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Modelling Natural Gas Markets with MAGELAN2:

Model Description

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Abstract

MAGELAN is a gas market model developed in 2006. It is designed as a long-term supply model that could be used to forecast future developments of a worldwide gas market especially under consideration of a scarcity of supply. Given real world developments in the following years, actually no gas scarcity could be observed most of the time. On the contrary, supply side (mainly technical progress such as the shale gas revolution or new LNG technologies) and demand side (such as plans for reduction or even phase-out of fossil fuels due to climate change) evolutions made traditional supply models appear somehow needless. The Russian invasion in the Ukraine in 2022 suddenly brings traditional security of supply issues back on the agenda. As the by-far largest gas supplier of the world, Russia, cuts off supplies to most of its main customers and simultaneously being unable to deliver these volumes to other markets in a short or even long term, world has to face again some kind of gas scarcity. As a massive expansion of renewables needs time and fuel switch to oil or coal is limited (either by capacity or in some countries by climate policy), new supply routes with corresponding investments in LNG, pipelines or production facilities are needed.

This paper presents MAGELAN2, an updated version of the original model from 2006. This new version introduces several new model nodes (166 compared to 136 in Version 1), a massive expansion of potential LNG connections and the transformation of many formerly exogenous production regions to endogenous production nodes, which considers the expansion of formerly smaller gas market players (such as China or India) and newcomers (such as Cameroon or Papua New Guinea).

Key words: Long-term gas market modelling, linear optimisation, gas demand and supply, LNG, pipelines, security of supply

Contents

1. Introduction

MAGELAN is a gas market model developed in 2006. It is designed as a long-term supply model that could be used to forecast future developments of a worldwide gas market especially under consideration of a scarcity of supply. Given real world developments in the following years, actually no gas scarcity could be observed most of the time. On the contrary, supply side (mainly technical progress such as the shale gas revolution or new LNG technologies) and demand side (such as plans for reduction or even phase-out of fossil fuels due to climate change) evolutions made traditional supply models appear somehow needless.

The Russian invasion in the Ukraine in 2022 suddenly brings traditional security of supply issues back on the agenda. As the by-far largest gas supplier of the world, Russia, cuts off supplies to most of its main customers and simultaneously being unable to deliver these volumes to other markets in a short or even long term, world has to face again some kind of gas scarcity. As a massive expansion of renewables needs time and fuel switch to oil or coal is limited (either by capacity or in some countries by climate policy), new supply routes with corresponding investments in LNG, pipelines or production facilities are needed.

This paper presents MAGELAN2, an updated version of the original model from 2006. A reality check for the results of original model version showed some improvement needs for the model structure and the geographical coverage (Seeliger 2023). This is considered in the new version, which introduces several new model nodes, a massive expansion of potential LNG connections and the transformation of many formerly exogenous production regions to endogenous production nodes.

Section 2 gives an overview over the model history, followed by a brief description of the renewed model MAGELAN2 (section 3). The paper finish with an outlook on further modelling steps (section 4).

2. Model History

MAGELAN is a long-term gas market model developed at the Institute of Energy Economics at the University of Cologne. The original version was released in 2006 (Seeliger 2006) and will now (retrospectively) named MAGELAN1. In 2023, the model data and structure as well as some features in the model code were updated, resulting in a new model version, MAGELAN2.

MAGLAN1 is a further development of an earlier model, also developed at the University of Cologne, named EUGAS. EUGAS is a model for the European gas market and was initially developed as an iterative add-on for an existing electricity market model, EIREM (Hoster 1996). EUGAS' first version was founded by a DFG project (von Weizsäcker/Perner 2001), aiming to provide model-based input data for the electricity model (mainly gas prices for power plants), which in turn delivers gas demand from power plants as input data for EUGAS. In the following, EUGAS became an independent gas market model with several model versions (Perner 2002; Perner/Seeliger 2004; Bothe/Seeliger 2005).

Given the gas market trends in the early 2000s (such as expansion of interregional gas trades by LNG and increasing competition in Europe and the USA) the ineptitude of a pure European model became obvious. In fact, EUGAS had already implemented some suppliers from abroad (such as Qatar or Trinidad & Tobago), but their supply volumes available to Europe were exogenous given - which had high predefining impacts on model results. Therefore, a new model with a global focus was introduced. This led to a reduction of granularity in Europe and the abolishment of several detailed functions included in EUGAS. In turn, the whole (gas) world was implemented and new functions were introduced, such as country specific supply curves.

Despite MAGELAN was used in several research and consultancy projects, further developments took place in the following years. The "official" successor, developed again at the Institute of Energy Economics, is named COLUMBUS (Hecking/Panke 2012). COLUMBUS uses wide parts of

MAGELAN but implemented various extensions, mainly on the demand side (e.g. seasonality and price elasticities of demand). Even if large parts of the model code were reused, a different solver and many other technical changes were conducted.

Another offspring branch is the TIGER model (Lochner 2011). TIGER is a completely new model development, resetting the focus to the European market with a very high resolution of individual pipeline routes within Europe, including storage facilities. However, TIGER uses some model elements of MAGELAN (mainly on the upstream side) as well as large parts of the model input database.

3. Model Description

This section provides a brief overview of the key characteristics of MAGELAN2. It contains information on the fundamental model design (3.1), the model structure (3.2), the geographical coverage (3.3) and the transport system (3.4). Subsequent, the mathematical formulation is presented. Section 3.5 presents the objective of the model and in 3.6 the most relevant constraints are added. Further details, especially on technical parameters or theoretical background of some model elements and assumptions, can be found in Seeliger (2006).

3.1. Model Design

MAGELAN2 is a long-term optimisation model for the worldwide gas market. The model is based on the following principles, which will be explained in brief in the following:

- Linear programming
- Interregional system
- Intertemporal optimisation
- Perfect competition

The model is designed as a linear optimisation problem. Its objective is the minimisation of the worldwide gas supply costs (see section 3.5). One advantage of linear optimisation to other approaches is the unambiguousness of results and comparably low requirements on computer hardware with short calculation times. The model is written in GAMS and is using CPLEX as solver (Brooke et al. 1998; GAMS 2023).

MAGELAN2 consists of 166 nodes which are connected with each other ("hub and spoke system"). Changes in parameters for one node could have impact on all other nodes, which is one of the main characteristics of a typical interregional network system. The regional coverage and the design of the transport system are described in more detail in section 3.3 and 3.4.

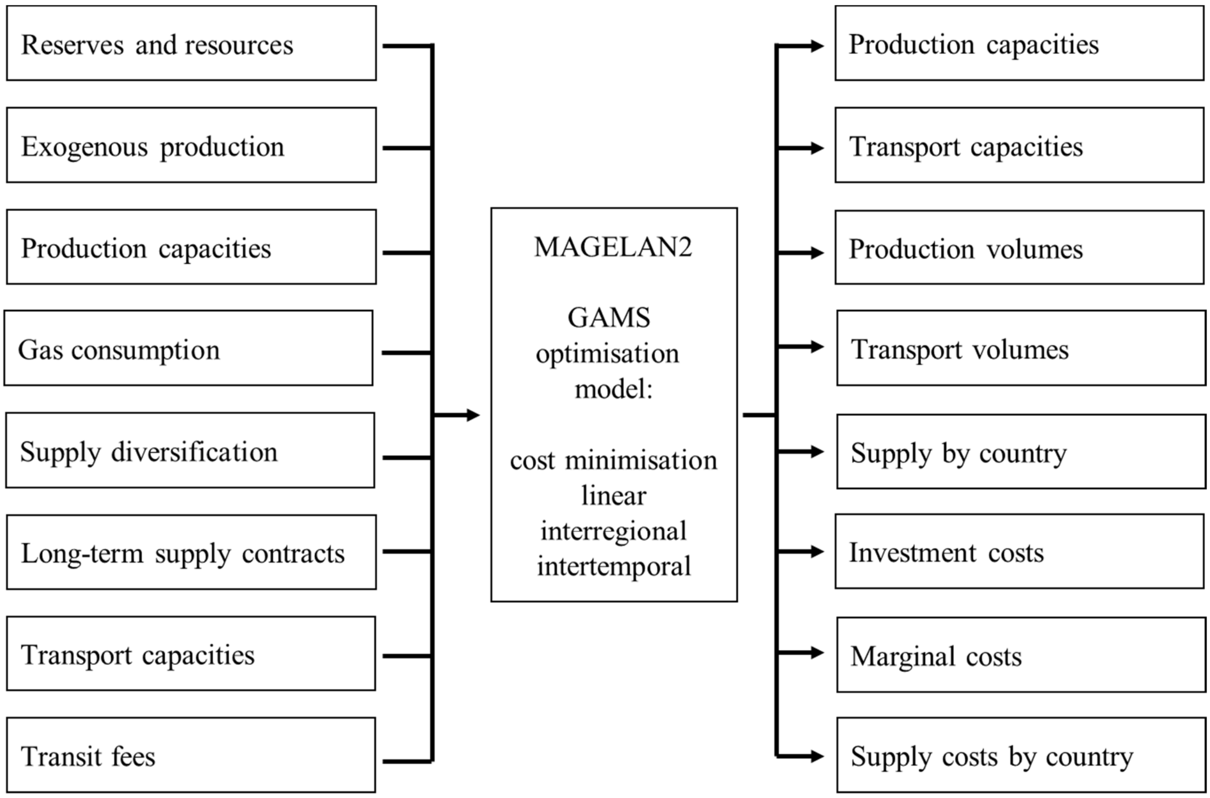
Intertemporal optimisation means, that the model is divided into various time periods that afflict each other. For example, if one gas unit is produced in the first optimisation period, it can't be used anymore in one of the following periods. Beside the production side, which follows the approach of neoclassical resource economics (esp. Hotelling 1931), also the transport segment has intertemporal dimensions, as gas pipelines and LNG facilities are large scale investments with a long lifetime. The model has to take the development of future demand into account when planning new infrastructure. One key assumption is that the model, which is some kind of central planer, has perfect foresight over the total optimisation time horizon (Keppo/Stubegger 2010). This is a more or less unrealistic assumption but makes the model much easier to operate. The forecast horizon covers five-years periods from 2020 to 2050. 2020 is used as a "training period" for model run parameterisation, which should come as close as possible to the actual values of 2020 in real life. However, the model works with a significant longer timeframe to consider (a) investment cycles based on construction years in the past (starting 1980) and (b) to avoid the so-called "end effect" (Grinold 1983) which would bias the results especially in the last forecast periods (so the model has to calculate until 2065).

Another important characteristic of MAGELAN2 is the assumption of perfect competition. The model works as a central planer who optimises all gas flows based on their marginal costs. Given the high capital intensity of the gas industry and the high share of fixed costs, the term marginal costs refer to so-called long-run marginal costs (LRMC). LRMC include a component for those fixed costs, which is in contrast to most neoclassical market models with perfect competition, where short-run marginal costs (i.e. no consideration of fix costs) dominate (Tooth 2014). Of course, this is a crucial assumption. Even if competition in the global gas market rose in the last decades, still no perfect competition prevails (and presumably never will). This has to be taken into account when using the model results. The supply costs calculated by MAGELAN2 (section 3.2) are therefore not a price forecast. However, the supply costs could be interpreted as a lower bound for prices. Depending on the actual market form and market structure, more or less surcharges on these costs needs to be added to create price forecasts.

3.2. Model Structure

Figure 1 summarises the key input (left side) respectively output (right side) parameters of MAGELAN2.

Figure 1: Model structure of MAGELAN2



Source: Own illustration

An obviously central input parameter for a long-term gas market model is the resource basis. Given the long time horizon, not only currently proven reserves are entered in the model but also resources. Those unknown or unsure resources are not available for optimisation in the first model period but will be added stepwise. The total resource basis (reserves plus resources) is clustered in up to five cost levels. By this, various sources of gas (onshore, offshore, ultra-deep water, different types of non-conventional resources etc.) could be implemented. For all cost levels, existing production capacities built in the past could be insert. To reduce calculation time and reduce complexity of model files, no optimisation of gas production is intended for some minor gas producers (see section 3.3 for details). For those countries, a predefined gas production path based on remaining resources is included.

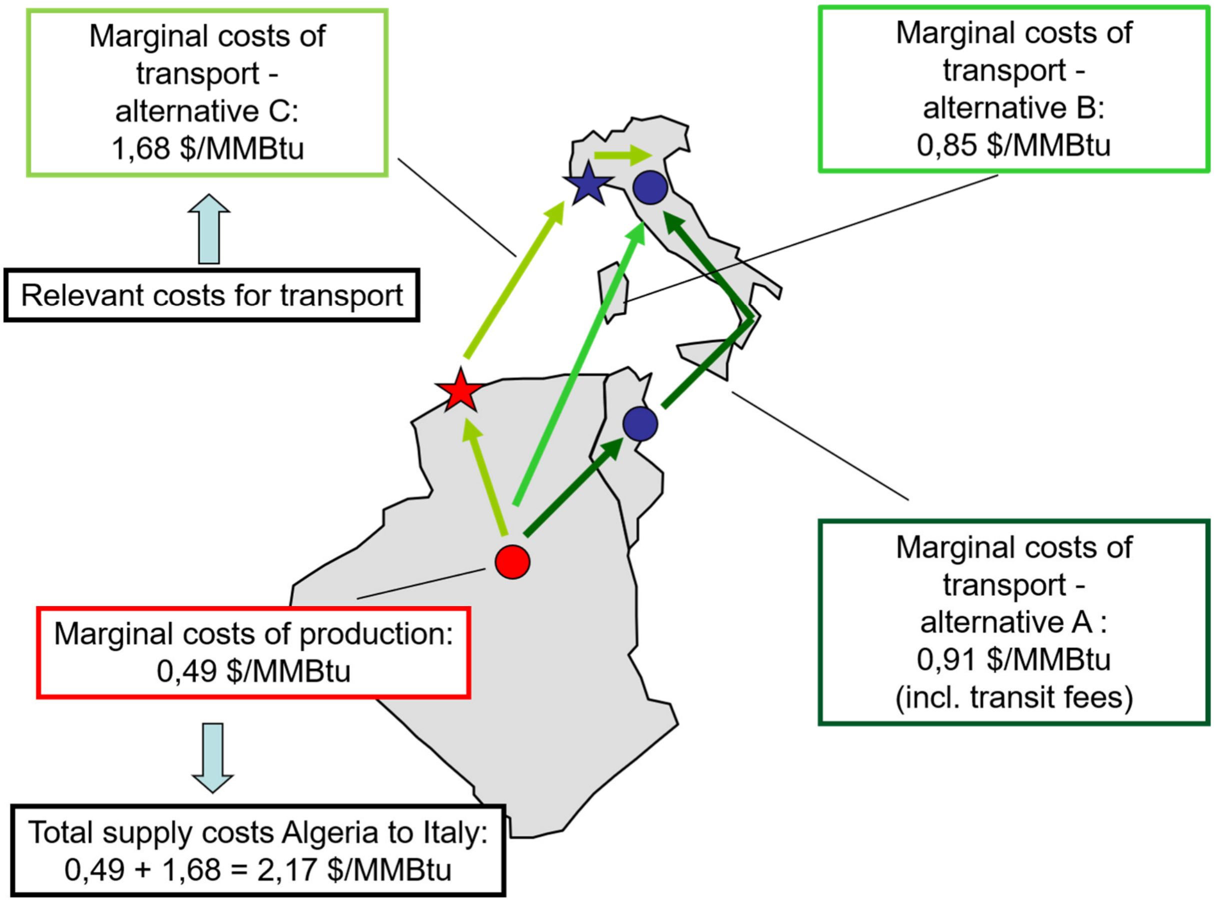
The second category of input parameters covers demand side issues. At first, gas consumption is entered exogenous for all model periods. As the model uses a pure cost-minimisation approach, in some cases one country could be delivered by only one, typically a close-by, supplier (e.g. Spain by Algeria or the Baltic States by Russia). In reality, most import dependent countries want to avoid such a situation and try to diversify their supply portfolio, even when this is resulting in higher procurement costs. MAGALAN2 could consider such strategies by constraints on import shares for individual suppliers (see section 3.6). Another parameter, which allows to converge model results more towards reality, is the predefinition of some gas flows between countries by implementation of existing (or future) long-term supply contracts. Given their actual duration, their impact on the model results is quite high in the first optimisation periods but is shrinking in the latter years.

The next major category of input parameters concerns all data around the transport sector. As for the production side, also for transport facilities (pipelines and LNG) historic capacities are included with their respective year of construction. In addition to the general cost parameters (e.g. capital and operation costs for pipelines and LNG) additionally transit fees, which are not covered by the other cost data, could be entered for single pipeline or shipping routes.

On the output side, MAGELAN2 provides various information on the transport and production sectors. The model calculates capacity additions and (for some technologies) decommissioning as well as total capacities in every period. Together with the produced volumes (for every region and within them for every resource cost level) a number of further indicators such as utilisation factor and reserve/production ratio ("static lifetime") could be extracted from the model data. For transport, MAGELAN2 provides transported volume for each pipeline connection and LNG facility. In combination with the capacity information, also average utilisations for every infrastructure element could be generated.

The output files show all relevant cost information. However, total cost for global gas production or investment costs for regasification plants worldwide might give some good indications and help for interpreting complete scenarios, but given the aggregated character and high impact of discount, most of these figures are not easy to interpret. More helpful than total cost information are marginal costs for individual production regions and transport routes. By combining production costs from one production country and all the costs for the needed transport sections passed towards an import country, supply costs could be calculated. When a supplier uses more than one route to deliver gas to a specific demand node, than the model takes the most expensive way as value for the transport costs (following the general logic of price setting by the marginal supplier). This is exemplary illustrated in Figure 2 for the supply costs of Algeria for sales to Italy.

Figure 2: Calculation of supply costs (example)

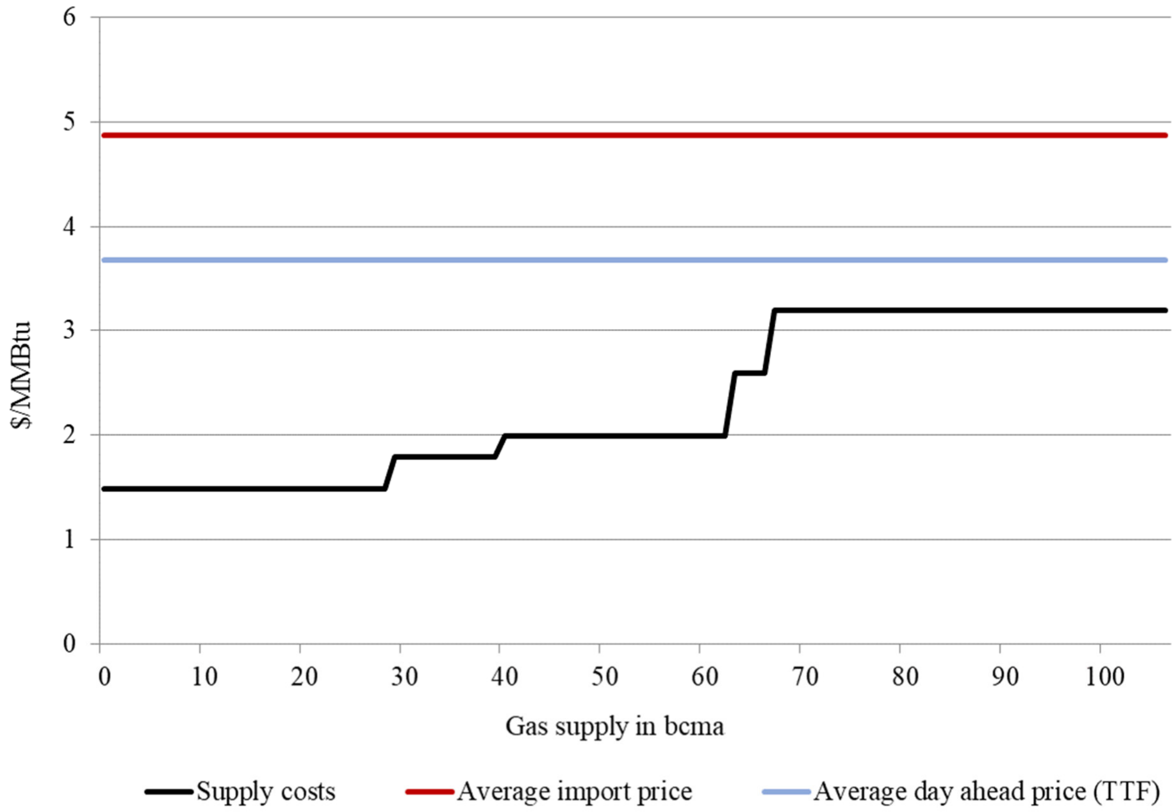


Source: Own illustration

Together with the supply volumes for each supply country to every consumption node those supply costs could be used to create country specific supply (or merit order) curves. The supply costs of the last needed supplier (the marginal supplier) defines the marginal supply costs for a consumption region and could be interpreted as a price, which would be realised if the market form really would be perfect competition. As this is usually not the case in gas markets, the difference between the marginal costs and the actual monitored price could be seen as a mark-up for a non-full-competitive market form in reality. However, this only is an option for years, where the actual price is known (which is true for the "training period" 2020) respectively reliable future prices on energy exchanges are quoted (which is the case for 2025 at present). Furthermore, the difference is the producer rent for each supplier. In theory, this producer rent could be split in a "normal" rent (so-called Ricardo rent) and another rent (Hotelling rent) resulting from capacity constraints in resource markets like the gas market (Energy Charter Secretariat 2007, p. 46). The Hotelling part of the rent is the difference between the marginal supplier's cost and the price, whereas the Ricardo rent is the area between the marginal supplier's cost and the marginal costs of all other suppliers.

Figure 3 shows an example for Germany in 2020. The supply curve starts (as usual) with the least-cost supplier (Netherlands in that case) and ends with the most expensive needed supplier (which is Russia in this example). When comparing the model supply curve with actual market prices, a mark-up and by this a Hotelling rent is observable. It is no surprise, that the mark-up is higher for the average import price (which still depends to some parts on long-term contracts with oil indexation) than for the short-term market price (which is the result of trading on competitive exchanges or OTC platforms), which is quite close to the costs of the marginal supplier.

Figure 3: Gas supply curve – indicative example for Germany 2020



Source: Own illustration

3.3. Regional Coverage

MAGELAN2 is designed as a system of various types of nodes. In total, there are 166 nodes, compared to 136 defined in MAGELAN1. 44 of these nodes are characterised as production regions (*preg*) which have both, (endogenous) production and (exogenous given) consumption. All production regions are allocated to a supply country (*sc*). Normally, every supply country has one production region, only Russia is divided in two regions (Russia West and East), as those regions are geographically separated and supply different costumer markets (mainly Europe from Russia West and mainly Asia from Russia East). So, in total there are 43 supply countries. In MAGELAN1 more countries were split in more than one region, which explains the difference between production nodes (39) and supply countries (34). The next category of nodes defines consumption regions (*creg*). They have an exogenous given gas production (if any) as well as an exogenous given consumption. The number of nodes is somehow lower than in MAGELAN1 (48 compared to 51), but in the older version some countries has been mapped with more than one node. In turn, some consumption nodes represent more than one country in both versions. To sum up, MAGELAN1 covers 87 and MAGELAN2 100 countries. Finally, LNG liquefaction (*lq*) and regasification (*rg*) plants are treated as separate nodes each. LNG plants, and here especially regasification, show the strongest increase in included nodes, which clearly shows a major trend in the global gas industry towards LNG in the last decade – and actually, this is one of the key arguments for an update of MAGELAN. Table 1 provides an overview of the regional coverage of both model versions.

***Table 1:** Regional coverage of MAGELAN1 and MAGELAN2*

	Code	MAGELAN1	MAGELAN2
Supply countries	sc	31	43
Production regions	preg	39	44
Consumption regions	creg	51	48
LNG liquefaction	lq	22	29
LNG Regasification	rg	24	45
Total number of nodes		136	166
Countries covered		87	100

Source: Own illustration

Table 2 shows all included countries and their respective nodes. For some countries both, liquefaction and regasification, plant types are given. This is due to the dynamic development of some countries. One example is Egypt: the country started to export LNG in the 2000s, but due to fast population growth and stagnating reserve development, a regasification plant was built in 2017 to keep the domestic consumption satisfied. However, given a wide resource basis (which nevertheless took time to be developed), market participants expect Egypt to return on the net-export side. In addition, liquefaction plants could be used in future for exports from Israel, which currently is an importer of LNG but due to new field discoveries, one could expect net-exports in the future. Another example accounts for the USA, which were forced to construct a large number of regasification plants because of a high forecasted supply gap. However, the shale gas revolution changed the picture dramatically and the USA turn to one of the largest export nations worldwide (but still has more than 60 bcma of import capacity – which could celebrate a comeback in one of the latter model periods).

***Table 2**: Node system of MAGELAN2*

Region	Country	sc	preg	creg	lq	rg
Africa	Algeria	X	X		X	
	Angola	X	X		X	
	Cameroon	X	X		X	
	Equatorial Guinea	X	X		X	
	Egypt	X	X		X	X
	Ghana			X		X
	Libya	X	X		X	
	Mauritania	X	X		X	
	Morocco			X		
	Mozambique	X	X		X	
	Nigeria	X	X		X	
	Senegal	X	X		X	
	South Africa			X		X
	Tanzania	X	X		X	
	Tunisia			X		
Asia Pacific	Australia	X	X		X	
	Bangladesh			X		X
	Brunei	X	X		X	
	China	X	X			X
	Indonesia	X	X		X	X
	India	X	X			X
	Japan			X		X
	Korea (South)			X		X
	Myanmar	X	X			X
	Malaysia	X	X		X	X
	Pakistan			X		X

	Philippines			X		X
	Papua New Guinea	X	X		X	
	Singapore			X		X
	Thailand			X		X
	Taiwan			X		X
	Vietnam			X		X
Europe	Austria			X		
	Belgium/Luxemburg			X		X
	Bulgaria			X		
	Croatia			X		X
	Czech Republic			X		
	Denmark/Sweden			X		
	Finland			X		X
	France			X		X
	Germany			X		X
	Greece			X		X
	Hungary			X		
	Italy			X		X
	Lithuania/Estonia/Latvia			X		X
	Netherlands			X		X
	Norway	X	X		X	
	Poland			X		X
	Portugal			X		X
	Romania			X		
	Serbia/North Macedonia/Bosnia			X		
	Slovakia			X		
	Slovenia			X		
	Spain			X		X
	Switzerland			X		
	Turkey			X		X
	United Kingdom	X	X			X
FSU	Azerbaijan	X	X			
	Belarus			X		
	Georgia			X		
	Kazakhstan	X	X			
	Moldova			X		
	Russia	X	X (x2)		X (x2)	
	Turkmenistan	X	X			
	Ukraine	X	X			
	Uzbekistan	X	X			
Middle East	Bahrain			X		X
	Iran	X	X		X	
	Iraq	X	X			
	Israel	X	X			X
	Jordan			X		X
	Kuwait			X		X
	Oman	X	X		X	
	Qatar	X	X		X	
	Saudi Arabia	X	X			
	Syria			X		
	United Arabic Emirates	X	X		X	X
	Yemen	X	X		X	
	Canada	X	X		X	X

North America	El Salvador/Nicaragua			X		X
	Mexico			X		X
	USA	X	X		X	X
South America	Argentina	X	X		X	X
	Bolivia	X	X		X	
	Brazil	X	X			X
	Chile			X		X
	Colombia/Panama			X		X
	Dominican Republic/Jamaica			X		X
	Peru	X	X		X	
	Trinidad & Tobago	X	X		X	
	Venezuela	X	X			

Source: Own illustration

3.4. Transport System

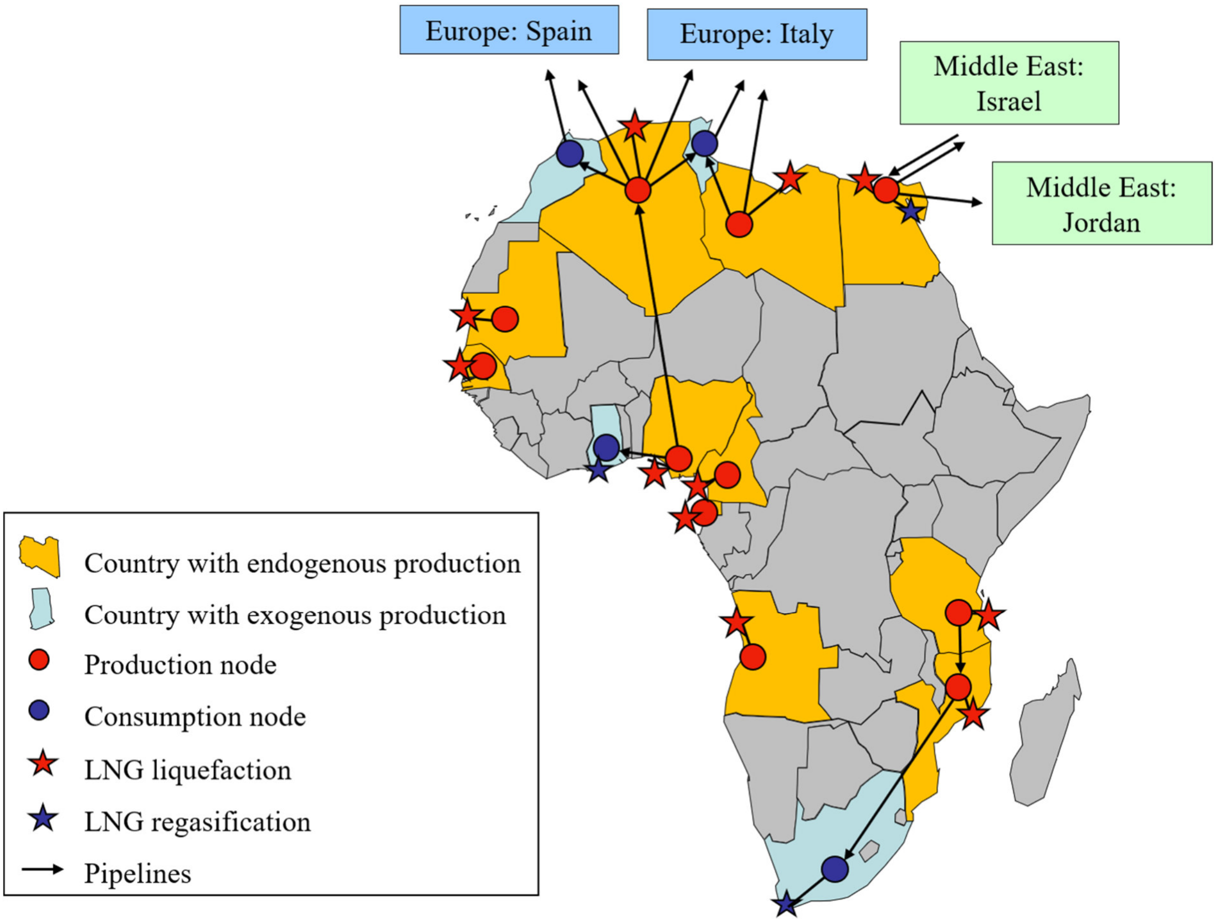
The transport network in MAGELAN2 is designed as a system of interlinked nodes. The nodes could be connected with each other by pipeline and by LNG routes.

Pipelines could be implemented as single direction lines (which was historically the standard case in the gas industry) or as a line in both directions (which is usual nowadays in many regions, especially in Europe). Every pipeline is entered in the system with a set of fundamental parameters such as length, diameter, onshore or offshore way or specific cost surcharges (e.g. for mountainous regions). Those parameters determine the route specific transport costs as calculated by the model. The need for compressor stations is calculated by the model during the optimisation process. Furthermore, historic capacities are also captured in the input data (if any, otherwise the start capacity is set to zero). If more than one pipeline exists in reality between two nodes (e.g. pipelines between the Netherlands and Germany) their capacities are aggregated.

LNG routes are defined as connections between liquefaction and regasification nodes. In contrast to pipelines, there is for technical reasons no reverse flow possible. Routes are mainly characterised by the shipping distance between the two ports. In principle, every liquefaction plant could send out its LNG to every regasification unit. To reduce complexity of the transport system (and by this calculation time and clarity of input/output files) some rather unlikely connections were excluded from the list of possible connections. This accounts mainly for connections between small exporters and small importers with a very long distance in between (e.g. Papua New Guinea to Finland). However, if developments in reality require an implementation of a specific route (e.g. if Finland would sign an LNG import contract with Papua New Guinea, for which reason ever), it could be reintegrated quickly.

Figure 4 demonstrates the structure of the node system for Africa as an example.

***Figure 4**: Transport system – example for Africa*



Source: Own illustration

3.5. Objective

As stated above, MAGELAN is a cost-minimisation model. The objective is to satisfy the world's gas demand with minimal costs as possible by given constraints. Total costs (*CW*) are compound of costs of gas production (*CP*) and gas transport (*CT*) as shown in Formula 1. All costs are sum up over all optimisation periods (*rt*) which are discounted with individual interest rates for production (*ip*) and transport (*it*).

$$(1) \qquad \underset{MIN}{CW} = \sum_{rt} \frac{CP_{rt}}{(1+ip)^{rt}} + \sum_{rt} \frac{CT_{rt}}{(1+it)^{rt}}$$

Production costs cover both capital (*CCP*) and operating (*OCP*) costs (Formula 2).

$$(2) \qquad CP_{rt} = CCP_{rt} + OCP_{rt}$$

Capital costs are calculated for each optimisation period as product of existing capacity in that specific period multiplied with an annuity factor (*acp*). The capacity consists of exogenous given capacity (*exop*) already installed in the past before the first optimisation period and capacity additions by the model (*CAP*). Both, annuity factor and capacities are individual for each production region (*pr*) and within those regions also for different classifications of resources (*cl*). These classifications could cover a wide range of different production conditions, ranging from super giants to small fields. Additionally, non-conventional resources such as shale gas could be implemented as separate classification levels. To consider the age structure of production facilities (which drives reinvestment needs), an additional time index (*at*) is implemented.

$$CCP_{rt} = \sum_{pr,cl} \sum_{at \le rt} ((exop_{pr,cl,at} + CAP_{pr,cl,at}) \cdot acp_{pr,cl,at,rt}) \tag{3}$$

Concerning operation costs of gas production, the majority of these costs are driven by capacity and only to a minor share by the actual production volumes (*PV*). The standard assumption is a split of 90:10 but of course, this could be changed easily. On the capacity related part, an annuity factor (*opp*) is multiplied with the existing capacity in each optimisation period (as before individual for each production region and resource classification). As could be seen in Formula 4, the capacity component could be lowered by a decommissioning of production facilities (*CDP*). By comparing with Formula 3 it becomes clear, that this decommissioning could avoid operation costs, but has no impact on the capacity costs (as these costs are sunk costs and will count for the objective relevant costs regardless if the production capacity is in operation throughout its planned lifetime or not).

$$\begin{aligned} OCP_{rt} = & \sum_{pr,cl} \sum_{at \le rt} (0{,}9 \cdot opp_{pr,cl,at,rt} \cdot (exop_{pr,cl,at} + CAP_{pr,cl,at} - CDP_{pr,cl,at})) \\ & + \sum_{pr,cl} (0{,}1 \cdot opp_{pr,cl,at,rt} \cdot PV_{pr,cl,rt}) \end{aligned} \tag{4}$$

The total transport costs consist of four elements: at first, as for production, capacity costs (*CCT*) and operation costs (*OCT*) for pipelines and LNG plants. In addition, costs for LNG ships (*CTS*) are included (but not allocated to a specific production region). Finally, also transit fees (*CTT*) for specific pipeline or LNG routes could be added to the total costs.

$$CT_{rt} = CCT_{rt} + OCT_{rt} + CTS_{rt} + CTT_{rt} \tag{5}$$

Capital costs for transport (Formula 6) have three subsegments with a comparable structure (Formulas 7, 8 and 9): capital costs for pipelines (*CCPIP*), LNG liquefaction plants (*CCLQ*) and LNG regasification plants (*CCRP*). All have an individual annuity factor (*acpip, aclq, acrp*) which is multiplied in each period with the historic given capacities (*exopip, exolq, exorp*) and the capacity additions as calculated by the model (*CAPIP, CALQ, CARP*). LNG facilities are allocated to a specific node in the system (*i*), whereas pipelines are defined as a connection between two nodes (*i to j*).

$$CCT_{rt} = CCPIP_{rt} + CCLQ_{rt} + CCRP_{rt} \tag{6}$$

$$CCPIP_{rt} = \sum_{i,j} \sum_{at \le rt} ((exopip_{i,j,at} + CAPIP_{i,j,at}) \cdot acpip_{i,j,at,rt}) \tag{7}$$

$$CCLQ_{rt} = \sum_{i} \sum_{at \le rt} ((exolq_{i,at} + CALQ_{i,at}) \cdot aclq_{i,at,rt}) \tag{8}$$

$$CCRP_{rt} = \sum_{i} \sum_{at \le rt} ((exorp_{i,at} + CARP_{i,at}) \cdot acrp_{i,at,rt}) \tag{9}$$

The treatment of operation costs of gas transport (Formula 10) is similar to the structure described above for operation costs of gas production. The operation costs for pipelines (*OCPIP*), liquefaction (*OCLQ*) and regasification plants (OCRP) are all split in a 90:10 ratio to a capacity related and a volume based component (*TV* as transported volume). The capacity component is a product of a specific annuity factor (*oppip, oplq, oprp*) with the existing capacity in every period. The capacities consist of historic built capacity (*exopop, exolq, exorp*) and new constructed facilities during the optimisation periods (*CAPIP, CALQ, CARP*). For LNG plants, the model has the option to deconstruct no longer needed capacity

(*CDLQ, CDRP*). For pipelines, this option is not implemented as a full recovery of pipelines out of the ground is rather uncommon in the gas industry. The operation costs are summarised in Formulas 11, 12 and 13.

$$OCT_{rt} = OCPIP_{rt} + OCLQ_{rt} + OCRP_{rt} \tag{10}$$

$$\begin{aligned} OCPIP_{rt} = & \sum_{i,j} \sum_{at \le rt} 0,9 \cdot oppip_{i,j,at,rt} \cdot (exopip_{i,j,at} + CAPIP_{i,j,at})) \\ & + \sum_{i,j} \sum_{sc} (0,1 \cdot oppip_{i,j,at,rt} \cdot TV_{sc,i,j,rt}) \end{aligned} \tag{11}$$

$$\begin{aligned} OCLQ_{rt} = & \sum_{i} \sum_{at \le rt} (0,9 \cdot oplq_{i,at,rt} \cdot (exolq_{i,at} + CALQ_{i,at} - CDLQ_{i,at})) \\ & + \sum_{i,j} \sum_{sc} (0,1 \cdot oplq_{i,at,rt} \cdot TV_{sc,i,j,rt}) \end{aligned} \tag{12}$$

$$\begin{aligned} OCRP_{rt} = & \sum_{i} \sum_{at \le rt} (0,9 \cdot oprp_{i,at,rt} \cdot (exorp_{i,at} + CARP_{i,at} - CDRP_{i,at})) \\ & + \sum_{i,j} \sum_{sc} (0,1 \cdot oprp_{i,at,rt} \cdot TV_{sc,i,j,rt}) \end{aligned} \tag{13}$$

The model does not include individual LNG ships which could be taken into account with their capacity costs. Instead, shipping costs (Formula 14) are covered by a transport volume related component. All LNG volumes between two nodes are multiplied with a specific annuity factor (*tcsh*) which also includes an overall component for capacity costs.

$$CTS_{rt} = \sum_{i,j} \sum_{sc} (tcsh_{i,j,rt} \cdot TV_{sc,i,j,rt}) \tag{14}$$

Optional, for some specific routes transit fees (*trans*) could be considered (Formula 15). These costs are in addition to all already included costs parameters. Examples for such transport cost increasing fees are the formerly transit payments of Russia to the Ukraine for using Ukrainian pipelines for exports to Western European countries or fees for passing the Suez channel.

$$CTT_{rt} = \sum_{i,j} \sum_{sc} (trans_{i,j,rt} \cdot TV_{sc,i,j,rt}) \tag{15}$$

3.6. Constraints

Formulas 16 and 17 describe equilibrium conditions for consumption and production regions. For both, the sum of all supplies (*SU*) has to cover the demand (*d*). For countries with exogenous given production, these volumes (*inpr*) reduce the demand which has to be covered by external suppliers.

$$d_{cr,rt} - inpr_{cr,rt} = \sum_{sc} SU_{sc,cr,rt} \tag{16}$$

$$d_{pr,rt} = \sum_{sc} SU_{sc,pr,rt} \tag{17}$$

Formula 18 shows a supply constraint for producers. The sum of supplies to consumption regions including transport losses (factor *lt*) must not higher than the sum of production of a supply country, also taking losses of production (factor *lp*) into account.

(18)

$$\sum_{cr} SU_{sc,cr,rt} + \sum_{i,j} (TV_{sc,i,j,rt} * lt_{i,j}) \leq \sum_{pr(sc)} \sum_{cl} PV_{pr,cl,rt} * (1 - lp_{pr,cl})$$

Several more constraints for producers are described in Formulas 19 to 21. The first one explains, that the produced volumes (PV) must be below or equal the existing capacity (which consists of historic plus new built minus decommissioned capacities, as already shown in Formula 4). Furthermore (Formula 20), produced volumes has to consider political or other upper bounds (*prcap*). This optional parameter could be used to implement political strategies such as the Dutch Groningen policy which limit the production volumes (in the past for resource protection and long-term optimisation reasons, nowadays due to earthquake risks). Finally (Formula 21), the produced volumes could only be as much as resources (*res*) are available.

(19) $$PV_{pr,cl,rt} \leq \sum_{at<rt} (exopr_{pr,cl,at} + CAP_{pr,cl,at} - CDP_{pr,cl,at})$$

(20) $$\sum_{cl} PV_{pr,cl,rt} \leq prcap_{pr,rt}$$

(21) $$\sum_{rt'<rt} PV_{pr,cl,rt'} \leq res_{pr,cl,rt}$$

The following three formulas deal with restrictions for transport. In general, the transported volume (left side of the formulas) must be lower or equal than the available capacity (right side). Formula 22 is for pipelines which nominal capacities are modified by an average utility factor (*alpip*) to consider non-availabilities due to planned maintenance etc. Same applies to liquefaction (*allq* in Formula 23) and regasification (*alrp* in Formula 24). For both LNG facilities, some losses on the transport volume side has to be considered (*llq, lrp*) as both treatment processes require some energy (so-called self-consumption).

(22) $$\sum_{sc} TV_{sc,i,j,rt} \leq \sum_{at<rt} ((exopip_{i,j,at} + CAPIP_{i,j,at}) \cdot alpip_{i,j})$$

(23) $$\sum_{sc} \sum_{j} (TV_{sc,i,j,rt} \cdot (1 + llq_i)) \leq \sum_{at<rt} ((exolq_{i,at} + CALQ_{i,at} - CDLQ_{i,at}) \cdot allq_i)$$

(24) $$\sum_{sc} \sum_{j} (TV_{sc,i,j,rt} \cdot (1 + lrp_i)) \leq \sum_{at<rt} ((exorp_{i,at} + CARP_{i,at} - CDRP_{i,at}) \cdot alrp_i)$$

The next two formulas are input/output constraints for consumption (Formula 25) and production (Formula 26) regions. Both have the same structure: on the left side, the output of every node is described. It consists of volumes with a further transport to other nodes and any supply remaining at the specific node (for final consumption). On the input side, transport losses (*ltr*) has to be taken into account, so that the input volume is somehow larger than the output volume. For production regions, produced volumes (again including a loss parameter) are also treated as an input (right side of Formula 26).

(25) $$\sum_{j} TV_{sc,i,j,rt} + SU_{sc,i,rt} \leq \sum_{j'} (TV_{sc,j',i,rt} \cdot (1 - ltr_{j',i}))$$

(26)

$$\sum_{j} TV_{sc,i,j,rt} + SU_{sc,i,rt} \leq \sum_{j'} \left(TV_{sc,j',i,rt} * (1 - ltr_{j',i})\right) + \sum_{cl} PV_{i,cl,rt} * (1 - lpr_i)$$

If long-term take-or-pay contracts are included in the model input data, then every supplier has to deliver at least the contracted volumes (*top*) to the contract partner (Formula 27). If the contracted volumes of one or more contracts in combination are more than the demand requirements of a specific node, than all contract volumes will be reduces pro-rata.

$$(27) \qquad SU_{sc,cr,rt} \geq top_{sc,cr,rt}$$

Formula 28 is a restriction to implement security of supply issues. The share of deliveries from a specific supplier in relation to the net-demand of a consumption region could be limited optional. This maximum share is defined as *mxsu*.

$$(28) \qquad \frac{SU_{sc,cr,rt}}{d_{cr,rt} - inpr_{cr,rt}} \leq mxsu_{sc,cr,rt}$$

4. Further Steps

The redesign of the model is only a first step. The most important next key milestone is the parameterisation of a reference scenario. Results from this model run are the benchmark for all coming variation runs, which means parameters have to be set carefully. When talking nowadays about a long-term supply model, then actually gas demand forecasts are a more crucial issue than production or transport parameters. Given climate policy, some countries are targeting to phase-out fossil fuels including natural gas during the forecast horizon of MAGELAN2. When taking climate action plans of some Western countries seriously, then a more or less sudden end could come – meaning that demand could erode from one period to another. This is clearly a new situation for gas modelling compared to 2006, when all demand forecasts showed in the same direction – strongly upwards.

In turn, resource scarcity on a global level doesn't seem to be a problem – the question is more, how expensive supply alternatives will get rather than if there are enough available. Even major consumers such as the USA, China or India have access to sufficient gas in place. However, the majority of these gas sources are not labelled as "reserves" but as more or less unknown "resources" in international statistics. Therefore, sensible assumptions on how many of these resources could be turned into reserves during the next decades have to be made. Furthermore, cost information on these resources are only very limited available, so a classification system and a cost model for resources seems to be appropriate.

On the geographical coverage, in principle every country in the world could be included as a production region. By this, also for the minor producers (or countries that didn't entered the gas market yet) no exogenous assumptions about their future production volume are necessary. In contrast to 2006, computer performance is no limiting factor anymore. However, as usual, there is a trade-off between a as wide as possible model coverage on the one side and calculation time and clarity of model files on the other side. So, it is doubtful, if transferring countries like Italy, Tunisia or Colombia into production nodes respectively the implementation of South Sudan or Nepal actually has any impact on model results and their overall quality.

Finally, one need to think towards the end of the gas industry. Obviously, no gas market model is needed if no gas market is left in reality. However, there will be a very long transitional phase, in which another gas might take over parts of natural gas demand and also using parts of the existing infrastructure: hydrogen. Depending on the speed and extent of a hydrogen world market start-up, it might be an interesting option to include hydrogen in a gas market model. However, given the fundamentally different economic framework and an expected fast ramp-up of hydrogen, a new development of a stand-alone hydrogen model might be more suitable.

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