

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[9] https://webstore.iea.org/natural-gas-information-2016
[10] https://webstore.iea.org/natural-gas-information-2018
[11] https://www.gie.eu/index.php/gie-publications/databases/storage-database
[12] https://www.eia.gov/naturalgas/ngqs/#?report=RP7&year1=2015&year2=2015&company=Name
[13] https://www.eia.gov/naturalgas/ngqs/#?report=RP7&year1=2017&year2=2017&company=Name

of three storage capacities assigned. At last, storages that cannot cover up to 2% of consumption with their capacity have been excluded from the model's input.[14]

Table 14: Categories for different storage types

Type	Category
Above ground	PEAK
Aquifer	SEAS
Cavern	PEAK
Cavern storage	PEAK
Depleted Field	SEAS
Depleted gas field	SEAS
Depleted gas/oil field	SEAS
Depleted oil field	SEAS
Granite cavern	PEAK
Line rock cavern	PEAK
LNG peak shaving unit	PEAK
LNG Storage	LNGS
Salt cavern	PEAK
Salt Dome	PEAK
Salt mine	PEAK
Storage field	SEAS

Data.xlsx– Sheet M - Market power

The model implements market power via a conjectural variation approach. Values range from 0 to 1, with 0 implying perfectly competitive behavior and 1 behavior à la Cournot. Values have been tuned in the calibration.

1) Assign domestic market power value (use EPS for 0 to prevent data reading errors.)
2) Assign general export market power value.
3) Assign non-zero values to specific countries if desired. Only if there is a value larger than 0 it will be used to override (if there is a need to assign a zero overriding value, one should a small positive value such as 0.001; note that *EPS* will not override).

The (moderation) factor is used to multiply the initial market power. This is done every period. The (minimum market power) ratio is the lowest multiplication factor though:

Model input value = Table value * MAX[factor ^ num periods, ratio]

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[14] There is an R-script available that aggregates the data from the internal data compilation file storage needed in sheet W. The script is called storage_data_processing_script.R and can be found with its accompanying readme.pdf in folder gas-setnav\data documentation\internal\Storage\R-script

Table 15: Categories for different storage types

	domestic	export	CHN	BLR	UKR	TUR	factor	ratio
NOR	EPS	0.25					0.70	0.50
QAT	EPS	0.50					0.70	0.50
DZA	EPS	0.50					0.70	0.50
NGA	EPS	0.50					0.70	0.50
RUS	EPS	0.50	0.001	0.001	1.00	0.25	0.70	0.50

E.g., in 2015, Russia does not exert market power domestically. Per default, Russia's market power value is 0.5 to export markets, but it does not exert market power in China and Belarus. In Ukraine, Russia exerts full market power, and in Turkey 0.25. To reflect moderated market power over time which seemed to be necessary in the model calibration, for 2020, these values are all multiplied by factor 0.7. Since 0.7x0.7=0.49, and this is smaller than ratio 0.5, for 2025 and beyond market power values are obtained by multiplying base values by 0.5.

File data_proj.xlsx

Production and consumption data

This section describes how the GGM reference values for production and consumption have been established. It documents sources and disaggregation approaches. To create the data in this file several steps are needed. The following paragraphs explain how the data was obtained and from which sources they originate.

1.1.6 Suggestions and traps that should be avoided

- Use consistent conversion rates from QBtu, Mtoe or TWh to bcm for all data types from all data sources. Make the conversion rate adjustable in the worksheets and make sure that all calculations adjust automatically based on the conversion rate.

1.1.7 Processing steps and internal data files

Since some data are proprietary we cannot make available all input data we have used. By describing the input data, the processing steps, and the resulting input files we aim for maximum transparency and to allow anyone else to reproduce the data sets from scratch if desired.

Three MS Excel files collect and compile the production and consumption data:

- “WEO_Scenarios_Input_data.xlsx” has the general information for all countries except the ones in the EU28
- “gas_demand_production_europe.xlsx” gives data on EU28 countries
- “regional_split.xlsx” concerns five countries, USA, Canada, Russia, India, and China, that are divided into more than one region. This means that country level data has to be broken down to a more detailed level. The calculation of how country level production and consumption data has been divided is done in this file.

Table 16 Summary of production and consumption data sources

	EU		Rest of World	
	Scenario	**Source**	**Scenario**	**Source**
Production	All scenarios	PRIMES 2016 reference	New Policies	WEO 2017
			Sustainable Development	WEO 2017
Consumption	Reference	PRIMES 2016	New Policies	WEO 2017
	Directed Vision	SET-Nav	Sustainable Development	WEO 2017
Consumption Seasonality	All scenarios	Eurostat 2014-2017	All scenarios	DOE EIA 2007 + estimates based on similar countries
Consumption Sector shares	All scenarios	SET-Nav	All scenarios	DOE EIA 2007 + estimates based on similar countries

The IEA’s World Energy Outlook (WEO) 2016 450 Scenario and the WEO 2017 Current Policies Scenario are not part of the data set in the open source version.

1.1.8 Explanation “WEO_Scenarios_Input_data.xlsx”

In the open-source model version, we provide production and consumption data for 2015, and outlook data for two scenarios: New Policies (NPS) and Sustainable Development (SDS).

Country level production and consumption data for the year 2015 were published in the 2018 report “World – Natural gas statistics” by the International Energy Agency (IEA). It was downloaded from the OECD iLibrary.

As the WEO spatial aggregation considers less regions than the Global Gas Model, the WEO regional information had to be adjusted. Regional information (e.g. consumption) was split up according to the countries’ share in the region in 2015.

The World Energy Outlook (WEO) 2017 provided worldwide production and consumption data for three different scenarios (New Policies Scenario, Current Policies Scenario, and Sustainable Development Scenario). In addition, we take the 450 ppm Scenario from WEO 2016 (which was discontinued in later editions of the WEO). Production data for the **New Policies Scenario** can be found on page 346, consumption data on page 339. Data on the production in the **Sustainable Development Scenario** can be found on page 645 and on consumption on page 452.[15]

As there was no data for every year in the modeling horizon, the missing ones between 2020 and 2035 were interpolated linearly. To obtain values for the periods 2045 and 2050, the change between 2035 and 2040 was multiplied by 0.9 (for 2045 values), and by 0.72 (0.9x0.8) for 2050 values, reflecting a moderated trend extrapolation. Values for 2055 and 2060 are the same as for 2050.

Regional data was broken down to the country level by taking the production or consumption share from 2015 and applying these shares to the following years.

1.1.9 Explanation of the data for Europe in file “gas_demand_production_europe”

Production data for Europe is taken from the PRIMES European Reference Scenario 2016 as well as the reference consumption. In addition, we have included SET-Nav pathways “Directed Vision”.[16] Not only the annual country level consumption can be found in the file, but also the sectoral share for each period for residential heating, industry, power, and transport.

Furthermore, in order to distinguish several seasons, monthly data on the supply of gas provided by Eurostat (n.d.) was used.

Three seasons: one with low consumption that includes months April through September, one with high consumption that consists of October until March with the exception of December, January and February. The peak consumption period includes December and January.

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[15] Current Policies data on production and consumption is available at p. 645 and 647 respectively. The 450 Scenario from WEO 2016 has production data at p. 549, and consumption on pp. 551-623. Here,For the 450 ppm Scenario, we use Total Primary Energy Demand (TPED) values for gas that are given in billion cubic meter (Mtoe in the WEO 2016 and that we converted to bcm)..

[16] Directed Vision, Diversification, Localisation, and National Champions

Five seasons: one with low consumption that includes the months April through September, one with high consumption that consists of October until March with the exception of February and one week in January, a peek week in January, and the peek month of February.

Exceptions:

- Netherlands – we have decreased Netherlands production outlook rather drastically compared to PRIMES 2016 reference to account for the phasing out of the Groningen field.
- Norway – we have modified reference production in a few years to smooth out some moderate swings in values.
- Cyprus – Reference consumption in Cyprus started a period earlier than production. Rather than accounting for a small regasifier, we have adjusted production to take off a period earlier.

1.1.10 Explanation of the “regional_split” for countries with multiple regions

For all these countries the approach was similar: the different parts of the country were assigned to the regions in the model, then the share of production and consumption of each region was calculated for the year 2015 and multiplied with the WEO values.

1.1.10.1 USA

Production and consumption data for the USA were taken from the U.S. Energy Information Administration (EIA)

- USA Census regions + Alaska: https://www2.census.gov/geo/pdfs/maps-data/maps/reference/us_regdiv.pdf

Please note that, for the USA, marketed production instead of gross production was used for determining regional shares. This is especially important since gross production in Alaska is about 10% of the country’s production (and includes natural gas re-injected in the oil and gas production), but marketed production from Alaska is more than 10 times smaller. For marketed production refer to:

https://www.eia.gov/dnav/ng/ng_prod_sum_a_EPG0_VGM_mmcf_a.htm

Outlook for future periods (https://www.eia.gov/outlooks/aeo/data/browser/#/?id=77-AEO2019&region=0-0&cases=ref2019&start=2017&end=2050&f=Q&sourcekey=0).

We have assigned state level production published by the EIA to the ten GGM USA regions (Source: https://www.eia.gov/dnav/ng/ng_prod_sum_a_EPG0_FGW_mmcf_a.htm). This allowed calculating regional shares in production for 2015. These shares are multiplied by the USA production reference value from the relevant WEO outlook.

Consumption values were also taken from the EIA (Sources: https://www.eia.gov/dnav/ng/ng_sum_snd_a_EPG0_VC0_Mmcf_a.htm and https://www.eia.gov/outlooks/aeo/data/browser/#/?id=77-AEO2019&region=0-0&cases=ref2019&start=2017&end=2050&f=Q&sourcekey=0). The regional shares in consumption for the years were calculated and again multiplied by the US consumption reference value from the relevant WEO outlook.

1.1.10.2 Canada

We have assigned state level production and consumption published by the National Energy Board (NEB) (Source: https://apps.neb-one.gc.ca/ftrppndc/dflt.aspx?GoCTemplateCulture=en-CA) to the two GGM Canada regions. This allowed calculating regional shares in production (respectively consumption) for the different years. These shares are multiplied by Canada's production (respectively consumption) reference value from the relevant WEO outlook.

1.1.10.3 Russia

State level production values are from the paper "Shrinking surplus: the outlook for Russia's spare gas productive capacity" published by the Oxford Institute for Energy Studies in 2018 (Source: https://www.oxfordenergy.org/wpcms/wp-content/uploads/2018/12/Shrinking-surplus-the-outlook-for-Russias-spare-gas-productive-capacity-Energy-Insight-42.pdf), figure on p. 9. State level information was assigned to the four GGM Russia regions, obtaining a share per region in total Russian production in 2015. These shares are multiplied by the Russia production reference value from the relevant WEO outlook.

Consumption was calculated according to the regional share of total GDP. As Sakhalin's share is very small, it was assumed to be equal to zero. Again, these shares are multiplied with the Russia consumption reference value from the relevant WEO outlook.

1.1.10.4 China

We have assigned state level production and consumption published by the Statistical Yearbook 2017 (Source: http://www.stats.gov.cn/tjsj/ndsj/2017/indexeh.htm) to the six GGM nodes in China. This allowed calculating regional shares in production (respectively consumption) for the different years. These shares are multiplied by the Chinese production (respectively consumption) reference value from the relevant WEO outlook.

1.1.10.5 India

We have assigned state level production published by the Ministry of Petroleum and Natural Gas (Source: http://petroleum.nic.in/indian-petroleum-and-natural-gas-statistics) to the four GGM India regions. This allowed calculating regional shares in production for the different years. These shares are multiplied by the Indian production reference value from the relevant WEO outlook. Consumption was calculated according to the share of total GDP. Again, these shares are multiplied with the Indian consumption reference value from the relevant WEO outlook.

Files data_calib.xlsx

There is a data_calib.xlsx for each scenario.

Calibration

Calibration is the process to reconcile model outputs with reference values by means of input data adjustments. In the process, one should take care to make logical and transparent choices, and maintain consistency. Parameter choices should still make sense if, for instance, in a different scenario or a what-if analysis, a country would not be an exporter but an importer. In contrast to perfectly competitive market models, multi-country oligopolistic market models are generally much harder to calibrate. Calibrating the GGM for a new scenario takes an experiences analyst at least several days. Especially after a major revision of the input data set this may extend to several weeks.

In the calibration of GGM we have focussed on annual production and consumption values, for individual countries in the EU and other European countries, and at the regional level in the rest of the world. The parameters adjusted in the calibration are production costs and capacities, reference prices, and market power assumptions. We have, e.g., not adjusted price-demand elasticities in the calibration. The model creates regional and country-level calibration reports showing the differences between model outcomes and reference values.

Given that reference production and consumption values must be consistent, if global consumption is too low (high), global production must also be too low (high). Let’s consider a few examples:

- If, for example, Russia does not produce enough (its production is lower than the reference value) but its consumption is high enough. That means its exports are too low. This can be due: 1) too high production costs, 2) too low willingness to pay in export markets, 3) too high market power of Russia.
- If, for example, China does not consume enough in a future year, it may be due to 1) too low domestic production, 2) too low willingness to pay, 3) too high market power level of exporters, 4) too high investment costs for pipelines or regasifiers, 5) too low expansion limits on infrastructure expansions, or 6) too high production costs in exporting countries.

Because of trade, the global market is a system of communicating vessels. Lowering production costs in one country will spill over internationally and increase consumption in many regions – albeit if often by modest amounts.

Which parameter values to adjust is up to some extent arbitrary. The analyst needs to combine market knowledge with model expertise and trade off choices.

We usually calibrate the base year by itself. This way we create a good foundation for costs, prices and market power assumptions with a model that solves quickly. Once the model reproduces the base year adequately close, we start calibrating future years.

There are many good and defendable ways to adjust parameter values and calibrate a model. There are also many wrong ways to calibrate a model. A wrongly calibrated model may give biased results for a scenario analysis hat are not due to modelling and market logic but due to invalid parameter choices.

Table 17: Sheets in workbook data_calib.xlsx

Sheet	Description
Readme	
GlobLoss	Account for value chain losses and mismatches in outlooks
PCapCalib	Production capacity parameters adjustments
PCostCalib	Production cost parameters adjustments
PriceCalib	Price /Willingness to pay adjustment parameters

Reconciling value chain losses

Most outlooks, including IEA WEO, project the same global production and consumption levels for future years. GGM accounts for losses. Losses in pipelines, the LNG value chain and storages. To account for this, we reduce the yearly consumption values in non-European countries by some percentage. We have chosen to only do this for non-European countries so that model outcomes for consumption would match demand projects by PRIMES and SET-Nav. Since international trade, and especially the amount of LNG traded, varies significantly among scenarios, the consumption reductions have to be calibrated by scenario.

Table 18 describes the contents of sheet GlobLoss in workbook data_calib.xlsx

Table 18: GlobLoss

Column	Description	Source
Year	Percentage deduction for consumption of non-European countries to account for inconsistencies in different outlooks and losses in global value chains.	Tuned during calibration of specific scenario

See section 6.2 below to see how GlobLoss is used.

Production calibration

Detailed and consistent production cost and capacity data is not available. We derive input values for production costs and capacities based on own assumption supported by some available information. The file “production costs some data points v0 20190408-RE.docx” presents some of this information.

Every production node in GGM has several calibration parameters for costs, and for capacities. These values vary by scenario and are stored in the file data_calib.xlsx, in folder data\SET-Nav\<scenario>.

For each resource at each production node, we indicate the share of the resource in the total production capacity at the node, and the slack percentage by which the capacity should be higher than the reference production. Table 19 indicates the columns in the capacity calibration sheet.

Table 19: PCapCalib

Column	Description	Source
Region	Auxiliary	Own creation
Node	Production node	Own creation
R1,R2,R3	Share of resource in total capacity	Own creation
2015-2060	Multiplication factor applied to reference production to calculate production capacity	Own creation, tuned during calibration

When removing the logarithmic (so-called Golombek) production function from a previous GGM version we have established a linear approximation and introduced multiple resources (at the moment three: R1, R2, R3, but this can be easily adjusted). To allow a steep cost increase close to capacity, in line with *Golombek*, we choose a steep cost curve for a modest capacity (R3). We assign values to R1 so that significant amount is produced virtually always, and to R2 to reflect the rest. The actual value choices for capacities and costs together determine the cost curve. The capacity shares are therefore somewhat arbitrary. For convenience, to limit the degrees of freedom and increase transparency, we have assigned the same resource capacity shares to all countries. R1: 50%, R2: 46% and R3: 4%. In the further calibration, we have only adjusted cost parameters

Based on experience, slack capacities should be at least a few percent, but not more than 7-10%. Values used are in the 3%-5% range, leading to multiplication factors in the 1.03-1.05 range.

Some data suggests that Russian *marginal production cost* are in the range € 25-35 / kcm.[17] For the USA, marginal supply costs vary around $ 70-100 / kcm, or € 60-85 / kcm.[18] Parameter values should reflect that marginal cost are the cost of the most expensive well with active production. To limit the degrees of freedom, we have chosen to adjust one value “base cost” for each production node in the calibration and use identical multiplication factors to calculate different parameter values used (Ref Section 6.1). Table 20 shows the columns in the cost calibration sheet.

Table 20: PCostCalib

Column		Description	Source
	Region	Auxiliary	Own creation
	Node	Production node	Own creation
base	cost	Marginal cost of the first unit	Own, tuned during base year calibration
R1-R3	c	Multiplication factor for lowest marginal cost of the resource	Own creation, See Section 6.1 for calculation explanations.
R1-R3	q	Multiplication factor for highest marginal cost of the resource	Own, See Section 6.1 for calculation explanations.
y	2015	1	Base year values
y	2020-2060	Cost adjustment factor	Own, tuned during scenario calibration

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[17] E.g., https://eegas.com/rep2017q2-prod-e.htm Accessed 8 Apr 2019

[18] www.eia.gov/dnav/ng/ng_pri_sum_dcu_nus_a.htm, www.eia.gov/dnav/ng/hist/rngwhhdm.htm, www.eia.gov/todayinenergy/prices.php, www.eia.gov/dnav/ng/hist/n9190us3m.htm (8 Apr 2019)

A small capacity share but high cost value for (R3,q) allows a very steep increase in the last part of the production cost function, similar to the Golombek cost function.

See section 6.1 below to see how production calibration parameters are used to calculate input values in the model implementation.

Consumption calibration

For each consumption node, the model calculates an inverse demand curve for every season, based on reference consumption, price, seasonal loads, sector shares, and sectoral price-demand elasticities.

We do not have price information for many countries. Market prices vary over time and are rather independent from actual consumption levels, partly due to contracts and index pricing still strongly correlated with crude oil prices. We wish the model to reflect prices that are relatively close to real world prices, but not too dependent on the base year of the model.

Table 21 Selected gas prices (Based on BP 2018, using conversion 38 MMbtu/cm)

	LNG		Natural gas				
	Japan	Japan / Korea	Germany	UK	Netherlands	USA	Canada
2013	$ 614	$ 629	$ 408	$ 404	$ 371	$ 141	$ 111
2014	$ 621	$ 527	$ 346	$ 314	$ 309	$ 165	$ 147
2015	$ 392	$ 283	$ 255	$ 248	$ 245	$ 99	$ 76
2016	$ 264	$ 217	$ 187	$ 178	$ 173	$ 94	$ 59
2017	$ 308	$ 271	$ 213	$ 221	$ 217	$ 112	$ 61

Table 22 GGM references prices 2015 selected countries

Consumption node	Price €/kcm
CAN_E	80
CAN_W	50
USA[18]	70 - 95
DEU	160
GBR	160
NLD	155
JPN	215
KOR	200

The sectoral price-demand elasticities are the same for every country. (See section 3.1.2 , Table 6). Sector shares and seasonal loads are stored in the file data.xlsx for non-EU countries (See Section 3.2) and in data_proj.xlsx for EU-countries (see Section 4.1.4). Other parameters for calibrating consumption are included in Table 23.

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Files data_calib.xlsx

Table 23 PriceCalib

Column	Description	Source
Region	Auxiliary	
Node	Consumption node	Own creation
price	Reference price	Tuned during calibration of base year 2015
L,H,P	Seasonal multiplication factor for reference price	Own creation
2015	1	2015 price should be the one in column “price”
2020-2060	Multiplication factor for reference price	Tuned during calibration of specific scenario
Hemisphere	Auxiliary	To provide default seasonal price adjustments

Parameter value calculations

GAMS file in_prod.gms

Calculation of production capacity and production cost function parameters, cost_pl and cost_pq in $c(q_{nrdy}) = \mathrm{cost}_{\mathrm{pl}}.\, q_{nrdy} + cost_{pq}.\, (q_{nrdy})^2$.

Table 24 Input parameters determined in in_prod.gms

Parameter	Description	Calculation
ref_p(n_p,y)	Reference production level in mcm/d	Transform bcm/y to mcm/d
cap_p(n_p,r,y)	Production capacity by resource	Reference production plus a margin for slack
cost_pl(n_p,r,y)	Constant term in unit production costs	See below
cost_pq(n_p,r,y)	Linearly increasing term in unit production costs	See below

Given the scenario choice for EU data (parameter %SET-Nav%) and non-EU data (parameter %WEO%), the production is read from data_proj.xlsx. The model code transforms bcm/y to mcm/d by multiplying by 1000/365 = 1/0.365

As described above in Section 5.3 for each resource at each production node, we indicate the share of the resource in the total production capacity at the node, and the slack percentage by which the capacity should be higher than the reference production:

NODE	R1	R2	R3	2015	2020
USA_2	0.50	0.46	0.04	1.05	1.05
USA_3	0.50	0.46	0.04	1.03	1.03

Now, for instance, for USA_2: resource R1 accounts for 50% of the total production capacity. The slack percentage is 5% in years 2015, 2020, etc.… For USA_3, resource R3 accounts for 4% of total production capacity. The slack percentage is 3% in years 2015, 2020, etc…

If for a production node the reference production is 100 mcm/d, with an R1 capacity share of 0.50 and 5% slack, the production capacity of resource R1 at that production node is 100x0.5x1.05=52.5 mcm/d.

To calculate the linear and quadratic cost terms in each year for each resource at each production node, we apply multiplication factors to the base cost.

		"linear"			"quadratic"				
	base	R1	R2	R3	R1	R2	R3	y	y
	cost	c	c	c	q	q	q	2015	2020
USA_2	12	1	1	1	1	5	8	1	1.15

An example of the relation between multiplication factor values and marginal costs.

USA_2, Base cost = 12

- R1
    - Multiplication factor (R1,c)=1, MC(R1) first unit: 12x1=12
    - Multiplication factor (R1,q)=1, MC(R1) at full capacity: 12x1=12
- R2
    - Multiplication factor (R1,c)=1, MC first unit: 12x1=12
    - Multiplication factor (R1,q)=5, MC(R2) at full capacity: 12x5=60
- R3
    - Multiplication factor (R1,c)=1, MC first unit 12x1=12
    - Multiplication factor (R1,q)=8, MC(R3) at full capacity: 12x8=96

USA_2, in 2020. Multiplication factor (y,2020): 1.15

- This multiplication factor is applied in addition to the cost inflator (see Section 3.1.3). Assuming this is 3%, and five year periods:
- MC(R3) at full capacity: 12x8x1.15x$(1.03)^5$ = 127.9838578

GAMS file in_cons.gms

Calculation of intercept and slope of demand curves: $p(q_{ndy}) = int_{ndy} - slp_{ndy} \sum_t q_{tndy}$ (with t the supplier index)

Table 25 Input parameters determined in in_cons.gms

Parameter	Description	Calculation
ref_c(n_c,y)	Reference consumption level in mcm/d	Transform bcm/y to mcm/d, adjust for losses; see below
slp(n_c,d,y)	Slope of the seasonal inverse demand curve	See below
int(n_c,d,y)	Intercept of the seasonal inverse demand curve	See below

As discussed in Section 5.2, we combine outlooks for the EU gas market developed with PRIMES and in SET-Nav with IEA WEO outlooks for the global market. The net imports by the EU in the EU outlooks do not necessarily match the net exports to the EU in the WEO outlooks. Additionally, outlooks ignore value chain losses. When determining reference consumption values in GGM we account for both discrepancies.

In in_prod.gms, we calculate ref_p_glob(y), the global aggregate reference production.

In in_cons.gms, we calculate ref_c_glob(y), the global aggregate reference consumption.

GlobLoss is read from data_calib.xlsx (See Section 5.2).

Given the scenario choice for EU data (parameter %SET-Nav%), and for other countries (based on parameter %WEO%) the reference consumption is read from data_proj.xlsx.

For all countries, the bcm/y values are transformed to mcm/d values.

For countries not in EU or Other European, we adjust the reference consumption values to account for global losses and the outlooks mismatch by using the following multiplication factor:

(1-l_glob(y))* ref_p_glob(y)/ref_c_glob(y).

By adjusting global loss percentages in the calibration, the reference values for consumption can be adjusted further if necessary.

To calculate the seasonal, country level demand curves, we determine:

Seasonal sector load: country load * sector share * seasonality.

Reference price:

[base year price] * [seasonal adjustment] * [price inflator] * [calibration adjustment]

Reference consumption:

EU: [reference year] * [seasonal sector share for specific year]

Other: [reference year] * [seasonal adjustment] * [sector share]

Seasonal sector intercept: int = price_ref * (1-1/elas) $int_{nkdy} = p_{ndy}^{ref}\left(1-\frac{1}{\epsilon_k}\right)$

Seasonal sector slope: slp = -price_ref / (elas*cons_ref) $slp_{nkdy} = \frac{-p_{ndy}^{ref}}{\epsilon_k Q_{nkdy}^{ref}}$

The seasonal sector slopes and intercepts are aggregated to country level slopes and intercepts[19]:

slp(n_c,d,y) = (1/SUM(k,1/dsss(n_c,k,d,y))); $slp_{ndy} = \frac{1}{\sum_k \frac{1}{slp_{nkdy}}}$

int(n_c,d,y) = slp(n_c,d,y) * SUM(k, dssi(n_c,k,d,y)/dsss(n_c,k,d,y)); $int_{ndy} = slp_{ndy} \sum_k \frac{int_{nkdy}}{slp_{nkdy}}$

GAMS file in_arcs.gms

This file calculates capacities, operational and investment costs, losses, and allowable expansions. The code also assigns specific sets, arc types, start and end nodes of arcs, etc.

Note that the table continues at the next page.

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[19] This is an approximation, as the actual aggregate inverse demand curve is piecewise linear.

Table 26 Input parameters determined in in_arcs.gms

Parameter	Description	Calculation
l_a(a)	Loss rate on arc	Pipelines: length x loss rate per unit of distance Liquefiers: identical input value for all Regasifiers: : identical input value for all Vessels: length x loss rate per unit of distance
cap_a(a,y)	Exogenous arc capacity in specific year	Read from input table, transformed from bcm/a to mcm,/d, and corrected with loss percentage assuming that capacities are output based
cost_a(a,y)	Operational arc costs in specific year	Pipelines: length (onshore/offshore) x base cost per unit of distance x cost inflator Liquefiers: identical input value for all, possibly calibration adjustment x cost inflator Regasifiers: identical input value for all, possibly calibration adjustment x cost inflator Vessels: length x cost per unit of distance x cost inflator
inv_a(a,y)	Arc unit investment costs per mcm/d	Pipelines: based on length, onshore/offshore, and cost per unit (see Section 3.1.1), calibration adjustment, and loss adjustment (see cap_a), x cost inflator, scaled by number of years between two periods. Liquefiers and regasifiers: the same calculation as for pipelines, but with length=1 and no offshore part. (See 3.1.1)
d_a_max	Maximum allowable arc expansion	First stage, second stage, all later stages. (Note a one period gap between investment decision and availability of newly invested capacity.)

GAMS file in_stor.gms

Calculations of capacities (both working gas and extraction), operational and investment costs, injection losses, and allowable expansions. The code also assigns specific sets, arc types, start and end nodes of arcs, etc.

Table 27 Input parameters determined in in_stor.gms

Parameter	Description	Calculation
l_i(n,w)	Loss rate on injection	Fixed input value dependent on type w
cap_x(n,w,y)	Exogenous extraction capacity (in specific year)	Read from input table, in mcm/d
cost_x(n.w.y)	Operational extraction costs	Read from input table, adjusted by cost inflator and calibration adjustment.
inv_x(n,w,y)	Extraction capacity unit investment cost	Basic input value, adjusted by cost inflator and calibration adjustment, scaled by number of years between two periods.
cap_w(n.w.y)	Working gas capacity	Read from input table, in mcm, adjusted by number of days in low demand season to account for possible use of representative periods rather than full periods
inv_w(n,w,y)	Working gas investment costs	Read from input table, adjusted by cost inflator and calibration adjustment, scaled by number of years between two periods.
d_x_max	Maximum allowable extraction expansion	Second and later stages. (Note a one period gap between investment decision and availability of newly invested capacity.)
d_w_max	Maximum allowable	Second and later stages.

	working gas expansion	

GAMS file in_market.gms

Calculation of supplier node, resource access, and market power exertion parameters. Suppliers do not have or do not need access to all nodes. E.g., a supplier does only need access to its own liquefiers. If it has no liquefier, it does not need access to regasifiers. You may limit market access which we did in earlier model versions to reduce the model size. However, it seems that does not affect calculation times (anymore). Hence, all suppliers get access to all consumption nodes, even if they cannot reach them (e.g. USA would not need access to Russia or Australia).

Concerning market power exertion parameters, see Section 3.6.

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Appendix A: How to Run GGM?

The Global Gas Model (GGM) is a partial equilibrium model to analyze the investment decisions in gas transportation and storage infrastructure and volumes of production, consumption, and trade, while considering market power. The model is currently set up for a time horizon up to the year 2050 in steps of five years. It is written as a quadratic program, and implemented in GAMS as a quadratically constrained program (QCP) solved with CPLEX.

The model serves to analyze the consequences of long-term projections of consumption and production values of the global natural gas market on infrastructure investments and trade. The model requires a sophisticated calibration and is thus to be handled with caution. Any changes in the code or data should be based on profound economic and modelling knowledge.

Version and license

GGM in short

Note that the table continues at the next page.

GGM	▪ A multi-period model for analyzing the world natural gas market. ▪ Country level; with large countries disaggregated (USA, CAN, RUS, CHN, IND). ▪ Focus on infrastructure investment and trade, taking into account market power. ▪ Production, pipelines, liquefaction, regasification, shipping, storage. ▪ Implemented in GAMS. ▪ Input data files are MS Excel workbooks.
Inputs	(Country and sub-country level) ▪ Reference values for production, consumption, prices, market power for base year and future years' projections.

	▪ Capacities, investment and operational costs, depreciation and loss rates of production, transportation, and storage infrastructure. ▪ Demand seasonality, sector shares and elasticities, production costs.
Outputs	(Country and sub-country level) ▪ Pipeline, liquefaction, regasification, storage expansions and utilization. ▪ Seasonal production, consumption, trade and prices. ▪ Sector profits, costs, consumer surplus and social welfare impacts.

Model structure

GGM is a multi-period optimization model determining the expansion of transportation and storage capacities given detailed characteristics for production, consumption and infrastructure, considering the global context. Over 90 countries distributed over nine world regions are incorporated in the data set. The current data set considers 109 consumption nodes, 93 production nodes, 50 storage nodes as well as 28 LNG liquefaction and 50 regasification nodes. Reference data points for production and consumption are exogenously determined, as is market power which is considered for some exporting countries. Infrastructure capacities are exogenously given but can be endogenously expanded.

Folder structure

The code files and data files that make up the GGM are distributed over several file folders. The main folder of the (deterministic) GGM contains several subfolders.

- *data* contains all input data files. See below for an overview of what these files contain.
- *gdx* contains the intermediate and output files of the model in the .gdx format. This is the GAMS data exchange format from which the results can be further processed.
- *model* contains the GAMS files with the model equations and the solve statement.
- *reports* includes the GAMS files for the reporting of the model results.
- geo_map *contains scripts and files for a plotting and mapping of model results*
- *excel* contains output files in xlsx format.

Model files

To structure the entire model code, different GAMS files are specified for specific purposes. The following table connects the relevant GAMS files on the left with a short contextual description on the right. Note that the table continues at the next page.

GAMS file	Description
main.gms	Main model file from which the model is run
__READ_ME.txt	License file
create_excel_dumps.gms	Transfers calibration results, results for the IIASA IAMC platform, and results for the geo-maps tool to MS Excel files.
merge_gdx_files.gms	Merges results from different scenarios and transfers them to MS Excel.
DATA	
2015.gms, 2060.gms	Definition of the years set
all_input_data.gms	File from which all other data files are included
in_arcs.gms	Definition and declaration of all transportation (“arc”) data, i.e.

	pipelines, liquefiers, shipping, regasifiers
in_cons.gms	Preparation of all consumption data
in_market.gms	Definition of market access and market power
in_prod.gms	Preparation of all production data
in_sets_parms.gms	Declaration and processing of all sets and parameters
in_stor.gms	Preparation of all storage data
MODEL	
all_eq_and_var.gms	All model equations and variables
solve.gms	Solve statement
REPORTING	
report.gms	Calculates report values and transfers them to gdx files .

Model input

As described in previous sections of this document, this version of the model uses three MS Excel input files.

Table 28 MS Excel workbooks with input data

File name	Location	Type of data	Comment
data.xlsx	data\set-nav	Scenario independent data	
data_proj.xlsx	data\set-nav	Future projections consumption and production by scenario + EU demand sector shares and demand seasonality	Seasons and sectors non-EU are in data.xlsx
data_calib_<scenario>.xlsx	data\set-nav\	Calibration data for production and consumption	<scenario> is currently SDS-Vision or NPS-Ref

d*ata.xlsx* contains input data in corresponding sheets (see Section 3 for more details):

- *N* for all data concerning nodes;
- *A* for all data concerning arcs, i.e. pipelines, LNG and regasification terminals;
- *V* for all data concerning vessels, i.e. shipping distances;
- *W* for all data concerning storage capacities;
- *M* for all data concerning market power; and
- *Other* for all other data.

Model execution

To run the model, follow these steps:

1. Install GAMS with a license that can solve QCP.
2. Open the *_GGM.gpr* file in the main folder. This is the GAMS project file, and opening it by double clicking correctly sets the working directory.
3. Use “CTRL+o” to open new files, then double click the file *main.gms*. This is the main file of the model and includes all data processing, model set up, and reporting files.
4. On lines 17-20 of *main.gms* select the scenario that should be analyzed.
5. To run the model, select a scenario and press *F9.*
6. If desired, open, select a scenario and execute create_excel_dumps.gms
7. If desired, open and execute merge_gdx_files.gms

Model output reports and suggested gdx layout

The output of this model version includes six types of gdx reports. The report generating code for these is found in the folder *reports.* This is included by the file *main.gms* when the model is run via the include file *reports.gms*. Formatted Excel reports can be created using *create_excel_dumps.gms* or *merge_gdx_files.gms.*

1.1.11 Mass balances

rep_mass_bal.gms shows the mass balances, i.e. it depicts the consumption, production, incoming and outgoing pipeline and LNG flows, storage injections and extraction, and market prices and marginal production costs on country (yearly, bcm) and node level (seasonal, mcm/d). Using drag and drop, the layout of gdx files in the GAMS interface can be adjusted. Suggested layout:

Table 29 Country mass balance

				+					-					0
				Prod	pipe	LNG	stor	TOT	Cons	pipe	LNG	stor	TOT	price
RUS	RUS	RUS	2015	642	428		48	1119	447	609	14	49	1119	74
RUS	RUS	RUS	2020	693	345		24	1062	445	543	50	24	1062	79
RUS	RUS	RUS	2025	718	349		24	1091	446	570	51	24	1091	83
RUS	RUS	RUS	2030	749	384		24	1157	430	651	51	24	1157	96

Table 30 Nodal mass balance

					+					-					0	
					Prod	pipe	LNG	stor	TOT	Cons	pipe	LNG	stor	TOT	price	MC
RUS	RUS	RUS_E	2015	L		69			69	69				69	92	
RUS	RUS	RUS_E	2015	H		57			57	57				57	92	
RUS	RUS	RUS_E	2015	P		50			50	50				50	107	
RUS	RUS	RUS_S	2015	L	37				37			37		37		24
RUS	RUS	RUS_S	2015	H	37				37			37		37		24
RUS	RUS	RUS_S	2015	P	37				37	0		37		37		24
RUS	RUS	RUS_VU	2015	L	108	1235		148	1491	948	543		0	1491	75	75
RUS	RUS	RUS_VU	2015	H	108	1107		0	1215	822	167		227	1215	74	74
RUS	RUS	RUS_VU	2015	P	108	756		0	864	813	45		6	864	75	75
RUS	RUS	RUS_W	2015	L	1637			115	1752	301	1452		0	1752	70	70
RUS	RUS	RUS_W	2015	H	1611			0	1611	255	1356		0	1611	67	67
RUS	RUS	RUS_W	2015	P	1556			0	1556	267	945		344	1556	63	63
RUS	RUS	RUS_E	2020	L		70			70	70	0			70	95	

1.1.12 Calibration

rep_calib.gms depicts the calibration results on country and region level, in billion cubic meter (bcm). The report shows reference values and model outcomes for production and consumption, and absolute and relative deviations. Showing % is only possible when data are transferred or copied to MS Excel.

Table 31 Country calibration

			Cons	Cons	Cons	Cons	Prod	Prod	Prod	Prod
			Ref	out	abs	rel	Ref	out	abs	rel
RUS	RUS	2015	446	447	2	0%	638	642	4	1%
RUS	RUS	2020	443	445	2	0%	681	693	12	2%
RUS	RUS	2025	444	446	2	0%	718	718	0	0%
RUS	RUS	2030	449	430	-19	-4%	730	749	19	3%
RUS	RUS	2035	454	430	-25	-5%	752	769	17	2%

Table 32 Region calibration

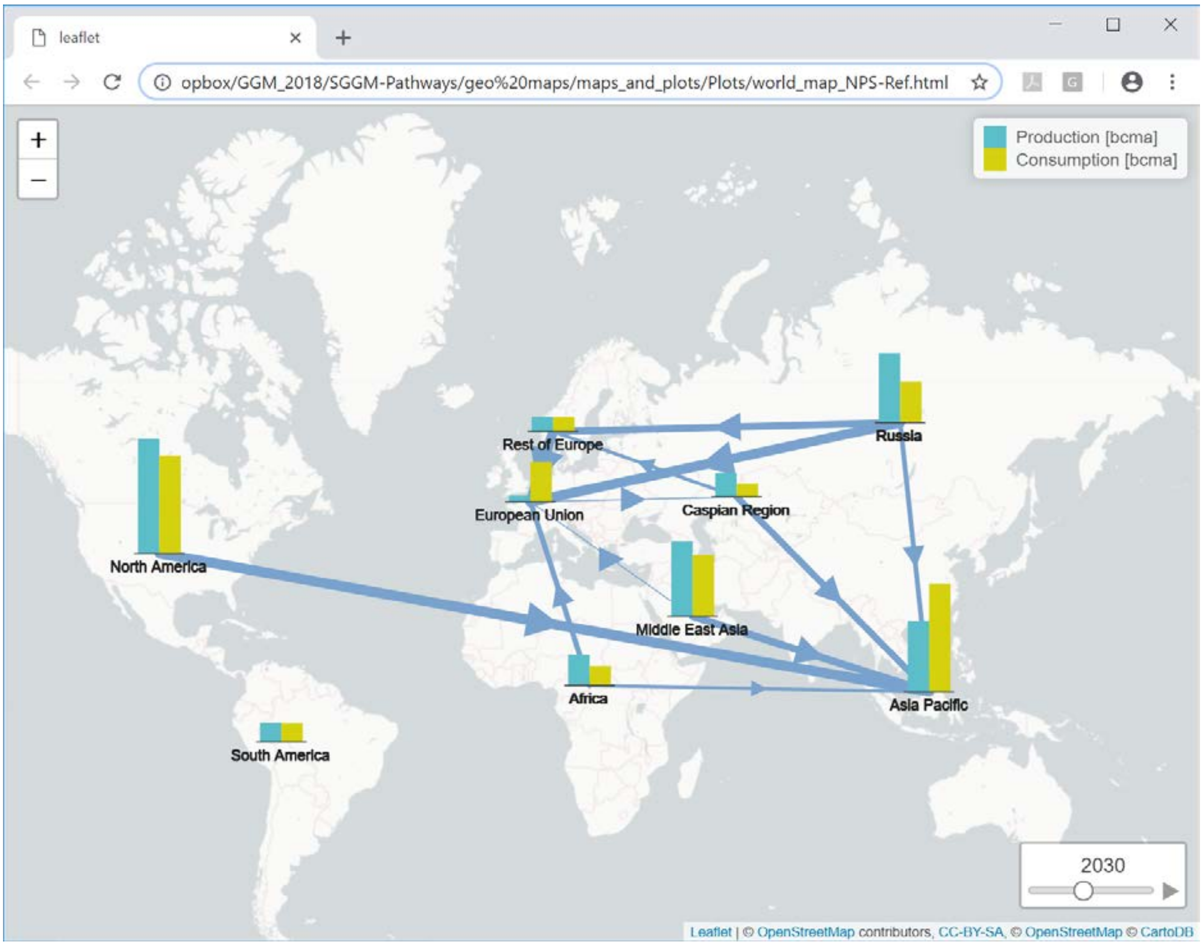
		Cons Ref	Cons out	Cons abs	Cons rel	Prod Ref	Prod out	Prod abs	Prod rel
EU	2015	442	445	3	1%	131	132	1	1%
EU	2020	375	380	5	1%	98	97	0	0%
EU	2025	320	324	4	1%	82	80	-2	-2%
EU	2030	269	272	2	1%	66	65	-1	-2%
EU	2035	239	241	1	1%	59	59	0	0%

1.1.13 Geo maps tool

rep_geo_map.gms details results on the production, consumption, trade and capacities.

		Cons	Prod	pipe	LNG	trade	captot-P+	captot-P-	captot-L	captot-R	captot-WG	Cons
		2015	2015	2015	2015	2015	2015	2015	2015	2015	2015	2020
RUS	RUS	447	642	-181	-14	-195	485	854	14		74	Etc.
NAM	CAN	99	163	-63		-63	136	283			20	Etc.

File create_excel_dumps.gms will generate an MS Excel file that after some additional steps, see below, can be read by the Geo map tool (an R-script), to show results such as:



The outcome of the Global Gas Model (GGM) is processed in an R Script in order to generate some visualization tools and standard result graphs. See folder GGM/geo_map; *WorldMaps_ProjectFile.Rproj* and *readme_maps-plots.html*. The general workflow is as follows:

- Model optimization and generation of an output file from GAMS
- Processing of Data in R for visualization purposes
- Generation of plots and maps in R

1.1.14 Steps for generating html-plots with R to visualize GGM results

1. Install R and R Studio, e.g., from
    - https://cran.r-project.org/bin/windows/base/
    - https://www.rstudio.com/products/rstudio/download/
2. Open the project file *WorldMaps_ProjectFile.Rproj* located in folder GGM/geo_map (R Studio will open)
3. Open these four scripts in this order and run each of them separately using Ctrl + Alt + R[20, 21]

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[20] This may take a while when executed for the first time. R will download and install all necessary packages.

        - *data_file_generation_maps.R*
        - *plot_design_characteristics.R*
        - *static_plots_Europe.R*
        - *static_plots_REGIONS.R*

        Execution is finished showing "End of execution" in the Console

4. No errors? Perfect!! / Errors? the web might find a solution
5. Check for files in folder GGM/geo_map. You will find all plots and maps here (9 pdf files and 4 html files).
    - The html files show numerical information when clicking on bars or arrows.

More details on these steps in "*readme_maps-plots.html*"

We advice to test the code using the existing input data files. Once the code executes without problems, new input data can be used. In order to do so, renew the .csv files rep_geo_map_<scen>.csv (for consumption and production) and rep_geo_map_<scen>_flow (for trade). The GAMS file "create_excel_dumps.gms" can be used to generate new MS Excel files, which are the basis for the csv input files used by the R-scripts. Open the relevant xlsx file in the folder GGM/geo_map. Click worksheet *rep_geo_map*. Choose File/Save As. Select .csv. Choose the name of the existing csv file that should be overwritten. E.g.,

*SET-Nav_**NPS**-Ref_2060_rep_geo_map.xlsx*, rep_geo_map replaces "rep_geo_map_**NPS**.csv" and rep_geo_map_flow "rep_geo_map_**NPS**_flow.csv". Go to Step 2 in the list above "Open the project file *WorldMaps_ProjectFile.Rproj* located in folder GGM/geo_map (R Studio will open)" in the list above and follow the steps to update the pdf-plots and maps.

WARNING: The files "countries_middle_lat_lon.csv" and "geo_data.csv" contain crucial information to create the plots. One may replace them with the same type of information and structure if necessary.

1.1.15 Infrastructure

rep_infra.gms calulates the infrastructure expansions, capacities in million cubic meters per day at the country level; working gas storage expansions are in mcm, as well as utilization rates. The reports (rep_infra_pipe, rep_infra_liq, rep_infra_regas, rep_infra_stor) account for gross and loss rate adjusted capacity expansions.

You obtain the following tables by region, country, year:

---

[21] If only a chunk of the code needs to be run, mark the code and press Ctrl + Enter; for only one line, move the cursor to the line and press [RUN]

Table 33 Liquefaction infrastructure

			capexog	expans	expcum	captot	capnet	usage	usage-L	usage-H	usage-P	util%
NAM	USA	2015	0.62			0.62	0.56	0.62	0.62	0.62	0.62	100%
NAM	USA	2020	138.5	26.7		138.5	124.7	105.8	126.5	118.5	20.4	76%
NAM	USA	2025	138.5	3.4	26.7	165.2	148.7	134.7	153.2	153.2	44.2	82%
NAM	USA	2030	138.5	0.6	30.0	168.5	151.7	146.2	168.5	156.5	60.1	87%
NAM	USA	2035	138.5	0.0	30.6	169.1	152.2	153.2	169.1	157.1	98.3	91%

Table 34 Regasification infrastructure

			capexog	expans	expcum	captot	capnet	usage	usage-L	usage-H	usage-P	util%
ASP	CHN	2015	55.8			55.8	55.0	17.9	12.9	23.9	21.1	32%
ASP	CHN	2020	84.6			84.6	83.4	37.4	30.4	47.5	38.6	44%
ASP	CHN	2025	84.6	0.0		84.6	83.4	56.5	51.4	67.3	50.8	67%
ASP	CHN	2030	84.6	3.9	0.0	84.6	83.4	65.8	64.8	69.9	60.7	78%
ASP	CHN	2035	84.6	21.1	3.9	88.5	87.2	73.8	73.8	73.8	73.8	83%
ASP	CHN	2040	84.6	19.2	25.0	109.6	108.0	94.8	94.8	94.8	94.8	87%
ASP	CHN	2045	84.6	11.8	44.2	128.8	126.9	114.1	114.1	114.1	114.1	89%
ASP	CHN	2050	84.6	0.0	56.0	140.6	138.5	125.8	125.8	125.8	125.8	89%

For pipeline infrastructure, the table includes more details, namely on the bilateral pipeline links. Hence, the following table is by outgoing region and country, and ingoing region and country, and year:

Table 35 Pipeline infrastructure

					capexog	expans	expcum	captot	capnet	usage	usage-L	usage-H	usage-P	util%
RUS	RUS	EU	DEU	2015	57.2			57.2	55.0	47.5	57.2	57.2	0	83%
RUS	RUS	EU	DEU	2020	114.3			114.3	110.0	94.9	114.3	114.3	0	83%

Table 36 Storage infrastructure

				extr								WG						
				capexog	expans	expcum	captot	usage-L	usage-H	usage-P	delmax	capexog	expans	expcum	captot	usage	delmax	util%
RUS	RUS	Seas	2015	568.8			568.8	263.1	0	0		74200			74200	48152.8		65%
RUS	RUS	Seas	2020	571.2			571.2	114.9	0	46.8	19998	74200	0		74200	23925.5	15000	32%
RUS	RUS	Seas	2025	571.2			571.2	114.9	0	47.7	19998	74200	0	0	74200	23984.4	15000	32%

1.1.16 IIASA platform IAMC

As part of the SET-Nav project, IIASA set up an updated version of its model result reporting platform IAMC (https://data.ene.iiasa.ac.at/set-nav/). We uploaded the results of the GGM model runs of the SET-Nav pathways to the IIASA platform. For this, we created specific reporting files.

rep_IAMC.gms calculates market prices and volumes, total capacities and expansions as well as utilization rates specifically for upload to the IIASA data platform. Units are €/kcm and bcm. It also calculates regional trade flows (bcm) specifically for upload to the IIASA data platform.

For each country and year:

GGM item	Value	Description	Unit
Cons	0.0	Annual consumption	bcm
Prod	0.0	Annual production	bcm
price	€ -	nominal prices	EUR /kcm
pipe	0.0	Net pipeline trade	bcm
LNG	0.0	Net LNG trade	bcm
stor	0.0	Storage usage	bcm
trade	0.0	Net trade	bcm
captot-P+	0.0	Net pipeline import capacity (exogenous and endogeous)	bcm
captot-P-	0.0	Net pipeline export capacity	bcm
captot-L	0.0	Net LNG export pipeline capacity	bcm
captot-R	0.0	Net LNG import capacity	bcm
captot-WG	0.0	Net storage working gas	bcm
pipe+	0.0	Pipeline import	bcm
LNG+	0.0	LNG import	bcm
pipe-	0.0	Pipeline export	bcm
LNG-	0.0	LNG export	bcm
trade+	0.0	Net import	bcm
trade-	0.0	Net export	bcm
capexog-P+	0.0	Exogenous pipeline import capacity	bcm
capexog-P-	0.0	Exogenous pipeline export capacity	bcm
capexog-R	0.0	Exogenous LNG import capacity	bcm
capexog-L	0.0	Exogenous LNG export capacity	bcm
capexog-WG	0.0	Exogenous working gas capacity	bcm
util-P+	0%	Utilization rate of import pipelines	Percentage
util-P-	0%	Utilization rate of export pipelines	Percentage
util-R	0%	Utilization rate of regasifiers	Percentage
util-L	0%	Utilization rate of liquefiers	Percentage
util-WG	0%	Utilization rate of storage working gas	Percentage

In existing, pre-formatted Excel files for upload, such as “SET-Nav_<Scenario>_2060_rep_IAMC.xlsx”, the sheet Lists contains the mapping from GGM report items to the “reporting hierarchy” used in the platform.

Appendix B: Mathematical Model Formulation

This section presents the mathematical formulation of the deterministic Global Gas Model. It is a revised version of the model presented in: Egging (2013).

Notation and units of measurement

Volumes & capacities in billion m^3 per year (bcm/y)

Costs & prices in € / 1000 m^3 (= €/kcm), which is the same as million € per billion m^3 (M€/bcm).

Flow-based infrastructure expansion costs in €/kcm/d/y (= M€/bcm/d/y). (Working gas) Volume-based expansion costs in €/kcm/y (= M€/bcm/y).

Table 37 Sets

Symbol	Description
A	Transmission arcs *a*
A_n^+	Inward arcs into node *n*
A_n^-	Outward arcs from node *n*
D	Seasons *d*
Y	Years *y*
N	Geographical nodes *n*
R	Production resource types *r*
W	Storage facility types *w*
T	Suppliers *t*
Z	Generalized Infrastructure and Infrastructure Services: A Arc Transmission (includes pipelines, liquefiers, LNG ships, regasifiers) I Storage Injection X Storage Extraction W Storage Working Gas
Z_n^+	Infrastructure services sourcing gas to the node. (Arc inflows and storage extractions)
Z_n^-	Infrastructure services taking gas away from the node. (Arc outflows and storage injections)

Table 38 Infrastructure Parameters

Symbol	Description
$c^P_{tnry}\left(q^P_{tnrdy}\right)$	Production costs (quadratic: $c^P_{tnry}\left(q^P_{tnrdy}\right) = c^P_{tnry} q^P_{tnrdy} + d^P_{tnry}\left(q^P_{tnrdy}\right)^2$)
c^Z_{zy}	Operational cost for infrastructure usage. *Z={A,I,X,W}*
$c^{\Delta Z}_{zy}$	Marginal costs for infrastructure expansion
CAP^P_{tnry}	Exogenous production capacity
CAP^Z_{zy}	Exogenous infrastructure capacity
$\overline{\Delta}^Z_{zy}$	Limit to endogenous infrastructure expansion
l^Z_z	Loss rate for *flow* by infrastructure service type
n^+_z	Geographical node receiving flow from infrastructure service
n^-_z	Geographical node sending flow into infrastructure service

Table 39 Market Parameters

Symbol	Description
cv_{tny}	Market power level (conjectural variation value)
d_d	Season length (number of days in season)
INT_{ndy}	Intercept of inverse demand curve
SLP_{ndy}	Slope of inverse demand curve
r_y	Discount rate

Table 40 Variables

Symbol	Description
Δ^Z_{zy}	Infrastructure capacity expansion
f^Z_{tzdy}	Supplier infrastructure service flow
q^P_{tnrdy}	Quantity produced
q^S_{tndy}	Quantity sold
π_{ndy}	Market price (auxiliary)

The partial equilibrium problem is set up as an optimization model. We present the optimization problems of the suppliers and consumers, the infrastructure costs and restrictions, and the market power adjustment (*MPA*) term. See Egging et al. (2018) to verify that this model solves the imperfect market equilibrium problem as intended.

Supplier

Suppliers are the central agents in the gas market model. They may produce from different resources at different geographical region nodes, and sell domestically or export to other markets. They purchase infrastructure services to transport and store gas. We present here the objective function of a perfectly-competitive supplier and show in a next section how to account for market power.

Suppliers maximize their Net Present Value (Eq. (9.1)): discounted r_y, season-length weighted d_d profits resulting from sales revenues minus costs for production and infrastructure services (transmission and storage).

$$\forall t \qquad \max_{q^S_{tndy},\, q^P_{tnrdy},\, f^Z_{tzdy}} \left[\sum_{d,y} r_y d_d \left\{ \sum_n \left(\pi_{ndy} q^S_{tndy} - \sum_r c^P_{tnry}\left(q^P_{tnrdy}\right) \right) - \sum_z c^Z_{zy} f^z_{tzdy} \right\} \right] \tag{9.1}$$

Production is restricted by a capacity limit (Eq. (9.2)). If a supplier does not have access to a resource type at a node, the relevant capacity value is zero. Nodal mass-flow balance must be maintained (Eq. (9.3)). In each storage cycle the loss-adjusted injections into storage must equal the extractions (Eq. (9.4)).

$$s.t. \qquad \forall t,n,r,d,y \qquad q^P_{tnrdy} \le CAP^P_{tnry} \tag{9.2}$$

$$\forall t,n,d,y \qquad \sum_r q^P_{tnrdy} + \sum_{z \in Z^+_n} \left(1 - l^Z_z\right) f^Z_{tzdy} = q^S_{tndy} + \sum_{z \in Z^-_n} f^Z_{tzdy} \tag{9.3}$$

$$\forall t,w,d,y \qquad \left(1 - l^I_w\right) \sum_d f^I_{twdy} = \sum_d f^X_{twdy} \tag{9.4}$$

We model neither reserves nor endogenous production capacity expansions.

All storages losses are borne by the injection activity. Injection losses are accounted for in Eq. (9.4). Consequently, extraction loss values in the model are assumed to be zero: $l^X_w = 0$ in Eq. (9.3).

Consumer surplus

Consumer surplus considers the area between the inverse demand curve and market price: the squared total supply in each consumption node times the slope of the inverse demand curve, weighted by discount rate and season length, divided by two:

$$CS = \tfrac{1}{2} \sum_{n,d,y} r_y d_d SLP_{ndy} \left(\sum_t q^S_{tndy} \right)^2 \tag{9.5}$$

Supplier market power

Suppliers may act competitively or exert market power with respect to end users. We apply a conjectural variation approach. Parameter $cv_{tny} \in [0,1]$ may vary by supplier, geographical node and year. A value of *0* implies perfectly competitive behavior; a value of *1* Cournot behavior, and values in between moderate levels of market power exertion. Consequently, the sales revenues term of a market power exerting supplier can be written as:

$$\left(cv_{tny} \left(INT_{ndy} - SLP_{ndy} \sum_{t'} q^S_{t'ndy} \right) + \left(1 - cv_{tny}\right) \pi_{ndy} \right) q^S_{tndy} \tag{9.6}$$

Market power adjustment term

The market power adjustment term (ref. Egging et al. (2018)) that will account for the conjectural variation considers the squared sales by each supplier, weighted by its market power conjecture, the slope of the inverse demand curve, the discount rate and season length, divided by two:

$$MPA = \tfrac{1}{2} \sum_{t,n,d,y} r_y d_d SLP_{ndy} cv_{tny} \left(q^S_{tndy} \right)^2 \tag{9.7}$$

The *MPA*-term makes this model different from a social welfare maximization problem.

We represent two infrastructure service types, transmission and storage. All capacities are assumed to be subject to complete Third Party Access (TPA) regimes.

Infrastructure restrictions

The network of transmission arcs includes pipelines as well as liquefaction, shipping and regasification activities in the LNG value chain. Arcs are directed. A pair of nodes may have two connecting arcs, at most one in each direction. LNG liquefaction and regasification are represented using auxiliary geographical nodes. (So that a country exporting both LNG and pipeline gas to another country does not have two the same connecting arcs.)

There can be different types of storage at a geographical node. For each type, we represent working gas and extraction capacity. We assign all losses to injection and all operational costs to extraction. In the model, injections and extractions must balance within each year. Additionally, working gas can be filled only once every year. Note that individual suppliers are responsible for their own storage cycle balances, see Eq. (9.4).The model accounts for discounted capacity expansion costs (Eq. (9.8)). Budgetary, regulatory or other restrictions may apply to capacity expansions (Eq. (9.9)).

$$\sum_{z,y} r_y c^{\Delta Z}_{zy} \Delta^Z_{zy} \tag{9.8}$$

$$\forall z,y: \quad \Delta^Z_{zy} \le \overline{\Delta}^Z_{zy} \tag{9.9}$$

Since extraction considers flows and working gas considers aggregate flows, we have a separate capacity constraint for the latter. Arc transmission and storage extraction capacity restrictions impose that aggregate services flow cannot exceed the capacity – including expansions – as reflected in Eq. (9.10).[22] Loss-corrected aggregate injections cannot exceed working gas capacity (Eq. (9.11)).

$$\forall z \in \{A, X\}, d, y: \qquad \sum_{t} f_{tzdy}^{Z} \le CAP_{zy}^{Z} + \sum_{y'<y} \Delta_{zy'}^{Z} \tag{9.10}$$

$$\forall w, y: \qquad \left(1 - l_w^I\right) \sum_{t,d} d_d \, f_{twdy}^{I} \le CAP_{wy}^{W} + \sum_{y'<y} \Delta_{wy'}^{W} \tag{9.11}$$

Optimization model

The objective function sums up total revenues and consumer surplus and subtracts the market power adjustment term and total operational and investment costs.

Objective

The first term provides sales revenues. The second term represents consumer surplus. The third term is the *MPA*-term. The fourth term represents the costs for production and the fifth the costs for infrastructure services. The sixth term is the cost for infrastructure expansion.

$$\max_{q_{tndy}^{S}, q_{tnrdy}^{P}, f_{tzdy}^{Z}, \Delta_{zy}^{Z}} \sum_{y} r_y \left[\begin{array}{l} \sum_{d} d_d \left\{ \begin{array}{l} \sum_{t,n} \left(INT_{ndy} - SLP_{ndy} \sum_{t'} q_{t'ndy}^{S} \right) q_{tndy}^{S} \\ + \frac{1}{2} \sum_{n} SLP_{ndy} \left(\sum_{t} q_{tndy}^{S} \right)^2 \\ - \frac{1}{2} \sum_{n} SLP_{ndy} \sum_{t} cv_{tny} \left(q_{tndy}^{S} \right)^2 \\ - \sum_{t,n,r} c_{tnry}^{P} \left(q_{tnrdy}^{P} \right) \\ - \sum_{t,z} c_{zy}^{Z} f_{tzdy}^{z} \end{array} \right\} \\ - \sum_{z} c_{zy}^{\Delta Z} \Delta_{zy}^{Z} \end{array} \right] \tag{9.12}$$

The feasible region is restricted by all restrictions listed in Sections 9.2 and 9.6 above.

Since the model units are €/kcm, and mcm & mcm/d, the objective function is scaled by a factor of one thousand (10^3).

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[22] The superscript *Z* provides the service type, and the subscript *z* the specific infrastructure item. For extraction services, the superscript is *X* and the subscript *w.*

Appendix C: Pipeline characteristics

This Appendix summarizes the economic characteristics such as investment costs as well as operational costs and losses for pipelines.[23]

Pipeline construction costs are strongly dependent on local characteristics and vary cyclically. For example, steel makes up a large share of the costs and its prices can vary a lot over time.

The pipeline location, if it is onshore or offshore, the terrain that it is crossing (e.g., mountains, marshlands) and the sea depth have a big impact on the economic pipeline characteristics. However, there are no simple relationships between the location and the pipeline characteristics: an "easy" offshore pipe in low sea depth is cheaper than an onshore pipeline in mountainous terrain.

Generally, there is very little data available publicly on economic pipeline characteristics and we had to make our assumptions based on very few data points. Here we present a range of acceptable values. The actual data choices are made during calibration and can be found in Table 6 in Section 3.1.

Table 41: Overview of pipeline data ranges

	Investment cost		Operational	Losses
	€/kcm/1000 km /year	**€/kcm/1000 km /day**	**€/kcm/1000 km**	**/ 1000 km**
Pipeline Onshore	75-200	27375-73000	5-20	2%-3%
Offshore		Multiply by two	Multiply by two	

Pipeline investment costs

We present a very limited number of data points, some rather old (Table 42). Costs are very dependent on local characteristics. When we know that pipelines are offshore, we multiply the costs by the value of parameter *BIPipeOffshMult* in Table 6). Further pipeline specific adjustments can be adjusting the calibration parameters in data.xlsx.

Table 42: Exemplary data points for pipeline investment costs

		Investment costs M$	Cap bcm	Length (1000 km)	$/kcm/ 1000 km	Comment, source
Medgaz	offshore	1000	8	0.21	600	Small, deep offshore, unclear if onshore part included
Nordstream	offshore	8000	55	1.224	120	Huge, so economies of scale, but offshore
Large,High	onshore	1500	15	1000	100	WEO 2001 in Cornot-Gandolphe 2003
Large, Low	onshore	1000	30	1000	33	WEO 2001 in Cornot-Gandolphe 2003
BBL	offshore	€ 500	16	230	€ 136	Not so deep. Capacity up 20%

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[23] This is described in more detail in internal document Pipeline characteristics 20190214.docx

						after adding a compressor.

Operational costs and losses

We take an aggregated view of the gas value chain and focus on the supplier perspective. However, we know that for the supplier the fees to the pipeline TSOs are costs. IFP (2003, p 6) reports that gas transport costs can exceed half of the gas market value (price). Here, “costs” should probably be interpreted as “tariffs / fees”. We base our assumptions on operational costs of 7-20 € / kcm and losses of 2% on a limited number of data points reported below.

Table 43: Overview of operational pipeline cost data

Value	Region	Text	Source
Rate $ 7 / 1,000 m^3 / 1000 km	Russia	Rate in effect since October 1, 2004 RUR 19.37 (approx. $ 0.70) per 1,000 m3/100 km. {...} rate fails to cover the costs of upgrading {...}	Gazprom n.d.
€ 11 (per entry / exit fee!)	Europe	entry AND exit fee €1/MWh (and costs € 0.1)	REKK 2017
Same order magnitude as REKK		Entry-Exit tariffs in the order of several to lower double digit euros per 1000 m^3 (e.g., Fluxys 8-25 €/m^3/h/y) x (1000/yearly load hours e.g. 4000): 2-6 x 2 for both entry and exit 4-12	ADL 2004

Table 44: Overview of pipeline loss data

Losses	Sources
0.22% /100 km in Czech Republic	18.1.3. The service gas *“For a distance of 100 km such service gas is 0.22 % of the volume delivered at the entry point for transportation.”* European TPA Tariff Comparison 2003 V3 Page 78 of 100

Literature references for pipeline data

ADL 2004, Arthur D Little May 2004, Gas transport services, West European Gas Transmission Tariff Comparisons.

Cornot-Gandolphe, Sylvie et al. (2003), (Various authors from IEA, IFP, Cedigaz), *The challenges of further cost reductions for new supply options (pipeline, LNG, GTL)*, 22nd World Gas Conference 1-5 June 2003, Tokyo, Japan

Gazprom n.d. http://eng.gazpromquestions.ru/page8.shtml (Accessed July 2007)

REKK 2017 Toth et al. 2017 Follow-up study to the LNG and storage strategy. EUR 2016.4053 EN

Appendix D: LNG value chain characteristics

This Appendix summarizes all data related to the LNG value chain, i.e. LNG liquefaction, regasification, and shipping. This includes investment costs as well as operational costs and loss rates for liquefaction, regasification and shipping.[24]

Here we present a range of acceptable values. The actual data choices are made during calibration and can be found in Table 6 in Section 3.1.

Table 45: Overview of LNG data ranges

Item	**Investment**		**Operational**	**Losses**
	€ / kcm / yr	**€ / kcm / d**	**€ / kcm**	
Liquefaction	400-1000	146000-365000	5-30	10%-14%
Regasification	90-150	32850-45625	2-20	0.5%-1.5%
			/1000 sea miles	**/1000 sea miles**
Shipping	Not represented		5-15	0.25-0.4%

- To get from € / kcm / yr to € / kcm / d multiply by 365
- Investment costs for liquefaction have been roughly 3-6 times higher than for regasification
- To reflect anticipated cost decreases we can opt for lower end investment cost estimates for liquefaction, and lower end loss rates and operational costs.

Unit conversion and exchange rate

LNG is usually measured in tons of LNG. However, liquefied natural gas has another energy density than gaseous natural gas. GGM works with (gaseous) natural gas as standard (homogenous) commodity. Hence a need to convert from LNG tons to cubic meters

We use the following conversion assumptions:

1 ton LNG = 1350 cubic meter natural gas,

1 Mtpa LNG = 1.35 bcm natural gas

This comes from the ranges found in the literature and reported in Table 45

Table 46: Natural gas energy content: overview of literature estimates

		kWh	**mbtu**
Low	1 cm	10.5	35.8
in GGM	1 cm	11.4	38.9
High	1 cm	12	40.9

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[24] More details in internal document LNG_characteristics_20190214.docx

LNG tends to have higher end energy density than “regular” natural gas due to purification. Since we have both gaseous and liquefied natural gas we choose to multiply by 40 to convert costs per Mbtu to costs per kcm.

A significant share of the data uses USD amounts whereas we use EUR, hence the need to convert. The exchange rate has been averaging around 1.2 USD/EUR[25]. In the period 2000-2002, it was mostly less than 1 USD/EUR. We recommend using the value 1 to convert from USD to EUR, and using the (somewhat) lower end of value ranges as input values.

Table 47: Historical average exchange rates US-Dollar vs. Euro

Period	Min	Max	Average
2000-2019	0.8252	1.5990	1.2130
2002	0.8578	1.0487	0.9456
2003	1.0377	1.2630	1.1308
2018	1.1261	1.2493	1.1810

Liquefaction

LNG liquefaction is usually done in a production node. We need to consider operational costs and operational losses, as well as existing capacities and investment costs in capacity expansion.

1.1.17 Liquefaction investment costs

We work with investment costs between 400 and 1000 € / kcm / year.

These values are based on the following literature.

Table 48: Overview of LNG liquefaction investment costs in the literature

Note that the table continues at the next page.

Description	mtpa	CAPEX	$-M	M-ton	$/ton/y	$/kcm/y	Sourcet
Cayrade	3.5	0.9	900	3.5	257.1	190.5	Cayrade 2004
Atlantic 1 Point Fortin	3.1	$1bn	1,000	3.1	322.6	238.9	BG 2005-2008
Atlantic 2+3	6.8	$1.1bn	1,100	6.8	161.8	119.8	BG 2005-2008
Atlantic 4	5.2	$ 1.2	1,200	5.2	230.8	170.9	BG 2005-2008
Idku, Egypt	3.6	$ 1.35	1,350	3.6	375.0	277.8	BG 2005-2008
Idku, 2	3.6	$ 0.55	550	3.6	152.8	113.2	BG 2005-2008

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[25] eurofxref-graph-usd.en.html at https://www.ecb.europa.eu

Vermeire					750.0	555.6	Vermeire 2009
Sabine Pass T1-4					550.0	407.4	Songhurst 2018
Sabine Pass T5					800.0	592.6	Songhurst 2018
Bintulu 9					650.0	481.5	Songhurst 2018
Angola					1100.0	814.8	Songhurst 2018
Petronas FLNG					800.0	592.6	Songhurst 2018
Elba					800.0	592.6	Songhurst 2018
Freeport					800.0	592.6	Songhurst 2018
Yamal					1300.0	963.0	Songhurst 2018
Gladstone					1300.0	963.0	Songhurst 2018
Pacific FLNG					1300.0	963.0	Songhurst 2018
Prelude FLNG					2000.0	1481.5	Songhurst 2018
Gorgon					2100.0	1555.6	Songhurst 2018
Liquefaction-low					600.0	444.4	Songhurst 2018
Liquefaction-high					1400.0	1037.0	Songhurst 2018
Mid 1990s					340	251.9	IEA WEIO p. 202, Fig 5.10
2002					260	192.6	IEA WEIO p. 202, Fig 5.10
2010 - estimate					200	148.1	IEA WEIO p. 202, Fig 5.10
2030 - estimate					160	118.5	IEA WEIO p. 202, Fig 5.10

The literature (Vermeire, 2009) also reports that liquefaction investments costs are 6.25 times as expensive as regasification investment costs at $90/kcm/y. Considering losses, one may round down to 6. Cayrade mentions a ratio of 3 of investment costs in liquefaction vs. regasification. Vermeire (2009) estimates are at the lower end of the more recent Songhurst (2018) estimates.

1.1.18 Liquefaction operational costs and losses

We assume operational costs between 15 and 30 € / kcm and a loss rate between 10 and 14%. This is based on the literature mentioned in the following table.

Table 49: Overview of estimates of LNG liquefaction operational costs in the literature

$/Mbtu	€/kcm	Comment	Source
0.8	30	lower end, price-based: much higher than operat costs	IELE 2003, p. 16
1.2	50	higher end, price-based	IELE 2003, p. 16
0.93	35	Egypt, Levelized, price based, Fig 5.31	IEA 2003 p. 263
0.97	40	Trinidad	IEA 2003 p. 263
1.02	40	Nigeria	IEA 2003 p. 263
1.10	45	Qatar	IEA 2003 p. 263
1.37	55	Venezuela – higher end, read from Fig 5.31	IEA 2003 p. 263

Table 50: Overview of estimates of LNG liquefaction operational losses in the literature

Value	Comment	Source
12%	On average 12% (…) used to fuel the liquefaction process.	Gaz de France –2004
10.3%	Natural gas consumption	IGU emissions from gas sector

Regasification

1.1.19 Regasification investment costs

We assume investment costs in LNG regasification capacity between 90 and 125 € / kcm / year. This is based on the estimates from the literature.

Table 51: Overview of LNG regasification investment cost estimates in the literature

Description	CAPEX	M-$	mtpa	$/ton/y	$/kcm/y	Source
Dragon LNG	£250 mio	425	4.4	96.6	71.5	BG 2005
		500	4.4	113.6	84.2	Different exchange rate
Brindisi 2005	€390 mio	400	6	66.7	49.4	BG 2005
		500	6	83.3	61.7	Different exchange rate
Brindisi 2008	€500 mio	500	6	83.3	61.7	BG 2008
		750	6	125.0	92.6	With 1.5 exchange rate
Vermeire					90	Vermeire 2009
Mid 1990s				150	110	IEA WEIO p. 202 Fig 5.10
2002				140	100	IEA WEIO p. 202
2010 - estimate				130	100	IEA WEIO p. 202
2030 - estimate				90	65	IEA WEIO p. 202
Germany Wilhelmshaven onshore	€1500 M		7.5-10		105-150	Deutsche Flüssiggas Terminal GmbH
Germany Wilhelmshaven FSRU	€ 10 M + several ten M € for the FSR unit		6 bcm(?)		Much lower order of magnitude	Nord-West Ölleitung (NWO) FSRU + lot of onshore infrastructure already in place.
Germany – Stade	€400 - 500 M		3		100-125	

Note: 1 ton LNG is approximately 1350 cm

1.1.20 Regasification operational costs and losses

We assume operational costs of LNG regasification of 2 to 20 € / kcm as well as loss rates between 0.5% and 1.5%). This is based on the following estimates from the literature.

Table 52: Overview of estimates of regasification operational costs in the literature

Description	Original value	EUR / kcm	Comment	Source
lower end	$ 0.3 / MMbtu	10	2002, price-based, higher than	IELE 2003, p. 16

			operational costs	
higher end	$ 0.5 / MMbtu	20	2002, price-based, higher than operational costs	IELE 2003, p. 16
Fig 5.31	0.5	20	Read from Fig 5.31	IEA 2003 p. 263
Lake Charles	27.34c / mmbtu	11	Fixed operation	BG 2005
Lake Charles	2.99c / mmbtu	1.2	Variable operation	BG 2005
Lake Charles		12	Blended	BG 2005
Lake Charles	low 0.20s / mmBtu	8-9	Blended	BG 2006, BG 2008
Elba Island	21c/mmbtu	8	Fixed operation	BG 2005
Elba	4.5c/mmbtu	2	Variable operation	BG 2005
Elba		10	Blended	BG 2005

The following table gives account of the – very few – estimates of the loss rates associated with regasification. According to BG 2005, the lower operational cost facility has higher loss rate.

Table 53: Overview of loss rate estimates in the literature for LNG regasification

Value	**Comment**	**Source**
0.43%	LNG regasification - Natural gas consumption: Energy	IGU emissions from gas sector
1.66%	Lake Charles	BG 2005
1.2%	Elba Island	BG 2005

LNG Shipping

We include shipping with the operational costs associated with it. These costs are distance-related.

However, we do not properly represent the freight market with shipping fees resulting from supply-demand equilibrium for freight services. We also do not include the investment perspective in new ships which is subject to dynamics that a gas-sector-only model can hardly represent.

We calculate shipping distances with the help of the following sources:

- www.distances.com
- https://sea-distances.org/
- National imagery and mapping agency 2001, PUB. 151, *Distances between ports*, 11th edition
- GIIGNL annual report, see https://giignl.org/

In case there is more than one LNG terminal in a country, there usually is a representative one chosen for the location of the LNG node. We aggregate all LNG capacities located in the same country or region and attribute the total capacity to the representative terminal location.

For new LNG terminal projects in countries with LNG yet, we chose a port location among existing ports to calculate the distances.

1.1.21 LNG shipping costs and losses

We assume shipping costs in the range 5-15 € / kcm / 1000 sea miles. Moreover, we assume losses between 0.25 and 0.4 % per 1000 sea miles.

We abstract from economies of scale and use average distance-related costs. However, we know that large ships such as ships of the Q-max category have significant economies of scale. For example, in December 2008, ExxonMobil reported that it's then largest LNG carrier in the world with a capacity up to 266,000 cubic meters (up to 80 percent more cargo than conventional LNG ships) requires approximately 40 percent less energy per unit of cargo than conventional LNG carriers due to economies of scale and efficiency.

Table 54: Overview of LNG shipping cost estimates in the literature

	Shipping $/Mbtu	**Approximate distance in sea miles**	**Source**	**Process calculation**	**€/kcm/ 1000 sea miles**
Trinidad	0.30 $/Mbtu	2,100	IEA 2003 WEIO	0.3x40/2	6
Nigeria	0.72 $/Mbtu	4,000	IEA 2003	0.7x40/4	7
Venezuela	0.27 $/Mbtu	1,700	IEA 2003	0.27x40/1.7	6
Egypt	0.70 $/Mbtu	5,500	IEA 2003	0.7x40/5.5	5
Qatar	1.23 $/Mbtu	9,000	IEA 2003	1.23x40/9	5.5
Several			DOE EIA 2003		6-7
IELE	0.000171	$/MMBtu/mile	IELE 2003 p 10, Fig	x40x1000	7
Lopak	8.75	$/kcm/1000 sea miles	Lopak 2008 + own corrections	See below	8

Note: the table reports the estimated costs and distance to the U.S. Gulf coast. Located along the US Gulf Coast are the U.S. States of Texas, Louisiana, Mississippi, Alabama, and Florida. These are the U.S.Censes (and GGM) regions 5, 6,and 7.

Note: IEA 2003 WEIO numbers are from p 263 and give levelized costs in $/Mbtu.

1.1.21.1 Lopak 2008

Lopak provides an insightful overview of the details of LNG shipping costs. However, it seems that the author does not account for the empty return trip (possibly in fuel costs, but not in other calculations).

	Lopak			**Per 1000 sea miles**
Crew, O&M, admin	17,764 /day			39,000
Speed	19 knots	456 sea miles / d		
Fuel	160 ton/day	When sailing		
Bunker fuel	500 $/ton	may be -50% / +100%	160x500x2.2=	176,000
	3 ton/day	When (un)loading	Not included	
loading	One day			Fixed
unloading	Two days			Fixed
	Lopak		**DOE EIA 2003 -p 52**	
Charter rates	55,000-60,000	contracts	$55,000 - $65,000.	
			60,000x2.2	132,000
	70,000+	spot	$27,000 -$150,000.	
Total, one.way				350,000

- 138,000 m3 x 23.3 Mbtu/m3 = 3.2 M Mbtu = 0.08 M kcm

- Empty return trip: 2 x ($ 350,000 / 80,000 kcm) = 70/8 = $ 8.75 / kcm / 1000 sea miles
- This does NOT account for loading and unloading days
- This can be 50% lower or double as high in specific case

1.1.21.2 DOE EIA 2003

We divide the shipping rates presented in DOE (2003), see Table 55 by estimated distances (Table 56) to obtain costs per unit of energy per unit of distance (Table 57).

Table 55 Shipping Rates ($/MBtu)

	Everett	Cove Point	Elba Island	Lake Charles
	Boston	Maryland	Georgia	Louisiana
	Region 1	Region 5	Region 5	Region 7
Algeria	0.52	0.57	0.6	0.72
Australia	1.76	1.82	1.84	1.84
Nigeria	0.8	0.83	0.84	0.93
Norway	0.56	0.61	0.64	0.77
Qatar	1.37	1.43	1.46	1.58
Trinidad & Tobago	0.35	0.35	0.32	0.38
Venezuela	0.34	0.33	0.3	0.35

Distances from our own database:

Table 56: Distances for these LNG trade relations in the GGM database (in 1000 sea miles)

	Region 1	Region 5	Region 7
Algeria	3.5	3.8	5.0
Australia	11.2	11.1	10.6
Nigeria	4.6	5.3	4.0
Norway	3.5	3.9	5.0
Qatar	8.1	8.5	9.5
Trinidad & Tobago	1.9	1.9	2.1
Venezuela	1.9	1.8	1.7

Resulting costs by dividing values in the previous two tables, and multiplying by 40:

- Algeria-Region 1: 0.52*40 (Mbtu/kcm)/3.5= 5.9; (at 38 (Mbtu/kcm): 5.6)
- Australia-Region 1: 1.76*40 (Mbtu/kcm)/11.2= 6.3; (at 38 (Mbtu/kcm): 6.0)

Table 57: Calculated estimates for LNG shipping costs ($ / kcm / 1000 sea miles)

	Region 1	Region 5	Region 5	Region 7
Algeria	5.9	6.0	6.3	5.8
Australia	6.3	6.6	6.6	6.9
Nigeria	7.0	6.3	6.3	9.3

Norway	6.4	6.3	6.6	6.2
Qatar	6.8	6.7	6.9	6.7
Trinidad & Tobago	7.4	7.4	6.7	7.2
Venezuela	7.2	7.3	6.7	8.2

Table 58: Overview of loss estimates of LNG shipping in the literature (boil off per 1000 sea miles)

Value	Comment	Source
0.35-0.4%	0.21% LNG transport (BAT – Best available technology, 1000 km) - Natural gas consumption – Energy	IGU emissions from gas sector
0.2-0.35%	0.1-0.15% for larger ships (up to 0.25% for small ships) per day	Lopak 2008

LNG value chain literature sources

We refer to the following sources for LNG data:

- BG Group 2005 LNG Fact Sheets
- BG Group 2006, A market leader in Global LNG, The Houstonian, 11 Sept 2006, Presentation
- BG Group 2008 LNG Fact Sheets
- Cayrade, Patrick 2004 Investments in Gas Pipelines and Liquefied Natural Gas Infrastructure. What is the Impact on the Security of Supply? NOTA DI LAVORO 114.2004, September 2004
- EIA DOE 2003, Energy Information Administration, U.S. Department of Energy, The Global Liquefied Natural Gas Market - Status & Outlook, December 2003, DOE/EIA-0637 (2003)
- GdF 2004, Gaz de France, European leader in Liquefied Natural Gas (LNG), July 2004
- IEA 2003 WEIO World Energy Investment Outlook OECD/IEA, 2003
- IELE 2003 University of Houston, Institute for Energy, Law & Enterprise. Introduction to LNG, An overview on liquefied natural gas (LNG), Its properties, the LNG industry, safety Considerations, January 2003
- IGU International Gas Union, emissions from gas sector
- Lopac, Andreja Ana 2008 Recent trends in transporting of lng, liquefied natural gas
- Songhurst, Brian 2018 LNG Plant Cost Reduction 2014–18, Oxford Institute for Energy Studies, OIES PAPER: NG137, October 2018
- Vermeire; Jean 2009, (President GIIGNL), global dynamics of LNG business, GIE annual Conference, Groningen, Netherlands, 6-7 MAY 2009

Appendix E: Storage characteristics

This Appendix lists and summarizes storage characteristics.[26] We include seasonal gas storage – which is mostly underground gas storage – in the model database. For some countries, we also include LNG storage (in particular Japan and South Korea).

We distinguish several activities / commodities related to gas storage: injection into storage facilities and extraction (EXTR) from storage facilities, as well as working gas (WG) which is the volume of gas in storage that can actually be retrieved. We assume that storage facilities are empty at the beginning of the year and at the end of the year. In other words, everything that is injected in one season is extracted in the other season ("storage cycle constraint").

Several types of geological (underground) storage facilities exist. Seasonal and long-term (strategic) storage generally uses depleted (oil and gas) fields and aquifers. Short cycle storage for daily churning as well as backup storage by the distribution sector is often using salt caverns but also LNG peak storage (the latter is generally not underground but often a unit in a regasification terminal).

We include the following data in the model data base:

- investment cost (incl. cushion gas)
- operational and maintenance cost
- loss rates

Here we present a range of acceptable values. The actual data choices are made during calibration and can be found in Table 6 in Section 3.1.

Table 59: Overview of storage data ranges

	Investment cost	**Operational**		**Losses**
	€/kcm	€/kcm/day		
Seasonal				
WG	150-500	N.A.		
EXTR	1258-70000	20-60		(Inj+Extr) 0.5%-1.5%
Peak	Too expensive	40		
LNG				
WG	As regasifier	N.A.		As regasifier (1.5%)
EXTR	For free	Very low		

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[26] This is based on document storage_characterists_20190206_v0_RE.docx

Construction costs of storage facilities depend strongly on local characteristics and behave very cyclically. This is largely due to the fact that cushion gas makes up a large share of the investment costs and natural gas prices vary a lot over time.

For peak shavers (salt caverns and LNG peak storage), we include existing capacities but ignore expansion.

For LNG terminal storage in Japan and S. Korea, we assume that storage injection and extraction is taking place at the regasification terminals. In this case, working gas capacity expansion possible at same cost as regasification capacity.