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Mathematical modelling of natural gas market

BTU Cottbus-Senftenberg
Chair of Energy Economics
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Content:

1. Why do we model gas market?
2. What was achieved already in this field?
3. What is inside a black box?
4. Where to find data?
5. How to apply it?

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Globalization process

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	Local gas markets 1800s–1970	Regional gas markets 1970–2005	Globalized gas market 2005–2020
Major markets	• USA • Italy • Netherlands	• North America • FSU/Russia • Western Europe • North East Asia (Japan, Korea)	• North America • Russia • Western Europe • North East Asia (Japan, Korea, China, India)
Main supply routes	• Local USA pipelines – SouthWest–Chicago – SouthWest–Appalachia – Texas–NorthEast • Local European pipelines	• Intra-regional pipelines – Canada–USA – Russia–Central Europe – Norway/Netherlands–West Europe – Algeria–Italy • Regional LNG	• Long-distance pipelines – Russia–China – Middle East–India – Middle East–Europe – North Africa–Europe • Global LNG arbitrage – Middle East – Atlantic Basin – Pacific Basin
Tech-nologies	• Basic pipelines	• Long-distance pipelines • LNG liquefaction and shipping	• Arctic E&P/LNG • Unconventional gas • CNG

Source: Kepis&Pobe based on Victor et al. (2006)

European policy on a political background

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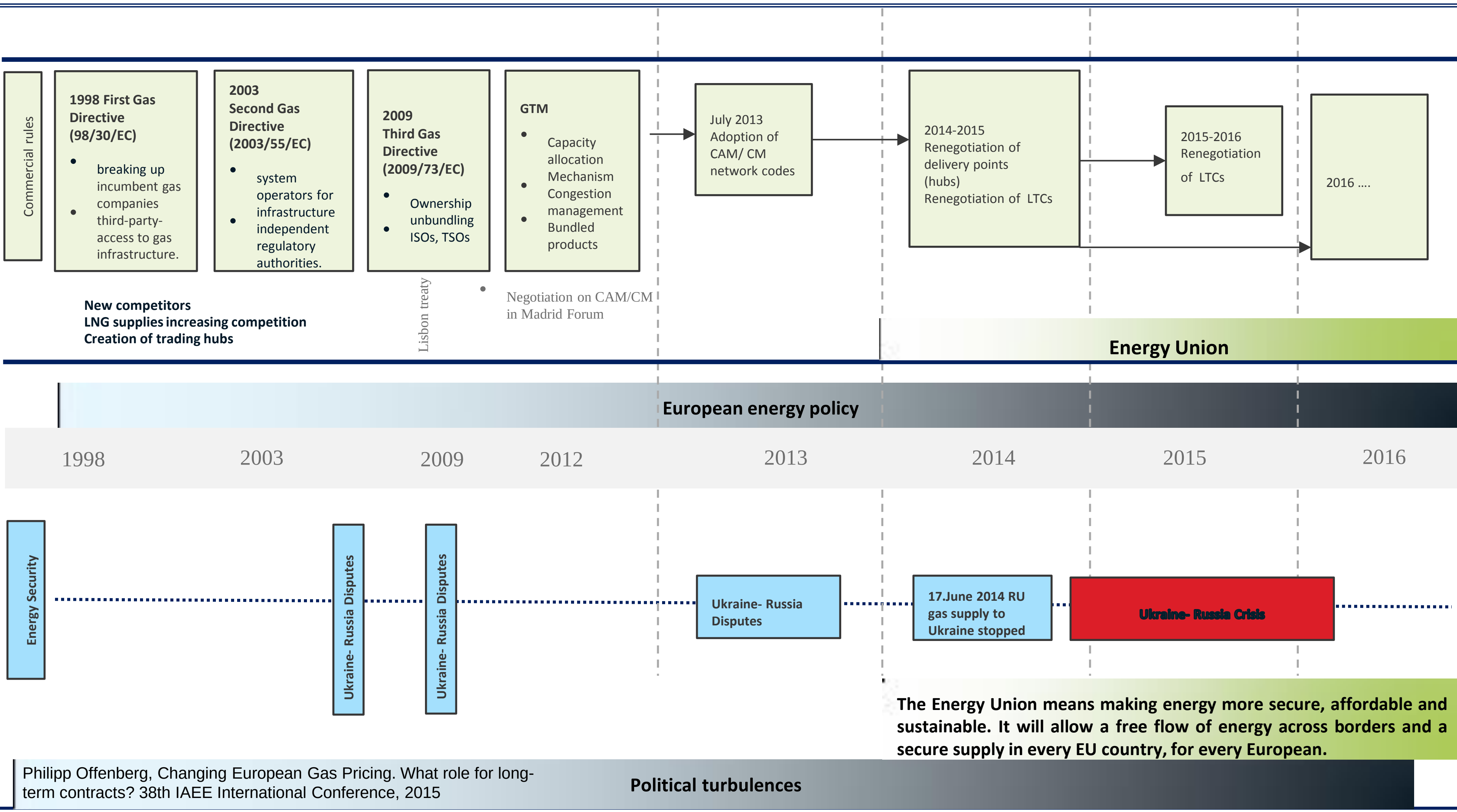

European gas production vs gas consumption

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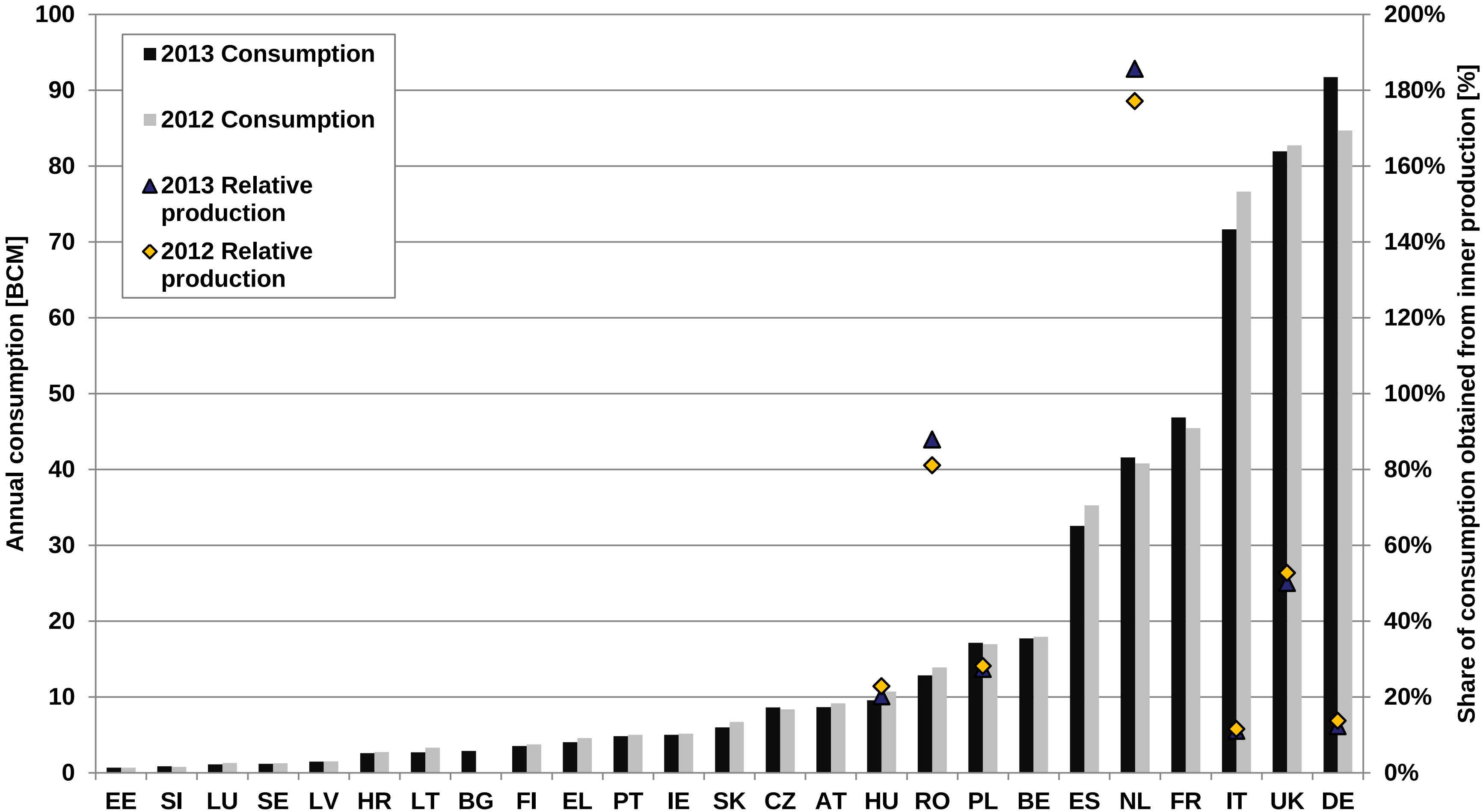
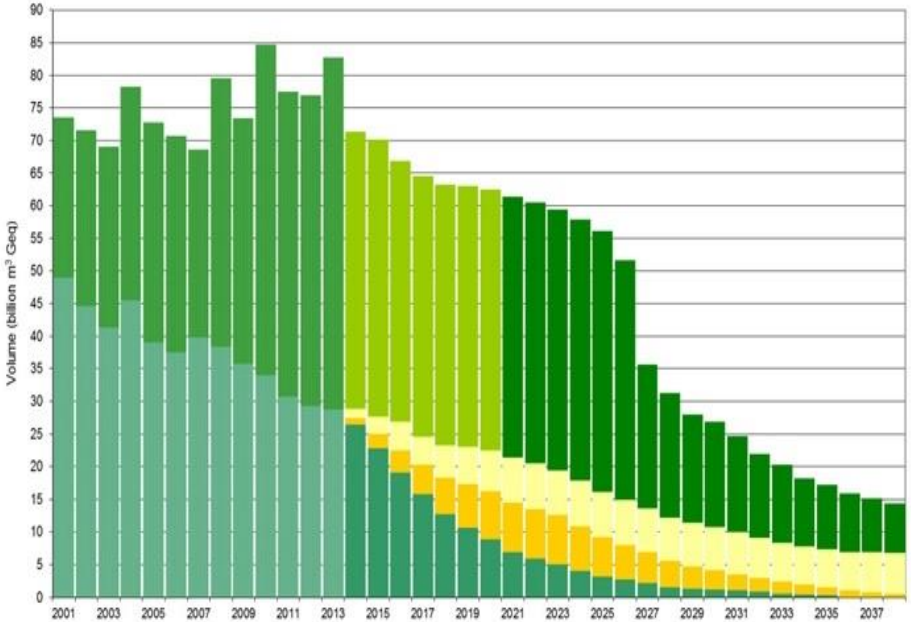


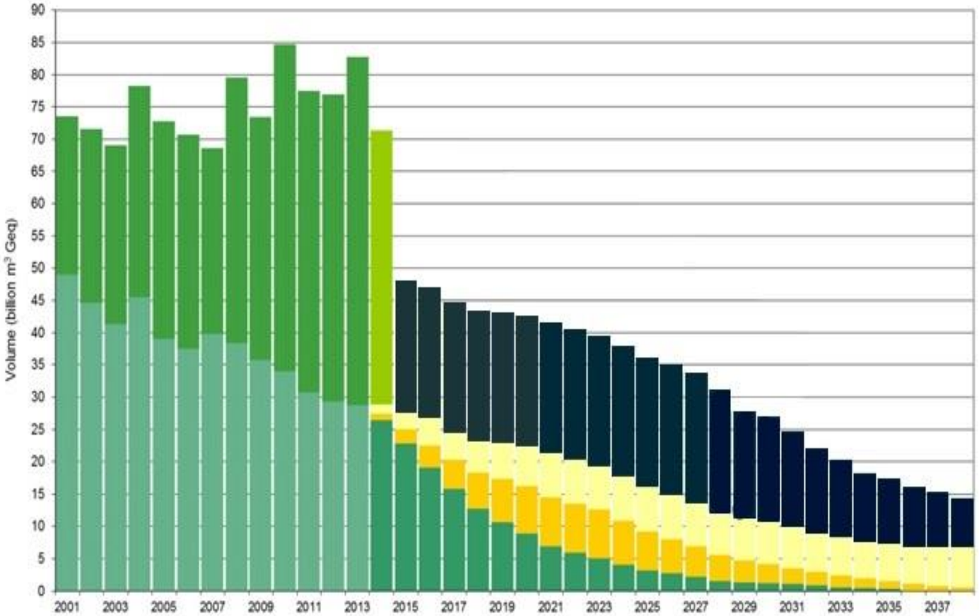
Based on data from EUROSTAT

Netherlands: actual production and prognosis

Actual production of natural gas in the Netherlands from 2001 - 2013 and production prognosis for the period 2014 - 2038



"Groningen production cap scenario"



- Historical production 'small fields'
- Historical production Groningen Field
- Expected supply from Reserves (PRMS)
- Expected supply from aContingent Resources (PRMS)
- Expected supply from as yet undiscovered accumulations
- Expected supply Groningen accumulation based on production plan (from 2021 onwards)
- Proportionally profiled production allowance Groningen accumulation (2011 - 2020)

"As yet no final decision has been taken on the updated production plan for the Groningen field, a production cap of 42 billion m3 in 2014 and 2015 and 40 billion m3 in 2016 is proposed. After these three years the situation will be evaluated to decide on further measures concerning production restrictions"

Ministry of Economics Affairs report, Netherlands, 2013.

European additional demand forecast:

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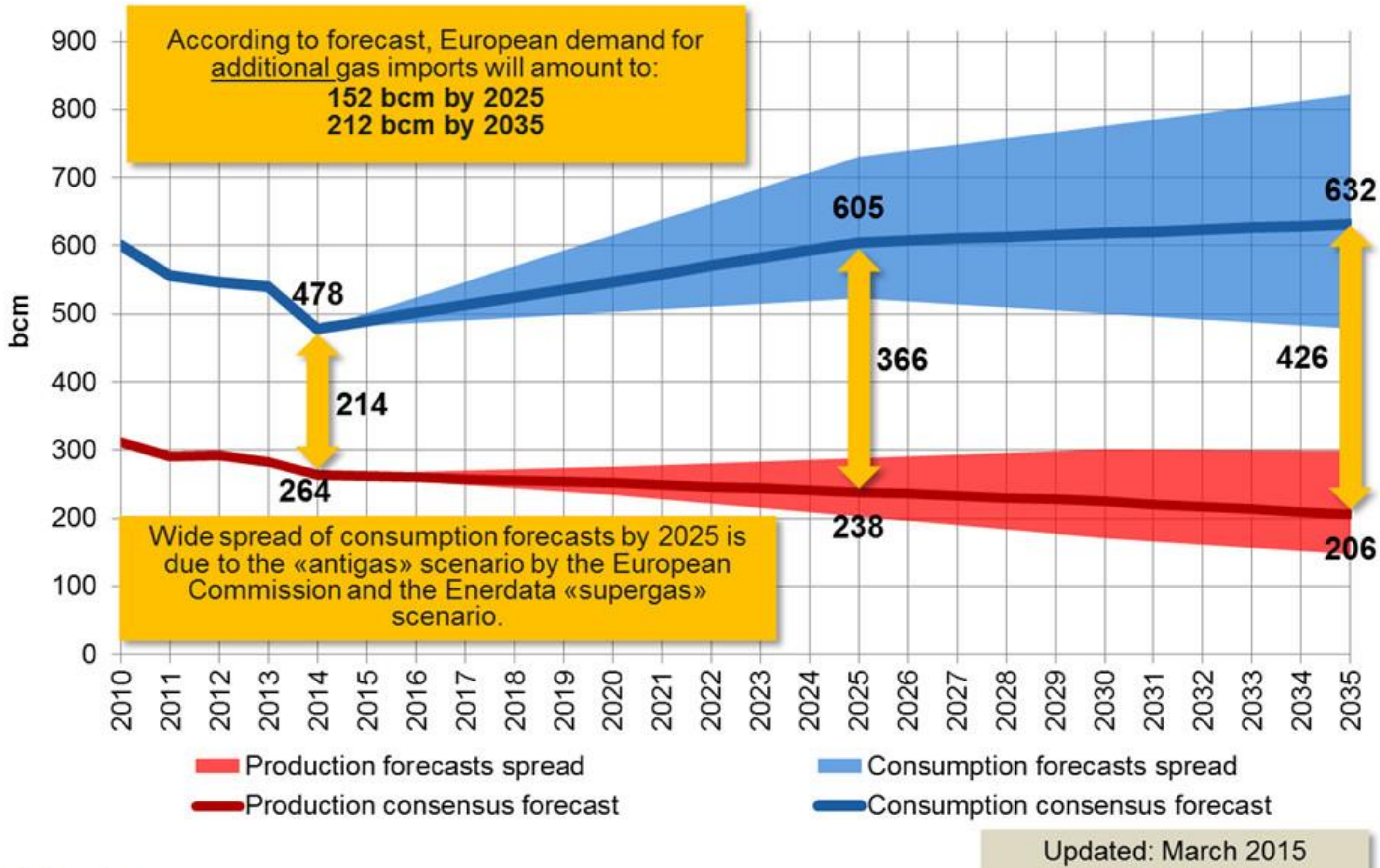
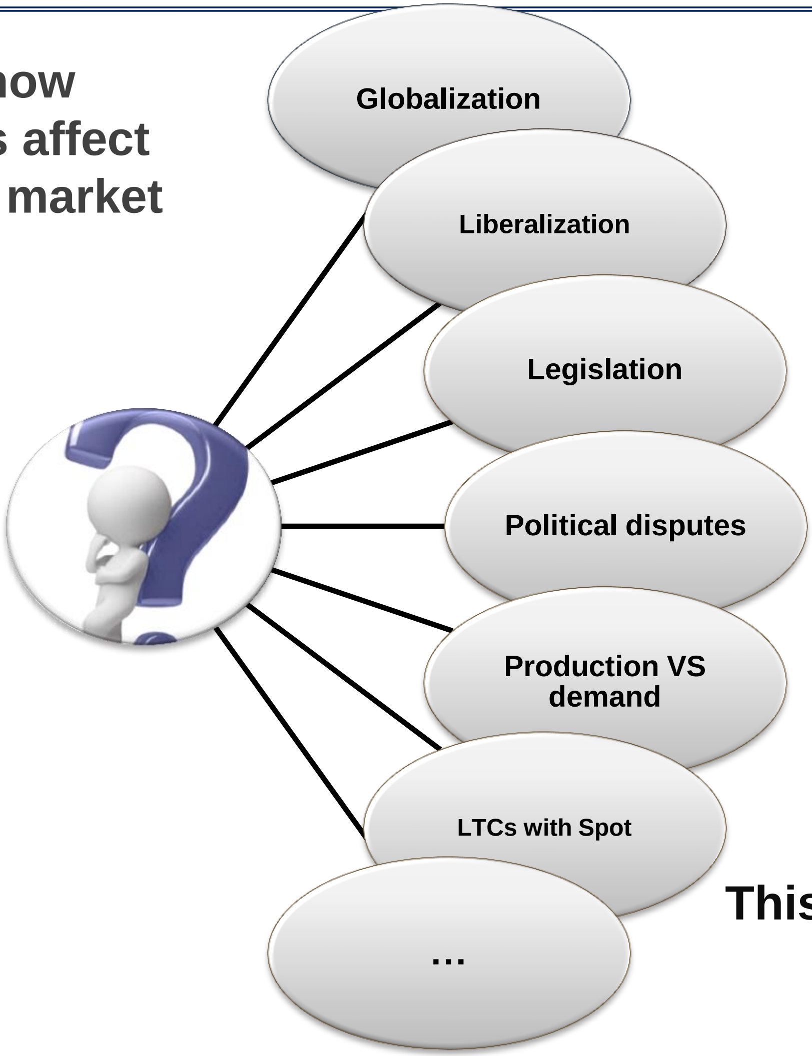
Due to falling indigenous production European demand for additional gas imports could be 152 bcm by 2025 and 215 bcm by 2035



Source: FLAME: Sergey Komlev, Gazprom Export

Why do we model gas market?

Need to understand how mentioned processes affect each other and a gas market in general



This creates a demand for a complex analysis and mathematical modelling

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Gas market models

Name	Author	Type	Region	MP	Nodes	Time Scale	Time resolution	Seasons	Dynamics
NEMS	EIA U.S.	LP	North America	no	15	2030	1 year	2	yes
ICF GMM	ICF Int.	NLP	US	no	114	several years	monthly	12	no
WGM	Egging	MCP	World	yes	41	2030	5 years	2	yes
FRISBEE	Statistics Norway	PE	World	no	13	2030	1 year	1	yes
COLUMBUS	Hecking and Panke, EWI	MCP	World	yes	-	2050	monthly(?)	12(2)	yes
GASMOD	Holz, DIW Berlin	MCP	Europe	yes	6	2025	10 years	1	yes
GASTALE	Lise and Hobbs	MCP	Europe	yes	19	2030	5 years	3	yes
TIGER	Lochner et al., EWI	LP	Europe	no	-	2020	monthly	12	yes
NATGAS	Zwart and Mulder	MCP	Europe	yes	-	2035	5 years	2	yes
-	**BTU LSEW**	**MCP NLP LP**	**Europe World(coming)**	**yes**	**>80**	**2030**	**Monthly Quarterly Yearly**	**12**	**yes**

Gas market models

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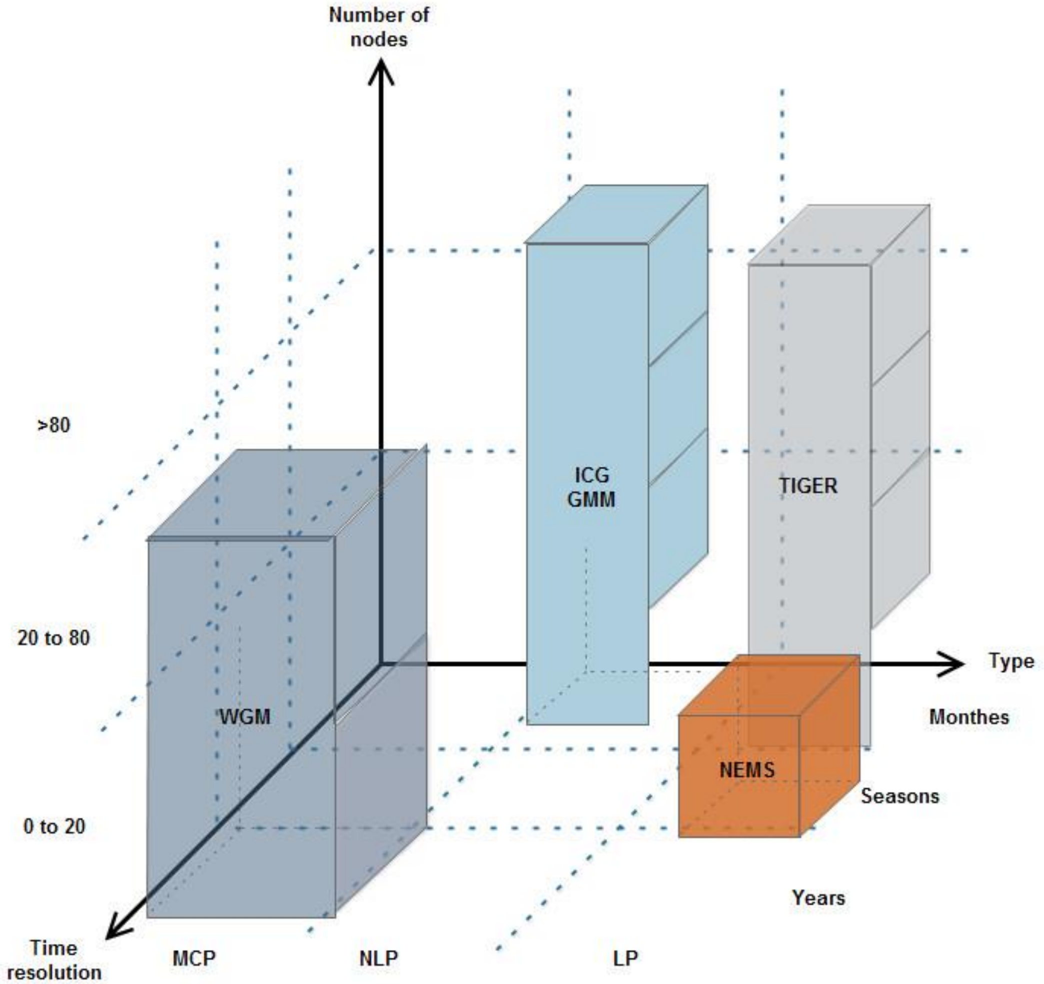
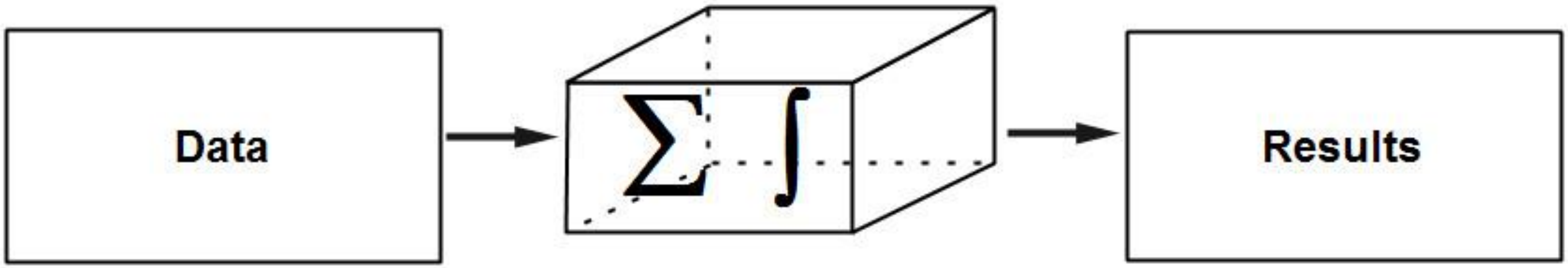
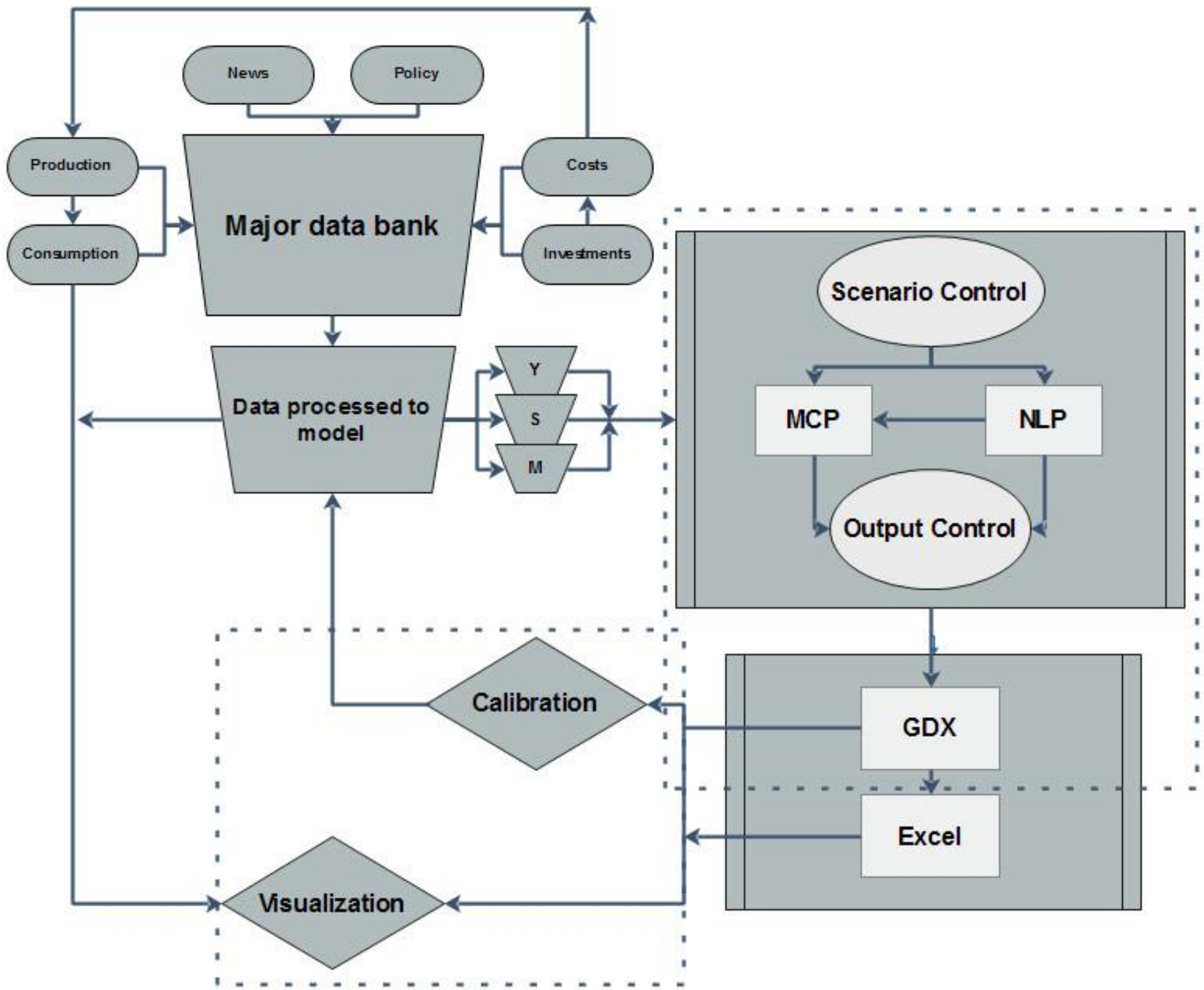


Content:

“I’m not a modeller”’s point of view



Model architecture: schematic overview



Model architecture: schematic overview

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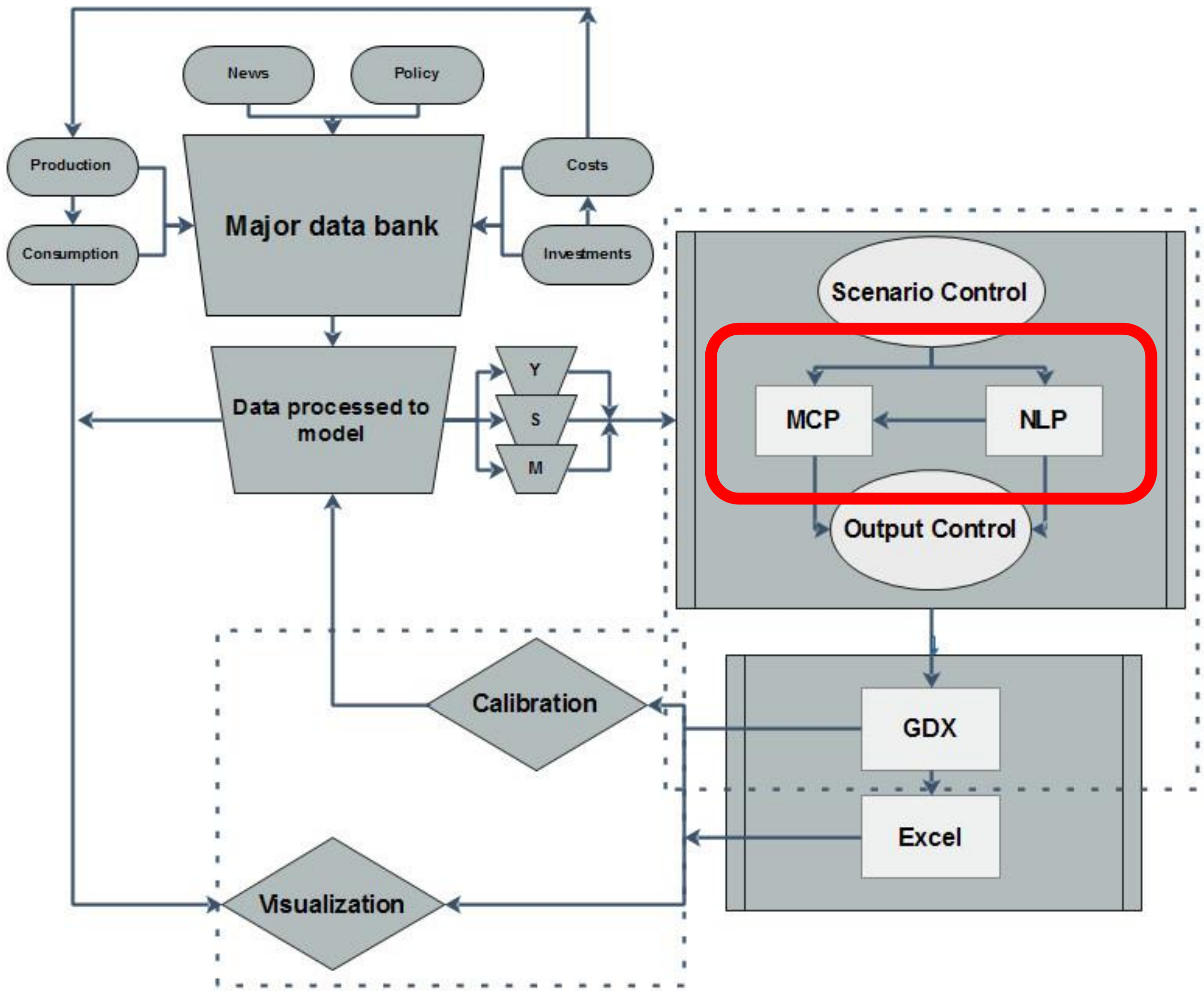

MCP and LP/NLP formulations

- MCP (mixed complementarity programming) and LP (linear programming) are a common modelling approaches that allow to describe various energy markets around the world.

- Complementarity models generalize linear programs (LP), quadratic programs (QP) and (convex) nonlinear programs (NLPs)

  - ✓ Complementarity problems are appropriate for modelling the regulated/deregulated, perfect/imperfect competition that characterizes today's energy markets

  - ✓ Linear programming allows to solve huge and computationally difficult problems

Types of optimization problems

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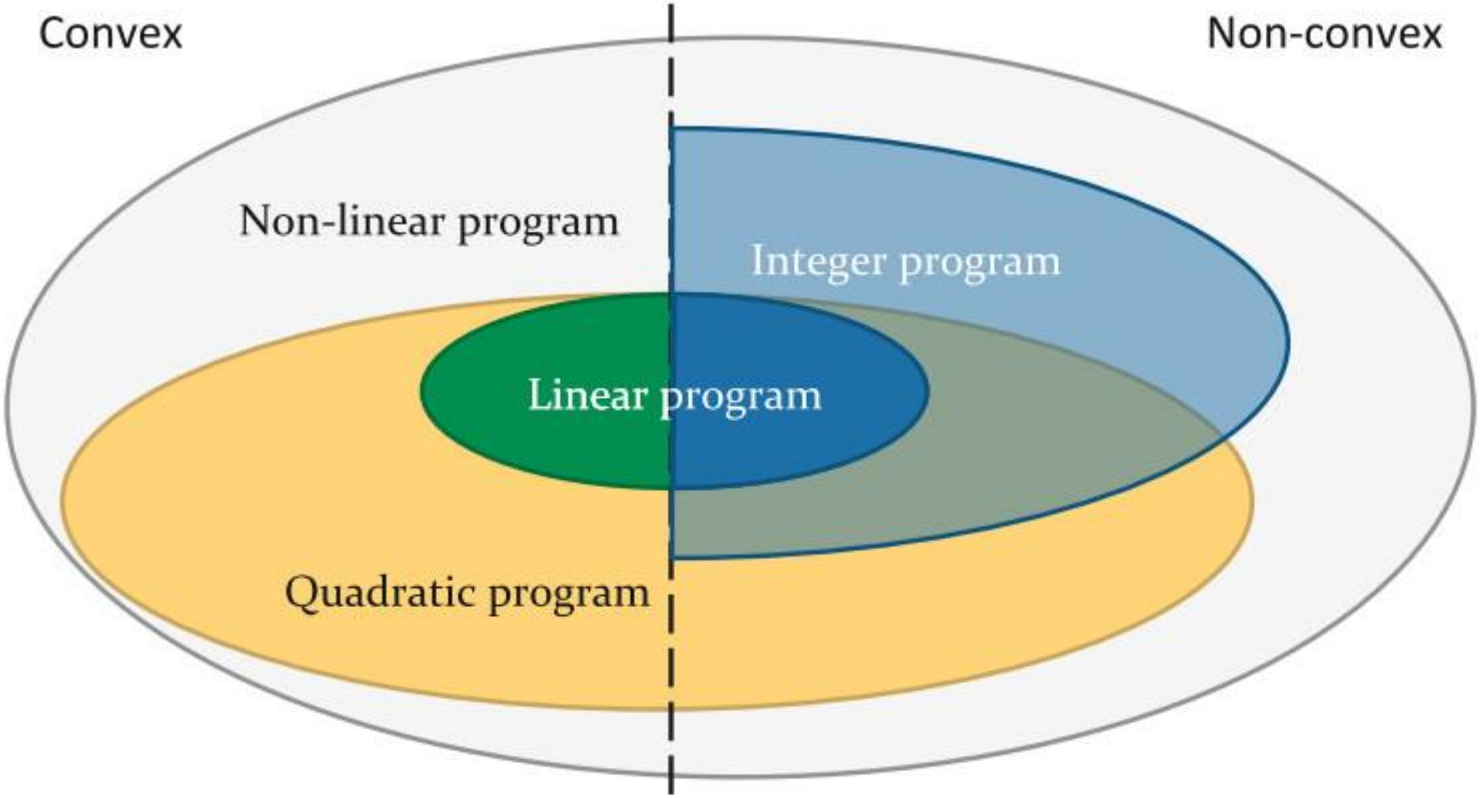
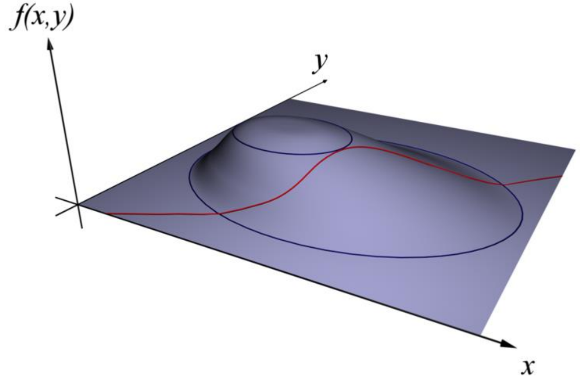


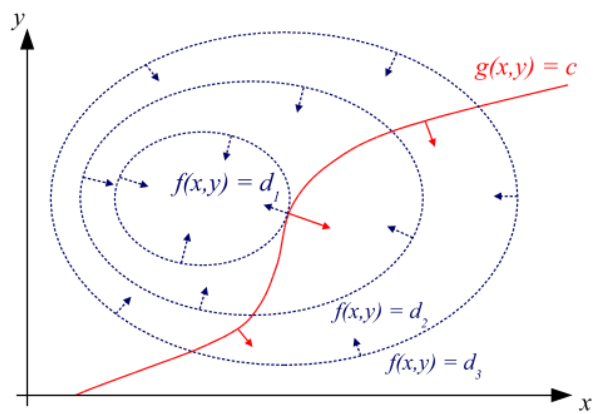
InfraTrain 2014 – One and Two-level Energy Market Equilibrium Modelling,
Daniel Huppmann

In mathematical optimization, the method of Lagrange multipliers *is a strategy for finding the local maxima and minima of a function subject to equality constraints:*



$$max\, f(x,y)$$

$$s.t.\, g(x,y) = c$$



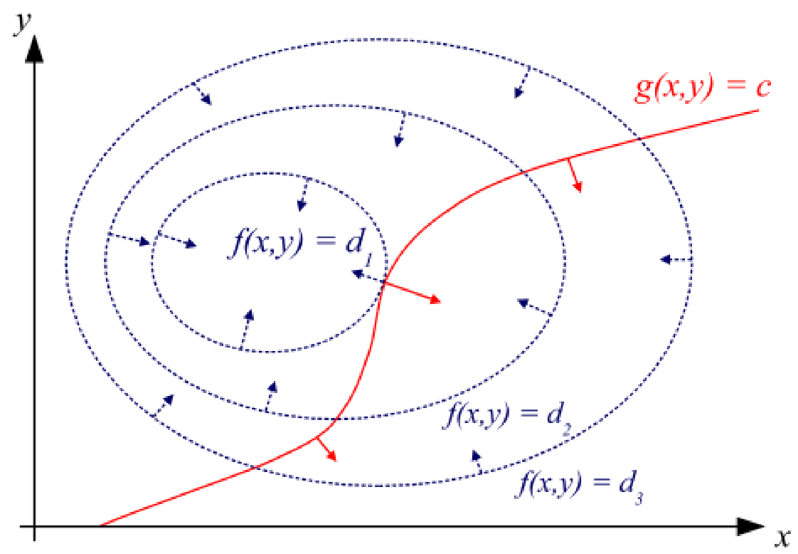
Where f(x,y) – objective function
g(x,y) - constraint

In mathematical optimization, the method of Lagrange multipliers *is a strategy for finding the local maxima and minima of a function subject to equality constraints:*

$$max\, f(x, y)$$

$$s.t.\, g(x, y) = c$$

Key point: 2 curves are tangent at the same point -> i.e. they have the same slope



MCP / Method of Lagrange multipliers

In mathematical optimization, the method of Lagrange multipliers *is a strategy for finding the local maxima and minima of a function subject to equality constraints:*

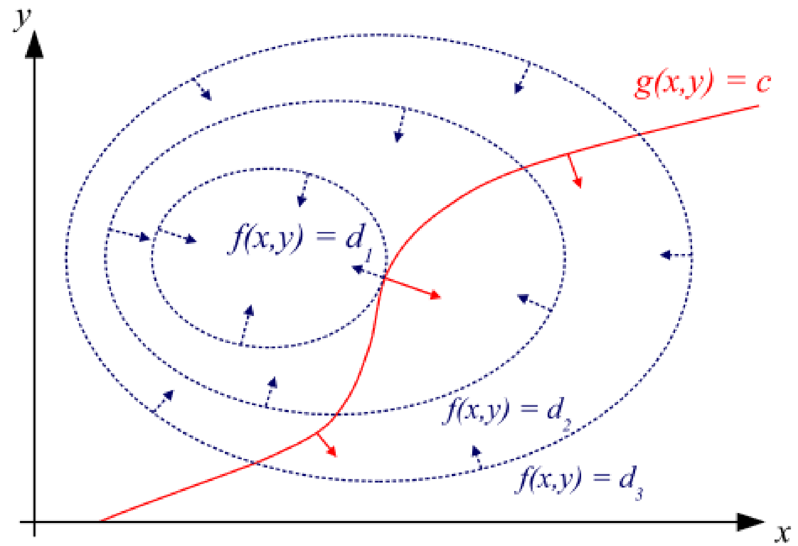
$$max\ f(x,y)$$

$$s.t.\ g(x,y) = c$$

$$\nabla f(x,y) = \frac{\partial f}{\partial x}, \frac{\partial f}{\partial y}$$

$$\nabla g(x,y) = \frac{\partial g}{\partial x}, \frac{\partial g}{\partial y}$$

Gradient of the function shows the direction of the max increase of the function:

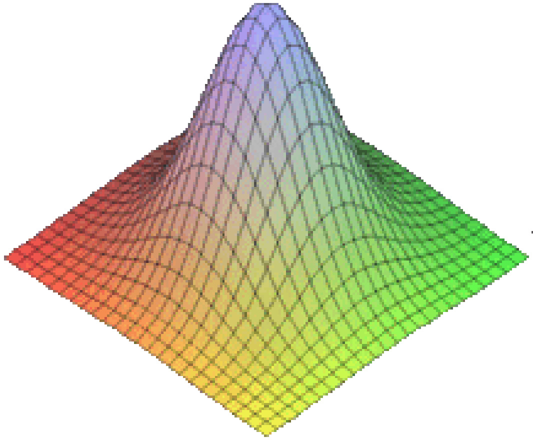


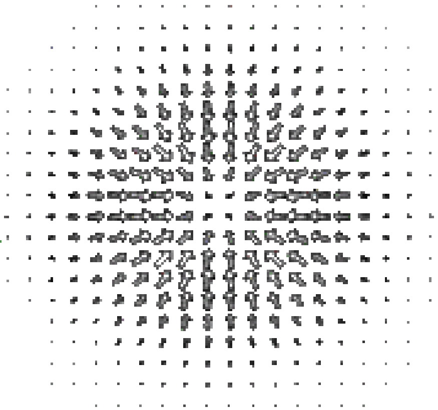
In mathematics, the gradient is a *generalization of the usual concept of derivative of a function in one dimension to a function in several dimensions.*

- ✓ Gradient points in the direction of the greatest rate of increase of the function and its magnitude is the slope of the graph in that direction

$$\nabla f = \frac{\partial f}{\partial x_1}\mathbf{e}_1 + \cdots + \frac{\partial f}{\partial x_n}\mathbf{e}_n$$

where the e_i are the orthogonal unit vectors pointing in the coordinate directions.





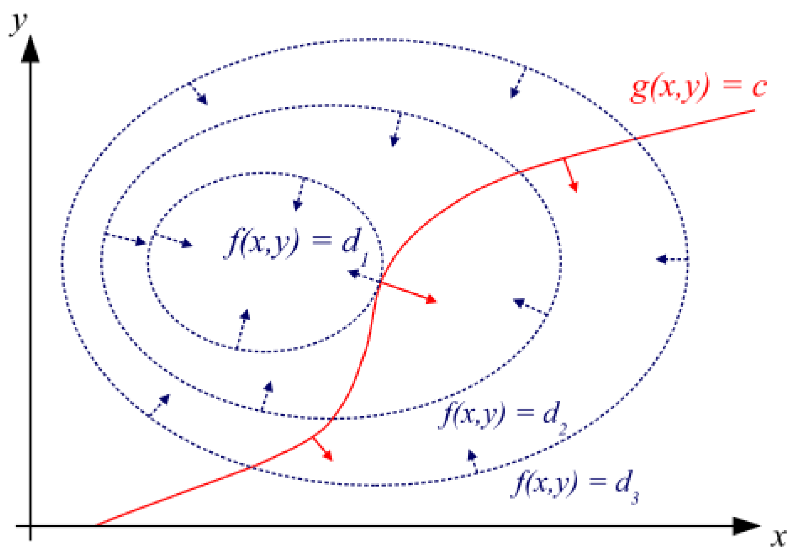
In mathematical optimization, the method of Lagrange multipliers *is a strategy for finding the local maxima and minima of a function subject to equality constraints:*

$$max\ f(x,y)$$

$$s.t.\ g(x,y) = c$$

If 2 vectors are orthogonal to the same slope, it has to be the case that they are parallel:

$$\nabla f(x,y) = \lambda \cdot \nabla g(x,y)$$



MCP / Method of Lagrange multipliers: economical interpretation

- ✓ In economics the optimal profit to a player is calculated subject to a constrained space of actions, where a Lagrange multiplier *is the change in the <u>optimal value of the objective function (profit)</u> due to the <u>relaxation of a given constraint</u>*

$$\nabla f(x, y) = \lambda \cdot \nabla g(x, y)$$

⇓

$$\frac{\partial L(x, y)}{\partial g(x, y)} = \lambda$$

in such a context λ is the <u>marginal cost</u> of the constraint, and is referred as the <u>shadow price</u>

MCP / Karush–Kuhn–Tucker conditions

- ✓ The Karush–Kuhn–Tucker (KKT) conditions *are first order necessary conditions for a solution in nonlinear programming to be optimal*, provided that some regularity conditions are satisfied.

- ✓ Allowing inequality constraints, the KKT approach applied to nonlinear programming generalizes the method of Lagrange multipliers, which allows only equality constraints.

MCP / Karush–Kuhn–Tucker conditions

- Let us consider the problem:

$$\min F(x) \tag{1.1}$$

$$s.t. \quad g_i(x) \leq 0 \quad (\lambda_i) \qquad \forall i = 1, \dots n \tag{1.2}$$

$$h_i(x) = 0 \quad (\mu_i) \qquad \forall j = 1, \dots m \tag{1.3}$$

- For this problem, the KKT conditions are:

$$\nabla f(x) + \sum_{i=1}^{n} \lambda_i \nabla \mathrm{g}_i(\mathrm{x}) + \sum_{j=1}^{n} \mu_i \nabla \mathrm{h}_j(\mathrm{x}) = 0 \tag{1.4}$$

$$0 \geq g_i(x) \perp \lambda_i \geq 0 \qquad \forall i = 1, \dots n \tag{1.5}$$

$$0 = h_i(x) \qquad \mu_j \text{ free} \qquad \forall j = 1, \dots m \tag{1.6}$$

The solution stationarity is ensured by the equation (1.4). Equations (1.5) and (1.6) ensure complementarity and feasibility of a solution

Source: [1]

How do we use MCP?

Let us provide the following illustration of such a mathematical structure based on a simple problem faced by a gas producer:

$$\max_{q \geq 0} \Pi = qp(q) - C(q) \qquad (1.7)$$

$$s.t.\, q \leq Q \qquad (1.8)$$

where:

q - gas sales

p(q) - affine inverse demand function

C(q) – production cost function

How do we use MCP?

The KKT conditions for this problem are:

$$0 \leq q \perp p + (\frac{\partial p}{\partial q} q) - C'(q) + \lambda \leq 0 \tag{1.9}$$

$$0 \leq \lambda \perp (q - Q) \leq 0 \tag{1.10}$$

Equation (1.9) is a short way to express the following complementarity problem:

$$0 \leq q$$

$$p - C'(q) + \lambda \leq 0$$

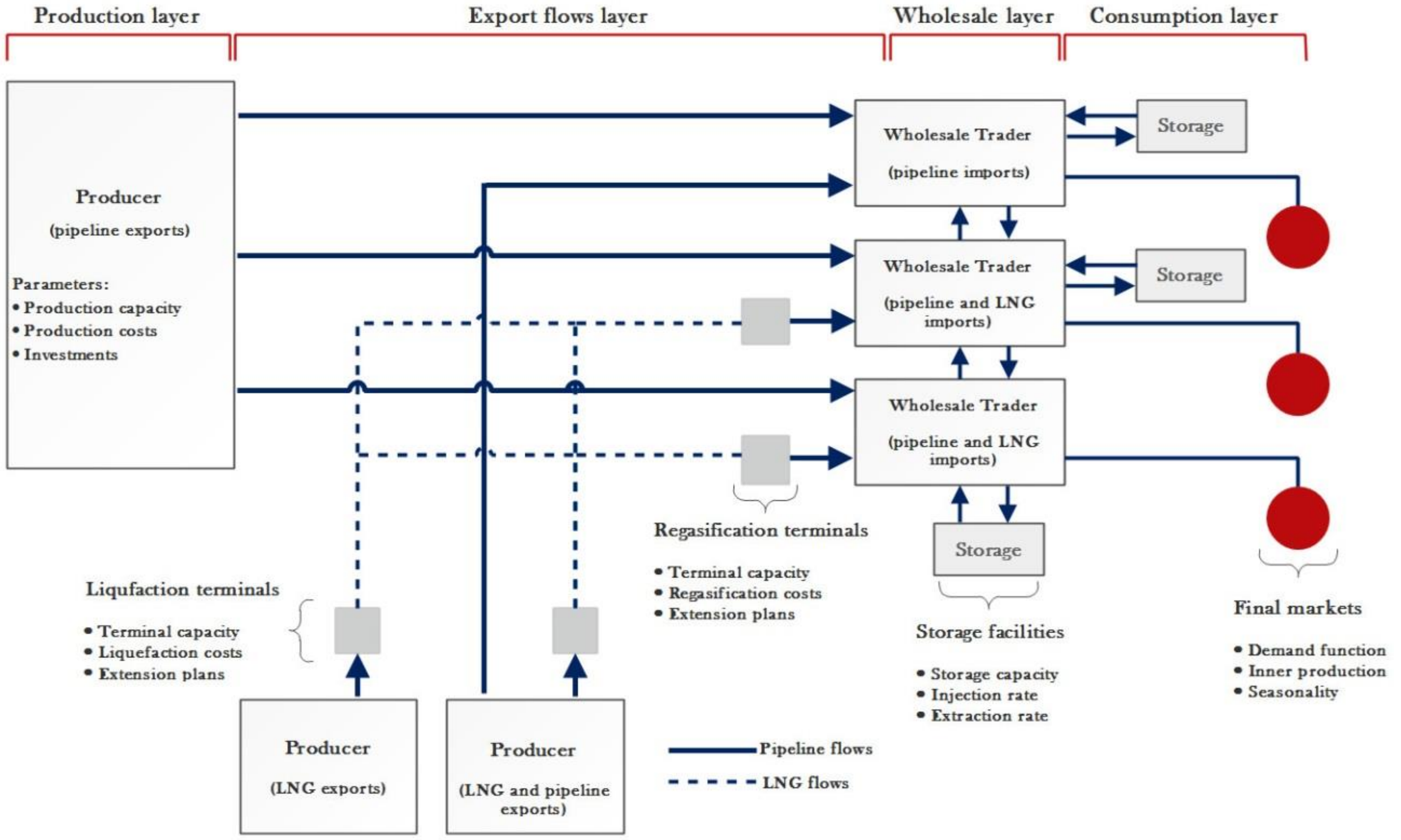
$$q(p - C'(q) + \lambda) = 0$$

where symbol ⊥ states orthogonality

Solving MCPs

- ✓ The complementarity model of a market is done by combining the KKTs of all market players with market clearing conditions.
- ✓ Numerical problems in MCP format can be efficiently solved with PATH solver by using the GAMS software.
- ✓ The General Algebraic Modelling System (GAMS) is a modeling system used for mathematical programming and optimization. GAMS is designed to model complex and large-scale problems, such as: LP, NLP, MIP, MINLP, etc.

Model structure: schematic overview



Network representation

- ✓ Market participants as producers, wholesale traders, final consumers, LNG terminals are represented in the model as nodes (*N*)
- ✓ There is a list of activities possible to happen in certain node accordingly to its geographical location: *production, export, import, consumption*
- ✓ All nodes in the model are interconnected through arcs. Data for the existing European gas infrastructure was taken from ENTSOG. Arcs have exogenously assigned capacity $cap_{n,m}^{pipe}$ in bcm/a
- ✓ Pipeline interconnections are modelled only by one-directional arcs, although transmission pipelines theoretically could be bidirectional. Gas flows which have to be feasible in two directions are achieved via two one-directional arcs
- ✓ The model neglects gas friction and pressure drops in the network

MCP vs NLP

$$\min F(x)$$
$$s.t. \quad g_i(x) \leq 0 \quad (\lambda_i) \quad \forall i = 1, \dots n$$
$$h_i(x) = 0 \quad (\mu_i) \quad \forall j = 1, \dots m$$
$$\nabla f(x) + \sum_{i=1}^{n} \lambda_i \nabla g_i(x) + \sum_{j=1}^{n} \mu_i \nabla h_j(x) = 0$$
$$0 \geq g_i(x) \perp \lambda_i \geq 0 \qquad \forall i = 1, \dots n$$
$$0 = h_i(x) \qquad \mu_j \text{ free} \qquad \forall j = 1, \dots m$$

$$\min \sum_{J=1}^{n} f_j(x_j)$$
$$s.t.$$
$$\sum_{j=1}^{n} a_{ij} x_j \geq b_i$$
$$0 \leq x_j \leq u_j$$
$$(i = 1 \dots . m); \; (j = 1 \dots . n)$$

Mixed complementarity problem (MCP)

- KKT 1
- …
- KKT n

Subject to:

- Constraints *(capacity, balances, clearings)*

Nonlinear problem (NLP)

- Objective function (maximization of social welfare)

Subject to:

- Constraints *(capacity, balances, clearings)*

Content:

Infrastructure: data is fully available and transparent

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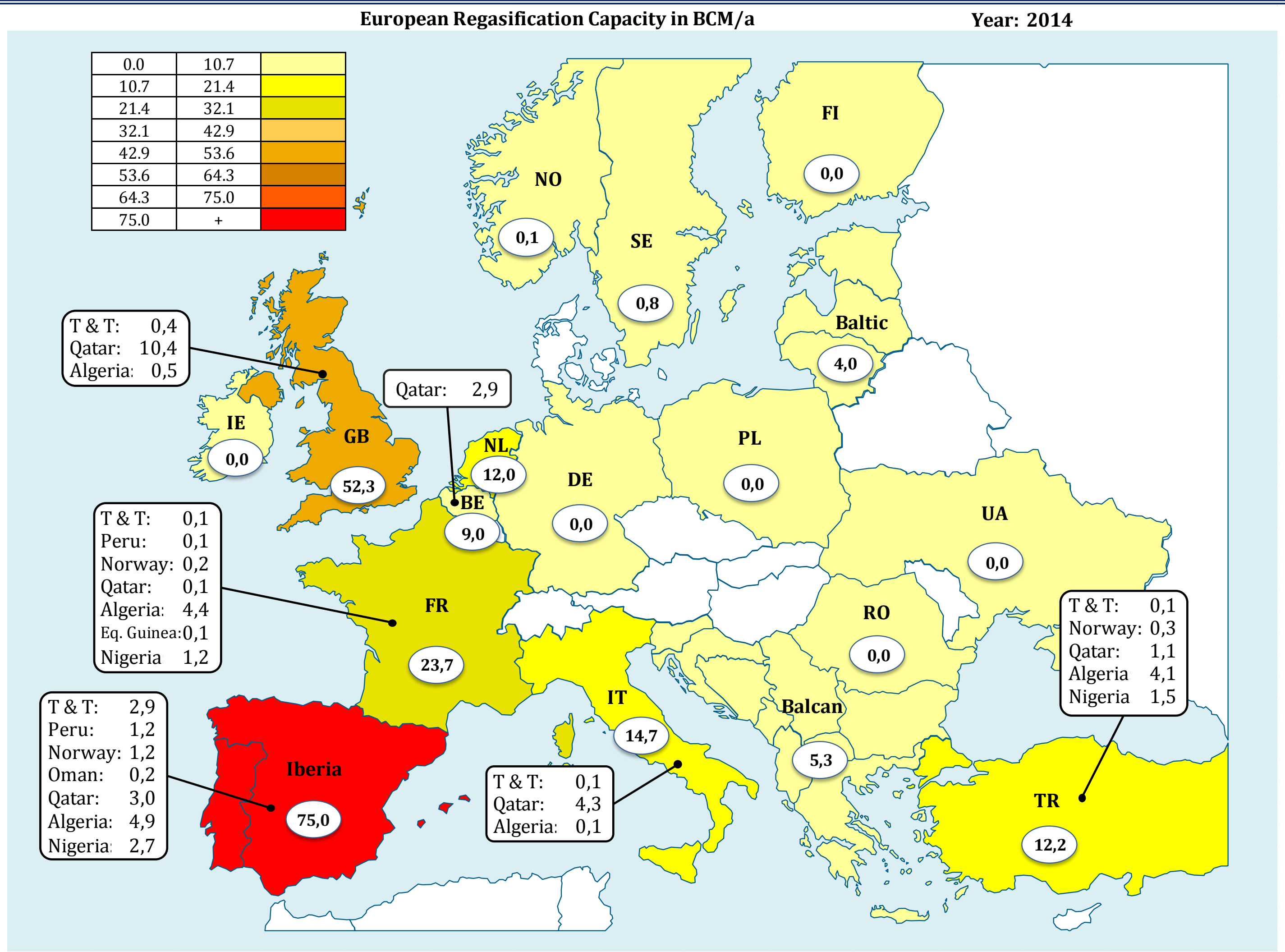
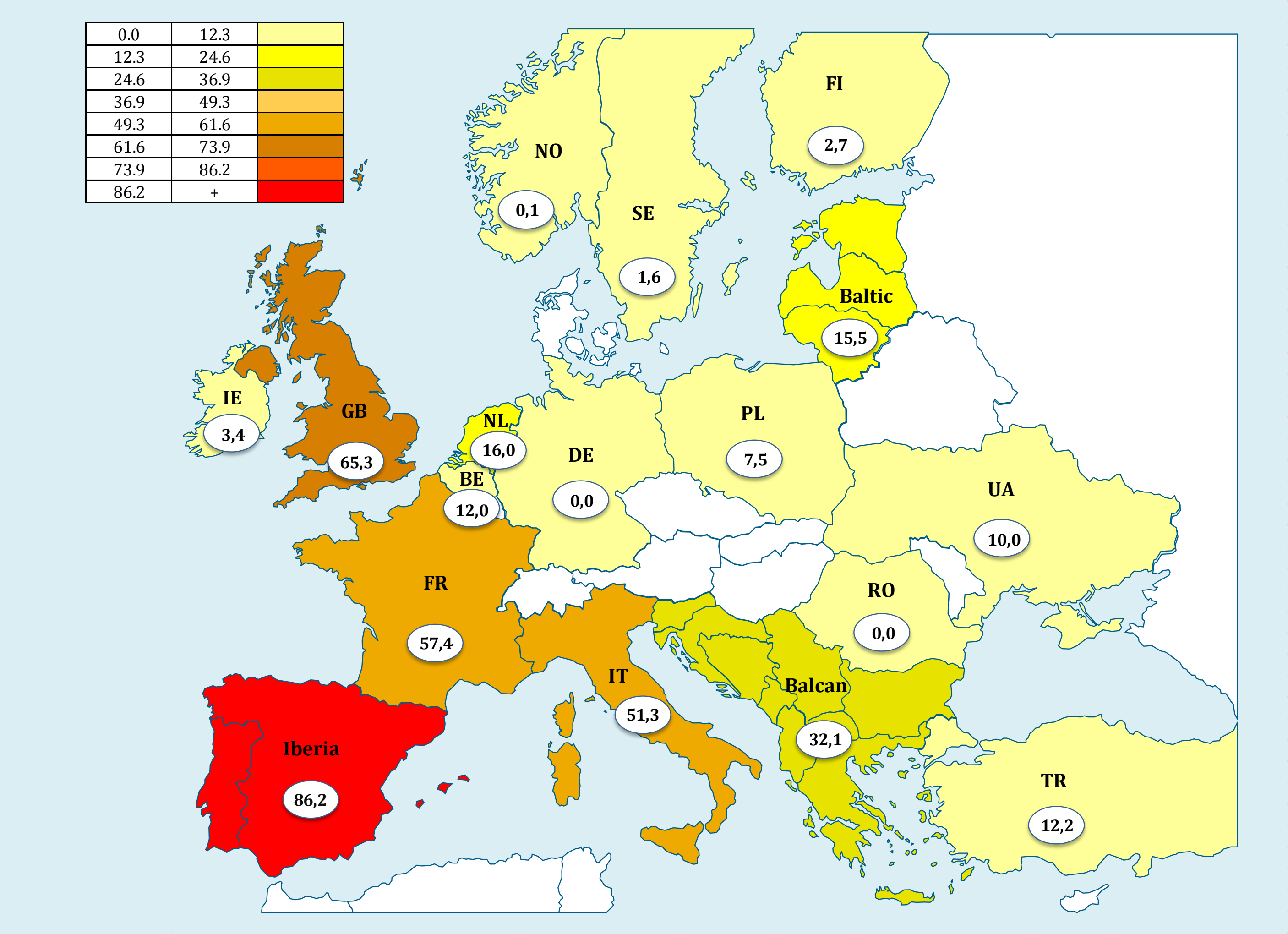
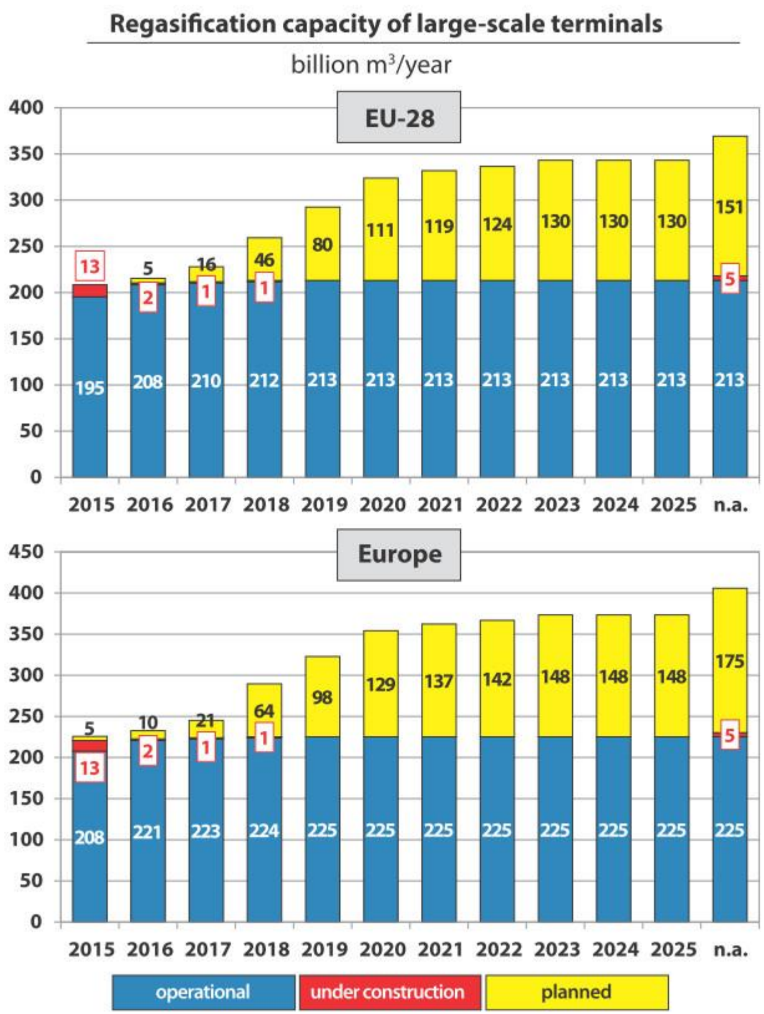


Infrastructure: data is fully available and transparent

European Regasification Capacity in BCM/a **Year: 2025**



Infrastructure: data is fully available and transparent



Annual regasification capacity of large-scale LNG import terminals per country

billion m³(N)/year

	operational	under constr.	planned
BELGIUM	9		3
CROATIA			6
ESTONIA			7
FINLAND			3
FRANCE	22	13	23
GREECE	5	2	11
IRELAND			3
ITALY	15		37
LATVIA			5
LITHUANIA	4		
MALTA			2
NETHERLANDS	12		4
POLAND		5	3
PORTUGAL	8		
ROMANIA			8
SPAIN	69	3	7
UK	52		26
TOTAL EU	**195**	**23**	**146**
ALBANIA			8
TURKEY	12		6
UKRAINE			10
TOTAL EUROPE	**208**	**23**	**170**

Number of LNG import terminals per type

	operational	under constr.	planned
LARGE-SCALE	24	4	22
FSRU & OTHERS	3		7
SMALL-SCALE	4	4	4
TOTAL	**28**	**8**	**26**

Consumption: some assumptions have to be made

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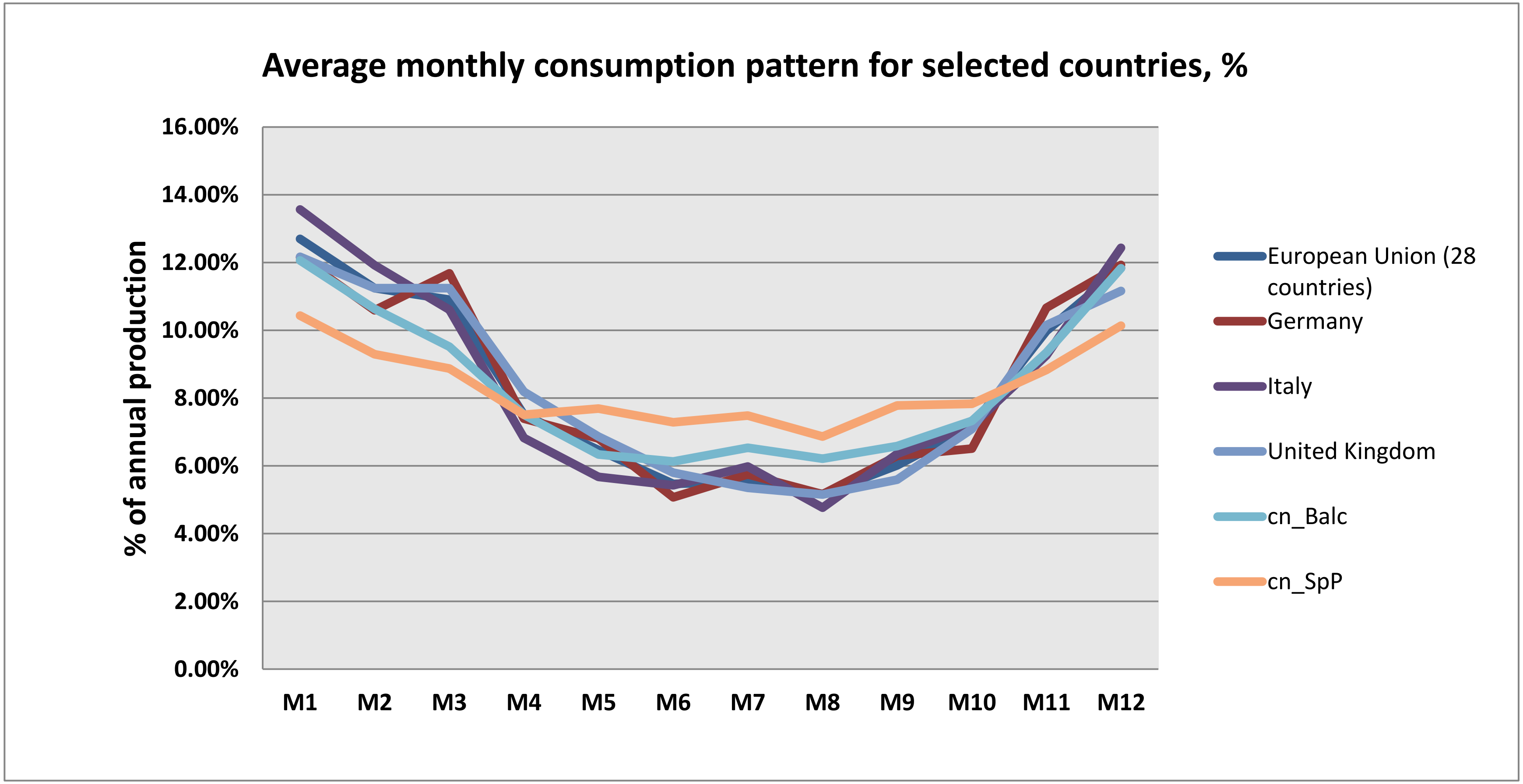

LNG shipping costs: very complex to acquire data

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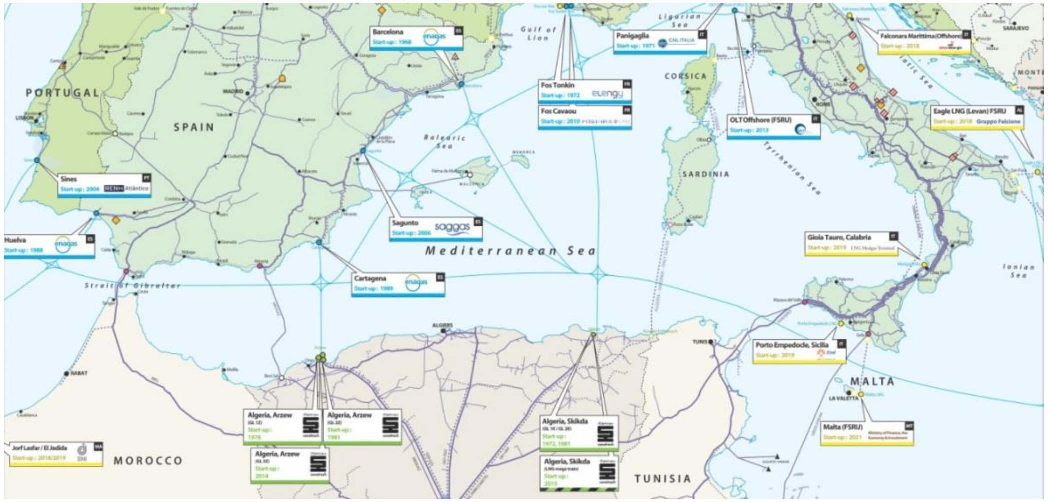

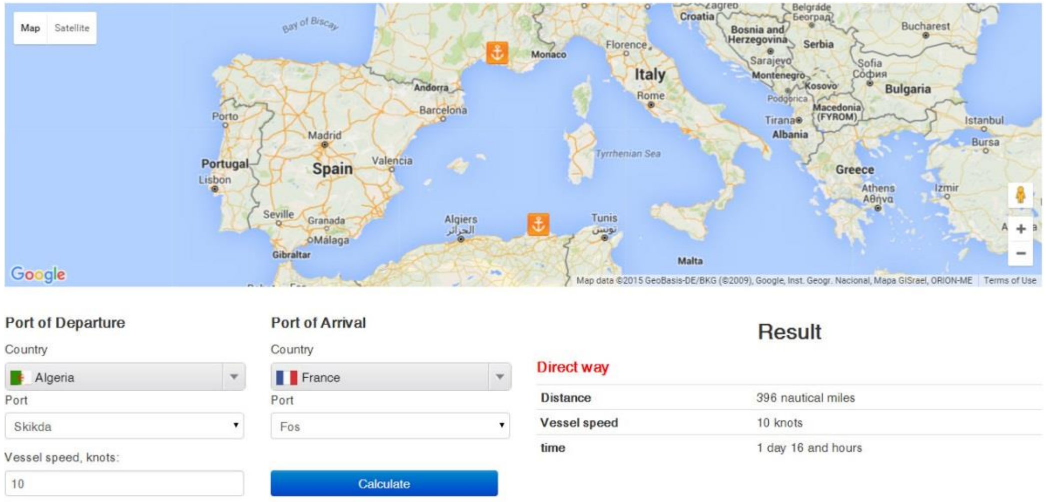

Model incorporates:

- ✓ LNG liquefaction and regasification terminals
  - ➢ Installed capacities
  - ➢ Investment plans
- ✓ Geographical location of corresponding harbors and sea distances
- ✓ Shipping cost own estimation based on
  - ➢ Shipping distance
  - ➢ Average speed of tankers
  - ➢ Average LNG carrier size

LNG terminals data, top:
GIE LNG MAP 2015

Sea distances calculation, bottom:
http://www.sea-distances.org

Content:

Spring 2015: Shale gas in Europe

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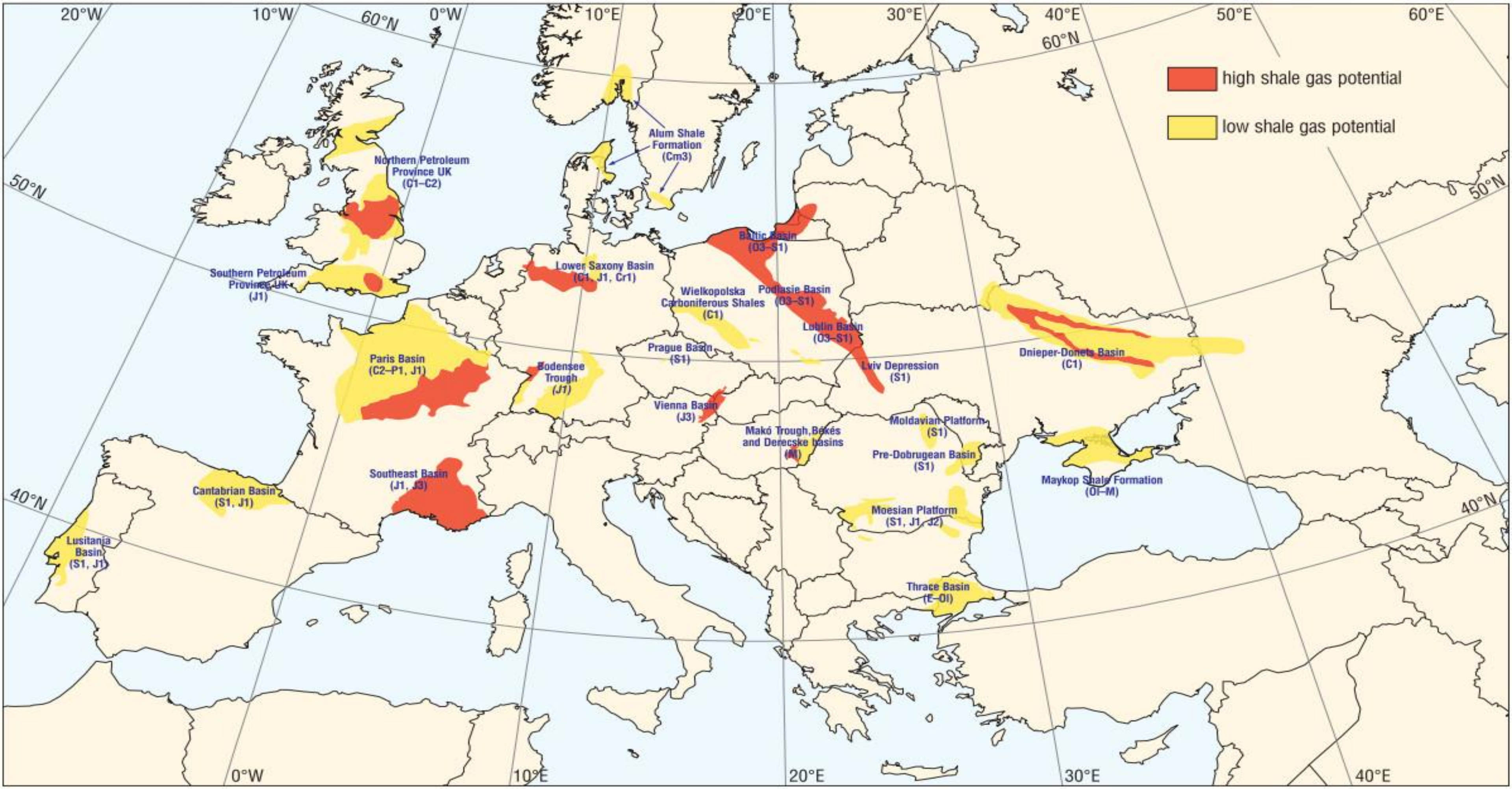

Spring 2015: Shale gas in Europe

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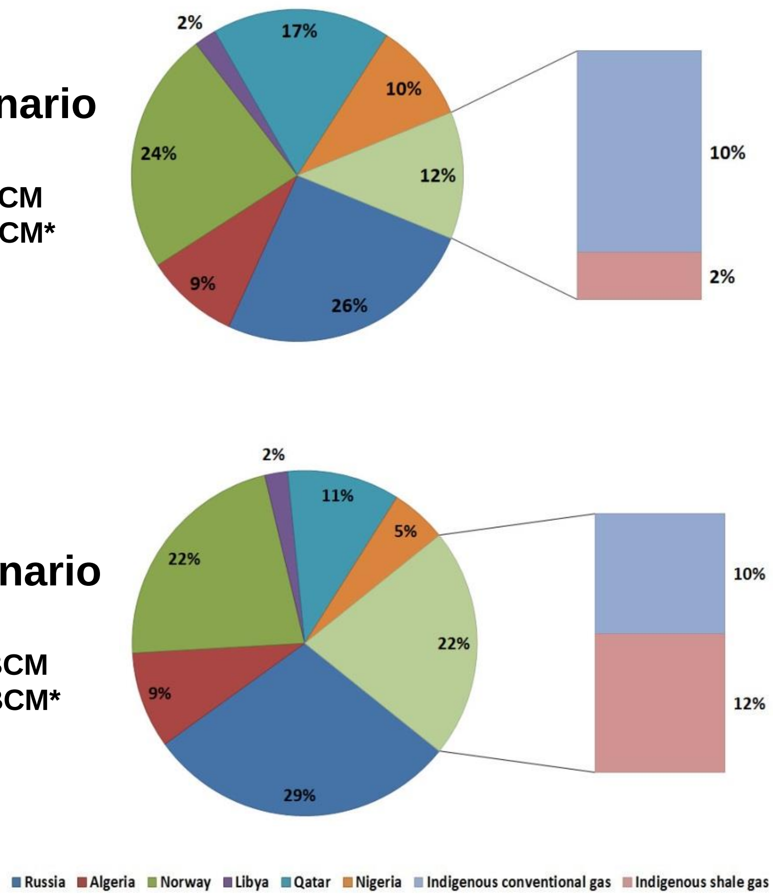
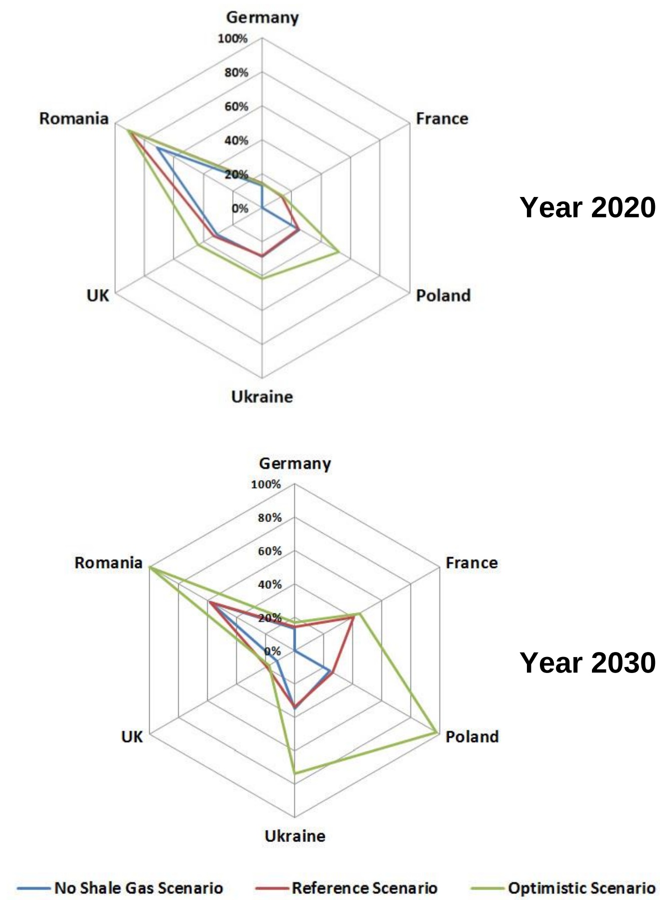
Reference scenario

Consumption: 526.2 BCM
Shale gas: 11.9 BCM*

Optimistic scenario

Consumption: 530.4 BCM
Shale gas: 59.1 BCM*





Autumn 2015: Groningen production cap scenario

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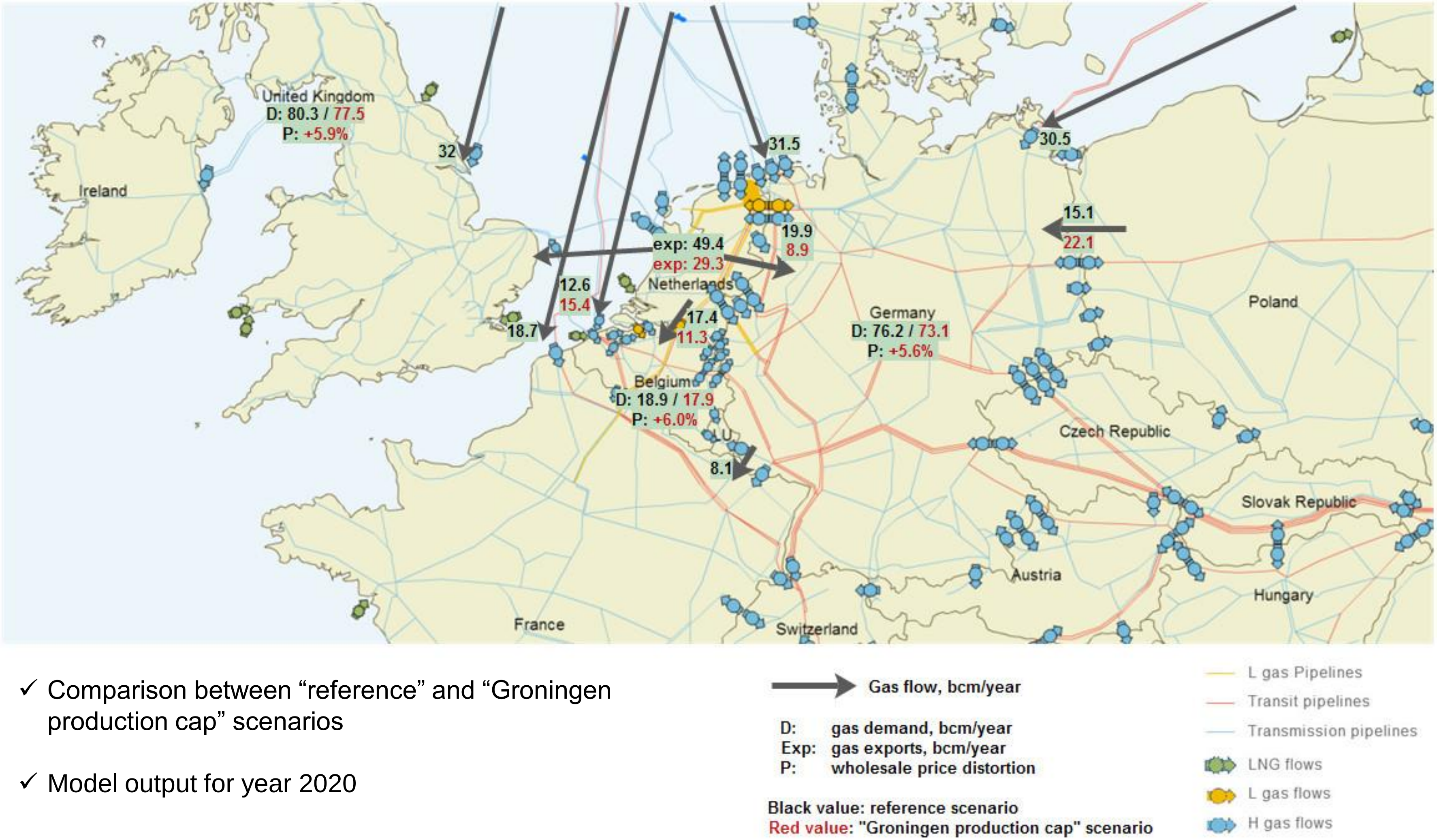
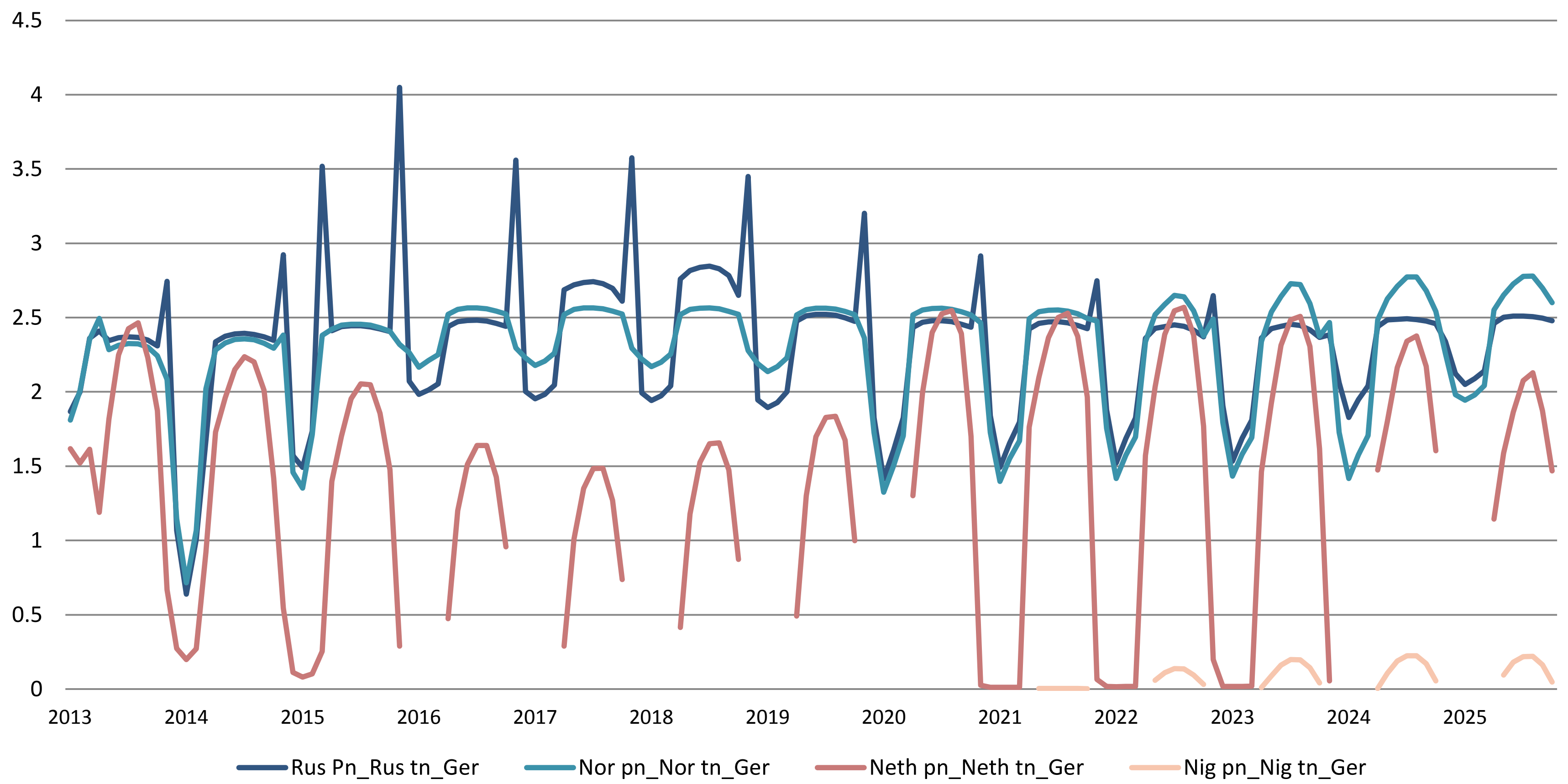
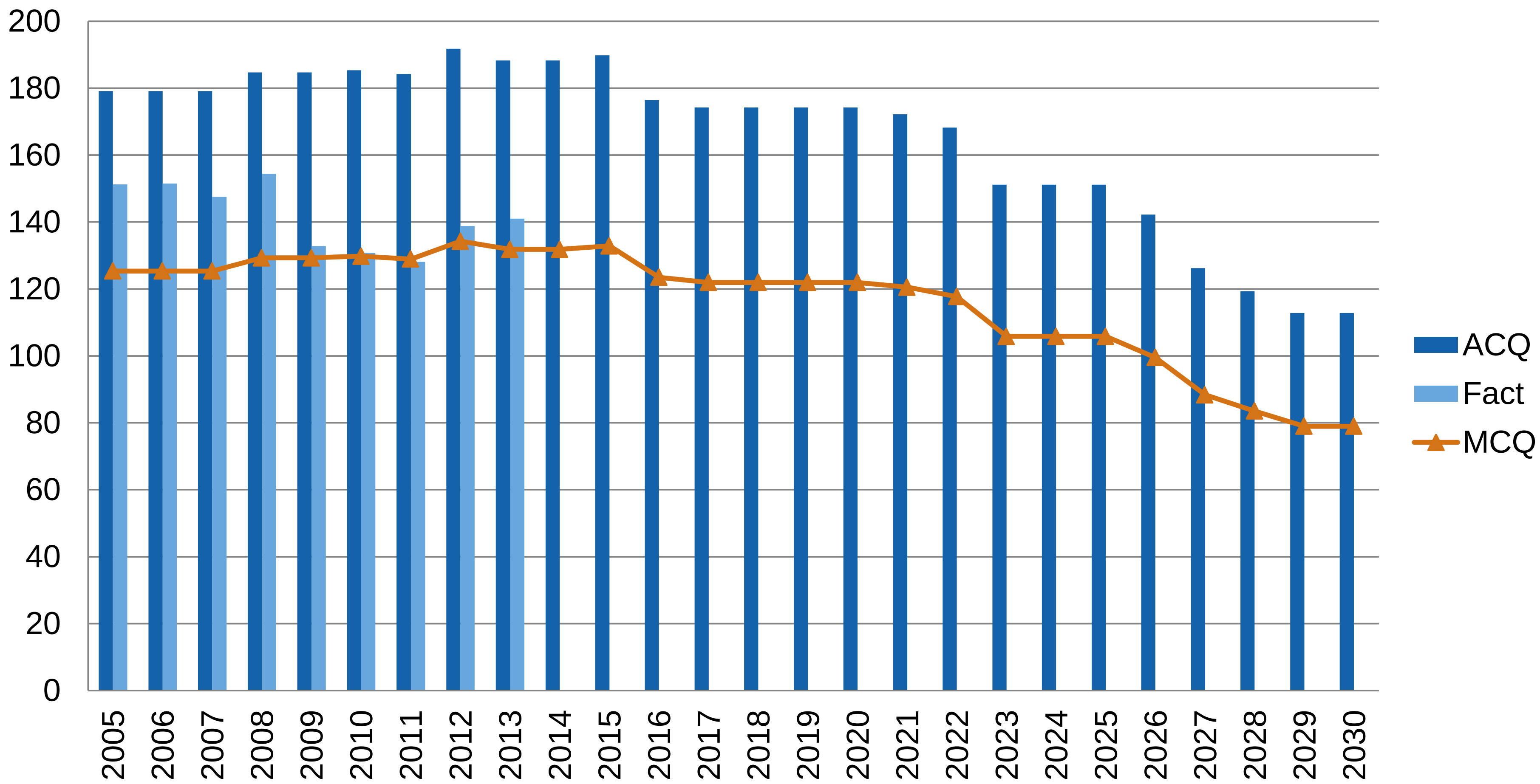


- ✓ Comparison between “reference” and “Groningen production cap” scenarios
- ✓ Model output for year 2020

January 2016: Monthly purchases pattern forecast

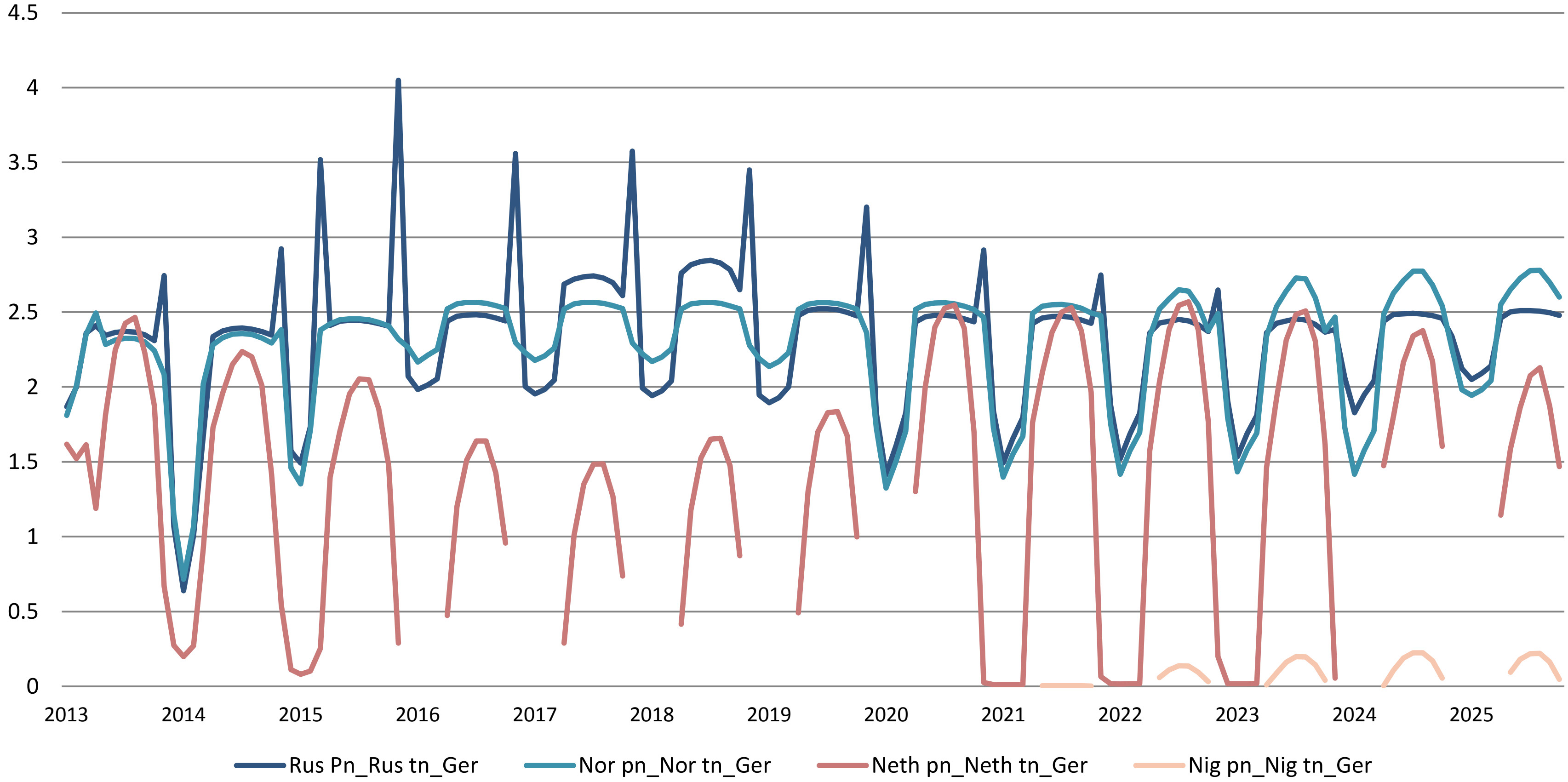


Contract volumes and supply volumes of Russian gas to Europe



Dr. Tatiana Mitrova, Changing Gas Price Mechanisms in Europe and RUSSIA`s gas pricing policy, 38th IAEE International Conference, 2015

January 2016: Monthly purchases pattern forecast



LNG chain

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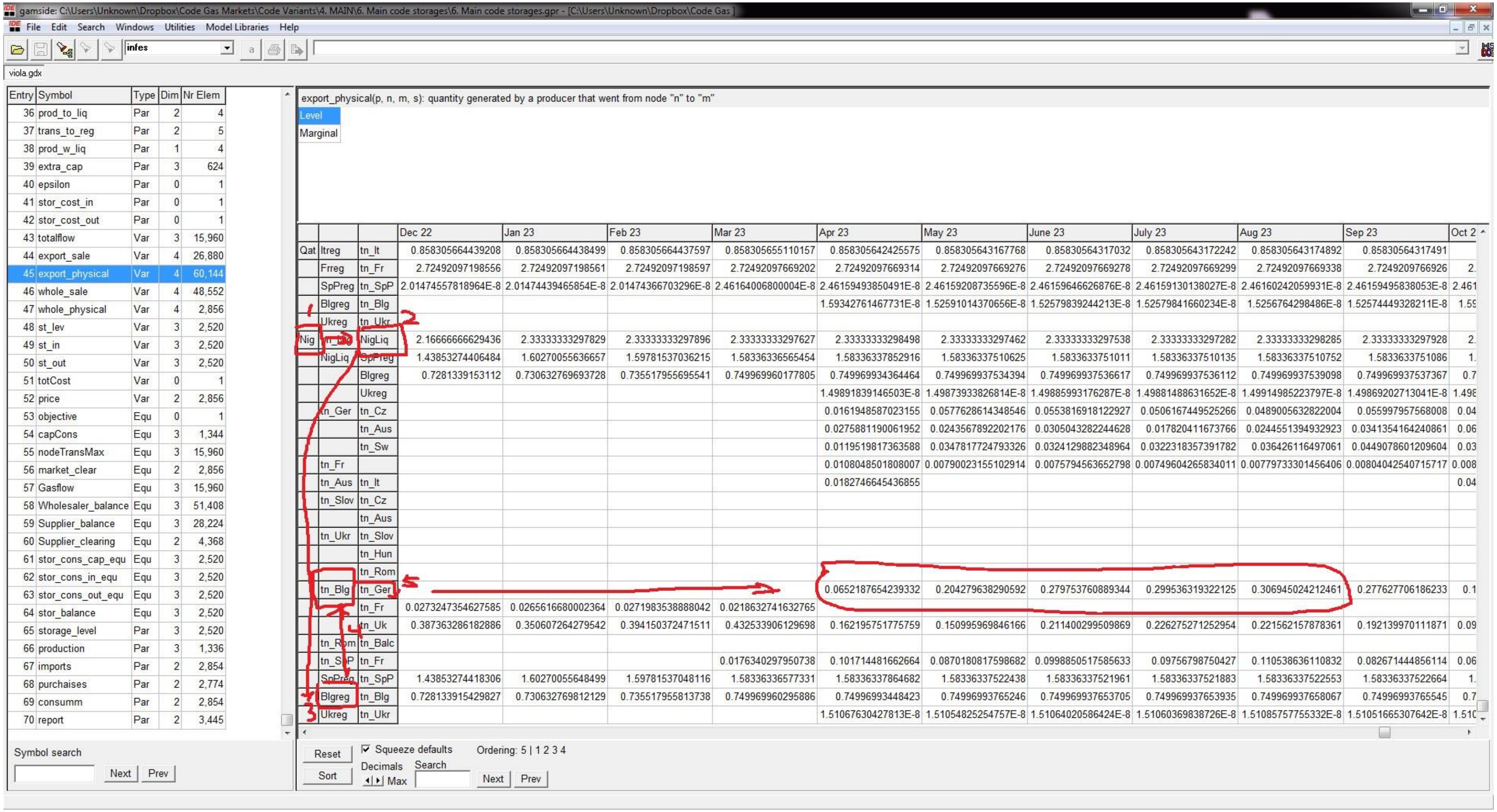

January 2016: German PFC

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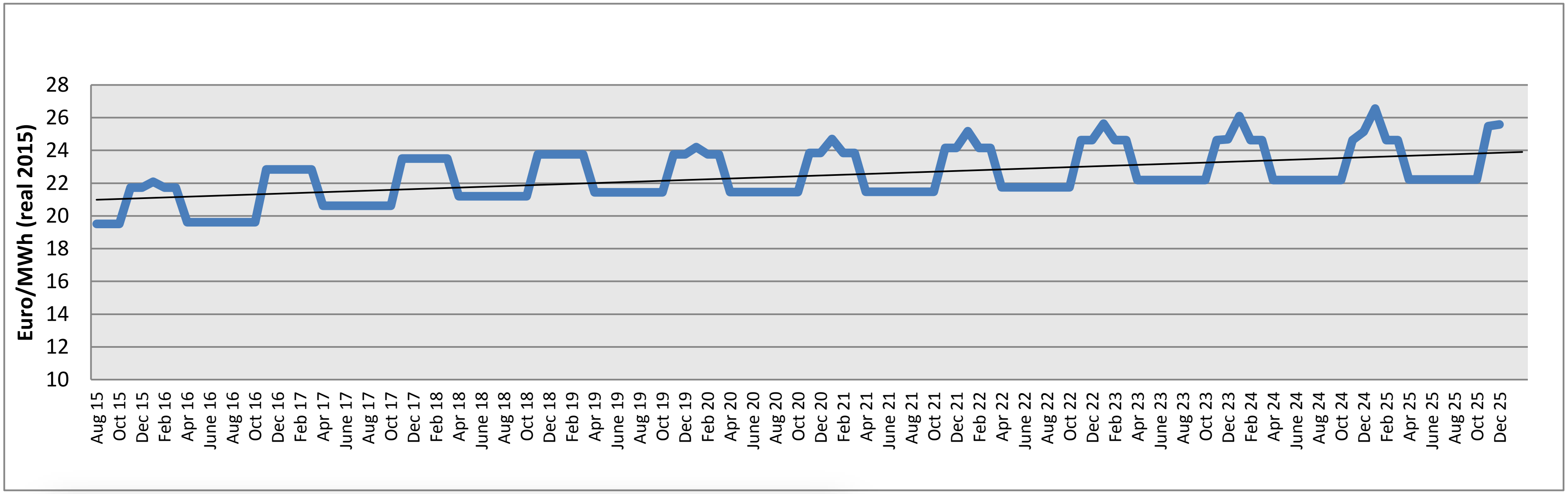

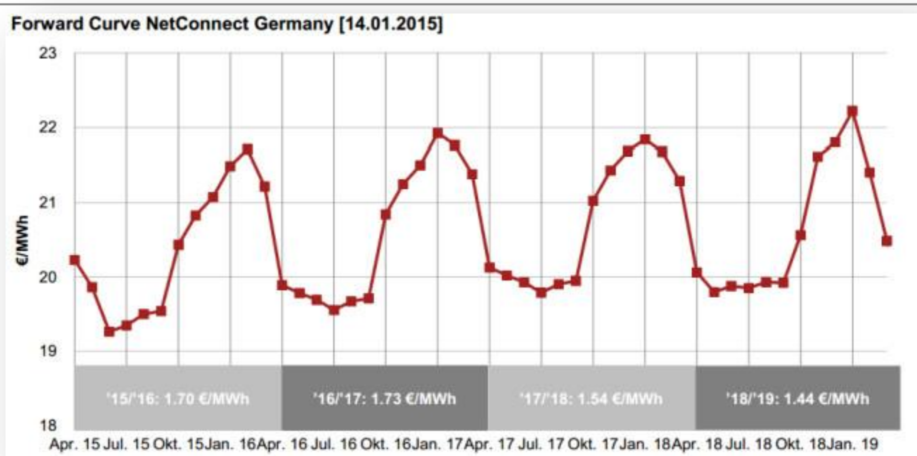

German PFC, top:
Model output, Jan 2016

PFC NCG, bottom:
European Commission report: the role of gas storages in internal market and ensuring security of supply (2015)

Conclusions

- ✓ Competition, security of supply and sustainability are at the core of EU energy policy
- ✓ Present energy systems face a number of major challenges, which need to be addressed urgently and simultaneously
- ✓ Models provide quantitative findings describing the market mechanism that can be used as basis for strategic business decisions, as well as a tool to evaluate and improve market design
- ✓ Further intensive and extensive model improvements are necessary to address complex challenges from real world.

Related literature

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6. Hafner, M., Karbuz, S., Esnault, B., El Andaloussi, H., 2008. Long-term natural gas supply to Europe: Import potential, infrastructure needs and investment promotion. Energy & Environment 19, 1131–1153.
7. https://ec.europa.eu/priorities/energy-union-and-climate_en
8. http://www.entsog.eu/
9. Philipp Offenberg, Changing European Gas Pricing. What role for long-term contracts? 38th IAEE International Conference, 2015
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Thank you!

Appendix A: The Energy Union

The Energy Union means making energy more secure, affordable and sustainable. It will allow a free flow of energy across borders and a secure supply in every EU country, for every European. New technologies and renewed infrastructure will cut household bills and create new jobs and skills, as companies expand exports and boost growth. It will lead to a sustainable, low carbon and environmentally friendly economy, putting Europe at the forefront of renewable energy production and the fight against global warming.

Objectives

- Pool resources, connect networks and unite the EU's power when negotiating with non EU countries.
- Diversify energy sources – so Europe can quickly switch to other supply channels if the financial or political cost of importing from the East becomes too high.
- Help EU countries become less dependent on energy imports.
- Reduce Europe's energy use by 27% or greater by 2030
- Build on the EU's target of emitting at least 40% less greenhouse gases by 2030
- Make the EU the world number one in renewable energy and lead the fight against global warming

https://ec.europa.eu/priorities/energy-union-and-climate_en

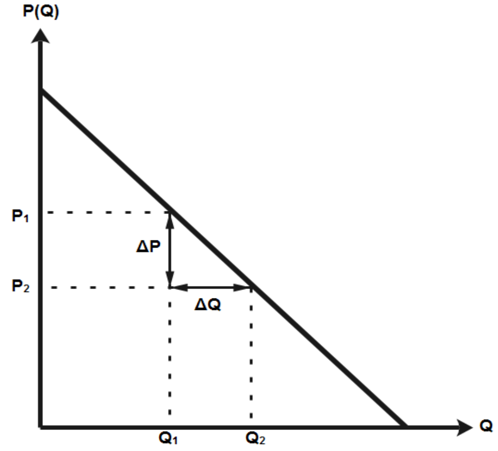
Appendix B: demand function

The affine inverse demand function is commonly expressed in the following way:

$$P(Q) = a + b \cdot Q \qquad (6.1)$$

where *P(Q)* represents the price of a good as a function of quantity demanded *(Q).* The constant *b* represents a slope of the function and the constant *a* is an intersection point with the vertical axis.

Inverse demand function is plotted on a coordinate system with the price on the vertical axis and quantity on the horizontal axis:



Appendix B: demand function

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Estimation of inverse demand function is done around the reference point *(p^{ref}, Q^{ref}):*

$$P^{ref} = a + b \cdot Q^{ref} \qquad (6.2)$$

where Q^{ref} is the total consumption in the node *n.* It aggregates consumption quantities of all the final consumers located in that node.

Using definition of the price elasticity of demand (PED), for the demand function the following definitions can be written (here indices are omitted for the sake of simplicity):

$$Q = -\frac{a}{b} + \frac{1}{b} \cdot p; \qquad \varepsilon = -\frac{\partial Q}{\partial p} \cdot \frac{p}{Q} = \frac{1}{b} \cdot \frac{p}{Q};$$

$$b = \frac{p}{Q} \cdot \frac{1}{\varepsilon}; \qquad a = p - b \cdot Q; \qquad (6.3)$$

Appendix B: demand function

Applying results obtained in (6.3) into (1.1) gives the following inverse demand curve:

$$p = P^{ref} - b \cdot Q^{ref} + \frac{P^{ref}}{Q^{ref}} \cdot \frac{1}{\varepsilon} \cdot Q$$

$$p = P^{ref}(1 - \frac{1}{\varepsilon}) + \frac{P^{ref}}{Q^{ref}} \cdot \frac{1}{\varepsilon} \cdot Q$$

⇓

$$pFC_n - \left(a_n + b_n \cdot \sum_{m \neq n} \sum_{w} whs_{w,m \rightarrow n} \right) = 0, \quad \forall n$$

Appendix C: basic assumptions

- We assume fully liberalized competitive market. Each player is rational.

- Growth rate of annual natural gas demand for European countries will be in line with Anouk Honoré, 2014: The Outlook for Natural Gas Demand in Europe

- We use an average monthly consumption pattern which is calculated for each European country individually based on Eurostat data.

- Gas production/field depletion of the main gas fields for each producer will follow an expected pattern.

- All gas infrastructure projects (pipeline and LNG extensions) which are at a completion stage or planned will be in operation within the declared time. (Model allows switching capacity scenario between only currently constructed / with all planned). All investment databases for Europe are taken from ENSTO-G transparency terminal. Investment plans for Qatar and Africa are taken from numerous sources (reports, news, etc.).

- There are no constraints for LNG vessel routes: from each liquefaction harbor one can reach any regasification harbor. Amount of vessels on a market is unlimited (current version).

- Long-term contracts are not included to the model (current version).

- There are no endogenous investment decisions within a model. (Version currently used for GU project)

- We use gas supply elasticity value of-0.76 which is econometrically analyzed in the following study: "Elasticities of Supply for the US Natural Gas Market", Micaela Ponce and Anne Neumann, 2014.

- The current conflict in east Ukraine will not have a direct impact on transit politics, i.e. Ukraine will continue to exploit gas infrastructure for transit services; no emergencies happen.